CHECK VALVE WEAR QUANTIFICATION FOR IMPROVED COST EFFECTIVENESS AND PLANT RELIABILITY

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ABSTRACT

Plant reliability and safety hinges on the proper functioning of several check valves. Over the past decade, the Nuclear Industry Check Valve Group (NIC), industry organizations, non-intrusive diagnostic equipment vendors, and engineering consulting firms have proactively developed solutions to address generic problems that result in unplanned maintenance and avoidable plant unavailability. Several utilities have performed reevaluations of safety- and reliability-significant check valve installations, and have instituted programs that employ a combination of testing, inspection, and maintenance to improve plant reliability. There is a wide variance in tools and techniques used to address check valve reliability. These tools range from those based principally on qualitative information to others that apply a combination of qualitative and quantitative methods to assess valve condition.

This paper describes the need for and benefits of applying quantitative wear and fatigue predictions to screen and prioritize safety-related, economically significant, and/or production-critical, “mega-watt robber” check valves. This technique has been used successfully at several U.S. nuclear units to identify misapplied check valves and to prioritize inspection and maintenance activities based on each valve’s propensity for accelerated internal wear. The population of valves recommended for inspection and/or modification can be reduced, allowing effort to be focused on those valves that are more likely to degrade prematurely. This Check Valve Analysis and Prioritization (CVAP) methodology results in an analytical framework for check valve condition monitoring and condition based maintenance. The methodology can provide a benefit to check valve applications regardless of whether they fall under the IST, INPO-SOER 86-03, and/or Condition Monitoring programs.

BACKGROUND

Initial Rapid Developments

Multiple check valve failures in the mid-1980s focused industry attention and led to an increased awareness that these valves are not the simple, passive devices they were once considered to be. In the wake of these events, the US nuclear power industry launched a numbers of initiatives to develop solutions. The Institute of Nuclear Power Operators triggered plantwide evaluations of safety-/reliability-significant check valves by issuing INPO-SOER 86-03 [1] to identify a target population. The owners groups requisitioned the Electric Power Research Institute (EPRI) to

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develop a Check Valve Application Guideline to develop a consistent and credible basis to respond to INPO-SOER 86-03 [2].
Various private companies and industry organizations funded research to develop and improve predictive methods and non-intrusive diagnostic devices for in-plant evaluation of check valves. Kalsi Engineering, under a U.S. Small Business Innovation Research grant, conducted an extensive research program to study disc stability and performed tests to validate wear and fatigue prediction models [3, 4]. This study involved developing first principles models and conducting over 4,000 dynamic flow loop tests on check valves of various sizes with different upstream flow disturbances. Framatome ANP and Crane Nuclear Services developed commercial non-intrusive diagnostic equipment for the evaluating condition and performance of check valves [19-23]

The Nuclear Industry Check (NIC) Valve Group was formed in the late 1980s. Over the years it has remained the focal point for the exchange of ideas and experiences, evaluation of common industry problems, and development of generic solutions. For example, the NIC conducted a comprehensive research program at the Utah Water Research Laboratory to evaluate the capability and limitation of non-intrusive diagnostic technologies (NIT) to determine a check valve's condition [5, 6, 7]. NIC has published, updated, and reviewed many documents to standardize the application of information and advance the state of industry best practices [2, 8, 9, 10, 11]. For example, the Check Valve Non-intrusive Analysis Guide standardizes guidance on the use of NIT, and valve-specific templates consolidate information on industry valve operating experience. The NIC has provided a constant link to check valve users at nuclear plants for input in the enhancement of industry codes and standards like the OM-22, and for interfacing with the various industry stakeholders as well as regulators. NIC has recently completed a set of tests at the Kalsi Engineering flow loop facility as part of a comprehensive NIC program to identify non-intrusive diagnostic parameters that may be trended to indicate internal wear.

The US Nuclear Regulatory Commission independently supported a number of studies to further the state of the knowledge and its implementation [3, 4, 9, 12-17]. For example the comprehensive study on industry check valve failure rate data performed by the Oakridge National Laboratory. EPRI Nuclear Maintenance Applications Center published the NMAC *Check Valve Maintenance Guide* [11] that provides technical guidance for determining valve condition and recommending proper and cost effective maintenance methods. Overall, the industry has benefited by working jointly to address topics of common concern.

