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USE OF COLLOIDAL CLAY SEDIMENTS IN SEALING IRRIGATION CANALS*

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SUMMARY

Seepage losses from irrigation canals constitute an exceedingly serious problem in the United States, and perhaps in other parts of the world as well. It is noteworthy, however, that few irrigation groups are actually doing much canal lining work. This general lack of large scale lining programs becomes more understandable when the following factors are considered : (1) miles of canal that need lining, (2) high costs per mile of commonly accepted canal linings, and (3) time required to install conventional linings.

The sediment lining method, however, offers a potential low-cost, mass-production answer to the above problems. In the sedimenting method the normal subgrade preparation costs are usually eliminated, and the hauling and placing costs are greatly reduced. Flowing canal water is used to carry and place the colloidal clay sealing agent in only the leaky zones of the canal bed.

Research and development work on this new canal sealing method has been accomplished through the Colorado A & M Research Foundation and with many co-operators, such as the U.S. Bureau of Reclamation and the Central Nebraska Public Power and Irrigation District.

The development program consists of two coordinated phases involving both practical field site installation trials and fundamental laboratory research. Field trials have been made on operating canals in (1) loess, (2) dune sands, (3) fractured rock, and (4) sandy to clayey alluvial materials. A high-swell bentonite has been used as the sediment in all of these trials.

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*Usage de l'argile colloïdale pour le colmatage des canaux d'irrigation.

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This report briefly outlines the results and general procedures followed in three years of field and laboratory research on the sedimenting method of sealing irrigation canals. In general, good sealing results have been obtained in the loessial and sandy soils. The initial results in fractured rock have not been entirely favorable, but special sedimenting procedures are being developed for sealing these more pervious and open materials. Significantly, even though the work is still in an experimental stage where the costs are rather high, the installation costs have commonly been less than the value of the water saved in the first season. More time is needed before the life of the sealing effect can be determined.

At the present stage of development work, the sedimenting method seems potentially to provide a truly low-cost, mass production method of sealing irrigation canals, but additional development work is needed to actualize this potential in any new area for sedimenting work.

RESUME

Les pertes par infiltrations dans les canaux d'irrigation constituent un problème extrêmement sérieux aux Etats-Unis comme peut être dans d'autres parties du monde. Il est à remarquer cependant que quelques groupes d'irrigation effectuent à l'heure actuelle beaucoup de canaux revêtus. L'absence générale de grand programme de revêtement devient plus compréhensible lorsque l'on considère les facteurs suivants: (1) les kilomètres de canaux nécéssitant un revêtement, (2) le prix élevé par kilomètres de canaux revêtus, et (3) le temps exigé pour l'installation du revêtement conventionnel.

Notons que le revêtement par la méthode de sédimentation offre des prix peu élevés, c'est une réponse au problème ci-dessus relatif à la construction à grande échelle. Dans la méthode par sédimentation les frais de préparation de plate-forme sont d'habitude éliminés, le coût de transport et de mise en place est grandement réduit. L'eau même du canal est alors utilisée pour transporter et mettre en place l'agent colmateur ou argile colloïdale.

Des travaux de recherches et de développements de cette nouvelle méthode du colmatage des canaux ont été éffectués au Colorado A and M Research Foundation avec l'assistance de nombreux collaborateurs tels que le Bureau des Reclamations, et le Service Public et Irrigation District du Central Nebraska.

Un programme de développement en deux phases coordonnées comprend des essais sur des installations déjà realisées et des recherches de base au laboratoire. Des essais sur des canaux en cours de fonctionnement ont été realisés, leurs lits se composaient de (1) loess, (2) de dunes de sable, (3) de roches fissurées, (4) soit de matériaux allant du sable à l'argile. Une bentonnite à grande expansion fut utilisée dans tous ces essais.

Ce rapport expose brièvement les résultats et les procédés generaux suivis durant trois années d'essais et de recherches sur la méthode du

colmatage sédimentaire des canaux d'irrigation. En général de bons colmatages ont été obtenus sur des terrains à base de loess et de sable. Les premiers résultats obtenus sur lit à base de roches fissurées n'ont pas été entièrement favorables; mais des procédés spéciaux ont été développés pour colmater les matériaux perméables. Bien que les travaux soient encore dans une phase expérimentale où les prix sont plutôt élevés le coût de l'installation fut généralement inférieur à la valeur de l'eau recuperée durant la première saison.

Dans l'état actuel des travaux, cette méthode de colmatage semble virtuellement offrir des prix peu élevés ainsi qu'une méthode de production en masse de canaux d'irrigation colmatés, mais des travaux de développement additionnel sont nécessaires pour réaliser ce potentiel dans n'importe quelle nouvelle région.

INTRODUCTION

Seepage losses from irrigation canals constitute a serious problem in the United States and other parts of the world. It is noteworthy, however, that few irrigation groups are actually doing much canal lining work This general lack of large scale lining programs becomes more understandable when the following factors are considered :

1. Miles of canal that need lining;
2. High costs per mile of commonly accepted canal linings; and
3. Time required to install conventional linings.

For most operating irrigation organizations, the combination of the above problems has restricted canal lining to trouble-spot applications. This "piecemeal" approach seldom saves much water when considered as a percentage of the over-all distribution system losses. Therefore, a truly low-cost, mass-production method of canal lining or sealing is one of the more important needs of irrigated agriculture. The sedimenting method (described herein) is potentially such a method and it has the added advantage of being applied by flowing canal water.

Research and development work on this new mass-production technique of canal sealing with water-borne clay sediments has been actively carried on since July of 1953. This work has been accomplished through the Colorado A and M Research Foundation with many co-operators, such as the U.S. Bureau of Reclamation and the Central Nebraska Public Power and Irrigation District. The work is still very much in an experimental and development stage, but because of an apparent general interest, the results to date are briefly outlined in this paper. The program is being continued and expanded in scope at the present time to cover a wider range of canal conditions and fundamental laboratory research.

PREVIOUS WORK

There are a number of important precedents for the sedimenting method, including:

1. Pervious materials, such as sands, have been sealed and cemented by geological processes involving the seepage injection of water-borne sediments.

2. Seepage from irrigation canals has been significantly reduced, both naturally and artificially, through the action of silt* sediments in the canal water.

