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CENTRIFUGAL SLURRY PUMP WEAR AND HYDRAULIC
STUDIES

Phase I Report: Pilot-Plant Experience and
Literature Search

October 1983
Date Published

Work Performed Under Contract No. AC22-82PC50035

Ingersoll-Rand Research, Inc.
Princeton, New Jersey

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CENTRIFUGAL SLURRY PUMP
WEAR AND HYDRAULIC STUDIES
PHASE I REPORT
PILOT-PLANT EXPERIENCE AND
LITERATURE SEARCH

Ingersoll-Rand Research, Inc.
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Date Published: October 1983

PREPARED FOR THE UNITED STATES
DEPARTMENT OF ENERGY

Under Contract Number DE-AC-82PC50035

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ABSTRACT

This report describes the work performed by Ingersoll-Rand Research, Inc. under Phase I, Pilot-Plant Experience and Literature Search for the contract entitled, "Centrifugal Slurry Pump Wear and Hydraulic Studies". This work was carried out for the U.S. Department of Energy under Contract No. DE-AC-82PC50035.

The pilot plants' operating experience on centrifugal slurry pumps was gathered from SRC-1, H-Coal, and EDS coal liquefaction plants. The details on these findings are presented in this report.

Hydraulic design, material selections, and slurry characteristics are some of the key areas which affect wear in centrifugal pumps. The effect of various design and operating parameters on pump wear at different locations is discussed.

Material properties as they affect wear, the slurry wear process, test methods, and key results are also presented.

CONCLUSIONS AND RECOMMENDATIONS

The Phase I "Pilot-Plant Experience and Literature Search" is complete and the following main conclusions and recommendations are made:

1. Successful commercial pumps in the pilot plants are generally designed for very low specific speeds--typically as low as 400. The pump for the commercial liquefaction plant based on this design approach will be very large in size and economically unattractive. Therefore, it is recommended that experimental and analytical studies be carried out to select optimum specific speed.
2. The internal components of the pump are generally made of fully hardened high-chrome steel (HC-250). This material is susceptible to thermal stress cracking during start-up and shutdown. Annealing pump components made from this material has significantly improved the thermal shock resistance. It is recommended that fully hardened HC-250 pumps be used only with slow start-up and shutdown. Further, it is recommended that thermal shock tests be carried out on promising materials to establish their limiting heating and cooling rates.

3. Erosive wear is the dominant factor for the life of pump internal components. Corrosive wear appears to be insignificant. The volute cutwater area shows highly accelerated wear and high loss of material. It is recommended that experimental studies be carried out to evaluate various promising materials for erosive wear prior to selecting material for the prototype pump. Also, hard insert materials should be considered for the cutwater area to improve the pump life.
4. Limited published information was found on the design and application of centrifugal slurry pumps to the typically viscous coal liquefaction slurries. However, considerable information exists on water-base slurry applications. Design suggestions and comments were obtained from coal liquefaction pilot-plant engineers. It is recommended that in order to design an improved prototype pump, baseline information be generated to understand the effect of various design and operating parameters and their relationship to wear in the pump.

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1.0 OBJECTIVES AND SCOPE OF WORK

The overall objective of the Centrifugal Slurry Pump Wear and Hydraulic Studies Program is to provide a technical data base on material wear and hydraulics for centrifugal pumps in coal liquefaction plant services. The development program is composed of three phases.

The objectives of Phase I, Pilot-Plant Experience and Literature Search, are (1) to visit pilot plants and report their experience and (2) to summarize wear correlation and the effect of hydraulic parameters on wear patterns.

The objective of Phase II, Experimental Studies, is to perform laboratory erosion tests for selected materials and hydraulic designs. The materials tests will determine the effect of various parameters such as slurry type, particle characteristics, and temperature. Tests will also determine the nature of erosion and the role played by corrosion. The hydraulic tests will be conducted in order to study the effect of various design and operating parameters such as impeller vane shape, number of vanes, pump-out vanes, and specific speed. Test facilities will be developed as required. The data generated during this phase will be analyzed and used to improve the centrifugal pump design for coal liquefaction services.

Phase III, Prototype Pump for Pilot-Plant Evaluation, consists of the detailed design of an ideal pump based on the information obtained in Phase II. Two pumps will be fabricated and tested in the laboratory followed by field evaluation at a DOE designated pilot plant. Technical support in related areas will be provided during this phase.

2.0 SUMMARY OF PROGRESS

This report documents the work performed under Phase I, Pilot-Plant Experience and Literature Search for the program entitled, "Centrifugal Slurry Pump Wear and Hydraulic Studies".

The literature search was initially carried out in the area of slurry pump flow, wear, material, etc. Simultaneously, visits were made to H-Coal and SRC-1 coal liquefaction pilot plants and information was gathered on experience in operating the centrifugal slurry pumps. Considerable information was also gathered from the EDS pilot plant. Based on this, the state-of-the-art centrifugal slurry pump features were identified. The detailed pump specifications, construction materials, the pump's locations in plant, and related comments were summarized and documented.

The key factor affecting pump life is the internal wear caused by the slurry. Hydraulic design, material properties, and slurry type are the most important parameters controlling the wear. The various locations where wear is generally seen in these pumps were identified. The factors affecting this wear were examined and ways of predicting pump life were studied.

The literature search in materials area concentrated on how material properties such as composition, structure, and hardness affect wear in slurry applications. The slurry wear process, various wear test methods, and

key results were studied. Additional information can be obtained from references cited in the text. Other useful references were also included in the report for completeness.

3.0 DETAILED DESCRIPTION OF TECHNICAL PROGRESS

3.1 STATE-OF-THE-ART SLURRY PUMP

A cross section of a typical coal liquefaction slurry pump is shown in Figure 1. Item 1 in the figure is the suction liner. Fluid enters the pump through the center of this liner and flows into the impeller. The eye size and maximum diameter of the blade leading edge (Item 2) follows from a choice of inlet blade angles which match the incoming flow. Very often, however, the design point flow rate is higher than the actual in-service flow rate. Some of the fluid emerging at the impeller outer diameter escapes radially inward past the front shroud and through the leakage space (Item 4) and rejoins the incoming flow to the impeller. The tangential velocities of the fluid can be quite high at the O. D. of this close clearance leakage space. Pump-out vanes (Item 3) are often employed to prevent the leaking fluid from rotating any faster than the impeller and to reduce the pressure at the inner radii of the leakage path, thereby reducing the leakage rate. Pump-out vanes, in that case, must also be used on the back side of the impeller (Item 3a) in order to balance the axial thrust on the impeller. They also serve to reduce the pressure imposed on shaft seal. The main body of the fluid flows radially outward from the impeller through the clearance space (Item 5) and then through the cutwater (Item 6). The fluid velocity is

FIGURE 1: TYPICAL COAL LIQUEFACTION SLURRY PUMP

mainly tangential in direction. The magnitude of this velocity varies approximately inversely with radius, beginning at a value of 50% to 70% of the impeller outside diameter tip speed at the impeller exit. The cutwater (Item 6) is cast integrally with the volute liner (Item 7) which can also include part of the front wall (Item 8). The back liner (Item 9) shown here integrally with the volute liner is often a separate piece. The impeller blading (Item 10) is commonly designed to produce a separated flow in a traditional slurry pump design. In general, this is accomplished by designing vanes that have approximately the same shape as those used in a conventional clear water pump except that they have about twice the thickness of clear water pump vanes. Flow separation is produced by the fact that the shrouds on both sides of the vane passage are parallel rather than converging as in the conventional clear water design. The result is a flow passage that increases greatly in cross-sectional area. This produces one-dimensionally a very low relative velocity at the impeller exit. Such a velocity probably does not occur because blade loading calculations indicate large zones of reversed flow within the passages to the extent that this kind of flow geometry is necessary for successful functioning of a slurry pump. It would appear that the separation of the flow causes the solid layers that would otherwise be forming

on the pressure sides of the blades to be well mixed with the consequently churning flow in the passages. It could be further reasoned that the absence of such separation and therefore churning could allow a layer of solids to build up on the pressure side of the blade which would abrade that pressure side of the blade especially near the trailing edge where the layer would be thickest.

