PUMP SELECTION AND APPLICATION IN A PRESSURIZED WATER REACTOR ELECTRIC GENERATING PLANT

by

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ABSTRACT

Various pump applications utilized in a nuclear pressurized water reactor electric generating plant are described. Emphasis is on pumps installed in the auxiliary systems of the primary nuclear steam supply system. Hydraulic and mechanical details, the ASME Code (Nuclear Design), materials, mechanical seals, shaft design, seismic qualification, and testing are addressed.

INTRODUCTION

Pumps utilized in a nuclear power plant vary in design, ranging from simple single-stage circulating water pumps to complex multi-stage pumps used for high pressure emergency reactor safety injection cooling. The design, manufacture, testing, and qualification of this equipment is carefully controlled by the equipment specification and purchase order contract. The Nuclear Regulatory Commission has established design rules and regulations which control the design, quality assurance, and qualification process for safety related equipment used in the nuclear power plant. It is the utility plant owner's ultimate responsibility to obtain the operating license which entitles him to operate the plant to produce electricity.

A typical Pressurized Water Reactor (PWR) nuclear power plant has traditionally been divided into two parts: the Nuclear Steam Supply System (NSSS) and the Balance of Plant (BOP). The utility selects an Architect Engineer (A/E) to design, build and oversee the construction of the plant, and a separate supplier for the nuclear steam supply system. Both the A/E and NSSS supplier become the owner's designee and provide design, qualification and construction support to the utility during the plant construction and licensing process. Because of the unique construction, qualification, and pump operating requirements, the utility often requires assistance from the NSSS supplier, A/E, or pump supplier to provide engineering, repairs, or technical parts service after the plant is operating, since any design changes and/or repair work must also follow approved procedures and be properly documented in the utility quality assurance program.

The design and qualification of the pumps provided by the NSSS supplier, with special emphasis on the "Auxiliary Pumps," will be described. These pumps are those which most typify the pump applications used in fossil power, chemical, and petrochemical plants.

PWR PUMP APPLICATIONS

A Pressurized Water Reactor (PWR) steam generating plant consists of two major systems to produce steam. The primary system, which contains the reactor, is the heart of the nuclear plant. The radioactive primary water, which is kept subcooled at 2250 psig and 570°F, flows through the tube side of the steam generators (or boilers). The secondary side of the plant contains the feedwater/steam system and turbine-generator. Feedwater flowing through the steam generator shell side boils to form steam at 1100 psig, 550°F.

There are also various auxiliary systems which service both the primary and secondary systems. Several of the major pumps found in a typical four loop 1100 megawatt nuclear plant are listed in Table 1. Note that the pumps are listed by system application.

The reactor coolant pumps circulate high pressure primary water through the reactor and into the steam generator where heat is transferred to the feedwater. A reactor coolant pump for a PWR plant is shown in Figure 1. The pump has an axial bottom suction and radial discharge. A major feature of the pump is the three-stage, controlled leakage mechanical seal (Figure 2). High pressure seal injection water is introduced into the seal area to act as a buffer to protect against the reactor coolant flowing up along the shaft and causing potential seal, shaft, and bearing damage. Controlled leakage is collected from the No. 1 and No. 2 seals. The reactor coolant pump is a primary pump, while the following applications are all considered to be auxiliary pumps.

The centrifugal charging, positive displacement charging and boric acid transfer pumps function in the chemical and

Table 1. Pressurized Water Reactor Principal Pump Applications.

Pump Application	No./Plant	Flow (GPM)	Head (Ft)	Design Press. (psi)	Design Temp. (°F)	ASME Section III Class	Seismically Qualified	Configuration	Speed (RPM)	No. Stages	Specific Speed	Suction Spec. Spd.	Driver Hp (Nominal)
Primary and Auxiliary Systems													
- Reactor Coolant	4	93000	305	2500	650	1	yes	Vertical	1200	1	4500	7326	7000
- Centrifugal Charging	2	150/550	5800/2400	2800	300	2	yes	Horizontal	4850	11	1020	11900	600
- Positive Displacement Charging	1	98	5800	3200	300	2	yes	Horizontal	200	5 Plunger	–	–	200
- Boric Acid Transfer	2	75	235	150	200	3	yes	Horizontal	3600	1	790	7762	25
- Residual Heat Removal	2	5500	250	600	400	2	yes	Vertical	1800	1	1540	12435	400
- Safety Injection	2	425	2500	1750	300	2	yes	Horizontal	3600	10	1150	10150	3600
- Containment Spray	2	450	2600	275	300	2	yes	Horizontal	1800	1*	741	9114	400
- Component Cooling Water	2	9500	245	250	180	3	yes	Horizontal	1800	1*	2794	10625	500
- Service Water	2	10800	125	150	150	3	yes	Vertical	1200	1	3080	7677	450
Secondary Systems													
- Steam Generator Feed	2	10500	2150	2000	450	NNS	no	Horizontal	4825	1*	1565	15272	6000
- Auxiliary Feedwater	3	800	3800	2300	100	3	yes	Horizontal	3600	10**	1180	8488	1200
- Condensate	2	6320	1250	300	250	NNS	no	Vertical	1200	8	2600	12670	2500
- Condenser Circulating Water	2	312,530	25	150	200	NNS	no	Vertical	270	1	13500	13710	7000

*Double Suction
**Double Section 1st Stage

Figure 1. Reactor Coolant Pump.

Figure 2. a) Shaft Seal Assembly. b) Simplified Shaft Seal Assembly.

Figure 3. Centrifugal Charging Pump.
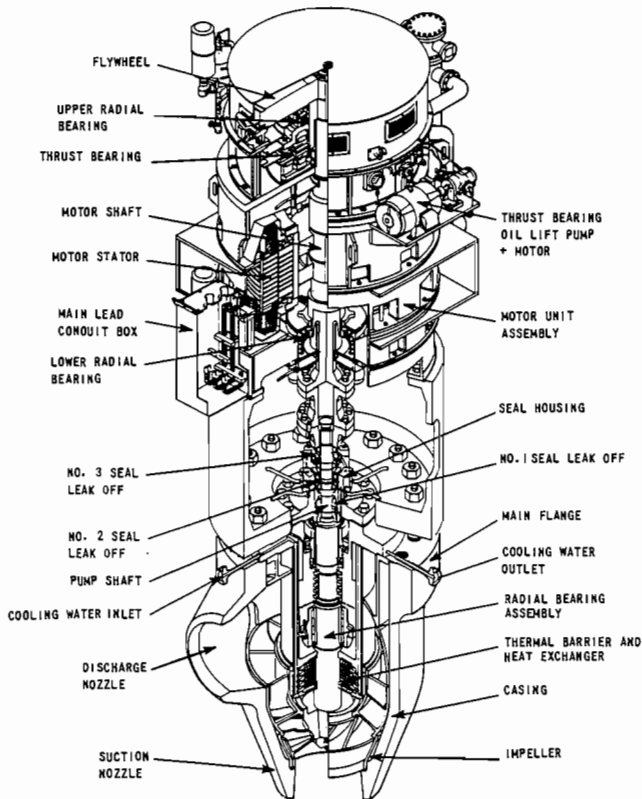
volume control systems. The charging pumps provide reactor coolant makeup flow to the reactor and seal injection flow to the reactor coolant pump. A centrifugal charging pump is shown in Figure 3. The centrifugal charging pump also serves as a high pressure safety injection pump in the emergency core cooling system, should a leak develop in the reactor coolant system.

