Results, Trends, and Insights of the Accident Sequence Precursor Program

1.0 Introduction

This enclosure discusses the results of accident sequence precursor (ASP) analyses conducted by the staff as they relate to events that occurred during fiscal years (FY) 2007–2008. Based on those results, this document also discusses the staff's analysis of historical ASP trends and the evaluation of the related insights.

2.0 Background

The U.S. Nuclear Regulatory Commission (NRC) established the ASP Program in 1979 in response to recommendations made in NUREG/CR-0400, "Risk Assessment Review Group Report," issued September 1978. The ASP Program systematically evaluates U.S. nuclear power plant operating experience to identify, document, and rank the operating events that are most likely to lead to inadequate core cooling and severe core damage (precursors).

To identify potential precursors, the staff reviews plant events from licensee event reports (LERs) and inspection reports. The staff then analyzes any identified potential precursors by calculating a probability of an event leading to a core damage state. A plant event can be one of two types, either (1) an occurrence of an initiating event, such as a reactor trip or a loss of offsite power (LOOP), with any subsequent equipment unavailability or degradation, or (2) a degraded plant condition depicted by unavailability or degradation of equipment without the occurrence of an initiating event.

For the first type, the staff calculates a conditional core damage probability (CCDP). This metric represents a conditional probability that a core damage state is reached, given an occurrence of an initiating event (and any subsequent equipment failure or degradation).

For the second type, the staff calculates an increase in core damage probability (ΔCDP). This metric represents the increase in the probability of reaching a core damage state for the period that a piece of equipment or a combination of equipment is deemed unavailable or degraded from a nominal core damage probability for the same period for which the nominal failure or unavailability probability is assumed for the subject equipment.

The ASP Program considers an event with a CCDP or a ΔCDP greater than or equal to 1×10^{-6} to be a precursor. The ASP Program defines a *significant* precursor as an event with a CCDP or ΔCDP greater than or equal to 1×10^{-3}.

Program Objectives. The ASP Program has the following objectives:

- Provide a comprehensive, risk-based view of nuclear power plant operating experience and a measure for trending nuclear power plant core damage risk.
- Provide a partial check on dominant core damage scenarios predicted by probabilistic risk assessments (PRAs).
- Provide feedback to regulatory activities.

The NRC also uses the ASP Program to monitor performance against the safety goal established in the agency's Strategic Plan (see Reference 1). Specifically, the program provides input to the following performance measures:

- Zero events per year identified as a *significant* precursor of a nuclear reactor accident (i.e., CCDP or ΔCDP greater than or equal to 1×10^{-3}).
- No more than one significant adverse trend in industry safety performance (determination principally made from the Industry Trends Program (ITP) but supported by ASP results).

Program Scope. The ASP Program is one of three agency programs that assess the risk significance of issues and events. (The other two programs are the Significance Determination Process (SDP) and the event response evaluation process as defined in Management Directive (MD) 8.3, "NRC Incident Investigation Program"). Compared to the other two programs, the ASP Program assesses additional scope of operating experience at U.S. nuclear power plants. For example, compared to the SDP, the ASP Program analyzes initiating events as well as degraded conditions where no identified deficiency occurred in the licensee's performance. The ASP Program scope also includes events with concurrent, multiple degraded conditions.

3.0 ASP Program Status

Table 1 summarizes the status of NRC's ASP analyses as of September 30, 2008. Specifically, the table identifies ASP analyses that the staff has completed for events that occurred during FY 2007–2008. (Note that, as of September 30, 2008, the staff had not yet screened all of the FY 2008 events.) The following subsections summarize the results of these analyses, which are further detailed in the associated Tables 1–4.

FY 2007 Analyses. The ASP analyses for FY 2007 identified nine precursors. All nine precursors occurred while the plants were at power. The staff used SDP and MD 8.3 analysis results to identify seven of the nine precursors.

None of the FY 2007 analyses exceeded 1×10^{-4}; therefore, in accordance with the streamlined review process (see Reference 2), the staff issued these ASP analyses as final after completion of internal reviews.

Table 2 presents the results of the staff's ASP analyses for FY 2007 precursors that involved initiating events, while Table 3 presents the analysis results for precursors that involved degraded conditions.

FY 2008 Analyses. The staff has completed all screening and reviews for potential *significant* precursors (i.e., CCDP or ΔCDP greater than or equal to 1×10^{-3}) through September 30, 2008. In particular, the staff reviewed a combination of LERs (as required by Title 10, Section 50.73, "Licensee Event Report System," of the *Code of Federal Regulations* [10 CFR 50.73]) and daily event notification reports (as required by 10 CFR 50.72, "Immediate Notification Requirements for Operating Nuclear Power Reactors") to identify potential *significant* precursors. The staff did not identify any *significant* precursors in FY 2008.

