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Development and Qualification of Advancements in Submersible Transfer Pump Performance and Life, and Implications for Advancing and Supporting Processing Options - 13343

David L. Stover, P.E.
Curtiss-Wright EMD, Cheswick, PA 15024

Wes Bryan and James Kelly
Washington River Protection Solutions, Richland, WA 99352

ABSTRACT

From the 1950s through the 1990s, relatively inexpensive, “off-the-shelf” type, vertical turbine pumps (VTP) were used to transfer Hanford waste. The technology of those pumps was rooted primarily in the mining and agricultural (irrigation) industries. HNF-3218, *Double Shell Tank (DST) Transfer Pump History and Reliability Report,* 1998, provides a summary of Hanford DST pump history to that date. Such pumps operated in the Hanford radioactive waste environment for an average of only 400 hours before failure. However, at that time, operating life was not a driving criteria within the Department of Energy (DOE) complex, as the failure of transfer pumps represented a relatively low replacement and disposal cost. The Environmental Protection Agency (EPA) issuance of the “Debris Rule” in 1992, which mandated that mixed radioactive waste contaminated equipment be decontaminated to a “low level waste” category prior to burial, elevated the significance of transfer pump reliability and decontamination capability as life-cycle cost criteria. Minimizing the frequency of transfer pump failures and design for decontamination became significantly important and served to drive the need toward specific, designed-for-application pumps to meet this challenge. To this end, Washington River Protection Solutions (WRPS) and the supplier, Curtiss-Wright EMD (EMD), have recently collaborated on an intense program to further transfer pump technology and performance.

INTRODUCTION

In 1993, impelled by the 1992 Debris Rule and the approaching Tank Farms mission change to waste feed delivery (WFD), Hanford initiated development of a new generation of transfer pump engineered to specifically address the VTP shortcomings in life expectancy, variable speed operability, universal waste type compatibility, and ability to decontaminate. This initiative resulted in the New Generation Transfer Pump (NGTP), which was deployed in 2000 in the SY-101 waste tank at Hanford as part of the Expedited Waste Transfer Program. The resulting first-of-its-kind NGTP was a blending of proven technologies and designs from other applications, including rugged, highly reliable integrated canned motor/pump technology originally developed for use as nuclear reactor coolant pumps for the U.S. Navy. Benefits of this technology included the elimination of the long, slender drive shaft and all mechanical shaft seals and thus their inherent reliability issues by using a tank waste fluid lubricated and cooled submersible motor with integrally mounted impeller. Building on this successful base, WRPS and EMD have recently collaborated in a program to further this pump technology and optimize its performance for the range of planned waste transfer campaigns to the new Waste Treatment Plant as defined in RPP-5346, *Waste Feed Delivery Transfer System Analysis*.

Key in the decision to transition away from these traditional, “off-the-shelf” VTPs was a realization that the desired duty and performance of the pumps being deployed in the waste tanks was beyond the criteria for which they had been developed in other industries. Even with the numerous incremental modifications incorporated through years of in-tank operational experience, the equipment was limited by the fundamentally less demanding services for which it had been developed and by limitations of the basic machine architecture. Unlike many of these more traditional pump applications, a total life-cycle cost evaluation of the in-tank pumps used within the DOE complex is now strongly biased toward high reliability, specifically designed-for-service equipment. When considering the costs associated with the decontamination and disposal of failed equipment, process interruption impacts, and most importantly, human exposure considerations for tank-top equipment intervention, the upfront cost of the equipment becomes relatively insignificant in the overall life-cycle cost evaluation if higher reliability and longer service life can be provided.

Further, by developing and employing specific, engineered-for-service pumps, significant improvements can be made in process flexibility, application coverage, and overall system optimization. This can be as basic as providing intrinsic design features unique to the in-tank applications such as consideration of decontamination upon removal from the tanks to more complex process related considerations such as designing and optimizing a single pump configuration to address a range of anticipated applications. Only through this deliberate approach of designing equipment for the specific, challenging and unique needs of in-tank pumping, can the true cost and performance benefits of an engineered system solution be realized.