As plants age, some problems have surfaced; others continue to lurk undetected. An application of new insights that are now available to predict wear rates, if uniformly applied can help detect some of these impending failures. As market forces continue to shrink budgets and demand greater plant availability the need to better pinpoint bad actors is as great as ever.

Check Valve Condition Monitoring

Major in-plant activities related to check valves center on meeting and fulfilling surveillance, in-service testing, in-service inspection, Section XI leak rate, and maintenance rule-related requirements and licensing commitments. IST testing generally comprises periodic stroke testing, or disassembly and visual inspection. The ASME Oma-1996 Code, 10CFR 50.55a rule offers check valve condition monitoring methodology as an alternative to the periodic IST testing to assure a check valve's present and continued ability to operate reliably [10, 28-31]. The

INPO-SOER program continues to monitor the performance of safety-related, production-critical and/or economically significant check valves whether or not they are in the IST program.

As some plants evaluate and adopt condition monitoring, check valve screening, analysis, and optimization activities have entered a new phase where the emphasis is shifting from doing just what is necessary to doing what is necessary *and* sufficient to build a knowledge base for future evaluations to identify performance trends. Through systematically tracking key parameters that reflect valve condition and analyzing changes, the focus is on accumulating sufficient knowledge on those valves that have been identified as more likely to malfunction. This knowledge base may then be applied to plan and justify required corrective or preventive maintenance on the subject valves and to optimize maintenance activities to assure long-term valve reliability.

More importantly this focus on condition monitoring has stoked continued discussions on what is necessary and sufficient to assure check valve condition. Condition monitoring offers plants the flexibility to apply analysis based on in-house strengths, circumventing the disadvantages of a one-size-fits-all approach. The value of a good condition monitoring approach lies in the fact that it not only assures operability, but can snowball into a knowledge base that can be used to predict future operability. The desire to pick the correct long-term strategy is requiring engineers to define and justify check valve program management plans. Documents referenced in this paper, along with NIC guidance, provide a framework and context on which to build a reliable and cost-effective check valve program

QUALITATIVE VS. QUANTITATIVE PERFORMANCE PREDICTION

On the most fundamental level, all check valve populations, regardless of the program they are classified under, can be thought of as requiring three key activities: (1) screening and evaluation to identify bad actors, (2) performance improvement activities; and (3) re-prioritization based on performance feedback. All three tasks require a mix of qualitative and quantitative data to determine valve condition. For example, the approach underlying the Check Valve Analysis and Prioritization (CVAP) methodology developed by Kalsi Engineering, since its first implementation in 1988, emphasizes the use of a combination of qualitative and quantitative data. Qualitative data is compiled from plant maintenance records, expert panel input, and industry failure trends; and quantitative data is derived from analytical wear/fatigue predictions and measurements of observed wear. This blended information is then used for screening and prioritizing valves based on their propensity for degradation. The methodology relies on the tracking and trending of field wear measurements to validate analytical predictions and an active feedback process to optimize inspection frequencies.

Benefits of Quantitative Wear Prediction

Qualitative data, though generally easier to procure and compile, is varied in consistency and usefulness. Quantitative data requires a greater level of effort to procure, but the end result is generally more tangible and definitive. Wear quantification enhances condition-monitoring activities for safety-related, production-critical and/or economically significant check valve applications by providing an analytical framework for trending valve performance data. For example, it allows for the proper normalization of tracked parameters to account for variations in condition that influence them, thus improving the active feedback process and facilitating problem resolution through planned design changes.

