NUCLEAR WASTE TRANSFER PUMP—DESIGN, ANALYSIS, TESTING, AND OPERATION

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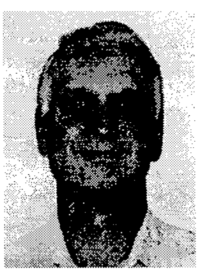

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ABSTRACT

There was a time when people worked on radiologically contaminated equipment with a low level of protection, when equipment leakage was considered unavoidable, and when contaminated equipment was disposed of with little environmental regard. Emphasis was placed on production and productivity. Those times are gone! Environmental and personnel safety are of utmost importance. Practices and equipment must be re-evaluated in light of this new value system.

This paper documents a synergistic teaming arrangement between user and manufacturer that resulted in a pump addressing this culture change. The pump, developed for high-level nuclear waste, has the following features:

- Extended pump life without maintenance
- Reduced disposal costs
- Improved pump operability
- Zero leakage

- Flexible transfer capability

The advanced design nuclear waste transfer pump manufactured for the Hanford Nuclear Reservation features a variable speed, submerged canned motor pump whose design, development, and operational features are described.

BACKGROUND

The United States Department of Energy's (DOEs) Hanford Site, in Richland, Washington, produced nuclear materials for the nation's defense programs for more than 50 years. The by-product of the processing operations generated liquid wastes that were stored in large underground tanks.

The task of coping with the massive amounts of radioactive materials, which remain hazardous for thousands of years, is complex. The potential impact of prolonged exposure to chemically and radiologically toxic materials is understood. Thus, technologists continue to search for better solutions for safeguarding the public, workers, and the environment in the management of this highly hazardous liquid waste.

INTRODUCTION

With the end of plutonium production in 1989 and the subsequent Project Hanford initiative for environmental cleanup, DOE entered into a tri-party agreement, "The Hanford Federal Facilities Compliance and Consent Order," with Washington State Department of Ecology and the U.S. Environmental Protection Agency (EPA). The key objective of this agreement was to assure Hanford's environmental restoration over the next 30 years.

The Office of River Protection (ORP) at Hanford is responsible for managing over 55 million gallons of radioactive liquids, slurries, saltcakes, and sludges stored in the site's 177 underground storage tanks. Mixer pumps and transfer pumps are installed in these storage tanks to prepare and transfer the waste for delivery to a vitrification facility where it will be converted into a solid, stable, glass-like substance. In the meantime, ORP manages the safe storage of the existing waste that includes products that generate high temperatures and flammable gases.

Figure 1 provides a representation of a typical tank installation. Double-shell tanks are located below ground with pumps and other equipment suspended from risers in the tank dome. Tank waste typically contains a saltcake/sludge on the bottom, supernate low specific gravity waste, and often a crust layer on top. Final disposition of these tanks will require mobilization, mixing to a homogeneous mixture, and transfer to a staging tank or the waste treatment facility.

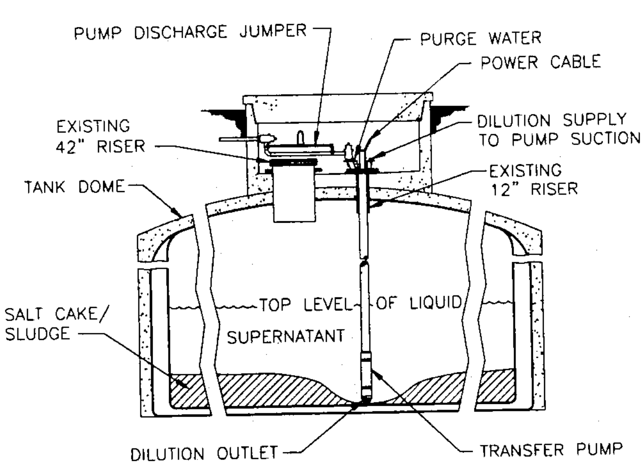

Figure 1. Typical Hanford Waste Tank Installation.

In 1992, the EPA revised their requirements covering the land disposal of hazardous wastes and debris in a regulation called the Debris Rule. The new regulation mandated a completely new approach to handling failed pumps. Since they had contacted the waste, they were now classified as radioactive mixed waste. Past practice methods of disposal for failed pumps was unacceptable. Consequently, estimated pump retrieval, treatment, and disposal costs escalated to levels exceeding $1,500,000 per pump.

Heretofore, inexpensive, largely off-the-shelf vertical turbine pumps had been used for most transfers. These pumps were inexpensive (i.e., $15,000 to $30,000) and had relatively short lives; most operated for approximately 3,000,000 gallons before they failed and required replacement since high levels of contamination did not allow maintenance. Increased costs associated with environmental compliance mandated changes in technology to:

- Reduce the quantity of radioactive mixed waste being created in the form of failed pumps
- Reduce the levels of contamination remaining on equipment being disposed
- Reduce disposal costs

The new EPA regulations became the primary incentive to develop an advanced nuclear waste transfer pump.

New Generation Transfer Pump Program

In 1993, the DOE initiated the development of the new generation transfer pump (NGTP), which was intended to produce an improved transfer pump with features that would significantly reduce site cleanup costs. The project focused on the following four design areas:

Extended Pump Life

Historically, the average transfer pump operating life has been approximately 400 hours before failure. Because of the high radiation levels, post operation examination and refurbishment was not feasible; thus, wholesale pump replacement was required. Pump failures commonly occurred as freeze-up (especially after prolonged periods of inactivity), seal leakage, and performance degradation.

As Hanford moves into the waste treatment phase of the environmental cleanup, maintenance-free pumps with significantly longer lives are needed to reduce the high cost of decontamination and disposal. Further, delays to processing of tank waste due to a failed pump could jeopardize the EPA cleanup schedule and result in increased cost. Thus, the NGTP was designed robustly to achieve a highly reliable, maintenance-free operating life.

Reduced Disposal Costs

The past pumping equipment employed 30-year-old technology procured solely based on initial cost. The metallurgy was typically cast-iron and carbon steel and the design placed little emphasis on decontamination of equipment prior to disposal.

A focus of the NGTP design is on ease of decontamination by the elimination of crud traps, attending to metallurgy and surface finish details to facilitate decontamination, and ensuring that the pump is completely self-draining with provisions for flushing pump internals.

Improve Pump Operability

Hanford tanks contain waste varying from a relatively "clear" supernate liquid, with a specific gravity near 1.0 to wastes containing up to 30 percent solids (some of which were highly abrasive). Past practice pumping operations took little note of the potential for transfer line plugging when low flow velocities resulted from a single speed pump operated closer to shutoff on its performance curve. Consequently, there are several plugged transfer lines at the tank farms.

The NGTP design effort focused on the actual tank waste remediation systems (TWRS) tank farm pumping requirements to achieve the best and most efficient pump performance for the required application.

Provide Universal Transfer Capability

Hanford transfer pumps have to accommodate varied flow destinations and fluid rheology. The same pump may be required to transfer 200 ft to an adjacent tank in one instance and several miles to a tank in another tank farm in another. Past practice at Hanford used pumps that were specified for one system curve (i.e., a single head and flow).

The NGTP design focused on providing a pump that is highly flexible and capable of meeting the requirements of each of the destination system curves. The pump specification identified to the pump manufacturer that multiple system curves needed to be accommodated by a single pump (Figure 2).

