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March 1993

Corrosion Mitigation in Civil Works Projects:
Minimization of Cavitation Repair in Turbines

Application of Thermal Spray and Ceramic Coatings and Reinforced Epoxy for Cavitation Damage Repair of Hydroelectric Turbines and Pumps

by
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The U.S. Army Corps of Engineers is one of the largest single producers of hydroelectric power in the United States. The Corps' ability to generate power can be reduced by cavitation in hydroelectric turbines. Cavitation is the damage that results from high velocity liquid flow and pressure changes. Cavitation can be repaired by traditional methods, such as welding or application of epoxy, or by the newer nonfusion methods, such as thermal spray and the use of reinforced epoxies.

This research shows that the performance of reinforced epoxies is sensitive to surface preparation and method of application. Repair by these compounds lasts from 6 months to 1 year, but the downtime for repair is very short. New thermal-sprayed metallized coating systems have been tested in the laboratory and show potential for application in cavitation repair. New ceramic coatings have improved cavitation resistance, but their application is limited by current thermal spray technology, which is improving.

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FOREWORD

This study was conducted for the Electrical and Mechanical Branch, Engineering Division, Directorate of Civil Works, Headquarters, U.S. Army Corps of Engineers (HQUSACE), under Civil Works Investigations and Studies (CWIS) Work Unit, 31204, "Corrosion Mitigation in Civil Works Projects," and under Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Work Unit, 32335, "Minimization of Cavitation Repair of Turbines," for which Dr. A. Kumar was Principal Investigator. The HQUSACE technical monitor at the outset of the research was Mr. Robert Pletka. The current Technical Monitor is Mr. Robert Kinsel, CECW-EE.

This research was performed by the Engineering and Materials Division (FM), of the Infrastructure Laboratory (FL), U.S. Army Construction Engineering Research Laboratories (USACERL). Paul Willis is employed by the U.S. Army Corps of Engineers, North Pacific Division Hydroelectric Design Center. Appreciation is expressed to Richard G. Lampo of CECER-FM, who contributed data relating to epoxy materials. Dr. Paul A. Howdysshell is Chief, CECER-FM, and Dr. Michael J. O'Connor is Chief, CECER-FL. The USACERL technical editor was Gloria J. Wienke, Information Management Office.

COL Daniel Waldo, Jr., is Commander and Director of USACERL, and Dr. L.R. Shaffer is Technical Director.

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APPLICATION OF THERMAL SPRAY AND CERAMIC COATINGS AND REINFORCED EPOXY FOR CAVITATION DAMAGE REPAIR OF HYDROELECTRIC TURBINES AND PUMPS

1 INTRODUCTION

Background

The U.S. Army Corps of Engineers is one of the largest single producers of hydroelectric power in the United States, operating more than 70 projects that house 344 turbine units. The Corps has about 30 percent of the total hydroelectric capacity in the nation, approximately 20.9 million kilowatts (kW). More than 60 percent of this capacity is generated in the Pacific Northwest.

The ability to generate power can be reduced by cavitation in hydroelectric turbines. Cavitation is damage that results from high velocity liquid flow and pressure changes. The Electric Power Research Institute (EPRI) has published a detailed report on cavitation and techniques used to mitigate and repair the damage in hydraulic turbines by using epoxy and welding techniques.¹

Nonfusion repair methods such as thermal spray and the use of reinforced epoxies have several advantages when compared to welding techniques. Welding requires high temperatures, and as a consequence, the component being repaired may become distorted and damaged by thermal stresses induced by frequent maintenance. Welding techniques also require that the substrate be maintained at an elevated temperature during repair. In contrast, nonfusion repair methods do not involve the high temperatures that may damage the component. Although reinforced epoxies may require added heat to achieve a specific curing temperature (e.g., if the temperature of the component being repaired is below 40 °F,* which is a typical lower temperature limit for these materials), the amount of heat needed usually would not be detrimental to the structure. Thermal spray methods involve particles with high temperatures and velocities, but not sufficiently high to damage the component.

Reinforced epoxy and thermal spray coatings are repair technologies that have been used for cavitation damage repair in turbines and pumps. Comparisons between traditional welding techniques and these nonfusion repair methods need to be researched and evaluated for Corps applications.

Objectives

The objectives of this research were to (1) identify nonfusion technologies such as reinforced epoxies, thermal spray, and ceramic coatings for further testing and evaluation in the cavitation damage repair of turbines and pumps and (2) summarize Corps experiences with the use of nonfusion materials for repair of turbines and pumps.

¹ J.P. Sinclair and P.R. Rodrigue *Cavitation Pitting Mitigation in Hydraulic Turbines*, Volumes I and II, EPRI AP-4719 (Electric Power Research Institute [EPRI], Acres International Corporation, August 1986).

* A metric conversion table is on page 40.

Approach

Emerging nonfusion repair technologies such as reinforced epoxy repair compounds, metallized coatings, and reinforced ceramic matrix coatings were identified and their cavitation rates evaluated by various investigators at the U.S. Bureau of Reclamation, Tennessee Valley Authority, and the Corps of Engineers. Advanced thermal spray technologies such as plasma arc and high velocity oxyfuel (HVOF) are being investigated by the Navy for rehabilitation of ship propellers. These technologies have potential application for turbines and pumps. Testing procedures used by the Navy, U.S. Bureau of Reclamation, and the electric power industry were identified and their use for evaluating rehabilitation compounds for turbines and pumps for further field testing was determined. Finally, field repair performances of these nonfusion coatings at Corps of Engineers projects was documented.

2 CAVITATION AND POWER EQUIPMENT

The Cavitation Process

Cavitation is a major problem confronting both designers and operators of modern high-speed hydrodynamic systems. Cavitation damages hydraulic turbines, pump impellers, and other surfaces as a result of high velocity liquid flow and pressure changes. The turbine components most often damaged include turbine runners, draft tube liners, discharge rings, and wicket gates. Maintenance personnel attempt to minimize cavitation damage by changing the operating conditions. Because cavitation results in high repair costs, significant downtime, high cost of replacement power, and an overall reduction in the service life of equipment. Cavitation in turbines and pumps can cause vibration which rapidly wears bearings and contributes to fatigue damage of components in the entire system.

Cavitation occurs when the pressure in a fluid drops below its vapor pressure. Vapor bubbles can then be created when the fluid flow is constricted in low-pressure areas. These bubbles are harmless until they are subjected to higher pressures when they subsequently implode and cause cavitation damage to the components. The bubble collapse creates intense shock waves that can yield pressures as high as 60,000 pounds per square inch (psi).² The impact of these shock waves can adversely affect both metallic and nonmetallic surfaces. In metals and alloys, cavitation can destroy passive films, tear surface particles, and plastically deform the materials in the cavitating region.³

Cavitation is not solely a mechanical phenomenon. Researchers⁴ concluded from results of laboratory tests wherein damage was observed to be more severe in seawater than in fresh water, that both mechanical and electrochemical factors are involved in cavitation. Reinforced epoxy materials can help mitigate galvanic corrosion that can occur as a result of using a weld metal that is dissimilar to the original component composition. Cavitation damage in fresh water can be simulated in the laboratory using a number of tests, including vibratory methods.⁵ The data obtained from the vibration apparatus reveals that smooth surfaces such as cold-rolled steel have better resistance to cavitation damage than rougher surfaces such as cast iron.⁶ This may be due to the fewer bubble nucleation sites associated with smooth surfaces.

Turbines

Hydraulic turbines extract energy from water as it passes through the rotating turbine runner system. As the water flows from a higher elevation to a lower elevation, the velocity gained from the potential energy (head) imparts momentum to the water. Water is stored behind a dam in the forebay and is released at desired intervals through an intake water passage, which directs the water to the turbine-driven generator that produces hydroelectricity. The output energy of a hydroelectric plant depends on the head and the volume of water available. The overall turbine efficiency is the ratio of the power output to the total available water power input, based on flow rate and the net head.

² M.G. Fontana and N.D. Greene, *Corrosion Engineering* (McGraw Hill, 1978), p 84.

³ *Corrosion Handbook*, H.H. Uhlig, ed. (John Wiley and Sons, 1948), p 597.

⁴ *Corrosion Handbook*.

⁵ ASTM G32-85, "Standard Methods of Vibratory Cavitation Erosion Test," *Annual Book of ASTM Standards*, Vol 03.02 (American Society for Testing and Materials, 1991).

⁶ H.H. Uhlig, *Corrosion and Corrosion Control* (John Wiley and Sons, 1971), p 112.

Hydraulic turbines are classified according to type and flow direction of the water through the runner. The three general types of hydraulic turbines currently used are: the Francis turbine; the propeller (fixed and adjustable) turbine, also known as a Kaplan turbine; and the impulse or pump-type turbine. The Francis type is a radial or mixed-flow turbine with fixed runner blades. It is most efficient at intermediate heads. The Kaplan turbine is an axial-flow turbine with either fixed or adjustable blades and is used in low head applications. The impulse turbine is a paddle wheel design typically used at high heads.

Cavitation damage can occur to components of all reaction-type turbine equipment, including fixed-blade propeller turbine units, adjustable blade propeller turbines, and reversible Francis pump-turbines. Impulse turbines generally do not experience cavitation but are exposed to erosion. Areas on Francis units where cavitation damage can be expected to occur (Figures 1 and 2) include:

- runner blades - suction side, near band and trailing edge
- runner blades - leading edge, near the band on both the suction side and the pressure side
- runner blades - trailing edge, on suction side
- runner blades - near crown (leading edge)
- the air vents in the crown on the runner
- the discharge ring opposite the runner band
- below the band on the draft tube liner
- wicket gates sides.⁷

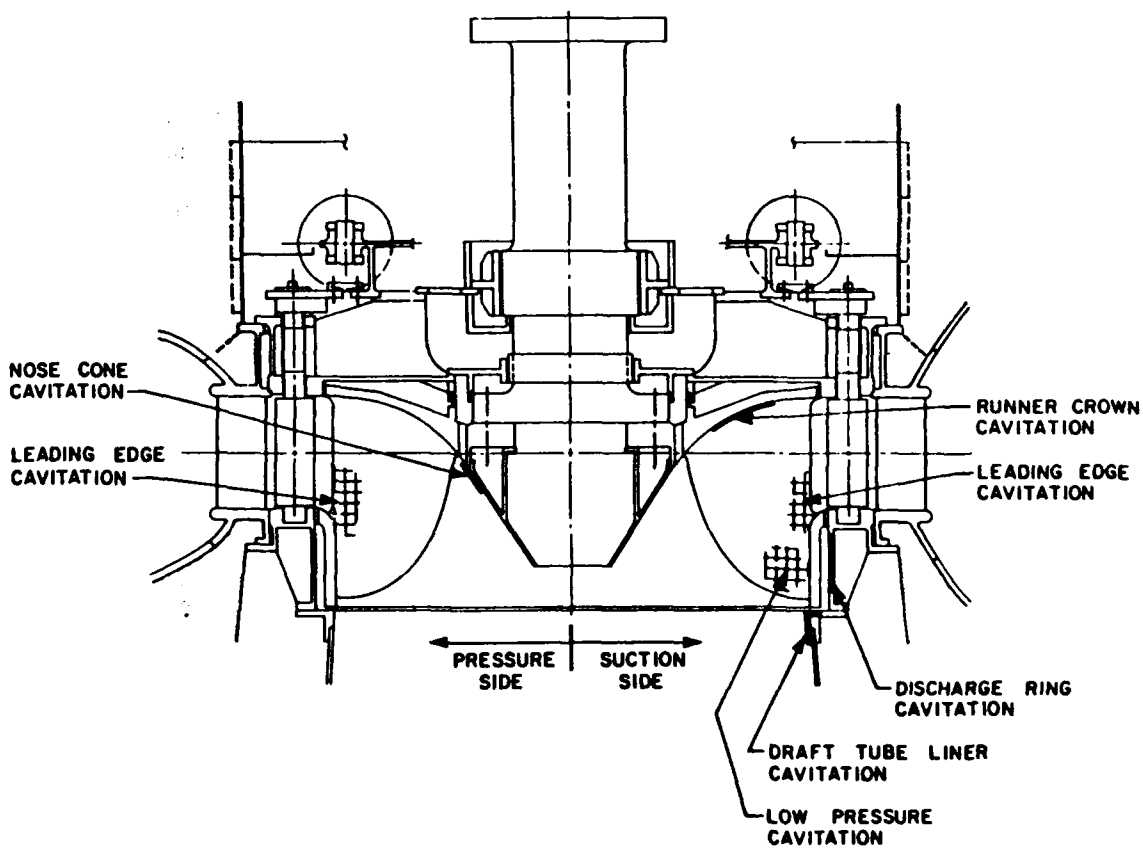


Figure 1. Typical Areas of Cavitation in Francis Turbines. (Copyright ©1986. Electric Power Research Institute. EPRI AP-4719. *Cavitation Pitting Mitigation in Hydraulic Turbines*. Reprinted with permission.)

⁷ J.P. Sinclair and P.R. Rodrigue.