3. The problems of canal seepage, bank erosion, and submerged water weeds have usually increased when the silt has been removed from the irrigation waters—commonly as a result of storage in a newly constructed upstream, regulatory reservoir(13).†

One important objective of sedimenting is to reproduce and improve on the canal sealing effects of "silting" while excluding the undesirable effects an uncontrolled muddy water can produce in canals and on irrigated land. Because of this relation between the silting and sedimenting methods, both methods are briefly covered in the following review of previous work.

SILTING

Natural silting is as old as irrigation. It has been commonly noticed that muddy water seems to flow farther than clear water in ditches and on irrigated land. Usually, however, the disadvantages of a very muddy irrigation water, such as sand deposits requiring removal by cleaning operations, far overshadow the advantages. Frequently, the advantages go unnoticed until canal cleaning or construction of an upstream dam emphasizes that there have been, after all, some beneficial aspects to the muddy water.

For example, after Guernsey Dam was completed, the amount of sediment in the waters released to the downstream irrigated areas in eastern Wyoming and western Nebraska, was greatly reduced. The canal cleaning problems, which had been troublesome, were almost eliminated, but to off-set this advantage, the canal seepage losses and the canal bank erosion seriously increased. The growth of submerged water weeds also appreciably increased in some reaches of canal. Figure 1 compares the canal losses and farm deliveries of the Interstate Canal Division for the period of 1914 to 1952. Note the significantly greater canal losses after 1927 when storage of water began in Guernsey Reservoir.

In recent years the sealing effect of infrequent muddy flows in the Interstate Canal has been noted‡. A slight mud content in the water

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* Catch-all term—generally means any sediment, ranging in size from sand to silt to clay.

† Number in parentheses refers to the bibliographical entry.

‡ Personal communication from Mr. G. H. Storm, formerly Superintendent, Pathfinder Irrigation District, Mitchell, Nebraska.

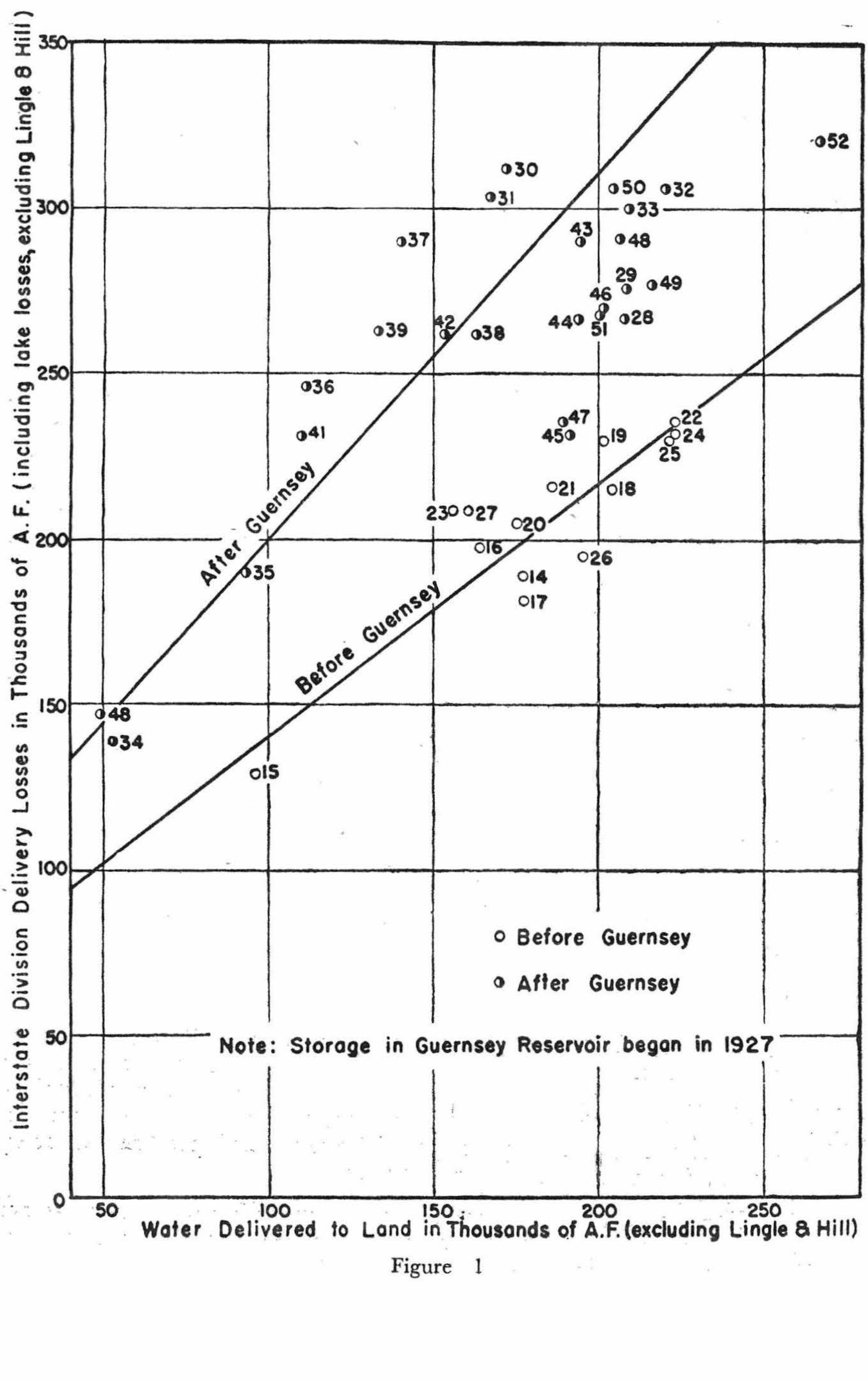
Interstate Division Delivery Losses in Thousands of A.F. (including lake losses, excluding Lingle & Hill)
Water Delivered to Land in Thousands of A.F. (excluding Lingle & Hill)
After Guernsey
Before Guernsey
Before Guernsey
After Guernsey
Note: Storage in Guernsey Reservoir began in 1927

Figure 1

(maximum of about 1000 ppm) will reduce the over-all losses in the Interstate Canal from about 600 cubic feet per second to 500 cubic feet per second. The normal maximum flow is about 2,100 cubic feet per second at the headgate. The sealing effect, however, is temporary, seldom lasting more than one week, or until the silt cake is eroded away.