The safety injection pump which serves solely in the emergency core cooling system is shown in Figure 4. The pump normally remains idle and is used only for periodic testing and the plant emergency condition.

The residual heat removal pumps (Figure 5) are low pressure circulating pumps, used to remove decay heat from the reactor for plant shutdown. These pumps also have a dual function, in that they provide low head safety injection flow to the reactor for emergency core cooling.

A large pipe break accident will cause the reactor containment building to fill with steam and dangerous radioactive
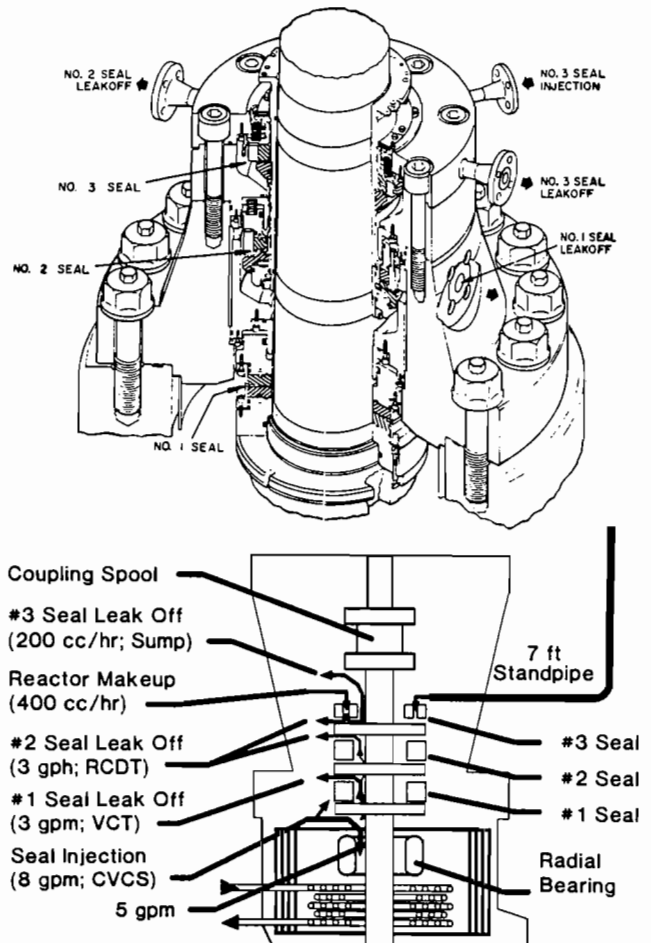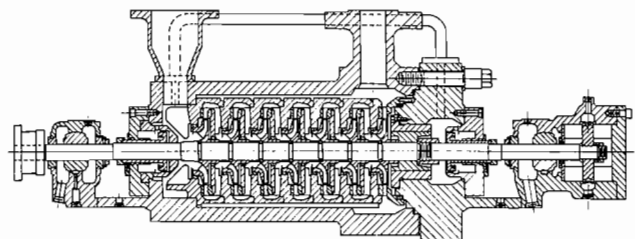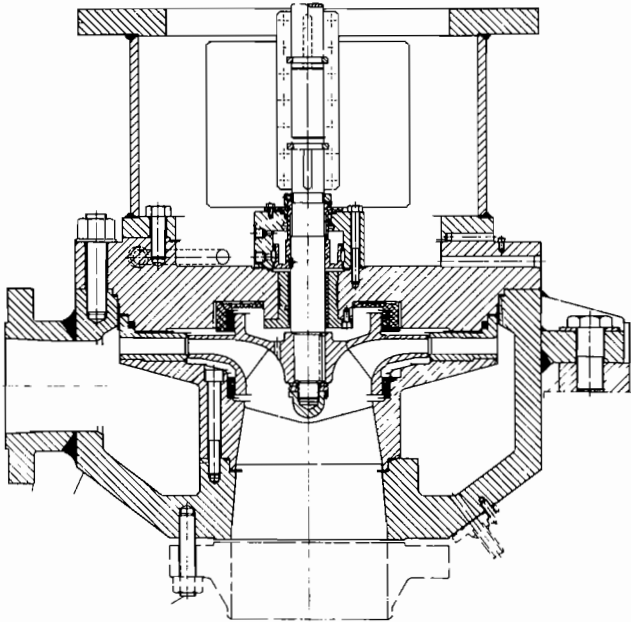
Figure 4. Safety Injection Pump.

Figure 5. Residual Heat Removal Pump.

gases. The containment spray pumps function to condense the steam and reduce the gas concentration in the containment building by spraying water through headers located at the containment ceiling.

The component cooling water pumps circulate clean closed loop water through the primary side vital heat exchangers, which include the reactor coolant pump thermal barrier and residual heat removal heat exchangers.

Removal of the primary heat load is eventually accomplished by the service water system. The service water pumps are installed in an open system which normally uses a river, lake or the ocean as a heat sink.

There are also other auxiliary systems, such as the spent fuel system, the waste procurement system, and the boron recycle system. These systems utilize American Voluntary Service (AVS), canned motor, and other low pressure pumps.

The secondary or steam system includes the turbine-generator and is similar to the conventional fossil plant steam system. The steam generator feed pumps supply water to the shell side of the steam generators. Converted steam flows through the turbine-generator, is condensed, and then pumped back to the feed pumps, via the condensate pumps.

The auxiliary feedwater pumps provide emergency feed-water to cool the steam generators, should there be a failure in the feedwater system. The auxiliary feedwater pumps are the only safety related pumps located in the secondary system.

Steam is condensed in the condenser by means of the circulating water system. The pumps draw river, lake, or ocean water and pump it through the condenser—normally into a cooling tower.

DESIGN CONSIDERATIONS

General

The basic philosophy used in nuclear pump design is similar to that used in American Petroleum Institute (API) and fossil plant pumps. However, differences arise from the fact that greater emphasis is placed on a) the pressure boundary integrity of equipment specifically containing radioactive primary water and b) the functional operability of those pumps which must function in order to safely shut-down the nuclear reactor.

Nuclear component design and quality requirements are specified by the Nuclear Regulatory Commission (NRC) in 10CFR part 50, Appendix B, entitled "Quality Assurance Criteria for Nuclear Facilities." Pressure boundary design integrity is governed by the ASME Boiler and Pressure Vessel Code, Section III, "Design of Nuclear Components." Various functional requirements which specify the operability of equipment required to perform under normal and emergency conditions are covered by NRC Regulatory Guides.

ASME Code Requirements

The ASME Code (Section III, Subsection NA-3250) specifies that an owner's equipment specification must be included in the pump purchase order. The equipment specification includes the pump functional definition, ASME Code pressure boundary class, hydraulic and mechanical design requirements, nozzle load, environmental conditions (radiation, chemistry, temperature, etc.), seismic qualification levels, stress limits, special material and fabrication requirements, and packaging.

The ASME Code categorizes pumps into three classes. All pumps installed in the primary pressure boundary are class 1. The reactor coolant pump is the only class 1 pump application in the PWR plant. For class 1 pumps, the Code requires that a detailed pressure boundary stress analysis be provided as part of the pump design verification. This includes a fatigue analysis of those parts which are subjected to thermal or pressure cycling. Class 2 pumps are those located in the auxiliary primary system. These pumps not only contain radioactive fluid, but are also the safety related pumps which must operate during an accident. Class 3 pumps are typically those which do not contain radioactive fluid, but are vital to safe plant shutdown. A detailed stress report is not required by the Code for class 2 and 3 pumps. However, some constructors require that the supplier provide a certified design and seismic analysis as part of the purchase order contract.

