Denver, Colorado, July 8, 1930

MEMORANDUM TO THE CHIEF DESIGNING ENGINEER

From        H. M. Westergaard, Senior Mathematician

Subject: Cracks Observed in Dams.

Synopsis

An account is given of observations gathered during a three weeks' trip for the purpose of inspecting cracks and joints in a number of dams. First, the results are summarized in a set of rules for cracks and joints, and thereafter the evidence is presented which leads to these rules.

Introduction

The Boulder Dam Consulting Board, meeting in Denver in April, 1930, recommended a comprehensive study of cracks in dams, the study to include a theoretical analysis combined with a field investigation. This study is one item in a program of investigations of volumetric changes in concrete under conditions applicable to dams.

I was assigned to the investigation of cracks. An analysis of possible states of stresses and deformations around cracks has been in progress for some time and will be reported separately. The present report deals with observations made during a three weeks' field trip (May 18 to June 8) during which the following dams were visited (in addition to the site of Boulder Dam): Elephant Butte Dam, New Mexico
(May 20); Stewart Mountain, Mormon Flat, Horse Mesa, Roosevelt and
Coolidge Dams, Arizona (May 21-22); Big Dalton, Santa Anita, Lake
Hodges, Mulholland, Pacoima, Shaver Lake,Excelsior, Don Pedro, Par-
dee, Calaveras, Lake Spaulding, and Stony Gorge Dams, California
(May 23 to June 2; site of Boulder Dam, May 27); Bull Run Dam, Oregon
(June 4); Arrowrock and American Falls Dams, Idaho (June 5-6).

Acknowledgments

Acknowledgments are made to the following officials of the
Bureau of Reclamation for making this field investigation possible:
Dr. Elwood Mead, Commissioner (Washington, D. C.), Mr. R. F. Walter,
Chief Engineer (Denver, Colorado), and Mr. J. L. Savage, Chief Design-
ing Engineer (Denver). In view of the short time available at each
dam, the effectiveness of this study became to a large extent depend-
ent on the assistance and cooperation extended by the organizations and
engineers in charge of the various dams. Indebtedness is expressed
therefore to the following engineers who, in addition to making the
visits to the dams possible, have in many cases furnished supplementary
information concerning the cracks: Mr. L. R. Flock, El Paso, Texas;
Mr. C. C. Cragin and Mr. F. J. O'Hara, Phoenix, and Mr. C. J. Wells,
Coolidge Dam, Arizona; Mr. Geo. W. Hawley and Mr. W. A. Perkins, Sacra-
mento; Messrs. L. C. Hill, H. W. Dennis; H. A. Van Norman, E. C. Eaton
and R. W. Carlson, Los Angeles; Mr. A. A. Blakesley, Merced; Mr. R. V.
Meikle, Turlock; Mr. F. W. Hanna, Oakland; and Mr. R. C. E. Weber, Or-
land, California; Mr. D. C. Henny and Mr. Ben S. Morrow, Portland, Oregon.
Cracks May Be Classified

By observing cracks and joints in a number of dams one is impressed with a certain regularity of the phenomena. Without referring to computations of stresses, the observed regularity is sufficient to make the statement that in producing each characteristic feature some simple law of nature is at work. The observed regularity alone makes it possible to state rules for the occurrence of cracks and for the behavior of joints. These rules represent a classification of the cracks.

The rules will be stated first without comments. Thereafter the supporting evidence will be presented. There will be added finally some general comments and suggestions.

Rules for Cracks and Joints

1. An expansion joint may be interpreted as a designed crack. The possibility of using sealing devices (especially copper seals) near the upstream face, and the better appearance on the exposed surfaces are obvious advantages. In other respects the joint functions as a crack. By looking at a number of dams, one cannot help acquiring a considerable amount of respect for the expansion joint.

2. Absence of expansion joints leads to cracks at some of the positions where joints would be used in normal practice. These cracks have irregular shapes and are likely to cause difficulties in regard to watertightness.
3. One or more vertical cracks, parallel to the expansion joints, are observed in a number of cases between two consecutive expansion joints. These cracks indicate that a closer spacing of the expansion joint might have been desirable.

4. No single distance can be stated defining the spacing of the vertical expansion joints necessary to avoid major cracks between them. As a general rule, a smaller height of the dam requires a closer spacing.

5. The scheme of letting some of the vertical expansion joints begin near the bottom of the dam and extend to the top while others (for example, alternate joints) begin near the middle and extend to the top, frequently leads to the short joints extending themselves as cracks, so that the combined length of a short joint plus crack becomes about the same as in the case of the long joint.

6. In general, cracks frequently start out from the bottom of a vertical joint. Joints which are too short, are a common cause of cracks.

7. A crack which has formed as an extension of a joint frequently takes a direction somewhat different from that of the joint. As a general rule the crack will approach the abutment in a direction nearly perpendicular to the abutment.

8. A tendency exists for cracks to form, starting from an inclined abutment and extending in a direction nearly perpendicular to the abutment. Such cracks were observed both on the downstream face and in galleries close to the upstream face.
9. The disturbance arising from cracks of the type just mentioned, as measured by the frequency of the cracks, by the occurrence of irregular systems of cracks, and by the amount of seepage of water, is on the whole the greater, the steeper the abutment.

10. A common and, it seems, important type of crack is the following: the crack starts from the abutment at a place where the slope of the abutment is changing so that the lower part of the abutment is steeper than the upper part. These cracks tend toward having a direction which is not far from being perpendicular to a line with the average slope of the abutment.

11. Instead of a crack forming under the circumstances just described a joint in the region where the slope of the abutment changes may open up rather widely. This condition is likely to exist where a gravity wing of relatively small height joins the dam proper.

12. More generally, one may expect cracks or open joints at the junction between two parts of the dam functioning differently; the following cases are examples:

(1) At the junction between a concrete gravity section and the concrete core wall of an earthfill section, an uneven settlement is probable and may cause severe cracking.

(2) In an Aabursen Dam cracks may occur across the corbels near the block filling the cut-off trench.

(3) A region of hard concrete joining one of less stiff concrete along an irregular boundary may lead to cracks along this boundary and to cracks extending into the region of weaker concrete.
13. The condition mentioned under 12(3) may be a result of some irregularity in the construction program or some irregularity made necessary by the method of construction. These irregularities may lead to a junction of hard and less stiff parts, but in any case they represent a disturbance which may account for some cracks and open joints. For example:

(1) Cracks and open joints may be found at a place where a contractor's tower was supported during construction; or

(2) Difficulties of leakage may occur where a tunnel was left open during the major part of the construction and the hole filled when the dam was nearly completed; the difference of age of the two portions may cause leakage in the joint forming the boundary between them.

14. Vertical joints in curved dams or arch dams and cracks in the arches of multiple arch dams are frequently open at the top of the dam through the whole thickness of the dam (or of the barrel) when the water in the reservoir is some distance below the top. There is ample evidence that in most cases these joints and cracks close at least partly as the water rises in the reservoir.

15. Unreinforced buttresses designed without joints are likely to crack in a direction sloping upstream as seen from the bottom. Large cracks of this kind appeared with striking regularity in the buttresses of one multiple arch dam. There is evidence that these cracks change their opening in the course of time; that is, they work as expansion joints. In forming, these cracks seek or start from weak places such as openings for doorways.
16. In properly reinforced buttresses cracks may occur, but the reinforcement performs the function of keeping the cracks small. With the buttress built in horizontal lifts, omission of reinforcement (or omission of reinforcement in one direction) in some of the lifts is not necessarily detrimental. The reinforced lifts (or the fully reinforced lifts) may keep the crack small in the whole buttress.

17. Expansion joints in buttresses following smooth lines indicated by the course of the major cracks mentioned under 15 can serve the purpose of avoiding these major cracks. If such a joint is not continued as far as the need for it exists the joint will tend toward extending itself as a major crack of irregular shape. These cracks are likely to seek weak places, such as openings (doorways).

18. When in a buttress a crack, such as those described under 15 and 17, starts from or seeks out doorway opening, it is likely to be particularly wide at the opening. If reinforcement is placed around the curved top of the doorway and close to the surface, and if the crack crosses this part, it is likely to cause a pulling out of the steel bars, with cracks following the steel bars in addition to the original crack crossing them. Working of the original crack (opening and closing) will then be severe on the concrete around the opening, and is likely to cause spalling off of the concrete.

19. The conditions mentioned under 15, 17 and 18 indicate that in general openings draw cracks toward them and tend toward exaggerating their widths as observed right at the opening. Cracks may be there because the opening is there. This rule is suggested by the observa-
tions of buttresses of the multiple arch and Ambursen dams, but it applies without doubt also to openings in solid dams, such as inspection galleries, sluiceways, and holes for penstocks.

20. A very common type of crack which may be observed in inspection galleries and at other openings, and which (as indicated under 18) can be diagnosed in most cases as existing because the gallery or opening is there, is a crack running along the ceiling of the gallery or opening. This crack may run for a distance and then stop. Sometimes it branches out into two cracks which later unite or disappear. Sometimes the crack follows for a distance the edge formed by the ceiling and one of the walls, and it may continue as a horizontal crack in the wall. As a rule the cracks in the ceilings are not very wide. In several cases where the crack could be observed at an entrance from the outside, it could be followed only a short distance up on the face of the dam. In such cases the crack represents only a minor local effect. In other cases a certain amount of seepage or dripping from the crack indicates that it may extend for some distance into the mass of the dam. In a gallery running parallel to the faces of the dam there may be reason for some concern over these cracks if they are wide; in this case one is led to consider the possibility of the crack extending itself so as to reach one of the faces of the dam, thus dividing the dam into two separate bodies. No evidence was found, however, indicating that this condition had been reached in any of the dams which were inspected.
21. The cracks in buttresses discussed under 15 suggest the possibilities of similar cracks in solid dams. The cracks along ceilings in galleries parallel to the faces of the dam (mentioned under 20) might be cracks of this type, but the evidence in the cases examined is that they are more localized effects. Another place where cracks of this nature may be looked for is in the entrance galleries which are perpendicular to the crest of the dam. Here these cracks should appear as transverse cracks, running through the height of the walls and across the floor and ceiling. Cracks which might be of this type, going part of the way around (for example, traced in walls and ceiling, but not across the floor) were observed in various cases. If these cracks are deep, they might reach, for example, the downstream face and divide the dam into two bodies (compare 20). In the cases examined, however, it is at least highly probable that these cracks were essentially local effects, brought about by the fact that the gallery is there.

22. Horizontal cracks in the walls of galleries are not uncommon. They usually follow the boundary line between two lifts.

23. Cracks sometimes start from a re-entrant corner in a keyway. Such cracks may be observed at the top of the dam, or in galleries. In a gallery the evidence may be furnished by a vertical crack close to a vertical joint. The position of the crack may indicate that a vertical block has sheared off between the joint, the crack, and the nearest protruding vertical plane in the keyway.

24. Irregular systems of cracks are likely to occur at the junction of two galleries or at a place where the cross section of the gallery is changed.
25. If two different openings, for example, a gallery and a sluice-way pass each other with a short distance between the nearest points, a system of cracks may develop in the region where the openings are close together, especially if there is water under pressure in one of the openings.

26. When observed in inspection galleries parallel to the upstream face, vertical joints and cracks are as a rule a little more widely open on the wall nearer the downstream face than on the wall nearer the upstream face. The same may apply to horizontal cracks.

27. Galleries close to the bottom of the dam are not particularly likely to show the widest and most frequent cracks. It may happen very well that the severest cracking occurs in a gallery close to the top.

28. There is observed frequently an irregular distribution of the openings of joints; in going from one end of the dam to the other some joints may be rather widely open and others nearly closed. This irregularity is observed especially near the top of the dam, and especially in the case of a non-symmetrical site.

29. Strain gage readings taken in galleries across cracks or joints throughout a year or more at regular intervals show the cracks and joints to open and close, the variation of width depending especially on the elevation of the water in the reservoir and on the temperature in the gallery.

30. Hair cracks (less than 0.01 inch wide) can be observed in dams very generally on the dry surfaces of concrete. As a rule, these cracks cannot be very deep, and they may be designated as surface cracks; there is little reason to attach a great deal of importance to them.
31. No dam can be expected to be absolutely watertight. Water comes through the drains, and usually some water finds its way to the downstream face through pores, joints, and cracks, forming a few wet spots on the downstream face. If water can reach the downstream face, it can reach the galleries close to the upstream face the more easily. Accordingly, scattered wet spots on the downstream face as a rule indicate a considerable number of wet areas on walls and ceilings of the galleries. Or, scattered wet spots on the downstream face indicate wetness inside the dam.

32. Leakage of water either through the bedrock or through the concrete can be stopped or reduced successfully by grouting.

33. Water leaking through for some length of time leaves a white deposit, either in layers (with ridges up to a couple of inches thick), or, by dripping from the ceilings of galleries in the form of stalactites (in one case as much as 3 feet long). These deposits tend toward stopping the leakage (only, it may be noted, they fill the crack at the less desirable end). In a great many cases white deposits which are now dry tell the story of past leakage, now ceased (it may be noted that a very thin white deposit sometimes is noticed shortly after the forms are removed; a very thin deposit therefore probably indicates merely that some water leaked out of the concrete shortly after it was placed; a thicker deposit on the other hand tells a story of passage of water through the thickness of the structure.
34. There is naturally no simple correlation between the amount of leakage through a crack or joint and the width of the crack or joint, even at a given depth under the water.

35. The problem of watertightness is serious in high dams. High dams are likely to be rather wet.

36. It appears to be possible to obtain an excellent connection between the concrete and the bedrock. Leakage is more likely to occur along seams in the rock than along the junction between rock and concrete.

37. Sand-cement used in some of the earlier dams accomplished successfully its purpose of reducing shrinkage. The dams built with sand-cement compare favorably with other dams built in the same period in regard to watertightness (in that period the control of Portland-cement concrete was not satisfactory). The surfaces of a dam built of sand-cement concrete may last well in a moderate climate, but in a climate with severe winters they will by now have suffered severely by weathering.

38. Too rapid construction of a part of a dam may cause weakness in this part, resulting in cracking.

39. Much may be achieved in the direction of watertightness by rigid control of Portland-cement concrete during construction.
The Evidence

In presenting the evidence leading to the rules just stated the same numbering is used again, but followed in each case by a small letter; for example, comments 20a, 20b, 20c refer to rule No. 20.

1a. Opening and closing of expansion joints, depending on the season and the water load, can be noticed almost anywhere. This feature is brought out particularly clearly in dams where strain-gage readings have been taken systematically across a number of joints, for example, in Pardee and Bull Run Dams (Exhibits G, H and J).

2a. Absence of expansion joints has led to four major cracks in Mulholland Dam. They cross the crest and extend toward the bottom of the dam or toward the abutments. Three of them showed some leakage, and the fourth showed signs of past leakage. The crack closest to the right bank was 0.08 inches wide upstream and 0.06 inches wide downstream at the crest. There were also numerous minor cracks (0.01 inch wide or less), which probably, however, have only a small depth.

3a. Vertical cracks between the vertical expansion joints are not uncommon. Don Pedro Dam and American Falls Dam (compare 4a) furnish good examples.