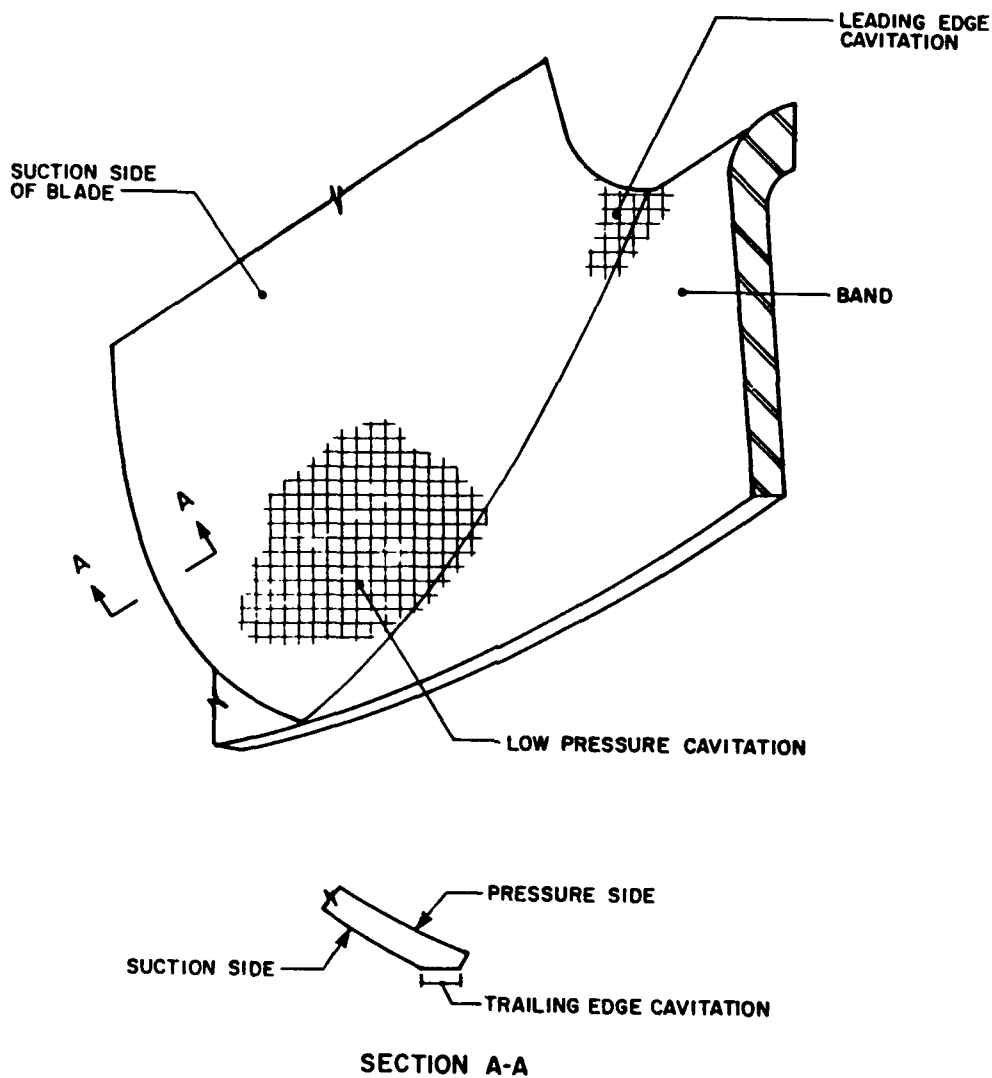


Figure 2. Areas of Cavitation on the Runner in Francis Turbines. (Copyright ©1986. Electric Power Research Institute. EPRI AP-4719. *Cavitation Pitting Mitigation in Hydraulic Turbines*. Reprinted with permission.)

Areas on propeller units where cavitation damage can occur (Figures 3 and 4) include:

- runner blades - suction side from the centerline to the trailing edge
- runner blades - leading edge, both the suction side and the pressure side
- runner blades - trailing edge, pressure side
- runner blade - suction side of the peripheral edge
- near the runner periphery, suction side
- the runner hub, discharge ring, and draft tube liner.⁸

⁸ J.P. Sinclair and P.R. Rodrigue.

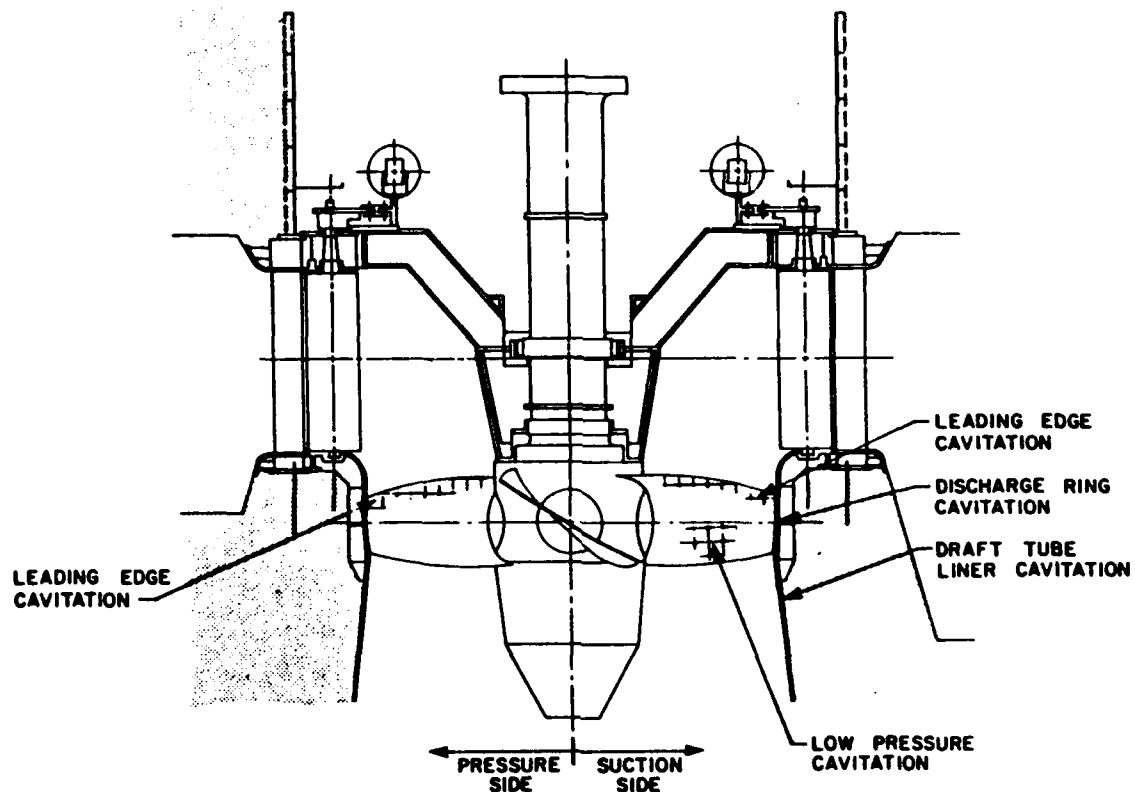


Figure 3. Typical Areas of Cavitation in Propeller Turbine. (Copyright ©1986. Electric Power Research Institute. EPRI AP-4719. *Cavitation Pitting Mitigation in Hydraulic Turbines*. Reprinted with permission.)

Areas on pump-type turbines where cavitation damage can occur (Figures 5 and 6) include:

- runner blades - suction side, near and at the pump leading edge
- runner blades - pressure side, at pump leading edge
- runner blades - both the suction side and pressure side, near the band at turbine leading edge
- crown, or runner blade, turbine leading edge near crown
- the discharge ring near the runner
- under the bottom of the band on the draft tube liner
- below the band on the draft tube liner
- wicket gates sides.⁹

⁹ J.P. Sinclair and P.R. Rodrigue.

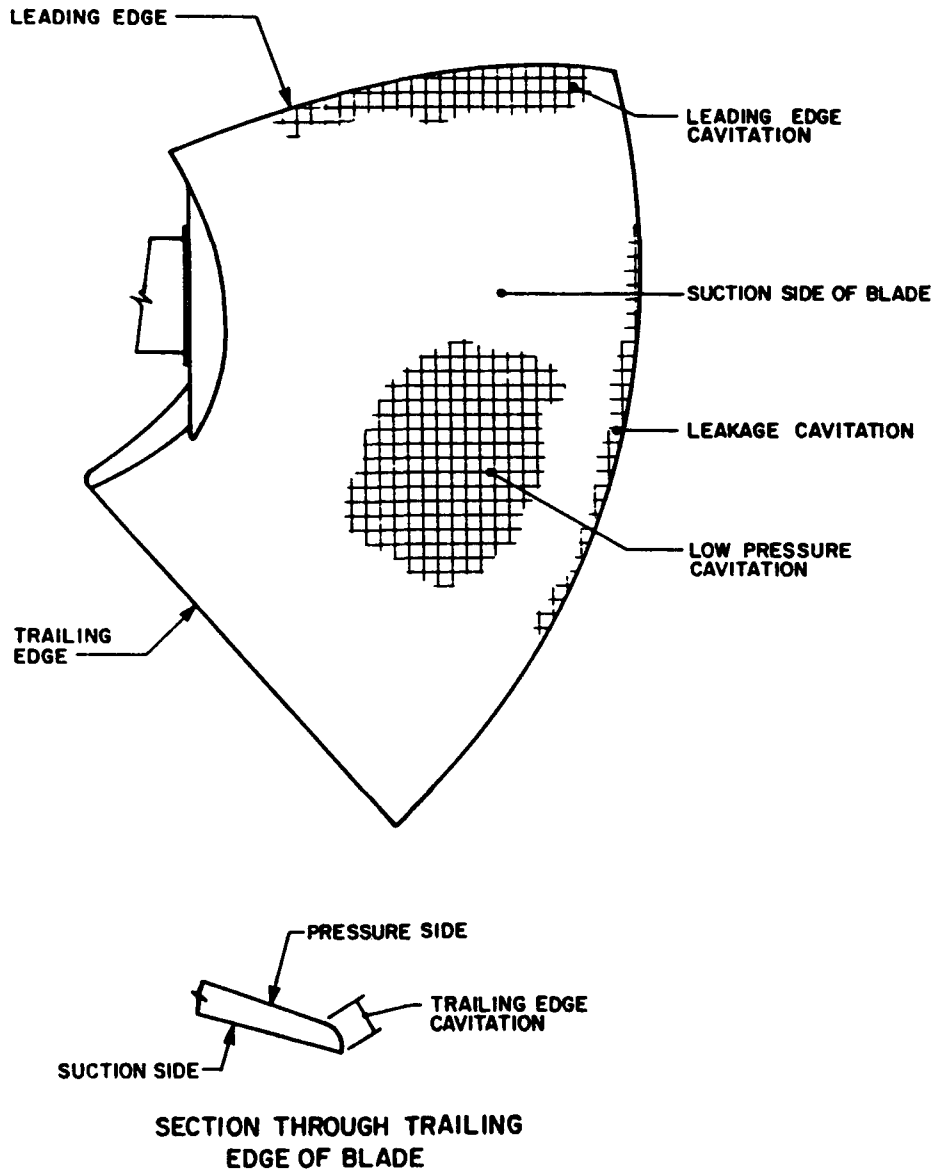


Figure 4. Areas of Cavitation on the Runner in Propeller Turbines. (Copyright ©1986. Electric Power Research Institute. EPRI AP-4719. *Cavitation Pitting Mitigation in Hydraulic Turbines*. Reprinted with permission.)

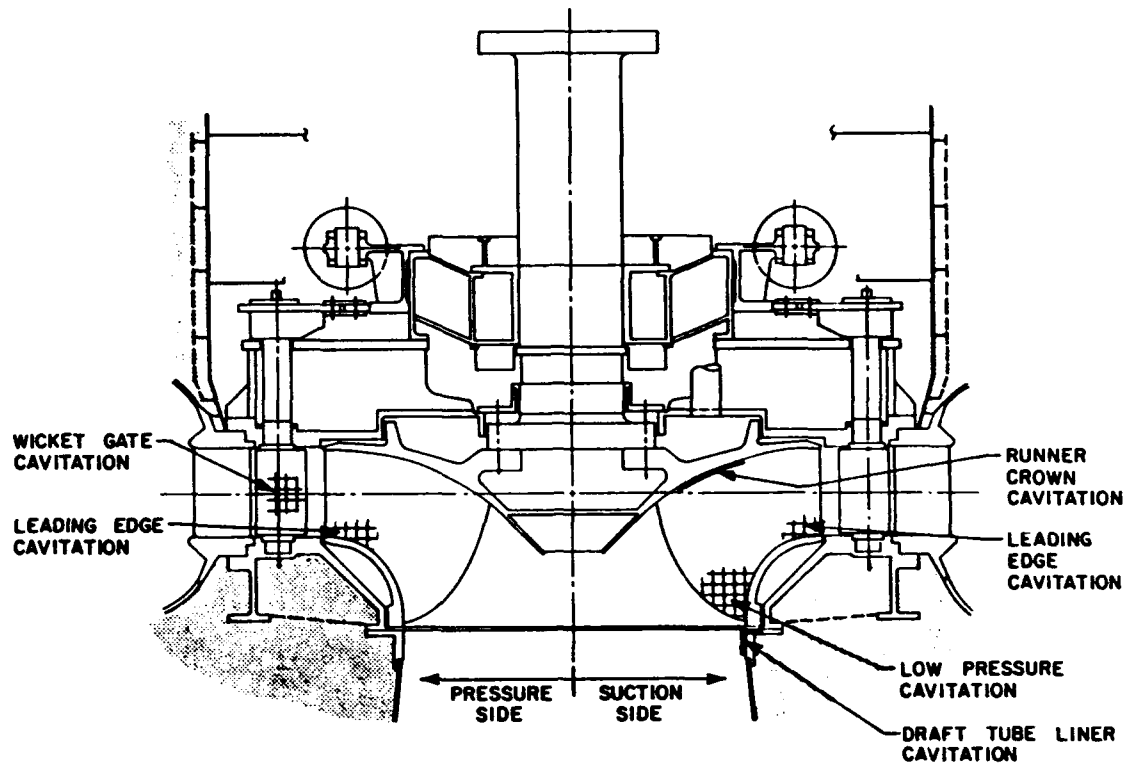


Figure 5. Typical Areas of Cavitation in Pump Turbines. (Copyright ©1986. Electric Power Research Institute. EPRI AP-4719. *Cavitation Pitting Mitigation in Hydraulic Turbines*. Reprinted with permission.)

