PAP-501

INTERIM REPORT
FOR
VALUE ENGINEERING TEAM NO. 8

Team Members

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<u>Section</u>

I. INTRODUCTION

In recent years the Bureau of Reclamation has experienced, as have other agencies in this country and abroad, serious damage to concrete in hydraulic structures caused by fluid flow cavitation, and by abrasive forces induced by the presence of solids in the flow. While there have been several papers dealing with cavitation as a damage-producing phenomenon, little has been written on the material response to it. Even fewer papers dealing with erosion caused by abrasion have been published.

It is widely accepted that the principal direct cause of damage in a cavitation environment is the mechanical stressing due to the pressure produced by the collapse of cavitation bubbles on a solid surface.

Investigators agree that the presence of abrasive solids in the region of highly turbulent flows will cause concrete to erode at a rapid rate.

Value Engineering Team No. 8 has concerned itself in not only the mechanism of cavitation and abrasion erosion, but in the resistance of various materials to erosion, and the design of structures to eliminate or greatly reduce the chances of erosion. Although the team is not prepared to conclude its findings, it is hoped that this interim report will provide designers and researchers with a clearer course for future work in this field.

II. STATEMENT OF PROBLEM

Value Engineering Team No. 8, consisting of M. A. Jabara, Chairman; W. E. Wagner, K. A. McGibbon, and J. A. DeLapp was appointed May 1, 1967, and was assigned the project of "Protecting Stilling Basin Surfaces from damage." The objective is to study the problem of protecting stilling basin surfaces from damage and to make a report of the findings. However, because many problems experienced by the Bureau in the design and maintenance of hydraulic structures derive from cavitation and abrasion forces on critical areas of concrete flow surfaces, the objective was broadened and redefined as follows:

> Endeavor to develop protection of concrete flow surfaces in hydraulic structures against cavitation and abrasion damage at the lowest ultimate costs to meet the requirements for improved performance, greater reliability, and reduced maintenance.

In determining methods of eliminating or greatly reducing the chances of erosional damage, the team will consider all concrete flow surfaces which may be subjected to such damage, such as, areas immediately downstream from slide gates, outlet works stilling basin chutes and stilling basins, diversion tunnels, tunnel spillways, etc.

III. LITERARY RESEARCH

While considerable research has been done and many contributions have been made to enhance cohesive thinking in the field of cavitation in the past few years, there remains much fundamental dispute. In pursuit of our efforts and to avoid duplicity as much as possible, letters fully describing our problem and soliciting suggestions were directed to representatives of the Corps of Engineers, TVA, State Departments of Resources, educators and directors of leading university hydraulic research laboratories, and prominent consultants in the field of water resources.

Many responded to our inquiry, but it is quite apparent that although considerable attention is being paid to cavitation and abrasion phenomena, experience is extremely limited. No exciting suggestions for design improvements or resistive coatings were offered. However, the data and references given were very helpful in our evaluations and may very well lead to possible solutions.

Dr. A. T. Ippin, Massachusetts Institute of Technology, responded to say that Dr. Roger E. Arndt had just completed an extensive doctoral thesis at the M.I.T. Hydrodynamics Laboratory on determining the cavitation inception index and that it will be published as their Technical Report No. 104, entitled, "Cavitation Near Surfaces of Distributed Roughness." He later forwarded a copy to the team. It will prove helpful in correlating cavitation indexes for materials to be tested in the future.

Dr. Ippin also referred us to the book "Erosion by Cavitation or Impingement," a symposium presented at the 69th Annual Meeting of the American Society for Testing Materials. The Bureau's Office of Engineering Reference obtained a copy for the team's exclusive use. The papers contained in the book focus mainly on the damage and material response to it. Tests described are confined to metal surfaces. However, significant differences appear in the quantitative values derived from the various test programs.

Professor Sam Shulits, Pennsylvania State University, provided the team with a paper in German authored by Dr. F. Hartung titled "Cavitation Research Problems in Hydraulic Steel Structures." Arrangements for translation of the paper were made by our Office of Engineering Reference.

Dr. Hartung describes the cavitation phenomenon and mentions the Kernpf and Remmers cavitation stand which was scheduled to be installed in the Obernach Laboratory in the fall of 1967 for the purpose of pursuing a crash program in cavitation research. The cost of the program until the first results are obtained is about $250,000, including $100,000 for the stand, $35,000 for the necessary measuring devices and high-speed camera capable of 20,000 frames per second, and $115,000 for staff and operation. A letter has been dispatched to Dr. Hartung requesting available test results.

Mr. Fred Brown, Corps of Engineers, Vicksburg, Mississippi, described problems of cavitation and abrasion encountered at several Corps of Engineers' dams. These are quite similar to those experienced by the Bureau including failure of stilling basin divider walls, but little was offered as possible solutions, except that the use of offsets and the introduction of air have produced favorable results.

Replies from others were generously sympathetic, but included no significantly helpful information.

In response to a telephone request made to J. Douma and S. B. Powell, Office, Chief of Engineers, Corps of Engineers, reports covering the damage to and repair of the flood control conduits at Detroit Dam were furnished to the team by the Portland District. Also described was the test outlet at Detroit Dam constructed specifically to simulate flow conditions through the flood control outlets under prototype head conditions. By telephone Mr. Larry Metcalf, Portland District, apprised Messrs. Jabara and Wagner of the limited number of coatings tested. Although the team was extended the priviledge of using the facility, Mr. Douma suggested that associated administrative and funding problems would make it impractical. Moreover, considerable modification of the facility would be required to permit testing objectives desired. Officials of the Office, Chief of Engineers, have concluded that preliminary tests have shown conclusively that unprotected concrete surfaces of the best quality that could be expected to be placed in sluices of high-head dams could not withstand the forces present downstream from the partially opened test valve operating under 320 feet of head.

Dr. Edward R. Holley, Assistant Professor, Civil Engineering Department, University of Illinois, while on a 16-month Ford Foundation assignment with the Bureau's Division of Research, lectured to the team on the subject of boundary layers and the effects of secondary currents induced by centrifugal forces. In accordance with the theories advanced, computations disclose that with water having an initial velocity of 100 feet per second flowing over a flat steel plate would form a fully developed boundary layer in approximately 400 feet. However, it is widely accepted that the boundary layer needs only to be developed to a depth greater than the maximum depth of flow surface irregularities to protect against cavitation damage. In a cavitation environment such as that experienced in the Yellowtail Dam tunnel spillway elbow where erosion was apparently caused by abrupt irregularities as small as 1/8-inch in depth, gives rise to the belief that the boundary layer did not develop to that depth or was destroyed by secondary currents.

IV. SEARCH FOR PROPRIETARY PRODUCTS

In early March 1968, representatives of the Gates Rubber Company, Mr. Wilber Strovast, Technical Specialist, and Mr. William Negal, Engineer, met with the team to discuss methods of determining the resistance of materials to abrasive forces. Mr. Negal explained that abrasion resistance is a level of performance that results from a combination of properties inherent in a material and the severity of the conditions under which the properties are used. He theorized that true abrasion resistance of a material must be determined by its strength and stretch and how long it can maintain these properties. Experience has shown that unprotected concrete cannot adequately resist abrasive forces. Sprayed, sheet or plate coatings must have strength, stretch, and endurance properties to satisfactorily resist abrasion. Rubber and synthetic rubber compounds are being used extensively in mining, construction, and other industries for abrasion protection. Major uses are in conveyance ducts and belts.