The result of the latest collaborative development program, referred to as the Hanford Submersible Transfer Pump (HSTP), is the next step toward optimized in-tank pumping performance. It is the culmination of various designs and features, including the NGTP and other more recent EMD mixer and transfer pumps, along with the operational and process experience provided from both the Hanford and Savannah River sites. The overall design was governed by several basics tenets: a 10 year, 10,000 hour service life; maximized leverage of proven technologies; and applicability to the wide range of envisioned transfers from all 28 DSTs (currently projecting over 1,300 individual waste transfers) including sample loop transfers and ultimately to the WTP.

HSTP SYSTEM DESIGN

In addition to leveraging and merging the best features from the various NGTP and derivative designs, including mixer pumps, the HSTP also incorporates several new design enhancements. Most notably, is a telescoping support column which will provide 14 foot of vertical installation depth adjustment for the pump while maintaining all of the moving components within the tank vapor space below the valve pit on top of the tank. Telescoping is accomplished using a sliding gland seal configuration adapted from other applications to accommodate the higher pressures developed by the HSTP. This telescoping feature allows the HSTP to be employed in all 28 DSTs with full extension to within 5 inches of the bottom of the deepest tank. In the fully retracted position, it can be positioned to just above the deepest sludge for the initiation of the first mixing and transfer campaign.

Unlike other telescoping concepts deployed previously into waste tanks in rigid caissons to protect the pump, the HSTP column is designed to independently withstand all of the potential in-tank loads including adjacent mixer pump jet impingement and seismic events. With this, the HSTP can be deployed in any DSTs without major modifications required to the existing riser openings or valve pits. To further minimize tank-top operator intervention, a cable hoist mechanism will be utilized for raising and lowering the HSTP allowing for remote adjustment. It will also provide enhanced insertion depth adjustment capability over the fixed, incremental pin arrangement used previously to provide nearly infinite and real-time adjustability as the process requires.

Hydraulic Design

As shown in Figure 1, the HSTP hydraulic configuration is a three-stage, low specific speed, centrifugal pump designed to deliver 140 GPM at a maximum of 777 feet of head. The rotational speed was selected to be nominally 3,600 RPM to match the synchronous speed of the two-pole motor at typical 60 Hz line power, with performance adjustments achieved by a variable speed drive. The three-stage configuration was optimized to achieve the necessary hydraulic performance for the upper bound transfer head of 777 feet while balancing mechanical design limitations (rotor dynamics) of the rotating assembly.