The staff is still screening and reviewing LERs concerning other potential precursor events that occurred during FY 2008.[1] Six FY 2008 precursors have been identified thus far. The staff plans to complete all FY 2008 analyses by September 2009.

4.0 Industry Trends

This section discusses the results of trending analyses for all precursors and *significant* precursors.

Statistically Significant Trend. The trending method used in this analysis is consistent with those methods used in the staff's risk studies (see Appendix E to Reference 3). The trending method uses the p-value approach for determining the probability of observing a trend as a result of chance alone. A trend is considered statistically significant if the p-value is smaller than 0.05. The figures at the end of this enclosure show the p-value for each trend.

Data Coverage. Based on insights gained in SECY-06-028, "Status of the Accident Sequence Precursor Program and the Development of Standardized Plant Analysis Risk Models," dated October 5, 2006, the staff chose FY 2001 as the trend analyses' starting point to provide a data period with a consistent ASP Program scope and to align it with the first full year of the Reactor Oversight Process (ROP). ASP Program changes that occurred in FY 2001 (e.g., inclusion of SDP findings and external initiated events) resulted in a step increase in the number of precursors identified compared to those identified in previous years. The data period for trending analyses ends in FY 2007 (the last full year of completed ASP analyses) but will become a shifting 10-year period in the future.

The following exception applies to the data coverage of the trending analyses:

- ***Significant Precursors.*** The trend of *significant* precursors includes events that occurred during FY 2008. The results for FY 2008 are based on the staff's screening and review of a combination of LERs and daily event notification reports.[2] The staff analyzes all potential *significant* precursors immediately.
- ***Integrated ASP Index.*** The integrated ASP index is not used for trending; therefore, older data may be used. A data period of 10 years (FYs 1998–2007) is used when reporting this index.

4.1 Occurrence Rate of All Precursors

The NRC's ITP provides the basis for addressing the agency's safety-performance measure on the "number of statistically significant adverse trends in industry safety performance" (one measure associated with the safety goal established in NRC's Strategic Plan). The mean occurrence rate of all precursors identified by the ASP Program is one indicator used by the ITP to assess industry performance.

Results. Figure 1 depicts the occurrence rate for all precursors by fiscal year during the period of FY 2001–2007. A review of the data for that period reveals the following insights:

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[1] Licensees have a 60-day grace period after an event or discovery of a degraded condition to submit an LER.

[2] The staff has completed all screening and reviews through September 30, 2008.

- The mean occurrence rate of all precursors exhibits a statistically significant decreasing trend for the period from FY 2001–2007 (see Figure 1).
- The analysis detected a statistically significant decreasing trend for precursors with a CCDP or ΔCDP greater than or equal to 1×10^{-4} during this same period (see Figure 2).

4.2 *Significant* Precursors

The ASP Program provides the basis for the safety-performance measure of zero "number of significant accident sequence precursors of a nuclear reactor accident" (one measure associated with the safety goal established in NRC's Strategic Plan). Specifically, the Strategic Plan defines a *significant* precursor as an event that has a probability of at least 1 in 1000 (greater than or equal to 1×10^{-3}) of leading to a reactor accident (see Reference 1).

Results. A review of the data for that period reveals the following insights:

- The mean occurrence rate of *significant* precursors does not exhibit a statistically significant trend for the period from FY 2001–2008.
- No *significant* precursors were identified in FY 2008.
- The staff has identified only one *significant* precursor since FY 2001. In FY 2002, the staff identified a *significant* precursor involving multiple degraded conditions at Davis-Besse. The specific conditions included cracking of control rod drive mechanism (CRDM) nozzles, degradation of the reactor pressure vessel (RPV) head, potential clogging of the emergency sump, and potential degradation of the high-pressure injection (HPI). Reference 4 provides a complete list of all *significant* precursors from 1969–2006, including event descriptions.
- Over the past 20 years, *significant* precursors have occurred, on average, about once every 5 years. The events in this group involve differing failure modes, causes, and systems.

5.0 Insights and Other Trends

The following sections provide additional ASP trends and insights from the period FY 2001–2007.

5.1 Initiating Events vs. Degraded Conditions

A review of the data for FY 2001–2007 yields insights described below.

Initiating Events

- Over the past 7 years, precursors involving degraded conditions outnumbered initiating events (70 percent compared to 30 percent, respectively). This predominance was most notable in FY 2001 and FY 2002, when degraded conditions contributed to 91 percent and 100 percent of the identified precursors, respectively.
- The mean occurrence rate of precursors involving initiating events is not statistically significant for the period from FY 2001–2007, as shown in Figure 3.
- Of the precursors involving initiating events during FY 2001–2007, 63 percent were LOOP events.

Degraded Conditions

- The mean occurrence rate of precursors involving degraded conditions exhibits a statistically significant decreasing trend during the FY 2001–2007 period, as shown in Figure 4.
- From FY 2001–2007, 41 percent of precursors involving degraded conditions had a condition start date before FY 2001.