Gates Rubber Company has prepared a design chart to determine the service life of rubber compounds of given thicknesses subjected to abrasion forces discussed above. Design factors considered are: particle weight, discharge rate in tons per hour, particle size, free fall velocity, contact or critical area, and time. Since it is extremely difficult to determine the frequency with which abrasive particles strike the floor surface of a stilling basin, and the size of the critical area or the area of maximum wear, the design charts cannot be considered reliable for determining abrasion resistance of materials in basins or on other flow surfaces. However, assuming a discharge rate of 0.50 tons per hour striking a critical area of 288 square inches, particle size of 12 inches, rubber thickness of 1 inch (Gates 60 K rubber), and velocity from free fall height of 5 feet, the design chart indicates a service life of 10 years. The cost of providing 1-inch-thick rubber sheet bonded to 1/4-inch-thick steel plate securely anchored into concrete is prohibitive.

The team met with Mr. Steinmetz, District Manager for GACO Western, Inc., to discuss GACO's synthetic rubber coating materials. It appears that the liquid applied coating of N-29 offers superior abrasive resistance, bond life, and resistance to damage by cavitation provided it is applied to a thickness of 70 mils. A patch, covering an area of approximately 150 square feet, of this material is currently undergoing prototype tests in the outlet conduits at Grand Coulee Dam; and, after 3 years, it still appears to be in good condition. There are, however, the following limitations:

1. The primer coat is adversely affected by the presence of moisture either on the surface to be coated or in the air during its application.

2. The toxic effect of the material requires that additional safety precautions be taken.

3. The material has limited "pot-life" that necessitates special handling.

4. Coating thickness is only 2 mils and a drying time of from 30 minutes to 2 hours is needed between each coat. To obtain the 70-mils thickness, 2 primer coats and 35 coats of N-29 are required.

The installed cost for the complete system of 70-mils thickness was estimated at $4 per square foot.

Later in March 1968, the team met in the offices and plant of the Ardco Company with Mr. E. M. Ardelt, owner, to discuss the properties and application of "Sprayable Neothane," a product of Goodyear Rubber Company. Also, Ardco does a considerable amount of work in bonding abrasive resistant rubber sheets to metal parts of all sizes and shapes. The "Sprayable Neothane" is reputed to have four times the resistance to abrasion as a comparable thickness of rubber and it can be sprayed (on the jobsite) on metal or concrete at a cost of approximately $1.50 to $2.00 per square foot per 1/16-inch of thickness. As the resistance to cavitation of both the vulcanized rubber and "Sprayable Neothane" was unknown, we arranged to have metal test plates coated with the materials, at no cost to the Government, for testing in the cavitation machine in the Hydraulic Laboratory. The results are covered under Paragraph VIII, Research Program.

In April 1968, the team met with Mr. Don Burns, District Manufacturer's Representative for SIKA Chemical Corporation, manufacturers of many epoxy filler and coating materials. The estimated cost of installed epoxy mortar was $2 per square foot for 1/8-inch thickness. The bonding compound which may be used on damp surfaces is slightly more expensive and slower to cure. Good abrasive resistance is obtained by mixing quartzite aggregate with the epoxy; however, Mr. Selander from the Bureau's Chemical Engineering Laboratory states that SIKA epoxy has been tested and displays poor cavitational resistant properties. Consequently the material was not considered any further.

V. CREATIVE AND ANALYTIC PHASES

The Creative (brainstorming) and the Analytic (evaluation) phases are vital steps in the Value Engineering process. The following lists illustrate some of the proposed solutions that have been considered to date:

A. Ideas considered to eliminate <u>cavitation</u> damage.

Ideas	Comments
1. Improve quality of concrete in critical areas by rigid specifications so that: a. Harmful deleterious material will be excluded. b. Angular aggregate will be used. c. Mix will be accurately controlled. d. Proper placement technique will be employed.	Deserves further consideration
2. Improve finish and alinement of concrete surfaces in critical areas by developing new techniques and close control in concrete placement.	Deserves further consideration
3. Prepare questionnaire to survey Bureau projects to determine types of outlet works and spillway designs that are least susceptible to damage.	This should be done
4. Based on the above data, prepare a list of the types of outlet works and spillways, listing them in order of preference.	This should be done

5. Establish a policy that the outlet works and spillways shall be selected from a preferred list. The policy should also require that the designer record the reason for selecting the type of energy dissipation finally adopted.	Deserves consideration
6. Investigate the effects of uniform surface roughness in preventing cavitation damage.	Deserves further consideration
7. Investigate the use of offsets and slots to provide for introduction of air.	Request laboratory to investigate
8. Use principle of sudden enlargement for energy dissipation such as: a. Vertical stilling wells. b. Horizontal sudden expansion. c. Use two gates in series (in line) with sudden enlargements downstream of each gate to step down pressure head.	Shows promise and deserves investigation
9. Investigate riprap and concrete plunge basins.	Shows promise and deserves investigation
10. Investigate elimination of stilling basins, by discharging directly into river channel.	Has promise, but limitations due to geologic conditions, possible damage to dam, and economics
11. Investigate protective coatings that will offer resistance to cavitational damage of the concrete surfaces. The following materials were reviewed:	
a. Epoxy mortar	Not too successful in field
b. Duralox brick	Previously tested in the laboratory and found inadequate

c. Terrazzo tile	Previously tested in the laboratory and found inadequate
d. Fiberglass reinforced polyester	Poor adherence to steel and concrete, brittle, poor resistance
e. Flexible epoxy resin	Promising lab tests, Coulee field tests poor
f. Steel-filled epoxy resin	Promising lab tests, Coulee field tests poor
g. GACO (Gates Engineering) N 200 (neoprene spray)	Inferior to N 29 in Coulee tests
h. Sprayable neothane (Goodyear)	Worthy of testing
i. GACO, N 29 (neoprene spray)	Undergoing tests at Grand Coulee - looks promising but costly
j. Polysulfide rubber	Worthy of further investigation
k. SBR rubber (Gates Rubber Co.)	Fabrication and installation impractical
l. Vulcanized synthetic rubber	Fabrication and installation impractical
m. SIKA epoxy	Not cavitational resistant
n. Polymer impregnated concrete (irradiated)	Superior physical properties but not adequately resistant to cavitation.

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12. Install protective liners made of:

a. Cast steel	Costly and vulnerable to cavitation
b. Steel plate weldments	Costly and vulnerable to cavitation
c. Cast iron	Costly and vulnerable to cavitation
d. Stainless steel including stainless-clad plate	Offers best resistance of any known material, but expensive and difficult to install

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13. Use pressure tunnels instead of free-flow for spillway tunnels such as Yellowtail.	May have merit, deserves further consideration
14. Eliminate or reduce angle of vertical bends in free-flow spillway tunnels.	Has possibilities for some installations