Other benefits of quantifying the internal wear/usage of important check valves include:

- Providing a finer screening to identify potential bad actors and predicting incipient failure to better define and prioritize preventive maintenance intervals based on valve usage;
  - This reduces the disassembly of undegraded valves, saving maintenance costs *and* avoiding the potential for performance problems created by improper reassembly.
  - It improves plant safety and reliability by reducing unpredicted failures.
  - It provides a basis to define preventive maintenance (PM) and test frequencies that are reflective of a valve's propensity for wear.
- Overcoming the limitations of trending only qualitative data collected during condition monitoring activities by providing added insights to analyze quantitative/field measurements to optimize existing processes;
- Improving tracking activities by ensuring that the information collected is necessary and sufficient to draw the desired conclusions, e.g., by increasing the application of non-intrusive diagnostic data;
- Predicting baseline valve performance based on valve design and application as a precursor to condition monitoring.
- Evaluating the impact of increased service and duty requirements associated with power uprate and plant life extensions

CHECK VALVE ANALYSIS AND PRIORITIZATION (CVAP) METHODLOGY

Since the issuance of INPO-SOER 86-03, the methods for screening and prioritizing check valves has evolved significantly. The CVAP methodology developed and implemented by Kalsi Engineering, Inc. is one of the most widely used technical approaches. It has been used to evaluate over 3,000 check valve applications. The paper [24] by Horst and Kalsi provides details of this methodology for implementing quantitative wear predictions. Wear quantification has been shown to offer a sound approach to check valve screening, prioritization and optimization of condition monitoring activities, and preventive maintenance programs.

Technical Approach

The underlying philosophy is based on a blended approach that tempers qualitative insights with quantitative model predictions. Each valve is evaluated as an application and not simply a stand-alone component. For example, screening of a target valve population is based on more than a simple comparison of operating flow velocity to the ideal minimum velocity, Vmin, required to lift the disc to its fully open position and hold its firmly against its backstop. The CVAP methodology, by quantifying the rate of degradation, provides a sound basis for prioritizing valves and better allocation of maintenance resources. Previous reviews [24] have shown that the majority of check valves in power plant applications fail to exceed this minimum velocity threshold. However a review of a large population of check valves revealed that only a small percentage fail in service [9]. This justifies the need for a prioritization-based approach. CVAP narrows the population from roughly 70% of valves that fail to meet Vmin requirements to about 15% of the valves with a higher propensity for wear or fatigue.

Key Elements of the Predictive Models

Key elements of the quantitative disk stability and wear prediction models are:

- Calculation of minimum flow velocity requirements,
- Estimation of the increase in velocity requirement on account of the presence of upstream flow disturbances,
- Prediction of wear in the hinge pin and bushing,
- Prediction of fatigue due to tapping.

Predicting Disc Stability

The minimum flow velocity is calculated using the EPRI Vopen and Vmin equations [2]. The Vopen equation was developed at Kalsi Engineering to explain the root cause of the swing check valve failures at San Onofre, one of the industry significant events that triggered the issuance of INPO-SOER 86-03 [25-27]. Further tests and refinements conducted at the Utah Water Research Laboratory by NIC yielded a refined equation that considers additional geometric relationships and is particularly useful in predicting the minimum velocity requirements of clearway type check valves. These valves are designed to have a small amount of the disc projecting into the flow stream. Since the flow has a smaller projected disc surface area on which to act in stabilizing the disk, such valves have higher likelihood of disk instability.

The CVAP methodology adjusts the minimum velocity requirements based on straight upstream pipe to account for instability caused by fluid turbulence and velocity skew induced by upstream disturbance sources. Kalsi Engineering conducted a comprehensive three-year research program [3] to quantify the effect of upstream disturbances on disk stability. Both the valve geometry and system application are considered in determining disk stability. A comparison of the actual operating flow against the required minimum velocity is then used to determine the disc behavior. The disc can be pegged open, oscillate freely in the flow stream, or tap against a stationary part of the valve internal geometry.

Quantifying Hinge Pin Wear

Wear prediction comprises a detailed evaluation of the design, dimensions and materials of construction of internal components that are susceptible to wear. The wear model is the result of a comprehensive research program [4]. This model accounts for the presence of upstream flow disturbance type and geometry. The model also considers the extent of valve usage in the operating conditions that contribute to internal wear. The "wear mileage" accumulated directly depends upon the service and duty cycle. A key element of this tribological evaluation is the proper consideration of wear coefficient and lubricity at rubbing surfaces. The CVAP methodology uses conservative numbers for wear coefficient and material hardness to estimate the volume of material worn away during a plant cycle. When available, disk opening angle and disk oscillation and frequency data obtained using nonintrusive diagnostic technologies may be applied to improved wear predictions.