The Code also contains rules for quality control during material procurement, manufacture, and nondestructive testing. A nuclear-stamp (N-stamp) pump builder must follow ASME guidelines and document a detailed quality assurance program, and meet these conditions through periodic ASME surveys, before he is entitled to affix an N-stamp to a supplied pump.

Materials

Materials used in the pressure boundary of ASME section III pumps must be listed as acceptable materials in the Code. This also applies to materials used in the design of the pump supports. Although not specifically required by the Code, requirements for "wetted" parts and critical load carrying members are also often specified.

Typically, all pressure boundary and wetted parts for class 1 and 2 pumps are stainless steel. The class 1 reactor coolant pump casing is fabricated from a two piece SA-351, Gr CF8 (304) casting. Class 2 pump casings are normally forged in a 300 series stainless steel. Forgings are used to minimize non-

destructive examination problems which often result with castings. Class 3 pump casings are typically carbon steel castings.

Examples of materials used in nuclear pump applications are shown in Table 2.

Table 2. Typical Materials.

Type	Stainless Steel	Carbon Steel
Forgings	SA-182, Gr 304, 316, 321, 347 SA-564, Gr 630 (17/4PH) SA-276, Gr 410, 414	SA-105, Gr I, II
Castings	SA-351, Gr CF8 (304), CF8M (316) SA-351, Gr CA6NM A-296, Gr CA-40	SA-216, Gr WCA, WCB, WCC
Plate	SA-240, Gr 304, 316, 321, 347	SA-515, Gr 55, 60, 65, 70 SA-516, Gr 55, 60, 65, 70
Piping	SA-312, Gr 304, 316 SA-213, Gr 304	SA-106 Gr 8
Bolting	SA-453, Gr 660	SA-193, Gr B6, B7, B8, B16 SA-194 Gr 8

Impellers and diffusers or volutes are cast from materials such as SA-351, GR CF8 or CF8M or SA-182 GR 304 or 316. Most of the multistage auxiliary pumps have flame hardened impeller wear surfaces. The stationary wear rings are constructed from high chrome steel and are machined with grooves to contain any debris which may cause possible galling of the rotating impeller.

Shafts

Normally, the shaft is the most highly stressed component in the pump. Since it is susceptible to fatigue and corrosion, it is necessary to select a shaft material which has high tensile strength to provide a sufficient endurance limit, with excellent corrosion resistance, yet be adquately ductile to have a low notch sensitivity.

Most safety related pump shafts are made from a 400 series forging such as SA-276, type 410 or 414. These materials offer high strength and good corrosion resistance; however, one must be extremely careful of the heat treatment process used with these materials. Specifications are sometimes utilized that require all 400 series steels used for shafting be either annealed or hardened and tempered at a temperature of 1100°F minimum, to assure proper fracture toughness and to preclude excessive notch sensitivity.

A fatigue analysis is completed on a safety related pump shaft using techniques such as the Goodman Diagram Method. These techniques not only consider alternating loads, but also the steady loads such as thrust and torsion, which are constant during pump operation. Stress concentration factors resulting from the various shaft irregularities must also be included to provide an accurate stress condition.

Some of the design and manufacturing features incorporated in nuclear pump shafts to improve reliability include:

• Careful control of material selection and heat treatment procedures.

• Ultrasonic inspection of the shaft forging to assure the absence of subsurface material flaws.

• Visual and mechanical examination of high stress areas, to assure a uniform and smooth surface to minimize stress concentration factors.

• Environmental fatigue testing of the shaft material to ascertain the endurance strength.

• Rolled threads as opposed to machine cut threads. Rolling enables a larger and more uniform root radius, which effectively reduces stress concentration factors.

• Maximized impeller split ring groove radii to reduce stress concentration factors.

• Final shaft straightening using peening techniques in lieu of a hydraulic press. This technique tends to minimize potentially harmful surface tensile residual stresses.

Additionally, several of the high pressure pumps use a flanged style locknut instead of a standard circular nut to lock the balance drum to the shaft (figure 6). The flanged nut distributes the pump axial thrust load evenly over all of the shaft threads, as opposed to the traditional fastening technique, which results in most of the load being concentrated in the first few engaged threads.

As mentioned earlier, one technique used to predict shaft life is to compare the equivalent alternating stress, to which the shaft is subjected, to the notched endurance limit of the shaft
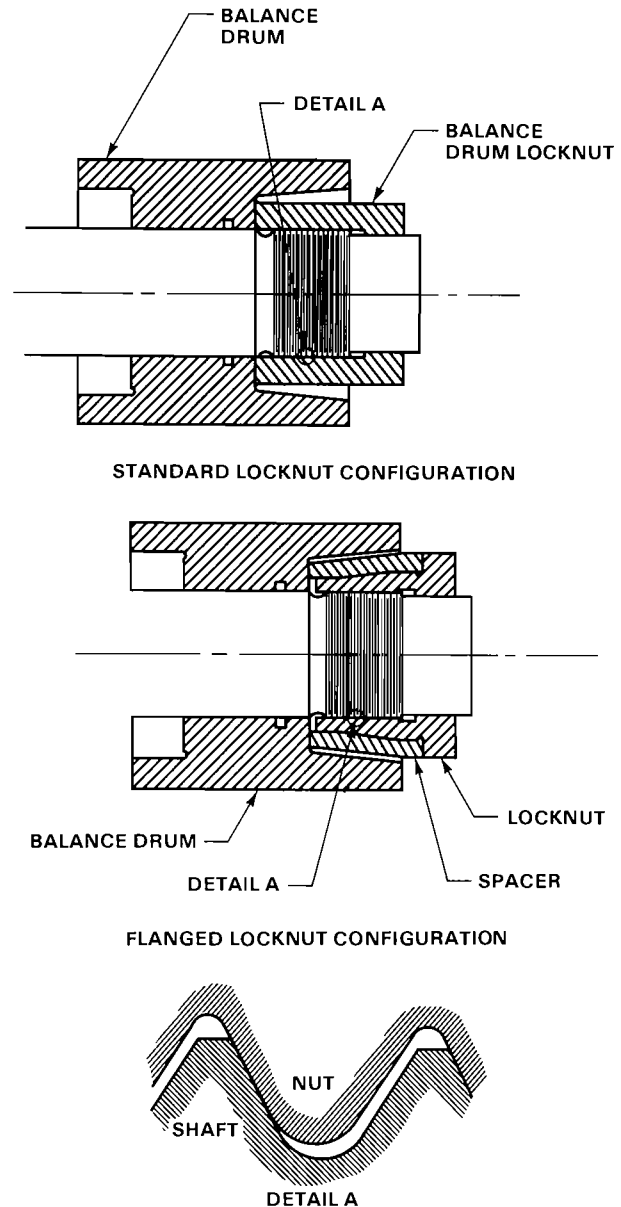

Figure 6. Shaft Balance Drum Locknut Configurations.

material. The notched endurance limit is given by the following formula:

$$\text{Sen} = S_e \, K_a \, K_b \, K_c \, K_e \, K_g \frac{1}{K_f}$$

where

Sen = Notched endurance limit (cycles)

S_e = Smooth (or unnotched) endurance limit

K_a = Surface finish factor

K_b = Size factor

K_c = Reliability factor

K_e = Environmental factor

K_g = Geometry factor (e.g., thread, keyway, etc.)