B. Ideas considered to eliminate <u>abrasive</u> damage.

Ideas	Comments
1. Improve designs so all foreign material (rock, scrap metal, etc.) can be kept out of concrete stilling basins by one or more of the following methods:	
a. Completely cover basin with a reinforced concrete roof so that falling or thrown rocks can be kept out.	Has merit for relatively narrow basins - being investigated by Spillway and Outlet Works Section
b. Use a low wall at the downstream end of the basin to keep rocks from being pulled into the basin by reverse currents.	In current use
c. Install protective fences on the side walls of the basin to hold back rock slides.	In current use
d. Install protective fences on side slopes to control rock slides.	Deserves further consideration
e. Use intercept trenches (similar to those along highways) to retain rock slides.	Has merit, particularly when combined with c. above, but still does not exclude thrown rocks; deserves further consideration, however
f. Clean basin prior to each use by utilizing some automatic cleaning device, i.e., rakes, mobile vacuum equipment.	Appears too costly, but warrants investigation

g. Install "gabions" to retain rock and prevent slides into basin.	Has merit and deserves further consideration
h. Construct basin so floor is above tailwater. Equip with drains to unwater basin automatically after each use. Any foreign material may be readily seen and removed before outlet is operated.	Cost appears excessive, limited to high-level outlet works
i. Cover basins with a steel mesh or screen to exclude rocks.	Not considered fully effective
j. Provide stilling basin immediately downstream of gate chamber in tunnels and conduits.	Limited to use in small systems
k. Protect aprons and channels downstream of basins by:	
(1) Paved concrete with weir at end	Has had limited use but is effective
(2) Asphalt bonded riprap	Deserves further consideration
(3) Gabions or Reno Mattress	Deserves further consideration
(4) Grouted riprap	Deserves further consideration

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2. Install protective liners made of:	
a. Cast steel	High initial cost and maintenance
b. Steel plate weldments	High initial cost and maintenance
c. Cast iron	High initial cost, but low maintenance
d. Stainless steel including stainless-clad plate	High initial cost, low maintenance also resists cavitation

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3. Investigate protective coatings that will offer resistance to abrasive damage. The following materials were considered:	
a. Epoxy mortar	Deserves further consideration

b. Duralox brick	Costly and difficult to install flat
c. Terrazzo tile	Costly and difficult to install flat
d. Ceramics	Not developed
e. Fiberglass reinforced polyester	Poor adherence to steel and concrete, brittle, poor resistance
f. Flexible epoxy resin	Promising lab tests; Coulee field tests poor
g. GACO (Gates Engineering) N 200	Has promise, needs to be tested
h. Sprayable neothane (Goodyear)	Has promise, needs to be tested
i. SBR rubber (Gates Rubber Co.)	Has promise, needs to be tested
j. Vulcanized synthetic rubber	Has promise, needs to be tested
k. SIKA epoxy	Has promise, needs to be tested
l. N 29 GACO (Gates Engineering)	Undergoing tests at Grand Coulee - costly
m. Polymer impregnated concrete (irradiated)	Impregnation of cast in place concrete not practical
4. Utilize Bureau experience to determine types of stilling basin designs that are least susceptible to abrasion damage.	This should be done
5. Use the above data to help prepare a "preferred" list.	This should be done
6. Prepare rigid specifications to force the construction contractor to clean up all debris in the tunnels, conduits, and stilling basins. Also insert that under no circumstance should the contractor be relieved of this responsibility.	Now in use
7. Require contractor to take special precautions to keep the cofferdam material out of the stilling basins when the cofferdam is removed.	Now in use

8. Slope stilling basin floor to a sump so stilling basin can be readily unwatered with a submersible pump for inspection.	Has merit

C. Additional comments on ideas considered for:

Subparagraph A1

Specifications should be reviewed to be sure that parts a. and b. are adequately covered. However, in certain instances, use of angular aggregate may be impractical because of limited availability. Parts c. and d. could be covered in the Design Considerations reminding the Construction Engineer of the importance of these items.

Subparagraph A2

One scheme would use a thick layer of sand-cement mortar as a final surfacing material and grind to obtain the desired smoothness and alinement.

Another scheme would be the development of a continually moving slip form that would utilize low-slump concrete to obtain accurate grade and alinement for tunnels and conduits.

Use of hinged forms to permit early finishing of inverts of circular tunnels such as those successfully used on Starvation Feeder Canal tunnel and Tiber Dam Auxiliary outlet works tunnel.

Development of this phase should be referred to the concrete laboratory for further investigation.

Subparagraph A3

The team believes that responses from appropriate Regional Directors to a questionnaire prepared for a list of selected earth dams would be valuable in the assessment of cavitation and abrasion damage resistance of various types of spillways and outlet works with special emphasis on stilling basins and flow surfaces immediately below regulating gates. The questionnaire would request the operational history, description of experienced damage to concrete, opinion as to cause of damage and under what head and discharge conditions damage was first observed, method of repair, performance since repair, and additional comments believed to be pertinent to the problem.

Subparagraph A6

Laboratory tests and experience indicate that the cavitation inception index is directly related to the skin friction coefficient for both smooth and rough boundaries. Tests show that an isolated irregularity on a smooth surface is more susceptible to cavitation than the same irregularity on a rough surface. Therefore, it may be advantageous to provide a uniformly rough surface rather than a smooth surface in areas susceptible to cavitation damage. Resolution would require testing for which adequate facilities are not presently available in the Division of Research laboratory.

Subparagraph A7

The effectiveness of air in alleviating cavitation damage cannot be fully tested in our present laboratory facilities. It is essential that the offsets and air grooves developed in the laboratory be proven in a prototype installation. The continuing cavitational problems and yearly operation of Palisades Dam outlet works makes this structure ideal for installation and testing of an air groove. Similar prototype tests can be conducted at Navajo Dam Auxiliary outlets where modifications are needed to alleviate cavitation damage.

Subparagraph A8, c.

A similar scheme using needle valves was reported in a paper published in the Journal of the Hydraulics Division, Proceedings of the ASCE for September 1969. The article by J. P. Tullis and M. L. Albertson, titled, "Needle Valves as Pressure Regulators," describes how needle valves discharging into sudden expansions are ideally suited as pressure regulators. Such a system can dissipate large quantities of energy at small discharges with a minimum of cavitation damage and pressure fluctuations. The scheme was first investigated for large scale use by Escher Wyss in 1957, for regulating the head for Chandoline Power Station, and subsequent reports indicated that the operation of the prototype was completely successful. Based on this success, the Metropolitan Water District of Southern California decided to use the scheme, which is scheduled for completion in 1971, to regulate releases from Castaic Reservoir into the Foothill Feeder which distributes water to the Los Angeles area.

The Value Engineering Team believes that similar pressure regulation using slide gates in place of needle valves can be utilized to make high head releases from outlet works without suffering cavitation damage. The slide gate has a higher coefficient of discharge (0.95 compared to 0.58) which is a definite advantage for larger releases; however, considerable laboratory and design work will be required to develop workable proportions for the systems.

Subparagraph A11

None of the materials tested, except GACO N 29 (Neoprene spray), show promise as adequate protective coatings for concrete flow surfaces subjected to cavitational forces.

Subparagraph A12

Although metals listed in a., b., and c., are more resistant to cavitation damage than concrete, they are markedly inferior to stainless steel. Stainless clad steel is now being used extensively in outlet conduits and gates, but it is not without limitations and problems.

Subparagraph A13

To reduce the likelihood of cavitation damage, a pressure tunnel with control gates at the outlet end should be considered. However, this concept transfers the problem of contending with cavitational forces to the exit of the system. Hydraulic model studies could provide a satisfactory solution to this problem.

Subparagraph A14

Secondary currents are known to exist in relatively sharp vertical bends in circular tunnel spillways. These are significant factors in the production of higher velocities and lower pressures adjacent to the invert. Designs which would eliminate or minimize vertical bends should be given consideration. Again, the problem is transferred to the outlet end if a stilling basin or flip bucket or a combination of both is used.

Subparagraph B1

From all evidence examined to date, it appears that the majority of the abrasive damage in concrete stilling basins is caused by the grinding action of rocks and other debris being recirculated within the basin by the high energy spillway or outlet jets. The abrasive action is similar to that experienced in a ball mill. The rock and debris enter the basins in several ways: falls or slides from adjacent canyon walls, thrown in by visitors or workmen, drawn in from the downstream channel by undertow currents, improper cofferdam removal, and lack of proper cleanup after construction.