Quantifying Disc Stud Fatigue

The fatigue prediction model, much like the wear model, comprises a detailed evaluation of the design, dimensions and materials of construction of internal components that are susceptible to fatigue. The model contains equations to estimate the disc impact energy, cyclic stresses at weakest cross-sections, stress concentration factors at geometric discontinuities, and the statistical distribution inherent in turbulent flow induced tapping.

Collectively these models provide a reliable basis for check valve screening and prioritization. The ability to experiment with the sensitivity of factors that influence degradation provides the check valve engineer with a deeper understanding of those factors that can be controlled. This facilitates improved performance tracking activities and trending based on field observations and wear measurements. Trendable data can be "normalized" if needed before comparison to other data obtained under similar but not identical conditions. As field data validates the model, the check valve application becomes more predictable and less of a black-box whose performance is just measured and not controlled. Therefore, use of quantitative methodologies like CVAP enable a proactive check valve program based on preventive and predictive maintenance rather than corrective or prescriptive maintenance. Such valve performance prediction results provide the baseline knowledge that can serve as a foundation to a sound check valve condition-monitoring program.

A recent survey of three plants supports this view. Plant A had an excellent corrective maintenance program. Plant B had an excellent preventive maintenance program based on prescriptive disassembly and visual inspections of almost the entire target check valve population. Plant C used a blended approach. As Plant A ages, a greater proportion of its check valves are becoming unpredictable and candidates for replacement and repair. Plant B has benefited from its inspection database accumulated over a decade; still, this plant had four instances of unpredicted valve failures. Plant C has the most complete check valve information base, and is able to apply the results of its wear quantification to optimize preventive maintenance activities.

Alternatives to Quantitative Predictive Analysis

The alternatives to quantitative screening, prioritization, and optimization are either extensive disassembly and visual inspection or trending qualitative data. Disassembly and inspection is the most conclusive means of determining the internal condition of a check valve wear; however, cumulative fatigue usage cannot be detected by inspection unless it has progressed to a level of a visible crack. Disassembly and inspection is resource-intensive and introduces the risk of future valve performance problems caused by improper valve re-assembly. Also, a program based solely on disassembly doesn't necessarily guarantee reliable operation. For example, a US plant with a mature disassembly-and-inspect program recently reported four unexpected failures not captured by their tracking and trending program.

Valve disassembly on a sampling basis will always play a key role in assuring the reliability of a check valve population; however, this method requires that it be applied judiciously. A "red, yellow and green light" graded approach to valve disassembly would shift the focus to the inspection of valves in the "yellow light" stage prior to the onset of incipient failure. The plant can reallocate maintenance resources by not performing unnecessary disassemblies on valves in a "green light" good condition. Plant safety and reliability will improve because incipient failures will be intercepted before they enter a "red light" failed condition.

CASE STUDIES IN WEAR QUANTIFICATION

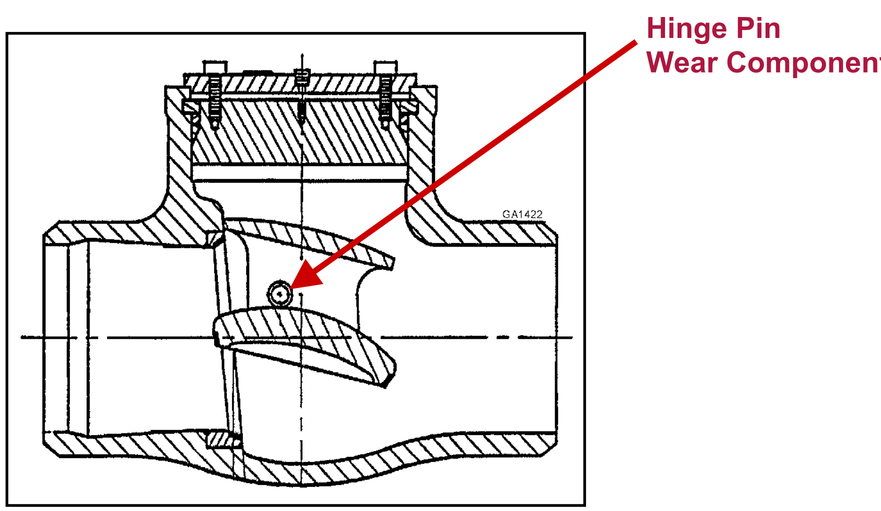
The following case studies highlight the benefit of quantifying wear in check valves.