K_f = Stress concentration factor = $1 + q(K_t - 1)$

q = Notch sensitivity factor

K_t = Tensile stress factor

The expected shaft loadings are determined and categorized as mean or alternating components. The equivalent alternating stress, to be used to evaluate fatigue life, is then determined as a function of the applied mean and alternating stresses, Figure 7. Shaft life is finally obtained by plotting the equivalent alternating stress values on the fatigue curves.
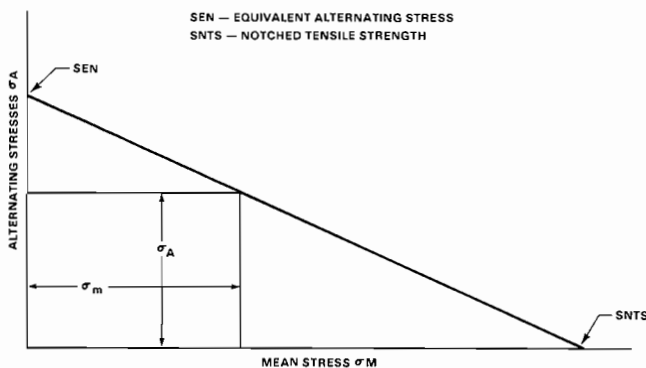
Figure 7. Equivalent Alternating Stress.

Examples of these calculations when applied to a nominal two inch diameter pump shaft show the following:

BALANCE DRUM LOCKNUT SHAFT THREAD

Geometry Change	Sen Improvement
Standard machine cut threads root radius increase of 200 percent	10 percent
Rolled thread vs. cut threads	200 percent
Flanged locknut vs. standard nut with cut threads	45 percent
Rolled threads and flanged locknut vs. standard nut with cut threads	300 percent

Mechanical Seals

Most pumps used in a nuclear power plant are furnished with balance end face rubbing seals. Although nuclear sealing temperatures and pressure are not extreme, the seals are subjected to mechanical and thermal cycling, radiation, and chemical attack.

Typically, these seals are designed to fit shaft sizes of two to three inches in diameter and to operate at conventional pump speeds of 3600 rpm. Sealing environments are usually below 200 psig, 300°F.

A light water reactor, such as PWR, uses boric acid as a moderator to control reactivity. Thus, the seal must also be able to operate in an up to four percent (by weight) boric acid concentration. A few auxiliary pump applications require operating in 12 percent boric acid solutions. Radiation is also a significant design consideration especially for the emergency

core cooling system pumps which may experience up to 10^8 rads of total radiation dosage following an accident. Because even small amounts of highly radioactive water leakage are considered unacceptable, the extreme outboard end of the seal was designed to include a "disaster bushing." This bushing is a spring loaded packing which rides near the shaft and forms a very tight leakage clearance to seal against catastrophic failure of the primary seal or its subcomponents.

A typical cross-section view of a mechanical seal used on nuclear pumps is shown in Figure 8. The seal is a pusher type, utilizing carbon on tungsten carbide for the primary sealing faces. The secondary seals (bellows, 0-rings) are constructed of an elastomeric material and the safety bushings from a graphite compound.
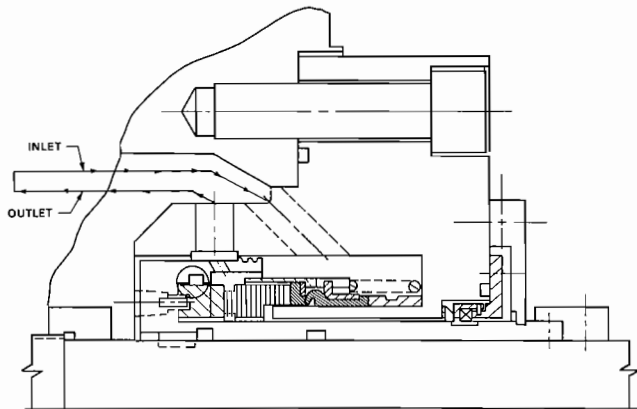

Figure 8. Mechanical Seal Assembly.

Note that the pumping ring and shaft sleeve are manufactured as an integral assembly, thus eliminating the need for setscrews, which have on occasion proved to be unreliable. Emphasis has been placed on minimizing the number of parts and fasteners which make up the seal. For many auxiliary pump applications, except the residual heat removal pumps (i.e., pumps operating <300°F), seal coolers have been eliminated and only the internal pumpage provides seal face flush and cooling requirements.

Two major seal suppliers have performed qualification tests to measure safety related pump seal performance under postulated emergency conditions. The parameters which were varied during these tests include boric acid concentration (0-12 weight percent), pressure (60-400 psig) and temperature (160-350°F). During several of the high temperature tests (i.e., >300°F), seal cooling was eliminated. These tests were conducted to project the seal life under extreme environmental conditions. Separate tests were completed to measure the flow through the disaster bushings as a function of differential pressure and fluid temperature.

The tedious domestic plant licensing process has resulted in much of the equipment and spare parts lying dormant in storage warehouses, following shipment from the supplier. Consequently, it is recognized that the elastomeric materials used in the mechanical seals have limited storage or shelf life. One of the major seal suppliers has defined elastomer shelf life as follows:

For elastomeric seal components stored under the following conditions

- Ambient temperature 120°F
- Minimum air exposure
- Shielding from sunlight, ozone and radiation

Elastomer Component	Shelf Life From Date of Manufacture

O-Rings (Nitrile, Neoprene, SBR, Viton, Silicone, Fluorosilicone EPDM)	5 years
Bellows and Seat Cups (Nitrile, Neoprene, EPDM, Butyl)	2 years
Bellow and Seat Cups (Silicone, Fluorosilicone, Viton)	5 years

Should storage periods or environmental conditions exceed the specified guidelines, the seal supplier recommends two relatively simple tests be performed to determine the material integrity.

Test A—Flex and Stretch Test

The material should be carefully flexed and/or stretched. No cracking or crazing should be apparent when the material is examined under $10 \times$ magnification.

Test B—Shore "A" Hardness Test

The original Shore "A" hardness value should not indicate a change of ± 5.

(*Note:* If any signs of deterioration are present, the component should be discarded, regardless of the storage time or environmental conditions).

It is common practice that the mechanical seal furnished with the pumping equipment be inspected against the above criteria, and, if necessary, be replaced prior to equipment startup.

QUALIFICATION AND TESTING

Seismic Qualification

Seismic loading is one of the major factors influencing nuclear pump design. The equipment specification requires that the pump supplier show by analysis (or test) that the pump can tolerate the seismic event. All critical part stresses must remain below defined stress criteria. In the case of "active" safety related pumps, the supplier must show that the pumps and drivers will operate safely through, during and after the earthquake, without functional impairment.

This analysis includes normal loads (pressure, temperature), maximum applied nozzle loads, and seismic loads, all of which must be applied simultaneously to the pump assembly. It is desirable to design the pumps and associated equipment to have natural frequencies greater than 33 Hz. This condition categorizes the equipment as "rigid," meaning that the equipment frequency does not coincide with seismic amplification regions, thus permitting a simplified static analysis to be used to analyze the equipment. The larger, more complex pump models are subjected to natural frequency shaker tests of the entire assembly, including all appurtenances, such as lube piping, heat exchangers, etc., to confirm rigidity. A dynamic analysis is performed on those pump units which do not meet rigidity conditions. Multi-stage vertical pumps usually require a dynamic analysis.