4a. That the spacing of joints necessary to avoid intermediate cracks is not some constant definite distance is exemplified in American Falls Dam. This dam is a long straight gravity dam the height of which increases slowly as one moves from the left bank toward the
spillway. The spacing of the vertical joints, as they appear in the long inspection gallery, alternates between 33 feet and 39 feet. The intermediate vertical cracks occur decidedly more frequently and regularly at the end where the height of the dam is small than in the higher portion near the spillway.

5a. Indications that the scheme of letting some of the vertical expansion joints extend only a part of the way from the top of the dam toward the bottom leads to the short joints extending themselves as cracks are found, for example, in Elephant Butte Dam (see Exhibit A), Exchequer Dam and Don Pedro Dam.

6a. The cases mentioned under 5a, 7a, and 17a are examples of joints extending themselves as cracks.

6b. A vertical joint in Santa Anita Dam, which had opened rather widely, has extended itself downward as a crack (Exhibit C).

7a. Cracks extending from the bottom of a vertical joint toward the abutment in an inclined direction nearly perpendicular to the abutment may be observed, for example, on the downstream faces of Don Pedro Dam (left bank) and Pardee Dam.

8a. Cracks nearly perpendicular to the sloping abutment were observed on the downstream face and in inspection galleries running up along the abutments near the upstream face in Exchequer, Don Pedro, Pardee, and Lake Spaulding Dams, and in the galleries of Arrowrock Dam.
9a. A comparison between the rather steep galleries at one abutment and the less steep galleries on the other side in Exchequer Dam as well as in Pardee Dam shows a more severe cracking on the steeper side. The same tendency appears also in other dams, for example, in Lake Spaulding and Arrowrock Dams.

10a. The two major cracks in the dome at the left bank in Coolidge Dam start from a part of the left-bank abutment where the slope changes so that the abutment becomes steeper as one moves down. These cracks were open about 0.06 inches when the dam was visited. The weather was then warm and the water in reservoir rather low (see Exhibit B).

10b. Cracks of this type were observed at the downstream face of various other dams; for example, at the right-bank abutment of Pardee Dam.

11a. An example of the case of a vertical expansion joint opening up near a place such as that dealt with under 10a is furnished by Shaver Lake Dam. A joint of this kind near the right end (right bank) lets a little water seep through.

12a. American Falls Dam, which is a straight concrete gravity dam, ends up at the right bank as an earthfill wing with a concrete core wall. The inspection gallery of the dam proper goes into the earthfill portion. At the junction a rather large crack has developed. It is essentially vertical, but zigzags several times on the way from the floor of the gallery to the ceiling. Where it slopes upward toward
the earthfill it was open about 0.10 inches, but it was closed on portions inclined upward toward the dam proper; this crack indicates then two relative motions: (1) a separation; and (2) a settlement of the earthfill portion relative to the dam proper.

12b. Another example of a crack near the junction of two parts functioning differently is furnished by Stony Gorge Dam, which is an Ambursen dam. At a number of the buttresses cracks occurred across the corbels near the block filling the cut-off-trench. Some of these cracks showed a small amount of leakage of water.

12c. In Big Dalton Dam (multiple arch dam), in one of the buttresses, there was observed a three-branched crack forming a "Y". The vertical branch was open only 0.01 inch. The branch pointing upstream was open 0.03 inches, and this branch was rather long. According to Mr. R. W. Carlson, Testing Engineer, Los Angeles Flood Control District, the concrete on the downstream side of the "Y" was poured early and was harder than the concrete through which the long upstream branch of the "Y" extends. Evidently, the case is again that of two parts performing differently, with cracks forming at the junction. The branch extending upstream may be interpreted as being of the type described under 10.

13a. An example of an irregularity caused by a feature in the construction program may be found in Pardee Dam. The horizontal inspection gallery near the bottom has rather wet walls, and at one point a fairly large sloping crack appears in the walls. According
to Mr. F. W. Hanna, Chief Engineer, East Bay Municipal Utility District, this crack is due to the fact that a contractor's tower was placed there during the construction.

13b. Another example of the effect of an irregularity made necessary by the construction program is the following: In Exchequer Dam on the right bank a railroad tunnel was left open during the major part of the construction, and the hole was filled with concrete later. The line marking the edge of the hole on the downstream face is visible, the top being shaped there as a Gothic arch. There is a small amount of leakage at the top of this former opening.

14a. In various cases it was reported by the engineers supervising the arch dams (or arched gravity dams) that the joints at the top tended definitely toward closing up when the water rises in the reservoir (examples: Santa Anita, Mulholland, Exchequer and Don Pedro Dams).

14b. In Big Dalton Dam (multiple arch), it is reported (see Exhibit C) that rain has passed through the cracks in the arches, yet with water in the reservoir the dam is quite tight.

14c. In Lake Hodges Dam (multiple arch), which was visited when the water was near the top, the arches showed some leakage right below the water surface. Farther down there was practically no leakage, but numerous spots of white deposits indicated past leakage.

15a. The grand example of cracks in buttresses which are designed without reinforcement to keep the cracks small and without expansion joints, is found in Lake Hodges Dam (multiple arch).
buttresses were observed from the inspection bridge under the dam. Everyone of these buttresses had a large crack which almost invariably extended from the doorway for the inspection bridge sloping upstream upward (to the springing lines of the arches) and downstream downward from the doorways. The widths measured at the doorways ranged from about 0.1 inch to 0.25 inches. At a couple of places patches had been placed across the cracks, and these patches had cracked, thus indicating that the cracks were working as expansion joints. In one buttress (near the left bank), which was readily accessible for inspection of a larger area of the side, there was noticed another crack farther downstream, similar to and nearly parallel to the one going through the doorway (but not as wide); similar parallel cracks may exist in other buttresses.

16a. In the reinforced buttresses in Stony Gorge Dam (Ambursen) the cracks are small even though some of the lifts in some of the buttresses are reinforced incompletely.

16b. The reinforced buttresses of Steward Mountain Dam (arch dam) have not developed any cracks worthy of notice.

17a. At Coolidge Dam the following conditions were observed in the buttress between the middle dome and the dome on the right bank: An expansion joint extends upward and upstream from a doorway through the buttress. There is reinforcement around the arched top of the doorway, quite close to the surface. The expansion joint has extended itself on the right side of the buttress as a crack, 0.05 inches wide, running along the reinforcement, and showing a tendency of the rein-
forcing bars to straighten out and pull out. On the other side of the buttress there is some spalling off, indicating that the expansion joint has opened and closed.

18a. In Lake Hodges Dam (multiple arch) there is reinforcement around the arched tops of the doorways through the buttresses. The reinforcing bars are close to the surface. In some of the buttresses the large crack reaching the doorway has caused the reinforcing bars to straighten out partly, with cracks formed along the bars, and there is some spalling off of the concrete. The action is the same as that which was described under 17a, and which occurred in one of the buttresses of Coolidge Dam.

19a. The condition in Lake Hodges Dam described under 15a indicates definitely that openings draw cracks. The cracks in the buttresses of Lake Hodges Dam are generally widest at the doorways; that is, the openings exaggerate the cracks.

19b. Mr. H. W. Dennis, Chief Civil Engineer, Southern California Edison Company, expressed the belief that a certain crack observed in a gallery in Shaver Lake Dam existed because the gallery was there.

19c. That cracks may actually be caused by the openings is shown by the fact that in various cases cracks are found to extend only short distances from the openings, when observed on the downstream face of the dam. The cases mentioned under 20a and 20b are examples. In many cases, of course, the cracks observed in the galleries are not local effects.
20a. In Elephant Butte Dam a short crack was noticed at the downstream face, extending about 1.5 feet upward from the top of one of the openings intended for penstocks. At the lower end this crack was 0.03 inches wide.

20b. Similar short cracks were observed over a couple of the entrances to the galleries on American Falls Dam.

20c. A similar crack, but perhaps 20 feet long was observed over one of the entrances on Exchequer Dam (left bank).

20d. Cracks in ceilings in galleries running in the direction of the gallery were observed on Exchequer, Don Pedro, Pardee, Lake Spaulding, Arrowrock and American Falls Dams.

21a. A crack parallel to the face of the dam was observed in Shaver Lake Dam on one of the entrance galleries. This crack has been studied closely by Mr. H. W. Dennis, Chief Civil Engineer, Southern California Edison Company (Exhibit E).

21b. Cracks of this kind are found also in Exchequer Dam (Exhibit F) and Pardee Dam (Exhibit G).

22a. A good example of horizontal cracks on galleries is found in American Falls Dam. Some of the vertical cracks found in this dam jog in crossing the horizontal cracks, thus indicating that the horizontal cracks were formed first.

23a. At Calaveras Dam which is under construction it was stated that some cracks had begun to form starting from re-entrant corners of keyways. No such cracks, however, could be seen on the day when this dam was visited.
23b. A number of such cracks were noticed at the top of Lake Spaulding Dam.

23c. A vertical crack close to a vertical joint and evidently starting from the keyway was observed at several places on the galleries of American Falls Dam.

24a. Examples of irregular systems of cracks at the junction of two galleries, or where the cross section of the gallery changes, are found in Exchequer Dam (Exhibit F) and in American Falls Dam, respectively.

25a. In Elephant Butte Dam one of the entrance galleries passes one of the sluiceways so that the distance between the nearest points is probably only about 5 feet. An irregular system of small cracks has appeared on the wall of the gallery (Exhibit A).

26a. The following table shows, as an example, the openings of some of the vertical joints, measured in the galleries of Shaver Lake Dam. These galleries are along the upstream faces of the dams. It is noted that generally the joints are open more widely on the downstream wall than on the upstream wall. The same tendency was observed in other dams.

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<th>Openings of Some Vertical Joints in Inches</th>
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<tr>
<td>Upstream Wall</td>
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<td>Downstream Wall</td>
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27a. In American Falls Dam the gallery closest to the top showed the most severe cracking (one longitudinal crack open 0.10 inches).

28a. The irregular distribution of openings of joints may be observed in most dams, especially at the top. For example, the top of Santa Anita Dam, which has a decidedly non-symmetrical site, showed a couple of widely open joints (0.15 inches and 0.10 inches maximum width) on the flatter side. Otherwise the openings were very small.

29a. The strain-gage readings taken systematically across cracks or joints in Pardee Dam (Exhibit G) and Bull Run Dam (Exhibit J) show clearly the working of the cracks and joints.

30a. Hair cracks can usually be observed on any dry surface of a concrete dam that one is able to get close to. American Falls Dam, for example, showed a system of hair cracks on the downstream face with a spacing of the order of 5 feet.

31a. Lake Spaulding Dam was decidedly the wettest of the dams that were inspected. Water trickled down at many places on the downstream face, and the galleries, correspondingly, were very wet. Exchequer, Don Pedro, and Pardee Dams had some scattered wet spots on the downstream faces and were rather wet in the galleries. Elephant Butte and Bull Run Dams can be classified as dry dams.

31b. Mormon Flat Dam, which has no inspection galleries, has a wet spot with a horizontal upper edge on the downstream face at the right abutment. According to the observations in the galleries
of other dams, this wet spot indicates a considerable wetness inside the dam in this particular region.

32a. Grouting has reduced the leakage in most of the dams that were visited.

33a. White deposits which are evidence of past leakage were observed at all the dams that were in service. In the cases of Exchequer, Don Pedro, and Pardee Dams the fairly large areas of white deposits, now dry, on the downstream faces, indicate a notable reduction of the leakage. The deposits in the galleries also indicate a reduction of leakage.

33b. Stalactites formed by water dripping from cracks in ceilings in galleries are not uncommon. Usually they are only a few inches long, but in Lake Spaulding Dam some were found that were about 3 feet long.

34a. That wetness and size of opening have no simple correlation is a simple consequence of differences of the depths of the cracks, and differences in the effectiveness of the seals and in the success of the grouting operations.

35a. All the high dams illustrate the seriousness of the problem of watertightness.

36a. An undergallery in Shaver Lake Dam cut so that the joint between bedrock and concrete could be inspected approximately along the original stream line showed an excellent connection between concrete and bed rock.
37a. Elephant Butte and Arrowrock dams, which were built with sand-cement compare very favorable in regard to watertightness with Lake Spaulding Dam which belongs to the same period, and which was built with Portland-cement concrete. The surfaces are in quite good condition at Elephant Butte where the climate is favorable, but not at Arrowrock where the more severe climate has caused a noticeable amount of weathering.

38a. A part of a section in Bull Run Dam near the center and near the bottom was reported to have been built too fast, and as a result a crack formed in the inspection gallery (this crack could not be discovered when the dam was visited).

39a. Bull Run Dam is an example of a dam built particularly well with modern methods of rigid control of the concrete. The expansion joints open and close in this dam (Exhibit J), but there are practically no cracks.

General Comments and Suggestions

A. Large concrete dams are structures on which heavy loads and severe conditions are at work. Like other structures built by man, dams require watching and maintenance, even those with the most solid sections.

B. Inspection of cracks, joints and seepage is a desirable method of watching the structural behavior of a dam. It is important that new cracks be discovered as early as possible.
C. Systematic strain-gage readings at a number of cracks or joints through some period, such as have been obtained at Pardee Dam by Mr. F. W. Hanna and at Bull Run Dam by Mr. Ben S. Morrow are a particularly useful method of watching a dam.

D. The bedrock is a part of the structure.

E. Grouting of cracks, joints and seams in the concrete and bedrock are an essential part of the maintenance of the dam as a structure.

F. In building a high dam control of the concrete, even to the extent of making life miserable for the contractor, is profitable.

G. Inspection galleries are desirable.

H. In a very high dam it appears desirable not to put the galleries quite so close to the upstream face as would be reasonable in dams of smaller height.

I. Stresses due to shrinkage present a problem which is farther from a final solution than is the problem of stresses due to loads. It is desirable that extensive investigations be made for the purpose of obtaining cement and concrete with low shrinkage.
Exhibits

The exhibits consist of material supplied by engineers who have cooperated. The following are submitted:

A. "Memorandum Report on Survey of Cracks in Elephant Butte Dam" by L. R. Flock, Superintendent, Bureau of Reclamation, El Paso, Texas. Supplemented by drawing showing the position of gallery B relative to sluice No. 2 in Elephant Butte Dam.

B. Data concerning Coolidge Dam, furnished by Mr. Clarke J. Wells, Assistant Engineer, Indian Field Service, Coolidge Dam, Arizona: (1) Letter dated June 26, 1930; (2) sketch showing position of leakage; (3) drawing showing the location of the three major cracks in the two side dikes.

C. Three reports to Mr. E. C. Eaton, Chief Engineer, Los Angeles Flood Control District, by Mr. R. W. Carlson, Testing Engineer, concerning cracks in dams of the Los Angeles Flood Control District: (1) Big Dalton Dam; (2) Big Santa Anita Dam; (3) Pacoima Dam.

D. Data concerning Mulholland Dam, furnished by Mr. H. A. Van Norman.

E. Letter from Mr. H. W. Dennis, Chief Civil Engineer, Southern California Edison Company, Los Angeles, dated June 6, 1930, concerning a crack in Shaver Lake Dam, parallel to the face of the dam, observed in one of the entrance galleries. Drawing sent with the letter, showing results of strain-gage readings across this crack. Drawing showing plan, elevation and sections of the dam.
F. Drawing furnished by Mr. R. V. Meikle, Chief Engineer, Turlock Irrigation District, Turlock, California, showing cracks in a gallery in Exchequer Dam.