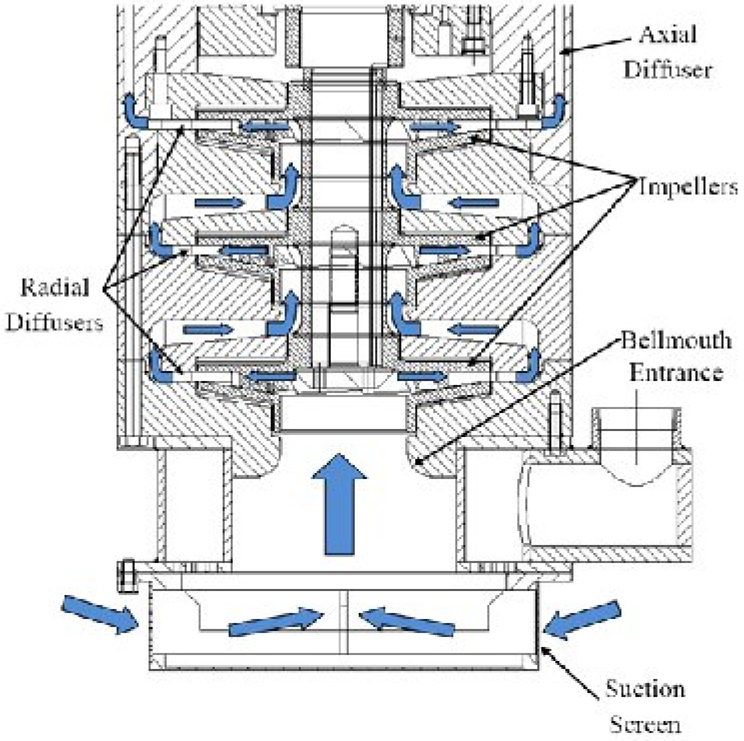

Figure 1 – HSTP Hydraulic Configuration w/ Primary Hydraulic Circuit

As shown in Figures 1 and 2, the hydraulic configuration of the HTSP is a bottom suction, top center discharge, three-stage centrifugal pump consisting of three radial impellers, three radial diffusers, two return guide vanes, and an axial diffuser. The inlet to the first stage impeller includes a perforated plate suction screen, a converging bellmouth in the suction adapter, and a diluent flow supply ring. As shown in Figure 2, the discharge flow path after the third stage axial diffuser flows through a jacket flow annulus, a Venturi ring, and a transition piece which directs the flow into a 4 inch discharge pipe. All of the hydraulic components are self-draining, and the primary hydraulic flow paths were sized to pass ¼ inch diameter particles.