Requirements that auxiliary pumps must meet seismic accelerations of 2.1 g in three directions are sometimes specified. These accelerations are at least twice that expected in a typical plant installation. Some of the critical parts analyzed include:

    Pressure retaining parts
    Supports and hold-down bolts
    Pump nozzles and flanges
    Thrust bearing
    Mechanical seal
    Shaft

Lube oil system (where applicable)
Coupling

Seismic Testing

Seismic testing was recently performed on a fully assembled centrifugal charging pump to demonstrate the pump's ability to perform during and after a seismic event. The pump baseplate was bolted to 16 ft × 16 ft aluminum shaker table (Figure 9) and filled with grout to simulate field installation. The pump nozzles were loaded by means of two pistons connected to flanges bolted to each nozzle, to simulate "faulted" tensile, shear bending and torsional nozzle loads and moments, respectively. The baseplate was oriented at an angle of 45° to the horizontal component of table motion. This orientation provided equal motion in the three major axes, i.e., parallel to the pump shaft, perpendicular to the shaft, and vertical. The pump was installed in a flow loop (Figure 10), so that it could be operated while being seismically excited.

The pump assembly was instrumented with accelerometers, strain gages, strain bolts, proximity probes and thermocouples. Tape recorders continuously recorded data. The instrument locations on the pump assembly are shown in Figure 11.

Pre- and post-test inspection of the pump, gear, and motor were completed by manufacturer's representatives. Pre-test pump assembly alignment was performed according to normal field installation procedures and supervised by a pump service representative. Test acceptance criteria was mutually agreed upon between user and the various equipment manufacturers. Criteria included pump hydraulic performance change, vibration, measurable wear, and general equipment functional performance.

The actual test sequence was as follows:

    a) Pre-test inspection.
    b) Development of shock spectrum.
    c) Pre-test operation at minimum flow.
    d) Resonant search without nozzle loads.
    e) Resonant search with nozzle loads.
    f) Pre-test operation at maxium flow.
    g) Seismic simulation.
    h) Post-test operation at minimum flow.
    i) Post-test resonant search.
    j) Mode shape analysis.
    k) Post-test inspection.

A shock spectrum analyzer was used to compare the test response spectrum, to ensure that each seismic simulation met its required response spectrum. Prior to the beginning of testing,
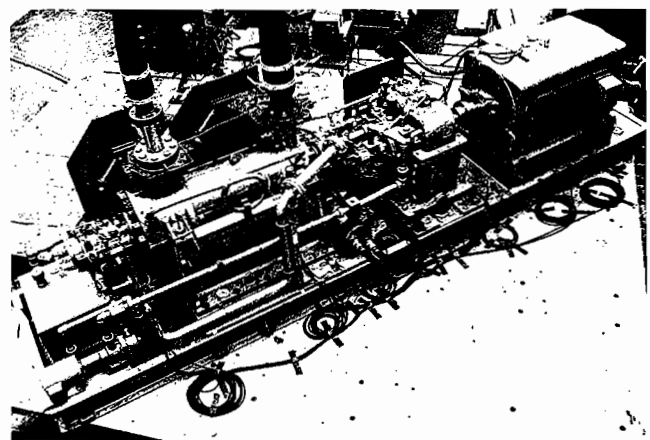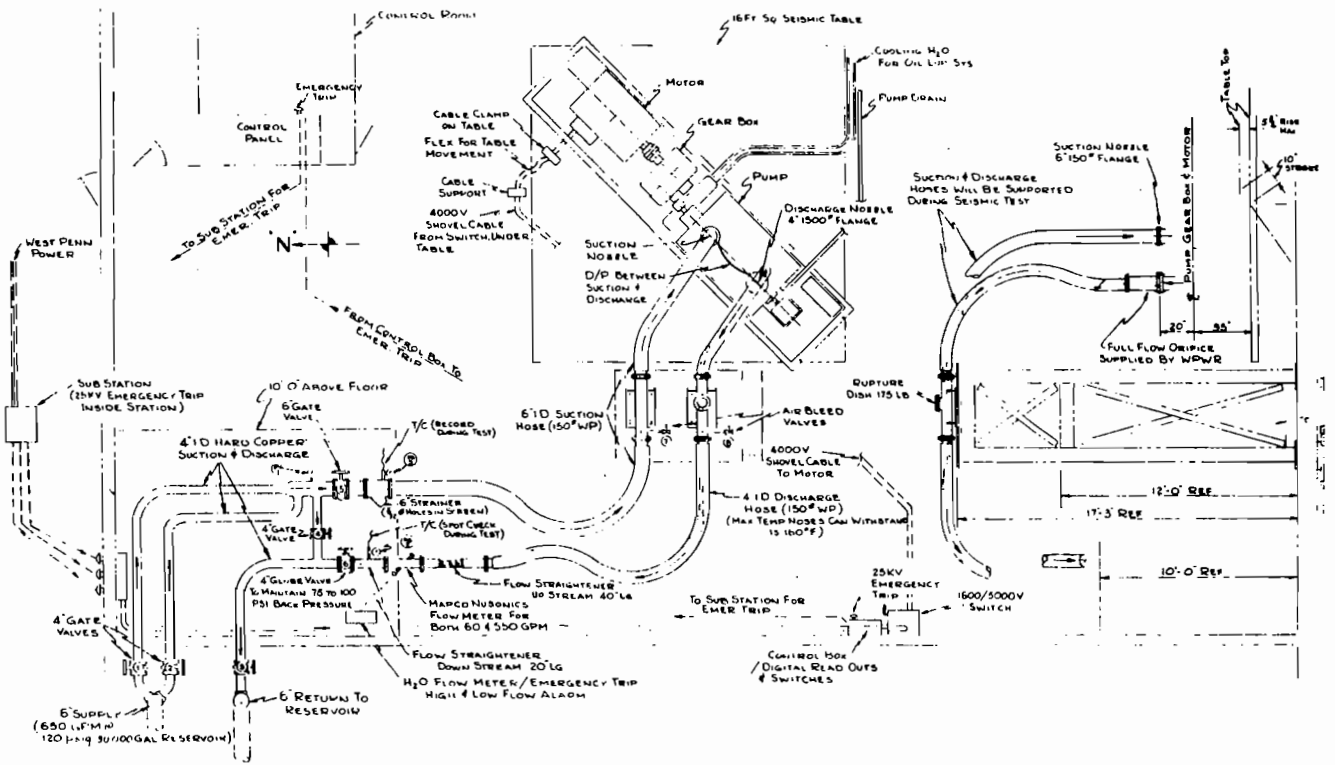

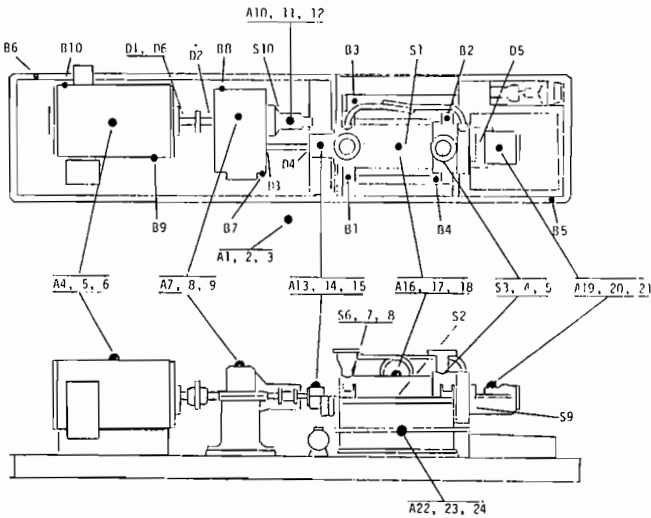Figure 9. Seismic Test Assembly.

