Trend and pattern analysis of failures of main feedwater system components in United States commercial nuclear power plants

C.D.Gentillon & T.R.Meachum
Idaho National Engineering Laboratory, EG&G Idaho, Inc., Idaho Falls, USA
B.M.Brady
Office for Analysis and Evaluation of Operational Data, US Nuclear Regulatory Commission, Washington, D.C., USA

1 INTRODUCTION

A prime objective of the United States Nuclear Regulatory Commission (USNRC) is to identify and apply in nuclear power plants (NPP) the lessons learned from operational experience that are relevant to safety. This is particularly a mission of the USNRC's Office for Analysis and Evaluation of Operational Data (AEOD). In addition to engineering reviews of individual events and specific concerns, AEOD has instituted a Trends and Patterns Program that provides a systematic and broad assessment of the operational experience at nuclear power plants. The purpose of this assessment is to identify and investigate potential safety concerns associated with events and failures of low immediate safety significance.

This paper summarizes current results of a trend and pattern analysis of component failure data. The data is from the Nuclear Plant Reliability Data System (NPRDS), a data base voluntarily supported by the US NPP industry and maintained by the Institute for Nuclear Power Operations (INPO). The data base includes records that provide pedigree information on the design characteristics of the components as well as records describing their failures.

Major components within the main feedwater (MFW) system of pressurized water reactors (PWRs) were the first components selected for analysis. This system was selected because loss of MFW is part of a majority of the dominant accident sequences in probabilistic risk assessments of PWRs. Furthermore, MFW transients are the major source of unplanned reactor scrams. To date, we have studied MFW flow control valves, bypass flow control valves, and turbine-driven pumps.

The goal of the trend and pattern analysis of MFW component failure data is to identify component attributes that are associated with relatively high incidences of failure. Manufacturer, valve type, and pump rotational speed are examples of component attributes under study; in addition, the pattern of failures among NPP units is studied. A series of statistical methods is applied to identify trends and patterns in failures and trends in occurrences in time with regard to these component attributes or variables. This process is followed by an engineering evaluation of the statistical results.

In the remainder of this paper, the characteristics of the NPRDS that facilitate its use in reliability and risk studies are highlighted, the analysis methods are briefly described, and the lessons learned thus far for improving MFW system availability and reliability are summarized.

2 NPRDS: A DATA BASE FOR COMPONENT OPERATING EXPERIENCE

The basic structure of the NPRDS was established in the 1971-1974 time period under the direction of the American Nuclear Society/ American National Standards Institute N18-20 Committee. Since INPO has encouraged all U.S. commerical power plants to report all component failures since January 1, 1984, our study analyzes MFW operating experience since that date.

A number of features of the NPRDS make it suitable for use in reliability and risk evaluations. INPO has developed a reporting procedures manual and a scope manual since many utility companies supply input data to the system. These manuals are crucial to ensure consistent definitions of systems and components for trend and pattern studies.

For most component types the data base contains engineering data for reportable components, regardless of whether these components have failed. For reliability and risk evaluations, this feature is essential; failure rates must be based on total population counts. The following are the major component attributes potentially under study for the MFW control valves and turbine-driven pumps:

- for all components, component manufacturer;
- for valves, valve type (e.g., globe), material, body type (cast, forged, fabricated), inlet size, and maximum operating pressure and temperature;
- for valve operators, operator type (e.g., pneumatic/diaphragm/ cylinder), subtype (e.g., reverse-acting), actuation speed, and force and torque ratings;
- for pumps, pump type, inlet size, type of shaft seal, flow rating, total developed head, and rotational speed; and
- for turbines, turbine type (no. of stages, type of flow, etc.), type blading (e.g., impulse), shaft power rating, speed, and inlet pressure rating.

Each instance in which a reportable component is not able to perform its intended function is reportable to NPRDS as a failure. Such failures may be sudden and complete, or the component may degrade over a period of time to an unacceptable performance level. Corrective actions taken to prevent unacceptable performance are regarded as incipient events; the reporting of these is optional.