The absence of separation in a slurry pump could also lead to a greater drop in pump head with increasing solids and concentration. In this case, the layer of solids building up on the pressure side of the passage could effectively block the relative flow area that is needed for the pump to maintain head. Not only would such blockage not occur in a separated flow if the solids were well-mixed, it would be of little consequence to the performance of an already oversized passage.

All of these findings are qualitative and would require accurate experimental verification. It should be noted that the shaft does not come through the hub of the impeller, thereby avoiding troublesome wear patterns that develop at joints and other surface discontinuities. With the large clearance between the cutwater and the impeller, it is not necessary for a double volute to be employed for the purpose of limiting radial thrust on the impeller.

3.2 PILOT-PLANT EXPERIENCE

3.2.1 GENERAL DISCUSSION

Considerable experience has been gained in the operation of centrifugal slurry pumps in coal liquefaction pilot plants. It is the purpose of this work to identify the significant factors with regard to centrifugal slurry pump life and performance in coal liquefaction plant service. In general, there are two types of slurries that are encountered by centrifugal pumps in these plants. The first is what might be called the front end slurry, which is a mixture of 40% by weight of coal with oil recycled from the process. The second is what might be called the back-end or bottoms slurry, the solids of which are reacted coal which is mainly in the form of ash at about 20% by weight. Front end slurry temperatures range from about 250⁰ to 450⁰F and the bottoms slurry temperatures range from 500⁰ to 700⁰F. Viscosity of the front end slurry is from 40 to as high as 300 centipoise and the back end slurry has a viscosity ranging from 800 to 3000 centipoise. If it were not for this latter fact, it would be expected that the bottoms slurry would produce more wear in a centrifugal slurry pump because of the high abrasivity of the ash, and even though the coal in the front end slurry is less abrasive, there is more of it and the viscosity of the slurry is lower; so, it is not obvious

which of these two slurries produce the most wear.

Implicit in this statement is the idea that substantial wear would occur if particles were able to cross streamlines easily, thereby allowing more of them to abrade the surfaces of the pump. Actually, the wear process is a complex interaction of many phenomena. Basically, material is removed by solid particles either by impinging on the surface and/or scrubbing it. For this to happen, the solid particle properties such as hardness, size, sharpness, and density are important and also the flow properties such as temperature, local velocity, local solids concentration, and particle impingement angle coupled with density and slurry viscosity. Next, the materials of construction of the pump are involved by way of their composition, structure, hardness, and corrosion resistance. Finally, the hydraulic properties of the pump design itself are involved through the passage shapes, velocity levels and distributions, and the head derived from these distributions as well as the pump speed and size. For a given design, the wear rate is generally assumed to vary as the second to third power of the velocity. For a given pump geometry or specific speed, all the velocities may be related by unique factors to the impeller O.D. tip speed. This, in turn, is directly connected with the head of the pump. Thus, the tip

speed or the head is a figure of merit for determining how long the pump will last under a given slurry pumping condition. The head is proportional to the square of the tip speed.

Different areas of the pump will experience more or less damage depending on the geometry of the pump mainly as expressed by the specific speed. Specific speed is defined as the product of the pump speed in rpm and the square root of the flow rate in gpm divided by the $3/4$ -power of the head in feet. For a given head and flow rate, the choice of speed determines the specific speed. Its influence is seen by the following explanation: Since the flow rate is fixed, the pump impeller will have roughly the same inlet eye size regardless of the speed that is chosen. The given head requires a fixed O.D. tip speed so that a high speed leads to a small impeller O.D. and a low speed to a large O.D. In the latter case, the impeller eye diameter is a smaller fraction of the O.D. than it is in the former case. The tip speed of the blades in the impeller eye is therefore lower in the case of the large slow-speed impeller since blade tip speed varies directly with diameter. The large pump is the lower specific speed one, and in view of its lower blade inlet tip speed, it should experience less wear in the blade inlet region. The question is: How large does the pump have to be and therefore how low does its speed and

specific speed have to be in order for the wear rate in this particular region to be acceptable? From this example, we are led to inquire as to what are the high velocity areas in the pump that should receive attention in the design stage. Two other factors, beside the blade inlet tip speed just mentioned, are of prime importance. First, the fluid velocity at the cutwater can be as high as 50% of the impeller O.D. tip speed or more. Second, assuming the use of closed impellers, the fluid that leaks past the front ring of the impeller back to the eye acquires a high velocity because of its tendency to maintain constant angular momentum as it swirls inward to the close-clearance leakage ring. Unless the swirl is prevented from occurring, the leakage ring can experience the highest slurry velocity in the pump.

The foregoing discussion can at best give us only a qualitative idea about slurry pump wear in coal liquefaction service. To date, experience has been with pumps in pilot plants. Net slurry flow rates in these plants varies from as little as 1 gallon per minute in the SRC-1 plant at Wilsonville to as high as the 300 gallons per minute that were pumped in the EDS plant at Baytown. Full-scale commercial plants

are expected to have a net slurry flow of up to 5,000 gallons per minute.

In addition to the specific speed choice and therefore the speed choice for the pumps in both the pilot and full-scale plants, a question of scaling also arises. At a given head and specific speed, the pump size will scale as the square root of the flow rate; therefore, the rotative speed varies inversely as the square root of the flow rate, but the particle dynamics associated with wear may not scale with size. For example, centrifugal force on a particle is proportional to its mass times the square of the tip speed divided by the radius of the impeller. Thus, for a given sized particle, a larger pump at the same head and therefore tip speed will experience less force. In this event, it may be that the larger pump of the full-scale commercial plant will experience less wear than a scale model operating at the same head in a pilot plant.

3.2.2 VISITS TO PILOT PLANTS

The SRC-1 coal liquefaction pilot plant at Wilsonville and the H-Coal pilot plant at Catlettsburg were visited to gather information. A meeting was also held with Exxon people to gather information on their experience at the EDS plant. In addition, several other people and organizations (ORNL and Battelle) were contacted on the telephone.

SRC-1

The locations of the slurry pumps which were used in the SRC-1 plant at Wilsonville are shown in Figure 2. Details on these pumps are given in Table 1. The front-end circulating pumps P102 and P103 were operating in a 38% by weight coal/oil slurry. The significant fact here is that these pumps operated at only 15% of their rated water capacity. The vacuum bottoms pump P119 operated at less than 40% of its designed flow rate. Experience with the P119 bottoms pump indicated that more than two feet required NPSH was actually needed for the pump to operate satisfactorily. This highly viscous slurry had trapped gases that necessitated four feet of NPSH to maintain stable pump operation. Despite these problems

FIGURE 2: SRC-1 PLANT FLOW SCHEMATICS

TABLE 1

PUMP SPECIFICATIONS (SRC-1 PLANT)

		<u>P-102 & 103</u>	<u>P-119</u>
Manufacturer	-	Worthington	Crane-Deming
Flow (gpm)	-	70	40
Head (ft.)	-	140	280
Water Design Point (flow rate, gpm)	-	450	105
(head, ft.)	-	140	280
Specific Speed	-	1845	524
NPSH required ft.	-	10	2
Temperature (°F.)	-	250 to 300	560 to 630
Solid Fraction (wt. %)	-	38.5	10 to 25
Viscosity (solvent)	-	3 to 16	800 to 3000 (600 to 700 when running)
(CP) (Slurry)	-	40 to 60	
Particle size (mesh)	-	95% minus 200	95% minus 200
RPM	-	3600	3500
Impeller Dia. (in.)	-	6½	8½
Impeller OD Tip Speed (ft./sec.)	-	100	130
Efficiency (%)	-	72	39
Designation	-	Slurry Mixing Tank	Vacuum Bottom
No. of Pumps (+1 Stand-by ea.)	-	1	1

for cold slurry (less than 250°F to 300°F)
and 316 stainless steel for hot slurry
(above 250°F to 300°F) pumps.