Figure 10. Flow Test Loop.

Figure 11. Test Instrumentation. A) accelerometers, B) strain bolts, D) proximity probes, S) strain gauges.

the required response spectrum was obtained by using the test input to shake the table prior to mounting the pump. Resonant searches of the pump assembly were performed to determine natural frequencies of the various components. The frequency range was from 1 Hz to 100 Hz.

Nine separate seismic tests were performed, consisting of five operating basis earthquakes (OBE) and four safe shutdown earthquakes (SSE). An SSE is that earthquake which produces the maximum vibratory ground motion for which certain structures, systems and components are designed to remain functional. An OBE is that earthquake which could reasonably be expected to affect the plant site during the operating life of the plant. An OBE is also that earthquake which produces the vibratory ground motion for which those features of the nuclear

power plant necessary for continued operation without undue risk to the health and safety of the public are designed to remain functional. A safety related pump is required to operate through one SSE and several OBEs as the design basis.

The pump assembly was oriented in four different configurations to envelope various field installations. Each of the tests consisted of a 20 second synthesized time history which was supplied in the form of sine beats of different frequencies. During four of the OBE tests, the pump was started before the seismic event. The pump was required to start during the first 0.5 to 3.5 seconds during the remaining tests. The pump continued to run after the table motion ceased for all tests. The maximum SSE seismic input acceleration was 3.3 g in three directions. The SSE spectrum is shown in Figure 12.
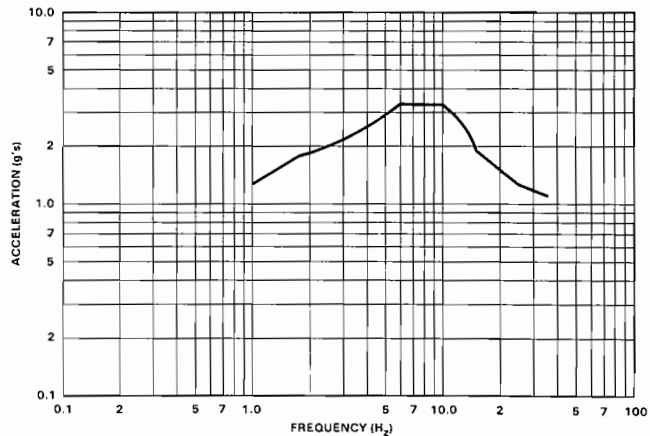

Figure 12. SSE Spectrum.

The post-test disassembly and inspection showed no unusual wear or loading on critical surfaces on parts. There was

virtually no change in hydraulic performance or vibration levels following the tests.

OPERABILITY TESTING

The pumps which operate in the emergency core cooling system of a nuclear plant may be subjected to fluid transients following the postulated accident. These pumps drain suction from an external tank (refueling water storage). Water in this tank is at ambient temperature. Once this souce is depleted, the pump suction is diverted to the reactor sump where water temperature could be as high as 300°F. Theoretically, this transfer could subject the operating pump to a step temperature transient of >250°F. As part of the design verification process, several of the current emergency core cooling system pump designs have been successfully subjected to a thermal transient test in the pump supplier's test facility. Areas of particular concern were:

• Would uneven heating of individual parts cause detrimental rubbings of internal parts?

• Would dimensional changes occur in the hardware so as to degrade pump performance beyond acceptable limits?

• Would excessive seal leakage be caused by either thermal shock or differential expansion?

• Would thermal shock and/or differential expansion cause excessive vibration of the pump?

• Would differential expansion cause detrimental changes in bearing loads?

Instrumentation for a typical thermal transient test performed on a horizontal multi-stage pump (Figure 13) include:

• Proximity shaft probes on the pump shaft (horizontal and vertical each end)

• Velocity sensors on the pump bearing housings (horizontal and vertical each end)

• Key phaser

• Displacement transducers on the casing and the shaft

• Thermocouples (multi-point continuous recording)

    a) In pump bearings (each sleeve and one each side of the thrust bearing)

    b) In pump oil drains

    c) In the pump oil inlet manifold

    d) In the pump suction

    e) In the pump discharge upstream of control valve

    f) On the pump casing (top and bottom of each end)

    g) On the pump head (top and bottom)

    h) On pump seal flush lines (one each end of the pump on the seal outlet)

• Torque meter

Test procedures were established before the test. A pre-test and post-test inspection was performed on the pump critical parts. These included the impeller wear surfaces, wear rings, pressure reducing sleeve, bushing, radial bearings, thrust bearing shoes, and the thrust collar. Acceptance criteria included the following:

1. Results of the performance test following the thermal transient shall meet the original pump contract requirements.

2. Wear part diametral clearances shall not have increased more than 0.003 in over those measured and recorded prior to the thermal transient test. Diametral clearances were determined after wear parts had been cleaned and significant surface irregularities removed where rubbing, if any, had occurred.

The pump was initially operated to obtain baseline data on cold water (70°F). The pump was then subjected to hot water (330°F) in as short a time period as possible. The approximate temperature profile is shown in Figure 14. Data was automatically recorded during the transient and after thermal stabilization. The test loop was then cooled and data were retaken. Typical before and after test results are presented in Figure 15. Following successful completion of the thermal transient test and all post-test examinations of hardware and data, the following were felt to be pertinent:

• Differential expansion of the shaft and the case was much less than conservative calculations had indicated might be experienced. The resultant rubbing of internal parts was therefore minimized and no serious damage occurred. In fact, no parts had to be replaced following the test. Polishing of certain wear surfaces was all that was required to bring all parts into "new" conditions.
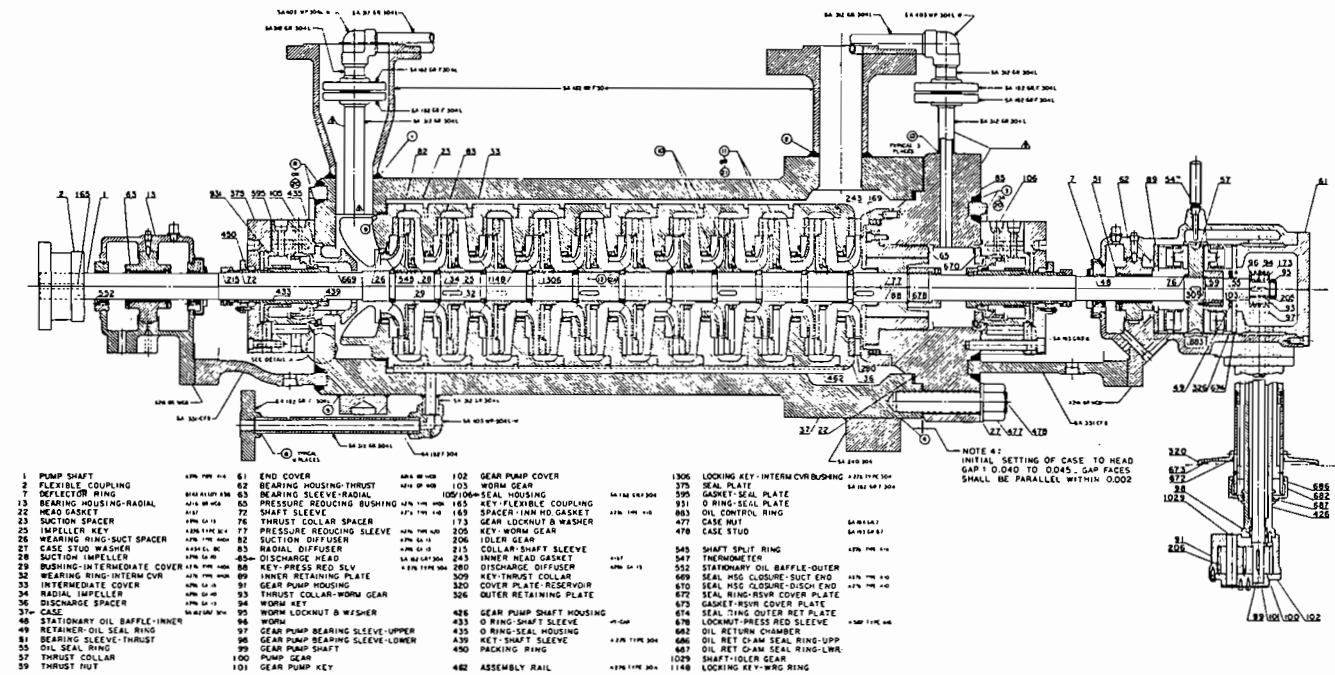