G. Data concerning cracks and joints in Pardee Dam, furnished by Mr. F. W. Hanna, Chief Engineer and General Manager, East Bay Municipal Utility District, Oakland, California, especially strain-gage readings and records of temperature.

H. Memorandum by Mr. R. E. Glover, Associate Engineer, Bureau of Reclamation, Denver, on "Correlation between water-surface elevation, temperature, and crack width at Pardee Dam, based on data furnished by Mr. F. W. Hanna, Chief Engineer and General Manager, East Bay Municipal Utility District, Oakland, California."

I. Four drawings, furnished by Mr. R. C. E. Weber, Superintendent, Bureau of Reclamation, Orland, California, showing cracks in Stony Gorge Dam in buttresses Nos. 22, 23, 25 and 51.

J. Data concerning Bull Run Dam, furnished by Mr. Ben S. Morrow, Chief Engineer, Water Bureau, Portland, Oregon, especially strain-gage readings across joints and records of temperature.
K. Drawings of dams.

1, 2. Stewart Mountain Dam.

3, 4. Mormon Flat Dam.

5. Horse Mesa Dam.

6. Exchequer Dam.

7, 8. Don Pedro Dam.

L. Six photographs furnished by Mr. W. A. Perkins, Department of Public Works, Sacramento, California, of four dams which are not included in the report: Melones, Kennedy, Diguito, and Little Rock Dams.

Letter from Mr. Perkins, dated August 4, 1930.

* * * *
Supplementary Reports Concerning the Individual Dams

The dams will now be discussed one by one in the order in which they were inspected (which is the order in which they were mentioned in the introduction). The accompanying drawings showing cracks are only sketches, indicating the conditions, and must not be interpreted as drawings to scale.

Elephant Butte Dam, New Mexico, gravity dam, 306 feet high, completed 1916, was visited on May 20 with Mr. L. R. Fiock. See Exhibit A (report by Mr. L. R. Fiock and drawing showing relative positions of sluice and gallery). Comments referring to this dam have been made under 5a and 6a (tendency for joints through a part of the height to extend themselves as cracks is indicated), 19c and 20a (local crack extending from top of opening for penstock), 25a (two openings too close together, causing system of cracks), 31a (dryness), and 37a (sand-coment).

There is little to add to the report of Mr. L. R. Fiock, Exhibit A, and to the comments already made. The supplementary drawing, Exhibit A, showing the position of gallery B relative to sluice No. 2 was made in the Denver office of the Bureau of Reclamation from the original drawings. The dam was not built in all details according to these original drawings, yet the supplementary drawing gives a reasonably accurate picture of the situation: the sluice and the gallery pass each other fairly closely. Mr. Fiock suggests in his report that the closeness of the two openings may account for the fairly recent development of systems of small cracks in that wall of the gallery which is closer to the sluice. Fig. 1 is copied from
sketches made during the inspection, and shows the general character of the systems of cracks developed at the places marked B_3 and B_1 on one of the drawings in Mr. Flack's report. B_3 is about 45 feet from the opening. Water stains were noted at the place B_1. The system of cracks at B_1 extends a part of the way across the floor of the gallery. At an intermediate place B_2 a system of cracks was noted similar to those at B_1 and B_3, but less developed.

Fig. 2 shows the small local crack over an opening, referred to under 20a.
FIG. 1

ELEPHANT BUTTE DAM

Sketch of systems of fine cracks in gallery B, observed by looking toward the left-bank abutment and toward the nearby sluice.

FIG. 2

ELEPHANT BUTTE DAM

Six openings for penstocks at downstream face. Short local crack at one of them.
Stewart Mountain Dam, Arizona, arch dam, about 200 feet high, completed recently, was visited on May 21, with Mr. F. J. O'Hera. The photograph, Fig. 3, and Exhibit K, drawings 1 and 2, show the dam. Comment 16t referred to the observation that the buttresses, which are reinforced, did not show any important cracks. No crack of any significance was noticed. About 8 gallons of water per second were discharged from the drains under the ogee section.

Mormon Flat Dam, Arizona, arch dam 225 feet high, built 1923-1225, was visited on May 21, with Mr. F. J. O'Hera. The photographs, Figures 4 and 5, and Exhibit K, drawings 3 and 4, show the dam. In comment 31b a wet spot on the downstream face near the right abutment was mentioned. Figures 4 and 5 show this spot; the water is trickling down from a horizontal line. There was also a small amount of leakage through the rocks on the right bank. Some small cracks, not more than about 0.01 inch wide were noticed extending across the top of the dam. At the first construction joint from the right-bank side a crack 0.01 inch wide extended up through the parapet on the upstream side. There appeared to be evidences of some crushing at one place along this crack, indicating the tendency for the joint to open and close. The central joint as observed on the parapets was open about 0.05 inches at the downstream side and 0.02 inches at the upstream side. This joint showed the greatest opening, yet no seepage was visible farther down (a tar-paper is used here for water-tightness). No significant cracks were visible from the top, or through field glasses from the shore upstream.
A joint which happens to go through some steps of the stairs at the beginning of the ogee-section may be described as being not good looking; the joint was open only 0.01 inch, but some of the steps showed corners broken off. Mr. O'Hara remarked that this experience with a detail had led to a preference for ramps rather than steps at similar places in later designs.

**Horse Mesa Dam, Arizona**, arch dam 311 feet high, built 1926-1927, was visited on May 21, with Mr. F. J. O'Hara. Exhibit K contains a drawing of this dam, and Fig. 6 is a photograph of the dam. No significant cracks were observed. The dam appeared to be in very good condition.

**Roosevelt Dam, Arizona**, gravity-arch dam, 280 feet high, completed 1911, was visited on May 21, with Mr. F. J. O'Hara, rather late in the afternoon. Fig. 7 is a photograph of the dam. The reservoir was only about 4 per cent full. The dam appeared to be in good condition.
Fig. 5

Mormon Flat Dam. Photograph. Some water is trickling from a horizontal line near the right bank.
Fig. 6

Horse Mesa Dam. Photograph furnished by Mr. F. J. O'Hara.
Fig. 7

Roosevelt Dam. Photograph furnished by Mr. F. J. O'Hara.
**FIG. 8**

**COOLIDGE DAM**

Sketch indicating positions of two major cracks at the left bank.

**FIG. 9**

**COOLIDGE DAM**

Sketch of crack at doorway thru the intermediate buttress closer to the right bank. (a) Looking toward the middle dome. (b) Looking toward the right bank.
Coolidge Dam, Arizona, triple-dome dam, 250 feet high, built 1926-1929, was visited on May 22, with Mr. Clarke J. Wells and Mr. F. J. O'Hara. See Exhibit B (data supplied by Mr. Clarke J. Wells) and the comments under 6a and 17a (cracks or expansion joints extending themselves as cracks), 10a (cracks starting from point of changing slope of abutment), and 18a (reinforcement along opening pulling out). The domes had three major cracks, which are shown on one of the drawings furnished by Mr. Wells, in Exhibit B. All three cracks extended from the abutments up into the domes. Scaffolds had been built inside the domes along these cracks, and grouting operations were in progress. One of these major cracks appeared in the right-bank dome, none in the middle dome, and two in the left-bank dome. The latter two have been mentioned under 10a. Fig. 8 is a rough sketch of them. These two cracks were about 0.08 inches wide. The engineers in charge stated about these cracks that in cooler weather they had been open about 0.10 inches.

Inside the right-bank dome, on the right buttress vertical hair cracks were visible, 0.01 inch wide at most, 4 to 5 feet apart and perhaps 15 feet long. These cracks frequently jogged at the horizontal construction joints. Marks of past seepage were noticeable at scattered spots. Only one spot on this dome showed some water actually seeping through. There was, however, some seepage through the rock at one place (see Exhibit B). In the intermediate buttress nearer the right bank the condition was
observed which is sketched in Fig. 9 and described in comment 17a (also referred to under 6a and 18a).

**Big Dalton Dam.** California, multiple-arch dam, 165 feet high, built 1928, was visited on May 23, with Mr. R. W. Carlson. See Exhibit C (report by Mr. R. W. Carlson to Mr. E. C. Eaton) and comments under 12c (Y-shaped formation of cracks where a harder portion of a buttress joins a portion less hard) and 14b (rain coming through cracks in arches when the water is low in the reservoir). Fig. 10 is a sketch of the Y-shaped formation of cracks described under 12c. Fig. 11 is a sketch indicating the way that the numerous deposits (probably containing a good deal of magnesia) are distributed in spots on the inside of the barrels. These spots tell the story of past leakage. In spite of these deposits and in spite of the reported condition that some cracks 0.01 inch wide had let rain through (comment 14b), the barrels appeared to be in good condition; the cracks evidently tend to close when the water rises in the reservoir.
Fig. 10
BIG DALTON DAM
Sketch of Y-shaped formation of cracks in abutment at left bank.
(looking toward the left bank)

Fig. 11
BIG DALTON DAM
Sketch indicating the distribution of deposits on the underside of the barrels.

Fig. 12
BIG SANTA ANITA DAM
Sketch showing the two joints on the flatter side of the canyon which have appreciable openings.

Fig. 13
BIG SANTA ANITA DAM
Sketch showing places of seepage on the downstream face.
Big Santa Anita Dam, California, arch dam 225 feet high, built 1926-1927, was visited on May 23 with Mr. R. W. Carlson. See Exhibit C (report by Mr. R. W. Carlson to Mr. E. C. Meton) and comments under 6b (joint extending itself as crack), 14a (joints tending to close when the water rises in the reservoir), and 28a (unsymmetrical site). Fig. 12 is a sketch indicating the only two joints that showed wide openings at the top; they are both on the side of the flatter abutment. It was stated by Mr. R. W. Carlson that the joints tended to close with rising temperature and rising water. On the particular day the water was 36 feet below the top of the dam; the openings had been wider before the water reached this level. Fig. 13 indicates the wet spots occurring especially on the flat side. The seepage through one of the spots on the side of the flatter abutment was estimated to be about \( \frac{1}{2} \) gallon per minute. Some springs appeared in the seams of the granite rock about 200 feet downstream from the dam.

Lake Hodges Dam, California, multiple arch dam, 136 feet high, built 1917, was visited on May 24, with Mr. L. C. Hill and Mr. W. A. Perkins. Comments have been made under 14c (leakage right below water surface, leakages farther down having stopped), 15a (cracks in buttresses), 18a (cracks especially wide at doorways, and reinforcement around opening pulling out), and 19a (openings draw cracks). Fig. 14 is a photograph of the dam. The water in the reservoir was close to the top of the spillway. Throughout the high part of the dam the barrels, which are
inclined 45 degrees, can be observed conveniently from an inspection bridge, which is near the bottom. The barrels showed a large number of deposits of loose material (probably a fairly large portion of magnesite), distributed about as in Fig. 11. Some of the spots were moist, but actual leakage was observed at the top only, near the water line (see comment 14c; compare the case of Big Dalton Dam). The barrels were found on the whole to be serving their purpose, the cracks having closed or been sealed except at the top.

The buttresses are numbered from the right bank toward the left, buttress No. 21 being the one farthest toward the left bank that could be observed from the inspection bridge. In walking through the length of this bridge one passes through doorways in the buttresses. The photograph in Fig. 15 and the sketch in Fig. 16 show one of the rather large cracks in the buttresses. All of the buttresses that could be observed from the inspection bridge showed cracks of the type indicated in Fig. 17. These cracks have been mentioned in comments 15a, 18a, and 19a. They range in width, observed at the doorways, from 0.10 inches to 0.25 inches. The sketches in Figures 18-20 illustrate further the severe conditions found in some of the buttresses. The cracks invariably had the greatest width at or near the doorway. The fact that the cracks go through the patches of mortar, as shown in Figures 15, 16, and 18, shows that the
opening of the cracks has progressed since these patches were placed.

By looking at the buttresses from the inspection bridge no other cracks were observed of the magnitude of those indicated in Fig. 17 and extending from the doorways. Most of the buttresses were rather inaccessible for observation except from the inspection bridge. One of them, however, No. 21, near the left bank, could be observed along the bottom. There was found in this buttress another crack, about 0.03 inches wide, essentially parallel to that shown in Fig. 17, and closer to the downstream edge of the buttress. It is possible that other buttresses have similar additional cracks.
Fig. 14

Lake Hodges Dam. Photograph furnished by Mr. W. A. Perkins.

Fig. 15

Lake Hodges Dam. Photograph of buttress No. 19 (looking toward the right bank), taken by Mr. W. A. Perkins from the inspection bridge on the day of the visit to the dam. The picture shows a large crack, which passes through a patch of mortar and between some plugs for strain gage points. Compare Fig. 10.
Opening in buttress.

FIG. 16
LAKE HODGES DAM
Sketch of Buttress No. 19, showing the same features as Fig. 15

FIGS. 17 TO 20
LAKE HODGES DAM
Sketches showing conditions of buttresses, especially at the doorways.

Fig. 17
Typical Crack

Fig. 18
Buttress No. 18

Fig. 19
Buttress No. 15

Fig. 20
Buttress No. 13
Mulholland (Hollywood) Dam, California, was visited on May 26, with Mr. Wm. H. Tate, Mr. Julian Hinds, and Mr. W. A. Perkins. See Exhibit D and comments under 2a (absence of expansion joints having led to four major cracks) and 14a (vertical cracks tending to close when the water rises). The dam is arched, and is approximately 200 feet high. The water in the reservoir is being kept 25 feet below the top of the dam. Fig. 21 is a sketch indicating the four major cracks, A, B, C, and D. Crack B showed signs of past leakage at the top. Crack C is the only one reaching down to the elevation 135 feet below the top, the others having joined the abutments before reaching this depth. Crack C at this depth was only about 0.01 inch wide; it was surrounded at this depth by a dark moist area. Crack D had been corked, material having been driven in perhaps a couple of inches; only one grout pipe was noticed. Crack D could be seen on the upstream side through field glasses. For further information concerning these cracks, see Exhibit D.

A large number of minor cracks, about 0.01 inch wide, 3 to 5 feet apart, were noticed both at the top and at the lower elevation where the conditions were examined, that is 135 feet below the top. At this elevation there were scattered small wet spots. The minor cracks appear to be only surface cracks.
FIG. 21
MULHOLLAND DAM
Sketch indicating the four major cracks A, B, C and D.

FIG. 22
PACOIMA DAM
Sketch indicating moist areas and cracks near the bottom.
Fig. 23

Pacoima Dam. Photograph taken on the day of the visit by Mr. W. A. Perkins. The bright strips indicate trickling water.
Pacocina Dam, California, arch dam, 380 feet high, built 1926-1928, was visited on May 26, with Mr. R. W. Carlson and Mr. W. A. Perkins. See Exhibit C (report by Mr. R. W. Carlson to Mr. E. C. Eaton). On account of the height of this dam the question of water-tightness is of particular interest. The comment was made by Mr. R. W. Carlson that the efforts to use a dry mix of concrete appeared to have been carried too far in the lower portion of this dam, with the result that the concrete shows signs of being a little porous in this portion. There were some moist areas on the downstream face, as indicated in the sketch in Fig. 22. This sketch also indicates roughly the positions of a couple of cracks. In the photograph in Fig. 23 the bright strips indicate water trickling down on the downstream surface. For further information concerning this dam, see Exhibit C.

The dam appeared to be in good condition.