Flame-sprayed Cr_2O_3 and plasma-sprayed WC
were tried on the casings, but they failed
through flaking and spalling. The slurry
penetrated the interface through the cracks
in the coating. LW-15 (WC) applied by the
D-Gun process worked best among all of the
thermal spray coatings. Eutectic 6715 weld
overlay was successful in the cutwater
(carbon steel welding was deposited as an
intermediate layer). They feel that some
cavitation is taking place in the cutwater.

H-Coal

The locations of the pumps in the H-Coal
plant at Catlettsburg are shown in Figure 3.
Specifications for these pumps appear in
Table 2. All of these pumps have very low
specific speeds which means that the impellers
are large and therefore have very low inlet
blade tip speeds. Here again, the only wear
that was noticed when the pumps were disassembled
was at the cutwater. However, this wear was not
serious and was never a cause for replacement
of the pumps during the 4,000 hours of plant
operation. These pumps also operated at flow

FIGURE 3: H-COAL PLANT FLOW SCHEMATICS

TABLE 2

PUMP SPECIFICATIONS (H-COAL PLANT)

	<u>J-227</u>	<u>J-217</u>	<u>J-229</u>	<u>J-213</u>	<u>J-233</u>
Manufacturer	<u>Lawrence</u>	<u>Lawrence</u>	<u>Lawrence</u>	<u>Lawrence</u>	<u>Lawrence</u>
Flow (gpm)	250	250	142		
Head (ft.)	179	302	332	132	139
NPSH required ft.	9	8		8	6
Specific Speed	497	392	324	234	305
Design Point (flow gpm) (head ft.)	350 179	315 302	142 332	57 132	67 139
Temperature (°F.)	400-500	600-700	550	600	550
Solid Fraction (wt.%)	40	20	20	25	25
Viscosity (solvent) (CP) (slurry)	300	4	1	1-13	1000
Particle size (mesh)	100				
RPM	1300	1600	2118	1223	1506
Impeller Dia. (in.)	19	19	15	16	14
Impeller OD Tip Speed (ft./sec.)	108	133	139	85	92
Slurry Specific Gravity	1.06	0.83		1.02	0.87
Efficiency (%)					
Designation	Slurry Transfer	Cyclone Feed	Filtrate Heater Feed	Vacuum Tower Feed	Vacuum lower Bottoms
No. of Pumps (+1 Stand-by ea.)	2	1	1	1	1

rates substantially below design values. Two of the pumps operated at about 200 feet of head, 500 gpm flow with 400 gpm recycled. Due to high viscosity and low NPSH the vacuum bottoms pumps (J-233) have been recently replaced by piston pumps.

Lawrence slurry pumps are used. The original pumps were made of fully hardened HC 250. Several impellers cracked due to thermal shock during start-up of these pumps, and therefore, they annealed all their HC 250 pump components. There has not been enough run time to determine the wear rate of the annealed material yet. In addition, all of the pumps are preheated before operation. The warm-up rate is about 100⁰F/hour. There have not been any cracking problems since.

Plasma-sprayed WC and Colmonoy 6 coating was tried in the casing without much success. The coating failed through spalling and flaking. The WC coating by the D-Gun process was much better. Diffusion bonded TMT5 coating was also used but it did not have enough test hours for evaluation.

Seals are the main problem in the H-Coal plant with life generally less than 3,000 hours.

EDS

Considerable data were obtained on an Ingersoll-Rand slurry pump (P-101-E) at the EDS plant.

The pump was designed with a conventional clear water blading and hub shroud profile.

This high-speed pump was tested in a special recirculating coal slurry loop. The fluid contained up to 45.6 percent by weight of solids which were abrasive. The particle sizes were considerably larger in this test compared to the one experienced in the other plants.

This pump had a design flow of 400 gpm at 330 feet of head. The speed was 3540 RPM. The specific speed was 914 and the impeller outside diameter tip speed was 143 feet per second.

The pump was operated for 600 hours near its design point. Solid particle sizes up to 3/4 of an inch were used and the impeller which had only 0.44" opening between blades was clogged. This situation was later remedied by modifications to the pump and also by using finer coal particles. Wear was observed at the cutwater as in the other pumps mentioned and also at the leading and trailing edges of the impeller blades. The suction liner was also worn at the leakage ring on the front of the impeller. The pump was subjected to apparently a more severe slurry environment

and had much larger impeller inlet diameter and tip speed than the other pumps discussed in this report. The impeller O.D. tip speed was also higher. The cutwater diameter was about 14% larger than the impeller diameter, which means that the flow velocity at the cutwater was fairly close to that which the fluid had when it left the impeller. Other EDS experience was with a pump that had nearly 50% larger cutwater diameter than the impeller. This led to reduced flow velocity at the cutwater because of the tendency of the fluid to maintain constant angular momentum between impeller and cutwater. It is reported that this pump experienced essentially no cutwater wear.

Most of the slurry pumps were made of HC 250 in both annealed and unannealed conditions. All hot pumps were annealed. Ni-Hard was also used in one pump and it worked satisfactorily in the suction liner but showed too much wear in the cutwater.

The HC 250 pumps showed wear mainly in the cutwater area. The cutwater leading edge receded and grooves were formed on the sidewalls at the base of the cutwater leading edge. Some wear was also observed at the impeller

blade leading and trailing edges. Wear patterns in the spiral shape were also observed at the front face of the suction plate.

Plasma-sprayed WC and Cr_2O_3 coatings were tried in slurry pumps. Although WC showed better durability than Cr_2O_3 , none of them were satisfactory.

In the EDS process, the corrosion wear becomes significant above 500°F slurry temperature.

3.3 FACTORS AFFECTING PUMP WEAR

3.3.1 HYDRAULIC DESIGN

3.3.1.1 Current Wear Experience

One of the objectives of this study is to study wear in centrifugal pumps used in synfuel slurry and to improve and predict the life of both pilot-plant and full-scale plant pumps. At present, limited data exist. The life of the pilot-plant pumps surveyed is probably less than a year, excluding seal failures and other minor problems unrelated to wear by hydraulic action in the flow passages of these machines.

Experience with wear in slurry pumps that have been employed in more traditional solids-handling applications is only of qualitative use because the carrier fluid is usually water and solids readily move normal to the main flow direction under the influence of forces initiated by turning of the fluid. This kind of motion and the attendant wear relationships would appear to be untypical of the more viscous synfuel slurries. Nevertheless, such experience is useful in delineating the specific locations in the pump where

we can expect to see wear due to the action of synfuel slurries. For example, tabulations of pump life for various concentrations of phosphate slurries exist (1)*. Furthermore, a comprehensive discussion of all aspects of wear and design of traditional slurry pumps was given by Wilson (2). Vocadlo (3) states in connection with his exposition of a performance model that the cross-streamline motion of solid particles is sufficiently turbulent to justify the use of a constant drag coefficient for such motion. The value of the drag coefficient under these circumstances is low and therefore permits more particles to wear loaded hydraulic surfaces. Further, such behavior has different consequences on speed, scale-up, head, and particle size effects on pump wear than if the cross-streamline motion of particles were laminar.