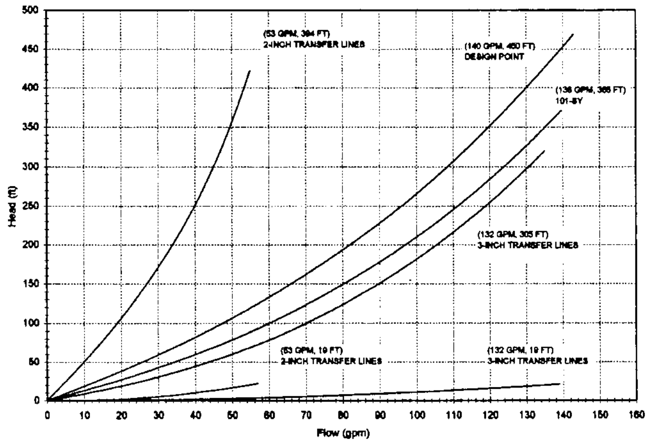

Figure 2. NGTP System Resistance Curves.

A cost benefit analysis (CBA) was performed comparing the cost associated with the current mode of operation and the projected cost of operating the facility with the NGTP. The analysis was based on the assumption that Hanford would be required to move approximately 509 million gallons of waste from 1997 to 2027. Applying the current vertical turbine pump technology and the historical useful life of these pumps, it was estimated that over 200 new pumps would be required to perform this task. For the same waste volume transferred, the analysis concluded only 46 NGTP units would be required. The comparative cost of equipment—including installation, removal, and disposal costs—showed that the NGTP has the potential to produce a net savings of $62 million over the life of the project. Figure 3 shows the cumulative savings that could be realized as a function of time.

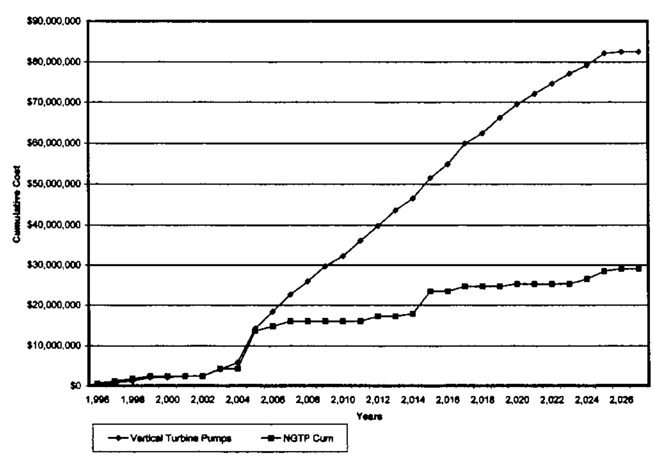

Figure 3. NGTP Cost Benefit Analysis.

The NGTP development program established a teaming arrangement whereby Hanford engineers most familiar with the conditions at the tank farms worked very closely with the Electro-Mechanical Division (EMD) of Westinghouse Government Services Company pump design team to develop a pump that is flexible and robust enough for the demanding service into which it has been introduced. This arrangement properly applied the expertise and skills from user and manufacturer to create a synergism that optimized the design of the NGTP.

TANK FARM PUMP APPLICATION

The procurement specification for the NGTP included the following critical design parameters:

- Develop 450 ft of head while pumping at a design flow rate of 140 gpm
- Operate in a flammable gas environment
- Operate continuously in a radiation field of 250 R
- Operate for 10,000 hours without maintenance over a 10-year period
- Operate with a maximum process fluid temperature of 200°F
- Operate with a specific gravity up to 1.50
- Operate with a fluid viscosity between 1.0 and 30 cP
- Tolerate process fluid containing up to 50 percent solids by volume, particle sizes up to 1000 microns, with abrasiveness up to 50 on the Miller Number Scale
- Provide up to 105 gpm dilution flow during operation
- Operate without any external cooling or lubrication system
- Be installed though a 12 inch diameter riser
- Be capable of being internally flushed and completely self-draining
- Preclude process fluid leakage above the pump mounting flange
- Operate with a variable frequency drive

NGTP DESIGN DESCRIPTION

The design approach adopted by the manufacturer to meet Hanford's NGTP procurement specification utilized a highly developed, mature, and proven canned motor pump technology, originally developed for the U.S. Navy.

The manufacturer's new generation transfer pump design shown in Figure 4 features the following key elements:

- A short, compact 60 hp, submerged canned motor unit, cooled by waste tank process fluid, driving an integral two stage centrifugal hydraulic unit
- A radiation resistant, high-temperature electrical insulation system
- Two hydrodynamic pivoted-pad radial bearings with silicon carbide operating surfaces
- A single-acting Kingsbury-type thrust bearing with silicon carbide operating surfaces
- No dynamic seals
- No external cooling system for the submerged canned motor
- No external lubrication system for the pump bearings
- A purge water system to flush the motor with water after shutdown and a dilution water system to supply water to the pump suction during operation
- A single piece, welded column assembly with hermetically sealed internals to preclude the entry of process fluid

- A bolted, hermetically sealed joint between the motor unit assembly and the column assembly for protection of power cables and ease of maintenance
- A variable frequency drive (VFD) to enable pump operation at any point within the design head-flow envelope

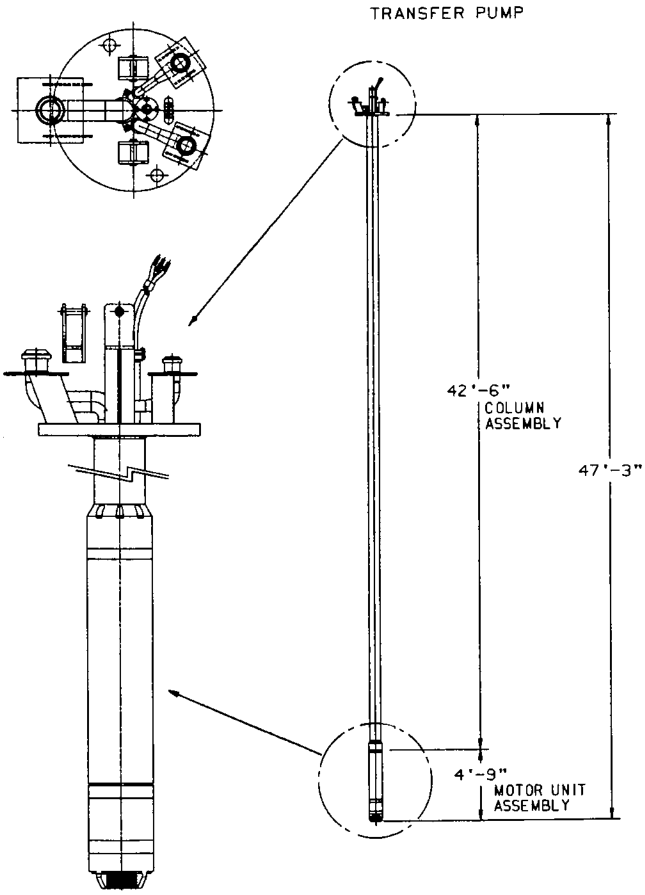

Figure 4. The Manufacturer's New Generation Transfer Pump.

Motor

The NGTP is powered by an induction motor with a high slip, high torque, two-pole configuration designed to operate at 3615 rpm when supplied with three-phase, 460 V power. The motor unit conforms to the NEMA MG-1 standard for electrical machines. The motor operates between 1420 rpm and 3860 rpm when driven by a VFD at frequencies between 24 and 71 Hz. The induction motor stator is constructed of a stack of silicon steel laminations and a set of random wound coils. The stator winding insulation system, consisting primarily of polyimide films, glass, and mica tapes, is radiation resistant up to 1000 Megarads and has a 40-year life at operating temperatures up to 220°C (428°F).