The introduction of an artificial sediment into flowing canal water has been tried on many irrigation projects—perhaps at one time or another on all of them. While information relating to these trials is exceedingly meager, it does appear that the best results have been obtained when the sediment penetrated into the cracks or voids of the in-place canal bed materials. In several canals good sealing results have been obtained with bentonite clay as the silting agent.

The common limitations of silting are, in effect, guideposts to avoid in the research and development work on the sedimenting method. Therefore, some of the more common limitations are outlined below:

1. **Permeability of "silt"**—In some extreme cases, sandy to silty materials of a pervious nature have been used for "silting". However, due to flocculation problems and over-size particles, even the most favorable appearing clayey materials can produce relatively permeable and vulnerable "silt" layer linings.

2. **Settling tendency**—When mixed in untreated canal water, most local clays will tend to settle to the canal bottom within a relatively short distance of flow, especially in a slowly flowing canal. Thus, almost all of the suspended load of "silt" may drop out in the first ponded reach of canal and not necessarily where the sealing is needed.

3. **Lack of penetration**—Almost all natural clays contain some sand and silt-size particles. This is unfortunate since only a small percentage of over-size sediment particles can produce a bridging action over the void openings of the pervious soils. Thus, the slower settling clay, which probably produces the main sealing effect, is commonly concentrated at the canal bed surface, where it is susceptible to erosion by water, puncturing by animals, deterioration by drying and cracking, or destruction by canal cleaning.

SEDIMENTING

In sedimenting, the sealing agent is stably dispersed; settling is virtually eliminated by one or a combination of methods, such as presettling, chemical dispersion, or by the turbulence of flowing canal water. By accomplishing this dispersion, the sedimenting action is automatically concentrated in only the leaky zones of the canal bed provided an adequate sealing-in-depth effect is being achieved.

The major previous work on the sediment lining method, as defined above, was accomplished by the U.S. Bureau of Reclamation on the Kendrick Project, near Casper, Wyoming(5).

Valuable information has been provided by the somewhat related uses of bentonite for water impedance work as follows:

1. A bentonite slurry was used in a reservoir sealing job in 1929 by Mr. C.H. Lee, Consulting Engineer for the San Francisco Water Board ([12]).

2. Model tests, involving the use of bentonite and water mixtures, were run during the investigations for the All-American Canal in southern California in 1939([8]).

3. Bentonite has been used for sealing canals and reservoirs as a buried membrane and as an admixture material for the pervious soils([9]) ([22]).

4. Bentonite has been used as an additive for drilling fluids in oil well drilling since about 1921 ([18]) ([15]).

A partial search of the literature has revealed considerable information of a relevant nature. Literature relating to grouting applications and drilling mud control have been especially helpful.

PRESENT RESEARCH AND DEVELOPMENT PROGRAM

The research and development project on sediment linings for canals was organized in July 1953, through the Colorado A and M Research Foundation, Department of Civil Engineering. The work has been supported by funds from contracts and contributions. The first contract was with the U.S. Bureau of Reclamation for studies starting in 1953. Since then, many additional groups have supported the research and development work.

To date, co-operative work has been initiated with 19 irrigation groups in Colorado, Nebraska, Wyoming, South Dakota, Arizona and California. In addition, technical and/or financial assistance has been furnished by four federal (U.S.) agencies, eleven bentonite companies, four chemical companies, and three equipment companies.

The general objectives of the research and development program are listed below:

1. To develop practical low-cost methods of sealing irrigation canals with colloidal clay sediments carried into place within the pervious soils by the canal loss water. This includes delineation of the physical phenomena involved, and learning to apply the results of such studies in a practical manner.

2. To evaluate such sealing methods in terms of cost, adaptability to old and new canals, reliability, ways to expand the present limits of application, and permanence.

3. To evaluate other effects of colloidal clay sedimenting, including the stabilizing effects on sandy canal bed soils, and the growth suppression effects on submerged water weeds.

The development program consists of two coordinated phases involving both field site and laboratory research. The field installation research is discussed first.

FIELD INSTALLATION RESEARCH

Because of the active support of the field installation phases of the research program, it has been relatively simple to arrange for new test sites. Thus, as a practical matter and because of the wide variations in canal site conditions from one area to another, the scope of the development work has been increased by adding carefully selected experimental installation sites.

The trials have been made at field sites on operating canals in (1) loess (wind-deposited silt or dust), (2) dune sands, (3) fractured rock (sandstones, siltstones and shales), and (4) sandy to clayey alluvial materials ([6]). Figure 2 is a map showing the locations of the experimental sites.

All of the installations have been made in relatively small canals, representative of the range of pervious canal bed soils and operating conditions found in each system. Consequently, the experience gained in each installation has immediate usefulness in helping to solve other similar canal sealing problems elsewhere in each system. In addition, the results have a long range utility when considered from the standpoint of the overall program.

Since emphasis has been placed on flexibility to meet the changing conditions from one site to another, it is difficult and perhaps unwise to generalize on the procedures followed in the field installations. However, because of the relatively large number of sites and the limitations of space placed on this paper, some generalization is necessary. Therefore, each experimental installation cannot be discussed in detail. A very generalized discussion of procedures is grouped according to (1) evaluation of site conditions, (2) selection of sediment, (3) final testing and planning, (4) installation procedures, (5) evaluation of results, and (6) other effects of sedimenting.

EVALUATIONS OF SITE CONDITIONS

Since adaptation of the sedimenting procedures to the canal site conditions is an integral part of the sedimenting process, careful consideration of the site conditions is essential. Usually each site has been evaluated several times in co-operation with the local project engineer or manager. This co-operative aspect is vital, if a full understanding of the site conditions is to be obtained. Evaluation factors have usually included the following:

1. Under dry conditions if possible, observations of: range, extent and character of pervious canal bed soils; presence or absence of actively eroding or eroded areas; extent, character, and movement of bed-load sand; silt cake on pervious canal bed soils, silt berms on banks; secondary void structures, such as worm or crayfish holes, root holes, drying cracks, and right-of-way accessibility—obstruction by trees, buildings.