A recent study of wear rates by Tuzson for particle sizes of 0.1 mm (100 μ m or 150 mesh) indicates that the cross-streamline particle drag is laminar (4), and this will be especially so in synfuel slurries with carrier kinematic viscosities from 10 to 1000 centistokes. To

*See References Section

draw useful conclusions about wear, it is necessary to use the appropriate particle-motion model. It is also shown that the dominant wear phenomena is scouring or sliding by particles on surfaces rather than impingement-type wear.

Zarzycki and Bak (5 and 6) investigated different types of impellers. Both report slightly higher wear rates for a conventional bladed design than for an unchokable channel type. Wiedenroth's visual studies (7) from his lacquer wear tests showed wear only on the suction side of the impeller blades when pumping sand but extending to the pressure side with fine gravel. Wear at the outlet tips increased with flow.

Herbish's report (8) on dredge pump design mentions that least wear occurred for a blade outlet angle of 22.5° , over the range of 22.5° to 35° ; the exit angle of the solid particles then corresponded closely to the blade angle.

Welte (9) while discussing wear patterns in dredge pumps states that wear is greatest at the impeller blade inlet and

outlet edges and on the outer shroud walls on the suction side. Casing wear is usually greatest near the cutwater. Generally, similar tendencies are noted by other authors (5, 6, 7, 10, and 11). Both German dredge pump papers (9 and 12) show designs having a relatively small volute side clearance. However, Bergeron (11) in discussing the effects of primary and secondary flow patterns on pump wear recommends a large side clearance except where scraper vanes are used as well as shrouded impellers and large radii of curvature of the blades.

Regarding the less conventional pump types, Warman (13) compares casing wear patterns using the conventional and his own design and claims that wear is reduced with the latter's special impeller shape. Reference 14 also mentions this aspect. Wear is also stated to be less in "TURO" design than the conventional (14) but the only comparison reported involves a different pump material for each type.

Expressions for predicting pump life are given in References 6, 10, and 11. Bak (6) gives a formula:

$$\text{Life in Hours, } T = A \frac{K Q^n}{H^{3/2} W_s X}$$

where A = constant factor (based on some known life figure); Q = solids concentration in mixture (pct); n = an exponent; K = impeller shape factor (1.0 for multi-bladed impellers and 1.4 for channel impellers); H = total head per stage; W_s = coefficient of abrasive wear for impeller material = (vol wear of test material) / (vol wear of cast iron reference material), and X = coefficient of abrasiveness of solids. Bergeron (11) also develops expressions for determining service lives of geometrically similar pumps of different size in terms of head and flow variations. Vasiliev (10) analyzes the statistical probability of a pump achieving a certain length of troublefree service defined by a specified maximum wear based on erosion tests.

It is questionable whether these complex theories can be used to predict pump life with any certainty--most involve empirical constants and other parameters difficult to determine for an actual pump. In fact, Bergeron indicates that

some of the assumptions made may be questionable. However, such theories are of some value in predicting likely trends of wear rates when only one or two of the relevant factors are altered.

3.3.1.2 Wear Locations and Phenomena

Good hydraulic design, particularly that which avoids rapid changes in flow directions, decreases wear. The slurry pump design has progressed in some instances to the point that a high degree of wear resistance has resulted. This has been accomplished through proper shaping of the hydraulic passages and adjacent flow elements over many years of development. Figure 1 shows a typical cross section of such a pump and is referred to throughout our discussion in this Section. The pump experiences critical wear in the following areas:

- a) Suction Pipe - Interactions of backflow from the pump impeller with front ring leakage causes toroidal vortices whose solid particles can cut deep rings into the suction pipe I.D. This happens at all flow rates but especially those that are substantially lower than the

pump design conditions.

- b) Impeller Blade Leading Edges - At the impeller inlet (Station 1), a high relative velocity W_1 seen by the blade can lead to many types of blade wear. Especially typical are horseshoe vortex gouges in the hub and shroud surfaces at the points where the blade leading edge intersects them.
- c) Impeller Blade Surfaces - The blade surfaces can develop holes--apparently originating on the driving face or pressure side. Scalloping (transverse to the flow) sometimes appears on the suction side or trailing faces--probably due to secondary flows. Blade thickness is about 4 percent of impeller outside diameter, i.e., about twice the thickness of blades of conventional clear water pumps. This lengthens pump life.
- d) Impeller Blade Trailing Edges - The blade land formed by the outside diameter machining of the impeller can develop circumferential grooves near the hub and shroud walls--possibly from the interaction of emerging boundary layer flow with the adjacent fluid at the O.D.

- e) Cutwater - Wear here is similar to that described for impeller blade leading edges and is the consequence of a high, largely circumferential approach velocity V_3 of the fluid emerging from the impeller. A large value of cutwater radius r_3 in comparison to r_2 --say $r_3/r_2 = 1.3$ or greater--leads to lower values of approach velocity V_3 because the fluid tends to maintain constant angular momentum in flowing from impeller to cutwater.
- f) Volute Outer Surface and Sidewalls - The volute liner experiences material removal by the action of particles moving at the scouring velocity--about equal to V_3 . Scalloping sometimes can be seen on these surfaces--again, probably the result of secondary flow in the volute cross sections.
- g) Suction Plate - Slurry that leaks from impeller outside diameter through the front ring acquires a very high circumferential velocity component because the angular momentum of the fluid tends to be conserved as it flows radially inward. With this velocity being about half of impeller tip speed Ωr_2 , it is

easy to see that the suction plate can experience the highest velocities in the pump. Spirally-oriented gouging often appears on the suction plate, and the front ring clearance can wear rapidly. This, however, is less objectionable than the Taylor-vortex-related circumferential grooving that would occur on the axially-oriented front ring clearance of conventional clear water pumps.

- h) Pump-Out Vanes - These are sometimes used to limit circumferential velocity components adjacent to the impeller; to reduce leakage and related ring wear and to provide axial thrust control. However, these vanes can cause objectionable wear on adjacent portions of the hub and shroud. The pump-out vanes help to protect the pump against seal failure.

It has been observed that the wide profile of the slurry pump impeller shown in Figure 4 leads to separation of the flow within the impeller, especially when combined with conventional blade shapes that yield large decelerations of the relative velocity W

within the impeller passages. The resulting churning of the flow may be thought of as producing unwanted wear (15). However, with width b_2 being so large (namely, that resulting from radially parallel hub and shroud surfaces)--a) there is more blade surface area to "spread" the particle abrasion load and b) the resulting separated mixing flow may greatly decrease the otherwise thick particle layer which Tuzson shows to be highly damaging (4).

3.3.2 SOLID PARTICLE PROPERTIES

The properties of the solid particles in the slurry, with respect to their hardness, size, shape, etc., have a great influence on pump erosive wear. This Section primarily discusses the information obtained during a literature search in this area.

3.3.2.1 Particle Hardness

Both Wellinger's (16) (dry) and Stauffer's (17) (wet) laboratory tests show that for metals in general, wear increases rapidly once the particle hardness exceeds that of the metal for both sliding ($< 45^\circ$ impingement angle) and impact ($> 45^\circ$ impingement angle) erosion. Beyond this,

the wear rate may become fairly constant or even reduce with increasing abrasive hardness.

From tests with various grades of very fine sand (< 200 microns) under dry conditions, Goodwin et al (18) found that erosion varied as (hardness)^{2.3} for various materials.

3.3.2.2 Particle Size

Most of the works indicate that in general, the absolute wear rate increases with grain size. Wellinger (16) states that wear is proportional to size for sliding erosion but is independent of size for impact erosion. Goodwin's tests (18) show that the erosion rate for impact erosion becomes constant only above a certain grain size (about 50 to 100 microns depending on velocity). Bergeron (19) found that wear is proportional to 0.75 power of size.

3.3.2.3 Distribution of Particle Sizes

Slurries of virtually single particle size are significantly more erosive than those of equal weight concentration which have a wide particle size distribution. A high percentage of fine material tends

to reduce the erosiveness of larger particles in the slurry and can render an otherwise erosive material relatively easy to handle in slurry pumping systems. The presence of small particles influences the viscosity behavior of the slurry flow also. High viscosity reduces erosion.

