NONMANDATORY APPENDIX S

ARTICLE S-1000
PUMP SHAFT DESIGN METHODS

S-1100 INTRODUCTION

(a) This Appendix provides guidelines for the design and evaluation of shafts for Section III nuclear pumps. They include suggestions for the loads to be considered and the method for arriving at a design that will sustain these loads for the life of the pump.

(b) The method presented is not intended to exclude other methods which may be equally satisfactory. Experience and expertise will be factors in determining the best method. In the final analysis the skill and judgment of the designer determine the quality of the design.

S-1300 DESIGN REQUIREMENTS

S-1310 DESIGN METHODS

The design rules presented in this section are provided as guidance to the designer of pump shafts. Alternative design methods may be used based on the pump manufacturer’s experience with pumps in similar service.

S-1320 OPERATING CONDITIONS

Pump shaft assemblies are subject to combinations of steady state and variable or transient loads. These loads include torsional, lateral, bending, axial, and thermal components. They may occur as a result of power input, hydraulically imposed forces, static or dynamic unbalance, rotating element runout, internal misalignment, thermal distortion, system and component vibration, and resonance. The operating conditions must consider all of these loadings on the shaft. System-applied external loads such as seismic loads and Service Levels A, B, C, and D loads must also be included.

S-1400 RESPONSIBILITY

(a) Owner’s Responsibility. It shall be the responsibility of the Owner or his designee to include in the Design Specification all external forces and operating conditions that may have an effect on the operability of the pump shaft.

(b) Pump Designer Responsibility. It is the responsibility of the pump Designer to include in the evaluation the specified pump loads and identify the type and magnitude of the internal operating loads on the shaft assembly.

S-1500 OPERATING LOADS

S-1501 MAXIMUM SHAFT OPERATING LOADS

In establishing maximum shaft operating loads, the design should take into account plant service that the pump will experience and external loads associated with these conditions. Other forms of off-normal operating loadings may include inservice testing, inadvertent starting and stopping, loss of coolant accident, etc.

S-1502 THERMAL LOADS

Thermal loads shall be considered as one of the internal operating loads.

S-1503 OFF-NORMAL OPERATING LOADS

The maximum steady state and transient loads will usually occur in the pump when it is operating away from its best efficiency point. Typically it will be the combination of loads producing stresses at regions of high stress concentration that may result in high cycle fatigue failures of shafts. The very nature of these loads makes it difficult to quantify them and in some cases a bounding estimate must be made. Examples of load sources include low flow recirculation, flow separation, and other hydraulic instabilities which cause radial and axial alternating or transient loads on the shaft. Lacking a thorough understanding of these loads, conservative design practices based on years of operating experience must be used to insure successful design of pump shafts.
S-1600 SHAFT FAILURE MODES

Shaft failures usually occur at points of high stress concentration or structural discontinuities. The most common locations of shaft failures are threaded regions, shaft grooves, shoulders, keyways, couplings, and collars (see Figure S-1600-1). Areas susceptible to erosion/corrosion, stress corrosion cracking, thermal transients, and steep temperature gradients are also possible locations for shaft failure.
Figure S-1600-1
Typical Centrifugal Pump Shaft Failure Locations

(a) Shaft Groove or Interstage External Damages

(b) Threaded or Shrink-on Parts
ARTICLE S-2000
DESIGN PROCEDURE

Any method of evaluation (analytical or experimental) which can be substantiated by data from pumps in service, experiencing conditions similar to the specified operating limits, may be used.

S-2100 CRITICAL SPEEDS

The evaluation shall address both torsional and lateral, and where applicable, axial critical speeds, shaft deflections, and stresses. Critical speeds and shaft deflections shall be such as to avoid any difficulties for the specified range of the design and operating conditions. The actual percentage difference between critical and operating speeds shall take account of the method of determination of critical speed. The percentage difference between stress allowed and calculated shall also take account of the accuracy of the design and the analysis method.

This polished specimen test endurance limit is then factored for the product of reduction factors that account for such items as environment, reliability, size, finish, duty cycles, etc., which is conservatively estimated as one-third. Consequently, this corrected material endurance limit stress can be represented as:

\[ S_e' = \frac{1}{K_t} \cdot S_e \]

where the terms used on the chart, Figure S-2300-1, are as follows:

- \( K_t \) = stress concentration factors. An initial value of 6.0 is suggested where reasonable stress riser control is exercised. Higher values may be required for designs with severe discontinuities (e.g., small fillet radii relative to shaft diameter). Lower values may be used if justified by design methods and/or testing that accounts for the specific shaft discontinuities under consideration.

S-2200 MAXIMUM TORSIONAL LOAD

The maximum torsional load shall be defined. The maximum torsional shear stress for this load (stress resulting from this load without application of concentration factors) shall be based on design experience or experimental evidence for the particular class of pump involved. The maximum driver horsepower may determine the maximum torsional loading for units with short shafts (typical of pump types A, B, and C). The motor startup torque may determine the maximum torsional load for pumps with relatively long shafts (typical of type L pumps). Torsional alternating or transient loads shall be considered if applicable.

S-2300 SHAFT EVALUATION

The flow chart, Figure S-2300-1, outlines a procedure for evaluation of pump shafts to meet load requirements. This procedure establishes a basic sizing criterion as well as a detailed fatigue evaluation method.

The basic shaft sizing criterion is based on maximum shear stress and conservative cyclic loading factors. These fatigue factors include an evaluation of the endurance limit of the unnotched and polished test specimen reverse bending test data in air \( (S_e) \), which in the absence of specified data can be approximated as:

\[ S_e = 0.5S_y \]

The fatigue life of a shaft is not always the limiting factor in its design. The effect of misalignment and deflection of a shaft on the performance of support bearings, seals, and couplings as well as on other key power transmission components must also be taken into account. Shafts can be strong enough to meet fatigue life requirements, yet not stiff enough to satisfy natural frequency and operational requirements.

S-2400 OTHER CONSIDERATIONS

The fatigue life of a shaft is not always the limiting factor in its design. The effect of misalignment and deflection of a shaft on the performance of support bearings, seals, and couplings as well as on other key power transmission components must also be taken into account. Shafts can be strong enough to meet fatigue life requirements, yet not stiff enough to satisfy natural frequency and operational requirements.
Figure S-2300-1
Steps in the Design of a Pump Shaft

- Establish the maximum operating loads on the shaft
- Size the pump shaft for maximum torque and axial load
- Evaluate the deflection and hydraulic shaft requirements necessary for pump operation
- Determine high stress regions of the shaft and evaluate the required stress concentration factors, $K_t$
- Determine the values of $S_b$, $S_t$, $S_p$, $S_a$, $S_{ss}$
  $$\left[\frac{S_b + S_t}{S_a}\right]^2 + \left[\frac{S_p}{S_{ss}}\right]^2 \leq 1.0$$
- Evaluate the stress concentration regions and modify the configuration to reduce $K_t$
  - Yes
  - $K_t$ reduced
  - No
- Break down load component into load cycles and develop load histories
- Determine the values of $S_b$, $S_t$, $S_p$, $S_{ss}$ and $S_{ss}$ for level A + B service loads
- Using available material fatigue data, define an S-N curve
- Calculate the shaft peak stress components and develop a peak stress history
- Evaluate the cumulative fatigue usage of the shaft
  $$U_t \leq 1.0$$
  - Yes
  - END
  - No
  - REDESIGN

ASME BPVC.III.A-2017