Shaver Lake Dam, California, gravity dam, was visited on May 28 with Mr. H. W. Dennis and Mr. W. A. Perkins. See Exhibit E (letter from Mr. Dennis concerning a particular crack, and drawing of the dam). Comments have been made under 11a (joint opening up where the slope of the abutment changes), 19b (crack possibly caused by a gallery), 21a (crack parallel to the face of the dam), 26a (joints open more widely on downstream walls of galleries than on upstream walls), and 36a (the under-gallery shows a good connection between concrete and bedrock). Interest is attached to the crack which is sketched in Fig. 24, and to which
reference has been made under 19b and 21a. This crack is in an entrance gallery on the side of the right bank. Information concerning this crack is given in the letter from Mr. H. W. Dennis in Exhibit E. If this crack should extend itself far into the mass of the concrete, reaching either the upstream or the downstream face, and especially if water under pressure should get into it, a serious situation might develop. For this reason it has been watched closely, under the supervision of Mr. H. W. Dennis, since it was first noticed by Dr. Fredrik Vogt about three years ago. When the crack was discovered, the water in the reservoir had not yet been above the elevation 5330 feet. On the day of the visit to the dam the elevation of the water was 5327 feet. The highest previous elevation was 5340 feet. On the day of the visit some water was trickling out of the crack and there was a layer of deposits around the crack (as there was around practically every construction joint in the longitudinal gallery). There appears to be no reason to believe, however, that the water coming through the crack is under great pressure. After scraping off the deposits, it was noticed that the edges of the crack were rounded (as is often the case with cracks that have existed for some time). The rounded edges made it difficult to measure accurately the width of the opening. This width was estimated to be about 0.02 inches. In view of this rather small width there is little reason to believe that the crack extends very far into the mass of the dam. If the crack is essentially a local effect, it is not improbable that, as suggested
by Mr. Dennis, the crack is caused by the presence of the gallery. It may be noted that the construction joints perpendicular to the crest of the dam are 50 feet apart, and that the crack divides the thickness of about 100 feet nearly evenly. It is possible, therefore, that the crack expresses a tendency for a division into 50-foot units, due to shrinkage stresses, this tendency applying here to the direction of the thickness of the dam. Strain-gage readings had been taken across the crack from time to time. This method of watching the behavior of the crack is without doubt desirable.

The longitudinal gallery running along the upstream face of the dam has drainage holes in the floor, spaced 12.5 feet and extending 20 to 30 feet into the bedrock. These holes had been used for the purpose of measuring the water pressures, the openings then being covered. In many of these holes the water could be observed a short distance below the floor of the gallery. Fairly large areas of the walls of this gallery were wet, with water trickling down, or they were moist. Only at one place, at a joint which was particularly wet, did the water come out as a squirt. This squirt was from the downstream wall, and almost reached the upstream wall. Haircracks seemed to be absent in this gallery. All the expansion joints examined were found to be open, the width of the opening as a rule being greater on the downstream wall than on the upstream wall. The width of the openings which were measured ranged from 0.01 inch to 0.12 inches. Examples of these widths have been given under 26a. The total flow of water from the gallery was stated to be about 15 gallons
per minute, this amount being about one-half of the total flow through the dam.

The gate-pipe gallery near the middle of the dam is about 20 feet farther downstream than the main longitudinal gallery. No cracks were found in the gate pipe gallery, and the walls were dry. Only one place showed evidence of past seepage.

In order to examine the connection between the concrete and the bedrock, an undergallery has been cut recently, following approximately the center of the original stream bed. No powder had been used in making this gallery. The joint between the concrete and the bedrock appears along the walls of this gallery. The connection was found to be excellent (as mentioned under 36a). The undergallery goes some distance into the dam and then turns at a right angle toward the right bank, extending about 24 feet in this direction. The walls of this gallery were dry near the downstream face of the dam. Farther in some water came out of the drill holes. At the end of the gallery some grouting had been done to replace decomposed granite in a seam. There was a total flow through this gallery of about 4 gallons per minute.

Along the top of the dam haircracks were noticed in the parapet wall about 3 feet apart.

The downstream face was quite dry, and showed little evidence of past seepage. Only two wet spots were found, near the ends of the dam. Their positions are indicated in Fig. 27.
**Fig. 24**

**SHAVER LAKE DAM**

Sketch showing crack in entrance gallery on the side of the right bank.

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**Fig. 25**

**SHAVER LAKE DAM**

Sketch indicating two wet spots near the ends on the downstream face, (a) at the right bank, (b) at the left bank.
Exchequer Dam, California, arch-gravity dam, about 300 feet high, built since 1924, was visited on May 29, with Mr. R. V. Meikle, Mr. A. A. Blakesley, and Mr. W. A. Perkins. See Exhibits F (drawing showing cracks in an entrance gallery) and K (drawing of dam). Comments have been made under 5a and 6a (intermediate expansion joints not reaching the full depth extending themselves as cracks), 8a (cracks perpendicular to sloping abutment), 9a (more severe cracking in the gallery along the steeper abutment than in the gallery on the less steep side), 13b (leakage at top of filled-in tunnel), 14a (joints closing with rising water), 30c (fairly long crack extending from the top of an entrance), 20d (longitudinal cracks in ceilings of galleries), 21b (cracks parallel to the face of the dam, observed in entrance galleries), 24a (irregular systems of cracks at the junction of two galleries), 31a (wetness), and 33a (dry deposits indicating a reduction of leakage).

The road across the dam is at the elevation 710 feet. On the day of the visit the water in the reservoir was at the elevation 666 feet. The dam has an inspection gallery forming essentially a flat V, with the sides of the V along the two abutments. Besides there are two entrance galleries on each side with the floors at the elevations 498 feet and 550 feet, respectively.

Mr. R. V. Meikle stated that the total seepage through the dam had been measured recently and found to be about 1 cubic foot per second. The preceding year the leakage had been greater.
The photographs in Figures 26 and 27 show the condition of the downstream face of the dam. A triangular dark spot at the bottom of Fig. 27 indicates leakage from an inclined crack. Another place of leakage is indicated by a dark vertical strip to the left of the triangular area. The much more extended white areas are evidence of past leakage, which has now ceased.

At the top of the dam most of the expansion joints were open about 0.01 inch. Three of the joints, on the side of the left bank (the steeper side of the canyon) were open about 0.04 inches, and near the end at the right bank the conditions indicated in the sketch in Fig. 28 were found at the top and near the top on the upstream face.

The sketches in Figures 29-31 indicate conditions observed on the downstream face. The crack in Fig. 29 extends from the top entrance on the right bank to the top of the dam. The opening for a tunnel for a railroad track, indicated in Fig. 30 was mentioned under 13b. The fairly long crack in Fig. 31 was mentioned under 20c. Another crack, 20 to 30 feet long extends from the top of the entrance on the right bank with floor elevation 550 feet; this crack is essentially vertical, and is shown on the drawing in Exhibit F. Fig. 32 shows a crack in the spillway wall near this entrance.

The sketches in Fig. 33 show cracks in the ceilings of three of the entrance galleries. The entrance gallery on the right bank, shown in Fig. 30 (but not shown in Fig. 33), had a crack
parallel to the face of the dam about 60 feet from the entrance.
Some grouting had been attempted at this crack.

The sketches in Fig. 34 indicate the conditions in the main inspection galleries. The walls and ceilings of the main inspection galleries and of the entrance galleries had deposits at many places, resulting from leakage during the past. These deposits were rather hard and solid; the ridges formed by them at some places were about \( \frac{3}{4} \) inches thick. The most severe conditions found in this dam are those represented in Exhibit F, Fig. 33(c), and Fig. 34(b).
Exchequer Dam. Photograph.

The light areas indicate past leakage. A dark triangular area near the bottom of the picture shows leakage from an inclined crack.
**Fig. 28**

EXCHEQUER DAM

Sketch indicating openings at two places in the upstream face at the right bank.

**Fig. 29**

EXCHEQUER DAM

Sketch of crack over the top entrance on the right bank.

**Fig. 30**

EXCHEQUER DAM

Sketch showing leakage over the filled-in tunnel for a railroad, on the right bank.

**Fig. 31**

EXCHEQUER DAM

Sketch of inclined crack starting from the entrance on the left bank with floor elevation 496 feet.
FIG. 32
EXCHEQUER DAM
Sketch of crack in wall of spillway on the left bank.

(a)

(b)

(c)

FIG. 33
EXCHEQUER DAM
Sketches of cracks in the ceilings of the entrance galleries. (a) Bottom gallery, (b) Gallery on the left bank with floor elevation 496 ft. (c) Gallery on the left bank with floor elevation 550 ft. The widths of these galleries are drawn to larger scale than the lengths.
A crack appears to have been open here, but is now closed.

0.01 in. wide, both upstream and downstream

(a)

Joints

0.03 in. wide on upstr. wall
0.02 in. wide on upstream wall

(b)

Cracks

0.02 in. wide on upstream wall
0.03 in. wide on downstream wall

Fig. 34

EXCHEQUER DAM
Sketches (looking upstream) indicating the conditions in the inspection galleries, (a) on right bank, (b) on left bank.
Don Pedro Dam, California, arch-gravity dam, about 230 feet high, built since 1920, was visited on May 29, with Mr. R. V. Meikle, Mr. A. A. Blakesley, and Mr. W. A. Perkins. Exhibit K contains two drawings of the dam. Comments have been made under 3a (vertical cracks between expansion joints), 5a and 6a (short expansion joints extending themselves as cracks), 7a (cracks from the bottom of an expansion joint to the abutment in a direction nearly perpendicular to the abutment), 8a (cracks nearly perpendicular to the abutment observed in galleries), 14a (joints closing with rising water), 20d (longitudinal cracks in ceilings of galleries), and 33a (deposits indicating reduction of leakage).

On the day of the visit the reservoir was practically full. Small scattered wet spots were noticed on the downstream face. The sketch in Fig. 35 indicates an open joint and a wet spot near the top on the right bank. The sketch in Fig. 36 indicated a rather large crack starting from the abutment on the left bank and joining an expansion joint.

The galleries were entered at the top on the right bank. The sketch in Fig. 37 indicates conditions observed in walking down through the sloping gallery. Fig. 38 indicates the cracks found in the second exit. This exit was on the whole dry. In walking farther down, from the second exit, there were noted a vertical joint or crack, open about 0.02 inches, about
50 feet from the bottom of the steps, and, between this place and the bottom, a vertical crack about 0.01 inch wide. The horizontal stretch of gallery following next was on the whole quite dry. A horizontal construction joint about 8 feet above the floor had the appearance of a crack; it showed no leakage. By walking up from the other end of this gallery through a sloping gallery, the exit to the power house was reached. Cracks in the ceiling of this exit gallery are indicated in Fig. 39. A return was made toward the right bank through an intermediate horizontal gallery. In this gallery there were deposits at some of the vertical joints, indicating past leakage. Water trickled out only at a few scattered places.

In the top horizontal gallery there was found, fairly close to the end at the left bank, a crack or joint which leaked a little on the downstream side. The joint or crack could be seen across the ceiling and a part of the way down on the upstream wall, but not all the way down. Between this place and the middle of the gallery a joint was noted which was open about 0.06 inches.
**Fig. 35**
DON PEDRO DAM
Sketch indicating an open joint and a leakage near the top on the right bank.

**Fig. 36**
DON PEDRO DAM
Sketch indicating an inclined crack joining an expansion joint on the left bank.

**Fig. 37**
DON PEDRO DAM
Sketch indicating conditions in the inspection galleries on the right bank.

- Entrance
- Relatively dry gallery.
- Joint open 0.10 in. on downstream wall, 0.04 in. on upstream wall.
- 1st. Exit; crack 0.01 in. wide along the top of this exit. The exit is dry except at one spot.
- Crack open about 0.02 in. This crack has sharp clear dry edges on the downstream side, indicating that it has formed recently. On the upstream wall the crack is surrounded by deposits.
- This joint leaked considerably at one time. It has been grouted, and the leakage has nearly stopped.
Crack, 0.01 in. wide, on both walls, but not visible on ceiling or floor, inclined about 25°; the crack is dry.

Crack along the top, open about 0.04 in. on a part of the way in the middle portion. White deposits along a part of it.

Crack surrounded by deposits, observed on the walls and ceilings.

Crack, 0.02 in. wide, not visible on the ceiling; inclined about 10°.

Small crack along the corner, making the system of cracks continuous.

(a) (b)

**Fig. 38**
**DON PEDRO DAM**
Sketch indicating cracks in the second exit gallery on the right bank. (a) Looking toward the right bank. (b) Looking upstream at the bottom.

**Fig. 39**
**DON PEDRO DAM**
Sketch indicating cracks in the ceiling of the exit gallery to the power house.
Pardee Dam, California, arch-gravity dam, was visited on May 30, with Mr. F. W. Hanna and Mr. W. A. Perkins. This dam is dealt with in Exhibits G (data furnished by Mr. F. W. Hanna) and H (study by Mr. R. E. Glover). Comments have been made under 1a (expansion joints open and close), 6a and 7a (inclined crack joining a vertical expansion joint), 8a (cracks nearly perpendicular to a sloping abutment), 9a (more severe cracking on the side of the steeper abutment), 10b (crack starting from a point where the abutment changes slope), 13a (irregularity resulting from the construction program), 20d (longitudinal cracks in ceilings of galleries), 21b (cracks parallel to a face of the dam), 29a (strain-gage readings show the working of joints and cracks), 31a (wetness), and 33a (white deposits indicating reduction of leakage).

Water was coming over the spillway on the day of the visit.

The photograph in Fig. 40 shows the downstream face. There were scattered wet places on the downstream face. Fig. 41 shows a triangular wet area at the bottom of the left bank. The water is trickling down from a crack. The white strip on the left shows deposits which have become dry, thus indicating a reduction of the leakage at this place.

The sketch in Fig. 42 indicates an inclined crack on the left bank starting from a place where the slope of the abutment changes. Fig. 43 indicates a case of flow through the seams of the rocks below the dam. The flow through the seams may be about $\frac{1}{8}$ cubic foot per second.

The main inspection galleries form a V with a flat bottom.
Exhibit G contains extensive information concerning the cracks and joints in the galleries. Only the following notes are added: The galleries were entered on the left bank near the bottom, next to the power house. In the entrance gallery a couple of small cracks running along the ceiling were noted. These cracks did not appear to be significant. The sketch in Fig. 44 indicates conditions in the horizontal gallery at the bottom. In walking up through the gallery on the right bank a major crack was noted, nearly perpendicular to the abutment. This crack had been corked, but not yet grouted. It was suggested that this crack might go through to the downstream face. After walking across the top of the dam, the galleries were entered on the left bank at the top. The left bank is steeper than the right bank, and the rock was stated to be of less good quality on this side. In going down through the gallery on the left bank there were noted three cracks essentially perpendicular to the abutment. The first two were wet, the third was dry. In the upper portion of this gallery some construction joints were open about 0.06 inches. The upper portion of this gallery was rather wet. The lower end was much dryer. A longitudinal crack running along the ceiling of the gallery did not appear to be significant.

_Calaveras Dam_, California, was visited on May 30, with Mr. W. A. Perkins. The dam was under construction. It is designed as a constant-angle arch dam, 124 feet high. A comment has been made under 23a (cracks tending to start from re-entrant corners of keyways). Fig. 45 indicates the condition referred to.
Pardee Dam. Photograph of a portion of the downstream face.