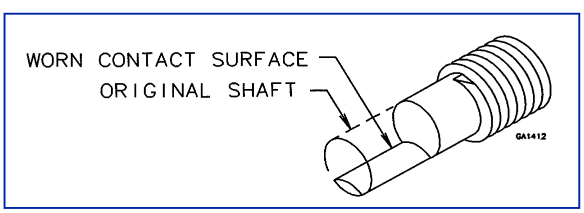
Case Study 1: Predictive wear/fatigue provides a cost-effective and reliable basis to Prioritize Maintenance

The CVAP methodology has been used to evaluate over 3,000 check valve applications in 20 US nuclear power plants. One BWR at which CVAP was used targeted 1,758 check valves for evaluation. The CVAP methodology was first used to screen out systems and valves that were not safety-significant, economically significant or production-critical, reducing the target population to 580 valves. A comprehensive quantitative evaluation was next performed to prioritize valves for maintenance. This process yielded 153 potential bad actors that could be segregated into 74 groups. The remaining valves were assigned lower inspection priorities and inspection frequencies that ranged from once every three to five plant cycles. Upon completion of the engineering evaluation, an expert panel reviewed the results of the predictive analysis to temper recommendations with in-plant knowledge and expertise. This approach streamlined maintenance through a systematic quantitative evaluation of each valve's likelihood of experiencing accelerated wear.

Case Study *2: Optimizing valve design to improve performance*

Quantitative analysis was used to improve the wear performance of a 4-inch tilting disk check valve. Once the wear predictions were validated against the observed wear rate, the wear model was used to evaluate potential design modifications and material choices. The final choice of materials suggested a 20-fold reduction in the rate of wear; actual wear levels tracked over a period of several plant cycles indicated a better than 30-fold reduction.



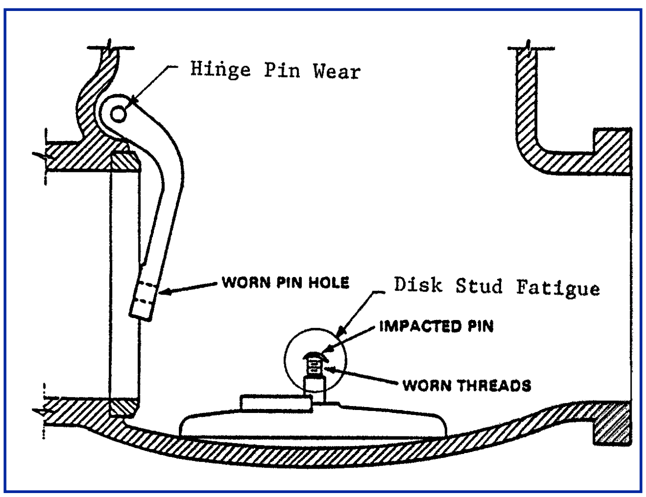


Accelerated Hinge Pin Wear Damage In 4-Inch Tilting Disc Check Valves

Wear Prediction Comparison
Bushing wear rate was predicted assuming two-body contact adhesive wear theory and the following design and operating conditions: Disc Weight = 4.5 lbs; Hinge pin- Bushing Sliding Velocity = 0.5 inch/sec (amplitude +/- 10 deg; freq. 2.9 Hz; 0.5" diameter); Period of wear = 12 months; Material Surface Hardness =288 BHN Load Bearing Area = 0.25 -> 0.125 $inch^2$ (bearing area)