Some of the remedial methods considered relate to keeping foreign material from these sources out of the basin, while others are concerned with better examination and removal, and still others involve protecting the concrete surfaces with coatings or linings.

VI. QUESTIONNAIRE SURVEY OF BUREAU PROJECTS

The team canvassed all Bureau projects and selected 111 structures for detailed examination as to head, discharge, type of flow control, and method of energy dissipation. The structures were divided into types of energy dissipators under two main headings: Free flow basins (in which the flow approached the stilling basin in an open channel) and control at the stilling basin (where the flow discharged directly into the stilling structure). See Table I. From this tabulation of selected projects, a total of 46 representative structures were chosen for review of their history of operation and maintenance. These structures with significant hydraulic and operational data are tabulated in Table II.

This review included a search of Review Maintenance Program folders in this office, and the preparation of a questionnaire dealing primarily with operational and maintenance problems on the 46 hydraulic structures. The questionnaire was sent to the appropriate regional offices for completion. The results of this review are summarized below:

Summary
of
Damage to Hydraulic Structures

Cause of damage	No. of structures	Range of maximum operating heads	Maximum Q
No damage	22	16 - 245'	5,140 cfs
Abrasion	8	70 - 336'	12,500 cfs
Cavitation	8	148 - 238'	17,000 cfs
Freezing and thawing	5	37 - 254'	7,500 cfs
Condition unknown or has not operated	3	97 - 100'	240 cfs
TOTAL	46	16 - 336'	240-17,000 cfs

No damage - Fifteen structures experiencing no damage operated at heads less than 135 feet. Of these, 12 had conventional hydraulic jump stilling basins. It is significant that of the 7 operating at heads above 135 feet, only 1 had the conventional stilling basin, and 6 discharged directly into the stream channel, plunge basin, or a stilling well.

Abrasion - Six of the eight structures having abrasion damage were conventional hydraulic jump stilling basins. The sources of the abrasive material appear to be from the downstream channel, overburden near the basin, and/or tossing of rocks into the basin by the public. No conclusion was evident as to which source contributed the most material.

Cavitation - All cavitation damage has occurred in concrete immediately downstream of outlet gates at operating heads ranging from 148 to 199 feet. Repairs were effective in five structures; one has not been inspected since repairs; one was not repaired; and one structure which operates at heads ranging between 155 and 237 feet continues to experience damage.

VII. DAMAGE AT SPECIFIC BUREAU STRUCTURES

Certain structures, where damage has been experienced, were not canvassed by questionnaire nor included in the survey because the experience was amply documented in this office. These structures were reviewed in detail by the team to determine the circumstances under which the damage occurred, the modifications that were made, type of repair, and the effectiveness of such modifications and/or repair. These structures are discussed individually.

1. Abrasive Damage

a. Trinity Dam Outlet works. - This structure operated under a range of discharge conditions up to 80 percent capacity and heads of 475 feet during the 1962-63 flood season prior to completion of the powerplant. Thus usage was at considerably higher heads and discharge than anticipated under normal project operation.

Following the flood season, an underwater inspection of the basin disclosed severe abrasive damage to the floor and sidewalls and loss of part of the divider wall. Several hundred cubic yards of material found in the basin had apparently been drawn from the outlet channel and circulated in suspension in the violent stilling action. The source of the material was the jointed greenstone rock in the outlet channel. Eroded gravels were also carried in by the outwash from spillway discharge.

The divider wall failed along a construction joint 20 feet above floor level. The absence of necking in the stubs of reinforcement steel indicated fatigue failure, and cracks along the base of the wall indicated compression failure of its base.

The basin floor was repaired with a reinforced concrete overlay, and roughened surfaces in the inclined chute were repaired with epoxy-bonded epoxy mortar. The undamaged portion of the divider wall was retained and embedded in the center of a heavily reinforced replacement wall. The eroded outlet channel was protected with anchored, reinforced concrete lining; riprap adjacent to the added lining was grouted; and rock cuts for several hundred feet around the end of the basin were scaled to remove possible future sources of abrasive material.

Following these repairs, the structure operated for 2 months at 10 to 30 percent of capacity. A later underwater examination disclosed about 5 cubic yards of rock and gravel in the basin and sufficient abrasion damage to expose aggregate in the chutes and floor of the basin. As a result of this experience, it was decided to use the auxiliary outlet gate for making outlet releases whenever possible and if it became necessary to use the hollow-jet outlets, to operate both valves at equal openings to maintain balanced heads on either side of the divider wall.

Based on this experience, the following conclusions have been reached:

(1) The divider wall suffered a vibrational-type failure caused by forces from the extremely turbulent water and unequal releases of water from the valves on either side of the wall plus a weakening of the wall by abrasive erosion.

(2) The value engineering team believes that this type of failure can be best avoided by providing support at the top of the wall or increasing the wall thickness and by keeping debris out of the basin.

(3) Stilling basins for hollow-jet valves are not self-cleaning and debris tends to accumulate and recirculate within the highly turbulent areas of the basin. It is therefore essential that all construction debris be removed, adjacent canyon walls carefully scaled and rock bolted where necessary, and downstream riprap or riverbed material stabilized.

b. Navajo Dam Outlet Works. - This structure was designed for a maximum discharge of 4,200 cfs and a static head of 382 feet. In the period July 1963 to April 1965, one outlet was operated at 10- to 20-percent valve opening and heads between 210 to 220 feet for about 6 months; two valves were opened 25 percent for a month at heads to 240 feet; and both valves were operated at 40-percent opening for 2 months at heads ranging between 130 to 240 feet.

An underwater examination following this period of operation disclosed seriously eroded areas in the floor and walls of the basin. This damage resulted from churning of large quantities of rock, gravel, reinforcement bars, and construction debris that was left in the basin following construction and drawn in from the downstream channel.

To permit release of the expected spring 1965 runoff, temporary repairs were made. Epoxy-bonded concrete and epoxy-bonded epoxy mortar were used to repair the floor and epoxy-bonded pneumatically applied mortar was used on the walls. The basin was cleaned, but no effort was made to remove the rounded riprap from the channel immediately downstream of the basin.

Releases were resumed in May 1965. Within 2 weeks with flows about 2,700 cfs, definite signs of damage were apparent. By July, the damage reached a critical state and releases were limited to 500 cfs through each valve for an additional 3-month period.

The cause of the damage again was the churning action of loose rock carried into the basin from the outlet channel.

Extensive hydraulic model studies showed the hollow-jet valve stilling basin could not be improved upon with respect to energy dissipation and stability of the turbulent action. However, the high efficiency produced areas of high turbulence which accelerated damage by the circulation of abrasive materials.

Because of the extensive damage to the divider wall and the basin floor and sidewalls and the desire to make the basin more nearly like the conventional hydraulic jump basin, the structure was modified by removing the converging wedges and divider wall and installing a 2-1/2:1 sloping chute at the upstream end of the basin. A stainless-clad plate covers the new, less steep slope. Also, the bottom and side slopes of the originally riprapped outlet channel were paved for a distance of 140 feet downstream from the basin. Walls at the top of the paved slopes were installed to trap material which might otherwise enter the basin. Because of the lower efficiency of the modified basin, the maximum discharge will be limited to 3,200 cfs. Also, equal valve openings will be required.

The structure has operated almost continuously since the modifications were completed in 1968, and the flow was maintained at 60 percent design capacity for 3 months in 1969. An underwater examination of the basin in May 1969 disclosed only minor spalling of the concrete near the steel liner plates and no abrasive materials in the basin.