Pardee Dam. Photograph showing leakage from an inclined crack at the bottom of the left bank. Water is coming down over the rocks. A trough for measuring the water may be noted. The wet triangular area under the crack can be seen in Fig. 40.
Fig. 42
Pardee Dam
Sketch of an inclined crack on the right bank near the bottom, starting from a place where the slope of the abutment changes.

Fig. 43
Pardee Dam
Sketch indicating leakage thru seams of rocks below the dam.

Fig. 44
Pardee Dam
Sketch (looking upstream) indicating conditions in the horizontal gallery at the bottom.

Small cracks like this reported to have been observed during the construction.

Fig. 45
Calaveras Dam
Crack starting from re-entrant corner of a keyway.
Lake Spaulding Dam, California, arch dam, 275 feet high, built 1912-1913, raised 1916 and 1919, was visited on May 31, with Mr. W. A. Perkins and Mr. C. A. Bissell. Comments have been made under 8a (cracks perpendicular to a sloping abutment), 9a (severe conditions on the side of the steeper abutment), 20d (cracks in ceilings of galleries), 23b (cracks starting from re-entrant corners in keyways), 31a (wetness), 33b (stalactites), and 37a (comparison with other dams from the same period).

On the day of the visit the water in the reservoir was at the top of the dam.

The condition of the downstream face appears from the photographs in Figures 46-52. There are many leaks. There are also leaks through the rocks, especially through the steep rock on the left bank. At and right over the top of the base the surface of the concrete is not in good condition, as appears especially from Figures 51 and 52.

The history of the construction of the dam is indicated in the sketch in Fig. 53. Fig. 54 is a sketch of some sloping cracks on the downstream face, starting from the abutment on the right bank. On the top of the dam a number of small cracks of the type shown in Fig. 55 were found.

Fig. 56 indicates the course of the inspection galleries. The shaft on the left bank was extremely wet and impassable; a part of the flow here comes through the rocks. The galleries in this dam were the wettest that were seen on the trip, yet there were dry areas both on the upstream and downstream walls. The drain
holes coming down to the galleries from the top had considerable amounts of deposits in them. Two of them were observed to be entirely clogged up. At the key block at the bottom an especially large amount of water came through the drain holes. The concrete was unsatisfactory here. On the whole the concrete in this dam did not appear to be very good; many pockets were noted both in the galleries and on the downstream face. Lines of cracks could be observed in the ceilings. Most of these cracks appeared to have sealed up. The same applies to some cracks that were perpendicularly to the sloping abutment on the left bank. Stalactites covered large parts of the ceilings, some of them 3 feet long. Stalactites 12 inches long could be seen almost anywhere.
Fig. 46
Lake Spaulding Dam. Photograph.

Fig. 47
Lake Spaulding Dam. Photograph.
The dark strips and spots show leaks.
Fig. 48

Lake Spaulding Dam. Photograph.
Fig. 49
Lake Spaulding Dam. Photograph showing the downstream face near the left bank.

Fig. 50
Lake Spaulding Dam. Photograph showing the steep rocks on the left bank.
Fig. 51
Lake Spaulding Dam. Photograph taken from the top of the base, showing water trickling down, and showing the condition of the surface.

Fig. 52
Lake Spaulding Dam. Photograph, close-up taken from the top of the base, showing the condition of the surface.
FIG. 53
LAKE SPAULDING DAM

FIG. 54
LAKE SPAULDING DAM
Sketch indicating some cracks on the downstream face on the right bank.

FIG. 55
LAKE SPAULDING DAM
Sketch indicating cracks on the top of the dam, starting from the re-entrant corners of the keyways.

FIG. 56
LAKE SPAULDING DAM
Sketch (looking upstream) indicating the course of the inspection galleries.
Stony Gorge Dam, California, Ambursen dam, 142 feet high, built 1926-1928, was visited on June 2, with Mr. R. C. E. Weber. See Exhibit I (drawings furnished by Mr. R. C. E. Weber, showing cracks in buttresses). Comments have been made under 12b (cracks across the corbels at the bottom) and 16a (cracks in the reinforced buttresses are small).

The buttresses are spaced 18 feet center to center and are designated by the numbers 10 to 55 from the left bank to the right bank. The buttresses were built in 12-foot lifts, which are designated by the letters A, B, C, ... from the top down. The face slab has the slope 1:1. On the day of the visit the water in the reservoir was 2 feet below the top of the spillway gates.

The photograph in Fig. 57 shows the dam. The photograph in Fig. 58 was taken from below between two buttresses (in all probability Nos. 48 and 49). The photograph in Fig. 59 shows a corner of buttress No. 53 at the bottom and a part of one of the adjacent face slabs. The dark spot on the face slab represents a small amount of moisture.

As seen from the top of the dam on the upstream side the joints between the face slabs and the buttresses appeared to be open about 0.03 inches at the top end. In the slabs of the walkway on the top of the dam some cracks at the corners, such as those sketched in Fig. 60, were noted. The majority of these cracks were fairly close to the ends of the walkway. The sketch in Fig. 61 indicates a crack in the parapet.
Under the dam the following observations were made:

The face slabs were in good condition. No cracks were observed in the face slabs. There was almost no leakage through the face slabs; the photograph in Fig. 59, which shows a very small dark moist spot at the bottom (in the shadow of a strut) may be taken as a representative example. In the buttresses there appeared cracks of four types:

1. Some long horizontal hair cracks, barely noticeable (without doubt only insignificant surface cracks).

2. Cracks which are essentially vertical, especially in lifts which lacked horizontal reinforcement.

3. Cracks across corbels.

4. Cracks at doorways.

The drawings in Exhibit I give information about the cracks in buttresses Nos. 22, 23, 25, and 51.

Buttresses Nos. 22 and 23 were among the first on which construction was started. Some vertical cracks developed in the three lifts at the bottom of buttress No. 23 during the construction (doubtless due to shrinkage), whereupon the policy was adopted to use not only vertical and sloping reinforcement, but also horizontal reinforcing bars (see "Dams and Control Works Constructed by the Bureau of Reclamation," 1929, p. 72). It appears that the more complete reinforcement in the upper lifts have kept these cracks in the lower lifts from widening and extending farther. The vertical cracks in the lower lifts in buttress No. 23 were found to be about 30 feet apart. No cracks could be seen from the bottom in the upper lifts. The sketches in Fig. 62 indicate some of the cracks and places of seepage found in
buttresses Nos. 22 and 23. According to Mr. R. C. E. Weber records of the earlier seepage at the lower end of the corbel in buttress No. 22 are on file in the Denver office of the Bureau of Reclamation.

The sketch in Fig. 63(a) indicates a crack starting from a corner in the doorway in buttress No. 24. Fig. 63(b) shows a typical crack, such as were found over several of the doorways.

In buttress No. 26 there were noted six small squirts at the corbel joint at the bottom.

Buttress No. 42 is representative of the buttresses which are reinforced fully in all the lifts. In the H-lift there were noted 5 or 6 vertical cracks about 0.01 inch wide. Buttress No. 45 is fully reinforced except in lifts A, C, and H. Some very small vertical cracks were visible in the G-lift.

The sketch in Fig. 64 shows a typical corbel crack. This particular corbel crack is in buttress No. 46. It showed evidence of past seepage. About one-half of the corbel cracks showed a small amount of seepage; and practically all the remaining ones showed past seepage.

In buttress No. 47 the bottom lift is G. Lifts B and D are fully reinforced. There were several vertical cracks in lift C, two were noticed in lift F, and one small crack in lift E.

The sketch in Fig. 65(a) indicates cracks in buttress
No. 50, which is incompletely reinforced. Other incompletely reinforced buttresses, such as No. 48 and 49 showed similar cracking. In buttress No. 51 cracks were noted in the bottom lift only (see Fig. 65(b)), except for one vertical crack, about 0.01 inch wide, farther up. Buttress No. 52, which is incompletely reinforced showed a crack about 0.04 inches wide as indicated in Fig. 65(c). In the two bays between buttresses Nos. 52 and 54 there was a small amount of trickling of water at the top of the cut-off trench block.

The cracks in buttresses that have been mentioned are characteristic of the general situation.

The dam gave the impression of being well-built, and appeared generally to be in very good condition.
Fig. 57

Stony Gorge Dam. Photograph.
Fig. 58
Stony Gorge Dam. Photograph taken under the dam between two buttresses.

Fig. 59
FIG. 60
STONY GORGE DAM
Sketch of cracks in the corners of the slabs in the walkway on the top of the dam. Eleven such cracks were counted in the 45 Slabs. Six of them close together on the right bank.

The crack in the parapet is visible on the upstream side. It is seen there to join the expansion joint at the floor of the Spillway Gate House.

FIG. 61
STONY GORGE DAM
Sketch (looking upstream) of a crack in the parapet.

FIG. 62
STONY GORGE DAM
(a) Sketch indicating two places of seepage in the corbel of Buttress No. 22.
(b) Indicating a crack in Buttress No. 23.
FIG. 63
STONY GORGE DAM
(a) Sketch indicating a crack over the doorway in buttress No. 24, (b) Typical crack over a doorway.

FIG. 64
STONY GORGE DAM
Sketch of Corbel Crack in Buttress No. 46 (typical corbel crack)

FIG. 65
STONY GORGE DAM
Sketches of cracks in buttresses:
(a) Buttress No. 50, (b) No. 51, (c) No. 52.
Bull Run Dam, Oregon, arch-gravity dam completed within the last few years, was visited on June 4, with Mr. Ben S. Morrow and Mr. D. C. Henny. See Exhibit J (data, especially strain-gage readings across joints, furnished by Mr. Ben S. Morrow). Comments have been made under 1a (strain-gage readings showing the opening and closing of joints), 29a (opening of joints depending on the level of the water and the temperature), 31a (dryness), 38a (too rapid construction undesirable), 39a (effective control of the concrete).

The dam was built in 40-foot sections, which are numbered from the right bank to the left bank. The photograph in Fig. 66 shows the dam. On the day of the visit 650 cubic feet of water per second were coming over the spillway.

The sketches in Figures 67 and 68 indicate some joints which were observed to be open on the top and on the downstream face. The downstream face was almost entirely dry. There were noted two moist spots on the left bank at joints which were open 0.02 inches and 0.04 inches, respectively. On the right bank there were two places where water trickled down about 15 feet, at one of these places reaching the steps right over the abutment. At a third place on the right bank there was a moist area of about 40 square feet. No squirt was observed anywhere.

The following notes concerning the galleries supplement the data contained in Exhibit J:

The main inspection galleries follow the abutments
and the bottom, forming a V with a flat bottom. The galleries were entered at the top on the left bank. At the joint between sections 20 and 19 the conditions stated in Fig. 67 were observed. On the way down on the left bank all the expansion joints showed dampness, and at some of them a little water trickled out. In going out through the exit gallery on the left of the gate house, some slightly wet spots were noted, but no cracks were seen. This gallery is close to the foundation.

In going through the horizontal gallery at the bottom toward the right bank, there were noted some wet spots and small amounts of deposits. The wet spots were larger on the downstream wall than on the upstream wall. The wet spots appeared mostly at the lines marking the end of a day's work. At the middle of the dam, at the middle of section 11, a vertical crack was reported to have existed, but it was not possible to see it. This part of section 11 was built in the winter and was reported to have been built faster than any other part of the dam. The joint between sections 11 and 10 had previously been open 0.02 inches. The wall was wet here over a width of 2 feet, and there were some deposits.

In the exit on the right of the power house there was a crack about 40 feet from the door, going all the way around except through the floor. This crack has been watched closely by means of strain-gage readings. The crack was barely visible.

In walking up through the gallery on the left bank
there was observed at the joint between sections 8 and 9 a stream of water coming from a drain. Mr. Ben S. Morrow stated that this leakage could be stopped when the water became low in the reservoir. At the middle of section 8 there were some wet spots on the downstream face.

The maximum observed flow through the dam was reported to have been 93 gallons per minute, about one-fifth of this amount coming through the one drain just mentioned, at the joint between sections 8 and 9.

Altogether, this dam was found to be in excellent condition. The success in obtaining a dry dam was ascribed by Mr. D. C. Henny to the rigid control of the concrete during construction.
Fig. 66

Bull Run Dam. Photograph.
Open joints: at times the opening is reported to be about 0.1 in.

Section 19

In the gallery this joint is open 0.15 in. on the upstream wall, 0.02 in. on the downstream wall; water trickles down on both walls at the joint.

**FIG. 67**

**BULL RUN DAM**

Sketch indicating openings of two joints at places where the abutments change their slopes.

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Joint open 0.03 in.  Joint open 0.04 in.

**FIG. 68**

**BULL RUN DAM**

Sketch indicating openings of two joints on the right bank near the top of the dam.
Arrowrock Dam, Idaho, arch-gravity dam, 349 feet high, completed in 1915, was visited on June 5. Comments have been made under 8a (cracks nearly perpendicular to the sloping abutments), 9a (more severe cracking on the side of the steeper abutment), 20d (cracks in ceilings of galleries), and 37a (sand-cement).

The photograph in Fig. 69 shows the dam. The downstream surface is not in particularly good condition. The photographs in Figures 70 and 71 show the situation. The climate has evidently been rather hard on the sand-cement that was used in this dam. No leakage appeared on the downstream face as seen from the top except at one place on the right bank where some moisture came out of a drain hole.

The sketch in Fig. 72 indicates the course of the galleries, the order of the numbers showing the route that was taken.

The galleries were entered near the top on the left bank (at point 1 in Fig. 72). In going down through the gallery on the left bank, it was noted that the walls were mostly dry, but the ceiling wet, yet only occasionally wet enough to drip; the water came in through a joint at the top end of this sloping gallery. There were some deposits on the walls at lines marking the end of a day's work. Small amounts of moisture were seeping out of the drain holes at the top, and under these drain holes there were strips with deposits, perhaps 2 or 3 feet wide.
The top horizontal gallery was entered next. Also here moisture came out of the drain holes, and underneath, on the walls, there were strips with deposits about 2 feet wide, \( \frac{1}{2} \) inch thick at some places. At the construction joint 400 feet from the left abutment, measured along the top of the dam, there was a small squirt on the downstream wall, and a somewhat broader area of trickling water and deposits than found elsewhere in this gallery.

At a place where the cross-section of the gallery changes from larger to smaller, so that the ceiling slopes down toward the right bank, there was noted a short longitudinal crack of small width in the ceiling. There was a small amount of seepage from this crack, not enough to make a drip, but enough to be felt. And there were deposits around this crack. Between the joints 900 and 950 feet from the left abutment, measured along the top of the dam, there was observed a longitudinal crack in the ceiling, about 30 feet long, 0.01 inch wide, and slightly moist at the middle portion of its length.

After reaching the end of the top horizontal gallery, the steep gallery on the right bank was entered. At the first vertical joint passed on the way up an appreciable stream of water, about 10 to 15 gallons per minute, was coming out. The sketch in Fig. 73 indicates some cracks in this steep gallery. The sketch in Fig. 74 indicates conditions in galleries at the bottom of the dam on the right bank.

In going through the bottom gallery toward the left
bank there were noticed, about 65 feet before reaching the steps at the end, a vertical strip of deposits on the downstream wall, and, 40 feet and 15 feet from the steps, two strips of deposits, each about 3 feet wide, and with a maximum thickness of about 2 inches. There were also two longitudinal cracks in the ceiling each about 12 feet long, running parallel to each other for a short distance; one of these cracks was marked by short stalactites.