	Predicted	***Actual***
Original	**>.36" / Yr**	**.3" To .5" / Yr (Completely Worn)**
Modified	**0.018" / Yr**	**0.010" / Yr (> 30 Times Improvement)**

Case Study 3 Evaluating the Impact of Altered Operating Conditions
A group of 16" feedwater valves installed in a commercial US nuclear plant had operated satisfactorily for several years, but failed simultaneously after just 15 months of operation at reduced power. The quantitative fatigue prediction model could explain the failure of the disk stud/nut connection by the reduced flow rates. The valve disc had transitioned from a pegged open state to one of continuous tapping against the backstop. The analytical prediction of 10-12 months of operation prior to valve failure correlated well with observed performance.

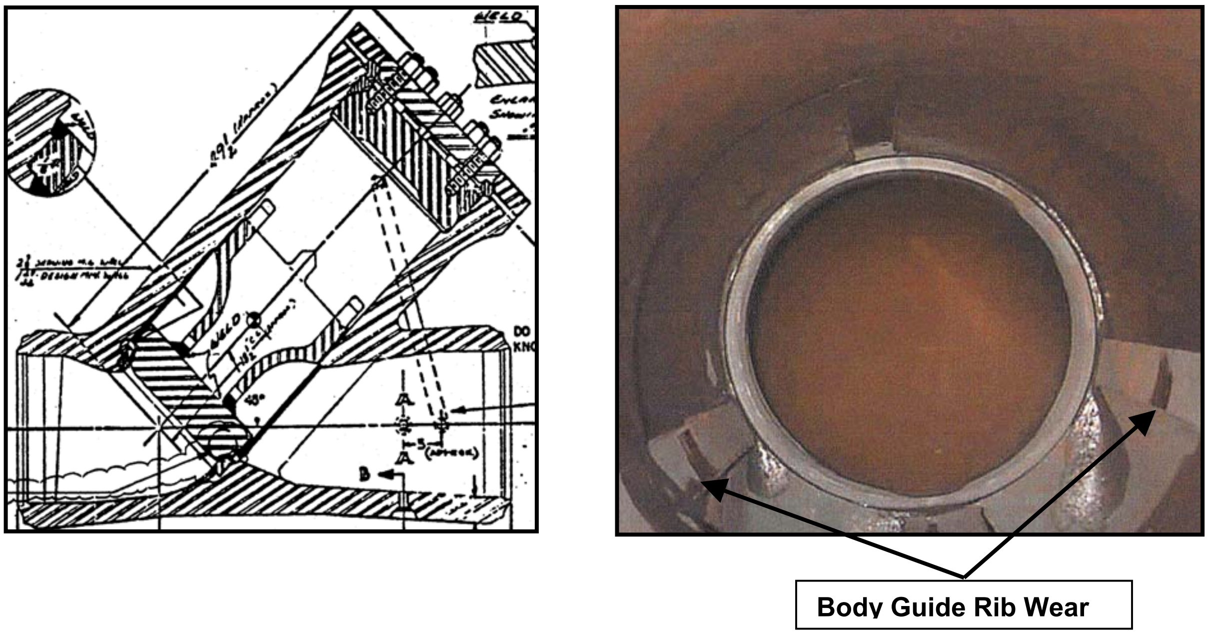


Disc Stud/Nut Connection Fatigue Failures in 16" Feedwater Swing Check Valves Caused Water Hammer, Resulting In Extensive Plant Damage

Case Study *4 Predictive Wear Is Used to Explain Magnitude of Wear Damage*
The level of wear observed in a localized area of body guide ribs of a large 24 inch, Y-pattern, piston check valve could be explained using a combination of Computational Fluid Dynamics