3.3.2.4 Grain Sharpness

The wear rate increases with grain sharpness. Wellinger (16) shows that the angular sand grains cause about twice the wear due to rounded ones in impact erosion.

3.3.2.5 Relative Density

Both Bovet (20) and Bergeron (13) give expressions that the wear varies directly with the density difference between solids and liquids.

3.3.2.6 Particle Concentration

Most of the works show that wear increases with concentration. Bergeron (13) suggested this applies only to small amounts of solids, but for larger values, wear increases more slowly. His theory states that wear $\propto$ number of grains per unit surface area, i.e., dependent on concentration and flow pattern. Kozirev's jet impact tests (21) show wear $\propto$ concentration up to 10 percent

solids. From the only pump test to consider this aspect, Vasiliev (20) concludes that wear $\propto (\text{conc.})^{0.82}$, independent of material or flow properties for sand/water mixtures between 3 percent and 15 percent by volume.

3.3.3 MATERIAL PROPERTIES

The pump wear is significantly affected by the selection of material for various pump components. The material properties as it affects the erosive wear in the pump is discussed below.

3.3.3.1 Material Composition and Structure

Wellinger's materials tests (16) show that a hardened steel (St. 70H), chilled C.I., and tool steel were better than the unhardened reference steel (St. 37) for sliding erosion but worse for impact erosion.

Shchelkanov's report (22) on water turbine steel tests states that microstructure and work hardening ability affects wear resistance considerably--austenitic and martensitic steels being notably better than ferritic. It recommends using low and medium (3.5 to 10.5 percent) Cr alloy hardening steels though both of these and hardened 11.5 percent Ni alloy and tool steels gave good erosion and cavitation resistance.

Pump service experience may be loosely divided into dredging, sand, gravel, and slurries generally. Welte and Ernst (9 and 12) recommend either Mn or Ni-Cr-Mo-V cast steel for impellers and casing liners for dredge pumps. Ni-Hard and high Cr cast irons

appear to be most commonly used for general solids handling pumps although Bergeron (11) states that though Ni-Hard is very resistant to sharp abrasives, it tends to be brittle, and hence, prone to shock damage so it is unsuitable for dredge pumps. He also says that the high Mn steels, being work hardened by impact, give good resistance against large, rounded solids but are not much better than unalloyed steels against sand--some of the Ni-Cr-Mo alloy steels are very resistant to sliding erosion but not to impact erosion. However, both Allis-Chalmers (23) and Warman (13) pumps use Ni-Hard for impellers handling coarse abrasives (up to 7.5 in diameter)--both also use high Cr cast iron (27 percent Cr). The use of hard facing Cr or Ni alloys by welding, electrodeposition, or metal spraying was also mentioned in some literatures.

Fulcher et al (24) investigated the role of carbide volume fraction in controlling the low-stress wear resistance in high chrome irons. The trends observed depend on the type of abrasive used in the low-stress rubber wheel test. For both SiO_2 and Al_2O_3 abrasives, wear resistance increases with carbide volume fraction in the hypoeutectic alloys and the eutectic carbides do not spall

or crack. For SiO_2 abrasive, wear resistance decreases with carbide volume fraction in the hypoeutectic composition range because the massive M_7C_3 carbides protrude from the worn surface and become vulnerable to cracking. Since Al_2O_3 abrasive particles cut the carbides effectively, the carbides do not suffer cracking and wear resistance is found to increase monotonically with carbide volume fraction.

There is very little information available on the use of ceramic and cermet materials in pumps. Hansen's sand blast test (25) showed that sintered SiC , WC (with Co binder), and B_4C (boronide) had wear resistance better than all the alloys tested. In Stauffer's grinding cup test (17), sintered WC and cast B_4C had the highest wear resistance. Sintered WC also showed the lowest erosive wear in Wong's nozzle and pump tests (15). Wellinger's sand blast and sliding wear tests (16) showed that sintered WC and Al_2O_3 were most resistant to erosive wear. Warring's review (14) states that sintered SiC has excellent wear resistance.

The Lawrence Pump Company has developed all ceramic pumps with Refrax (silicon carbide) linings. Hazleton also uses Refrax for making some wear parts such as front and back wearing

plates, suction head throat liners, and impellers. Hazleton also uses a new and stronger ceramic material called Hazleton Number 98E for some applications. Gould Pumps, Incorporated, claims to have developed a small all-ceramic pump in a special material called Cer-Vit. Most of the ceramic pumps are limited to the applications of small particle size due to the poor impact resistance of these materials.

3.3.3.2 Material Hardness

In very general terms, the wear resistance of ferrous metals tend to increase with hardness (16, 17, and 22). Antunes and Youlden (26) state that "most tests" show an almost linear variation, but Stauffer (17) found no straightforward relation between them. Bergeron (11) also states that hardness is not a criterion of wear.

Stauffer's results show the general trend, but there is a large scatter with some harder materials giving much lower wear resistance than the softer ones. It may be noted, however, the most wear resistant materials had hardness values ranging from 600 to 2450 VHN.

The hardness range of the impeller materials

in Zarzycki's pump test (5) varied from 80 to 540 BHN--the most wear resistant alloy (high Cr C.I.) had a hardness of 328 BHN while the next best (low Cr C.I.) had the much higher value of 516 BHN. Bak's results (6) were generally similar though the most wear resistant materials (Ni-Hard and high Cr C.I.) were, in fact, the hardest--about 800 BHN.

Such hardness values as are quoted for production pump materials vary from 400 to 650 for American dredge pump liners; 340 to 450 BHN (Cr C.I.) for Allis-Chalmers pumps (23); 550 BHN (Ni-Hard) for Warman pumps, and 250 to 700 BHN for various European solids handling pumps (6).

3.3.4 VELOCITY, IMPINGEMENT ANGLE, VISCOSITY

Other key parameters affecting the wear in centrifugal pumps are slurry velocity, viscosity, and impingement angles. These parameters were investigated by several people. The associated references and discussion is in this Section.

3.3.4.1 Slurry Velocity

The more straightforward wear theories (20 and 27) suggest that wear $\propto (\text{vel})^3$ or a (total head)^{3/2} if all other factors are constant. Even Bergeron's more complex expression (19) taking into account of the difference in velocity between fluid and particle gives a similar result. Bitter's theory (28 and 29), however, considers total wear as the sum of cutting and deformation erosion--both involving the material properties as well as speed so that wear cannot be stated as a simple function of velocity.

Material tests show some variation in the velocity index. Wellinger's sand blast tests (16) indicate that it depends on the material--for plain carbon steel, the index is 1.4. Stauffer (17) found that wear approximately $\propto (\text{vel})^3$ and Bergeron (13) suggests that the index is > 3 . Bidwell's

slurry impingement test (30) showed that the index is about 2 and in coal-oil slurry nozzle test (15), the index ranged from 0.9 to 2.1. Kozirev's jet impact tests (21) showed that for constant mixture concentration and without cavitation, $\text{wear} \propto (\text{vel})^{2.2}$. Goodwin (18) found that $\text{wear} \propto (\text{vel})^{2.3}$ for all materials tested and for particle size > 125 microns under dry conditions and at relatively high speed (up to 1800 ft./sec.). Antunes and Youlden (26) conclude from wear literature that for ductile materials wear approximately $\propto (\text{vel})^3$ if $\text{vel} < 100$ ft./sec. or $\propto (\text{vel})^2$ if velocity > 100 ft./sec. For brittle materials, the index may be higher. Bak's pump wear tests (6) also indicate that $\text{wear} \propto (\text{vel})^3$ -- the other pump tests do not investigate this aspect.