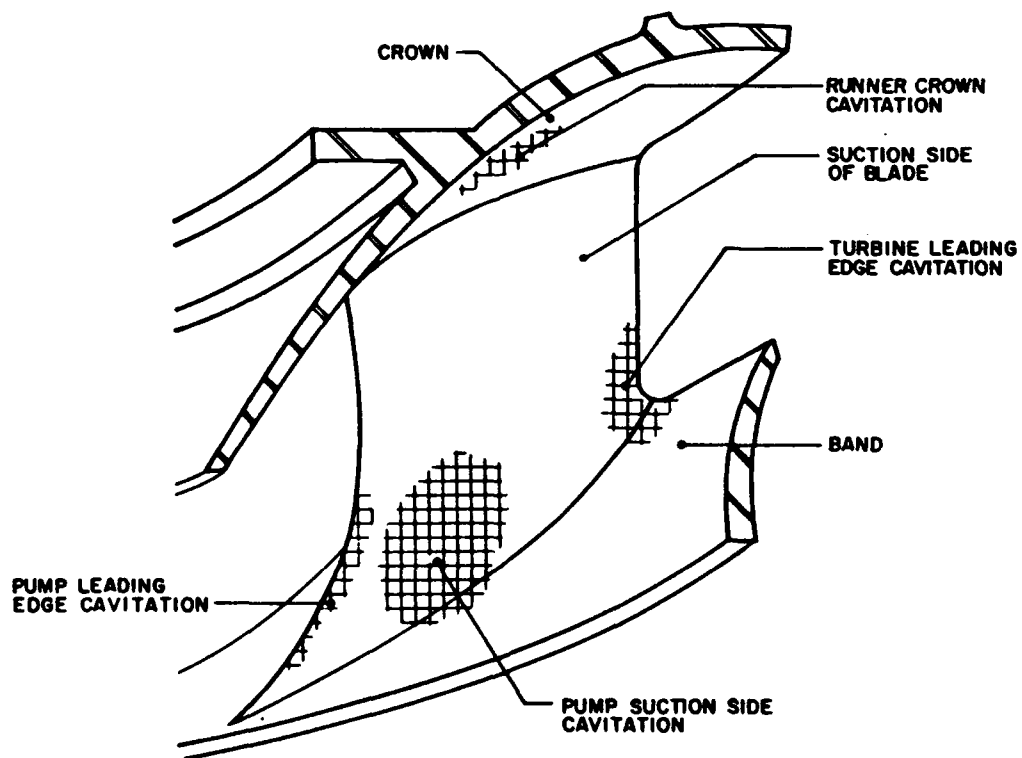


Figure 6. Areas of Cavitation on the Runner in Pump Turbines. (Copyright ©1986. Electric Power Research Institute. EPRI AP-4719. *Cavitation Pitting Mitigation in Hydraulic Turbines*. Reprinted with permission.)

3 REPAIRING CAVITATION

Repair Techniques

Techniques available for cavitation damage repair include: weld overlays and inlays, reinforced epoxy coatings, and thermal spray and ceramic coatings. Of these, the most commonly used method that produces the most durable coating is the weld overlay technique. This method involves removing material from the damaged areas (and any old repair material), filling the space with an alloy such as mild steel, and welding the top 1/4 in. with 308 stainless steel, which has good cavitation resistance.¹⁰ The material used to repair cavitation damage should be selected to optimize the costs and maximize the service life under expected operating conditions. Due to the condition of most cavitated surfaces, damage generally cannot be repaired by directly filling the pitted areas. The pitted surface is usually excavated (undercut) to remove the damaged area and to provide a surface that can adequately be cleaned before the filling repair.

Reinforced epoxies, which are nonmetallic coatings, have also been used widely. Although these materials have enjoyed some success, it is difficult to predict their performance. The bond strength between the epoxy and metallic substrate depends on the surface condition and, over time, the repair compounds may fail due to cavitation and mechanical fatigue of the bond interface.

Consider the following aspects when choosing a material for cavitation damage repairs:

- The material should be able to completely fill the cavitated area and be machined to the original component contours.
- The strong mechanical and chemical adhesion that must exist between the coating and the metallic substrate may not always be present in epoxy repair compounds.
- The material must not initiate galvanic corrosion between the repair material and the substrate.
- The costs of labor, materials, and system downtime vary.

The condition of the substrate surface is an important factor that can impart properties necessary for obtaining high quality coatings. Coatings that exhibit good adhesion and do not fail prematurely are considered high quality. Coating adhesion is directly related to the surface preparation method, surface cleanliness, and surface roughness. These factors and methods subsequently depend on the substrate material.

Surface Preparation

Adhesion is a macroscopic property influenced by the characteristics of the interface between the substrate and the coating, the magnitude of local stress levels, and the presence of deformation or failure modes.¹¹ Coating materials have good adhesion if the interface does not fail under normal operating conditions or at low stress levels. Substrate surface preparation is very important for assuring that the coating will exhibit good adhesion. The extent to which a surface must be cleaned is determined by the coating material and the coating process. Consequently, it is very important that the user understand the substrate, coating material, and operating environment in order to provide an adequately clean surface.

¹⁰ J.P. Sinclair and P.R. Rodrigue.

¹¹ D.A. Mattox, "Adhesion and Surface Preparation," *Deposition Technologies for Films and Coatings*, Rointan F. Bunshah, ed. (Noyes Publishing, 1982).

Surface contaminants can be reaction layers, adsorbed layers, particulate contaminants, or variable composition layers.¹² Reaction layers are typically in the form of oxides. Adsorbed layers form when the substrate adsorbs material from the environment or when contaminants are diffused over the surface from the surroundings. Variable composition contaminants may form by the diffusion of a minor constituent from the substrate to the surface, giving a high surface concentration, or by the formation of a second-phase material.

Cleaning procedures are designed to remove specific types of contaminants without changing the physical or chemical properties of the substrate surface. Cleaning can be done with solvents, which dissolve contaminants without attacking the surface, or with volatilization techniques, where the contaminant is vaporized by heating or is reacted with a gas to form a volatile compound. General cleaning techniques often involve removing some of the surface material as well as the contaminants. After cleaning, the surface must have a suitable profile that will enhance the coating adhesion. A rough profile has a greater surface area, which increases bonding capability.

The surface can be roughened by grit blasting or by macroroughening (machining the surface). These roughening techniques provide compressive surface stresses, aid in decontaminating the surface, increase the bond surface area, and create interlocking layers. The roughening technique must be matched to the substrate material, the coating material, the coating process, and the operating conditions of the part.

Grit Blasting

Grit blasting, the most commonly used surface preparation method, uses abrasive particles to impinge on the surface and create a rough profile. The substrate type, hardness, thickness, and size are factors affecting the choice of grit material used. Other factors to consider include coating type, roughness requirements, coating operating conditions, and blasting equipment parameters.

The American Welding Society has published information that can be used to properly match grit blasting material with the substrate.¹³ Correct choice of the type and size of the grit material is crucial. Sharp, angular, hard particles generally provide the best results—a rough profile. Refractory blasting materials, for example, can be used on hard substrates, such as martensitic steel, but may embed in softer surfaces. The grit material is available in different sizes to allow for various surface roughnesses. Generally, small particles increase the blasting velocity while large particles remove material more rapidly and produce rougher surfaces.

Macroroughening

Macroroughening involves grinding or machining the surface and can be used in conjunction with grit blasting and/or the use of bond coats. Undercutting, grooving, and coarse grit blasting are all macroroughening techniques. When cavitation damage is severe, the areas needing repair are usually undercut to remove the damaged material. The area is subsequently rebuilt to the original contour using the repair material. Undercutting provides a uniform thickness and removes surface material that has been work-hardened, oxidized, cavitated, or previously coated. Excessive undercutting, however, can significantly reduce the strength of the substrate and induce stress.

Grooving methods involve cutting deep, closely spaced striations into the substrate and are used to restrict shrinkage and internal stresses, and increase the bonding surface area. Grooving should be used

¹² D.A. Mattox.

¹³ American Welding Society, *Thermal Spraying: Practice, Theory and Application* (1985).

for coatings over 0.050-in. thick at the edges or for coatings with high shrinkage (over 0.030 in.) at the edges. Coarse grit blasting can yield results similar to grooving, when grooving is not practical.

Epoxy Compounds

A wide variety of nonfused materials have been used with varying success to repair cavitation damage on turbine components. Generally, the use of nonfused materials should be considered primarily as a sacrificial coating in areas of low-intensity cavitation and on nonrotating components.¹⁴ Compared to the weld overlay technique, the advantages of nonfused repair materials include: (1) significantly reduced labor costs, (2) avoidance of thermally-induced residual stresses in the repaired components, and (3) improved control of component contours through the use of templates. Although less time is required to apply epoxy repair materials, the time necessary for the material to cure must be considered in the downtime.

The primary concern associated with the use of reinforced epoxies for repair is in inadequate bonding between the coating/filler material and the substrate. Although polymeric coatings effectively absorb the energy produced during bubble collapse, in most applications, epoxy repair materials are used as sacrificial coatings extending the service life of the component.¹⁵ Although the resiliency of neoprene would be expected to mitigate cavitation damage by cushioning bubble collapse,¹⁶ neoprene is not a feasible option for cavitation damage repair of most components because it tends to separate (peel) from the substrate when subjected to even moderate cavitation intensity. When used as a sacrificial coating, epoxy compounds reinforced with ceramic and metal powders provide mechanical strength and galvanic protection from the carbon steel/stainless steel electrical potential difference.

Epoxy compounds are much cheaper to apply than weld metal, though they are not as resistant to cavitation damage as weld metal overlays. The major cost in repairs using epoxy is the labor involved and the cost of downtime. The cost of downtime in terms of the lost generated power and the cost of replacement electric current especially at peak loads, may be as much as several hundred thousand dollars, depending on the plant size.

Reinforced epoxies have met with limited success in repairing cavitation damage because their performance in laboratory tests is difficult to correlate with actual operating conditions and environment. Table 1 contains laboratory test data for several commercial reinforced epoxy repair materials. Although the materials were tested using American Society for Testing and Materials (ASTM) procedures, their performance as cavitation damage repair materials in field conditions is limited. The success of epoxy coatings for repair of dynamic systems such as turbine blades and pump impellers is not as impressive.

Due to these facts, the average life of epoxy coatings is relatively short—from 6 months to 1 year in turbines where cavitation is low. No coating is totally immune to cavitation damage. Some coating methods are better suited to long repair cycles while others offer temporary repair where it is costly and time consuming to replace parts or equipment. Epoxy coatings used sacrificially are relatively cost effective when materials and labor are considered. The fact that epoxy coatings need to be replaced frequently may make the life-cycle cost less impressive when compared to other repair methods. Analysis of epoxy coatings will need to be done on a case-by-case basis.

¹⁴ J.P. Sinclair, P.R. Rodrigue, and R.L. Voight, Jr., *Hydro Review*, Vol 9, No. 3 (June 1990).

¹⁵ P.A. March, *Evaluation of Relative Cavitation Erosion Rates for Base Materials, Weld Overlays, and Coatings*, Report No. WR28-1-900-157 (Tennessee Valley Authority [TVA] Engineering Laboratory, October 1986).

¹⁶ J.P. Sinclair, P.R. Rodrigue, and R.L. Voight, Jr.

Table 1
Results of Epoxy Laboratory Tests

PROPERTY	CERAMIC R-METAL	HARD WEARING	PUMP REPAIR COMPD	FEL- POXY	NR 858	CERAMIC S-METAL	IPI FLUID- CERAMIC	ASTM TEST PROCEDURE
MIXING RATIO, (wt.)	5:1	5.16:1	7:1	9:1	7:1	8.8:1	9.8:1	
MIXING RATIO, (vol.)	3:1	-----	4.3:1	-----	4.25:1	3.5:1	6:1	
CONSISTENCY	Stiff Paste	Fluid Paste	Stiff Paste	Fluid Paste	Stiff Paste	Liquid	Liquid	
CURED DENSITY (g/cm ³)	2.27 ± 0.02	2.02 ± 0.00	1.61 ± 0.01	2.74 ± 0.00	1.65 ± 0.00	2.34 ± 0.01	1.79 ± 0.01	D792-66, Method A-1
COMPRESSIVE STR. (psi)	13,659 ± 473	12,463 ± 198	14,734 ± 94	15,792 ± 86	12,236 ± 550	16,681 ± 107	14,052 ± 428	D695-80
FLEXURAL STR. (psi)	7,310 ± 108	6,499 ± 726	5,198 ± 722	5,739 ± 984	7,133 ± 1116	-----	-----	D790-81, Method I
TENSILE-SHEAR STR. (psi)	1,865 ± 99	2,029 ± 89	1,451 ± 165	1,806 ± 246	395 ± 118	2,308 ± 181	2,670 ± 233	D1002-72
TENSILE STR. (psi)	3,885 ± 377	3,844 ± 842	4,370 ± 417	3,532 ± 1045	3,124 ± 252	-----	-----	D638-82a
HARDNESS (Shore D)	89.9 ± 0.8	89.3 ± 1.5	89.2 ± 1.0	90.4 ± 0.8	89.1 ± 0.8	89.6 ± 0.8	86.8 ± 0.8	D2240-81
WORKING TIME (min)	25	25	20	35	35	23	24	
CURE SHRINKAGE (in/in)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	D2566-79
THERMAL EXPANSION (/°C)	1.1E-4	1.1E-4	2.0E-4	1.1E-4	1.5E-4	-----	-----	0°-80°C
SAG RESISTANCE	Exc	Fair	Exc	Good	Exc	Good	Poor	*
APPLICATION PROPERTIES	Exc	Exc	Exc	Exc	Poor	V. Good	Fair	*

When repairing cavitation damage using reinforced epoxies, the manufacturers' instructions should be followed closely. In most cases, the steps include: blast cleaning the area to near-white metal, mixing and applying the filler/paste material, and forming it to the desired contour, without voids. If conditions warrant, the component may be heated to a temperature of 130 to 140 °F using electric blankets or radiant heaters. The filler/paste material is allowed to cure for approximately 12 hours before the finishing material is applied to a thickness of 0.06 to 0.13 in. in two coats with contrasting colors. The filler and finish materials must be applied in strict accordance with the manufacturers' recommended procedures.

Thermal Spray Technologies

Applying a metallic or ceramic coating by thermal spraying can be accomplished using several different methods. The following temperature and velocity ranges are associated with the various thermal spray methods.

<u>Spray Method</u>	<u>Temperature Range, °F</u>	<u>Velocity Range, ft/s</u>
Flame spray	3500 to 5500	100 to 1100
Electric-arc	4000 to 10,500	800 to 1100
Plasma-arc	5000 to 30,000	1500 to 2300
High-velocity	4200 to 6000	approaches 4500

The temperature and velocity of the coating material is important for producing the desired coating. The temperature during application dictates the degree of melting of the coating material and the velocity imparted to the particles during application affects the final coating density.