The stator core is enclosed in a welded, hermetically sealed 304L stainless steel (SST) shell. Process fluid is prevented from entering the motor cavity by a 0.033 inch thick Hastelloy® C276 can that is welded to the inside of the shell. The stator cavity is potted with a sand-silicone resin mixture, which eliminates large voids and improves heat transfer from the stator winding end turns. The motor leads are routed out the top of the stator through an electrical standoff tube. In addition to the opening for the electrical leads, the stator contains passages for the main process fluid discharge flow, the process fluid internal circulation/bearing lubrication flow, the motor purge water flow, and the dilution water flow (Figure 5).

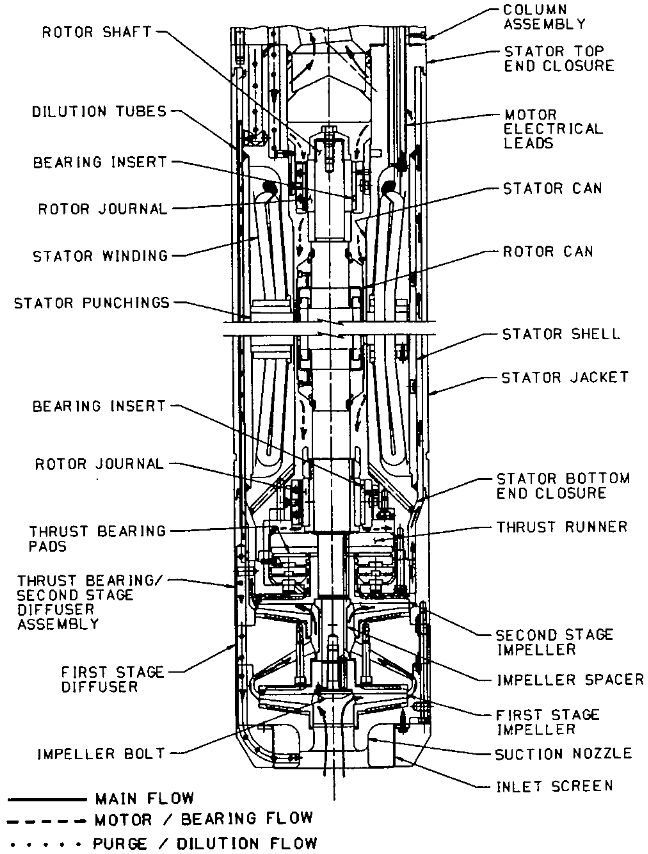

Figure 5. NGTP Motor/Hydraulics Internal Circulation Flow.

Bearings

The motor/pump design employs two radial bearings and one thrust bearing. The bearings are lubricated and cooled by the process fluid, which is pumped through the motor. The radial bearings are film riding, hydrodynamic, pivoted-pad bearings. Pivoted-pad bearings make the rotating assembly dynamically stable (no whirl) and allow the NGTP to operate with large angular misalignments between the motor shell and the rotating assembly. The operating surfaces of the bearing pads and the journals are direct sintered silicon carbide (α-SiC) to minimize bearing wear in the abrasive process fluid. The α-SiC pads are secured in 410 SST holders for structural support.

The thrust bearing is a single acting, film riding hydrodynamic, Kingsbury-type thrust bearing. The bearing contains six cylindrically crowned α-SiC shoes and an α-SiC thrust runner. The shoes and the thrust runner are secured in 410 SST holders for structural support. This design also contributes to the misalignment tolerance between the motor shell and rotating assembly.

Rotor

The rotating assembly consists of a 410 SST solid shaft and a brazed copper squirrel cage assembly. The squirrel cage is hermetically sealed from the process fluid by a 0.033 inch thick Hastelloy® C276 cylindrical can that is welded to the outside of the rotor. The α-SiC radial bearing journals are slip fit onto the rotor to accommodate differential radial expansion and are clamped axially in compression with shaft nuts to prevent journal movement during operation. The α-SiC thrust runner assembly, both impellers, and the spacer between them are slip fitted onto the rotor shaft. The thrust runner and impellers are keyed and axially clamped with a single impeller bolt. The arrangement facilitates quick disassembly of the rotor for inspection and decontamination.

Hydraulics

The short hydraulic length of a two diffuser arrangement allows both impellers to be located outboard of the lower radial bearing while operating significantly below the first rotor critical speed, eliminating the need for a third radial bearing, which significantly complicates alignment. Both impellers are similar in size and have six vanes with upper and lower shrouds. The impeller passages are sized to pass up to 0.25 inch diameter particles. At design point each impeller has a stage specific speed of 786.

The static hydraulics consist of the inlet screen, suction adapter, first stage diffuser, second stage diffuser, and stator jacket. The 304L SST inlet screen contains perforations to preclude the entry of particles larger than 0.25 inch into the pump. The screen size and perforation design minimize the pressure drop across the screen. The inlet screen also reduces the potential for vortexing at low tank fluid levels. The inlet screen is bolted to the end of the suction adapter.

The CF3 SST suction adapter contains four radial vanes that:

- Guide the pump into the waste tank riser,
- Reduce the potential for vortexing when the pump is operated at low tank levels, and
- House the discharge ports for the dilution system.

The suction adapter is bolted to the first stage diffuser. The 304L SST first stage diffuser uses an eight-vane crossover design. The first stage diffuser is bolted to the 304L SST second stage diffuser. The second stage diffuser has 27 vanes to turn the flow axially. The thrust bearing assembly is mounted over the second stage diffuser. The second stage diffuser is bolted to the stator assembly.

A 304L SST stator jacket fits over the outside of the stator shell with a 0.38 inch radial clearance to form a discharge flow annulus. It is shrunk-fit onto the second stage diffuser and the upper end of the stator assembly. The shrink fits allow for the removal of the jacket for inspection and decontamination.

Column Assembly

The hermetically sealed column assembly is fabricated from 8 inch, 304L SST pipe. It houses the main process fluid discharge piping, purge water piping, dilution water piping, and the electrical power cable. The bottom of the column assembly bolts to the top of the motor unit. The electrical power cables are brazed to the motor leads and sealed against the entry of water or waste tank process fluid with a carbon graphite gasket, a metal C-ring, and two ethylene-propylene (EPDM) O-rings. The mounting flange located at the top of the column supports the entire pump assembly. The electrical power leads exit the pump at the top of the column assembly and are routed outside the waste tank pit to the VFD. The inlet connectors for the purge water and dilution water lines and the process fluid discharge connector are located at the top of the column assembly.

Fluid Flow Path

Waste tank process fluid enters the bottom of the pump at the inlet screen and flows through the suction adapter inlet to the first stage impeller. The process fluid is pumped through the first stage impeller into the first stage diffuser where the fluid is turned radially inward and upward into the second stage impeller. Process fluid from the second stage impeller enters the second stage diffuser where it is turned axially upward into the annulus between the stator shell and the stator jacket. The process fluid flows up the annulus, removing heat generated by the stator windings. At the top end of the annulus the process fluid splits into two separate flows.

The main discharge flow passes through four radial openings in the stator assembly and into the column discharge header. From the header the main process fluid flows upward through the column discharge line to the discharge connector at the top of the column assembly.