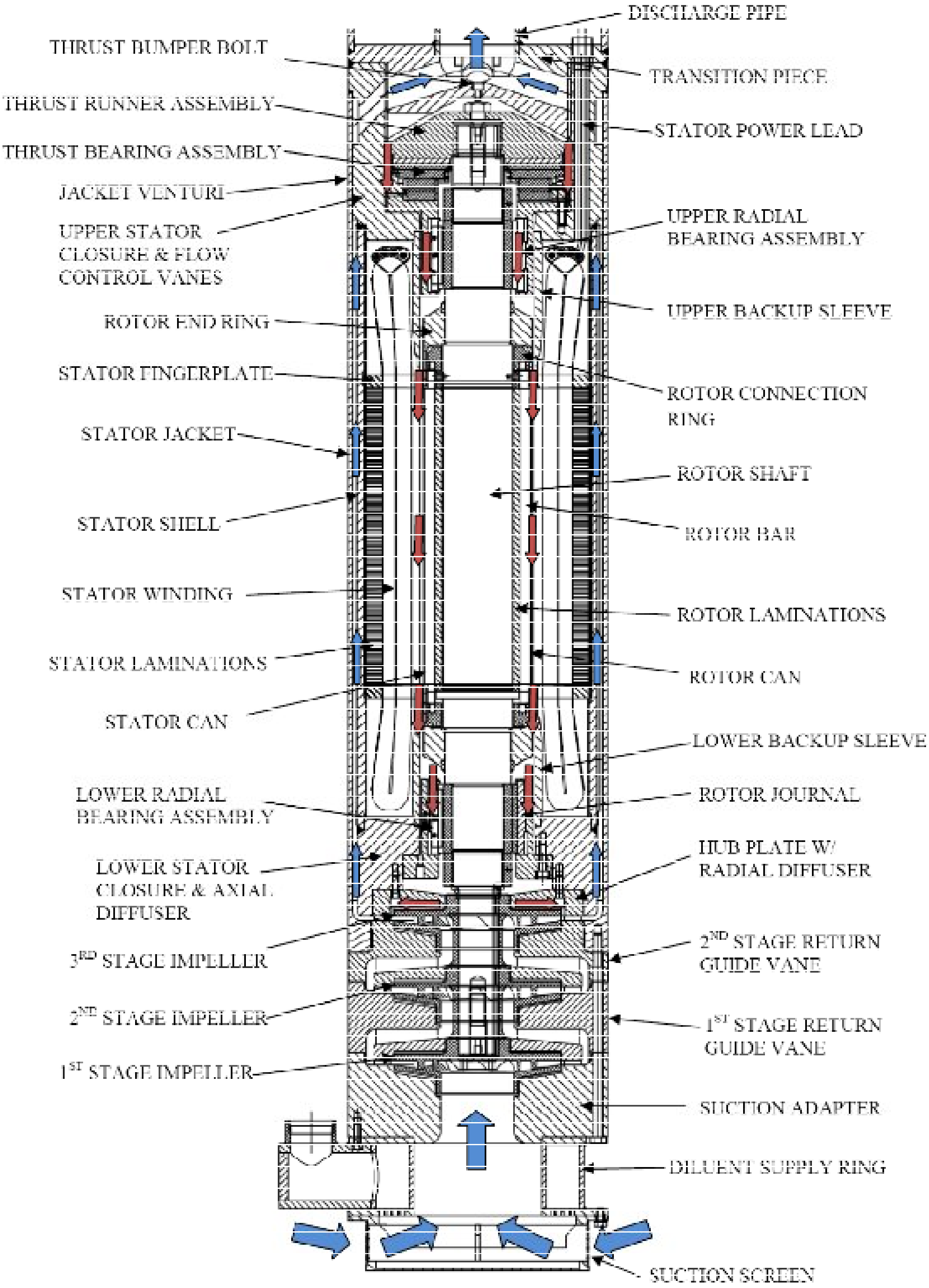

Figure 2 – HSTP Motor/Pump Unit Assembly
w/ Primary Hydraulic Circuit and Internal Circulation

The rotating impellers impart the energy into the flow, the radial diffusers and return guide vanes collect, slow and straighten the high velocity flow exiting the impellers for entrance into the subsequent stage. The axial diffuser deswirls and aligns the flow axially upward into the jacket flow annulus. This annular flow path passes the pumped fluid past the motor stator outer diameter to avoid a separate transfer line external to the pump column. The upper portion of the jacket annulus includes a Venturi ring to provide back pressure during flushing to force flush water into the motor internal cavities. Once through the Venturi ring, the flow dumps into the transition piece which collects the flow and directs it to the discharge pipe, while splitting a portion of the flow back down into the motor cavity for cooling and bearing lubrication. The discharge pipe then carries the fluid through the telescoping column to the top of the tank where it joins with the transfer line. The suction inlet of the pump is fitted with an inlet screen which prevents objects larger than ¼ inch from entering the pump. From there, the suction flow passes through contoured bellmouth entrance that provides enhanced low submergence performance. The suction assembly also includes a diluent flow supply ring that allows for varying in-process dilution of the tank fluid during operation without impacting pump performance.

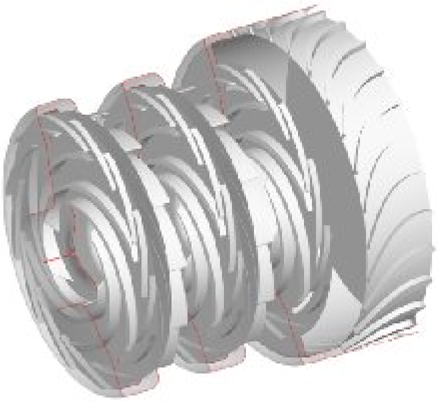

Figure 3 – Wetted Hydraulic Model

The HSTP hydraulic configuration is fundamentally based on the NGTP hydraulics while incorporating design features specific to the HSTP performance requirements and reflect actual performance experience with prior transfer pump designs. The design basis is a transfer flow rate of 140 GPM at 777 feet of head delivered to the top of the column, which encompasses the upper bound (highest head) transfer identified by WRPS to date. The pump performance is evaluated for fluid properties ranging from cold water (1 cP and 1.0 S.G.) to the most viscous slurry (20 cP and 1.5 S.G.).

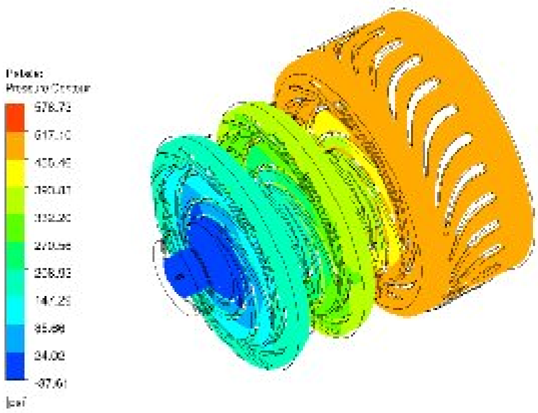

Figure 4 – Pressure Development

The design applied incorporated EMD's design experience with commercial pump design software to define the hydraulic flow path. A computational fluid dynamics (CFD) code was used to predict performance at various operating conditions including head rise and efficiency at the design points to validate the performance. The analysis was repeated at different flow rates to generate performance curves at different fluid properties, specific gravity and viscosity, to validate impacts on efficiency and pump performance. Likewise, the motor internal circulation flow rate was evaluated to ensure adequate flow at the entire range of anticipated performance and fluid property combinations. Through this analysis approach, the pump hydraulic performance is well characterized prior to first article testing. To ensure some design margin, the mechanical design is verified to 10% over the rated speed to allow for speed adjustment to be used throughout the life of the pump to offset any performance deterioration due to hydraulic component erosion due to abrasiveness of the pumped tank waste.