Engineers have three choices when they want to apply a hard facing onto high-wear steel substrates. They can use plating, overlay welding, or thermal spray coating. Thermal spray coatings are considered cold repair methods because they do not require an increase in the substrate temperature. The thermal spray coating is not fused to the surface as is the case with welding procedures. Thermal spraying involves propelling molten droplets of coating material against a substrate. These droplets flatten upon impact, cool, and coalesce.

Welding methods, in contrast to thermal spraying, apply metallic coatings that are more dense. One drawback is that welding adds heat to the substrate, which can be detrimental to the life of the component. The increase in temperature can be enough to change the physical structures of the substrate, which can introduce distortion and residual stresses that weaken the structure.

Thermal spraying is one of the most versatile methods available for applying a variety of coatings on a range of substrates. The development of thermal spray coatings over the past 20 years has been largely empirical, due to the lack of understanding of the physical and chemical processes involved.

Phases of Coating Film Formation

Thermal spray coatings are formed by a number of interacting mechanisms. Each step affects the physical characteristics of the final coating. The properties of the coating material, and the particle velocity and temperature will greatly affect the coating formation. A coating generally forms as outlined below.

Nucleation. Coating atoms lose kinetic energy by forming stable nuclei when they hit the surface and condense. When the coating atoms have a high affinity for the surface, the strong interface will produce a relatively high density of nuclei. Weak interfaces will result from widely spaced nuclei that form on surface discontinuities. These nuclei will continue to overlap and grow to form a continuous coating film layer.¹⁷

Interface formation. The type of interface formed during the coating deposition depends on the substrate surface morphology, the surface preparation, the interfacial chemical reactions, the available energy during interface formation, and the size and number of nucleating coating atoms.

Film formation. The coating nuclei overlap and form a layered interface. The manner in which the coating film develops determines the final properties of the coating. The factors that most strongly affect

¹⁷ D.A. Mattox.

the mechanical properties of the coating are the microstructure, incorporated impurities due to surface preparation, and internal stresses. These properties interact with the deposition variables.

Microstructure development. The microstructure of the coating is determined by nucleation and growth of the film from the coating atoms. Nucleation of the coating atoms will be affected by the interfacial interactions and the surface mobility of the coating atoms. Growth will be affected by the surface mobility of the coating atoms, atomic arrangement on condensation and subsequent rearrangement of the structure.

Bond Coats in Thermal Spraying

Bond coats were developed to increase the performance and reliability of coating systems. They are usually applied to substrates that will be repaired by thermal spray techniques because they serve as protective coatings that increase adhesion. The composition of bond coats has changed from materials consisting of molybdenum in the early 1940's, to nickel-chromium, nickel-aluminum, aluminum-bronze and prealloyed nickel aluminum used today. All of these materials have been developed to increase the adherence of coatings.

Thermal sprayed coatings may spall because corrosion products form at the coating/substrate interface, even when a metallic bond coat has been used. Nickel alloys play a key role in the thermal spray process by increasing coating adhesion. Many of the coatings for thermal spray application use nickel either as a bond coat alloy to provide a ductile interface between the substrate and the coating, or as an alloying element in a ductile corrosion-resistant matrix alloy.¹⁸ Because nickel-containing alloys have the ability to be self-bonding, they are used extensively as a bond coat. The most common alloy compositions are 95 percent nickel with 5 percent aluminum and 80 percent nickel with 20 percent aluminum. Selecting a proper bond coat must include consideration of the operating environment, substrate material, coating material, and coating process. Bond coats are generally 0.003 to 0.007 in. thick and often limit the thickness of the topcoat.

Nickel/aluminum (Ni₃Al) powders are widely used as bond coats although the mechanism that enhances adhesion is not well understood. The powder is a tough intermetallic material that increases in strength with increasing temperature, up to a maximum of 1472 °F. Studies have shown that a small amount of boron in Ni₃Al turns the brittle compound into a ductile alloy at room temperature. This material is extremely resistant to cavitation in pump impellers and hydroelectric power turbines.¹⁹

A zinc-nickel alloy bond coat can effectively protect a carbon steel substrate. Plasma sprayed coatings of Cr₂O₃ and Al₂O₃/TiO₂ deposited on steel without a zinc-nickel bond coat are susceptible to corrosion and exhibit a sharp decrease in bond strength in corrosive environments. A zinc-nickel bond coat provides protection by prohibiting chemically active ions from passing through the coating porosity.

Plasma Spraying

Plasma spraying is a line-of-sight process that has been used in industry for approximately 25 years. It consists of an inert carrier gas that is passed through a direct current (DC) arc formed between the gun housing (cathode) and the nozzle (anode).

¹⁸ Nickel Development Institute, *Nickel Alloys in Thermal Spray*, Vol 6, No. 3 (March 1991).

¹⁹ Nickel Development Institute.

Plasma spraying is a heat/momentum process that involves energy transfer from plasma gas to the powder particles. This superheated plasma is used to melt and accelerate powder introduced into the plasma stream. On impact, the powder forms a thin lenticular coating layer consisting of many overlapping molten particle deposits.

Plasma spraying is an intricate process that combines powder particle injection, melting/quenching, and consolidation into a single operation.²⁰ The major advantages of using a plasma spray system are the high particle velocities and the high temperatures that can be achieved.

Any material that can be made molten without chemical or physical decomposition can be used to form a plasma sprayed coating. The mechanics and theory behind the plasma spray process are not fully understood. With more than 50 interacting and interdependent macroscopic process parameters that affect the final coating properties, it is very difficult to establish and control optimum spraying conditions. Table 2 contains some parameters necessary to consider for the proper selection of coating material.²¹

The adhesive strength of plasma-sprayed coatings can be enhanced either by applying a bond coat or by post-heat treatments. Dense coatings with good adherence are obtained when the particles are molten as they strike the substrate, when they have sufficient momentum upon impact, and when the interfacial temperature is as great as possible.

Cavitation Resistance of Plasma Sprayed Coatings

The cavitation behavior of plasma sprayed coatings consists of an initial stage where the surface undergoes plastic deformation through the action of the cavitation bubbles. Weight loss at this stage is attributed to ductile removal of the coating material giving rise to pit formation. Entrapped bubbles can frequently cushion the surface from increased pitting, and as a result, the weight loss can plateau. Investigators have studied the mechanisms of this weight loss.²²

The microstructures and cavitation resistance of plasma-sprayed coatings have been investigated by many researchers.²³ Studies also include the use of plasma spray coatings for improving cavitation resistance of steel substrates.²⁴

Comparisons of air plasma spray (APS), vacuum plasma spray (VPS), and hypersonic flame spray coatings showed that post-deposition heat treatments produce a coating with a higher density than in the as-sprayed condition. Also, of the three, the vacuum sprayed coatings exhibited superior wear resistance and exceptional corrosion and oxidation resistance, and produced the most homogeneous coatings with the highest cavitation resistance. These coatings were produced in the laboratory and would not be practical for repair in turbines due the equipment necessary for the process and the system operating considerations.

²⁰ W.C. Roman, et al, "Laser/2-D Imaging Visualization of Plasma Spray Particle Distribution," *Thermal Spray Technology, New Ideas and Processes*, Proceedings of the National Thermal Spray Conference (1988).

²¹ R.C. Tucker, Jr., "Plasma and Detonation Gun Deposition Techniques and Coating Properties," *Deposition Technologies for Films and Coatings*, Rointan F. Busnshah, ed. (Noyes Publishing, 1982).

²² A. Akhtar, "Plasma Sprayed Coatings for Cavitation Protection in Hydraulic Turbines," *Materials Performance*, Vol 21 (1982).

²³ Xiao-Xi Guo, H. Herman, and S. Rangaswamy, "Cavitation-Erosion of Plasma Sprayed WC/Co," *Advances in Thermal Spraying*, Proceedings of the 11th International Thermal Spray Conference, Montreal, Canada (1986); H. Bhat, H. Herman, and M.F. Smith, "Cavitation-Erosion of Plasma-Sprayed Alloys," *Thermal Spray Coatings, New Materials, Processes and Applications*, Proceedings of the American Society of Metals (1985).

²⁴ M.M. Abachrev, *Vestn. Machinost.*, Vol 11 (1979).

Table 2

Consideration for Coating Material Selection

I. WEAR SYSTEM

A. Adhesive or Abrasive

1. Type of relative motion - impact, oscillating
2. Surface speed - velocity and frequency if cyclic
3. Load or impact energy
4. Abrasive particles - trapped or removed, size and composition
5. Conformability requirements
6. Embedability requirements

B. Erosive

1. Gas or solid particle
2. Media - gas or liquid
3. Gas or particle velocity and angle of impingement
4. Particle size, shape, mass, and composition

II. ENVIRONMENT

- A. Temperature - maximum, minimum and rate of change
- B. Media - gas or liquid
- C. Contaminants
- D. Corrosive characteristics - chemical, galvanic
- E. Lubricant

III. MATING MATERIAL

- A. Composition
- B. Heat treatment characteristics
- C. Hardness
- D. Surface roughness and topology

IV. SUBSTRATE MATERIAL

- A. Composition
- B. Heat treatment condition
- C. Dimensional changes after cooling
 1. During assembly due to press fit, shrink fit, etc
 2. In service due to thermal expansion/contraction or loading

V. COATING REQUIREMENTS

- A. Cost limitations
- B. Required life, time or maximum wear
- C. Compositional limitations
- D. Thickness limitations
- E. Coefficient of friction requirement
- F. Surface finish
- G. Geometric constraints
- H. Overspray limitations

High Velocity Oxyfuel (HVOF)

High velocity oxyfuel thermal spraying is the most significant development in the thermal spray industry since the introduction of plasma spraying. HVOF coating technologies could account for as much as \$160 million annually, worldwide. Since the 1982 introduction of the Jet Kote™ system designed by Browning Engineering Co., this technology has enjoyed extensive growth in both the development of

materials and equipment. Approximately 70 percent of all HVOF applications involve producing coatings that provide wear and erosion resistance for rehabilitation of structures and surfaces.

HVOF thermal spraying processes use internal combustion of an oxygen/fuel mix to produce a high velocity jet stream. Combustion fuels include propylene, acetylene, propane, and others, and when burned in oxygen, produce gas temperatures greater than 5000 °F. The coating powder particles are injected into the center axis of the jet where they are protected from oxidation by the enveloping combustion stream. This allows for oxygen-free deposition.

The mechanics of the HVOF system are relatively simple. A HVOF system consists of the torch, parameter controls, and a powder feeder, and requires cooling water reservoirs, fuel gases, oxygen, and an inert powder feed gas. Application methods depend on the feedstock melting temperature, powder particle size, fuel gases, and cooling system. A pilot flame, typically burning hydrogen and oxygen gases, is ignited manually; electrically operated solenoids activate the main combustion jet. The flow rates of jet gases are controlled by a flow meter. Pure metals, metal alloys, carbides, and certain ceramic and plastic powders can be fed into the high velocity gas jet in the coating gun nozzle. Torch-to-substrate distances are more flexible using HVOF thermal spraying than for other spray methods, such as plasma spraying.

Although a variety of coating materials can be sprayed using HVOF, the process typically involves the deposition of carbides, in particular, tungsten and chromium carbides. Developments in the area of noncarbide coatings shows that HVOF spray coatings have superior properties when compared with alternative spraying methods. HVOF spray coatings exhibited higher coating bond strength, lower oxide content, and improved wear resistance than corresponding plasma spray coatings. HVOF spraying also has a deposition efficiency of 75 percent (compared to 45 percent for plasma spraying), and because of fewer spraying parameters, coating reproducibility is increased.²⁵

Limited work has been done on developing coatings that can be HVOF-applied and used for cavitation resistance. Herman compared the cavitation resistance of two coating materials, aluminum-bronze and Hastelloy C-276, applied by both plasma spraying and by HVOF.²⁶ The weight loss versus time was measured using a modified version of the ASTM G32 vibratory cavitation test. The investigation found that after only 2 hours of testing, the plasma sprayed aluminum-bronze coating lost approximately 40 mg of mass, compared to the Jet Kote™ coating, which lost only 12 mg. The Hastelloy C-276 plasma sprayed coating lost approximately 24 mg of mass after 2 hours, compared to the Jet Kote™ coating, which lost only 12 mg.

The use of HVOF and plasma spray coatings may be limited for repair of cavitation damage because the methods do not yield thick (approximately 1/4 in.) coatings. These processes may have applications for certain aspects of cavitation damage repair.

Ceramic Coating Technologies

Ceramic coatings have been successfully used as bonding and coating materials. Porcelain enamels have received great attention for use as coating materials. Porcelain enamel coating technology is a method by which a thin glass coating is applied to a metal substrate. Although enamels often incorporate crystalline phases, they behave like amorphous materials.

²⁵ H. Herman, *Advanced Thermal Spray Techniques for Wear and Corrosion Protection* (Thermal Spray Laboratory, SUNY-Stony Brook, NY, 1989).

²⁶ H. Herman.

USACERL developed a porcelain enamel coating system for the repair of erosion and cavitation damage. It incorporates many oxides (Table 3) and results in a coating that has the composition given in Table 4. This coating system, given the name CERHAB, has advantages of both the enamel as well as fiber reinforcement. The fiber reinforcement used in CERHAB are wollastonite fibers which have the composition given in Table 5. CERHAB with the wollastonite fibers was shop-sprayed using a commercial coating system. Table 6 shows the processing parameters used.

Enamels are generally more complex than glasses and may contain up to 15 different materials. Most enamels are boro-silicate glasses containing alkali metals. Although enamels adhere better to contaminant-free surfaces, they can take surface oxides into solution at temperatures and rates that depend on the coating composition and surface condition. Enamels chemically bond to surfaces, as do epoxy compounds, which use silane coupling agents to form chemical bonds. In enamels, chemical bonding is achieved by forming oxide at the interface of a saturating metal, which controls the physical properties of the coating.

Researchers applied tungsten carbide/cobalt (WC/Co) coatings to stainless steel substrates for cavitation resistance.²⁷ These coatings exhibited high hardness and outstanding abrasion resistance. The WC/Co powder was air plasma-sprayed and the cavitation resistance of the coatings was measured using a modified version of the vibratory horn unit. The modification in the design of ASTM G32 was to use a static specimen placed 0.025 in. below the horn tip, rather than attaching the specimen directly to the horn.²⁸ The researchers found that the coatings did not exhibit an incubation period (the time association with plastic deformation) and that the surface finish had an effect on the extent of damage. The research showed that those coatings, which were diamond-ground, lost substantially less mass compared to the same as-sprayed coatings. They also found that cavitation resistance could be enhanced by reducing coating porosity and surface roughness and by increasing the grain size and metal content. Of the coatings tested, a cast-and-crushed material with the composition of WC-W₂C-12 weight percent Co, showed the best results.