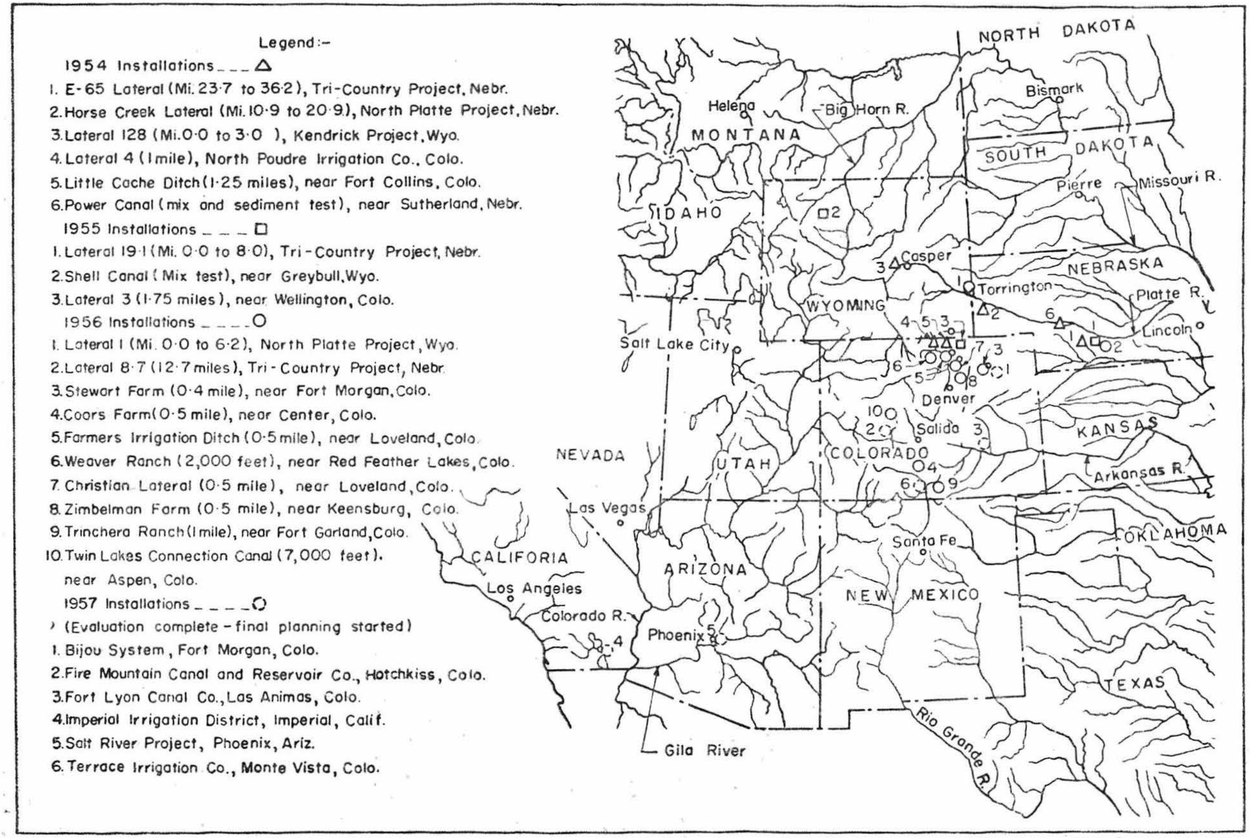

FIGURE 2:—Map showing locations of experimental installations

2. Under normal flowing water conditions, observations of: need for sealing; normal canal water losses; seep damage to nearby lands; best period for sedimenting; location of check structures; grade of canal; possibilities of ponding with the check structures under low flows; pattern of water deliveries —continuous (during season or year around) or intermittent; length of dried-up period, if any, between deliveries.
3. Testing of the site conditions has usually included some additional water measurements and canal water analyses. Inflow-outflow measurements over the entire irrigation season have been obtained when possible. Where seeped land has been involved, depth to ground water records have been started. Where possible, data on the dissolved and suspended solids in the canal water has been obtained for each site. Determination of water quality at periodic intervals throughout the entire irrigation season is advisable because of seasonal variations ([10]).

SELECTION OF SEDIMENT

With the site conditions fully in mind, the next consideration involves the selection of a sedimenting agent that will (1) remain stably dispersed and suspended during the flowing canal water phase of the process, and (2) produce an adequate sealing-in-depth effect within the pervious soils during the percolating loss water phase of the process. Unfortunately, the methods and materials used to satisfy one of the conditions, in some instances will not satisfy the other conditions. Obviously, both conditions must be satisfied, if the desired effects and economics are to be achieved.

In many areas local clays are available or the canal waters may occasionally carry a colloidal clay content that could be modified and perhaps controlled for use as a sedimenting agent, but in the trials to date it has been more economical and convenient to use the commercial grades of high-swell bentonite. These are reasonably uniform in quality, in good supply, and in common usage.

Depending on the amount of multi-valent cation (or salt) contamination in the available bentonites and in the site water, varying concentrations of a polyphosphate dispersant have been used to control the bentonite flocculation and settlement problems ([2]). This is especially important if a ponding procedure of sedimenting is contemplated. The polyphosphate additive has an additional beneficial effect in that it reduces the viscosity of the bentonite slurries, thus facilitating the mixing and pumping operations at the head end of the canal being sealed.

Considering the normal range of pervious soils and canal operating conditions, both within and between canals, it seems apparent that there is no all-purpose sediment. The high-swell bentonites, however, through the use of various grinds, come very close to providing such an all-purpose sediment for materials of the intermediate to very pervious ranges of permeabilities. For sealing materials of very open voids, granular rather than the normal powdered high-swell bentonites have been used, and in some instances supplemental sedimenting and bridging agents, such as a local clay, sawdust, *etc.*, have also been used. For sealing materials of relatively small void openings where sediment penetration is a problem, the dispersing agent alone has potentialities if the in-place soil clays are of a dispersable nature.

Two tests have been used to evaluate potential sediments: (1) grit content, and (2) colloidal yield. The grit content is the percentage retained after washing on a 325-mesh screen. The colloidal yield is the per cent of materials remaining in sespension after 18 hours. In the latter test 10 grams of sample is thoroughly mixed into 500 grams of distilled water and allowed to stand undisturbed for 18 hours ([7]).

FINAL TESTING AND PLANNING

The next considerations relate to the final testing and planning required to set up the sedimenting procedures. This has usually involved the following steps for each trial installation:

1. Additional trial mixes to determine type and concentrations of sediment and chemical dispersant.

2. Calculation of total volume of sedimenting charge and total amounts of bentonite and dispersant.

3. Preparation of final cost estimates and plan of installation.

4. Final preparations for delivery of water, materials, mixing equipment, and experienced help for mixing and ponding phases of the sedimenting work.