Motor Design

To meet the speed and torque required by the hydraulics, a 100 HP, 460 V, 2-pole, squirrel-cage, submersible, canned induction motor is used. The motor is designed to operate on variable frequency, 3-phase power, which allows the speed of the HSTP to be adjusted between 1000 and 4000 RPM to offer maximum operational flexibility.

The motor is similar in construction to a conventional squirrel-cage induction machine with the exception that both the rotor and stator assemblies are hermetically sealed using welded Hastelloy cans. The cans allow the process fluid to be used for both motor cooling and bearing lubrication while not penetrating the motor internals. It also ensures that the stator winding is maintained in a clean, dry, one-atmosphere environment for its entire life, which is paramount in providing ultimate motor longevity. For this application, EMD uses a nuclear grade, class N, inverter duty insulation system (200 °C with allowable excursions above this) using primarily glass and silicone based materials, as shown in Figure 5, with demonstrated in-tank life in excess of eight years. The materials were all selected based their suitability for the radiation exposure levels expected for 10 years in-tank without detrimental degradation.

Figure 5 – Transfer Pump Stator Electrical Winding

The internal circulation of the pumped waste tank fluid through the motor is established by the pressure developed by the impeller, where a small percentage of the overall impeller flow (approximately 20 GPM) is drawn from the main process flow above the motor and directed back down through the motor. The fluid passes through the thrust bearing, upper radial bearing, the annular gap between the stator and rotor cans, through the lower radial bearing and is then rejected back to the main process flow at the impeller. The majority of the heat developed by the motor is rejected to the internal circulation in the region between the cans. The internal circulation flow rate is sized to limit the temperature rise of the fluid to less than 10 °C.

This unique motor cooling and lubrication arrangement allows for the motor to be situated immediately adjacent to the impeller on a common shaft with minimal bearing overhang. The resulting short-shafted configuration offers excellent rotor dynamic stability and reduced bearing loads over the entire operating range compared to more traditional long-shaft pumps. And because the pumped tank waste is used to lubricate and cool the motor, which is hermetically sealed and protected by the cans, no mechanical shaft seal is required thereby eliminating two of the most common failure mechanisms of the long-shaft pumps.

Bearing Design

Two radial bearings and a single acting, axial thrust bearing support the rotor assembly in the motor. Each bearing is a hydrodynamic, process fluid lubricated, fluid-film type design and is designed to operate in both the forward and reverse direction. To withstand the abrasivity of the solids encountered in the waste tanks (primarily various oxide and hydroxide forms of iron, manganese, aluminum, calcium, nickel, uranium and plutonium, along with zeolite and garnet) all of the running surfaces of the bearings are made of alpha-sintered silicon carbide.

The upper and lower radial bearing assemblies each have four silicon carbide inserts (shoes) retained in stainless steel holders. The shoe assemblies are retained in rigid housings that capture and position the pads and which transmit the bearing loads to the stationary motor support structure. Each shoe assembly is independently self-adjusting to accommodate with the mating silicon carbide rotor journals, which are secured to and spin with the rotor assembly. To allow the bearings to operate in the range of viscosities expected in the tanks including functional testing in water with a viscosity of 0.45 cP, each radial bearing shoe is spragged. This feature, which is simply a very shallow taper at the leading and trailing edges of each pad, creates a “wedge” at the point of fluid entrance to aid in developing and maintaining an adequate fluid film.