Kreye and others²⁹ investigated 88 weight percent WC - 12 weight percent Co coatings that were applied to substrates by Jet Kote™. Using a wide range of spray parameters, they obtained coatings that had high density, high hardness, and high bond strengths.

Other ceramic powder compositions have been investigated for application by thermal spray. Chromium oxide ceramic coatings are characterized by their good abrasion, and erosion and cavitation resistance. Zirconia-based coatings that contain yttrium, magnesium, and calcium oxides have recently been investigated for plasma spray applications. Akhtar has investigated the cavitation resistance of plasma-sprayed coatings of aluminum, chromium, and aluminum/titanium oxides.³⁰ A major factor in the cavitation resistance of coatings is the resistance to nucleation and subsequent propagation of intercrystalline cracks. Many studies of the stabilized ZrO₂ coating systems have shown good cavitation resistance; however, the best resistance to cavitation damage results from the Y₂O₃ stabilized ZrO₂ system. Plasma sprayed coatings consist of thin lamellae with a very fine grain size. These layers bond together and stack up, allowing the coating to deform elastically under the oscillating stress field rather than fracturing. This mechanism gives rise to the exhibited good cavitation resistance.

²⁷ Xiao-Xi Guo, H. Herman, and S. Rangaswamy.

²⁸ H. Bhat, H. Herman, and M.F. Smith.

²⁹ H. Kreye, et al., "Microstructure and Bond Strength of WC-Co Coating Deposited by Hypersonic Flame Spraying (Jet Kote Process)," *Advances in Thermal Spraying*, Proceedings of the 11th International Thermal Spray Conference, Montreal, Canada (1986).

³⁰ A. Akhtar.

Table 3**CERHAB Enamel Batch Composition**

Material	Weight Percent
Custer Feldspar	24.13
Dehydrated Borax	19.41
Flint	25.76
Soda Ash	3.52
Soda Nitre	4.60
Fluorspar	10.58
Manganese Dioxide	3.31
Boric Acid	6.50
Cobalt Oxide	2.19
TOTAL	100.00

Table 4**Resulting CERHAB Enamel Composition**

Material	Weight Percent
SiO ₂	44.68
B ₂ O ₃	18.46
Na ₂ O	10.49
K ₂ O	4.40
CoO	2.21
CaF ₂	11.42
Al ₂ O ₃	4.77
MnO ₂	3.57
TOTAL	100.00

Table 5
Typical Composition of Wollastonite Fiber

Material	Weight Percent (typ.)	Weight Percent (theo.)
CaO	47.0	48.30
SiO ₂	50.0	51.70
Fe ₂ O ₃	1.0	
Al ₂ O ₃	1.0	
MnO	0.1	
MgO	0.3	
TiO ₂	0.05	
Moisture %	0.2	

Table 6
**Processing Parameters for the Application of
 CERHAB Reinforced With Wollastonite Fibers**

Coating Deposition System:	TeroDyn 3000
Powder Feed Unit:	5002
Nozzle Type:	RL 200
Spray Rate:	2 - 2.5 lb/hr
Back Pressure:	170 psi
Spray Distance:	5 in.
Oxygen Flow Rate:	50 psi/30 flow
Acetylene Flow Rate:	12 psi/50 flow
Carrier Gas Flow Rate:	55 psi/55 flow

4 TESTING PROCEDURES

An important element in determining the cavitation resistance of the reinforced epoxy, ceramic or thermal sprayed coating is the design of the laboratory tests. Although no test can completely duplicate conditions in the field, several tests have been designed in an attempt to simulate cavitating conditions.

Weight loss measurements have traditionally been used to compare the cavitation resistance of coatings. ASTM G32 has successfully been used to screen materials for cavitation resistance. It is based on the generation of cavitation bubbles that collapse on the face of a test specimen vibrating at high frequency in the test liquid under specified test conditions.

A study that compared various cavitation conditions was conducted to verify that a vortex generating unit produced cavitation conditions similar to that observed in hydraulic machinery.³¹ Specimens of indium and brass were subjected to different cavitation conditions in a Francis turbine model, a cavitation water tunnel, a vibratory cavitation device, and a vortex generating unit. In all cases, except for the vibratory cavitation device, the cavitation damage started with the formation of isolated hollows and craters in the specimens of similar morphologies and sizes, followed by collapse. In the vibratory cavitation unit, the damage was scattered uniformly over the specimen surface. It was found that material removal rates of specimens exposed to flow cavitation were higher than those exposed to vibratory cavitation.

Vibratory Methods

This method uses an ultrasonic transducer with an attached velocity transformer and provides a greater amplitude of vibration at the free end than at the driving end. A specimen button of known mass is attached to the tip of the horn. The apparatus produces axial oscillations on the test specimen partially immersed in the surface of the test liquid.

Vibratory Cavitation Testing of CERHAB

Generally, glassy materials used as a coating develop internal stresses during the cooling phase from liquid. These internal stresses, coupled with stresses due to differences in thermal expansion between the coating and substrate, cause the coating to fail due to fracture and disbonding. This is especially true on large surfaces. Annealing cycles may be necessary to relieve the stresses in the coating during the cooling stage. The CERHAB coating process would not be applicable in field situations where the substrates are large and annealing the coating would be difficult. The annealing procedure used in the shop test to produce the CERHAB coatings involved maintaining the coating at 1000 °F for 2 hours, and then cooling at a rate of 122 °F/hr until room temperature was reached.

The results of the shop-sprayed CERHAB coating were mixed. Cavitation resistance testing was performed using a vibratory cavitation unit. A commercially available reinforced epoxy was tested with formulations of CERHAB that had different weight percents of added fibers. Figures 7 through 9 contain the data of CERHAB with fiber additions of 5, 7, and 10 percent, respectively. The tests were also performed with a reinforced epoxy and CERHAB with no fiber added for baseline information. Figure 7 shows that after approximately 10 minutes of testing, the epoxy had lost more than 6 times the weight of either of the two CERHAB compositions. The CERHAB composition with no fiber reinforcing performed slightly better during the entire test. It appears that the added fracture toughness imparted to

³¹ A. Karimi and F. Avellan, "Comparison of Erosion Mechanisms in Different Types of Cavitation," *Wear*, Vol 113, No. 3 (1986).

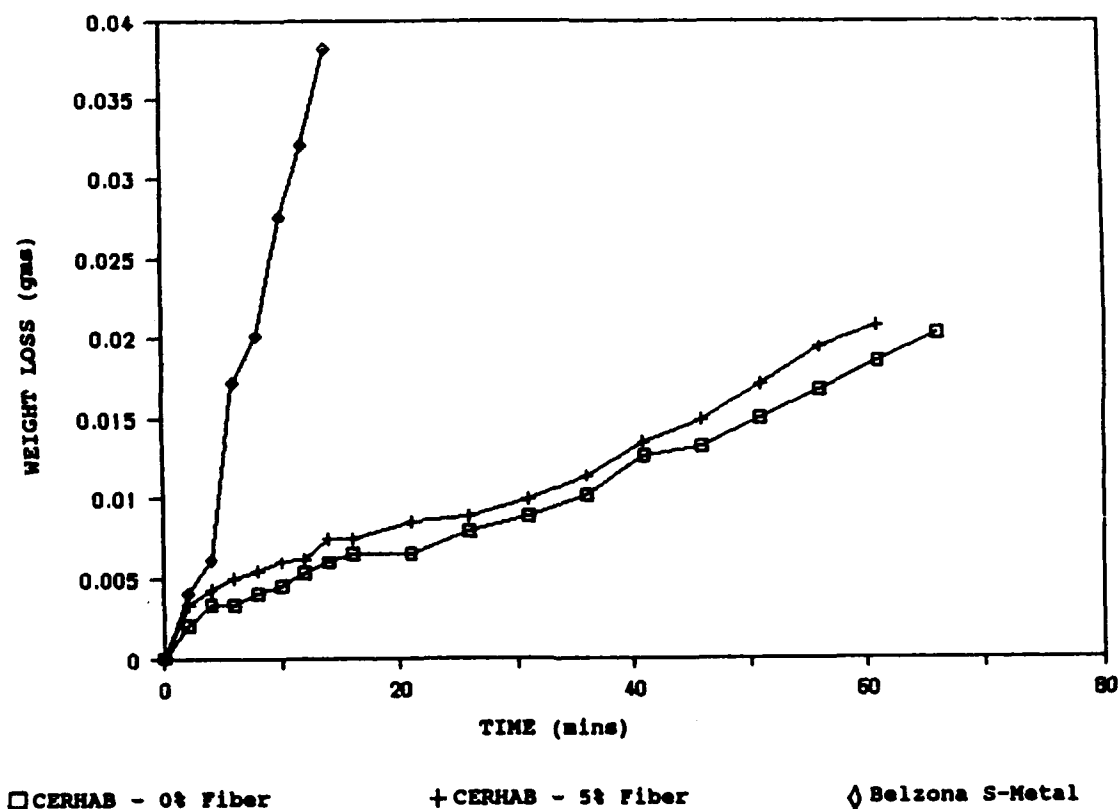


Figure 7. Vibratory Cavitation Test Results Comparing CERHAB With 0% and 5% Fiber to Epoxy.

the enamel by the fibers has little effect on the coating's cavitation resistance. Figures 8 and 9 show similar cavitation resistance behavior for the coatings. It is interesting that as the weight percent of the fiber reinforcement increases, the resistance to cavitation damage slightly decreases. It appears that there may be an optimum fiber weight percent to give maximum performance, as is true with many fiber reinforced coating systems.

Cavitating Jet System

The cavitating jet apparatus consists of a submerged jet that produces a cavitating stream, which is directed toward the specimen and impinges on it in a uniform and controlled manner. The cavitating jet system allows the selection of a wide range of specimen sizes and shapes, monitoring of cavitation noise generation, selection of a wide range of cavitation intensities, and the investigation of localized cavitation erosion.

The cavitating jet system, Figure 10, operated by the Tennessee Valley Authority's (TVA's) Engineering Laboratory consists of a cartridge-style filter, a three-plunger positive displacement pump rated for a flow of 3 gallons per minute (GPM) at 10,000 pounds per square inch (psi), and a 25 horsepower electric motor. The unit has a flow control valve, to set the operating flow and pressure, an unloading valve, to temporarily interrupt a test for specimen removal and weighing, and a bypass valve, as a safety backup and for pressure relief. Gauges monitor the inlet and discharge pressures during operation and record the accumulated operating hours for maintenance records. The test chamber is constructed of stainless steel, 18 in. x 18 in. x 18 in., and has windows for monitoring the specimens.

The nozzle contains an internal centerbody that produces a flow separation downstream. The low pressure associated with the high velocity jet produces a region of intense cavitation that can be directed toward the test specimen. Cavitation tests are calibrated with 308 stainless steel to verify consistency in the test results.

The TVA has conducted a limited number of tests on highly resistant materials at 10,000 and 6000 psi. A 4000 psi pressure was used as a standard for accelerated cavitation tests with base materials and weld overlays. It was found that soft coatings experienced mechanical damage, therefore they were subjected to a reduced pressure of 2000 psi. The test samples were located approximately 0.875 in. from the nozzle tip.

Multiple test results with the same material were geometrically averaged rather than arithmetically averaged because the logarithms of wear data generally have a Gaussian distribution. The cavitation rates were correlated with the wear rate for 308 stainless steel to give relative cavitation rates, as suggested by