In some instances, trial permeability tests (both field and laboratory) have been run to determine the concentration of sediment and ponding or exposure time needed to produce a satisfactory sealing effect ([11]).

The bentonite concentration has usually been set at one per cent. At this concentration the viscosity of the mix is very close to that of water alone. Problems can be produced at the higher concentrations owing to the viscous nature of the mixes, and at the lower concentrations owing to the lack of sediment stability. The concentration of dispersant required depends on the water and the sediment. It has usually ranged from none for soft water to as much as 20 per cent (by weight of bentonite) for very hard waters.

The calculations of total volume depend on the situation and, for the first installation in any new area, are at best an estimate. They have been computed in several different ways: (1) 0·5 to 1·0 pound of bentonite per square foot of pervious wetted area in the reach of canal being treated, (2) ¼ to 2 tons per cubic foot per second of capacity per mile of canal—adjusted according to the intensity of seepage losses, and (3) volume of largest pond plus volume of estimated shrinkage in upstream sedimenting ponds.

The time for sedimenting has usually been set by practical considerations, such as a period before, between, or after the normal irrigaion water deliveries. Where sediment penetration problems have been anticipated, running into a dry canal has been recommended.

INSTALLATION PROCEDURES

If properly planned and executed, the sedimenting process is a four-phase operation:

1. **Mixing**—An appropriate kind and amount of sediment (plus dispersant and/or supplemental bridging agent, if needed) is adequately dispersed into the flow of sedimenting water into the canal reaches being treated.

2. **Transportation**—The stable sedimenting mixture is controlled and routed down the canal reach being treated.

3. **Penetration**—During its controlled travel (by ponding, if possible) down the canal, increments of the sedimenting mixture seep into the voids of the pervious zones of the canal bed and banks.

4. **Sealing**—The sedimenting material in the seepage water is retained in the voids to produce a sealing-in-depth effect—this probably being due to the accumulative actions of filtration, adsorption, gelation, ionic exchange, *etc.*

With the above operation as an objective in the present development work, the installation procedures at each site have usually involved the following steps: (1) presedimenting work, (2) mixing of sediment, (3) routing of sedimenting mixture, and (4) follow-up phase.

The presedimenting work required at each site has varied with the conditions from one site to another, but usually it has involved: (1) release of water for sedimenting run, (2) assembly of equipment and materials, and construction of mud pit, if needed, at head end of canal reach being treated, (3) preliminary mixes of water, sediment and dispersant to check stability and to calibrate hydrometers,* (4) cleaning of weeds from canal and waterproofing of check structures, and (5) arrangement for mixing and water running crews.

The mixing operation usually has involved the following steps: (1) mixing of bentonite slurry, (2) retention of slurry in a mud pit, and (3) dilution of slurry to concentration for sedimenting.

Various mixing methods have been used to disperse the sediment into the sedimenting charge of canal water. The most economical and effective mixing has been accomplished with the multiple jet devices, such as developed by The Central Nebraska Public Power and Irrigation District and Cronese Products, Inc. (see Figure 3 and 4). On the smaller jobs and where the above jet mixers were not readily available, compressed

* Various types have been used—including standard Bouyoucos hydrometer with range of 2-60 grams/liter and extra sensitive hydrometer with 0 to 10 grams/liter range.