In the second flow circuit, the process fluid enters the motor internals through two radial holes in the stator designed to centrifugally separate and divert solids in the waste stream away from the holes, thereby minimizing plugging and wear in the motor internals. The fluid flows into the rotor cavity passing over the upper radial bearing, providing cooling and lubrication. The process fluid then enters the annulus formed by the stator and rotor cans, removing heat from the rotor squirrel cage and stator windings. It continues through the lower radial bearing and the thrust bearing and then exits the motor at the second stage impeller upper shroud. The motor process fluid then rejoins the process fluid being discharged from the second stage impeller.

Purge Water System

Purge water is provided to close-tolerance pump internals to provide initial bearing lubrication prior to pump startup and to provide a means of minimizing solids (salts) buildup during prolonged periods of shutdown. Purge water can be injected into the pump at the top of the column assembly through an inlet connector. The purge water flows down through a water line in the column assembly into a connecting line in the top of the stator assembly. The purge water enters the motor internals at the upper radial bearing where it splits, flowing downward through the rotor-stator annulus and outward through flow holes into the bearings and stator jacket to stator shell annulus.

Dilution Water System

Dilution water can also be injected into the pump suction through another connector at the top of the column assembly. This flow is fed internally down through the pump, mixing with the process fluid at the suction adaptor as the process fluid enters the pump.

Variable Frequency Drive System

Input power to the manufacturer's NGTP is supplied by a 125 hp variable frequency drive. The VFD motor controller converts 460 V, three-phase, 60 Hz utility power to adjustable voltage and frequency, three-phase, AC power for stepless motor speed control. The VFD utilizes pulse width modulation (PWM) for power conversion. The VFD conforms to IEEE 519 for harmonic distortion. The VFD is housed in a environmentally controlled enclosure. The enclosure contains a thermistor to control the separate heating and air conditioning systems within the enclosure. The climate control maintains a constant temperature inside the enclosure during all weather conditions.

ANALYSIS AND TESTING

Significant analysis and testing was performed to ensure the manufacturer's NGTP would meet all design requirements.

Hydraulics Design

The hydraulic components were selected combining design experience for similar performance requirements and test data. A suction specific speed of 7500 was chosen to meet the 10.6 ft NPSHa requirement. This resulted in an operating speed of 3725 rpm at design flow. Establishing a nominal impeller diameter of 8.75 inches to meet the 11 inch maximum pump diameter envelope, a two-stage hydraulic design driven by a two-pole motor operating at 3860 rpm was determined to produce the required pump discharge head of 450 ft (500 ft required at the hydraulics using a 50 ft elevation correction) at 140 gpm flow. With a calculated hydraulic efficiency of 50 percent, the required brake horsepower (bhp) for the motor was calculated to be 63 after applying the Hydraulic Institute Standard (HIS) correction for the process fluid maximum specific gravity (1.50) and the maximum viscosity of 30 cP.

Hydraulics

Air testing was performed on the full-scale hydraulics to determine the head-flow characteristics of the impellers and diffusers. The manufacturer has routinely and successfully employed air testing for over 20 years to predict the pump total head versus flow performance in water. The test impellers were fabricated from aluminum, and the diffusers were rapid prototyped from acrylonitrile butadiene styrene (ABS) plastic. Numerous operating speeds were tested in addition to the rated speed required for the design head and flow.

Internal Circulation Design

The test program included variations in impeller seal clearances and different second stage diffuser designs. Based on the testing, the manufacturer selected an optimum clearance of 0.60 inches for the impeller seals and a second stage diffuser with 27 slotted vanes.

Using the test data, the manufacturer completed the internal circulation analysis at all six operating points and selected extremes of the head-flow operating envelope. The size and quantity of circulation flow holes in the motor were adjusted to tune the flow rates and rotating assembly axial thrust loads. The results of the analysis are presented in Table 1 for design point (450 ft at 140 gpm) operation in water and process fluid.

Table 1. Design Point Circulation and Axial Thrust.

	Water	Process Fluid
Specific Gravity	1.0	1.5
Viscosity	1.0 cP	30.0 cP
Motor Internal Circulation	66 gpm	45 gpm
Rotating Assembly Axial Thrust	2044 lbs down	3134 lbs down

Motor Design

The NGTP canned motor was designed based on a nominal 63 bhp load as discussed above. The motor was designed with a large startup torque for breakaway and a large rotor-stator can gap to reduce the possibility of solids in the process fluid "bridging" the cans. The motor utilizes a random wound stator consisting of 24 coils connected in a two parallel wye configuration and a 17 bar squirrel cage rotor. Table 2 lists the predicted variable speed performance of the pump.

The internal circulation and motor performance data were used in the thermal analysis of the motor to determine the maximum winding surface temperature (MWST) of the stator winding. For a canned motor the MWST usually occurs in the winding end turn knuckle. Using the maximum ambient tank fluid temperature of 200°F, the calculated MWST was 205°C (401°F). For the Class "N" insulation system used in the design of the windings, the allowable MWST for 10,000 hours of continuous operation is 250°C (482°F).

Bearings Design

A static analysis of the film riding, hydrodynamic, four-pad, pivoted pad radial bearings was performed on the upper bearing (2.50 inches in diameter and 2.50 inches long with a 0.0025 to 0.0030 inch radial clearance) and the lower bearing (3.25 inches in diameter and 2.30 inches long with a 0.0030 to 0.0035 inch radial pivot clearance). The following forces were considered to be acting on the rotor:

Table 2. NGTP Variable Speed Performance at Variable Frequency Inputs.

Parameter	22 Hz	31 Hz	40 Hz	48 Hz	57 Hz	67 Hz
Terminal Voltage (volts)	169	238	307	368	437	460
Frequency (Hz)	22	31	40	48	57	67
Calculated Load (hp @ rpm)	3.9 @1260	7.6 @1780	12.9 @2300	19.2 @2820	27.4 @3340	36.3 @3860
Scaled Load (hp)	4.2	8	13.5	18.9	27.1	36.7
Synchronous Speed (rpm)	1320	1860	2400	2880	3420	4020
Rated Speed (rpm)	1288	1813	2335	2804	3326	3874
Slip (p.u.)	0.0244	0.0248	0.0269	0.0265	0.0276	0.0363
Input Power (KW)	4.9	8.8	14.5	20.2	28.7	37.9
Line Current (amps)	53	56	59	62	68	73
Current Density (amps/in^2)	1875	1965	2090	2200	2380	2560
Power Factor	0.31	0.38	0.46	0.51	0.56	0.66
Efficiency	64.10%	67.80%	69.80%	69.90%	70.40%	72.20%
Rated Torque (ft-lbs)	17	23	31	35	43	50
Starting Torque (ft-lbs)	150	138	126	117	110	82
Pull-Out Torque (ft-lbs)	151	162	167	170	172	139
Stator MWST (deg C)	157	159	161	164	168	172

Notes:

1 - Based on the rated operating conditions of 460 volts and 60 Hz
2 - Assuming no voltage drop in the cables
3 - Parameters based on pump operation in water
4 - Load values scaled due to VFD operation at integral frequency values

- Hydraulic radial thrust from each of the impellers determined from the air testing
- Can annulus radial forces created by the eccentric rotor operation within the stator bore
- Radial magnetic pull forces causing the rotor core to rotate eccentrically from the magnetic center of the motor

A minimum film thickness of 0.0005 inch was calculated for both radial bearings over the range of operating speeds and fluid property conditions.

A static analysis was also performed for the film riding, hydrodynamic, six-shoe, Kingsbury-type thrust bearing. The thrust shoes were designed to have tangential cylindrical crowns for operation in either direction using the axial loads predicted in the internal circulation analysis for various fluid property conditions and operating speeds. The analysis indicated the minimum film thickness would exceed 0.0006 inch for all operating conditions.