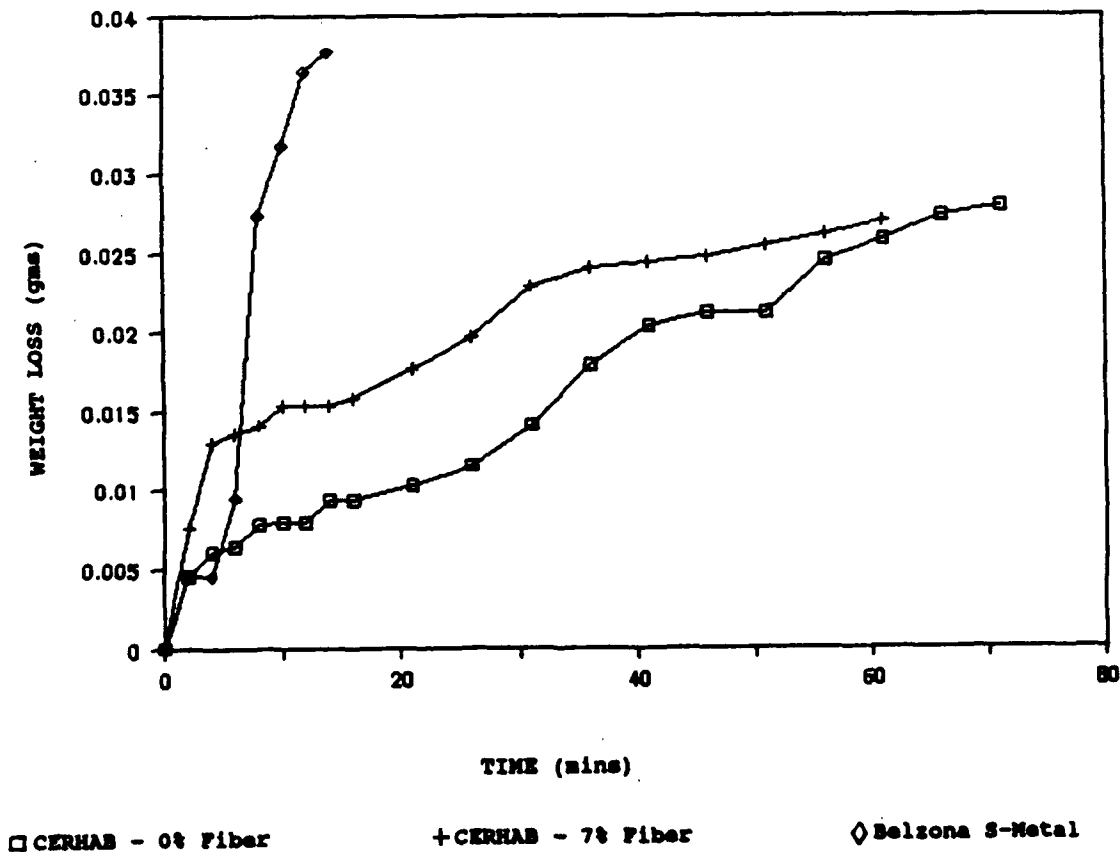
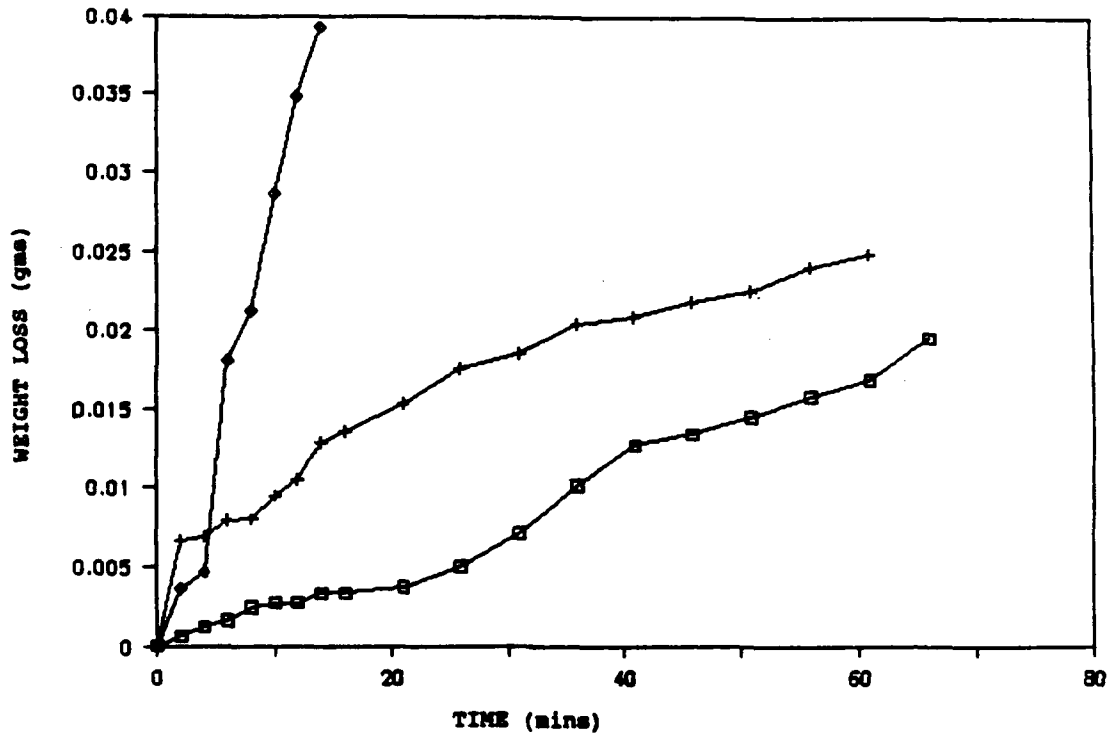


Figure 8. Vibratory Cavitation Test Results Comparing CERHAB With 0% and 7% Fiber to Epoxy.



□ CERHAB - 0% Fiber + CERHAB - 10% Fiber ◇ Belzona S-Metal

Figure 9. Vibratory Cavitation Test Results Comparing CERHAB With 0% and 10% Fiber to Epoxy.

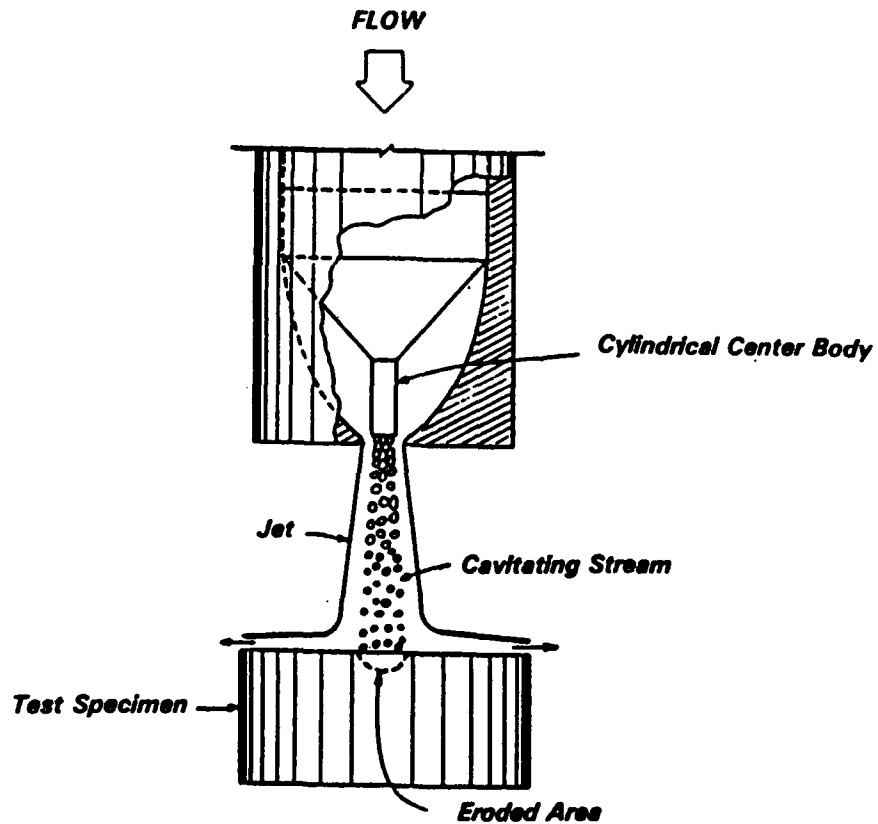


Figure 10. The Tennessee Valley Authority Cavitating Jet System.

Heymann.³² Results from the cavitating jet operated at 4000 psi were compared to the results for the same materials subjected to the vibratory cavitation test. Rank-order correlation coefficients were computed for the cavitating jet and the vibratory cavitation tests, and were in reasonable agreement with each other. This indicates that relative cavitation erosion rates may be considered as a material property. Table 7 contains the results for the less resistant coating materials tested at 2000 psi. Table 8 contains a summary of the results obtained for the cavitating jet system operating at 4000 psi. The columns titled "Erosion Rate" actually are rates of weight loss (erosion of the specimen) due to cavitation damage.

Table 9 lists the coatings systems that were tested at both 2000 and 4000 psi, and compares the effects of cavitation intensity. Certain coatings may perform well at low cavitation intensities while failing at slightly higher intensities. The table shows that the epoxies have a fairly low weight loss at 2000 psi. Doubling the pressure to 4000 psi increases the weight loss tenfold. One coating system actually performed better at 4000 psi than it did at the lower pressure. Tests were performed by the TVA at higher pressures on thermal spray and other weld coatings.³³

Table 7
Cavitation Rates for Tests at 2000 psi
as Determined by the Tennessee Valley Authority

Material*	Erosion Rate (mg/hr)	Comments
Belzona D&A Elastomer	----	surface punctured
Belzona EC over R-Metal	24	
Belzona R with S-Metal	5.6	
Devcon Pump Repair	13.9	
Belzona Ceramic EC	20.0	
Plasmadyne Stellite 21	45.6	
Techthane 80 SS	840	
Devcon 95800	555	
Devcon 95650	3540	
Devcon 95600	18.5	
Cr ₂ O ₃ flame spray	27.6	sudden surface failure
442 SS flame spray	40	
Metco 447	148	

* Coating materials described in Appendix D.

³² F.J. Heymann, "Conclusions From the ASTM Interlaboratory Test Program With Liquid Impact Erosion Facilities," *Proceedings of the 5th International Conference on Erosion by Solid Liquid Impact*, Cambridge, England (1979).

³³ P.A. March.

Table 8
Cavitation Rates for Tests at 4000 psi as
Determined by the Tennessee Valley Authority

Material*	Erosion Rate (mg/hr)	Relative Rate	Comments
316 SS	7.6	0.8	
304 SS	7.0	0.7	
308 SS weld	9.8	1.0	
347 SS weld	13.7	1.4	
Stellite 21	0.9	0.1	
Carbon Steel	15.9	1.6	
309 SS weld	9.1	0.9	
316 SS weld	13.4	1.4	
Al-Bronze weld	36.0	3.7	
Devcon WR2	792.0	80.8	
Belzona EC over R-Metal	274.0	28.0	
Devcon Pump Repair	190.0	19.4	
Hardco spray 110	660.0	67.3	
Plasmadyne Stellite 21	105.6	10.8	
Hardco Stellite 21	----	----	surface delamination
Techthane 80 SS	----	----	surface punctured
Stoody 2110 weld	3.2	0.3	
Eutectic 646XHD	7.1	0.7	
Eutectic Eutectrode 40	10.2	1.0	
Stoody-6	2.1	0.2	surface cracking
IREQ IRECA weld	0.2	0.02	

* Coating materials described in Appendix D.

Venturi-Flow System

The venturi-flow system, Figure 11, is capable of testing metallic coated as well as concrete specimens. The inlet pressure is controllable and directly affects the water velocity that flows through the throat. By adjusting the inlet pressure, a variety of cavitating environments may be simulated.

The venturi-flow system operated by the U.S. Bureau of Reclamation in Denver was used to test cavitation-resistant coatings. The inlet pressure was maintained at approximately 60 psi, producing a water velocity through the throat of approximately 70 ft/s. This generated a sustained, moderately cavitating environment. A criteria for coating failure was established and the test panels were inspected at regular

Table 9

Comparison of Cavitation Rates of Materials
at 2000 psi and 4000 psi

Material	Erosion Rate 2000 psi (mg/hr)	Erosion Rate 4000 psi (mg/hr)
Belzona EC over R-Metal	24	274.0
Plasmadyne Stellite 21	45.6	105.6
Techthane 80 SS	840	surface puncture
Devcon Pump Repair	13.9	190.0

intervals to determine the time to failure. Failure for the coated panels was defined as the time when 1 to 2 percent or more of the coating had been removed down to the substrate. When the criteria for failure is reached, the number of elapsed hours is recorded for each panel at that level of cavitation. An uncoated mild steel test panel was run as a control.

Two coating systems were tested in the venturi-flow testing unit. The first coating system consisted of a 1- to 2-mil thick bond coat with a composition of 20 percent-Al, 80 percent-NiAl. A second wire-fed flame spray metallized coating of 20 percent-Cr, 35 percent-Ni, 45 percent-Fe was applied with a thickness

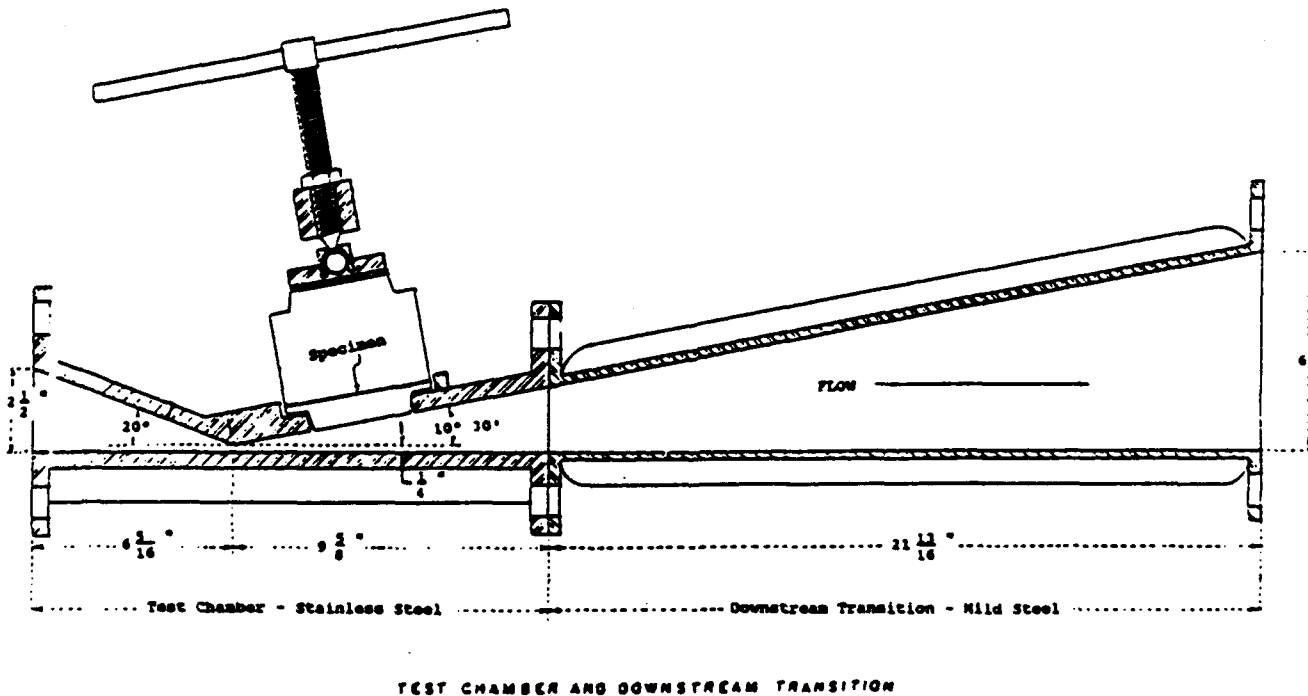


Figure 11. U.S. Bureau of Standards Venturi-Flow Cavitation Testing Unit.

of 38 mils. An elastomeric polyurethane topcoat was finally applied with a thickness of 5 to 10 mils. The second system tested consisted of a 24-mil thick powder-fed oxygen-propylene HVOF metallized coating with the composition 28.5 percent-Mo, 8.5 percent-Cr, and 57.0 percent-Co. It also was topcoated with an elastomeric polyurethane coating with a thickness of 5 to 10 mils. The polyurethane topcoats were applied by brush in both test coating systems. The ability of these coatings to protect substrates from cavitation is questionable. The topcoats were not properly chosen for the test because the urethane failed after only short exposure times.