Figure 13. Centrifugal Charging Pump Assembly.

• Pump hydraulic performance was essentially unaffected by the thermal transient.

• Seal leakage after the thermal excursions was nil and was not at all excessive even during transient and high temperature operations.

• Vibration levels never exceeded acceptable levels even though the pump mounting used for the test setup was less rigid than the base plate would be when installed at the site.

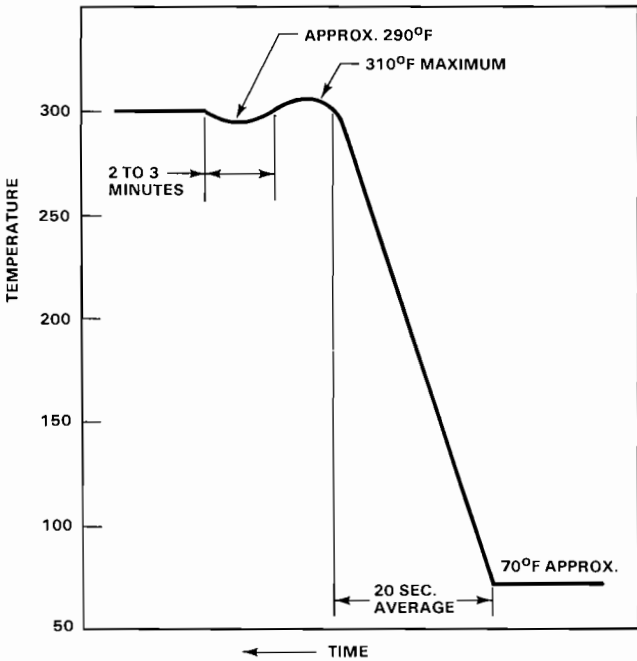• Bearing loads, as evidenced by bearing temperatures, were essentially unaffected by the thermal transient.

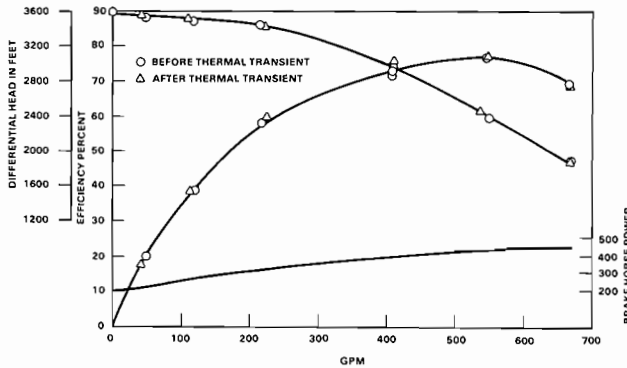Figure 14. Temperature-Time Profile, Thermal Transient Test.

Figure 15. Thermal Transient Test Results.

Other operability tests included a thermal transient with foreign particle injection. The reactor sump may also be filled with debris which has been washed into it, following an accident. Although there is a screen filter in the sump, it will only trap particles greater than 1/8 in; consequently, smaller particles will pass into the pumps.

Vertical turbine pumps (Figure 16) were selected for safety injection service in several plants. These pumps employ special carbon bearings in the suction bowl and column supports. The pump shaft, ASTM A276 Gr410, was heat treated to a hardness of 250 to 300 Brinell and functions as the journal for these bearings. The head and impeller bowl bearings are constructed of 17 chrome stainless ASTM A276 Gr440A, with heat treat-
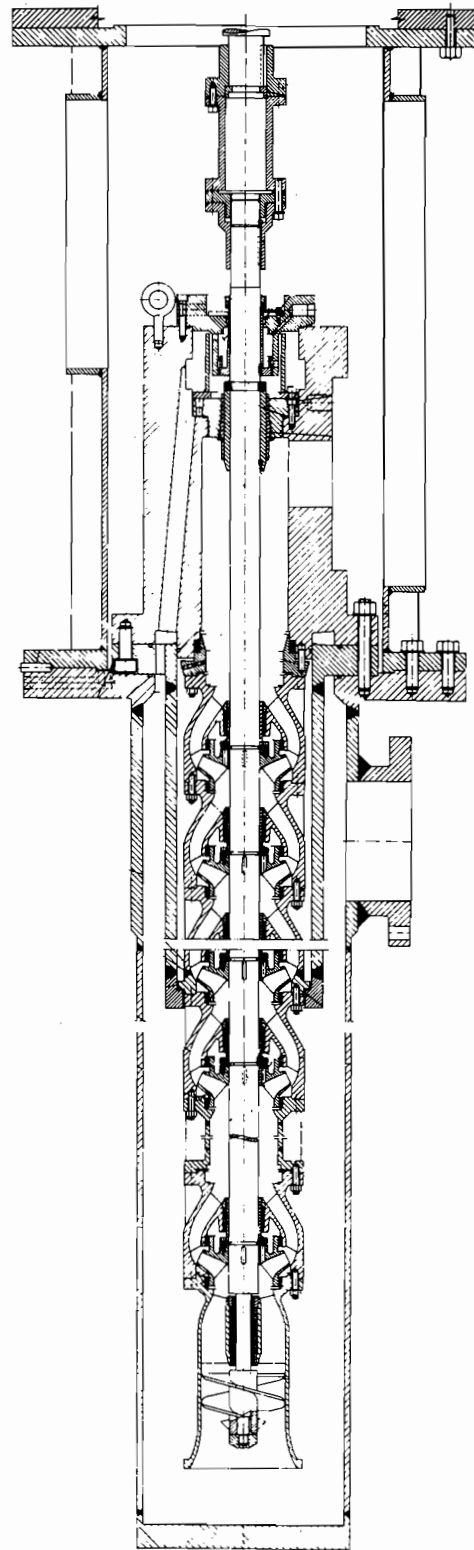

Figure 16. Vertical Pump.

ment to achieve a minimum hardness of 450 Brinell, which operates against 11-13 chrome journal sleeves of ASTM A276 Br420 heat treated to 430-450 Brinell. Since the bearings were lubricated by the pumpage, qualification tests were performed to determine the ability of these pumps to operate through the transient and with reactor building debris in the pumpage. The concentration of foreign material, which consisted of concrete, glass, asbestos fibers, and paint chips, was 92 ppm. The pumps

successfully passed these tests with a resulting developed head change of less than 1 percent. A schematic diagram of the thermal transient and foreign particle test loop is shown in Figure 17.
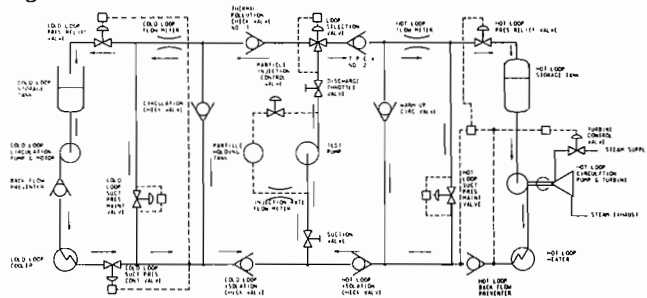

Figure 17. Transient Test Loop Schematic Diagram.