Dynamics Analysis

A classical critical speed analysis of the NGTP rotating assembly was performed. The classical critical speed calculated was 96 Hz, about 1.5 times the highest pump running speed.

An undamped natural frequency analysis and a damped rotordynamic analysis were also performed on the NGTP. With the pump running in water at 3860 rpm the undamped modal analysis indicated the first rotor-rocking mode occurs at 35.2 Hz.

A damped harmonic response analysis was also performed. All modes were found to be stable. Vibration levels in water were predicted to be generally higher than levels in the process fluid because of the higher damping characteristics of the process fluid; however, all vibration levels were predicted to be less than 0.002 inch peak-to-peak.

Abrasive Wear Testing

Since the NGTP was designed to operate in an abrasive process fluid (Miller number of 50 or less per ASTM G75-82), abrasion testing was performed on the critical components of the pump—the bearings, the stator and rotor cans, and the diffusers—using the nonradioactive simulant identified in Table 3. This simulant is a 20 percent by weight solids mixture that has a "true" Miller number of 112 and an "as-tested" Miller number of 100. (The "true" Miller number is determined with a 50 percent mixture.)

Table 3. Recipe for Simulant.

% Weight Solids In Solution	20
Solution Composition	Deionized Water
% Solids Composition By Weight:	
0.27	Nominal 8 micron SiO_2 Powder
0.27	Nominal 2 micron SiO_2 Powder
0.03	Nominal 10 micron Al_2O_3 Powder
2.58	Nominal 20-24 micron Clinoptilolite (Zeolite)
63.92	Nominal 4-5 micron Geothite (Ochre Pigment)
32.93	Nominal 10-11 micron Albite (Sodium Feldspar)
Modified Miller Number	100

Candidate bearing materials were tested in a radial bearing test rig with a 360 degree sleeve bearing. Materials tested included α-SiC, diamond-coated tungsten carbide, and chromide-coated 403 SST. Based on testing both α-SiC and diamond-coated tungsten carbide were considered capable of successfully operating for 10,000 hours in the NGTP. For this application, the manufacturer opted for the α-SiC because of difficulties encountered with the consistent deposition and adhesion of the diamond coating on the tungsten carbide.

The manufacturer also conducted a test of the Hastelloy® C276 rotor and stator can material to examine its wear resistance to the abrasive fluid environment. The can test rig consisted of a short length mockup of the rotor-stator annulus of the NGTP. Based on the testing, 0.033 inch thick cans were selected for the required 10,000 hours of pump life.

The erosion of the diffuser from the impingement of impeller discharge flow was also simulated by test. The test rig consisted of test coupons exposed prototypically to a jet flow of simulant from a fixed nozzle. Specimens tested were CF3 SST and chromide-coated CF3 SST. Based on the test results, the estimated wear of the CF3 SST coupon was 0.092 inch for 10,000 hours, and the estimated wear of the chromide-coated coupon was less than 0.001 inch for 10,000 hours of operation. As a result, the manufacturer elected to coat the impeller and diffuser seal surfaces and diffuser impingement surfaces.

Flushing Capability Testing

Two full-scale plastic models of the NGTP were built to investigate the flushing capability of the design. One model simulated the internal rotor-bearing cavity; the second simulated the second stage diffuser and stator jacket annulus. The bearings were simulated by steel and brass components. A purge line was placed prototypically at the upper radial bearing. The transparent models aided the viewing of the internal flow areas. A simulant consisting of 30 percent weight silica and water was introduced into each model and observed during draining to identify any settling/clogging action of the solids. The flushing potential of the purge line was also observed. The results were videotaped to record the characteristics of the simulant in the annuli. Based on this testing, the design was modified in the following areas:

- The volume between the lower radial bearing and can annulus was increased to prevent settled particles from migrating up into the narrow can annulus where they would potentially increase the starting torque
- Larger bypass holes were added around the lower radial bearing to optimize the exit of solids
- A vaned "chopper" was added above the lower radial bearing journal to enhance the breakup of settled solids

NPSH Testing

Cavitation testing of the first stage impeller was performed at an independent testing facility in a special test loop facility designed to test for low NPSH hydraulic designs. The test article consisted of the prototype impeller with wear rings and a screened inlet. The fluid medium was cold water and the impeller was operated at the 3860 rpm design speed. Figure 6 shows the required NPSH at various flow rates.

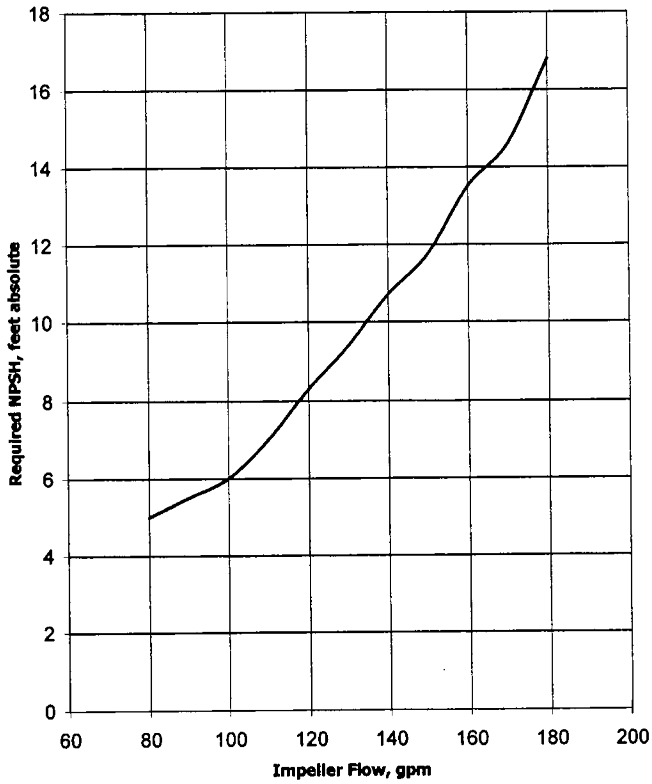

Figure 6. NGTP Required NPSH.

Explosive Environment Evaluation

The manufacturer's NGTP could potentially operate in an explosive atmosphere environment and, therefore, has to meet the requirements of Class 1, Division 1, Group B operating conditions as defined by Sections 500 and 501 of the 1996 National Electric Code (NEC). The manufacturer contracted with an independent agency to evaluate the design considering the initial ignition mechanisms, contact between ignition mechanisms and explosive materials, physical separation of initial ignition from further elements in the ignition train, absorption of thermal and shock energy, available quantity of explosive reactants, and physical resistance of the containment structure to rupture. The study concluded that the unique design of the sand potted, canned motor pump precluded the pump as a potential source of explosion and, therefore, the design was not in conflict with the NEC and was acceptable for installation into hazardous waste tanks with potentially explosive atmospheres.