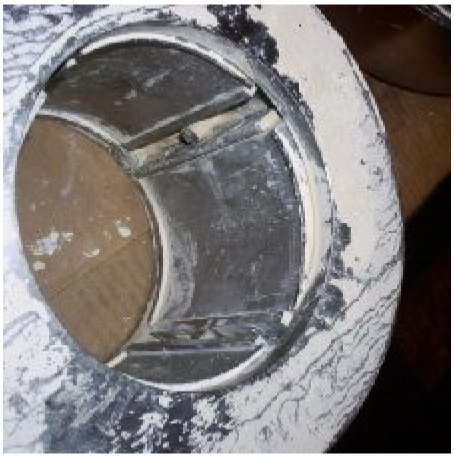

Figure 6 – Radial Bearing from Kaolin/Sand Test

A single acting thrust bearing is integrated directly into the upper radial bearing house as shown in Figures 7 and 8. It is a five-pad Kingsbury type design with silicon carbide inserts which run against a solid silicon carbide plate which is fitted and keyed to the top of the rotor assembly in a thrust runner assembly. The pad assemblies are load self-equalizing to accommodate any component misalignment and rotor motion during operation while maintaining a uniform load across all six pads. Similar to the spragging on the radial bearing shoes, each thrust shoe is contoured with cylindrical crowns which serve to optimize fluid film thicknesses during operation.

Figures 7 and 8 – Upper Radial Bearing and Thrust Bearing with and w/o Pads

TECHNOLOGY READINESS LEVEL (TRL):

In addition to the development and delivery of the two NGTPs to Hanford in the 1990s, a number of other in-tank pumps utilizing the same technology have since been developed, tested and delivered to both the Savannah River (SRS) and Hanford sites. These include: 17 Submersible Mixer Pumps (SMP), four Submersible Blender Pumps (SBP) (used to dissolve the salt layer on the top of some of tanks), and seven Submersible Transfer Pumps (STP) for the SRS, along with one Submersible Supernate Pump (SSP) and the design of a SMP for the Hanford site.

Figure 9 – SMP Qualification in Kaolin/Sand

Figure 10 – SMP Low Tank Level Testing

To minimize overall program risk and the associated design development costs, each of these different designs leverage many of the key qualified features from the original NGTPs and the initial SMP program, which endured an extensive qualification test program including kaolin/sand operation prior to deployment. By this approach, many key, qualified attributes (such as the bearings and material selections) are utilized to deliver a "deployment ready" TRL 9 or 10 pump system, while still offering the process flexibility (flow, head, tank-top interface configuration, ancillary systems, etc.) to optimize the pumps for specific applications.

HSTP TECHNOLOGY ADVANCEMENTS

In addition to the universal design approach and the incorporation of a fully supporting telescoping column, a number of other technology advancements have been developed and incorporated into the HSTP design. One of the most significant was the incorporation of a new material treatment applied to the silicon carbide bearings to allow for "dry start" of the pump. The use of fluid film bearings eliminates much of the concern over limitations associated with L-10 life related issues with conventional rolling-element type bearings. However, they presented a challenge in starting the pump when the tank level was below the bearings, leaving them non-submerged. The time required to prime and initiate the internal circulation of fluid to the bearings was near the limit of survivability of the silicon carbide due to a thermal runaway condition during dry running. Recently in the shaft seal industry, where dry running of seal faces presented similar challenges in upset conditions, a process was being developed to transform the free carbon at the surface of the carbide into various carbon species including planar graphite and particulate nanocrystalline diamond. The resulting surface is low friction, self-lubricating, and able to run dry. In laboratory tests, the treated carbide exhibited several orders of magnitude better dry run performance than untreated carbide. This not only provides adequate margin for the several seconds required to start-up dry, it would also provide adequate time to intervene in the event of an upset condition (loss of prime, fouled suction screen, etc.) before damaging the pump. Additionally, unlike a coating, it does not have an adhesive bond line which makes it more suitable for application in the aggressive waste environment where traditional coatings tend to "flake" or otherwise fail after time.

The "dry start" capability of the bearings along with the incorporation of the Venturi ring into the jacket annulus allowed for the elimination of the need for a separate flush water line to inject water directly into the motor for flushing and low tank level starting where the bearings are not fully submerged. The treated bearings are fully tolerant of the several seconds of dry running it takes for the pump to begin circulating fluid to the internals of the motor during a low-tank level start-up. And while flushing through the main discharge line, the Venturi ring serves to provide significant resistance to the flow to ensure an adequate portion of the total flow is directed through the motor internals to displace and mobilize solids instead of simply bypassing the motor through the main flow annulus around the outside of the motor.