The conclusions in this case are essentially the same as those listed for Trinity. Namely, that all debris must be kept out of the basin and the divider wall, if used, needs top support or additional thickness. Also, angular riprap of adequate size to resist movement by the turbulent flow must be used in the downstream channel.

c. Yellowtail Dam Outlet Works. - As a result of the damage experienced at Navajo and Trinity outlet works stilling basins, special precautions were taken to prevent channel material from entering the hollow-jet valve stilling basin at Yellowtail Dam outlet works. The limestone surfaces of the right bank immediately downstream from the basin were lined with pneumatically applied mortar securely anchored to the rock. To prevent material from being drawn into the basin, concrete retaining walls were extended 50 feet downstream from the end sill and angular riprap was placed for channel floor protection.

The top of the divider wall is fixed by a concrete slab covering the basin. The slab not only provides additional support for the wall, but also shelters the basin from falling rock. Pressure transducers and accelerometers were installed in the wall. Tests conducted in November 1967, for balanced flows of 3,000 to 5,000 cfs and asymmetrical flows of 500 to 2,500 cfs through one valve at a head of 442 feet, disclosed entirely satisfactory stilling basin operation. Nominal differential pressures across the divider wall were observed and the accelerometer recordings showed no evidence of stilling basin wall movement or vibration.

This structure has operated extensively since it was completed in the winter of 1965-66. In 1967 and 1968, the basin operated for about 4 months at discharges up to 80 percent of maximum and a head of 460 feet. Subsequent examination of the stilling basin disclosed no damage.

This experience indicates that the hollow-jet valve stilling basin will provide excellent service at comparatively high heads if adequate precautions are taken to prevent foreign materials from entering the basin.

d. Glen Canyon Dam Diversion Tunnel Outlets. - This structure was designed to pass about 30,000 cfs at heads ranging up to 350 feet. The outlets operated continuously from May 1963 to September 1964 at flows ranging from 1,000 to 19,600 cfs and heads up to 336 feet. Subsequent to this operation, an underwater examination disclosed extensive abrasion damage to the tunnel concrete lining about 400 feet downstream from the tunnel plug. The most severely damaged area was in a tunnel section, 200 feet long, where reinforcement was exposed from the invert nearly to the tunnel spring line.

Because there was insufficient time to repair the tunnel lining before the spring runoff, the decision was made to make controlled releases up to the maximum capacity of 29,600 cfs. The outlets were operated at discharges ranging between 12,500 cfs and 29,600 cfs, and near maximum heads of 360 feet for almost 2 months without measurable increase to the unrepaired damage. It was concluded that the damage was caused by accumulated construction debris in the tunnel which could not escape from the energy dissipating hydraulic jump which formed only at low discharges. A controlled 1-week test with a comparable hydraulic jump in the tunnel substantiated this conclusion. The lip of the downstream flip bucket contributed to the formation of the hydraulic jump by restricting the flow causing the water level in the tunnel to raise. A remedy for this situation is to defer installation of the flip bucket until all diversion of water through the tunnel is complete.

This experience indicates that comparatively rough concrete with exposed aggregate and abrupt surface irregularities will withstand the dynamic forces of high velocity flows without significant damage by impact or cavitation if the flow is adequately aerated. In passing from the tunnel plug to the concrete lining, the jets traveled about 125 feet through air and apparently entrained sufficient air to reduce the destructive effects of cavitation as the flow passed over the irregular surfaces. The dynamic forces in a hydraulic jump will not damage concrete surfaces if abrasive materials are kept from the turbulent action.

e. Wanship Dam Outlet Works. - The outlet works for Wanship Dam has two 3-foot 6-inch by 3-foot 6-inch H.P. regulating gates discharging horizontally into a 216-foot-long concrete chute and stilling basin. A divider wall extends from the gates through the 120-foot-long chute and into the stilling basin for a distance of 64 feet. The stilling basin portion of the divider wall is 24.5 feet high and consists of two 25-foot and one 14-foot-long panels separated with contraction joints. The structure was designed for a maximum discharge of 1,550 cfs and a static head of 150 feet.

Downstream water demands are normally met by releases through the powerplant which is located adjacent to the outlet stilling basin.

The outlet gates are used only 3 to 4 months a year during the spring runoff for flood releases and at times when the powerplant is not operating. To insure continual releases, the controls of the right outlet gate are set to automatically open should the powerplant operation be interrupted. Gate operation with this arrangement has resulted in nearly all of the releases being made through the right outlet gate. The left outlet gate was used only when demands exceeded one gate capacity. From 1958 to 1969, the right outlet gate has been used 3 to 4 months a year with releases of 600 to 800 cfs while the left gate has been used 1 to 2 months a year with releases of 100 to 200 cfs. All releases were at heads ranging from 100 to 140 feet.

During the summer of 1969, the downstream panel of the divider wall failed by falling over against the left outside basin wall, while the right outlet gate was releasing 640 cfs at 112 feet of head. Ten days later the adjacent panel failed in a similar manner while the right outlet gate was releasing 740 cfs at 112 feet of head. At this time the third panel was observed to be vibrating an estimated 1/2 inch at the top before the outlet gates were closed.

Following the divider wall failures, an underwater examination was made. This examination disclosed seriously eroded areas in the floor and at the base of the walls, undoubtedly resulting from the churning effect of rocks and construction debris found in the basin. The base of the divider wall was separated from the floor except for the left side layer of reinforcing bars. The absence of necking in the stubs of reinforcement bars extending from the floor indicated fatigue failure or insufficient embedment.

The repair specification calls for removal of the three downstream wall panels. The floor is to be repaired with a 12-inch-thick reinforced concrete overlay and the eroded surfaces of the sidewalls and inclined chute floor will be repaired with epoxy and epoxy-bonded epoxy mortar.

Following removal of the failed divider wall and dewatering of the basin, it was clear that the wall's instability was due to improper placement of reinforcement. The main vertical bars were embedded into the floor concrete only 2 to 4 inches instead of the specified 24 inches. The imposition of a relatively small unbalanced force would have caused the wall to overturn. This experience points to the necessity of close scrutiny of reinforcement and concrete placement, and an awareness by the responsible field engineer that inspectors must be trained to an acceptable degree of proficiency.

Some observers attribute deliberate departures from design requirements to fraternization by exploitable Bureau inspectors with responsible contractor officials. Rules prohibiting such action by Bureau personnel should be made clearly understood and rigidly enforced.

f. Anderson Ranch Spillway. - The spillway is designed for a maximum discharge of 20,000 cfs. Flows pass through a chute into a conventional hydraulic jump stilling basin which also serves the outlet works consisting of five 72-inch hollow-jet valves operating at heads up to 330 feet.

The combined spillway and outlet works stilling basin has been plagued over the years with damage from abrasive solids which enter the basin and spillway chute from the excavated slope along the left wall of the chute. Although the left sidewall of the chute and basin projects above the backfill, the wall height is insufficient to trap material rolling down the slope. In 1962, a chain-link fence was constructed along the top of the left spillway wall from the top of the rock slope to the downstream end of the basin. This barrier was ineffective in the vicinity of the stilling basin, and in 1968, a 6-foot-high concrete wall replacement was constructed from the air intake structure to the downstream end of the stilling basin.

The spillway operates each year. The stilling basin was unwatered in 1959, and the floor of the basin was eroded to a maximum depth of 5 inches. About 600 cubic yards of rock and gravels were removed from the basin. In the spring of 1962, the eroded floor was repaired with epoxy-bonded concrete at a total cost of $17,379. The repair epoxy was Probond ET-150.