Failure duration is another desirable feature of a reliability/ risk evaluation data base. NPRDS failure records contain the estimated starting time of a failure, the discovery time, and the failure end time. However, the component may remain in service during portions of this time.

In summary, NPRDS has many desirable features as a data base for reliability and risk evaluations. The importance of explicit definitions of reportable components and their boundaries, of what constitutes a failure, and of each attribute that is to be reported (for example, the difference between angle and globe valves; or whether reported turbine inlet pressure ratings should be based on high (start-up) or low-pressure steam) cannot be overemphasized. For trend and pattern analyses, consistency and completeness are needed.

3 TREND AND PATTERN ANALYSIS METHODS

The initial step in the trend and pattern analysis is a review of data with follow-up calls, under NRC direction, to the designated NPRDS contacts at the utilities to verify or clarify any data that seems atypical or inconsistent. Although differences exist among PWR plant MFW systems, the common function of the specific components under study provides a relatively homogeneous population.

The second step is to select, from the attributes listed above, a set of component attributes (i.e., statistical variables) to analyze for their statistical relation to failure. Some of the conditions or attributes are not applicable and are not included in the analysis.

A series of statistical methods is then applied to the data to identify trends and patterns in failures with regard to the variables being analyzed. Most of the methods are statistical techniques from the field of survival analysis (Kalbfleish, 1980). The methods use the component lifetimes (i.e., times between failures) and the component attributes. The lifetimes are grouped according to values of a particular attribute, probability distributions for time to failure for each group are estimated and differences among groups are evaluated, and the process is then repeated for other attributes. This process identifies possible factors that influence the failure time distributions. For numerical attributes such as valve inlet size, a method tests for trends. All of these statistical methods are tailored to use truncated lifetimes (shortened by the data cutoff date or the study start date) as well as actual times between failures. In addition, the failures are studied in calendar time (Kenett, 1983) to detect shifts in the rate of component problems and identify specific attributes with rates significantly above an average baseline failure rate.

The final step is an engineering follow-up for the statistical results. The factors identified by the statistical analysis are starting points for this investigation. Failures for components with attributes flagged in the statistical analysis are reviewed, considering reported event details as well as component attributes. Root causes for these failures are sought through extensive discussions with appropriate plant personnel, NRC inspectors, and component manufacturers. By identifying the underlying causes and the practices that prevent recurrence, the benefits of experience can be shared to upgrade the MFW system performance for the entire PWR nuclear power plant industry.

4 ANALYSIS RESULTS

Separate analyses have been performed on MFW flow control valves, bypass flow control valves, and turbine-driven pumps. Table 1 shows the numbers of components, failures, nuclear power plant units, and stations with data for each study.

Table 1. Counts for completed trend and pattern analysis studies.

Study	Components	Events	Units	Stations
Flow control valves	121	107	42	17
Bypass flow control valves	101	52	36	22
Turbine-driven pumps	50	76	25	15

The primary finding of each of these studies is that differences among units and stations have a greater influence on the performance of these components than any of the other component attributes studied. For example, there were no highly significant correlations between the failures and component manufacturers. Since plant-specific NPRDS data are proprietary, plant differences cannot be identified here. The problems and the approaches being used to solve them are summarized below.

4.1 Flow control valve findings

Results for the flow control valves and the bypass (start-up) flow control valves are similar; therefore, they are discussed together. Table 2 presents the findings. Most of the recommendations involve improved maintenance, the upgrading of the instrument air system, and the use of improved valve packing.

4.2 Turbine-driven pump findings

Contamination in supporting oil systems and/or moisture dominate in causing turbine-driven pump problems. Contaminated oil contributes to the degradation of gaskets, O-rings, and plugs, thus causing leaks. Plugged orifices and other oil problems caused approximately half of the cases of spurious or nonresponsive governor signals. Moisture is particularly of concern in the oil systems because, with carbon steel lines, corrosion and rust contamination follow.