Water Testing

The NGTP was performance tested at both the manufacturing site and a second site's test facilities. The manufacturer only tested the motor unit. The second site tested the complete NGTP (motor unit and column assembly). The test setup at the second site included head and flow instrumentation, a thermocouple to measure tank temperature, and velocity probes on the top and bottom of the column assembly. The VFD was instrumented to measure input and output voltage, frequency, and current. The motor end of the pump unit was submerged in an open tank at the second site and operated for more than 30 hours including a 24-hour endurance run. The steady-state peak-to-peak vibration was less than .002 inch at the submerged motor end of the pump. Initially, because of what proved out to be excessive leakage into the dilution water line, the design head could not be achieved at design flow at the second site. However, the second site's testing did confirm acceptability of the following key design features:

- The hermetic seal between the motor unit and column for the electrical lines
- The α-SiC pivoted-pad radial bearings
- The α-SiC Kingsbury-type thrust bearing
- Axial clamping of the α-SiC rotor journals
- Slip-fit impellers and thrust runner on the high-speed shaft
- The use of double-overhung impellers in a two-bearing system

With the return of the NGTP to the manufacturer, the internal leakage problem was corrected, and the head-flow performance verified by testing only the motor unit. The manufacturer's tests confirmed the NGTP met the head-flow performance requirements.

The design point performance of 450 ft of delivered head at 140 gpm was achieved at 3614 rpm with 63 Hz input from the VFD. The performance was achieved at 3614 rpm in lieu of the calculated 3860 rpm because the impeller vanes had been underfiled to increase the delivered head. The rated performance is delineated in Table 4 and in Figure 7.

Table 4. NGTP Performance Test Results at Design Head and Flow.

Delivered Flow (gpm)	Motor Unit Head (ft)	Delivered Head (ft)	Operating Speed (rpm)	Input Frequency (Hz)	Motor Slip (%)	Water Temp (F)	Input Power (KW)	Line Voltage (volts)	Line Current (amps)	Power Factor	Overall Efficiency Motor Unit (%)	Overall Efficiency Delivered (%)
38.6	558.1	506.1	3681	63.1	2.77	78.8	26.1	465.8	58.7	0.552	15.5	14.1
60.2	552.0	500.0	3667	63.2	3.30	78.0	28.8	465.1	61.5	0.581	21.7	19.6
80.5	545.1	493.1	3652	63.2	3.69	79.0	31.4	465.1	64.3	0.606	26.3	23.7
99.5	538.1	486.1	3643	63.3	4.08	79.4	33.8	465.0	67.0	0.625	29.8	26.9
120.2	525.5	473.5	3626	63.3	4.48	79.6	36.2	464.6	69.9	0.642	32.8	29.6
140.7	507.8	456.8	3614	63.3	4.84	80.4	38.3	463.4	72.6	0.657	35.0	31.5
159.9	489.0	437.0	3600	63.4	5.36	81.3	40.2	463.6	75.1	0.666	36.5	32.7
182.1	467.0	415.0	3590	63.4	5.63	82.7	42.2	463.8	77.8	0.678	37.9	33.6
220.3	419.1	367.1	3566	63.4	6.26	84.1	46.0	462.6	81.8	0.687	38.6	33.8

The pump was also operated at five off-speed demonstration points required by the Hanford operating specification as noted in Table 5. Figure 8 shows head-flow performance at all test points. The test results verified that there were no flow instabilities over the continuous flow range of 40 gpm to 220 gpm at design speed or at any of the off-speed demonstration points.

In a separate test, with the NGTP operating at design point (450 ft of head at 140 gpm flow), a hot shutdown resistance test was conducted to determine the average core/motor winding temperature rise during operation. The test results revealed that the core and windings experienced an average temperature rise of 22.8°C (41°F) above the ambient water temperature during steady-state operation at the design point. This agreed within 1°C of the predicted temperature rise. To achieve a 10,000 hours insulation life, the maximum allowable NGTP stator winding temperature rise—above a maximum 93°C (200°F) process fluid ambient temperature—is 157°C (283°F), suggesting that there is ample thermal margin during all operating conditions in the waste tank process fluid.

With operation at design point in water at 3614 rpm and a VFD input of 63.3 Hz, the input line current to the motor was 72.6 amp

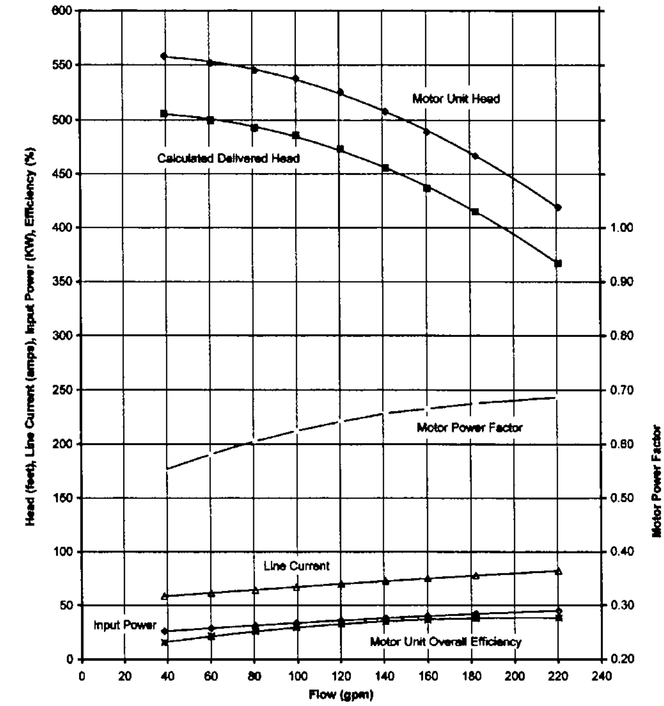

Figure 7. NGTP Performance Curves at Rated Operating Speed (63 Hz).

Table 5. NGTP Operating Specification Points.

Head ft-H_2O	Flow gpm	Nominal Speed rpm
450	140	3614
366	138	3600
305	132	3350
19	132	2063
394	53	3410
19	53	1490

at 463.4 V. The overall pump unit efficiency was determined to be35.0 percent. Since the motor efficiency was calculated to be 70 percent, the hydraulic efficiency was estimated to be 50 percent. A total of 36 shaft horsepower (shp) was required by the hydraulics at the design point in water.

For operation in process fluid with a 1.50 sg and a viscosity of 30 cP a correction was applied to hydraulic efficiency to account for increased losses. Applying the correction in accordance with guidelines of the HIS for increases in viscosity and sg, the estimated hydraulic efficiency in the process fluid is 39.5 percent. This increases the required shaft horsepower from 36 in water to 67 in the process fluid. The motor analysis (which accounts for increased "windage" losses in the canned motor in the process fluid) indicated the motor efficiency would increase to 75 percent in process fluid due primarily to power factor improvement. The current would increase from 72.6 amp in water to 122 amp in the

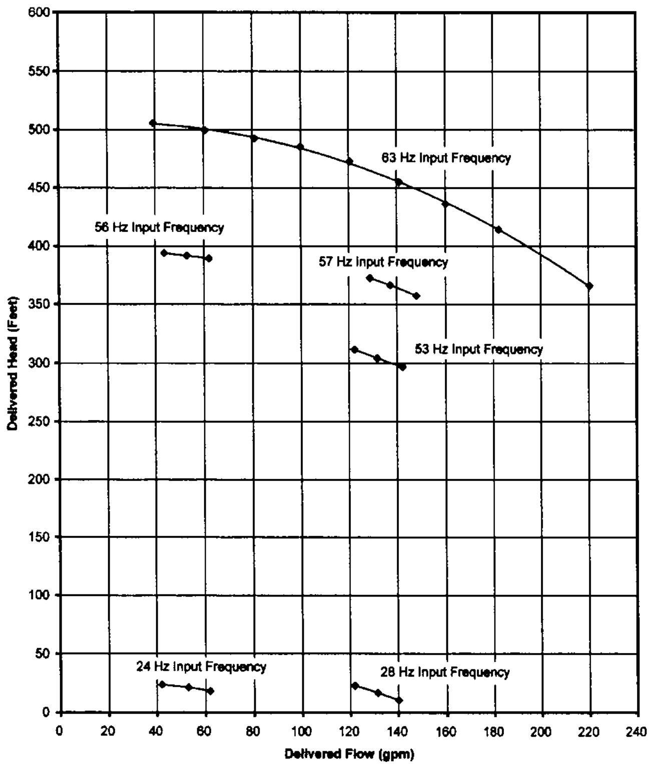

Figure 8. NGTP Performance Curves at Off-Design Operating Points.

process fluid. With the increased rotor slip, the VFD input frequency increases from 63 Hz in water to 73 Hz in process fluid to maintain the 3614 rpm. Since the thermal analysis calculates a maximum allowable motor winding temperature rise of 157°C (283 °F) for a motor current of 160 amp, the manufacturer's NGTP has ample thermal margin to run continuously at the projected 122 amp.