Also, a diluent supply system was incorporated enabling inhibited water to be injected directly into the pump inlet. This injected water can be used to perform a transfer line preheat to remove calcifications from the line or in-line dilution to adjust the properties of the transferred waste. A supply ring at the pump inlet acts as a flow manifold to evenly distribute the diluent water to the first stage, ensuring consistent pump performance regardless of the diluent flow rate. The diluent flow rate can be continually modified to transfer diluent water only or to achieve any desired level of dilution without impacting pump performance. This system interfaces directly with supply systems in the valve pit at the top of the tank.

POTENTIAL NEXT STEPS

Recognizing the desire to address, quantify and control the mobilization and delivery of solids, the HSTP could be adapted to tailor the transfer system capabilities relative to particle size and density. Depending on the ultimate desire of the WFD process, the pump could be configured to achieve a range of particle transfer tasks including:

- *Minimum particle transfer:* aggressively limit the number of particles drawn into and transferred through the transfer pump;
- *Particle size limit by separation:* selectively limit the maximum particle size that can be transferred out of the transfer pump using a rotating separator;
- *Particle size limit by size reduction:* use an integrated particle crusher/grinder to reduce the size of particles drawn into the transfer pump;
- *Maximum particle transfer:* aggressively maximize the size of particles drawn into and transferred through the transfer pump.

The three-stage hydraulic configuration is capable of exceeding the maximum head requirements of all of the identified transfers. A single stage of the pump could be modified by replacing the impeller with alternate tools to control the pump particle transfer performance while still achieving the required bulk transfer performance. With this, the motor is capable of providing in excess of 30 HP to this new tool, which would be simply installed on the common rotor shaft. The following list provides some of the tools currently considered for direct incorporation into the HSTP either individually or in combination:

- *Inlet auger:* a rotating "screw auger" penetrating the bottom of the suction screen to actively draw sludge and particles into the pump inlet;
- *Suction screen shielding:* a suction screen configuration to shield the transfer pump inlet from mixer pump jets and reduce the inlet velocities to minimize particle transport;
- *High transport suction screen:* maximize opening size and inlet velocities to maximize the size and number of particles drawn into the pump;
- *Particle grinder/crusher:* a rotating component incorporated directly into the pump to reduce particle sizes to a maximum size limit;
- *Bypass mixing jets:* redirect excess pumped liquid from the first impeller stage to the pump suction to create localized impinging jets to entrain particles
- *Rotating particle separator:* utilize the density difference between solids and liquid to selectively remove particles from the flow where they can be redirected from the primary process flow;
- *Rotating filter:* employ a rotating separator, similar to those currently envisioned for Small-Column Ion Exchange (SCIX), to control transferred particle size

Many of these tools, including particle size reducers and inlet augers, are established and available technologies in slurry, mining and municipal waste processing industries. The basic tenets of each can be evaluated and engineered to meet the specific needs of WFD. Joint evaluation by EMD and the Hanford teams could determine the optimum approach desired and select the preferred configuration. This would result in one or more variants within the basic HSTP configuration that capitalize on the established technology to meet specific waste transfer needs.

LESSONS LEARNED

In order to develop fully functional, optimized solutions to the challenging and unique applications in the tank farms within the DOE complex, often specifically designed for service equipment offers the best, lowest overall cost solution. In simply adapting existing technologies, the equipment is often fundamentally limited by the lower criteria for which it had been developed for in other industries. Engineered solutions often require more up-front effort to fully define the requirements, understand limitations, and evaluate design option trade-offs, but ultimately provides the best overall solution when considering process reliability, employee safety, and application flexibility.

The effort must collaboratively merge the knowledge of the process and environment with the specific equipment design know-how of the supplier. Too commonly the unilateral development of equipment specifications without detailed knowledge of the equipment, or conversely developing a product without considering the specific nuisances of the application, leads to sub-optimum solutions. Justification of the up-front investment comes later, in the field, with equipment that is appropriately designed and configured for the challenging work in the tank farms.