Careful maintenance of the oil systems is critical to avoid these problems. Cleaning the oil sump tanks during outages and monitoring the pressure in the turbine steam exhaust during operation to ensure that the vacuum is maintained are helpful. Other methods to avoid contamination include the use of (1) air purges for the labyrinth seals separating the turbine bearings from the casing, (2) rotor-stator seals for turbine bearings, (3) nitrogen purges at the oil resevoirs, and (4) vent line drip traps. Centrifugal purification, coalescence, and vacuum dehydration are three methods to remove water.

Approximately 15% of the failures were cases of misalignments or excessive vibration of MFW or lube oil pump impellers, bearings, controller drive shafts, or turbine bearings. Causes for these include manufacturing problems, foreign material, and poor previous maintenance or installation. Temperature differences caused two of these events. In one event, thermal expansion from warm feedwater and cold seal water caused gauling of labyrinth seals. In the

Table 2. Findings of MFW flow-control valve studies.

Problem	Cause	Actions to prevent problems
Valve operator failure	System or valve-induced vibration	Use flexible stainless steel instrument air lines. Use vibration-resistant connectors and fasteners (especially for the solenoid valves).
Valve operator failure	Oil, moisture and/or rust, or foreign particles in the instrument air system	Upgrade the instrument air system with improved blowdown valves and dryers. Monitor instrument air quality and establish maintenance schedules allowing prompt corrective action.
Valve operator failure	Outdoor weather conditions	Use waterproof solenoids.
Valve and valve operator failures	Poor maintenance procedures	Use detailed maintenance procedures that assure the completion of proper maintenance and adjustments before system start-up. Provide adequate training and support of the maintenance personnel. Consult with valve manufacturers to establish efficient routine maintenance schedules. Have valve manufacturers refurbish the valve trim instead of doing this in-house. Cover disassembled valves during maintenance.
Valve released leakage	Packing leaks	Use new packing materials with low shrinkage and designs that maintain constant pressure on the packing (spring-loaded, for example).
	Bonnet/flange	In maintenance, carefully inspect the flange before reassembly.
Valve contained leakage	Improperly adjusted valve operators	Use improved, valve-specific maintenance procedures.
	Damaged valve trim (plug and cage or seats)	Use proper maintenance. Consult valve manufacturers for advice on improved valve trim designs and materials for actual plant conditions such as higher pressure drops.

other case a cold pump was started while the other pump was warm and on-line; the cold pump seized due to the resulting different piping thermal expansion loads. In another event, a vibration problem was eliminated by using an elliptical rather than spherical bearing in the turbine.

Another problem area concerns responsiveness for protective pump or turbine trips and/or reactor trips. Installing metering valves in control oil lines going to the pressure sensor has allowed a more reasonable transition time for switching oil pumps.

Four oil leaks resulted from cracked hoses and two from loose or broken swage lock fittings. These leaks could be avoided by appropriate preventive maintenance.

5 CONCLUSIONS

The engineering evaluation of the statistical results from the trend and pattern analysis shows that proper maintenance and the use of appropriate materials dominate in avoiding problems with MFW components. Athough the MFW system is not a safety system, upgrades of that system and supporting systems such as the control air and oil systems to make the MFW system more reliable will reduce reactor scrams and unnecessary demands on safety systems.

ACKNOWLEDGEMENTS

This work was sponsored by the United States Nuclear Regulatory Commission, Office for Analysis and Evaluation of Operational Data, under Department of Energy Contract No. DE-AC07-76ID01570. The authors thank N. E. Pace and R. D. Fowler of the INEL for engineering evaluations that contribute to this paper and G. L. Plumlee III of NRC/AEOD for his review.

REFERENCES

Kalbfleish, J. D. and R. L. Prentice. 1980. The statistical analysis of failure time data. New York: John Wiley and Sons.

Kenett, R. and M. Pollak. 1983. On sequential detection of a shift in the probability of a rare event. J. Am. Statistical Assoc. 78: 389-395.

NOTICE