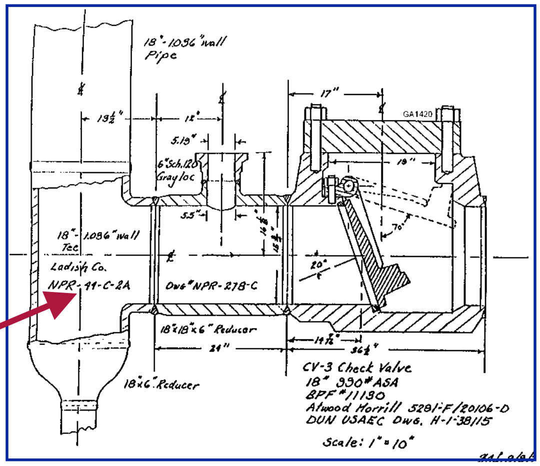
(CFD) analysis [32] and quantitative wear analysis. Once the root cause of failure was identified, closed-form oscillation frequency predictions, together with a wear analysis that factored in the load, materials of construction, stroke length, and duration of operation, could explain the rate of material removal. The CFD analysis provided a basis of eliminating the fluctuation and the root cause of accelerated wear.

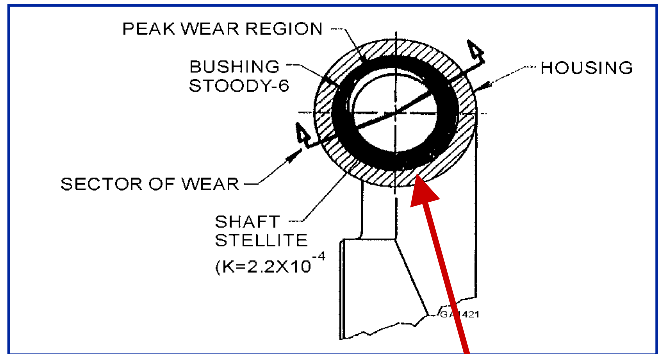
Wear Prediction Comparison: The predicted guide wear rate of 0.017 inches per cycle compared well with the observed guide wear rate of 0.006 to 0.036 inches/cycle and the average reported wear rate of 0.010 inches/cycle. This analysis assumed the two-body contact adhesive wear theory and the following design and operating conditions: Wear Coefficient for hardened steel on Stellite; Plug weight + hydrodynamic effects quantified by CFD analysis = 362 lbs; a sliding velocity = 1 inch/sec (amplitude 0.5 inch; frequency 1 Hz); duration of wear =16 months/cycle; material surface hardness = 350 BHN and bearing area = 18 sq. inches.



Internal Body Wear in a 24" Y-Pattern Piston Check Valve

Case Study *5: Predicting the Performance of Good and Bad Actors*
In this case study, quantitative wear analysis was used to explain the performance of a significant number of large swing check valves. Sixteen of 32 eighteen-inch swing check valves installed at a US nuclear reactor experienced high levels of bushing wear. All valves were identical and had been operated over the same duration. The only difference was that 16 of these valves were installed with a Tee at 1.5D and the remaining 16 had straight pipe upstream. Over a period of eight years of operation, a number of these valves had lost their bushing, some of which had worn through and floated into downstream equipment. Quantitative wear models were able to corroborate the wide difference in wear performance and ascribe it to the upstream piping configuration. The models were able to reliably predict the performance of both the good *and* the bad actors.





18” Valve Bushing Wear Prediction

	Predicted	*Actual*
16 Valves with Tee at 1.5D	**.033" per Year**	**.022" To .027" per Year**
16 Valves with straight pipe	**Very Low, > 30-Year Life**	**Negligible after 8 Years**

CONCLUSIONS

Check valve screening, prioritization, and optimization activities can benefit from a mix of qualitative and quantitative tracking and trending of valve performance parameters. A blended approach to developing a knowledge base that draws on predictive analyses, tracking and trending of performance indicators, valve operating history in plant as well as in the industry, and a judicious application of non-intrusive diagnostic technologies leverages strengths offered by individual techniques. Such knowledge base will help streamline maintenance, prepare for a transition to condition monitoring, and be available to address the emerging check valve evaluations required to support plant power uprate and life extensions.

Wear quantification is a useful tool to improve the reliability of a check valve program. The predictive wear models discussed in this paper are based on the key elements of the EPRI check valve application guide, the results of a three-year research program that studied check valve performance, and insights from 15-years of experience in applying wear quantifications methodologies to develop plant check valve programs. These models provide a systematic method of quantifying check valve wear and fatigue to improve plant reliability and cost effectiveness.

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