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

This enclosure discusses the results of accident sequence precursor (ASP) analyses conducted by the U.S. Nuclear Regulatory Commission (NRC) as they relate to events that occurred during fiscal years (FY) 2006–2007. Based on those results, this document also discusses the NRC's analysis of historical ASP trends and the evaluation of the related insights. The four tables and eight figures that augment this discussion appear at the end of this enclosure.

1.0 ASP Event Analyses

Table 1 summarizes the status of the NRC's ASP analyses as of September 30, 2007. Specifically, the table identifies ASP analyses that the NRC staff has completed for events that occurred during FY 2006–2007. (Note that, as of September 30, 2007, the staff had not yet screened all of the FY 2007 events.) The following subsections summarize the results of these analyses, which are further detailed in the associated Tables 1–4.

FY 2006 Analyses. The ASP analyses for FY 2006 identified 14 precursors. Of the 14 precursors, 13 occurred while the plants were at power. The staff used significance determination process (SDP) analyses to identify 11 of the 14 precursors.

Table 2 presents the results of the staff's ASP analyses for FY 2006 precursors that involved initiating events, while Table 3 presents the analysis results for precursors that involved degraded conditions.

FY 2007 Analyses. The staff has completed all screening and reviews for potential *significant* precursors (i.e., conditional core damage probability (CCDP) or increase in core damage probability (ΔCDP) greater than or equal to 1×10^{-3}) through September 30, 2007. In particular, the staff reviewed a combination of licensee event reports (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 FY2007.

The staff is still screening and reviewing LERs concerning other potential precursor events that occurred during FY 2007.[1] The staff plans to complete all FY 2007 analyses by September 2008.

2.0 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 1). 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) significantly increased the number of precursors identified compared to those identified in previous years. The data period for trending analyses ends in FY 2006 (the last full year of completed ASP analyses)

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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.

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 2007. The results for FY 2007 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.

2.1 Occurrence Rate of All Precursors

The NRC's Industry Trends Program (ITP) provides the basis for addressing the agency's performance goal measure on the number of "statistically significant adverse industry trends in safety performance" (one measure associated with the safety goal established in the NRC's Strategic Plan). Precursors identified by the ASP Program are 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 2001–2006. A review of the data for that period reveals the following insights:

- The mean occurrence rate of all precursors does not exhibit a trend that is statistically significant for the period from FY 2001–2006, as shown in 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).

2.2 *Significant* Precursors

The ASP Program provides the basis for the FY 2006 performance goal measure of "zero events per year identified as a *significant* precursor of a nuclear accident" (one measure associated with the safety goal established in the 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 2).

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 2001–2007.
- The staff identified no *significant* precursors in FY 2007.
- The staff has identified only one *significant* precursor since FY 2001 (Davis-Besse, FY 2002). Reference 3 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 4 years. The events in this group involve differing failure modes, causes, and systems.

3.0 Insights and Other Trends

The following sections provide additional ASP trends and insights from the period FY 2001–2006.

3.1 Initiating Events vs. Degraded Conditions

A precursor can be the result of either (1) an operational event involving an initiating event such as a loss of offsite power (LOOP) or (2) a degraded condition found during a test, inspection, or engineering evaluation. A degraded condition involves a reduction in safety system reliability or function for a specific duration (although no reactor trip initiator actually occurred during this time that challenged the degraded condition).

A review of the data for FY 2001–2006 yields insights described below.

Initiating Events

- Over the past 6 years, precursors involving degraded conditions outnumbered initiating events (70 percent compared to

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[2] The staff has completed all screening and reviews through September 30, 2007.

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 2001–2006, as shown in Figure 3.
- Of the precursors involving initiating events during FY 2001–2006, 68 percent were LOOP events.

Degraded Conditions

- The mean occurrence rate of precursors involving degraded conditions exhibits a statistically significant decreasing trend during the FY 2001–2006 period, as shown in Figure 4.
- From FY 2001–2006, 45 percent of precursors involving degraded conditions had a condition start date before FY 2001.

3.2 Precursors Caused by Degraded Conditions

Most precursors involving degraded conditions result from equipment unavailabilities. Such events typically occur for extended periods without a reactor trip, or in combination with a reactor trip in which a risk-important component is unable to perform its safety function as a result of a degraded condition.

A review of the data for FY 2001–2006 yields insights described below concerning the unavailability of safety-related equipment.[3]

Equipment Unavailabilities at Boiling-Water Reactors

- Of the 15 precursors involving the unavailability of safety-related equipment that occurred at boiling-water reactors (BWRs) during FY 2001–2006, most were caused by failures in the emergency power system (60 percent), residual heat removal system (20 percent), or high-pressure coolant injection system (20 percent).