A standard practice often used is to subject all new complex safety related pump designs to a 100 hour endurance test. The objective of this test is to demonstrate the operational compatibility and integrity of the pump assembly as a fully assembled train and to verify that vibration amplitudes and pump performance characteristics remain stable throughout. The pump unit is repeatedly started and stopped and operated at various capacities along the characteristic curve. Instrumentation is similar to that installed in the transient test. During the endurance, test Bóde and Campbell diagrams are also generated to confirm rotordynamic characteristics.

Variable speed tests are completed on pump units to verify that no abnormal responses are in close proximity to running speeds that could cause undesirable rotor responses. Usually, the pump is operated at ±25 percent of normal operating speed, while measuring the response. Rotor unbalance response tests have also been performed on a few of the higher speed pumps to determine the sensitivity of the pump rotor to unbalance. This is to simulate deterioration of production balance due to mechanisms such as creep, unsymmetrical thermal or pressure distortion, erosion, corrosion, wear material deposits, etc.

Each production pump assembly should receive a performance test which includes a mechanical and hydraulic test (including NPSH). The unit is assembled using the job driver and mounted on the baseplate with all functioning auxiliaries. The baseplate is secured to the test floor to simulate the installed condition.

OTHER SPECIAL CONSIDERATIONS

Performance Bands

Unlike most fossil power or chemical plant applications, many of the nuclear pumps must be designed to operate at more than one point on the characteristic curve. Several limitations are placed on the hydraulic designer to comply with the specifications. A sample performance curve is shown in Figure 18. The equipment specification requires that the pump performance test results show that the developed head falls within a normally specified band. The top curve is intended to prevent system overpressure at pump shutoff and to limit fluid energy relative to the containment building at runout flow. The bottom curve reflects the minimum acceptable flow which the pump must provide to the reactor to meet emergency core cooling. The fluid system and nuclear safety analysis engineer performs the reactor and containment analysis at various size pipe breaks, which will dictate the necessary cooling flow. Required net positive suction head (NPSH) must also be limited because available NPSH is minimal following the accident. Finally, since an emergency diesel-generator powers the pump of the

emergency safeguard pump's motors, during loss of offsite power conditions, brake horsepower must be limited so as to control the load capacity requirement and ultimately the size of the diesel-generator.
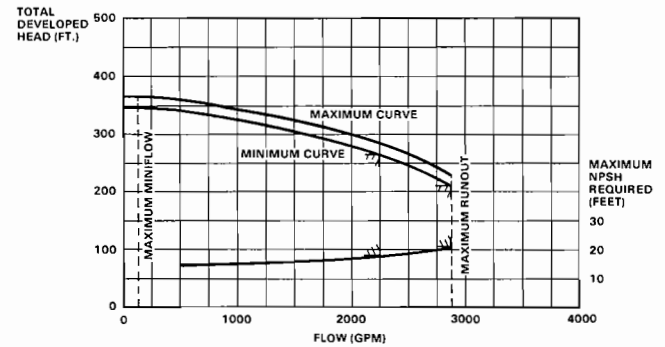

Figure 18. Specification Performance Curve.

Driver Design

Most of the nuclear pumps are driven by electric motors. The design of these motors includes standards such as NEMA MG1, IEEE-232, 334 and 344. Probably the most stringent requirement placed on the motor is that it must start and accelerate the driven equipment (pump and occasionally gear) to speed, while at full operating load and within a specified time. All of this must be accomplished with minimum starting voltage at the motor terminals. The specified time is usually five sec-
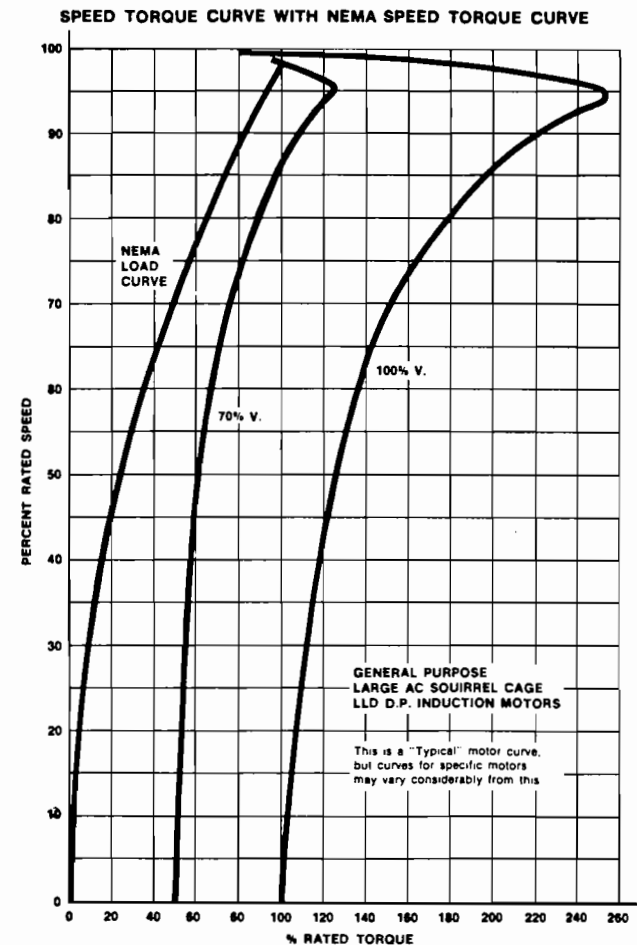

Figure 19. Motor Torque-Speed Curves.

onds, and minimum voltage is 80 percent of full line voltage (although 70 percent is not uncommon). Confirmation of this condition is performed by loading the motor with a dynamometer in the motor supplier's shop and determining its torque-speed characteristic. The driven load-speed characteristic is superimposed on the motor characteristic, and a mathematical integration is performed to determine the acceleration time.

This condition represents a postulated accident, coincident with loss of offsite power. To prevent diesel-generator overload, the emergency safeguard pumps are sequenced to start every 10 sec following the diesel start. A typical motor torque speed curve at full and reduced voltage is shown in Figure 19.

Inservice Tests

The active, safety related pumps must be mechanically and hydraulically tested quarterly in the plant. Pressure boundary and structural integrity must also be verified through the plant life, using nondestructive examination techniques. These tests are defined under ASME Section XI, Inservice Inspection Requirements.

CONCLUSIONS

Nuclear pump design philosophy is based on the rules and experience gained from all areas of pump application. Since structural integrity and functional operability are essential to nuclear plant and public safety, conventional design applications must be altered, analyzed and, in many cases, tested to assure that design specifications have been met. Only a few of the features unique to nuclear pump design and application have been discussed herein.

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