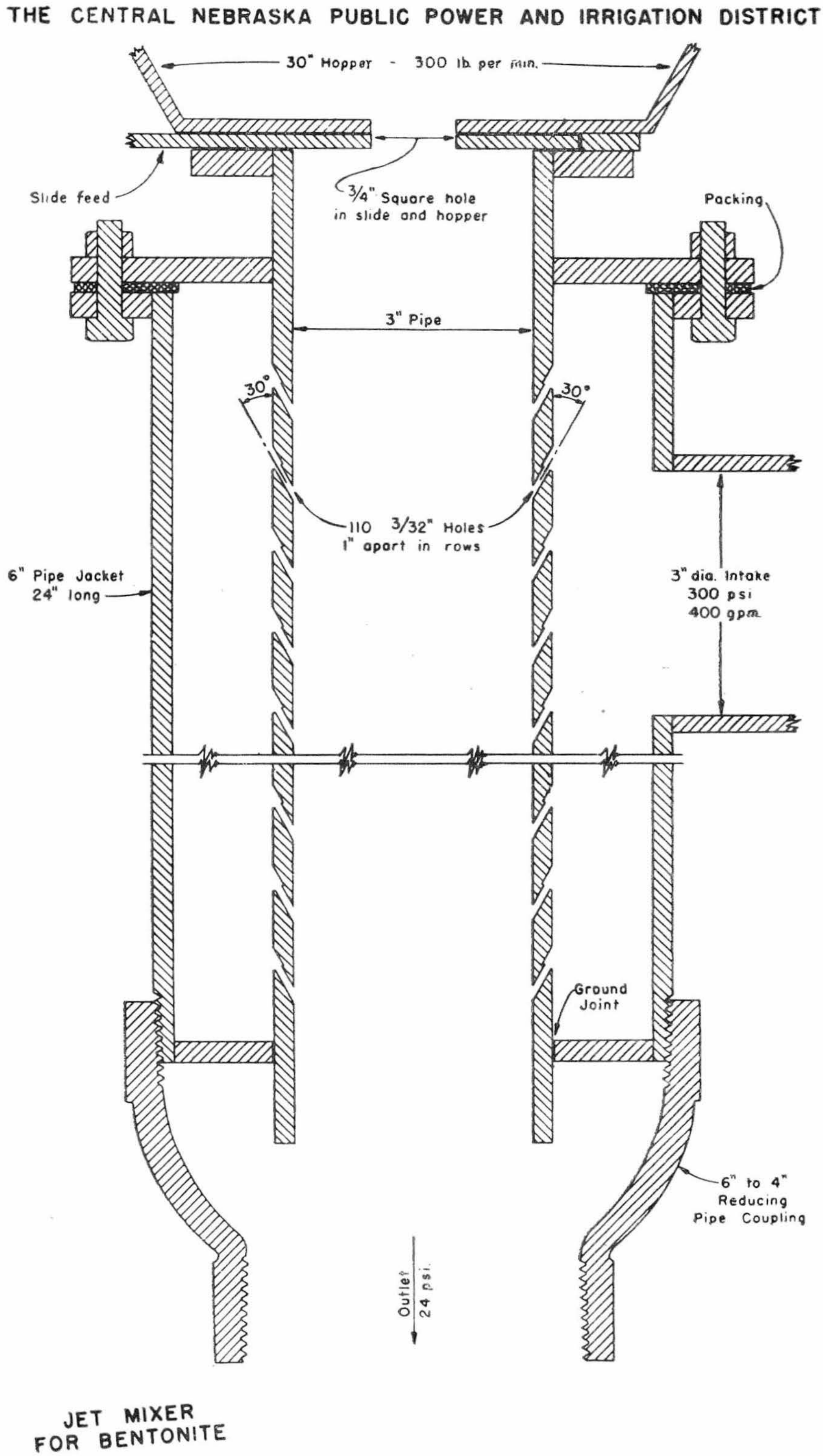

FIGURE 3:—Details of jet mixer

FIGURE 4:—View of Cronese mixer during Lateral 1 installation on North Platte Project in Wyoming. Photo courtesy of Wyoming Natural Resource Board.

FIGURE 5:—Mixing method involving the use of compressed air jetting into a wet layer of bentonite. Photo courtesy of U. S. Bureau of Reclamation.

air jetting into a wet layer of bentonite has been used (see Figure 5). Single jet mixers and propeller type mixers, such as commonly used to mix oil field drilling and cementing fluids, and circulation methods through centrifugal pumps have also been used.

Where possible, the bentonite slurry has been pumped into a long narrow retention pit before metering into a diluting flow of sedimenting water. This mud pit cycle provides (1) a control so that when necessary lumpy unsatisfactory mixes can be supplementally mixed by additional jetting, (2) extra time for "curing" or complete wetting of the bentonite, and (3) a standby volume and better control for slurry additions into the diluting water. The desired sedimenting concentration has usually been reached by regulating the diluting flow of clear water—assuming a constant rate of slurry additions.

The actual sealing process is accomplished during the routing of the sedimenting mixture. Two general methods have been used: (1) ponding with existing structures and under very low flow conditions, and (2) full flow procedures where canal structures are not sufficiently close-spaced for adequate ponding. The main consideration at this stage is one of providing a sufficiently ample ponding time or exposure time over the pervious areas so that an adequate sealing-in-depth effect is produced. Factors, such as the anticipated penetration and sealing problems, and the canal grades and locations of structures, will determine which method or a combination of methods will be feasible.

Upon completion of the sedimenting run, several alternative courses of action have been used: (1) a clear water after-drive is run in immediately behind the sedimenting charge, (2) the canal is allowed to dry out after the sedimenting, and (3) normal deliveries of irrigation water are resumed immediately after the sedimenting. The recommended procedure will vary with the water delivery demands, and to some extent, with the anticipated penetration and sealing problems. If penetration seems to be a potential problem, a clear water phase of ponding may be advisable. If penetration is easily achieved and sealing is the problem, it may be advantageous, if possible, to dry up the canal immediately after the sedimenting.

EVALUATION OF RESULTS

If sealing of an existing canal is the sole purpose for the sedimenting operation, the important evaluation factors are somewhat simplified and will usually include: (1) actual amount of water and land saved, (2) the life expectancy of the sealing effect, and (3) the relation between costs and benefits.

As previously mentioned, a continuous record of the inflow and outflow for each test section of canal, both before and after the sedimenting, is desirable, but from a practical standpoint such a complete record is usually not obtainable. This situation is caused by (1) the length of the representative test reaches of canal, ranging from 0·4 to 12·5 miles long, and

(2) the large number of turn-out flows. Thus, as a compromise, measurements over one relatively short period of the irrigation season such as obtained by ponding and seepage metering, have been obtained. These loss figures have been translated to estimated seasonal loss figures, which of course are subject to question, but they are better than no loss measurements. It is hoped that these problems can be somewhat alleviated in future trial installations.

The life expectancy of a sediment sealing has not as yet been fully determined. This is one of the research objectives. It seems likely, however, that the life of the sealing is closely related to the effectiveness of the adaptation of the procedure to the site conditions. Evaluations are not complete as yet, but preliminary indications are that most of the sediment linings are still holding up satisfactorily—some since the spring of 1954.

Where possible and as the necessary supporting data are obtained, cost-to-benefit comparisons are being made. The common method of comparing linings is by cost per square yard. Thus, the square yard costs, which are actually very low, have been calculated, but in addition, a cost per acre-foot of water saved has also been estimated. Significantly, even though the experimental costs of mixing, *etc.*, are still quite high, the presently available costs per acre-foot of salvaged water have usually been less than $ 3.00. Stated in another way, the experimental costs have usually been less than the value of the water salvaged in the first season. In some installations, value of reclaimed land is an added benefit, but as yet these benefits have not been calculated.

In general, good sealing results have been obtained in the loessial and sandy soils. The initial results in fractured rock were not entirely favourable, but special sedimenting procedures are being developed for sealing these more pervious materials. Table I summarizes the available data for the experimental installations (as of June 1, 1956).

SECONDARY EFFECTS OF SEDIMENTING

Several potential secondary effects of sedimenting have been encountered in the research and development program, including: (1) effect of sedimenting mixture on irrigated land, (2) stabilizing effects on non-cohesive canal bed soils, and (3) suppression effects on growth of submerged water weeds.

One of the most frequent questions asked by irrigators concerns the possible sealing effects that the sedimenting clay could produce on irrigated soils. Research activities on this possibility were originally planned, but initial installation experience indicates that with a minimum amount of precautions all of the clay is used up in the canal being sealed. During three years of experience no trouble of any kind has developed in this regard.