Emergency Core Cooling Systems in Pressurized-Water Reactors

- The unavailability of safety-related high- and/or low-pressure injection trains contributed to 58 percent of all identified precursors that occurred at pressurized-water reactors (PWRs) during FY 2001–2006. Failures in either the emergency core cooling system (ECCS) (11 percent) or emergency power sources (22 percent) caused most of these unavailabilities, or they resulted from design-basis issues involving other structures or systems that impact either the ECCS or one of its support systems (58 percent).
- A condition that affected sump recirculation during postulated loss-of-coolant accidents of varying break sizes caused 16 of the precursors.

Auxiliary/Emergency Feedwater Systems in Pressurized-Water Reactors

- The unavailability of one or more trains of the auxiliary and emergency feedwater (AFW/EFW) systems contributed to 41 percent of all precursors that occurred at PWRs. Most of these unavailabilities resulted from failures in the AFW/EFW systems (13 percent) or emergency power sources (38 percent), or they resulted from design-basis issues involving other structures or systems that impact either the AFW/EFW systems or one of their support systems (50 percent).
- The four precursors that involved a failure in an AFW/EFW train yield the following insights:
  - One of the train failures occurred following a reactor trip.
  - All four of the precursors involved the unavailability of the turbine-driven AFW/EFW pump train.

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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.

Emergency Power Sources in Pressurized-Water Reactors

- The unavailability of emergency power sources, such as emergency diesel generators (EDGs) and hydroelectric generators (at Oconee), contributed to 29 percent of all precursors that occurred at PWRs.[4] Most of these unavailabilities resulted from random hardware failures in the emergency power system (35 percent).
- The other unavailabilities were attributable to design-basis issues (48 percent) and losses of service water (17 percent).
- In all the analyzed LOOP events at PWRs, the turbine-driven AFW/EFW pumps were operable.

Section 3.3 discusses insights related to precursors that involved a LOOP with simultaneous EDG unavailability.

3.3 Precursors Involving Loss of Offsite Power Initiating Events

Only one LOOP event (resulting in two precursors) occurred in FY 2006. The dual-unit LOOP event occurred at Catawba.

Results. A review of the data for FY 2001–2006 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 2001–2006, as shown in Figure 4.
- Of the LOOP events that occurred during the FY 2001–2006 period, 52 percent resulted from a degraded electrical grid.
- A simultaneous unavailability of an emergency power system train was involved in 2 of the 21 LOOP precursor events during FY 2001–2006.

3.4 Precursors at Boiling-Water Reactors versus Pressurized-Water Reactors

A review of the data for FY 2001–2006 reveals the results for BWRs and PWRs described below.

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 2001–2006, as shown in Figure 6.
- An average of five precursors per year occurred at BWRs during FY 2001–2006.
- LOOP events contributed to 69 percent of precursors involving initiating events at BWRs.

PWRs

- The mean occurrence rate of precursors that occurred at PWRs does not exhibit a trend that is statistically significant for FY 2001–2006, as shown in Figure 7.
- An average of 12 precursors per year occurred at PWRs during FY 2001–2006.
- LOOP events contribute to 67 percent of precursors involving initiating events at PWRs.

3.5 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 the 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

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[4] Not all EDG unavailabilities are precursors. The ASP Program screens out an EDG unavailability for a period of less than one surveillance test cycle (1 month), assuming no other complications. In addition, the risk contributions of EDG unavailabilities vary from plant to plant and may result in a ΔCDP less than the threshold of a precursor (1×10^{-6}).

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 2001–2006. A review of the ASP indices leads to the following insights:

- Based on order of magnitude, the average integrated ASP index for the period from FY 2001–2006 is consistent with the CDF estimates from the SPAR models and the licensees' PRAs.
- Precursors over the 6-year period (FY 2001–2006) 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 45 percent of the average integrated CDF from precursors over the 6-year period. The *significant* precursor (Davis-Besse, FY 2002) existed for a 1-year period.
  - Two precursors contribute 24 percent of the average integrated CDF from precursors over the 6-year period. The two precursors stem from long-term degraded conditions at Point Beach Units 1 and 2 (discovered in 2001) that involved potential common-mode failure of all AFW pumps. The associated ΔCDPs of the degraded conditions at Point Beach were high (7×10^{-4}), and the degraded conditions had existed since plant construction.
  - The remaining 31 percent of the average integrated CDF from precursors over the 6-year period resulted from contributions from 101 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 must also 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 since the discovery of precursors involving longer term degraded conditions in future years may change the cumulative risk from the previous year(s). Because of these and other limitations, the staff has primarily used the rate of CCDPs and ΔCDPs as a trending indication.

3.6 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 2001–2006 reveals that approximately 31 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.

4.0 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 2006 or FY 2007. The ASP Program provides the basis for the FY 2005 performance goal measure of “zero events per year identified as a *significant* precursor of a nuclear accident.” The NRC’s Performance and Accountability Report for FY 2007 and the NRC Performance Budget for FY 2008 will report these results.
- ***Occurrence Rate of All Precursors.*** The mean occurrence rate of all precursors does not exhibit a trend that is statistically significant for the period from FY 2001–2006.