In 1965, the basin again was unwatered. The chute floor was eroded to depths of 1/2 to 1-1/2 inches. The epoxy-bonded concrete repairs showed less erosion. No reinforcement bars were exposed and 150 cubic yards of rock were removed. No repairs were made. No cavitation damage was reported.

This experience shows that repairs of concrete surfaces damaged by abrasion are only temporary unless the source of the abrasive solids is removed. In this case, a chain-link fence was an ineffective barrier in the reach of the slope. The effectiveness of the concrete wall remains to be proved.

g. Palisades Dam Outlet Works. - Rockslides along the steeply excavated left side slope for the outlet works stilling basin occur with regularity. Snow carrying rock debris glides over the deeply accumulated ice on the adjacent berm to the left and enters the basin in sizable quantities. An underwater examining team inspected the basin in October 1968 and found considerable damage in the floor and an accumulation of gravel and loose aggregate. Scouring of the floor and walls in Bays 1 and 2 exposed reinforcement immediately downstream from the chute blocks. Erosion in the floor had progressed to a depth of about 5 inches. Several cubic yards of loose fines were deposited in three piles, and a few larger rocks were randomly scattered about the floor. Considerably more damage was found in Bay 3. The floor immediately downstream from the chute blocks had eroded unevenly to a maximum depth of approximately 6 inches. Reinforcement was exposed and some 3/4-inch transverse bars were missing. In Bay 4 many reinforcing bars, some loose and some embedded near the center of the bay, were found heaped near the chute blocks adjacent to the left training wall. Much of the rubble exceeded 8 inches in diameter. Report of the underwater examining team leads one to the conclusion that most of the rock found in the basin was drawn in from the outlet channel. The team has considered several alternatives as possible solutions to the prevention of rocks entering the basin. However, the only apparent practical solution would be to construct a weir across the outlet channel along a line where the exposed rock terminates and riprap begins to intercept rock before it is drawn into the basin.

Similar damage was disclosed when the basin was dewatered in the fall of 1965. The cost of repair was $85,625. The cost of repairing the present damage, when performed, can be expected to exceed that amount. Although the team believes it would be infeasible to prevent or divert sliding rock off the side slope, an attempt should be made to prevent the movement of rock from the outlet channel, which is now believed to be the major source of damaging debris, into the basin by construction of the concrete weir or barrier mentioned in the preceding paragraph. A capital expenditure of approximately $400,000 would be warranted.

2. Cavitation Damage

a. Palisades Dam Outlet Works. - The tunnel outlet works and tunnel penstocks are located in the left abutment of the dam in parallel alinement. The outlet pipe trifurcates with each branch in turn bifurcating and leading to four 7.5- by 9.0-foot slide gates and two 96-inch-diameter hollow-jet valves. Two branches from the power penstock manifold lead to two additional 7.5- by 9.0-foot slide gates. The gates and valves, located side by side, discharge horizontally into a stilling basin. Three divider walls form four bays in the basin. Three of these bays receive releases from the slide gates; the remaining bay confines discharges from the two hollow-jet valves.

The fabricator of the slide gates provided 3-inch radius fillets in the corners of the downstream frame. Concrete immediately downstream was placed with square corners. These abrupt offsets caused cavitational erosion when initial release of water was made in 1956.

The damage extended approximately 17 feet downstream from the gate frames, nearly 6 feet above the floor, and on the floor about 2 feet from each wall. Reinforcement bars were exposed over a large portion of the eroded areas.

Repairs were made by saw cutting the edges and excavating the damaged surfaces to a depth of 1 inch below the bars and backfilling with concrete. The offsets were corrected by constructing fillets in the corners to match the gate frames. The fillets transitioned from a 3-inch radius to 0 in 3 feet. Following large, continuous releases in the spring of 1964, cavitation erosion was found beginning only a few inches downstream from the joint separating the control house and the chute which is about 20 feet downstream from Gates No. 1 and 2. Each of the two eroded areas were about 38 feet long, up to 8 feet wide, with a maximum depth of 5.5 feet. The cavitation apparently was induced by small offsets extending into the flow at the floor joint.

Repair was accomplished by saw cutting and chipping the eroded area to a minimum depth of 6 inches and backfilled with low slump concrete.

In July 1968, the project superintendent expressed deep concern over the constantly recurring cavitation damage downstream from the outlet works slide gates. In the 4-year span, it was necessary to make several repairs of concrete damage in bays immediately downstream from all slide gates. The extent of damage below each gate seemed to vary proportionately with frequency of gate operation. Serious damage was reported to the floor and wall on the left side of the bay below Gate No. 6 (numbered from left). Examination by Wagner and Jabara of this team in September 1968 revealed that cavitating pressures resulted directly from a spalled epoxy patch only 3/32-inch in depth located just downstream from the diverging fillet at the intersection of the floor and wall where pressures could be expected to be reduced. This low pressure undoubtedly contributed to the intensity of cavitation. Although the floor received the greatest damage, the wall upstream from the stoplog groove was also severely eroded. However, damage downstream from the groove was limited to the floor. This clearly indicates that air was introduced through the groove and prevented erosion of the wall downstream from the groove.

Introduction of air into slots formed in the floor and walls at the end of the gate frame would unquestionably minimize or perhaps even prevent cavitation damage. The value engineering team model discussed in Paragraph VIII, 3, was designed to accommodate testing of conditions in the Palisades slide gate bays.

In response to a request by the visiting members of the team, the history of operation beginning with the spring of 1964 was compiled and forwarded to this office. It was hoped that correlations of damage and reservoir operation could be accomplished. However, the data submitted, though the best available, does not permit positive determination of when and under what conditions damage occurred. Graphical representation of the data is shown in Table III.

Cavitation damage repair costs in 1964 amounted to $11,174. Several repairs have been made in years following for which cost records are not immediately available. Assuming expenditures to have been $25,000 every fifth year, without structural modifications, and will continue at that rate, a capital expenditure of approximately $125,000 to prevent recurrence of cavitation damage would be warranted. If test results of the team's hydraulic model are favorable, a proposal will be made to modify at least one of the outlets accordingly to test the prototype environment.

b. Cavitation in Glen Canyon Dam Diversion Tunnel Outlets. - Although the conduits through the tunnel plug were lined with carbon steel plate, damage by cavitation occurred at several critical points near and downstream from the regulating gates during the operation at discharge ranging up to 29,600 cfs and heads up to 336 feet. The most severe damage occurred in the top of the left fluidway between the guard and service gates where a hole 3 feet wide and 8 inches in the direction of flow was eroded through the 1-inch steel plate. This damage was triggered by a 1/8-inch offset protruding into the flow and superimposed on the 65:1 slope between the guard gate recess and the body joint.

Progressive-type cavitation damage was noted on the flow surfaces of the gate bodies, particularly downstream from the gate slots and in the vicinity of the gate recesses and at surface irregularities in the conduit lining. Damage was evident in all three conduits and varied from paint removal in most instances to pitting of the metal downstream from the gate slots and at other critical surface irregularities. Cavitation in the conduit liner downstream from the gates was caused by poor alinement of the liner joints, projecting joint welds, and minor ridges and depressions in the paint coating. It was noted that offsets protruding as little as 1/32-inch into the flow produced marked damage and the degree of damage increased with larger offsets, where 1/8- to 1/4-inch offsets resulted in some pitting of the metal. Depressed surface offsets about 1/8-inch deep appeared to cause no damage while 1/4-inch depressed offsets produced paint removal and minor pitting.