5.2 Precursors Involving Loss of Offsite Power Initiating Events

Only one LOOP event occurred in FY 2007 (Brunswick, Unit 2).

Results. A review of the data for FY 2001–2007 leads to the following insights:

- The mean occurrence rate of precursors resulting from a LOOP does not exhibit a trend that is statistically significant for the period from FY 2001–2007, as shown in Figure 5.
- Of the LOOP events that occurred during the FY 2001–2007 period, one-half resulted from a degraded electrical grid outside of the nuclear power plant boundary.
- A simultaneous unavailability of an emergency power system train was involved in 2 of the 22 LOOP precursor events during FY 2001–2007.

5.3 Precursors at Boiling-Water Reactors Versus Pressurized-Water Reactors

A review of the data for FY 2001–2007 reveals the results for boiling-water reactors (BWRs) and pressurized-water reactors (PWRs) described below.[3]

BWRs

- The mean occurrence rate of precursors that occurred at BWRs does not exhibit a trend that is statistically significant for the period from FY 2001–2007, as shown in Figure 6.
- LOOP events contributed to 67 percent of precursors involving initiating events at BWRs.
- Of the 17 precursors involving the unavailability of safety-related equipment that occurred at BWRs during FY 2001–2007, most were caused by failures in the emergency core cooling systems (59 percent), emergency power system (35 percent), electrical distribution system (24 percent), or essential service water system (18 percent).

PWRs

- The mean occurrence rate of precursors that occurred at PWRs exhibits a statistically significant decreasing trend during the FY 2001–2007 period, as shown in Figure 7.
- LOOP events contribute to 60 percent of precursors involving initiating events at PWRs.
- Of the 63 precursors involving the unavailability of safety-related equipment that occurred at PWRs during FY 2001–2007, most were caused by failures in the emergency core cooling systems (38 percent), auxiliary feedwater system (22 percent), emergency power system (19 percent), or electrical distribution system (10 percent).

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[3] The sum of percentages in this section does not always equal 100 percent because some precursors involve multiple equipment availabilities.

- Of the 24 precursors involving failures in the emergency core cooling systems, 17 precursors (71 percent) were due to conditions affecting sump recirculation during postulated loss-of coolant accidents of varying break sizes. Design errors were the cause of most of these precursors (88 percent).
- Of the 14 precursors involving failures of the auxiliary feedwater system (AFW), random hardware failures (43 percent) and design errors (43 percent) were the largest failure contributors. Twelve of the 14 precursors involved the unavailability of the turbine-driven auxiliary feedwater pump train.
- Of the 12 precursors involving failures of the emergency power system, 10 precursors (83 percent) were from random hardware failures.
- Design errors contributed 53 percent of all precursors involving the unavailability of safety-related equipment that occurred at PWRs during FY 2001–2007.

5.4 Integrated ASP Index

The staff derives the integrated ASP index for order-of-magnitude comparisons with industry-average core damage frequency (CDF) estimates derived from probabilistic risk assessments (PRAs) and NRC's standardized plant analysis risk (SPAR) models. The index or CDF from precursors for a given fiscal year is the sum of CCDPs and ΔCDPs in the fiscal year divided by the number of reactor-calendar years in the fiscal year.

The integrated ASP index includes the risk contribution of a precursor for the entire duration of the degraded condition (i.e., the risk contribution is included in each fiscal year that the condition exists). The risk contributions from precursors involving initiating events are included in the fiscal year that the event occurred.

Examples. A precursor involving a degraded condition is identified in FY 2003 and has a ΔCDP of 5×10^{-6}. A review of the LER reveals that the degraded condition has existed since a design modification performed in FY 2001. In the integrated ASP index, the ΔCDP of 5×10^{-6} is included in FYs 2001, 2002, and 2003.

For an initiating event occurring in FY 2003, only FY 2003 includes the CCDP from this precursor.

Results. Figure 8 depicts the integrated ASP indices for FY 1998–2007. A review of the ASP indices leads to the following insights:

- Based on order of magnitude (10^{-5}), the average integrated ASP index for the period from FY 1998–2007 is consistent with the CDF estimates from the SPAR models and industry PRAs.
- Precursors over the 10-year period (FY 1998–2007) made the following contributions to the average integrated CDF:
  - The one *significant* precursor (i.e., CCDP or ΔCDP greater than or equal to 1×10^{-3}) contributed to 26 percent of the average integrated CDF from precursors over the 10-year period. The *significant* precursor (Davis-Besse, FY 2002) existed for a 1-year period.