Levy (31) determined the following velocity exponents (n) of erosion rates of hot rolled 1018 steel using 30 wt% coal (200 mesh) in kerosene at room temperature at different impingement angles (α):

$$\alpha = 20^\circ, n = 2.01$$

$$\alpha = 50^\circ, n = 2.12$$

$$\alpha = 60^\circ, n = 1.71$$

$$\alpha = 90^\circ, n = 1.62$$

It indicates that the effect of velocity on the erosion rate decreases with increasing impingement angles. These values of the velocity exponent are lower than those measured by him in gas-solid particle erosion where they are generally > 2.4 indicating that the viscosity-lubricity of the kerosene fluid decreases the impingement angle effect on the force of the particles on the target metal.

Many of the service experience references (9, 12, 13, 14, 23, and 26) on pumps give speed and/or head limitations. For dredge pumps, maximum impeller tip speeds vary from 70 to 150 ft./sec. and maximum heads from 80 to 300 ft. (9 and 12). For sand and slurry pumps, maximum heads quoted range from 160 to 260 ft./stage in general (14) and with Ni-Hard linings up to 260 ft. for Warman Series A pumps or 320 ft. for Allis-Chalmers pumps. Ceramic linings like rubber linings are said to be unsuitable for high heads (26)-- the first of the new Gould range is designed for 60 ft. head. Warman (13) also states that a lower specific speed design for a given duty results in reduced wear although heavier and more costly since lower peripheral speeds are involved compared to the higher specific speed

alternatives.

3.3.4.2 Impingement Angle

Bovet's theory (20) results in wear depending on the tangential component of particle velocity so that as the impact angle is increased, wear is reduced. Bergeron's simpler theory (27) directly applies only to pure sliding wear but the more complex one (32) deals with the more general case of oblique impact. Bitter's expressions (28) for cutting and deformation wear imply that total wear depends on both normal and tangential velocity components.

Wellinger's sand blast tests (16) show the effect of impact angle depends on the type of material; for both steels and C.I., both absolute and relative wear rates tend to increase with angle reaching a maximum between 60° and 90° . Stauffer (27) and Welte (22) all observed Wellinger's results.

Levy (33) studied the erosion of 4340 steel in three different heat treatment conditions--as quenched, 400°F tempered and spheroidized using 30 wt% coal (-200 mesh) in kerosene at room temperature with a nozzle jet velocity of 40 ft./sec. He observed that the general

trend is for the steel to undergo an increasing erosion rate with impingement angle with the highest erosion rate occurring at $= 90^{\circ}$ and a secondary erosion peak occurring in the $= 40^{\circ}$ to 60° range. The major erosion rate difference occurring between the as-quenched and the tempered and spheroidized heat treatments is unlike that which he found in gas-solid particle erosion of 4340 steel where there was almost no effect of heat treatment on the erosion rate. Since the Charpy impact strength of the as-quenched material and its fracture toughness are both significantly lower compared to the 400°F temper material, these properties may affect liquid-solid particle erosion rates whereas the gas-solid particle erosion rates are not affected by them.

Tuzson (4) suggested that the wear of a slurry pump is most likely a scouring type of wear in which the particles or a compacted layer of particles are pressed against the wall by flow forces and are dragged along by the mainstream. This suggests that very low impingement angles are the rule in most portions of slurry pumps. His model assumes that there is a layer of slurry particles along the wall which approaches maximum packing density. Because of streamline

curvature, the particles are forced toward the wall of the impeller. The material removal process consists of plowing and shearing and resembles the action of sandpaper except that the slurry particles are not fully restrained and can tumble to some extent.

3.3.4.3 Slurry Viscosity

As the viscosity of the slurry increases, the erosion rate decreases since the drag force on the particles due to the fluid increases. Levy (33) studied the erosion behavior of a number of commercial steel alloys using 30 wt% coal in kerosene oil and 30 wt% coal in creosote oil at 350⁰F and 45 ft./sec. nozzle velocity. The alloys, in general, showed less erosion in more viscous creosote oil.

3.4 SLURRY WEAR PROCESS, TESTS, AND RESULTS

3.4.1 INTRODUCTION

Wear may be regarded as the undesirable flow or removal of material from a surface. It can be kept within bounds either by controlling the flows of force and energy, for example, by design or by absorbing the flows of force and energy such as by appropriate material selection.

This survey has been limited to material wear due to the flow of abrasive particles suspended in a liquid except for some references made with regard to material wear due to abrasive particles under dry conditions for comparison. This type of slurry erosive and erosive-corrosive wear is an increasing problem due to the growing demand for both pumps and water turbines which have to deal with abrasive solids in an either corrosive or noncorrosive liquid, particularly with the current trend to higher slurry running speeds.

With slurry erosion as with most modes of abrasion, it is a matter of damage being caused by the impact of solid particles when small amounts of material are cut or broken away due to the shear force exerted on the abrasion surface. The overall contact pressure is

small, of course, but the specific contact pressure is high due to the sharp points and jagged edges of the abrading particles. The local stresses exceed the breaking strength of the material at the point of collision.

Corrosion, on the other hand, is a process of removal of material from the surface due to its chemical reaction with its surrounding (slurry-liquid) in this case. The existence of corrosion in addition to erosion can greatly magnify the rate of wear since erosion is continuously removing the reaction product and exposing fresh metal surface.

3.4.2 CURRENT UNDERSTANDING OF EROSION WEAR PROCESS

Although considerable data exists on material erosion covering different applications, very little quantitative data exists on erosion by abrasive slurries. Most laboratory erosion tests have been conducted by directing hard particulate matter such as sand or aluminum oxide in an air or gas jet against a target material. From such tests, it has been observed empirically that materials of a ductile nature such as aluminum and copper and materials of a brittle nature such as glass erode differently but in very characteristic ways.

One of the most striking differences between ductile and brittle materials is the material erosion varies as a function of particle impact angle. Aluminum alloy reaches a maximum erosion at 15 to 20 degrees impact angle and glass reaches a maximum erosion at 90 degrees angle.

3.4.2.1 Ductile Materials

Finnie (32 and 34) considered the ductile wear mechanism to be similar to the cutting action of a machine tool. When a moving particle (airborne) came in contact with a surface, it was assumed to encounter a constant resistance or pressure from the plastic flow stress of the target material. The equations of motion of the particle through the material were then derived and the erosion rate was related to the volume of material gouged out by the particle. At low impingement angles (angles less than 60°), he obtained reasonable agreement between his calculated erosion rates and experimental erosion rates obtained on aluminum, copper, and steel using airborne silicon carbide and alumina particles; however, the agreement was poor at high angles with the calculated rates being considerably lower than the experimental rates. This appears to be indicative of the simultaneous

operation of at least two different erosion mechanisms although severe surface roughness normally obtained at high angles could increase the cutting action of particles impinging at high angles.