An apparent shortcoming of this test apparatus is the placement of the test sample. The test sample will cavitate more violently in the area nearest the opening. Also because of the design, cavitation will probably affect the unit on the upstream side of the constriction. The flow will cause cavitation on both sides of the constriction. A better design would be to have the specimen located in the area of the flow constriction, giving a more even measurement of cavitation.

More testing must be done using this unit to establish a baseline of cavitation using a standard such as 308 stainless steel. Then the HVOF coating can be applied and the specimen can be tested for its relative cavitation resistance. Finally, the epoxy topcoat can be applied and the cavitation resistance measured. This would determine whether the additional epoxy topcoat adds any extra benefit to the HVOF coating by filling and smoothing the pits associated with metallized coatings.

5 FIELD REPAIR EXPERIENCES

An effective cavitation damage repair procedure should (1) restore the runner and other components within the turbine to an "as-new" condition, (2) correct profile conditions or irregularities that are responsible for the deterioration, and (3) avoid blade-shape distortion, which could initiate damage in the future. When it is practical and economically feasible, cavitation damage should be repaired soon after it is first identified. Waiting until excessive cavitation damage has occurred should be avoided. Excessive repairs to a turbine can lead to reduced performance and useful operating life. Cavitation damage, once initiated, will continue at an increasing rate due to the increasing number of bubble nucleation sites.

Several sites that currently use epoxy repair compounds and welding procedures were identified. Evaluation of these systems included cost comparison between competing methods of rehabilitation. The following are locations where evaluations have been performed.

Granite-Goose Project

The Granite-Goose Project of the Walla-Walla District, WA, consists of the Little Goose Lock and Dam, the Lower Granite Lock and Dam, and related facilities and systems. Each powerhouse at the two locations has six turbines (three Allis-Chalmers and three Baldwin-Lima Hamiltons) rated at 212,400 hp at 93 to 102 ft of head at Little Goose and 76 to 105 ft of head at Lower Granite. Each turbine passes approximately 22,000 cubic feet per second (CFS) of water while producing 155 megawatts (MW) of power.

Cavitation had been detected in 1981 at Lower Granite on one of the Allis Chalmers turbines. Cavitation seemed to be concentrated on the underside of each blade next to the hub and at a small area at the underside of the blade near the trailing edge. Cavitation also occurred diagonally on the discharge ring and appeared to be more concentrated at the areas under the wicket gates. The Baldwin-Lima Hamilton (BLH) turbines at each of the two dams are less prone to cavitation compared to the Allis Chalmers turbines, although they still cavitate and require repair.

The cavitation repair at the Little Goose powerhouse is generally accomplished using stainless steel welding methods. An alternate approach of repair has been used at the Lower Granite Dam. The process involved the use of reinforced epoxy compounds. Both repair procedures require steps that are common, such as unwatering the scroll case and placing scaffolding, lights, and ventilation fans in the area. When the repair is completed, the equipment is then removed and the scroll case is watered.

Preventative maintenance is performed annually on the turbines, and every 6 years a unit is completely overhauled. Cavitation repair is a major portion of the maintenance during the overhaul. A limited amount of time is allotted for the unit overhaul. The reinforced epoxy repair has been used successfully with the units operating satisfactorily with over 14,000 hours of run time.

For the basis of the cost comparison, those items common to both methods were not considered. Labor and material requirements for the welding repair of two units varied, therefore, an average of costs was calculated and used for the comparison. The cost of repair based upon the area of surface that was repaired for each of the two methods is shown in Appendix A. Costs for the weld repair of the Little Goose did not include the many hours of overtime expended. The total material and labor repair costs for using epoxy is approximately 6.5 times less than the costs for using a welding method. Since the welding and sacrificial coating repairs have different durabilities, the life cycle cost needs to be determined when the repair method is considered. The repair costs vary widely from site to site because the cavitation intensity damages the structures to different degrees. This affects the amount of repair needed to bring the structure to proper operating conditions.

Camino Powerhouse

Camino powerhouse unit No. 1 at the Sacramento Municipal Utility District (SMUD) is a BLH turbine with a rating of 100,000 hp at a head of 1000 ft. The test objective was to evaluate different materials and methods of coating the wicket gates for cavitation damage repair. The coating systems tested included both reinforced epoxy coatings and metallized coatings.

The SMUD disassembled the unit; 20 wicket gates were made available for testing. SMUD assigned five wicket gates per coating system for the evaluation of its ability to prevent the substrate from cavitation damage. After the coating systems were applied (Table 10) SMUD reassembled the turbine and the unit was put into service. The coating systems were inspected after 1102 hours and after 3016 hours of operation. The results (Table 11) show that most of the coating systems inadequately protected the gates.

It is estimated that the epoxies failed shortly after the unit was put into operation. All of the epoxy coatings and methods deteriorated to a point of offering little or no protection against cavitation except those on wicket gates #9 and #12. The five metallized wicket gates showed the most consistent protection of the coatings tested. It should be noted that each of the five metallized wicket gate flanges were below the level of the wear ring, thus being in an area of extreme cavitation.

Cordell Hull Lock and Dam

Cordell Hull powerhouse in the Nashville District is located on the Cumberland River and has an ultimate operating capacity of 100,000 kW. The powerhouse consists of three turbines. The cavitation damage is most prevalent under the leading edge of the blades, in against the hub, and on the discharge ring. The turbine maintenance cycle is 3 years. Standard repair at Cordell Hull consists of gouging, rebuilding with type 308 stainless steel, and grinding to original contour, each turbine blade or discharge ring. The Operations and Maintenance staff at Cordell Hull have had limited success using reinforced epoxy compounds for repair. Generally the epoxy is entirely stripped away from the blade or ring during the 3-year cycle, and cavitation initiates in the area adjacent to the repair area. Repair using welding methods at Cordell Hull involve two shifts of workers, each shift contains two welders and two grinders. Each shift operates for 10 hours per day, for 8 days. Labor is about \$22/hr for each person on the project, which results in costs of about \$14,000 annually.

Rocky Reach Point

A cost comparison between reinforced epoxy repair and conventional welding methods was conducted at the Rocky Reach Plant at the Chelan County Public Utility District, WA. The plant operates with a 90-ft head and is designed to operate at a specific wicket gate opening of approximately 96 percent. At this opening, laminar flow exists in the system and the units are designed to reduce the possibility of cavitation. Cavitation becomes a problem when a higher output is required. The operator opens the wicket gates, which lowers the efficiency of the plant while increasing the power output. Flow in the system changes from laminar to turbulent, resulting in extreme cavitation damage.

The cost figures in Appendix B were compiled by the Supervisor at the Chelan County Plant. Chelan County saved \$28,000 on this specific repair and had 5 weeks downtime. Repairs using epoxies appear to be cost effective when applied every year.

Table 10

Wicket Gate Coating Designations Assigned in
Sacramento Municipal Utility District Field Test

Wicket Gate #	Coating System*
1	Metco #405 Bond Coat/Nicro #40 Top Coat
2	Belzona R-Metal/EC Barrier
3	Metco #405 Bond Coat/Nicro #40 Top Coat
4	Palmer Duraquartz Primer, DP and DL
5	Palmer Duraquartz Primer, DP and DL
6	Belzona R-Metal/EC Barrier
7	Devcon #95600, FL10, FL20, #95350 and #15350
8	Devcon #95600, FL10, FL20, #95350 and #15350
9	Devcon #95600 and #95800
10	Metco #405 Bond/Nicro #40 Top Coats (sanded)
11	Metco #405 Bond/Nicro #40 Top Coats (sanded)
12	Devcon #95600 and #95800
13	Devcon #95600, FL10, FL20, and #15350
14	Palmer Duraquartz Primer, DP and DL
15	Palmer Duraquartz Primer, DP and DL
16	Belzona R-Metal, S-Metal, and EC Barrier
17	Belzona R-Metal/EC Barrier
18	Belzona R-Metal, S-Metal, and EC Barrier
19	Palmer Duraquartz Primer, DP and DL
20	Metco #405 Bond/Nicro #40 Top Coats (sanded)

* Coating system described in Appendix D.

Vicksburg District

The Vicksburg District made repairs to three pumps in 1977, 1978, and 1982. Original repair methods included using torch-applied metal powder; subsequent repairs were made with reinforced epoxy materials. In 1977, the undercut impeller bowls were filled with a stainless steel metal powder. Significant material expansion and shrinkage problems caused the material to lose adherence. As a result, the bowls were undercut approximately 3/8-in. deep and grooved to aid in adhesion. An aluminum bronze bond coat was torch applied and remained until 1978.

By the inspection in 1978, entire sections of the aluminum bronze material were eroded away. For repair, the impeller bowl was undercut approximately 1/2 in. deep and a liner of steel plate was installed and secured with stainless steel bolts. The complete liner was turned to original contours.

Table 11

Coating Conditions after Operation and Inspection on Assigned Gates in Sacramento Municipal Utility District Field Test

Wicket Gate #	Condition after 1102 hr	Condition after 3016 hr
1	Coating in good shape	Unable to inspect
2	Coating in good shape	Coating missing-fillets
3	Coating in good shape	Coating wearing-fillets
4	50 percent removed	Coating gone
5	75 percent removed	Coating gone
6	Leading edge chipped	Missing-lead edge
7	Completely off	Coating gone
8	Completely off	Coating gone
9	Coating in good shape	Coating intact
10	Coating in good shape	Wear in fillets
11	Coating in good shape	Wear in fillets
12	4-in. hole removed - center	Coating intact
13	Completely off	Coating gone
14	Completely off	Coating gone
15	Completely off	Coating gone
16	Gone in fillets	Coating missing-fillets
17	Coating in good shape	Coating gone - fillets
18	Coating in good shape	Gone in fillets and face
19	Completely off	Coating gone
20	Coating in good shape	High wear in fillets

* Coating system described in Appendix D

During the 1982 inspection, significant erosion and corrosion were found in two of the pump impeller bowls. The stainless material was in place in one of the pumps, while another pump had cracks in the aluminum bronze material and was about to spall out.

For repair, all three impeller bowls were coated with reinforced epoxy materials. The aluminum bronze material was completely removed from all of the bowls, and each bowl was blasted to provide a rough surface. Cleaner and degreaser were used to prepare all the surfaces. The two-part epoxy, which had a working life of 35 minutes at 41 °F, was applied to build up the surface to contour. The second part was then applied, but the short working life and difficulty working with the epoxy caused the bowl to be underfilled. High spots were ground by hand and the bowl was blasted to remove all of the surface glaze. Additional epoxy was used to fill void areas.

The second bowl was blast cleaned and coated with an epoxy that provided a relatively smooth coat and filled the eroded areas in the liner. Although the work was done in direct sunlight, the material performed well during application.

The third bowl was turned out to remove the aluminum bronze. An improved epoxy that is very machinable and easier to work with was used to fill the voids. The working life of this material was also 35 minutes at 41 °F and was worked into large areas with a spatula and smoothed out by hand. The high spots were ground down to with 0.005 in. when the impeller clearance was set.

The epoxy materials performed satisfactorily as sacrificial coating systems for the average 6-month to 1-year lifetimes.

6 CONCLUSIONS AND RECOMMENDATIONS

Conclusions

1. Reinforced epoxies have been used for cavitation damage repair in the Army Corps of Engineers. The performance of these repair compounds is sensitive to surface preparation and method of application.
2. Repair by reinforced epoxies can be accomplished rapidly without significant downtime and lasts anywhere from 6 months to 1 year.
3. Industry has developed many types of metallized coatings which can be applied by thermal spray technology. Some of these coatings have potential for application for cavitation repair.
4. Some of these emerging metallized coating systems have been tested in the laboratory at the United States Bureau of Reclamation in Denver and in hydroelectric projects at Chelan County with good results.
5. New emerging ceramic coatings, such as fiber reinforced ceramic matrix composites (CERHAB), tungsten carbide cobalt, and yttria or magnesia stabilized zirconia have improved cavitation resistance properties. However, their application is limited by current thermal spray (flame spray, plasma spray, and HVOF) technology which is rapidly progressing.

Recommendations

1. Reinforced epoxies should be used only when cavitation is such that the repair will be expected to last approximately 6 months to 1 year. Periodic recoating will, therefore, be necessary and needs to be planned for.
2. Metallized coatings such as nickel-aluminum based coatings and others developed by industry have shown potential for application in the laboratory and in field tests at Chelan County and should be tested in Corps projects where cavitation is mild.
3. Emerging ceramic coatings with superior cavitation resistance should be identified and tested in the laboratory using thermal spray technologies.

METRIC CONVERSION TABLE

1 cu ft	=	0.028 m ³
1 gal	=	3.78L
1 in.	=	25.4 mm
1 lb	=	0.453 kg
1 oz	=	28.3 g
1 psi	=	178.6 g/cm
1 watt	=	0.014 kg-cal/min
1 sq ft	=	0.093m ²
°C	=	0.55 (°F-32)

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APPENDIX A: Summary Cost Comparison for Repair Using Reinforced Epoxies and Welding Methods at Granite-Goose Hydroelectric Project

Epoxy Repair Method

\$77.00/sq ft. of repaired area

Materials: Epoxy materials, sandblasting abrasives, grit, sandblaster, electric blankets, cleaners, degreasers, acetone, and miscellaneous items.

\$58.00 per sq ft.

Labor: Crew foreman, mechanic, crane operator, rigger, painter and trainee.

\$19.00 per sq ft.

Welding Repair Methods (average costs)

\$499.00/sq ft. of repaired area

Materials: 304L stainless steel plate (3/16-in. thick), grinding stones, helium/carbon dioxide/argon gas bottles, 308L stainless steel weld wires, carbon arc rods, respirators, MIG welder rental, carbon air arc welder, grinder, and miscellaneous items.

\$115.00 per sq ft.

Labor: Crew foreman, utilitymen, and mechanics.

\$384.00 per sq ft.

APPENDIX B: Summary Cost Comparison for Repair Using Reinforced Epoxies and Welding Methods at Rocky Reach Hydroelectric Plant

Epoxy Repair Method

\$40,707.00 total repair

Materials: Epoxy material, blasting sand, cleaner, degreaser, air arc rod, and 308 stainless steel wire.