- Four precursors contribute 40 percent of the average integrated CDF from precursors over the 10-year period. Specifically, long-term degraded conditions at Point Beach Units 1 and 2 (discovered in 2001) involved potential common-mode failure of all AFW pumps, while long-term degraded conditions at D.C. Cook Units 1 and 2 (discovered in 1999) involved a number of locations in the plant where the effects of postulated high-energy line break events would damage safety-related components. The associated ΔCDPs of the degraded conditions at Point Beach and D.C. Cook were high (7×10^{-4} and 4×10^{-4}, respectively) and the degraded conditions had existed since plant construction.
- The remaining 34 percent of the average integrated CDF from precursors over the 10-year period resulted from contributions from 137 precursors.

Limitations. Using CCDPs and ΔCDPs from ASP results to estimate CDF is difficult because (1) the mathematical relationship requires a significant level of detail, (2) statistics for frequency of occurrence of specific precursor events are sparse, and (3) the assessment also must account for events and conditions that did not meet the ASP precursor criteria.

The integrated ASP index provides the contribution of risk (per fiscal year) resulting from precursors and cannot be used for direct trending purposes because the discovery of precursors involving longer-term degraded conditions in future years may change the cumulative risk from the previous year(s).

5.5 Consistency with Probabilistic Risk Assessments and Individual Plant Examinations

A secondary objective of the ASP Program is to provide a partial validation of the dominant core damage scenarios predicted by PRAs and individual plant examinations (IPEs). Most of the identified precursor events are consistent with failure combinations identified in PRAs and IPEs.

However, a review of the precursor events for FY 2001–2007 reveals that approximately 30 percent of the identified precursors involved event initiators or failure modes that were not explicitly modeled in the PRA or IPE for the specific plant where the precursor event occurred. Table 4 lists these precursors. The occurrence of these precursors does not imply that explicit modeling is needed; however, such modeling could yield insights that could be incorporated in future revisions of the PRA.

6.0 Summary

This section summarizes the ASP results, trends, and insights:

- ***Significant Precursors.*** The staff did not identify any *significant* precursors (i.e., CCDP or ΔCDP greater than or equal to 1×10^{-3}) in FY 2008. The ASP Program provides the basis for the safety-performance measure of zero "number of significant accident sequence precursors of a nuclear reactor accident." The NRC's Performance and Accountability Report for FY 2008 and the NRC Performance Budget for FY 2010 will report these results.

- ***Occurrence Rate of All Precursors.*** A statistically significant decreasing trend was detected in the occurrence rate of all precursors during the FY 2001–2007 period. This

ASP trend provides the basis for one performance indicator used by the ITP to assess industry performance. The NRC's Performance and Accountability Report for FY 2008 and the NRC Performance Budget for FY 2010 will report the overall performance indicator results.

- ***Additional Trend Results.*** During the same period, statistically significant decreasing trends were detected for three groups of precursors—precursors with a CCDP or ΔCDP greater than or equal to 10^{-4}, precursors involving degraded conditions, and precursors that occurred at PWRs.

7.0 References

1. NUREG-1100, Vol. 24, "Performance Budget, Fiscal Year 2009," U.S. Nuclear Regulatory Commission, Washington, DC, February 2008.

2. Regulatory Issue Summary 2006-24, "Revised Review and Transmittal Process for Accident Sequence Precursor Analyses," U.S. Nuclear Regulatory Commission, Washington, DC, December 2006.

3. NUREG/CR-5750, "Rates of Initiating Events at U.S. Nuclear Power Plants: 1987–1995," U.S. Nuclear Regulatory Commission, Washington, DC, February 1999.

4. SECY-06-0208, "Status of the Accident Sequence Precursor Program and the Development of Standardized Plant Analysis Risk Models," U.S. Nuclear Regulatory Commission, Washington, DC, October 2006.

Table 1. Status of ASP Analyses

Status	FY 2007	FY 2008[a]
Analyzed events that were determined not to be precursors	76	28
Events to be further analyzed	—	24
ASP precursor analyses	2	—
SDP (or MD 8.3) results used for ASP program input	7	6
Total precursors identified	9	6

a. As of September 30, 2008, the staff has not yet screened all of the FY 2008 initiating events and degraded conditions.

Table 2. FY 2007 Precursors Involving Initiating Events

Event Date	Plant	Description	CCDP
10/11/06	Surry 2	Partial loss of offsite power with subsequent reactor trip. ***50-280/06-11***	2×10^{-6}
10/19/06	River Bend	Automatic reactor scram due to inadvertent isolation of main feedwater. ***LER 458/06-007***	3×10^{-6}
11/1/06	Brunswick 2	Loss of startup auxiliary transformer results in Unit 2 manual reactor protection system actuation. ***LER 324/06-001***	6×10^{-6}