In going up one flight on the left bank deposits were noticed at a couple of places. At the entrance to the middle gallery deposits and moisture appeared above the entrance and along a vertical line along that side of the entrance which is nearer the left abutment.

The sketch in Fig. 75 indicates some cracks in the bottom exit gallery on the left bank.

After returning to the main galleries there were noted on the way up to the top horizontal gallery about four vertical joints surrounded by belts of deposits about 3 feet wide. In the lower part of this flight the walls were rather wet, but at the upper end of the flight they were mostly dry. At one joint near the top end of the flight, that is, near the entrance to the top horizontal gallery, a place was found with deposits covering a triangular area about 4 feet wide at the bottom. At this place some water trickled out mainly at one point.

In the vertical shaft connecting the top horizontal gallery with the middle horizontal gallery some deposits were
found in the lower portion on the walls and along the corners. The walls were moist in the lower half of the shaft.

In the middle horizontal gallery a small crack was noticed running along the ceiling through practically the whole length. Deposits occurred in vertical belts and scattered spots on the upstream wall, and in scattered spots on the downstream wall. The downstream wall was dryer than the upstream wall. Near the end where this gallery connects with the galleries along the left abutment a crack occurred essentially perpendicular to the abutment. This crack extended from the floor half-way up the wall of the gallery. Some spalling off had occurred at the edges of this crack.
Fig. 69
Arrowrock Dam. Photograph.

Fig. 70
Arrowrock Dam. Photograph. Close-up showing the condition of the surface on the downstream face, on the right bank. The surface is moist due to the spray from the outlets.
Fig. 71

Arrowrock Dam. Photograph showing the condition of the surface at an entrance on the right bank.
Fig. 72
ARROWROCK DAM
Sketch (looking upstream) indicating the course of the galleries. The numbers, in order, indicate the route followed.

Fig. 73
ARROWROCK DAM
Sketch (looking upstream) indicating some cracks in the steep gallery on the right bank.
**Fig. 74**

**ARROWROCK DAM**

Sketch (looking upstream) indicating conditions in galleries on the right bank at the bottom of the dam.

**Fig. 75**

**ARROWROCK DAM**

Sketch (looking toward the left bank) indicating conditions in the bottom exit gallery on the left bank.
American Falls Dam, Idaho, earth fill and concrete gravity dam, 77.5 feet high, completed in 1927, was visited on June 4. Comments have been made under 3a (vertical cracks between expansion joints), 4a (cracks between expansion joints most frequent where the height of the dam is small), 12a (cracking at the junction with the core of the earth fill), 19c and 20b (local cracks over entrances to galleries), 20d (longitudinal cracks in ceilings of galleries), 22a (horizontal cracks in walls of galleries), 23c (cracks starting from keyways observed in galleries), 27a (the severest cracking appeared in a gallery close to the top), and 30a (many hair cracks on the downstream face).

The dam is described in "Dams and Control Works Constructed by the Bureau of Reclamation", 1929, pp.62-68. The length of the concrete-gravity portion of the dam is 3096 feet, 2376 feet of which are occupied by the left abutment section. The height of this section increases slowly from the left to the right. The seven entrances to the galleries running through the concrete portion are numbered from the right bank toward the left. The vertical expansion joints appear in the longitudinal gallery with the spacing 33 feet and 39 feet alternating. Lights in the longitudinal gallery are placed approximately midway between pairs of consecutive joints. The elevation of the top of the dam through the major part of its length is 4359.5 feet. On the day of the visit the water in the reservoir was at the elevation 4345 feet.

On the downstream face, through the length of the left ault-
ment section there appeared with notable regularity systems of fine cracks as indicated in the sketch in Fig. 76. At the horizontal joints between the five-foot lifts some spalling off of the concrete was observed here and there. In the upper, vertical portion of the downstream face there were noted some spots showing past seepage, on the average about 50 feet apart; at some places these spots occurred as horizontal strips about 15 feet long with intervals of about 20 feet between the strips. Small cracks, as indicated in Fig. 77, were found over entrances No. 7 and No. 6, but cracks of this type were absent at entrances No. 5 and No. 4.

The galleries were entered through entrance No. 7, which is the one farthest to the left (on the left bank). At the first vertical joint in the longitudinal gallery the conditions sketched in Fig. 78, section 2-2, were observed. The sketch representing the horizontal section 1-1 gives an explanation of the crack A; the crack doubtless starts from a re-entrant corner of the keyway, as shown in the sketch.

At the first light, about 20 feet farther toward the right bank, about mid-way between two expansion joints, a crack was noticed all the way around the gallery, open about 0.02 inches. A longitudinal crack in the ceiling, 0.01 inch wide, could be traced from entrance No. 7 to this light and beyond it. At the next light, however, the crack in the ceiling was only barely noticeable. At this light there was a crack going all the way around the gallery, similar to the one at the first light. These cracks are intermediate vertical cracks between expansion joints. Such a crack was found
also at the third light, but it was not more than 0.01 inch wide, and was only barely visible across the ceiling. Fig. 79 indicates the nature of the longitudinal crack in the ceiling at this place: the crack diminishes upward in the facet for the light. The same condition was found at a number of other lights. This observation indicates that these narrow longitudinal cracks are not deep.

The expansion joint following showed some past seepage. In this portion of the gallery a horizontal crack was found on each wall, following the top of a lift. Deposits indicated past seepage from these horizontal cracks at and near their intersections with those vertical joints at which there had been seepage. The longitudinal crack in the ceiling was found to run for a while and then disappear. The sketches in Fig. 80 indicate the conditions at a light about 140 feet to the left of entrance No. 6. At this place no longitudinal crack could be seen in the ceiling.

Shortly before reaching entrance No. 6 the following observations were made: The horizontal crack in the walls was open 0.02 inches on the downstream wall and was barely visible on the upstream wall. The vertical jointappearing here was open 0.10 inches on both walls.

After passing entrance No. 6 it was noted that the intermediate cracks between vertical joints did not appear with great regularity. For example, in one of the sections (33 feet or 39 feet) between entrances No. 6 and No. 5 there were three small intermediate cracks, in the next section there was none, and in the following there was again one. In approaching entrance No. 5, about six consecutive sections were found to have no intermediate vertical cracks. The
vertical joints were open as a rule about 0.10 inches (a typical condition is an opening of about 0.10 inches on the downstream wall and somewhat less, perhaps only 0.03 inches, on the upstream wall). Just before reaching entrance No. 5 one intermediate vertical crack was found again. The smaller frequency of intermediate vertical cracks in this portion may possibly be explained by the fact that the dam is higher here than in the portion closer to the left end.

On the way through the gallery from entrance No. 5 to entrance No. 4 there were found no cracks at all on a considerable distance. There were some scattered spots showing past seepage. A small amount of drainage water trickled over the bottom of the trench. About mid-way toward entrance No. 4 a horizontal crack appeared again on the downstream wall, running for about 20 feet. It was open 0.01 inch and had dry clear edges. Shortly afterward a stretch was passed where about one-half of the area of the upstream wall was covered by deposits. The vertical joints were open about 0.04 inches. About 200 feet to the left of entrance No. 4 the horizontal crack appeared again on both walls, open 0.01 inch on the downstream wall and barely visible on the upstream wall. There were a few spots of deposits on the downstream wall (about 50 feet apart), and a larger number of such spots on the upstream wall. About 100 feet to the left of entrance No. 4 a vertical joint, open about 0.03 inches, showed a small trickle of water. A joint at entrance No. 4 was barely moist at one spot (water leaking, but evaporating), and at this point there was some spalling off of the concrete. At three or four places cracks similar to that
shown in Fig. 78 were noted (cracks starting from a re-entrant corner of a keyway).

After passing entrance No. 4, there was noted a longitudinal crack in the ceiling beginning about 30 feet to the right of entrance No. 4. This crack was open about 0.01 inch and was found to jump here and there from one line to another, like the vertical crack in Fig. 78. About 70 feet to the right of entrance No. 4 a horizontal crack appeared on the walls, 0.01 inch wide on the downstream wall and barely visible on the upstream wall. About 100 feet to the right of entrance No. 4 the longitudinal crack in the ceiling was found to divide into two branches, one branch continuing in the ceiling, and the other reaching the upstream wall and going down the upstream wall, across the floor in a jumping course (as in the case of the vertical crack in Fig. 78), and then about half-way up the downstream wall. On the upstream wall there were deposits and moisture at this crack. About mid-way between entrance No. 4 and the stairs a moist joint was passed. The moisture appeared in drops all the way around the joint, and there was a belt of deposits at this joint. In this portion of the gallery there were some tongue-shaped areas of deposits on the upstream wall extending downward from the line marking the top of a lift. About 60 feet from the stairs the crack in the ceiling had disappeared. A horizontal crack was noted on each wall. There were no deposits on the downstream wall, but there were some on the upstream wall, extending downward from the horizontal crack. At the top of the flight of stairs leading to the lower gate gallery there were a number of spots of deposits on the upstream wall and on the ceiling, but only very
few scattered spots on the downstream wall.

By going down the flight of stairs the gate gallery was reached. No cracks were observed in this gallery, but there were many spots of thin deposits on the upstream wall and some on the downstream wall. There was very little moisture in this gallery. In going up the stairs at the other end (nearer the right hand bank) no cracks were seen except a horizontal crack at the top of the stairs at entrance No. 3. This crack was open 0.01 inch on the upstream wall and had a jumping discontinuous course there. This crack was barely visible on the downstream wall.

The upper gallery of the spillway section begins at entrance No. 3. The floor of this gallery (according to a drawing made in the Denver office of the Bureau of Reclamation) is 12.5 feet below the top of the spillway, which is at the elevation 4343.2 feet. This gallery showed the most severe cracking found in this dam. The sketch in Fig. 81 indicates cracks in the ceiling at the beginning of this gallery, near entrance No. 3. The crack indicated in Fig. 81 as 0.10 inches wide was found to continue for about 100 feet, running most of the way along the intersection between the arched ceiling and the downstream wall. The crack was 0.12 inches wide in the middle portion of its length. It stops practically at a vertical expansion joint. This joint was open about 0.03 inches. The crack just before reaching the joint (on the left side of the joint) was 0.05 inches wide. It continued beyond this joint only as a minor crack in the downstream wall, at most 0.02 inches wide, about 4 feet long, and in a direction sloping downward toward the right bank. At this cross-section of the gallery there appeared a
longitudinal crack about at the center of the ceiling, and this crack continued for some distance, zigzagging from one side of the ceiling to the other. This crack was 0.05 inches wide at some places. In this portion of the gallery there appeared also an irregular crack on the downstream wall. This crack was mainly horizontal, but zigzagged up and down, and at some places it jumped from one line to another.

About 250 feet to the right of entrance No. 3 the longitudinal crack was 0.08 inches wide and followed the intersection between the ceiling and the downstream wall. About 10 feet farther toward the right bank this crack stopped, and the conditions indicated in Fig. 82 were found. There were some deposits on the downstream wall in this part of the gallery. After passing this point, a crack in the ceiling, surrounded by deposits, was noted.

Farther toward the right bank the cracks became irregular. About 200 feet from entrance No. 2 the condition indicated in Fig. 83 was noted. Between this point and entrance No. 2 the major longitudinal crack at some places followed the line of intersection between the ceiling and the downstream wall, and at other places it followed a line farther up toward the top of the arched ceiling, but remained on the downstream half of the ceiling. At some places this crack jumped from one line to another. Occasionally it branched off, the branch becoming a minor vertical crack. At entrance No. 2 the upstream wall had fairly large areas of deposits, and there appeared a horizontal crack on the walls, about 0.02 inches wide.

In walking down the stairs beyond entrance No. 2 to the lower gallery there was noted only one minor vertical crack 0.01 inch wide.
The gallery on the lower level, reached in this manner, leads to entrance No. 1 on the right bank, the part of the gallery nearest entrance No. 1 being a concrete gallery through the earthfill. No cracks of interest were noted in the portion of this gallery through the concrete section, but at the junction with the earthfill portion there appeared a large crack such as indicated in Fig. 84. In the concrete gallery through the earthfill there were some cracks indicating uneven settlement of the fill.

A return was made to the spillway section, and the bottom gallery of this portion was entered by walking down the stairs on the side of the right bank. This gallery was then walked through in the direction toward the left bank. At the beginning of this gallery there appeared a slight amount of seepage from a construction seam on the downstream wall, enough to make the wall moist. There was also some seepage from the first five expansion joints and from a horizontal construction seam on the downstream wall between the fourth and fifth joints. No open cracks had been seen thus far. About 250 feet from the stairs at the right end there was a vertical crack surrounded by deposits. This crack probably was closed altogether. It extended a part of the way across the ceiling, and at the point that appeared to be the end of it there was a stalagmite about 1 inch long. About 250 feet from the stairs at the left end of this gallery there was some dripping from the ceiling on a distance of about 30 feet. There were some stalagmites in the ceiling, about 4 inches long, and some deposits which probably covered a crack.
On the last 120 feet of this gallery two sections were found with a wet construction seam on the downstream wall, and with deposits under the seam. There was also some moisture on the upstream wall. About 100 feet from the stairs at the left end a crack, the line of which was marked by dry deposits, extended from the upstream wall diagonally to the top of the arched ceiling in a direction downstream and toward the left. A similar crack, in the same direction, appeared about 50 feet from the stairs at the left end. There was some dripping from this crack, and it was surrounded by deposits.

The stairs at the left end of the bottom gallery in the spillway section lead up to a short horizontal gallery which joins the other galleries. No cracks or leakages of any significance were noted here.
FIG. 76
AMERICAN FALLS DAM
Sketch indicating systems of fine cracks on the downstream face of the left abutment section.

FIG. 77
AMERICAN FALLS DAM
Sketches of cracks over Entrances No. 6 and 7.

FIG. 78
AMERICAN FALLS DAM
Sketch of crack on the upstream wall of the gallery near Entrance No. 7.

FIG. 79
AMERICAN FALLS DAM
Sketch (looking upstream) Typical condition of the longitudinal cracks in the ceiling of the long gallery at the facets for the lights.
FIG. 80
AMERICAN FALLS DAM
Sketches representing conditions in the longitudinal gallery at the light about 140 feet to the left of Entrance No. 6. (a) Upstream wall, (b) Downstream wall.

FIG. 81
AMERICAN FALLS DAM
Sketch (looking downward) indicating cracks near Entrance No. 3, in the ceiling of the top gallery of the spillway section.

FIG. 82
AMERICAN FALLS DAM
Sketch (looking downstream) indicating conditions in the top gallery about midway between Entrances No. 3 and No. 2.
Fig. 83
AMERICAN FALLS DAM
Sketch indicating cracks in the downstream wall of the top gallery between Entrances No.3 and No.2 about 200 feet from Entrance No.2.

Fig. 84
AMERICAN FALLS DAM
Sketch indicating a crack in the upstream wall of the gallery at the junction between the concrete and the earthfill sections on the right bank.
Corrections on Pages 1 - 27 (in the part of the memorandum dated July 8, 1930).

Page 17, last line on the page: Replace the number 21 by "About 12".

Page 21, Change the paragraph beginning "24a", so that it reads as follows:

"24a. An example of an irregular system of cracks at the junction of two galleries is found in Exchequer Dam (Exhibit F)".