Based on the combined results of the supporting analysis and the water testing, the manufacturer's NGTP was expected to meet or exceed all requirements for operation in Hanford's hazardous waste tanks.

HIGH VISCOSITY OPERABILITY EVALUATION

After design and delivery of the lead unit NGTP, ORP considered the NGTP for a special mission in the 241-SY-101 tank. Operation in this tank would require the pump to operate outside its original design parameters. The manufacturer was requested to evaluate the NGTP at the following new design point conditions:

- 60 gpm flow rate
- 100 ft of delivered head, maximum
- 1.0 to 1.70 sg
- 1 to 1000 cP viscosity

The following design areas were considered in the evaluation:

- Radial bearings and thrust bearing power consumption
- Hydraulics efficiency changes and power consumption
- Motor power draw and torque capability
- VFD current draw
- Motor winding temperature
- Internal fluid circulation through the motor
- Rotating component fluid friction losses and axial thrust
- Motor unit and column vibrations

The analysis was performed at viscosities of 30, 250, 375, 600, and 1000 cP with the following fluid property assumptions:

- Fluid temperature: 120°F
- Specific heat: 0.75 Btu/lbm−°F (75 percent of water)
- Thermal conductivity: 0.091 Btu/hr-ft−°F (25 percent of water)
- Newtonian fluid

Hydraulics Analysis

Hydraulic performance of the impellers was calculated using the water test results as the basis. Per HIS recommendations, the head correction factor (C_H), flow correction factor (C_Q), and efficiency correction factor (C_E) were adjusted for the higher specific gravity and the viscosities being evaluated. The impeller operating speed and hydraulic power at each viscosity was then calculated for the new design operating point. Based on previously calculated axial loads for water operation, the axial thrust of each impeller was calculated assuming axial thrust is proportional to speed squared and specific gravity. The radial loads on each impeller were extrapolated from impeller air test data assuming radial loads are proportional to head and specific gravity. Table 6 summarizes the impeller operating speeds and loads at the new design point for various fluid specific gravities and viscosities.

Table 6. NGTP Parametric Performance Summary at New Design Point.

Transfer Pump Viscosity Performance at 60 gpm Flow and 100 Feet Head						
Fluid Properties						
Specific Gravity	1.0	1.70	1.70	1.70	1.70	1.70
Viscosity, Centipoise	1	30	250	375	600	1000
Temperature, deg F	120.0	120.0	120.0	120.0	120.0	120.0
Specific Heat, Btu/lbm*F	1.000	0.750	0.750	0.750	0.750	0.750
Conductivity, Btu/hr*ft*F	0.364	0.091	0.091	0.091	0.091	0.091
Operating Speed, rpm	1918	1942	2020	2060	2151	2262
Pumped Fluid Flow Rates, gpm						
Hydraulics Discharge Flow	90.9	88.3	74.4	70.3	66.3	63.5
Pump Discharge Flow	60.0	60.0	60.0	60.0	60.0	60.0
Motor Internal Flow	30.9	28.3	14.4	10.3	6.3	3.5
Reynolds No., Can Annulus	37504	2130	257	173	113	71
Mechanical Losses, bhp						
Thrust Bearing	0.2	1.3	5.4	7.3	10.7	16.5
Thrust Runner	0.2	0.7	2.0	2.5	3.5	5.5
Chopper	0.4	0.7	0.9	1.0	1.2	1.5
Lower Radial Bearing	0.0	0.4	3.9	6.2	10.7	19.8
Rotor-Stator Annulus	0.2	1.0	3.2	4.2	5.8	10.0
Upper Radial Bearing	0.0	0.2	2.2	3.4	6.0	11.0
Miscellaneous	0.0	0.1	0.2	0.3	0.4	0.6
Hydraulics	6.8	12.0	16.1	18.3	22.9	29.1
Total Mechanical Losses	7.8	16.4	33.9	43.2	61.2	94.0
Motor Performance						
Maximum Torque, ft-lbs	152.8	152.8	152.8	152.8	152.8	152.8
Terminal Voltage, volts	240	250	275	291	stall	stall
Supply Frequency, Hz	32.7	34.1	37.5	39.7	stall	stall
Line Current, amperes	52.3	63.2	97.4	118.6	stall	stall
MWST, deg C	75	90	253	351	stall	stall
Insulation Life, hours	2.03E+09	7.18E+08	8894	10	stall	stall
Input Power, KW	8.2	15.6	32.6	42.6	stall	stall
Total Electrical Losses, KW	2.4	3.4	7.3	10.4	stall	stall
Efficiency, %	70.9	78.4	77.5	75.6	stall	stall
Fluid Temperature Rise, deg F						
Impeller Discharge Fluid	0.2	0.3	0.8	1.1	stall	stall
Motor Circulation Fluid	1.4	2.3	8.9	15.8	stall	stall
Axial Thrust, lbs						
First Stage Impeller	56	97	105	109	119	132
Second Stage Impeller	60	105	114	119	129	143
Motor	278	469	595	621	665	702
Rotating Assembly Weight	140	125	125	125	125	125
Total Axial Thrust	534	796	939	974	1038	1102
Radial Loads, lbs						
First Stage Impeller	4.6	7.9	7.9	7.9	7.9	7.9
Second Stage Impeller	2.6	4.4	4.4	4.4	4.4	4.4

Motor Internal Circulation Analysis

The flow rate of fluid through the motor internals affects motor cooling capability. Therefore parametric calculations were performed to determine the internal circulation rate expected at the new design point with the higher liquid density and viscosities. Based on pressures calculated around the rotating assembly in the motor circulation analysis, axial thrust of the rotating assembly was calculated for the operating conditions under consideration. Table 6 identifies the motor internal circulation flow rate and rotating assembly axial thrust calculated for the new design point for various fluid specific gravities and viscosities.

Bearings Analysis

Based on previously calculated operating speeds and axial loads (impeller thrust, rotating assembly thrust, and rotating assembly wet weight), the minimum film thicknesses and power losses in the Kingsbury-type thrust bearing were determined at the new design point. The predicted thrust bearing power loss results are delineated in Table 6.

Radial bearing power loss calculations were made assuming Couette flow through the upper and lower pivoted-pad bearings. The results of these calculations are presented in Table 6.

The NGTP motor was analyzed for operation at the new design point in high viscosity fluids using the manufacturer's canned motor design code. The operating speed and total power losses at each viscosity studied (Table 6) were used to evaluate motor performance. The results of the evaluation are presented in Table 6. No solution was obtained in the manufacturer's motor code for the 600 and 1000 cP cases. This indicated that the motor will not come up to operating speed and will stall when trying to reach new design point operation in viscosities above 375 cP. Figure 9 plots required motor torque and available motor torque versus fluid viscosity at the new design point; this figure reveals that required torque exceeds available torque (and the motor cannot reach required operating speed) around 440 cP. Refer to Table 6 for a delineation of the motor analysis results.