Table 3. FY 2007 Precursors Involving Degraded Conditions

Event Date[a]	Condition Duration[b]	Plant	Description	ΔCDP/ SDP Color
10/10/06	454 days	Fort Calhoun	Faulty maintenance causes the inoperability of a containment spray train for 454 days. ***EA-07-047***	WHITE
11/2/06	9 days	Brunswick 1	Emergency diesel generator inoperable due to failure of foreign material exclusion practices. ***EA-07-024***	WHITE
1/5/07	85 days	Farley 2	Residual heat removal containment sump suction valve inoperable for 85 days. ***EA-07-173***	YELLOW
1/18/07	57 days	Cooper	Inadequate procedures result in failure of emergency diesel generator voltage regulator. ***EA-07-090***	WHITE
2/14/07	14 days	Fort Calhoun	Emergency diesel generator failure during test due to degraded field flash contacts. ***EA-07-194***	WHITE
6/14/07	10 years	Cooper	Inadequate post-fire procedure could have prevented achieving safe shutdown. ***EA-07-204***	WHITE

a. ASP event date is the discovery date for a precursor involving a degraded condition.
b. Condition duration is the time period when the degraded condition existed. The ASP Program limits the analysis exposure time of degraded condition to 1 year.

Table 4. Precursors Involving Failure Modes and Event Initiators that Were Not Explicitly Modeled in the PRA or IPE Concerning the Specific Plant at Which the Precursor Event Occurred

Plant	FY	Event Description
Cooper	2007	Inadequate post-fire procedure could have prevented achieving safe shutdown. ***EA-07-204***
Clinton	2006	Potential air entrapment of high-pressure core spray because of incorrect suction source switchover set point. ***EA-06-291***
Oconee 1, 2, & 3	2006	Failure to maintain design control for the standby shutdown facility flooding boundary. ***EA-06-199***
Kewaunee	2005	Design deficiency could cause unavailability of safety-related equipment during postulated internal flooding. ***EA-05-176***
LaSalle 1 & 2 Crystal River 3	2005	Single-failure vulnerability of safety bus protective relay schemes caused by common power metering circuits. ***EA-05-103, EA-05-114***
Watts Bar	2005	Component cooling backup line from essential raw cooling water was unavailable because silt blockage. ***50-390/04-05***
Watts Bar	2005	Low-temperature, overpressure valve actuations while shut down. ***EA-05-169***
Calvert Cliffs 2	2004	Failed relay causes overcooling condition during reactor trip. ***LER 318/04-001***
Palo Verde 1, 2, & 3	2004	Containment sump recirculation potentially inoperable because of pipe voids. ***LER 528/04-009***
Shearon Harris	2003	Postulated fire could cause the actuation of certain valves, which could result in a loss of the charging pump, reactor coolant pump seal cooling, loss of reactor coolant system inventory, and other conditions. ***LER 400/02-004***
St. Lucie 2	2003	RPV head leakage because of cracking of CRDM nozzles. ***LER 389/03-002***
Kewaunee	2003	Failure to provide a fixed fire-suppression system could result in a postulated fire that propagates and causes the loss of control cables in both safe-shutdown trains. ***50-305/02-06***
Crystal River 3 Three Mile Island 1 Surry 1 North Anna 1 & 2	2002	RPV head leakage because of cracking of CRDM nozzle(s). ***LER 302/01-004, LER 289/01-002, LER 280/01-003, LER 339/02-001***
Columbia	2002	Common-cause failure of breakers used in four safety-related systems. ***50-397/02-05***
Davis-Besse	2002	Cracking of CRDM nozzles and RPV head degradation, potential clogging of the emergency sump, and potential degradation of the pumps. ***LER 346/02-002***
Callaway	2002	Potential common-mode failure of all AFW pumps because of foreign material in the condensate storage tank caused by degradation of the floating bladder. ***LER 483/01-002***
Point Beach 1 & 2	2002	Potential common-mode failure of all AFW pumps because of a design deficiency in the AFW pumps' air-operated minimum flow recirculation valves. The valves fail closed on loss of instrument air, which could potentially lead to pump deadhead conditions and a common-mode, non-recoverable failure of the AFW pumps. ***LER 266/01-005***
Shearon Harris	2002	Potential failure of Residual Heat Removal Pump A and Containment Spray Pump A because of debris in the pumps' suction lines. ***LER 400/01-003***
Oconee 1, 2, & 3 Arkansas 1 Palisades	2001	RPV head leakage because of cracking of CRDM nozzle(s). ***LER 269/03-002, LER 270/02-002, LER 287/03-001, LER 313/02-003, LER 255/01-004***