Page 22, 4th line in paragraph beginning 31a: Strike out: ", Don Pedro,".
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

CRACKS OBSERVED IN DAMS (IN PART)

Memorandum to Chief Designing Engineer
By H. M. Westergaard, Senior Mathematician

Denver, Colorado,
July 9, 1930.
Denver, Colorado, July 8, 1930

MEMORANDUM TO THE CHIEF DESIGNING ENGINEER

From  H. M. Westergaard, Senior Mathematician

Subject: Cracks Observed in Dams.

Synopsis

An account is given of observations gathered during a three weeks' trip for the purpose of inspecting cracks and joints in a number of dams. First, the results are summarized in a set of rules for cracks and joints, and thereafter the evidence is presented which leads to these rules.

Introduction

The Boulder Dam Consulting Board, meeting in Denver in April, 1930, recommended a comprehensive study of cracks in dams, the study to include a theoretical analysis combined with a field investigation. This study is one item in a program of investigations of volumetric changes in concrete under conditions applicable to dams.

I was assigned to the investigation of cracks. An analysis of possible states of stresses and deformations around cracks has been in progress for some time and will be reported separately. The present report deals with observations made during a three weeks' field trip (May 18 to June 8) during which the following dams were visited (in addition to the site of Boulder Dam): Elephant Butte Dam, New Mexico
(May 20); Stewart Mountain, Mormon Flat, Horse Mose, Roosevelt and Coolidge Dams, Arizona (May 21-22); Big Dalton, Santa Anita, Lake Hodges, Mulholland, Pacoima, Shaver Lake, Exchequer, Don Pedro, Pardee, Calaveras, Lake Spaulding, and Stony Gorge Dams, California (May 23 to June 2; site of Boulder Dam, May 27); Bull Run Dam, Oregon (June 4); Arrowrock and American Falls Dams, Idaho (June 5-6).

Acknowledgments

Acknowledgments are made to the following officials of the Bureau of Reclamation for making this field investigation possible: Dr. Elwood Mead, Commissioner (Washington, D. C.), Mr. R. F. Walter, Chief Engineer (Denver, Colorado), and Mr. J. L. Savage, Chief Designing Engineer (Denver). In view of the short time available at each dam, the effectiveness of this study became to a large extent dependent on the assistance and cooperation extended by the organizations and engineers in charge of the various dams. Indebtedness is expressed therefore to the following engineers who, in addition to making the visits to the dams possible, have in many cases furnished supplementary information concerning the cracks: Mr. L. R. Flock, El Paso, Texas; Mr. C. C. Cregin and Mr. F. J. O'Hara, Phoenix, and Mr. C. J. Wells, Coolidge Dam, Arizona; Mr. Geo. W. Hawley and Mr. W. A. Perkins, Sacramento; Messrs. L. C. Hill, H. W. Dennis, H. A. Van Norman, E. C. Eaton and R. W. Carlson, Los Angeles; Mr. A. A. Blakesley, Merced; Mr. R. V. Meikle, Turlock; Mr. F. W. Hanna, Oakland; and Mr. R. C. E. Weber, Orland, California; Mr. D. C. Henny and Mr. Ben S. Morrow, Portland, Oregon.
Cracks May Be Classified

By observing cracks and joints in a number of dams one is impressed with a certain regularity of the phenomena. Without referring to computations of stresses, the observed regularity is sufficient to make the statement that in producing each characteristic feature some simple law of nature is at work. The observed regularity alone makes it possible to state rules for the occurrence of cracks and for the behavior of joints. These rules represent a classification of the cracks.

The rules will be stated first without comments. Thereafter the supporting evidence will be presented. There will be added finally some general comments and suggestions.

Rules for Cracks and Joints

1. An expansion joint may be interpreted as a designed crack. The possibility of using sealing devices (especially copper seals) near the upstream face, and the better appearance on the exposed surfaces are obvious advantages. In other respects the joint functions as a crack. By looking at a number of dams, one cannot help acquiring a considerable amount of respect for the expansion joint.

2. Absence of expansion joints leads to cracks at some of the positions where joints would be used in normal practice. These cracks have irregular shapes and are likely to cause difficulties in regard to watertightness.
3. One or more vertical cracks, parallel to the expansion joints, are observed in a number of cases between two consecutive expansion joints. These cracks indicate that a closer spacing of the expansion joint might have been desirable.

4. No single distance can be stated defining the spacing of the vertical expansion joints necessary to avoid major cracks between them. As a general rule, a smaller height of the dam requires a closer spacing.

5. The scheme of letting some of the vertical expansion joints begin near the bottom of the dam and extend to the top while others (for example, alternate joints) begin near the middle and extend to the top, frequently leads to the short joints extending themselves as cracks, so that the combined length of a short joint plus crack becomes about the same as in the case of the long joint.

6. In general, cracks frequently start out from the bottom of a vertical joint. Joints which are too short, are a common cause of cracks.

7. A crack which has formed as an extension of a joint frequently takes a direction somewhat different from that of the joint. As a general rule the crack will approach the abutment in a direction nearly perpendicular to the abutment.

8. A tendency exists for cracks to form, starting from an inclined abutment and extending in a direction nearly perpendicular to the abutment. Such cracks were observed both on the downstream face and in galleries close to the upstream face.
9. The disturbance arising from cracks of the types just mentioned, as measured by the frequency of the cracks, by the occurrence of irregular systems of cracks, and by the amount of seepage of water, is on the whole the greater, the steeper the abutment.

10. A common and, it seems, important type of crack is the following: the crack starts from the abutment at a place where the slope of the abutment is changing so that the lower part of the abutment is steeper than the upper part. These cracks tend toward having a direction which is not far from being perpendicular to a line with the average slope of the abutment.

11. Instead of a crack forming under the circumstances just described a joint in the region where the slope of the abutment changes may open up rather widely. This condition is likely to exist where a gravity wing of relatively small height joins the dam proper.

12. More generally, one may expect cracks or open joints at the junction between two parts of the dam functioning differently; the following cases are examples:

   (1) At the junction between a concrete gravity section and the concrete core wall of an earthfill section, an uneven settlement is probable and may cause severe cracking.

   (2) In an Ambursen Dam cracks may occur across the corbels near the block filling the cut-off trench.

   (3) A region of hard concrete joining one of less stiff concrete along an irregular boundary may lead to cracks along this boundary and to cracks extending into the region of weaker concrete.
13. The condition mentioned under 12(3) may be a result of some irregularity in the construction program or some irregularity made necessary by the method of construction. These irregularities may lead to a junction of hard and less stiff parts, but in any case they represent a disturbance which may account for some cracks and open joints. For example:

(1) Cracks and open joints may be found at a place where a contractor’s tower was supported during construction; or

(2) Difficulties of leakage may occur where a tunnel was left open during the major part of the construction and the hole filled when dam was nearly completed; the difference of age of the two portions may cause leakage in the joint forming the boundary between them.

14. Vertical joints in curved dams or arch dams and cracks in the arches of multiple arch dams are frequently open at the top of the dam through the whole thickness of the dam (or of the barrel) when the water in the reservoir is some distance below the top. There is ample evidence that in most cases these joints and cracks close at least partly as the water rises in the reservoir.

15. Unreinforced buttresses designed without joints are likely to crack in a direction sloping upstream as seen from the bottom. Large cracks of this kind appeared with striking regularity in the buttresses of one multiple arch dam. There is evidence that these cracks change their opening in the course of time; that is, they work as expansion joints. In forming, these cracks seek or start from weak places such as openings for doorways.
16. In properly reinforced buttresses cracks may occur, but the reinforcement performs the function of keeping the cracks small. With the buttress built in horizontal lifts, omission of reinforcement (or omission of reinforcement in one direction) in some of the lifts is not necessarily detrimental. The reinforced lifts (or the fully reinforced lifts) may keep the crack small in the whole buttress.

17. Expansion joints in buttresses following smooth lines indicated by the course of the major cracks mentioned under 15 can serve the purpose of avoiding these major cracks. If such a joint is not continued as far as the need for it exists the joint will tend toward extending itself as a major crack of irregular shape. These cracks are likely to seek weak places, such as openings (doorways).

18. When in a buttress a crack, such as those described under 15 and 17, starts from or seeks out doorway opening, it is likely to be particularly wide at the opening. If reinforcement is placed around the curved top of the doorway and close to the surface, and if the crack crosses this part, it is likely to cause a pulling out of the exnek steel bars, with cracks following the steel bars in addition to the original crack crossing them. Working of the original crack (opening and closing) will then be severe on the concrete around the opening, and is likely to cause spalling off of the concrete.

19. The conditions mentioned under 15, 17 and 18 indicate that in general openings draw cracks toward them and tend toward exaggerating their widths as observed right at the opening. Cracks may be there because the opening is there. This rule is suggested by the observa-
tions of buttresses of the multiple arch and Ambursen dams, but it applies without doubt also to openings in solid dams, such as inspection galleries, sluiceways, and holes for penstocks.

20. A very common type of crack which may be observed in inspection galleries and at other openings, and which (as indicated under 19) can be diagnosed in most cases as existing because the gallery or opening is there, is a crack running along the ceiling of the gallery or opening. This crack may run for a distance and then stop. Sometimes it branches out into two cracks which later unite or disappear. Sometimes the crack follows for a distance the edge formed by the ceiling and one of the walls, and it may continue as a horizontal crack in the wall. As a rule the cracks in the ceilings are not very wide. In several cases where the crack could be observed at an entrance from the outside, it could be followed only a short distance up on the face of the dam. In such cases the crack represents only a minor local effect. In other cases a certain amount of seepage or dripping from the crack indicates that it may extend for some distance into the mass of the dam. In a gallery running parallel to the faces of the dam there may be reason for some concern over these cracks if they are wide; in this case one is led to consider the possibility of the crack extending itself so as to reach one of the faces of the dam, thus dividing the dam into two separate bodies. No evidence was found, however, indicating that this condition had been reached in any of the dams which were inspected.
21. The cracks in buttresses discussed under 15 suggest the possibilities of similar cracks in solid dams. The cracks along ceilings in galleries parallel to the faces of the dam (mentioned under 20) might be cracks of this type, but the evidence in the cases examined is that they are more localized effects. Another place where cracks of this nature may be looked for is in the entrance galleries which are perpendicular to the crest of the dam. Here these cracks should appear as transverse cracks, running through the height of the walls and across the floor and ceiling. Cracks which might be of this type, going part of the way around (for example, traced in walls and ceiling, but not across the floor) were observed in various cases. If these cracks are deep, they might reach, for example, the downstream face and divide the dam into two bodies (compare 20). In the cases examined, however, it is at least highly probable that these cracks were essentially local effects, brought about by the fact that the gallery is there.

22. Horizontal cracks in the walls of galleries are not uncommon. They usually follow the boundary line between two lifts.

23. Cracks sometimes start from a re-entrant corner in a keyway. Such cracks may be observed at the top of the dam, or in galleries. In a gallery the evidence may be furnished by a vertical crack close to a vertical joint. The position of the crack may indicate that a vertical block has sheared off between the joint, the crack, and the nearest protruding vertical plane in the keyway.

24. Irregular systems of cracks are likely to occur at the junction of two galleries or at a place where the cross section of the gallery is changed.
25. If two different openings, for example, a gallery and a sluice-way pass each other with a short distance between the nearest points, a system of cracks may develop in the region where the openings are close together, especially if there is water under pressure in one of the openings.

26. When observed in inspection galleries parallel to the upstream face, vertical joints and cracks are as a rule a little more widely open on the wall nearer the downstream face than on the wall nearer the upstream face. The same may apply to horizontal cracks.

27. Galleries close to the bottom of the dam are not particularly likely to show the widest and most frequent cracks. It may happen very well that the severest cracking occurs in a gallery close to the top.

28. There is observed frequently an irregular distribution of the openings of joints; in going from one end of the dam to the other some joints may be rather widely open and others nearly closed. This irregularity is observed especially near the top of the dam, and especially in the case of a non-symmetrical site.

29. Strain gage readings taken in galleries across cracks or joints throughout a year or more at regular intervals show the cracks and joints to open and close, the variation of width depending especially on the elevation of the water in the reservoir and on the temperature in the gallery.

30. Hair cracks (less than 0.01 inch wide) can be observed in dams very generally on the dry surfaces of concrete. As a rule, these cracks cannot be very deep, and they may be designated as surface cracks; there is little reason to attach a great deal of importance to them.
31. No dam can be expected to be absolutely watertight. Water comes through the drains, and usually some water finds its way to the downstream face through pores, joints, and cracks, forming a few wet spots on the downstream face. If water can reach the downstream face, it can reach the galleries close to the upstream face the more easily. Accordingly, scattered wet spots on the downstream face as a rule indicate a considerable number of wet areas on walls and ceilings of the galleries. Or, scattered wet spots on the downstream face indicate wetness inside the dam.

32. Leakage of water either through the bedrock or through the concrete can be stopped or reduced successfully by grouting.

33. Water leaking through for some length of time leaves a white deposit, either in layers (with ridges up to a couple of inches thick), or, by dripping from the ceilings of galleries in the form of stalagtites (in one case as much as 3 feet long). These deposits tend toward stopping the leakage (only, it may be noted, they fill the crack at the less desirable end). In a great many cases white deposits which are now dry tell the story of past leakage, now deceased (it may be noted that a very thin white deposit sometimes is noticed shortly after the forms are removed; a very thin deposit therefore probably indicates merely that some water leaked out of the concrete shortly after it was placed; a thicker deposit on the other hand tells a story of passage of water through the thickness of the structure).
34. There is naturally no simple correlation between the amount of leakage through a crack or joint and the width of the crack or joint, even at a given depth under the water.

35. The problem of watertightness is serious in high dams. High dams are likely to be rather wet.

36. It appears to be possible to obtain an excellent connection between the concrete and the bedrock. Leakage is more likely to occur along seams in the rock than along the junction between rock and concrete.

37. Sand-cement used in some of the earlier dams accomplished successfully its purpose of reducing shrinkage. The dams built with sand-cement compare favorably with other dams built in the same period in regard to watertightness (in that period the control of Portland-cement concrete was not satisfactory). The surfaces of a dam built of sand-cement concrete may last well in a moderate climate, but in a climate with severe winters they will by now have suffered severely by weathering.

38. Too rapid construction of a part of a dam may cause weakness in this part, resulting in cracking.

39. Much may be achieved in the direction of watertightness by rigid control of Portland-cement concrete during construction.
The Evidence

In presenting the evidence leading to the rules just stated the same numbering is used again, but followed in each case by a small letter; for example, comments 20a, 20b, 20c refer to rule No. 20.

1a. Opening and closing of expansion joints, depending on the season and the water load, can be noticed almost anywhere. This feature is brought out particularly clearly in dams where strain-gage readings have been taken systematically across a number of joints, for example, in Pardee and Bull Run Dams (Exhibits G, H and J).

2a. Absence of expansion joints has led to four major cracks in Mulholland Dam. They cross the crest and extend toward the bottom of the dam or toward the abutments. Three of them showed some leakage, and the fourth showed signs of past leakage. The crack closest to the right bank was 0.08 inches wide upstream and 0.06 inches wide downstream at the crest. There were also numerous minor cracks (0.01 inch wide or less), which probably, however, have only a small depth.