\$13,006.00

Labor: 75percent surface preparation, 25 percent application of materials.

\$31,647.00

Welding Repair Methods (average costs)

\$72,914.00 total repair

Materials: Stainless steel rod (Type 308/316), grinding wheels, carbon air arc materials, welding materials, and grinding materials.

\$9400.00

after welding and (Note: Approximately 20 percent of the welding rod is left on the repaired surface grinding takes place).

Labor: Regular Time: 3952 hours, overtime: 600 hours

\$63,500.00

33 percent on (Note: Labor breakdown: 33 percent on air arc preparation, 33 percent on welding, and grinding).

APPENDIX C: Detailed Testing Procedures

The evaluated synthetic metal repair compounds listed in Table 1 were provided in standard packages as two-component mixtures. The materials are prepared for application by mixing a known volume or weight of component "A" (resin and filler) with component "B" (hardener) in a specified ratio. Mixing times and procedures are recommended by the supplier. Samples were prepared by mixing on a weight ratio basis per manufacturer's instructions.

Density. ASTM Procedure D792-66, Method A-1 was followed to determine the density and specific gravity of the synthetic metal compounds. Samples were prepared by casting the synthetic metal compounds into 0.5 x 0.5 x 0.5-in. cubes. Specimens were allowed to cure 24 hours at room temperature ($23^{\circ} \pm 2^{\circ}\text{C}$) before demolding and testing.

Compressive Strength. ASTM Procedure D695-80 was used as a basis to determine the compressive strength of the synthetic metal compounds. Test specimens were molded into 0.5 x 0.5 x 0.5-in. cubes, and allowed to cure 24 hours at room temperature ($23^{\circ} \pm 2^{\circ}\text{C}$) before demolding and testing in compression. At least three specimens per material were tested at a constant crosshead rate of 0.050-in./min.

Flexural Strength. ASTM Procedure D790-81, Method I was used to determine the flexural properties of the synthetic metal compounds. A specimen geometry of 0.625 x 0.625 x 8.0-in. was obtained by molding. Specimens were allowed to cure 24 hours at room temperature ($23^{\circ} \pm 2^{\circ}\text{C}$) before demolding and testing. At least three bars per synthetic metal compound were tested in flexure. Using a support span-to-depth ratio of 9.6 to 1, the specimens were loaded to failure at a constant crosshead rate of 0.050-in./min.

Tensile-Shear Strength. ASTM Procedure D1002-72 was followed to determine the comparative shear strengths of the synthetic metal compounds in bonding to a carbon steel surface. Test joints were prepared from 3.0 x 1.0 x 0.058-in. panels that had been degreased and grit blasted (with Al_2O_3 beads) to white metal. The synthetic metal compounds were prepared according to manufacturer's instructions, spread thinly (approximately 0.005-in. thick) over the prepared end of a metal panel, and then sandwiched with another panel to produce a lap joint with a nominal overlap of 0.50-in. Five test specimens were prepared for each compound. The specimens were clamped and allowed to cure for 24 hours at room temperature ($23^{\circ} \pm 2^{\circ}\text{C}$) before testing. The adhesive joints were tested in tensile until failure at a constant crosshead rate of 0.050-in./min.

Tensile Strength. ASTM Procedure D638-82a was used to determine the tensile properties of the synthetic metal compounds under evaluation. Samples were molded into 4-in. long bars with a square cross-section of 0.625 in. After complete curing at room temperature ($23^{\circ} \pm 2^{\circ}\text{C}$), tensile specimens were prepared by grinding the molded bars into a dumbbell-shaped geometry with the width at the center of the specimen equal to 0.325 in. At least three specimens per compound were tested under tensile loading with a constant crosshead rate of 0.050-in./min.

Hardness, Shore D. ASTM Procedure D2240-81 was followed to determine the Shore D hardness of the synthetic metal compounds. The hardness values were taken from molded test specimens fully cured at room temperature ($23^{\circ} \pm 2^{\circ}\text{C}$). Six measurements were taken on each of three different test specimens.

Working Time. The synthetic metal compounds were mixed in batches of 100 grams according to manufacturers specifications. Determination of working time began on initiation of mixing, and were halted when the material's viscosity increased to a point where placement was difficult. All samples were tested at room temperature ($23^{\circ} \pm 2^{\circ}\text{C}$).

Cure Shrinkage. ASTM Procedure D2566-79 was used to determine the linear cure shrinkage of the synthetic metal repair compounds. The synthetic metal compounds were mixed according to manufacturers instructions and were cast into 1.0 x 1.0 x 1.0-in. molds. Dimensional changes were determined after curing 24 hours at room temperature ($23^{\circ} \pm 2^{\circ}\text{C}$).

Coefficient of Linear Thermal Expansion. Estimates of the linear thermal expansion coefficients for the synthetic metal compounds were determined over a temperature range 0° to 80°C . Specimens were prepared by molding the synthetic metals into 1 x 1 x 1-in. cubes. All samples were allowed to cure 24 hours at room temperature ($23^{\circ} \pm 2^{\circ}\text{C}$) before demolding and testing. The linear dimensions of each test specimen were determined to an accuracy of 0.001 in. at room temperature, and after immersion for 48 hrs at 0°C and 80°C in a temperature-controlled water bath accurate to $\pm 1^{\circ}\text{C}$.

Working Properties. The sag resistance and application properties of the synthetic metal repair compounds were determined qualitatively on application to a vertical metallic substrate. The synthetic metal compounds were mixed according to manufacturers instructions and were immediately applied to a degreased and grit-blasted carbon steel panel at room temperature ($23^{\circ} \pm 2^{\circ}\text{C}$). The panels had two machined grooves, 0.250-in. wide x 0.125-in. deep x 2.0-in. long at right angles representing both horizontal and vertical cavities.

APPENDIX D: Product Literature

Belzona Molecular
2000-T N.W. 88 Court
Miami, FL 33172
305/594-4994

Ceramic R Metal - Designed as a paste grade material with outstanding nonslump characteristics. It can be used to rebuild deeply damaged and eroded equipment and is excellent for use in overhead and vertical applications.

Ceramic S Metal - The fluid grade counterpart to Ceramic R Metal designed for resurfacing and coating. Ceramic S Metal is also an excellent choice where injecting or pouring of a material is required to accomplish the application.

Ceramic EC Barrier - A resurfacing material similar to Ceramic S Metal that offers several outstanding advantages in certain applications. It provides excellent protection against cavitation damage. Where coating weight is a factor, Ceramic EC Barrier is one of the lightest materials of its kind available. This product solidifies to a smooth finish aiding fluid dynamics. Ceramic EC Barrier is fully compatible with high voltage spark testing procedures, aiding maintenance engineers to establish coating integrity prior to service.

D & A Elastomers:

HI-BUILD ELASTOMER - Durable and abrasion-resistant elastomer for repair and protection of equipment operating in severe wear areas. Applied by spatula in thick sections without slump on vertical or overhead surfaces.

HI-COAT - Designed for application by brush to provide an abrasion-, chemical- or cavitation-resistant protective coating.

FLUID ELASTOMER - Easily and simply poured to produce fault-free moulding and castings.

DEVCON
30 Endicott St.
Danvers, MA 01923
508/777-1100

95800 Online Corrosion Resistant II Resin (95850) - Filled epoxy resin.

95650 Brushable Ceramic (11760-red, 11765-blue, 11770-white) - A high performance, high density, ceramic-filled brushable epoxy to seal and protect new or repaired surfaces from cavitation, erosion, and wear. Ideal for rebuilding worn areas less than 1/16 in. deep.

95600 Ceramic Repair (11700, Pump Repair Compound) - A high performance, nonsagging epoxy designed for pump repair. The ceramic filled epoxy protects against extreme wear, abrasion, and turbulence, and also has excellent chemical resistance. Pump Repair Compound is used for repairing, rebuilding, and protecting of water service, slurry, and centrifugal and ash pumps.

15350 Flexane High Performance Brushable Resin - This is the resin component of a liquid abrasion-resistant polyurethane elastomer kit. It is a solution of isocyanate-terminated polyethers. After curing, the product is a nonhazardous solid.

Flexane High Performance Brushable Curing Agent - This is the hardener component of the two-part kit. It is a polyamine solution that forms a nonhazardous solid after curing.

FL-10 Flexane FL-10 Primer (15980) - Vinyl resin solution. When applied to metals, rubber, wood, fiberglass, and previously-applied Flexane, FL-10 improves the adhesion of other Flexane products to the substrate.

FL-20 Flexane FL-20 Primer (15985) - Polyurethane solution. When applied to metals, rubber, wood, fiberglass, and previously-applied Flexane, FL-20 improves the adhesion of other Flexane products to the substrate.

Wear Resistant Putty (WR2) A ceramic-filled epoxy putty that results in repairs with a smooth, low-friction finish. It can be used to rebuild and protect interfacing metal surfaces such as machine ways and flanges that are subjected to wear, and it protects metal from bimetallic corrosion. It can also be used to repair some plastics.

Eutectic Corp.
40-40 172nd Street
Flushing, NY 11358-9981
718/358-4000

Xuper 646 XHF - Xuper 646 XHD is a high alloy electrode that produces deposits with excellent strength combined with a high degree of toughness. This produces crack-resistant weldments capable of withstanding high impact. These unusual properties give Xuper 646 XHD the versatility to serve as a joining electrode, an electrode for wear protection applications, and as a cushion before applying another protection alloy. Spray transfer provides exceptionally good weldability.

Eutectrode 40 - An all-position electrode used as a base or padding for deposits where severe impact and compressive forces are continually encountered. It provides sound, high-strength buildups, not subject to spalling or over roll. Also used for joining manganese steel. The balanced chemistry produces a quiet, stable arc with very little spatter.

Imperial Clevite
419/499-2541

WC-204 - A 70 percent tungsten carbide with the remaining balance composed of nickel, chromium, silicon, and boron powder. The coating offers excellent protection in most acidic environments with moderate abrasion resistance.

METCO INC.
1101 Prospect Ave.
Westbury, LI, NY
516/334-1300

METCO 405 - A nickel-aluminide (Ni₃Al) wire especially developed to be a better self-bonding material than molybdenum wire, particularly with regard to bond strength. In addition, it has many applications as a single coat system where dense coatings, resistant to oxidation, high temperatures, and temperature changes are required.

METCO 447 - A molybdenum-nickel-aluminum composite powder, especially developed as a general purpose material for producing medium-hard coatings for hard bearing and wear resistance applications. This material offers two major advantages: one-step spraying and high integrity coatings. METCO 447 was designed to produce moderately hard, low-shrinkage, high-strength coatings that are recommended for wear resistance, resistance to particle erosion, and for the salvage and buildup of both machinable and grindable carbon steels. METCO 447 coatings are extremely tough, exhibit good erosion resistance, and can withstand impact without cracking.

Palmer/Enecon
3280 Sunrise Highway, Suite 144
Wantagh, NY 11793-4024
215/574-3214

DURAQUARTZ PRIMER - Primer material for DuraTough DP and DL.

DuraTough DP - Polymer matrix remetalizer compound for the repair, rebuilding, and resurfacing of all types of machinery and components damaged by wear, erosion, corrosion, fluid flow, cavitation, and impingement. Formulated as a blue paste.

DuraTough DL - Polymer matrix remetalizer compound for the repair, rebuilding, and resurfacing of all types of machinery and components damaged by wear, erosion, corrosion, fluid flow, cavitation, and impingement. Formulated as either a green or blue liquid.

Stoody
PO Box 1901
Industry, CA 91749
818/968-0710

Stellite 21 - A low carbon, molybdenum strengthened, cobalt-chromium alloy. Its excellent high temperature strength and stability are responsible for its use as a hot die material, while its inherent resistance to galling (under self-mated conditions), cavitation erosion, and corrosion have made it a popular fluid valve seat facing alloy.

Stoody 6 - (Stellite 6) The most commonly used cobalt alloy, having excellent resistance to many forms of mechanical and chemical degradation over a wide temperature range. Particular attributes are its outstanding self-mated, antigalling properties, high temperature hardness, and a high resistance to cavitation erosion, which results in its wide use as a valve seat material. The alloy is ideally suited to a variety of hardfacing processes. It is machinable with carbide tools and bonds well with weldable alloy steels, including stainless.

Stoody 2110 - A solid core, extruded electrode with alloys in the coating designed for buildup of austenitic manganese steel parts subject to high impact loading without limitations to deposit thickness. It is a modified high chromium, high manganese, steel that combines toughness and wear resistance.

Stoody 110 - A modified high chromium, high manganese, steel widely used in the rebuilding of manganese steel parts subject to severe impact loading. This material offers excellent cavitation resistance, good toughness and wear resistance. It is sometimes used as a final hardfacing layer in extreme impact situations.

Technical Urethane, Inc.

PO Box 61
Clearbrook, VA 22624

703/667-1770

TECHTHANE-80 SS - A two-component, polyether type urethane system designed for spray application using two-component airless spray equipment. TECHTHANE-80 SS becomes tack-free minutes after spraying, has high early strength, and cures at ambient temperatures to a urethane elastomer that has high physical properties and outstanding resistance to abrasion from small particles. Because of its chemical composition, it also has high resistance to oils, fatty acids, and most floatation reagents. The fast set time of TECHTHANE-80 SS permits quick coating buildup to a thickness of 1/4 in. or greater. With proper surface preparation and primers, most surfaces can be coated with TECHTHANE-80 SS.

Wear Control Technology

317/456-6905

Nylon II - A thermoplastic polymer alloy that can be applied via thermal spray using acetylene, propane, or propylene as the fuel gas, and argon, nitrogen, or air as the powder carrier gas. The coating exhibits excellent chemical resistance, and frictional characteristics. In addition, it has good impact resistance, and thermal properties. Typical industrial applications include: sealer for cold process coatings, and top coat for corrosion control coatings.

Thermotec 18949 - A prealloyed, multicomponent, cobalt-based alloy that can be applied using conventional plasma or high energy thermal spray systems. Since it will undergo an exothermic reaction during application, the coating will achieve higher bond strengths on most conventional metal substrates. This coating material has been designed for resistance to high temperature oxidation, erosion, corrosion, and slag attack.

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