In an extension of Finnie's work, Bitter (28) did consider both "cutting wear" and "deformation wear" to be occurring simultaneously and he developed a mathematical model for erosion which includes terms for both types of wear. The portion of the model attributed to cutting wear was similar to that developed by Finnie with additional consideration of particle geometry. For the portion of his model attributed to deformation wear, Bitter alluded to the Hertzian treatment of elastic plastic interactions of contacting bodies. He reasonably assumed that an eroded surface will be in a work hardened state and that the yield strength of the work hardened surface will remain constant during the erosion. He also made the simplifying assumption that the volume of the target material removed is equivalent to the volume of the plastically deformed crater. Bitter's theoretical calculations show reasonably good agreement with experimental results. Nielson and Gilchrist (35) attempted to simplify Bitter's equations by

assuming that the cutting and deformation equations could be algebraically added. Their approach appears to be more tractable than Bitter's. Goodwin, Sage, and Tilly (18) in their studies on 11 percent Cr steel and titanium, nickel and aluminum alloys impacted with dry sand showed conclusively from particle size analyses that as the size of the eroding particles increased, they became susceptible to fragmentation. Tilly and Sage (36) and Tilly (37) managed to obtain some excellent high-speed photographs of the actual fragmentation of individual sand particles during impact on the 11 percent Cr steel. They also obtained some excellent micrographs of erosion scars resulting from impact of individual particles using both optical and scanning electron microscopy and these micrographs showed conclusively that fragmented particles caused extensive secondary damage (i.e., damage caused by the particle fragments) around the primary impact area. In addition, Tilly (37) presented metallographic evidence that material removal by large particles during erosion can be similar to the removal of metal chips by machine tools. He also presented scanning electron micrographs that showed clear

evidence of extrusion around impacting particles. Tilly utilized this evidence of secondary damage to modify the equations developed by Bitter (29) and showed that primary damage was predominant at low angles of impact and secondary damage was predominant at high angles of impact for a 11 percent Cr steel.

Recent experiments by Winter and Hutchings (38) strongly supports the importance of secondary damage. They have simulated erosion damage by impacting a single relatively large particle (approximately 2 mm) on lead and steel targets and they studied the resulting impact damage by metallographic techniques. Their results clearly indicate that a particle which fractures during impact can cause extensive secondary damage by either forming additional impressions in the original impact crater or forming additional impact craters. An even more important facet of the secondary damage is that the fragments of the fractured particle can cut the extruded lip that forms around the periphery of the primary impact crater.

3.4.2.2 Brittle Materials

The first simple model for brittle erosion

was developed by Finnie (34). He considered the analogous case of an elastic sphere striking perpendicularly onto a brittle surface and assumed that only elastic deformation occurred until the initiation of fracture. The maximum tensile stress in this idealized system occurs along a ring that is concentric with the periphery of the contact area and is expressed by a Hertzian equation. Assuming that a circular crack formed at the position of maximum tensile stress, Finnie was able to express the diameter of the crack as a function of particle velocity and the elastic constants of the particle and matrix. He obtained reasonable agreement between his calculations and experimental data obtained from the impact of spherical iron particles onto glass. However, he indicated that a more accurate model would be difficult to develop because of the complex nature of crack formation and fracture in brittle materials.

3.4.2.3 Composites: Metal-Bonded Hard Carbide Materials

A very limited amount of work on the erosive wear behavior of carbide base materials has been discovered in the open literature. In WC-cobalt alloys it appears that the rate of erosion in a stream of dry alumina particles,

measured as weight loss per given weight of erodent, increases in an approximately linear manner with increasing cobalt content up to 12 percent (25). In the dry quartz sand test, Uuemyis et al (39) found the rate of erosion increase in an approximately parabolic manner with increasing cobalt content from 4 to 15 percent. The rate of erosion also increases with increasing mean carbide grain size for the WC-6 percent Co alloy--a change from 1.5 to 10.6 microns resulting in a thirty fold increase (39). These differences in behavior were attributed to fracture followed by the removal of fragments of the larger carbide grains. For all carbide grain sizes, whole grains were also removed from the surface during erosion probably due to the wear of softer binder material around the carbide grains.

Shetty et al (40) investigated the mechanisms of material removal in cobalt base powder metallurgy alloys containing M_7C_3 carbides in a co-rich fcc matrix phase by a scratch test to simulate low stress abrasion wear. The test exhibited ploughing and coarse slip band formation in the matrix phase. Evidence of extensive cracking of coarse carbides pulling out of carbides and

formation of cracks along the carbide-matrix interface was also observed.

3.4.2.4 Corrosive Wear (By Process Coal Solvent)

Quantitative chemical analysis performed on the representative coal liquids obtained from liquefaction pilot plants and the post-test liquids from autoclave tests showed that the following may be the suspected corrosive species:

- 1) Sulfur Compounds Such As Sulfides
- 2) Chlorine Compounds Such As Chlorides
- 3) Oxygen Compounds Such As Phenols, Water, Etc.
- 4) Nitrogen

Correlation of corrosion data obtained in the autoclave runs (41) gave strong indications that sulfur compounds were the dominant corrosive species. Hydrofined coal liquids with low sulfur content (< 0.06 percent) remained essentially noncorrosive over the entire temperature range. By contrast, streams containing 0.3 to 0.8 percent sulfur caused steeply increasing metal loss above about 480⁰F (250⁰C).

Other data obtained in autoclave runs

established an inverse relationship between corrosion rate and chromium content of metal specimens. As expected, 18 Cr - 8 Ni stainless steel was nearly completely corrosion resistant.

3.4.3 WEAR TESTS ON LABORATORY MACHINES

There are basically four different types of slurry wear tests found in the literature as follows:

1. Impeller Test (42)
2. Grinding Cup Test (17)
3. Slurry Impingement Test (30)
4. Nozzle Test (15 and 43)

3.4.3.1 Impeller Test (42)

The apparatus consists of a converted drill press, a stainless steel impeller, and a polyethylene slurry tank. The impeller is made of a stainless steel shaft holding four equally spaced stainless steel arms. A Teflon holder containing a specimen is attached to the end of each arm by stainless steel bolts. The shaft of the impeller is held in the chuck of the drill press which rotates the impeller arms through an abrasive slurry. The slurry tank is made rectangular to break up the vortex. The test parameters are:

Slurry - 40 wt pct sand in water

Particle Size - AFS 50-70

Specimen Leading Angle - 30°

Speed - 260 RPM (15 ft./sec.)

Test Time - 20 Hours

Specimen Size - $2\frac{1}{4}$ " x 1 x $\frac{1}{4}$ "

PH - Controlled by buffer solution

The order of ranking of the materials tested is as follows:

1. 2C - 28 Cr
2. 2C - 20 Cr - 2 Mo - 1 Cu
3. 2.5C - 20 Cr - 2 Mo - 1 Cu
4. 3.5C - 3.5 Cr - 3.5 Ni
5. 3.5C - 3 Cr - 4 Ni
6. 1C - 4 Cr - 5 Mo - 2V - 6I

3.4.3.2 Grinding Cup Test (17)

The apparatus consists of a vertical motor attached to a vertical spindle (through a V-belt) and a circular base plate of 6" diameter with four clamping heads for holding four specimens. The lower part of the spindle with the base plate and specimens are submerged in sand-water slurry inside a steel container. The specimens are cylindrical and attached vertically downward to the base plate. The test parameters are:

Slurry - 66 wt pct sand in water

Particle Size - River Sand of 3
to 5 mm Grain

Impingement Angle - Different at
Different Points
on the Specimen

Speed - 730 RPM (18 ft./sec.)

Test Time - 15 Hours with Slurry
Changed After 1.3
and 7 Hours

Specimens - 3 Test Specimens and
One Reference Specimen of Unalloyed Case
Hardened Steel C 15

This test method was submitted for standardization by the German Standards Committee. Three hundred (300) materials were tested and the order of ranking of the six best materials and their resistance factor-- $R = (\text{vol wear of the reference material})/(\text{vol wear of the test material})$ --are given in Table 3. The most wear resistant material of all was sintered tungsten carbide ($R = 49.3$) followed by Stellite 6 weld overlays ($R = 18.0$) and hard chromium plating ($R = 12.4$).