3a. Vertical cracks between the vertical expansion joints are not uncommon. Don Pedro Dam and American Falls Dam (compare 4a) furnish good examples.

4a. That the spacing of joints necessary to avoid intermediate cracks is not some constant definite distance is exemplified in American Falls Dam. This dam is a long straight gravity dam the height of which increases slowly as one moves from the left bank toward the
spillway. The spacing of the vertical joints, as they appear in the long inspection gallery, alternates between 33 feet and 39 feet. The intermediate vertical cracks occur decidedly more frequently and regularly at the end where the height of the dam is small than in the higher portion near the spillway.

5a. Indications that the scheme of letting some of the vertical expansion joints extend only a part of the way from the top of the dam toward the bottom leads to the short joints extending themselves as cracks are found, for example, in Elephant Butte Dam (see Exhibit A), Exchequer Dam and Don Pedro Dam.

6a. The cases mentioned under 5a, 7a, and 17a are examples of joints extending themselves as cracks.

6b. A vertical joint in Santa Anita Dam, which had opened rather widely, has extended itself downward as a crack (Exhibit C).

7a. Cracks extending from the bottom of a vertical joint toward the abutment in an inclined direction nearly perpendicular to the abutment may be observed, for example, on the downstream faces of Don Pedro Dam (left bank) and Pardee Dam.

8a. Cracks nearly perpendicular to the sloping abutment were observed on the downstream face and in inspection galleries running up along the abutments near the upstream face in Exchequer, Don Pedro, Pardee, and Lake Spaulding Dams, and in the galleries of Arrowrock Dam.
9a. A comparison between the rather steep galleries at one abutment and the less steep galleries on the other side in Exchequer Dam as well as in Pardee Dam shows a more severe cracking on the steeper side. The same tendency appears also in other dams, for example, in Lake Spaulding and Arrowrock Dams.

10a. The two major cracks in the dome at the left bank in Coolidge Dam start from a part of the left-bank abutment where the slope changes so that the abutment becomes steeper as one moves down. These cracks were open about 0.08 inches when the dam was visited. The weather was then warm and the water in reservoir rather low (see Exhibit B).

10b. Cracks of this type were observed at the downstream face of various other dams; for example, at the right-bank abutment of Pardee Dam.

11a. An example of the case of a vertical expansion joint opening up near a place such as that dealt with under 10a is furnished by Shaver Lake Dam. A joint of this kind near the right end (right bank) lets a little water seep through.

12a. American Falls Dam, which is a straight concrete gravity dam, ends up at the right bank as an earthfill wing with a concrete core wall. The inspection gallery of the dam proper goes into the earthfill portion. At the junction a rather large crack has developed. It is essentially vertical, but zigzags several times on the way from the floor of the gallery to the ceiling. Where it slopes upward toward
the earthfill it was open about 0.10 inches, but it was closed on portions inclined upward toward the dam proper; this crack indicates then two relative motions: (1) a separation; and (2) a settlement of the earthfill portion relative to the dam proper.

13b. Another example of a crack near the junction of two parts functioning differently is furnished by Stony Gorge Dam, which is an Ambursen dam. At a number of the buttresses cracks occurred across the corbels near the block filling the cut-off-trench. Some of these cracks showed a small amount of leakage of water.

13c. In Big Dalton Dam (multiple arch dam), in one of the buttresses, there was observed a three-branched crack forming a "Y". The vertical branch was open only 0.01 inch. The branch pointing upstream was open 0.03 inches, and this branch was rather long. According to Mr. R. W. Carlson, Testing Engineer, Los Angeles Flood Control District, the concrete on the downstream side of the "Y" was poured early and was harder than the concrete through which the long upstream branch of the "Y" extends. Evidently, the case is again that of two parts performing differently, with cracks forming at the junction. The branch extending upstream may be interpreted as being of the type described under 10.

13a. An example of an irregularity caused by a feature in the construction program may be found in Pardee Dam. The horizontal inspection gallery near the bottom has rather wet walls, and at one point a fairly large sloping crack appears in the walls. According
to Mr. F. W. Hanna, Chief Engineer, East Bay Municipal Utility District, this crack is due to the fact that a contractor's tower was placed there during the construction.

13b. Another example of the effect of an irregularity made necessary by the construction program is the following: In Exchequer Dam on the right bank a railroad tunnel was left open during the major part of the construction, and the hole was filled with concrete later. The line marking the edge of the hole on the downstream face is visible, the top being shaped there as a Gothic arch. There is a small amount of leakage at the top of this former opening.

14a. In various cases it was reported by the engineers supervising the arch dams (or arched gravity dams) that the joints at the top tended definitely toward closing up when the water rises in the reservoir (examples: Santa Anita, Mulholland, Exchequer and Don Pedro Dams).

14b. In Big Dalton Dam (multiple arch) it is reported (see Exhibit C) that rain has passed through the cracks on the arches, yet with water in the reservoir the dam is quite tight.

14c. In Lake Hodges Dam (multiple arch), which was visited when the water was near the top, the arches showed some leakage right below the water surface. Farther down there was practically no leakage, but numerous spots of white deposits indicated past leakage.

15a. The grand example of cracks in buttresses which are designed without reinforcement to keep the cracks small and without expansion joints, is found in Lake Hodges Dam (multiple arch). 21
buttresses were observed from the inspection bridge under the dam. Everyone of those buttresses had a large crack which almost invariably extended from the doorway for the inspection bridge sloping upstream upward (to the springing lines of the arches) and downstream downward from the doorways. The widths measured at the doorways ranged from about 0.1 inch to 0.25 inches. At a couple of places patches had been placed across the cracks, and those patches had cracked, thus indicating that the cracks were working as expansion joints. In one buttress (near the left bank), which was readily accessible for inspection of a larger area of the side, there was noticed another crack farther downstream, similar to and nearly parallel to the one going through the doorway (but not as wide); similar parallel cracks may exist in other buttresses.

16a. In the reinforced buttresses in Stony Gorge Dam (Amburston) the cracks are small even though some of the lifts in some of the buttresses are reinforced incompletely.

16b. The reinforced buttresses of Stewart Mountain Dam (arch dam) have not developed any cracks worthy of notice.

17a. At Coolidge Dam the following conditions were observed in the buttress between the middle dome and the dome on the right bank: An expansion joint extends upward and upstream from a doorway through the buttress. There is reinforcement around the arched top of the doorway, quite close to the surface. The expansion joint has extended itself on the right side of the buttress as a crack, 0.05 inches wide, running along the reinforcement, and showing a tendency of the rein-
Forcing bars to straighten out and pull out. On the other side of the buttress there is some spalling off, indicating that the expansion joint has opened and closed.

18a. In Lake Hodges Dam (multiple arch) there is reinforcement around the arched tops of the doorways through the buttresses. The reinforcing bars are close to the surface. In some of the buttresses the large crack reaching the doorway has caused the reinforcing bars to straighten out partly, with cracks formed along the bars, and there is some spalling off of the concrete. The action is the same as that which was described under 17a, and which occurred in one of the buttresses of Coolidge Dam.

19a. The condition in Lake Hodges Dam described under 15a indicates definitely that openings draw cracks. The cracks in the buttresses of Lake Hodges Dam are generally widest at the doorways; that is, the openings exaggerate the cracks.

19b. Mr. H. W. Dennis, Chief Civil Engineer, Southern California Edison Company, expressed the belief that a certain crack observed in a gallery in Shaver Lake Dam existed because the gallery was there.

19c. That cracks may actually be caused by the openings is shown by the fact that in various cases cracks are found to extend only short distances from the openings, when observed on the downstream face of the dam. The cases mentioned under 20a and 20b are examples. In many cases, of course, the cracks observed in the galleries are not local effects.
20a. In Elephant Butte Dam a short crack was noticed at the downstream face, extending about 1.5 feet upward from the top of one of the openings intended for penstocks. At the lower end this crack was 0.03 inches wide.

20b. Similar short cracks were observed over a couple of the entrances to the galleries on American Falls Dam.

20c. A similar crack, but perhaps 20 feet long was observed over one of the entrances on Exchequer Dam (left bank).

20d. Cracks in ceilings in galleries running in the direction of the gallery were observed on Exchequer, Don Pedro, Pardee, Lake Spaulding, Arrowrock and American Falls Dams.

21a. A crack parallel to the face of the dam was observed in Shaver Lake Dam on one of the entrance galleries. This crack has been studied closely by Mr. H. W. Dennis, Chief Civil Engineer, Southern California Edison Company (Exhibit E).

21b. Cracks of this kind are found also in Exchequer Dam (Exhibit F) and Pardee Dam (Exhibit G).

22a. A good example of horizontal cracks on galleries is found in American Falls Dam. Some of the vertical cracks found in this dam jog in crossing the horizontal cracks, thus indicating that the horizontal cracks were formed first.

23a. At Calaveras Dam which is under construction it was stated that some cracks had begun to form starting from re-entrant corners of keyways. No such cracks, however, could be seen on the day when this dam was visited.
23b. A number of such cracks were noticed at the top of Lake Spaulding Dam.

23c. A vertical crack close to a vertical joint and evidently starting from the keyway was observed at several places on the galleries of American Falls Dam.

24a. Examples of irregular systems of cracks at the junction of two galleries, or where the cross section of the gallery changes, are found in Exchequer Dam (Exhibit E) and in American Falls Dam, respectively.

25a. In Elephant Butte Dam one of the entrance galleries passes one of the sluiceways so that the distance between the nearest points is probably only about 5 feet. An irregular system of small cracks has appeared on the wall of the gallery (Exhibit A).

26a. The following table shows, as an example, the openings of some of the vertical joints, measured in the galleries of Shaver Lake Dam. These galleries are along the upstream faces of the dams. It is noted that generally the joints are open more widely on the downstream wall than on the upstream wall. The same tendency was observed in other dams.

Openings of Some Vertical Joints in Inches

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27a. In American Falls Dam the gallery closest to the top showed the most severe cracking (one longitudinal crack open 0.10 inches).

28a. The irregular distribution of openings of joints may be observed in most dams, especially at the top. For example, the top of Santa Anita Dam, which has a decidedly non-symmetrical site, showed a couple of widely open joints (0.15 inches and 0.10 inches maximum width) on the flatter side. Otherwise the openings were very small.

29a. The strain-gage readings taken systematically across cracks or joints in Pardee Dam (Exhibit G) and Bull Run Dam (Exhibit J) show clearly the working of the cracks and joints.

30a. Hair cracks can usually be observed on any dry surface of a concrete dam that one is able to get close to. American Falls Dam, for example, showed a system of hair cracks on the downstream face with a spacing of the order of 5 feet.

31a. Lake Spaulding Dam was decidedly the wettest of the dams that were inspected. Water trickled down at many places on the downstream face, and the galleries, correspondingly, were very wet. Exchequer, Don Pedro, and Pardee Dams had some scattered wet spots on the downstream faces and were rather wet in the galleries. Elephant Butte and Bull Run Dams can be classified as dry dams.

31b. Mormon Flat Dam, which has no inspection galleries, has a wet spot with a horizontal upper edge on the downstream face at the right abutment. According to the observations in the galleries
of other dams, this wet spot indicates a considerable wetness inside
the dam in this particular region.

32a. Grouting has reduced the leakage in most of the dams
that were visited.

33a. White deposits which are evidence of past leakage were
observed at all the dams that were in service. In the cases of Ex-
chequer, Don Pedro, and Pardee Dams the fairly large areas of white
deposits, now dry, on the downstream faces, indicate a notable reduc-
tion of the leakage. The deposits in the galleries also indicate a
reduction of leakage.

33b. Stalagmites formed by water dripping from cracks in
ceilings in galleries are not uncommon. Usually they are only a few
inches long, but in Lake Spaulding Dam some were found that were about
3 feet long.

34a. That wetness and size of opening have no simple corre-
lation is a simple consequence of differences of the depths of the
cracks, and differences in the effectiveness of the seals and in the
success of the grouting operations.

35a. All the high dams illustrate the seriousness of the
problem of watertightness.

36a. An undergallery in Shaver Lake Dam cut so that the
joint between bedrock and concrete could be inspected approximately
along the original stream line showed an excellent connection between
concrete and bedrock.
37a. Elephant Butte and Arrowrock dams, which were built with sand-cement compare very favorably in regard to watertightness with Lake Spaulding Dam which belongs to the same period, and which was built with Portland-cement concrete. The surfaces are in quite good condition at Elephant Butte where the climate is favorable, but not at Arrowrock where the more severe climate has caused a noticeable amount of weathering.

38a. A part of a section in Bull Run Dam near the center and near the bottom was reported to have been built too fast, and as a result a crack formed in the inspection gallery (this crack could not be discovered when the dam was visited).

39a. Bull Run Dam is an example of a dam built particularly well with modern methods of rigid control of the concrete. The expansion joints open and close in this dam (Exhibit J), but there are practically no cracks.

**General Comments and Suggestions**

A. Large concrete dams are structures on which heavy loads and severe conditions are at work. Like other structures built by man, dams require watching and maintenance, even those with the most solid sections.

B. Inspection of cracks, joints and seepage is a desirable method of watching the structural behavior of a dam. It is important that new cracks be discovered as early as possible.
C. Systematic strain-gage readings at a number of cracks or joints through some period, such as have been obtained at Pardee Dam by Mr. F. W. Hanna and at Bull Run Dam by Mr. Ben S. Morrow are a particularly useful method of watching a dam.

D. The bedrock is a part of the structure.

E. Grouting of cracks, joints and seams in the concrete and bedrock are an essential part of the maintenance of the dam as a structure.

F. In building a high dam, control of the concrete, even to the extent of making life miserable for the contractor, is profitable.

G. Inspection galleries are desirable.

H. In a very high dam it appears desirable not to put the galleries quite so close to the upstream face as would be reasonable in dams of smaller height.

I. Stresses due to shrinkage present a problem which is farther from a final solution than is the problem of stresses due to loads. It is desirable that extensive investigations be made for the purpose of obtaining cement and concrete with low shrinkage.
Exhibits

The exhibits consist of material supplied by engineers who have cooperated. The following are submitted:

A. "Memorandum Report on Survey of Cracks in Elephant Butte Dam" by L. R. Fiock, Superintendent, Bureau of Reclamation, El Paso, Texas. Supplemented by drawing showing the position of gallery E relative to sluice No. 2 in Elephant Butte Dam.

B. Data concerning Coolidge Dam, furnished by Mr. Clarke J. Wells, Assistant Engineer, Indian Field Service, Coolidge Dam, Arizona: (1) Letter dated June 26, 1930; (2) sketch showing position of leakage; (3) drawing showing the location of the three major cracks in the two side domes.

C. Three reports to Mr. E. C. Eaton, Chief Engineer, Los Angeles Flood Control District, by Mr. R. W. Carlson, Testing Engineer, concerning cracks in dams of the Los Angeles Flood Control District: (1) Big Dalton Dam; (2) Big Santa Anita Dam; (3) Pacoima Dam.

D. Data concerning Mulholland Dam, furnished by Mr. H. A. Van Norman.

E. Letter from Mr. H. W. Dennis, Chief Civil Engineer, Southern California Edison Company, Los Angeles, dated June 6, 1930, concerning a crack in Shaver Lake Dam, parallel to the face of the dam, observed in one of the entrance galleries. Drawing sent with the letter, showing results of strain-gage readings across this crack. Drawing showing plan, elevation and sections of the dam.