It has been recognized that by depositing a sedimenting clay in the pores of the canal bed and banks, stabilizing effects as well as seepage reduction effects could be obtained. In practice, definite stabilizing effects

TABLE I

Summary of Data—Experimental Installations

Site	Dominant soils Max. size canal Length of reach	Construct. period Mixing method Instal. method	Amt. of Bent. Total cost Cost/mile/sq. yd.*	Water saved (A.F.)† Cost/A.F. Evaluation method	Remarks
1954 E-65 Lateral Tri-County Proj. Nebraska	Loess 100 cfs head end 12.5 miles	4-5 to 4-16-54 Johnson multi-jet slow ponding	403 tons $15,000 $1200 and $.075	10,600 in 2 yrs. $ 1.42 ponding, end of yr.	Ponding tests of 54 and 55 seasons indicate losses 1/5 original rate.
Horse Crk Lat. N. Platte Proj. Nebraska	Sand, silt, rock 100 cfs head end 10 miles	4-23 to 5-10-54 oil field sing. jet, slow ponding	175 tons $11,000 $1100 and $.10	Not directly applicable combination	Sealing primarily to save land. Groundwater level 1 to 3 feet lower.
Lat 128 Kendrick Proj. Wyoming	Rock, silt, sand 50 cfs head end about 3 miles	5-13 to 5-16-54 oil field sing. jet combination	55 tons 3100, $1033 and not determined	Not determined " " combination	Job cut short because of breakdown of installation procedure.
Lat. No. 4 near Wellington, Colorado	Sand, with clay layers 3 cfs 1 mile	Intermit. 54, 55 comp. air jetting full flow	10 tons $300 $150 and $.075	100 in 2 yrs $3.00 inflow-outflow	Mainly for mix tests. Losses cut from 50% to 7% after sedimenting.
Little Cache near Ft. Collins, Colorado	Sand, with clay layers 2.5 cfs 1.25 miles	Intermit. 54 Mix Co. prop type full flow	2 tons $60 $48 and $.005	40 in 2 yrs $1.50 inflow-outflow	Mainly for mix tests. Losses cut from 40% to 20% after sedimenting.
1955 Lat 19.1 Tri-County Proj. Nebraska	Loess 60 cfs head end 8 miles	4-11 to 4-20-55 Johnson multi-jet slow ponding	290 tons $10,000 $250 and $.08	3600 in 1st yr $2.78 ponding, end of yr	Ponding tests, end of 55 season, indicate losses 1/8 original rate.

TABLE I—*Continued*

Summary of Data—Experimental Installations

Site	Dominant soils Max. size canal Length of reach	Construct. period Mixing method Instal. method	Amt. of Bent. Total cost Cost/mi/sq yd*	Water saved (A.F.)† Cost/A.F. Evaluation method	Remarks
Shell Canal near Greybull, Wyoming	Sandstone and shale 100 cfs head end	8-29-55 comp. air jetting full flow	6 tons $25 Not determined	Not applicable ,, ,, inflow-outflow	Mixing test—more bentonite needed for sealing effect.
Lat No. 3 near Wellington, Colorado	Sandy to clayey 6 cfs 1·75 miles	9-13 to 9-24-55 comp. air jetting full flow	4 tons $125 $71 and $.06	Not as yet available inflow-outflow	Mainly for mix tests. Losses cut from about 10% to 5% after sedimenting.
1956					
Lat No. 1 N. Platte Proj. Wyoming	Dune sand 100 cfs head end 6·2 miles	3-29 to 4-10-56 Cronese multi-jet slow ponding	240 tons $11,800 $1900 and $.16	Not as yet available combination	Losses before about 22%. Immed. after from about 1·5% to 16·5%.
Lat 8.7 and sub lats Tri- County Proj. Nebraska	Loess 40 cfs 12·7 miles	4-11 to 4-20-56 Johnson multi-jet slow ponding	280 tons $10,000 $788 and $.10	Not as yet available combination	
Stewart Farm near Ft. Morgan, Colorado	Sand 5 cfs 0·4 mile	4-25, 27-56 comp. air jetting ponding	2 tons $125 $312 and $.14	Not as yet available combination	Preliminary measure- ments indicate savings of about ·77 cfs.
Miller Farm near Sterling, Colorado	Sand 2·25 cfs 1000 feet	4-3, 5 and 6-27-56 comp. air jetting ponding	3 tons $175 $925 and $.35	Not as yet available inflow-outflow	Extra bentonite used to stabilize eroding banks.
Coors Farm near Center, Colorado	Sand, gravel 6 cfs 0·5 mile	5-24 to 5-26-56 comp. air jetting ponding	6 tons $370 $740 and $.21	Not as yet available combination	Very coarse soil bentonite alone may not be enough.

* Not accurate since wetted area is estimated and in some cases not all of the area needs lining.
† Includes 1954 and/or 1955 evaluations—no 1956 evaluations available at this time, June 1, 1956.

have been noted when a non-cohesive soil, such as a dune sand, has been sedimented. A fundamental study of this effect has also been started as part of a dissertation being prepared by I.S. Dunn of the Civil Engineering Department, Colorado A and M College.

Some varities of submerged water weeds will not grow in muddy waters. Thus, the effect of sedimenting on the water weeds in some of the field sites has been noted. There are some indications that the clay has a smothering effect, but additional observations are needed to determine the effects more conclusively.

FUNDAMENTAL RESEARCH PROBLEMS

During the field installation phases of the research and development work, a number of problems have been encountered that can advantageously be approached by research work of a fundamental nature. Thus, the fundamental research phase of the project program has included work on the following general subjects:

1. General characteristic of bentonites,
2. Dispersion characteristics of clay minerals, and
3. Fundamentals of penetration and sealing.

The primary objectives of these studies are to determine the fundamental principles involved in the sedimenting process. To expedite these studies, testing under closely controlled and restricted conditions has been emphasized. It has involved some of the more obvious and simplified variables of the actual sedimenting procedures and field site conditions.

GENERAL CHARACTERISTICS OF BENTONITES

Since bentonite has been the basic sediment in all of the trials to date, some of its general characteristics are outlined.

Bentonite is a generalized term which refers to a rather heterogeneous substance, composed mainly of the clay mineral montmorillonite and fragments of other minerals, such as feldspar, gypsum, calcium carbonate, quartz, and traces of other minerals. Its chemical composition can vary to a considerable extent but a highly colloidal nature seems to be one distinguishing feature common to all high-swell bentonites ([7], [18]).

The colloidal properties and the stable dispersion potential of a high-swell bentonite may be ascribed to the very small size and inherent negative charge of the dispersed particles. The charge of the very small particles is apparently closely related to the character of the absorbed cations. Therefore, when speaking of bentonite, it is necessary to keep in mind two general classes:

1. Those of a high ratio of sodium to calcium that can absorb large quantities of water, swelling considerably in the process, and remain reasonably dispersed and suspended in thin watery concentrations (such as used in sedimenting).

2. Those of a low ratio of sodium to calcium that can absorb much smaller quantities of water, do not swell greatly, and have a pronounced tendency to flocculate and settle rapidly from dilute suspensions in water.