No cavitation damage was found in the concrete-lined tunnel downstream from the tunnel plug.

This experience emphasizes the need for well-alined flow surfaces free of abrupt offsets in the vicinity of regulating gates, unless air is introduced into the flow to negate the effects of cavitation. The fact that the roughened concrete lining of the downstream tunnel suffered no apparent cavitation damage indicates that sufficient air was entrained in the flow as it left the tunnel plug to alleviate cavitational effects.

c. Yellowtail Dam Spillway. - During the 1967 flood season, the spillway was used to pass discharges up to 18,000 cfs in a 3-week period. The discharges averaged about 10,000 cfs for the first 5 days or operation to an average of about 15,000 cfs for the remainder of the operational period. Velocities in the tunnel ranged up to about 130 fps.

An inspection of the tunnel following this operation showed major damage had occurred in three areas - two in the tunnel elbow and one in the horizontal reach immediately downstream from the elbow P.T. These eroded areas ranged from 3 to 19 feet in width, 6 inches to 6 feet deep, and 30 to 126 feet in length. In all three cases, damage was the result of cavitation triggered by a surface irregularity resulting from a bonding failure of an epoxy patch.

In addition to the above-described damage, random areas in the elbow exhibited minor effects of cavitation damage. These were initiated by calcium deposits on the concrete surfaces, by aggregate popouts from concrete that had been ground to meet specifications requirements for finishes and tolerances, and by bonding failure of mortar veneer that had been placed in limited areas to obtain alinement and grade.

Repair procedures included backfill concrete to the major damaged areas, application of an epoxy mortar veneer to cover minor surface deficiencies, and application of epoxy-bonded concrete to areas too deep to repair with epoxy mortar and too shallow for the usual backfill concrete placement. The lower half of the tunnel periphery in the elbow and for about 200 feet downstream from the elbow were painted with a two-coat epoxy-phenolic paint to help bond aggregate susceptible to popout in the region of the tunnel elbow.

An aeration slot was placed immediately upstream from the tunnel P.C. to introduce air to the invert surfaces of the elbow where cavitation might be initiated.

In June 1969, a controlled release of 5,000 cfs for 5 days was made through the repaired spillway tunnel. Examination of the tunnel following this test indicated 10 to 12 spots where the epoxy repair veneer failed. The largest area was about 8- by 4- by 1/4-inch deep; there was no evidence of cavitation damage at these surface irregularities. On June 27, a 24-hour test release of 15,000 cfs was made. No enlargement of the damaged areas or cavitation damage was noted.

Although inconclusive for sustained releases at higher flows, these tests are encouraging and indicate that the air slot is supplying sufficient air to prevent cavitation.

VIII. RESEARCH PROGRAM

For several years, the Research Division, Bureau of Reclamation, has pursued a limited program to identify and develop a variety of coating materials for resistance to damage by abrasion and cavitation. The purpose of this program, which involves both laboratory and field tests, is to develop coatings for repairing flow surfaces damaged by cavitation and abrasion forces or for use on surfaces of new structures that might be subjected to such forces.

The test facilities are briefly described and the significant test results are summarized in the following paragraphs:

1. Cavitation-Resistance Tests

The laboratory tests are conducted in a venturi-type apparatus with a flow velocity of about 90 fps which produces a relatively mild cavitation environment. The coatings are applied to exposed surfaces of concrete or steel specimens which are placed in the apparatus and subjected to cavitation forces until failure of the coating occurs.

The apparatus produces notable cavitation damage in good concrete in 3 hours of operation. Some protective coatings fail after a few hours exposure while others sustain only a slight roughening after an exposure of over 1,800 hours.

In 1962, four coatings which at the time appeared to have exceptional cavitation-damage resistance were chosen for field tests in four outlets in the intermediate tier of outlet conduits at Grand Coulee Dam. These were a liquid-applied neoprene rubber (N 29), a liquid-applied polysulfide rubber, and two trowel-applied epoxy polyamide systems. The coatings were applied to the conduit walls immediately downstream from the ring seal gates where severe cavitation occurs as the gates are opened and closed. At normal operating conditions, the flow velocity is about 125 fps before the conduit fills, and a time interval of about 6 minutes is required to open or close the gates. All four coatings exhibited varying degrees of damage in the cavitation zone. The damage varied from cuts, tears, and disbonding from base metal of the neoprene in the cavitation zone to 75 percent loss of epoxy test lining.

The results of the cavitation-resistance tests can be summarized as follows:

a. Neoprene or polysulfide rubber coatings show excellent promise as a cavitation-resistant material. The 25-mil average thickness of coating used in the Grand Coulee outlets is insufficient. It appears that a 60- to 70-mil film thickness is needed to absorbthe energy without significant damage to the coating.

b. The neoprene appears to be superior to polysulfide rubber which tends to experience fatigue failure in a cavitation environment.

c. A neoprene coating (N 29), film thickness of 65- to 70-mils, has been tested in the laboratory venturi-type apparatus for over 1,860 hours with only a slight roughening of the coating surface. However, such coating has to be applied in 2-mil-thickness coats with a drying period of from 30 minutes to 2 hours, depending upon atmospheric conditions. This makes the installation time consuming and costly.

d. Epoxy, phenolic, and vinyl compounds are hard and brittle and show very little resistance to cavitation damage.

e. The performance of a material in a severe cavitation environment as found in the Grand Coulee outlets cannot be predicted in the laboratory venturi-type apparatus. Laboratory tests in this apparatus are useful only in selecting materials for field testing.

The VE team made arrangements to use the cavitation test facility to evaluate the resistance of "Sprayable Neothane." Evidence of cavitation damage began to appear after 240 hours of continuous operation. Laboratory personnel require that a material withstand 250 hours of continuous testing before it may be considered to have promise as an effective coating.

2. Abrasion Tests

The laboratory test facility consists of a pebble mill which accommodates two pipe specimens. It was constructed to evaluate the relative resistance of coatings to the erosive forces produced by silt-, sand-, and gravel-laden water flowing in pipes. These erosive forces are much milder than those resulting from the "ball-mill" type of action occurring in the large-scale turbulent flow of energy dissipators.

The results of these tests generally show that the epoxy mortars, neoprene, and the polyurethane coatings have good resistance to abrasive erosion.

The VE team arranged to have "Sprayable Neothane" tested. The results of the test indicated that it had relatively good abrasion resistance.

3. Design Studies

Experience and research by the Value Engineering Team indicated a need for a change in the design of flow surfaces immediately downstream from high head regulating gates. At the team's request, a hydraulic model was constructed to study methods of alleviating cavitation damage downstream of gates. Initial testing would involve the introduction of air along the sides and bottom of the jet, and investigation of a plunge-type basin in lieu of a hydraulic jump-type basin.

One of the easiest methods of supplying air around the periphery of a jet is by offsetting the flow surfaces away from the flow. However, this method tends to create objectionable fins of water along the walls of the conduit where the jet spreads and impinges on the flow surfaces. Since the Pueblo Dam outlets were being designed, it was decided to investigate offsets away from the flow as a means of introducing air in these outlets.

It was determined that the objectionable fins of water originated primarily from the impingement of the jet on the invert of the conduit. It was further determined that the fins could be eliminated by making the bottom offset about twice as large as the offsets on each side. The smaller side offsets permitted the jet to spread the full width of the outlet passage and suppress the fins that tended to form farther downstream where the bottom of the jet impinged. This arrangement provides adequate aeration of the jet for all but the lower range of heads where cavitation is not a problem. Details of these offsets are now being finalized and will be included in the Pueblo Dam outlets design.