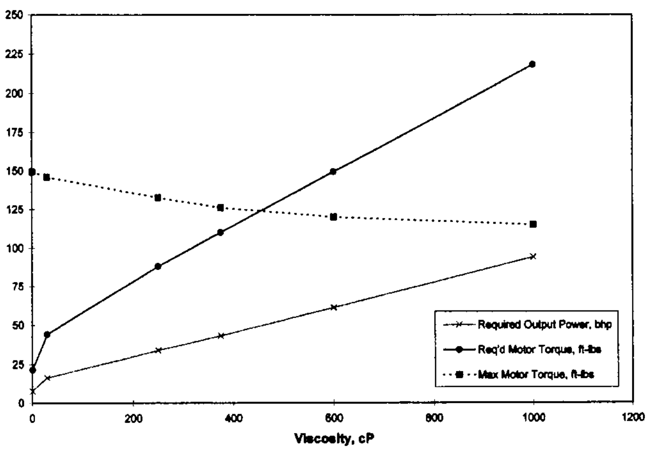

Figure 9. NGTP Motor Mechanical Performance Versus Viscosity at New Design Point.

Thermal Analysis

A thermal analysis of the motor windings was performed using the electrical current, motor internal circulation flow, and the motor annular gap Reynold's number at the new design point for water and for fluids with a specific gravity of 1.70 and viscosities of 1.0, 30, 250, and 375 cP. No analysis was performed for viscosities above 375 because the motor analysis revealed motor stall above 440 cP. The primary interest of the thermal analysis is the insulation operating life. The manufacturer's NGTP has a Class "N" insulation system with a 40-year (350,000 hours) minimum continuous operating life with a maximum winding surface temperature (MWST) of 200°C. The continuous operating life of this insulation system is halved for each 10°C rise in MWST. The thermal analysis indicated that a 5000 hours operational life for the NGTP could be achieved at the new design point with a fluid specific gravity of 1.70 and a viscosity up to approximately 250 cP (Figure 10). Refer to Table 6 for a summary of the thermal analysis results.

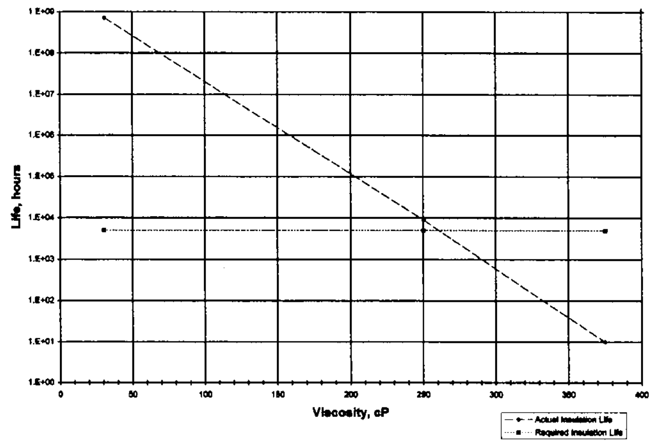

Figure 10. NGTP Motor Insulation Life Versus Viscosity at New Design Point.

Dynamics Analysis

An undamped modal analysis of the entire NGTP was performed for the new design point with a fluid viscosity of 250 cP. The results of the undamped modal analysis were input into the damped frequency analysis of the pump rotating assembly in the NGTP to evaluate rotor stability and vibration amplitudes. The dynamic analysis revealed that the rotor was stable for all modes. At 250 cP viscosity, the vibration analysis results were compared with the predictions for water operation at the original design point. The results revealed that vibration magnitude at the new design point is significantly lower due primarily to the higher damping.

The viscosity study indicated that there were two items that limited operation of the manufacturer's NGTP in a high viscosity fluid. One is the torque output of the motor, and the second is the operating life of the motor electrical windings. At the new design point the required operating torque approaches maximum motor torque (breakdown torque) at approximately 440 cP. Above this viscosity the motor is not capable of coming up to operating speed and will stall. The operating life of the motor is limited to approximately 8900 hours at 250 cP and 10 hours at 375 cP. Therefore, of the two limiting items, motor winding life is the controlling parameter.

OPERATION IN 241-SY-101 TANK

Actual waste transfer began on December 18, 1999, using the NGTP for the first time. Approximately 90,000 gallons of radioactive liquid waste was transferred to the adjacent storage tank with this first of three campaigns, greatly reducing the problems related to hydrogen buildup in the SY-101 tank. The transfer was completed in 23 hours.

Pump operation actually exceeded expectations by achieving the necessary head and flow at a slower speed than predicted. All other indicators related to pump operation, i.e., vibration, and power consumption, remained within acceptable, expected limits for this operation.

Two additional campaigns were completed during the first three months of 2000 bringing the amount of waste pumped from SY-101 up to 265,000 gallons. During the third campaign, the speed of the pump was varied from 29 Hz (producing a flow of 125 gpm) to 56 Hz (producing a flow of 239 gpm). No anomalies were noted at any operating speed.

The "higher than expected" pump performance was the result of:

- A conservative performance analysis that used a high friction factor for the transfer line, and
- A lower waste viscosity than was used in the analysis.

CONCLUSIONS

All indications from the successful completion of testing and operation conducted to date suggests that the pump's advanced design can be expected to contribute significantly to life-cycle savings in operating and maintenance costs of the waste management operations at Hanford. The pump design capitalizes on proven canned motor technologies successfully developed and applied over the past 40 years by the manufacturer. The integral submerged motor/pump design eliminates the need for externally supplied cooling and lubricating systems. Also, the sealless (dynamic) design and abrasion-resistant, film riding, two-bearing system offer substantial benefits over the vertical lineshaft pump systems currently in use.

The design approach and technology used in development of the NGTP has direct spinoff applications to other light- to heavy-duty industrial pumping applications with aggressive fluid properties. In related applications at waste management sites such as Hanford, similar designs can be employed for mixer pumps used for stirring and dilution of concentrated radioactive slurries. Potential benefits of this type of pump should not be limited to the nuclear industry. High reliability, long life, extremely low maintenance, and ease of decontamination can have immense impact in other hazardous and highly regulated areas of pumping such as the petrochemical industry.

A key element in the success experienced by this project is the collaboration between pump user and pump producer. Each party had invaluable keys, in terms of knowledge and skill, needed to solve difficult pumping problems. Applying these keys in a cooperative fashion resulted in a superior product that could not have been produced by either party independently.

NOMENCLATURE

α-SiC = Alpha silicon carbide
AC = Alternating current
CBA = Cost benefit analysis
cP = Viscosity in centipoise
DOE = Department of Energy
EPA = Environmental Protection Agency
gpm = Gallons per minute
HIS = Hydraulic Institute Standards
Hz = Cycles per second
lb = Pounds
MWST = Maximum winding surface temperature
NEC = National Electric Code
NGTP = New generation transfer pump
NPSHa = Available net positive suction head
ORP = Office of River Protection
PWM = Pulse width modulation
R = Rads
rpm = Revolutions per minute
sg = Specific gravity
SST = Stainless steel
TWRS = Tank waste remediation systems
VFD = Variable frequency drive
°C = Degrees Centigrade
°F = Degrees Fahrenheit

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