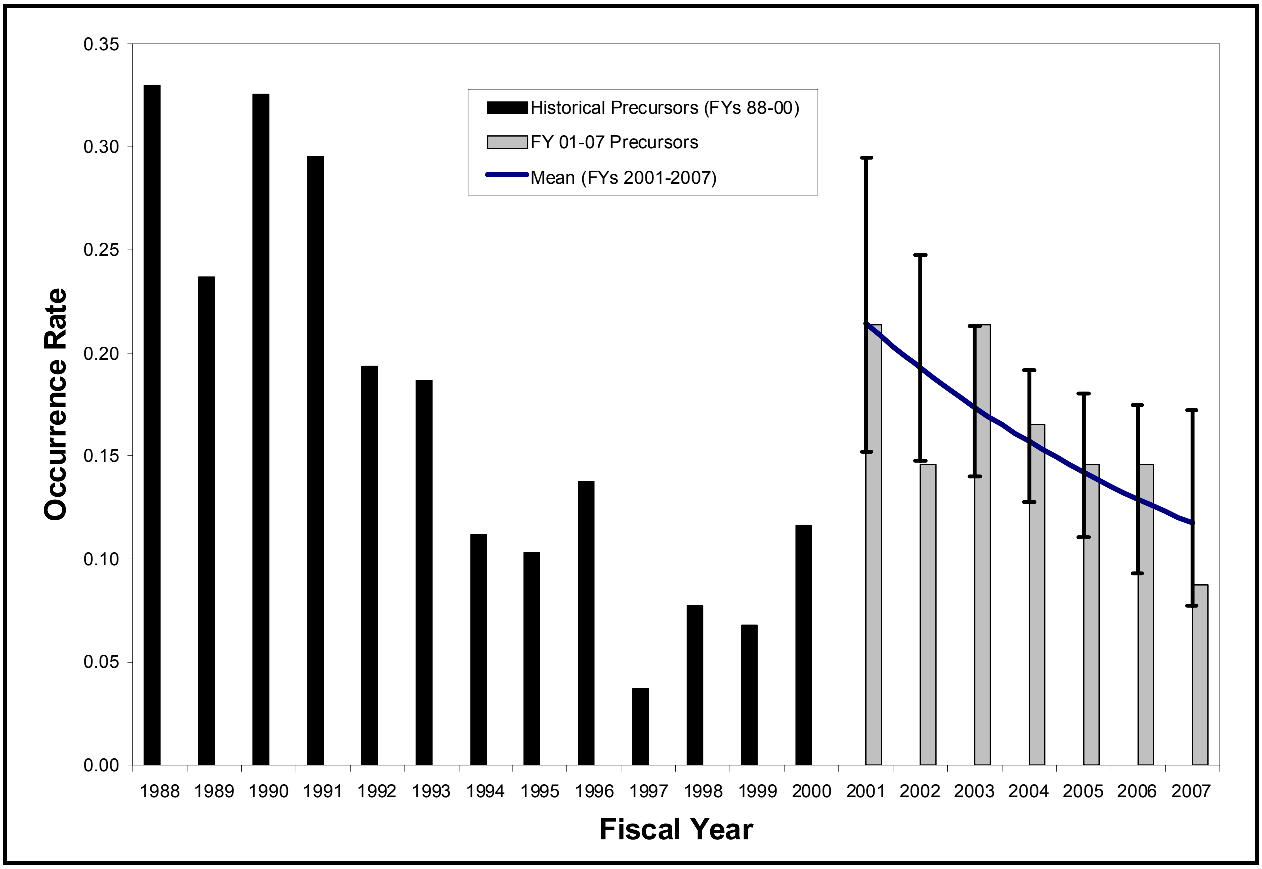

Figure 1. Total precursors—occurrence rate, by fiscal year. Data for FY 1988–2000 are shown for historical perspective. A statistically significant decreasing trend (p-value = 0.03) is detected for the FY 2001–2007 period.

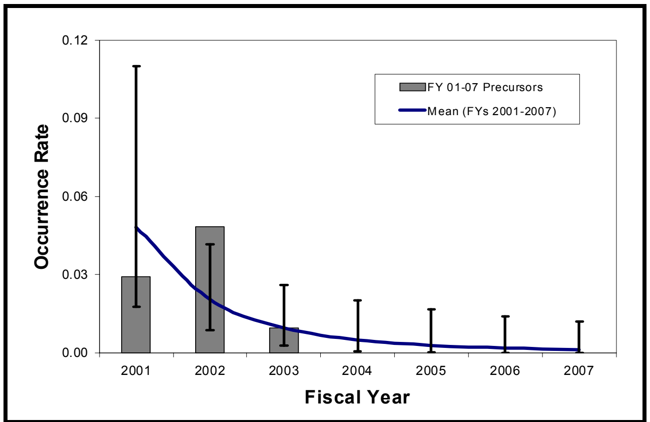

Figure 2. Precursors with a CCDP or ΔCDP ≥10^{-4}—occurrence rate by fiscal year. A statistically significant decreasing trend (p-value = 0.0005) is detected for the FY 2001–2007 period.