3.4.3.3 Slurry Impingement Test (30)

The erosion tester consists of a horizontal rotating plate of 7" diameter that holds four cylindrical specimens of 0.495"

TABLE 3

SELECTED RESULTS OF GRINDING CUP TEST (17)

<u>Material</u>	<u>Composition (%)</u>	<u>Vicker's Hardness</u>	<u>Resistance Factor R</u>
Sintered WC	6 Co - 94 WC	1600	49.3
Stellite 6 Weld	28 Cr - 67 Co - 4 W - 1 C	420	18.0
Hard Cr Plating on Steel	----	847	12.4
Ni-Hard	----	605	6.05
Oil Hardened Chrome 2002 Steel	12 Cr - 2 C	847	6.02
HC 250	26 Cr - 3 C	787	5.43

diameter and 1" long standing vertically at equal distance along the periphery. The specimens rotate through a gravity-flow curtain or cascade of abrasive-laden water. The slurry is recirculated during the test through a large tank but never reused. The test parameters are:

Slurry - 15 wt pct SiC in water

Particle Size - 325 mesh (average)

Speed - 5500 RPM (140 ft./sec.)

Test Time - 1 Hour

The Relative Erosion Resistance
(RER) =

$$\frac{10,000}{(\text{pct wt loss})^2} - 1$$

The order of ranking of the common materials are as follows:

1. Sintered WC - 9% Co (RER - 705)
2. Tool Steel (RER - 275)
3. Hot Rolled Steel (RER - 200)
4. Cold Rolled Steel (RER - 150)

3.4.3.4 Nozzle Test (15 and 43)

The coal-oil slurry jet was used in this test to evaluate various materials. Two studies were conducted by this nozzle test:

1. Material Evaluation for Let-down Valves for Coal Liquefaction Service
2. Material Evaluation for High Volume, High Pressure, Centrifugal Coal Slurry Feed Pump for Coal Liquefaction

The erosion wear test apparatus used in both investigations consists of a bellows-type pump, mixing vessel and test chamber and relies on gas pressure to drive the slurry through a nozzle in the test chamber. A bellows pump is used to fill the mixing vessel with slurry (which enters the vessel from the bottom) and to mix and maintain suspension of solid particles during operation. The pressurized mixing vessel feeds the test chamber and nozzle through a high pressure line heated to a high temperature. The tungsten carbide nozzle produces a high velocity jet that impinges a material specimen. The angle of impingement is obtained by adjusting the specimen holder. The material test conditions are:

Study 1 - Phase I

Impingement Angle - 45°

Slurry Pressure - 2,000 PSI (Argon-Driver Gas)

Slurry - 25 wt pct of Unfiltered High Ash Containing SRC Product Dissolved in Anthracene Oil

Slurry Temperature - 300⁰ F

Particle Size - 23 Microns (Average)

Test Time - 2½ Hours

Study 1 - Phase II

Impingement Angle - 20⁰

Slurry Pressure - 2,000 PSI (Hydro-
gen-Driver Gas)

Slurry Temperature - 650⁰ F

Others As Above

Study 2

Impingement Angle - 20⁰ and 70⁰

Slurry Velocity - 185 and 375 ft./sec.

Slurry - 33 wt pct of Coal in Creosote
Oil

Slurry Temperature - 200⁰ F

Particle Size - Minus 200 Mesh

Test Time - 1 to 4 Hours

The specimens are cylindrical (3/8" diameter
x 2" long) with impingement on one end.

The nozzle is 0.02" in diameter and 0.22"
from the specimen. The maximum erosion depth
is measured in each specimen.

Test Results - Study 1

1. Tests conducted on specially-designed
letdown-type specimens (5/16" diameter
x 3/4" long with letdown channel in
the center) yielded a material ranking

order different from the results obtained from impingement-type tests made at a 45° angle. The 20° impingement angle test, however, resulted in a close correspondence of erosion values with those of letdown tests.

2. The velocity exponent for wear ranged from 0.9 to 2.1.
3. The erosion mechanism was believed to be the loss (by cutting) of softer binder material or matrix and pullout of larger more erosion resistant particles.
4. Table 4 shows a summary of erosion evaluation of some selected materials. Sintered tungsten carbide (Kennametal K703) was by far the most erosion resistant material. Both borided surface and vapor deposited titanium carbide had a low wear rate. The 15-3 alloy, Stellite 6 weld deposit, and plasma-sprayed tungsten carbide also performed well.
5. The nozzle test results correlated fairly well with the pump test run with coal-oil slurry in which K703, TiC coating,

TABLE 4

MATERIAL EROSION TEST RESULTS USING COAL-OIL SLURRY (15)

Material	Nozzle Test Maximum Erosion Depth Per Hour (Inch)				Pump Test
	V = 185 = 20°	Ft./Sec. = 70°	V = 375 = 20°	Ft./Sec. = 70°	Thickness Loss Per Hour (Inch)
1. Sintered WC (K703)	--	--	0.5×10^{-3}	$.4 \times 10^{-3}$	$.5 \times 10^{-6}$
2. Vapor Deposited TiC Coating	$.03 \times 10^{-3}$	--	0	24×10^{-3}	2.4×10^{-6}
3. Borided Surface	$.4 \times 10^{-3}$	2.2×10^{-3}	1.8×10^{-3}	--	6.0×10^{-6}
4. 15-3 Alloy	2.4×10^{-3}	7.4×10^{-3}	--	--	5.7×10^{-6}
5. Stellite 6 Weld Deposit	4.8×10^{-3}	28×10^{-3}	11×10^{-3}	76×10^{-3}	40.0×10^{-6}
6. Plasma Sprayed WC	4.1×10^{-3}	4.8×10^{-3}	$>15 \times 10^{-3}$	--	10.0×10^{-6}

borided surface and 15-3 alloy performed the best (see Table 4).

3.4.4 Wear Tests on Pumps

Quantitative wear tests on pumps are few-- only two Polish papers (5 and 6), one Russian (10), and one American (15) have been discovered. The two Polish pump wear reports give generally similar results.

Zarzycki's (5) laboratory tests were carried out in commercial rotordynamic pumps of Type EW-50 in which the impellers were made of different materials. Three types of impellers were used as follows:

1. Multivane Type (Standard).
2. Two-Channel Blade Type
3. Propeller Type - Of Two Different Diameters (5.3" and 4.5")

Sand-water slurry of average 50 mesh particle size was pumped at a RPM of 2850.

Of the thirty-one materials tested, cast basalt impellers had the highest wear resistance followed by 14 percent Cr cast iron, 4 percent Cr cast iron, and 23 percent Cr cast steel as shown in Table 5. The wear ratio = (vol wear of test material)/(vol wear of reference material) and the reference

material was gray cast iron Z125.

The article on Vasiliev's (10) pump test could not be obtained for this report.

Wong et al (15) used six specimens of dimensions, $1\frac{1}{2}$ " x $\frac{3}{4}$ " x $\frac{1}{8}$ ", mounted in a ring assembly and tested simultaneously in a slurry pump using coal-oil slurry.

The specimen ring was stationary and mounted at the impeller discharge thus simulating dynamic flow conditions typically encountered by the pump cutwater or volute tongue. The test conditions were:

Slurry - 38 wt pct of Coal in Creosote
Oil

Particle Size - Minus 200 Mesh

Temperature - 150°F

Slurry Velocity - 100 ft./sec.

Impingement Angle - 7° (at the Specimen
Leading Edge)

Table 4 shows the thickness loss of various test materials per hour of test. Sintered tungsten carbide (K703) was the most wear resistant material followed by plasma-sprayed titanium carbide, 15-3 alloy, and borided surface.

TABLE 5

RESULTS OF PUMP IMPELLER EROSION TESTS (5)

<u>Material</u>	<u>Composition (%)</u>	<u>BHN</u>	<u>Wear Ratio</u>
Basalt	----	8 Mohs	0.17
High Cr C.I.	14.3 Cr - 2.1 C	328	0.20
Low Cr C.I.	4.3 Cr - 2.5 C	516	0.22
High Cr Cast Steel	22.8 Cr - 1.5 C	340	0.24

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B. SLURRY PUMP: PERFORMANCE, APPLICATION, AND DESIGN

C. SLURRY FLOW

D. WEAR IN SLURRY PUMPS

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