Abrupt offsets and air grooves must be carefully designed to supply adequate air to the flow. The tests showed that abrupt offsets or air grooves on the invert will fill with water unless the offsets are comparatively large or the downstream conduit is placed on a downward slope. Large offsets or a downward slope is needed to prevent a small component of the flow from backing upstream to fill the offset or groove and cut off the supply of air.

The next phase of this study will be to investigate offsets for use with other arrangements of outlets. A high-priority phase of the study will be to develop a method of introducing air around the jets of existing structures. Palisade Dam outlets have a continuing problem of cavitation damage and one of the Team's objectives is to develop an air slot for these outlets which can be tested under prototype conditions to determine the effectiveness of this method of alleviating cavitation damage. Model studies will also include investigation of installation involving tilted rectangular gates discharging into a stilling basin, similar to the outlet works for Wanship, Ruedi, Stampede Dams, and others. The principle of the introduction of air, either naturally or artificially, by means of slots or offsets will be pursued. A similar principle will be applied in testing installations involving free-flow outlet works systems subjected to heads in excess of 150 feet.

IX. PROPOSAL FOR NEW TEST FACILITIES

Cavitation-resistant Materials - In reviewing the Bureau's research effort to develop new and improved materials for resisting damage by cavitation and abrasion, the Team worked closely with the Chemical Engineering Branch, Division of Research. It was generally agreed that useful but limited information was being derived from the Bureau's cavitation and abrasion test facilities. However, the length of time required to evaluate a material and the relatively mild damage sustained in the laboratory seemed to dictate that new and more elaborate tests facilities were needed to locate and develop new coatings to protect flow surfaces from damage.

A memorandum to the Chief Engineer was prepared outlining new research objectives to ascertain the availability of better materials, reassess past test results, review current studies of the Navy and others, and consider the development of new cavitation test equipment. To assist us in this effort, it was proposed that an outside organization experienced in both the hydraulics and engineering aspects of cavitation would be engaged to evaluate our needs and to develop a new test facility meeting our requirements.

Following approval of this memorandum by the Chief Engineer, Hydronautics, Inc., Laurel, Maryland, was contacted and they expressed an interest in assisting us in this study. Permission from the Commissioner was obtained to negotiate a contract with Hydronautics, Inc., who was then invited to Denver to examine our facilities and discuss the proposed study.

Mr. Virgil E. Johnson, Jr., Chief Engineer, Hydronautics, Inc., visited the laboratories on March 7, 1969, and the needs for the study and the general requirements for the structure were discussed with members of the Team and personnel of the Research Division. More precise requirements were furnished Hydronautics, Inc., in a letter dated March 20, 1969. On May 2, 1969, Hydronautics, Inc., wrote that their preliminary estimates indicated that the cost of the proposed test facility would be about $95,000. By using their existing test facilities, Hydronautics estimated about $60,000 would be needed to generate data on offsets protruding into the flow and offsets away from the flow at velocities up to 160 fps, and to test six candidate materials.

It was concluded that our research efforts should be directed toward eliminating cavitation by proper design rather than developing a material to resist cavitational forces.

X. CONCLUSIONS

The following conclusions have been reached as of the date of this interim report. There are two primary causes of damage to concrete flow surfaces in the Bureau's hydraulic structures:

1. Cavitation

a. Cause. - A survey of Bureau structures indicates that cavitation damage is apt to occur under the following conditions:

(1) Heads in excess of 150 feet.

(2) Irregularities in the concrete surface. Small abrupt irregularities of 1/4 inch in the concrete surface can lead to cavitation.

(3) Boundary layer that is not sufficiently developed.

b. Remedy. - While the causes of cavitation appear of a simple nature, the remedies are more complex. Since the heads are a design requirement and cannot be reduced, it is necessary to find a means of protection against the high velocities. Following is a list of suggested remedies; some are already in use:

(1) A list, in order of preference, of types of stilling basins least apt to suffer cavitation damage which is to be used as a guide for designers, is given under recommendations in this report.

(2) The use of offsets or slots to provide introduction of air at the gates offers the most promise for reducing cavitation

downstream of regulating gates. Further tests are scheduled to be run on the value engineering model in the laboratory to determine if the slots can be applied to existing as well as proposed structures.

(3) The principle of sudden enlargement for energy dissipation offers promise for a type of basin that would perhaps eliminate damage by cavitation. This will need to be investigated further in the laboratories.

(4) More care should be used in placing concrete, in areas subject to cavitation, to prevent irregularities in the concrete surface.

(5) The most effective method now in use for controlling cavitation damage downstream of gates has been stainless-clad metal liner plates. However, the metal plates are costly and present installation problems.

(6) The Value Engineering Team investigated many commercial products for use as a coating material. Only one, N 29, previously tested by the laboratories, appeared to show any promise. The neoprene coating N 29 is currently undergoing tests at Grand Coulee Dam. It does not appear that most materials now commercially available are capable of resisting cavitation.

2. Abrasion

a. Cause. - The survey of Bureau structures also indicates that abrasive damage will occur when solids are present in highly turbulent flows. The solids are supplied from the following sources:

(1) Riprap drawn into the basin from the downstream channel.

(2) Construction materials such as reinforcing steel, wire, metal, concrete, and other debris left in the basin during construction.

(3) Careless removal of cofferdam allowing rocks and gravel to enter the basin.

(4) Rocks falling into the chute or basin from the cut slopes.

(5) Rocks and debris thrown into the basin.

b. Remedy. - The designers should give careful consideration in stilling basin design to ways and means of keeping abrasive materials from entering the stilling basins. Following are some suggested schemes for controlling abrasive solids:

(1) Place riprap large enough that water currents cannot pull it back into the basin. If the riprap available is too small, it should be grouted with cement or asphalt mortar. A paved apron downstream from the basin is effective but generally more costly than riprap. In either event, provisions to relieve uplift pressures must be made.

(2) Construct protective fences and ditches at the toes of the side slopes to prevent rocks from entering the basin.

(3) A cover over the basin should be considered where the span is not prohibitive. This would provide stability against vibratory forces and some protection against rocks from sliding or being thrown into the basin.

(4) The removal of cofferdams should be carefully supervised to see that rocks and gravel do not enter the basin.

(5) Metal liners are resistant to abrasion but are very costly. Liners may be used under extreme conditions where the source of abrasion cannot be removed and other types of protection are not adequate.

(6) Epoxy mortar has had some successes but does not appear practical to use as a protective coating for a complete basin.

(7) Several commercial coating materials have been considered but will require further tests before they can be fully evaluated.

XI. RECOMMENDATIONS

Value Engineering Team No. 8 has concluded that the most effective method of reducing or eliminating erosion damage to concrete flow surfaces is through improved designs. While the team has explored many possible modifications in design concepts, it believes that recommendations involving design changes should not be made until each phase of the current and planned model and prototype testing has advanced far enough to permit unqualified conclusions to be drawn. Therefore, the following recommendations are limited to testing believed to be essential in achieving this objective:

1. The laboratories run hydraulic tests on stilling wells for larger, higher head releases in cooperation with the appropriate design groups to develop a workable design free of cavitation.

2. Continue studies with the VE hydraulic model for the introduction of air through offsets and slots immediately downstream of rectangular outlet gates to prevent damage to flow surfaces by cavitation.

3. The laboratories investigate the relationship between roughness of flow surfaces and cavitation damage.

4. A forceful request be made to the Regional Director to permit a 4-day test release of 15,000 cfs at Yellowtail Dam spillway tunnel to prove the effectiveness of the air slot in alleviating cavitation damage.