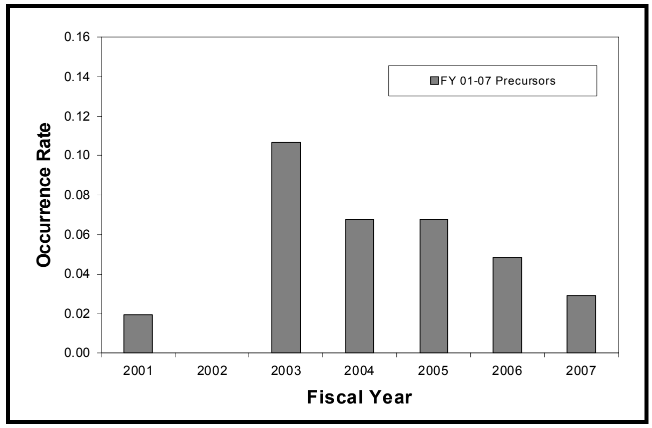

Figure 3. Precursors involving initiating events—occurrence rate by fiscal year. No trend line is shown because no statistically significant trend (p-value = 0.45) is detected for the FY 2001–2007 period.

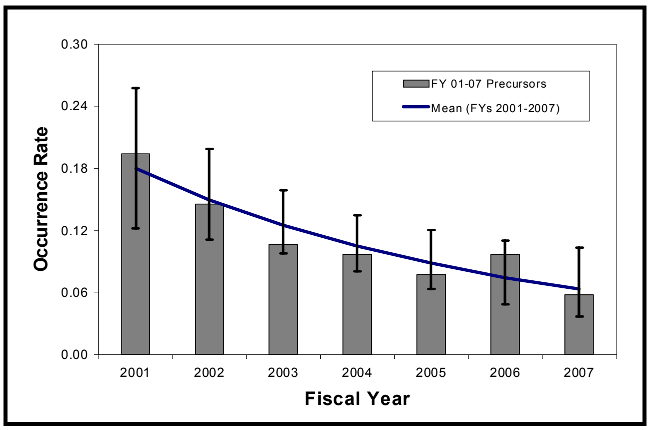

Figure 4. Precursors involving degraded conditions—occurrence rate by fiscal year. A statistically significant decreasing trend (p-value = 0.002) is detected for the FY 2001–2007 period.

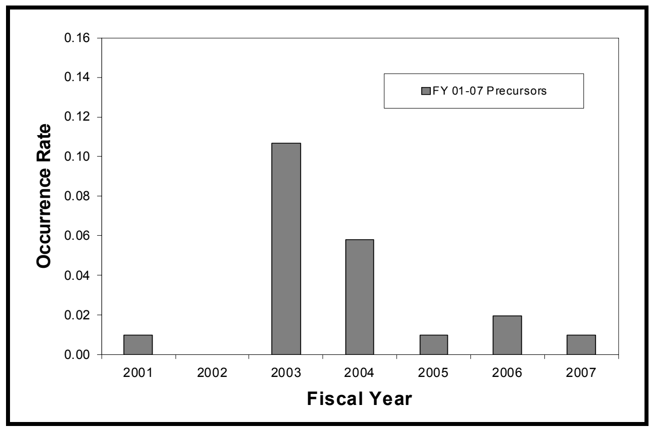

Figure 5. Precursors involving LOOP events—occurrence rate by fiscal year. No trend line is shown because no statistically significant trend (p-value = 0.52) is detected for the FY 2001–2007 period.

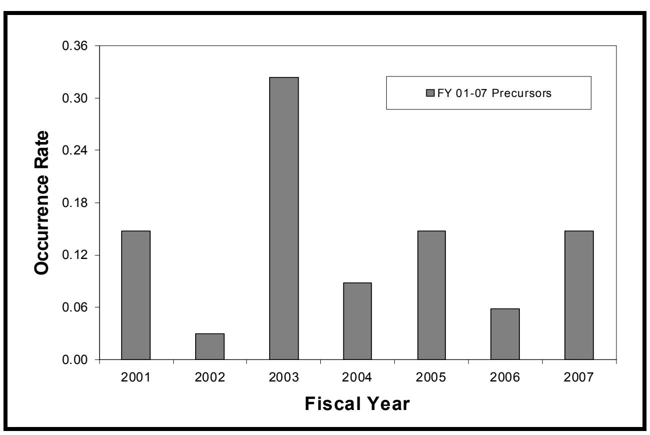

Figure 6. Precursors involving BWRs—occurrence rate by fiscal year. No trend line is shown because no statistically significant trend (p-value = 0.70) is detected for the FY 2001–2007 period.