A good high-swell bentonite can absorb nearly five times its own weight in water and at full saturation or hydration it occupies a volume 12 to 15 times its dry bulk. The swelling is reversible; it can be wetted and dried an infinite number of times provided the water is pure. When mixed with 7 to 10 parts water, it makes a gelatinous paste which will gel or set-up ; with 15 to 20 parts of water, a milky flowable suspension is formed ; and in a very dilute mixture, such as one part bentonite to 100 parts of water, 70 to 90 per cent of the bentonite will remain in suspension almost indefinitely in a nearly pure or salt-free water. The last concentration and dispersed state are of interest in the present sediment lining work.

Bentonite deposits or beds are found in many parts of the world, but the high-swell bentonites are principally found in the United States in Wyoming, South Dakota, Montana, Utah and California. Current prices range from $1.00 to $3.00 per ton, unprocessed at the pit, and from $10 to $50.00 per ton, processed and sacked at the plant or mill—the higher prices usually include engineering and/or other service.

DISPERSION CHARACTERISTIC OF CLAY MINERALS

The study on the dispersion of sedimenting colloids has been directed by B.N. Rolfe of the Technical Coordination Branch of the U.S. Geological Survey. It is a co-operative venture also involving Colorado A and M College and several chemical companies.

The research program on the dispersion of sedimenting colloids was undertaken to determine the factors affecting suspensions and their relation to sedimenting. As previously mentioned the dispersion potential is apparently closely related to the particle size and flocculation character of the clay. Flocculation and dispersion of colloidal particles represent end stages in a long sequence of varying repellent and attractive forces. The primary components of these forces in colloidal clay suspensions are: (1) electrolyte content of the water, (2) kind and amount of cations present, and (3) kind and amount of colloid.

The attractive forces between colloidal clay particles are proportional to the electrolyte content of the water ; the effect on the clays is slight at lower concentrations but increases sharply to coagulation at higher concentrations.

The amount of electrolyte needed for flocculation will vary with the kind of ions involved. Generally, the coagulant effect varies with ionic valence. For example, less trivalent aluminum is needed for flocculation than divalent calcium or univalent sodium.

The third factor in clay suspensions is the mineralogical and chemical nature of the colloid. Clay minerals such as montmorillonite have a large specific surface and cation exchange capacity. Kaolinite exhibits reverse properties, having a small specific surface and cation exchange capacity. Therefore, the effect of a native cation on kaolinite is negligible whereas that on montmorillonite is quite significant.

The polyphosphates aid in dispersion by (1) tying-up the multi-valent cations in the water, (2) reducing the viscosity of the bentonite mixtures, and (3) providing sodium ions to assist in the process.

FUNDAMENTALS OF PENETRATION AND SEALING

The study of penetration and sealing aims to determine the conditions under which the sedimenting mixture may render adequate penetration and effective sealing-in-depth in the pervious soils. Initial studies in this regard have been accomplished under research assistantship arrangements by (1) R.B. Curry from June 1954 to July 1955, and (2) E.C. Newman from September 1955 to August 1956.

Studies by Curry ([3])

In order to reduce the number of variables to a minimum, Curry limited his materials to (1) four relatively inert sands and one highly reactive sand, (2) Wyoming high-swell bentonite, and (3) Fort Collins tap water. He found that a stably dispersed bentonite would pass through the inert sands without retention or sealing, except for the very fine sands where a surface filter-cake type of sealing (without penetration) took place. By flocculating the dispersed bentonite within the pervious soil, a sealing could be produced, but only if the flow was stopped for 24 hours. Relatively high hydraulic gradients were used in this study. The need for chemical reactivity within the pervious soils was indicated, if a sealing was to be achieved with a dispersed bentonite.

Studies by Newman ([14])

Following the suggestions by Curry's work, Newman used the following materials: (1) dune sand with small amount of chemical activity due to small clay content, (2) Wyoming high-swell bentonite, (2) polyphosphate dispersant; (4) flocculating agent, and (5) Fort Collins tap water. He found that (1) the hydraulic gradient affected the entry of dispersed bentonite into the sand and the retention of bentonite, (2) the dispersed suspensions caused a leaching of soil clays and subsequent settlement and lower permeability of soil, (3) non-colloidal materials accelerated the formation of a surface filter cake, and (4) flocculated suspensions did not enter the test soil at hydraulic gradients up to 0 9 and the filter cake was considerably more permeable than a similar filter cake of dispersed bentonite.

CONCLUSIONS AND COMPARISONS

It is an old adage that "if at first you do not succeed, try and try again." With this in mind it seems likely that the sedimenting methcd of sealing irrigation canals can probably be adapted to the conditions found in almost any canal. Past experience is helpful, but in any new area trial and error methods must still be used to some extent to find the sediment and procedure to fit the site conditions. Thus, adaptation is a major problem and adaptability is a major advantage of the method, but by the very nature of the latter advantage, the sedimenting method is not suitable for standardization.

After 3 years of experimental work, several important objectives and characteristics can be listed:

1. The sedimenting method is aimed at solving the serious canal lining problems facing many irrigation groups—they have miles of canal to be lined but they cannot afford the conventional canal linings.
2. In many of the present-day canal lining operations, the canal site is altered and fitted to the canal lining method. In the sedimenting process, the reverse is true. The method is adapted to the site conditions.
3. In conventional lining methods accurate location of the leaky zones in the canal bed is desirable since these are the ones to be lined. In the sedimenting method, this expense is largely avoided, since the sealing action is automatically concentrated in the leaky zones.
4. In conventional lining methods, equipment costs for subgrade excavation and canal lining placement are a major item of expense. In sedimenting method, these costs are almost entirely eliminated. The only equipment needed is for (1) canal cleaning, if needed, and (2) sediment mixing at head end of canal system being lined.
5. Finding construction time for major lining jobs is commonly a serious problem for conventional methods. In contrast, the sedimenting method is very fast. An entire canal system can be treated in the time it takes for checked-up water to flow slowly through the system.
6. A considerable amount of extra labor and specialized help is normally required for large scale operations with conventional methods. In the sedimenting method, a major part of the work is best accomplished by the normal irrigation canal crews.
7. Because of the high costs, conventional canal linings are commonly restricted to trouble-spot applications. This "piecemeal" approach seldom saves much water when considered on a percentage basis of the over-all distribution system losses. Thus, the ultimate goal of the present development program is to produce a low-cost, mass-production method that can be practically applied in one system-wide operation.

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