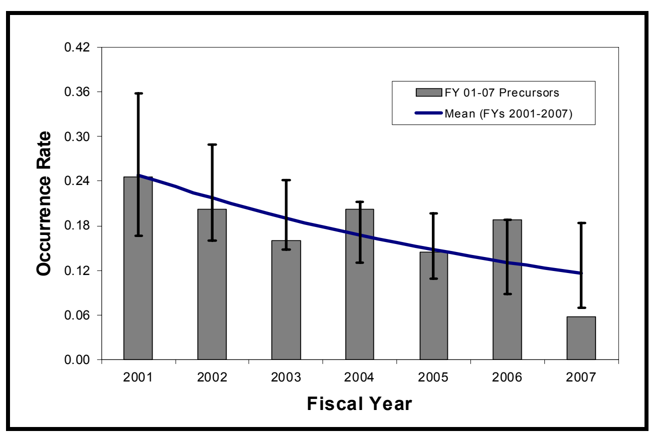

Figure 7. Precursors involving PWRs—occurrence rate by fiscal year. A statistically significant decreasing trend (p-value = 0.02) is detected for the FY 2001–2007 period.

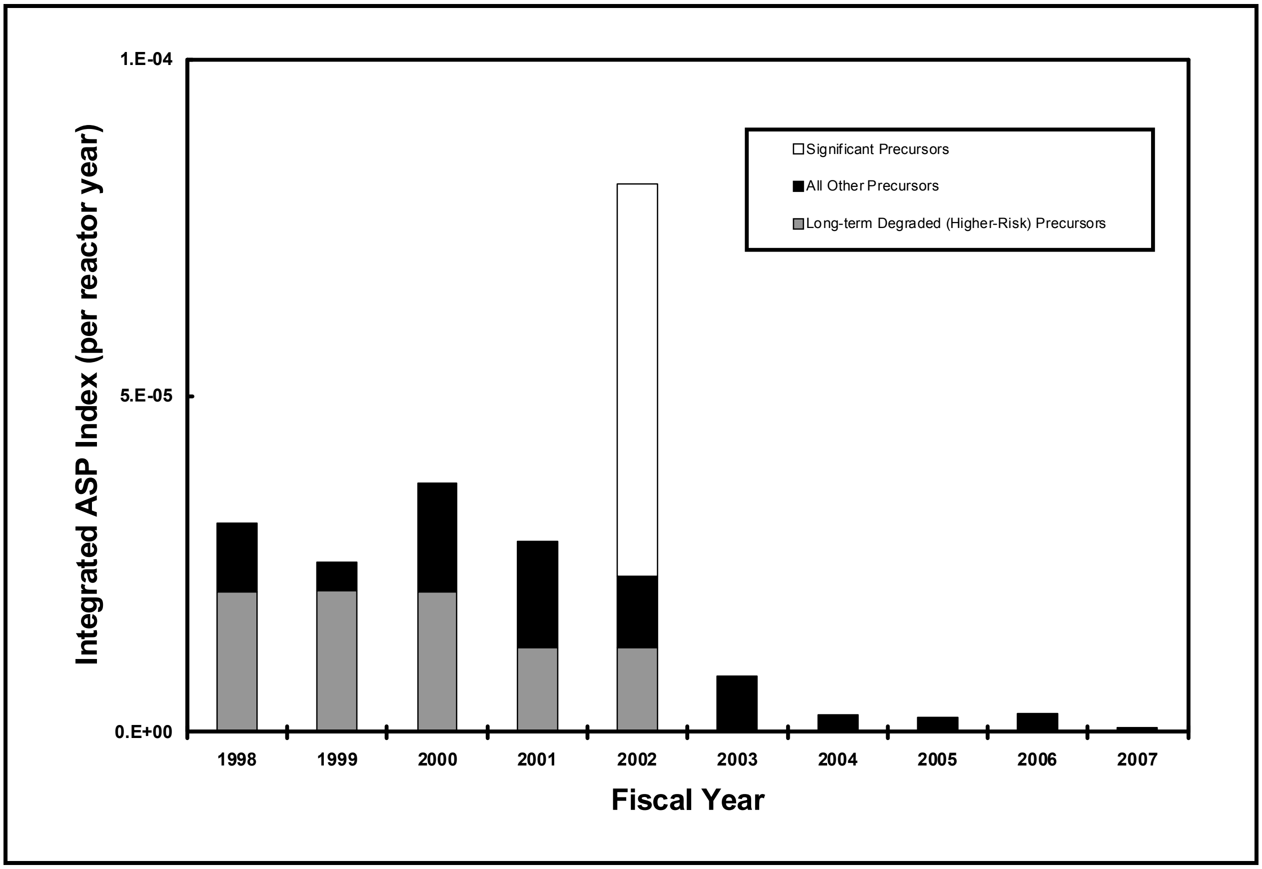

Figure 8. Integrated ASP index—risk contribution from precursors per fiscal year. The risk contribution from precursors involving degraded conditions is included in all fiscal years when the degraded condition existed. The risk contribution from precursors involving initiating events is included in the fiscal year in which the event occurred. The multiple, short-term degraded conditions at Davis-Besse contributed to the single significant precursor in FY 2002.