  During the same period, the analysis detected a statistically significant decreasing trend for precursors with a CCDP or ΔCDP greater than or equal to 10^{-4} and precursors involving degraded conditions.

5.0 References

1. NUREG/CR-5750, “Rates of Initiating Events at U.S. Nuclear Power Plants: 1987–1995,” U.S. Nuclear Regulatory Commission, Washington, DC, February 1999.
2. NUREG-1100, Vol. 21, “Performance Budget, Fiscal Year 2006,” U.S. Nuclear Regulatory Commission, Washington, DC, February 2005.
3. 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 (as of September 30, 2007)

Status	FY 2006	FY 2007[a]
Analyzed events that were determined not to be precursors	95	32
Events to be further analyzed	—	18
ASP precursor analyses	3	—
SDP (or MD 8.3) results used for ASP program input	11	4
Total precursors identified	14	4

a. As of September 30, 2007, the staff has not yet screened all of the FY 2007 events and unavailabilities.

Table 2. FY 2006 Precursors Involving Initiating Events (as of September 30, 2007)

Event Date	Plant	Description	CCDP
2/23/06	Millstone 2	Reactor trip caused by loss of instrument air. ***LER 336/06-002***	8×10^{-6}
3/8/06	Turkey Point 3	Loss of RHR while in Mode 5 because of electrical complications. ***EA-06-200***	White
5/20/06	Catawba 1	Dual Unit LOOP. ***LER 413/06-011***	9×10^{-5}
5/20/06	Catawba 2	Dual Unit LOOP. ***LER 413/06-011***	6×10^{-5}

Table 3. FY 2006 Precursors Involving Degraded Conditions (as of September 30, 2007)

Event Date[a]	Condition Duration[b]	Plant	Description	ΔCDP/ SDP Color
11/7/05	2 years	Turkey Point 3	AFW pump inoperable for greater time than allowed by technical specifications. ***EA-06-027***	White
12/1/05	147 days	Quad Cities	ERVs were inoperable during extended power uprate conditions because of inadequate power uprate evaluation. ***EA-06-112***	White
1/20/06	since plant startup	Clinton	Potential air entrapment of HPCS because of incorrect suction source switchover setpoint. ***EA-06-291***	White
3/24/06	9 years	Calvert Cliffs 1	Degraded EDG caused by inadequate feeder breaker. ***LER 317/06-001***	White
4/28/06	2 years	Oconee 1	Failure to maintain design control for an SSF flooding boundary. ***EA-06-199***	White[c]
4/28/06	2 years	Oconee 2	Failure to maintain design control for an SSF flooding boundary. ***EA-06-199***	White[c]
4/28/06	2 years	Oconee 3	Failure to maintain design control for an SSF flooding boundary. ***EA-06-199***	White[c]
5/1/06	1 year	Oconee 3	Potentially degraded containment sump recirculation because of debris. ***EA-06-295***	White
7/25/06	58 days	Palo Verde 3	Inoperable EDG caused by inadequate maintenance procedures and corrective actions. ***EA-06-296***	White
8/17/06	51 days	Kewaunee	Degraded EDG caused by fuel oil leak. ***EA-07-058***	Yellow

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.

c. Final SDP color may or may not change to GREEN pending the outcome of the licensee's appeal.

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	Year	Event Description
Point Beach 1	2006	Calculation errors could lead to degraded long-term ECCS cooling. ***LER 266/05-006***
Clinton	2006	Potential air entrapment of HPCS because of incorrect suction source switchover setpoint. ***EA-06-291***
Oconee 1, 2, & 3	2006	Failure to maintain design control for an SSF 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 4160 V ESF bus protective relay schemes caused by common power metering circuits. ***LER 302/05-001, LER 373/05-001***
Watts Bar	2005	Component cooling backup line from essential raw cooling water was unavailable because silt blockage. ***IR 390/04-05***
Watts Bar	2005	Low-temperature, overpressure valve actuations while shut down. ***IR 390/05-03***
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, RCP seal cooling, loss of RCS 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***
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 339/01-003, LER 339/02-001***
Columbia	2002	Common-cause failure of breakers used in four safety-related systems. ***IR 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 HPI pumps. ***LER 346/02-002***
Callaway	2002	Potential common-mode failure of all AFW pumps because of foreign material in the CST caused by degradation of the floating bladder. ***LER 483/01-002***
Point Beach 1 & 2	2002	Potential common-mode failure of all auxiliary feedwater (EFW) pumps because of a design deficiency in the EFW 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, nonrecoverable failure of the EFW pumps. ***LER 266/01-005***
Shearon Harris	2002	Potential failure of RHR 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 269/00-006, LER 269/02-003, LER 269/03-002, LER 270/01-002, LER 270/02-002, LER 287/01-001, LER 287/01-003, LER 287/03-001, LER 313/01-002, LER 313/02-003, LER 255/01-002, LER 255/01-004***
Kewaunee	2001	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. ***IR 305/02-06***

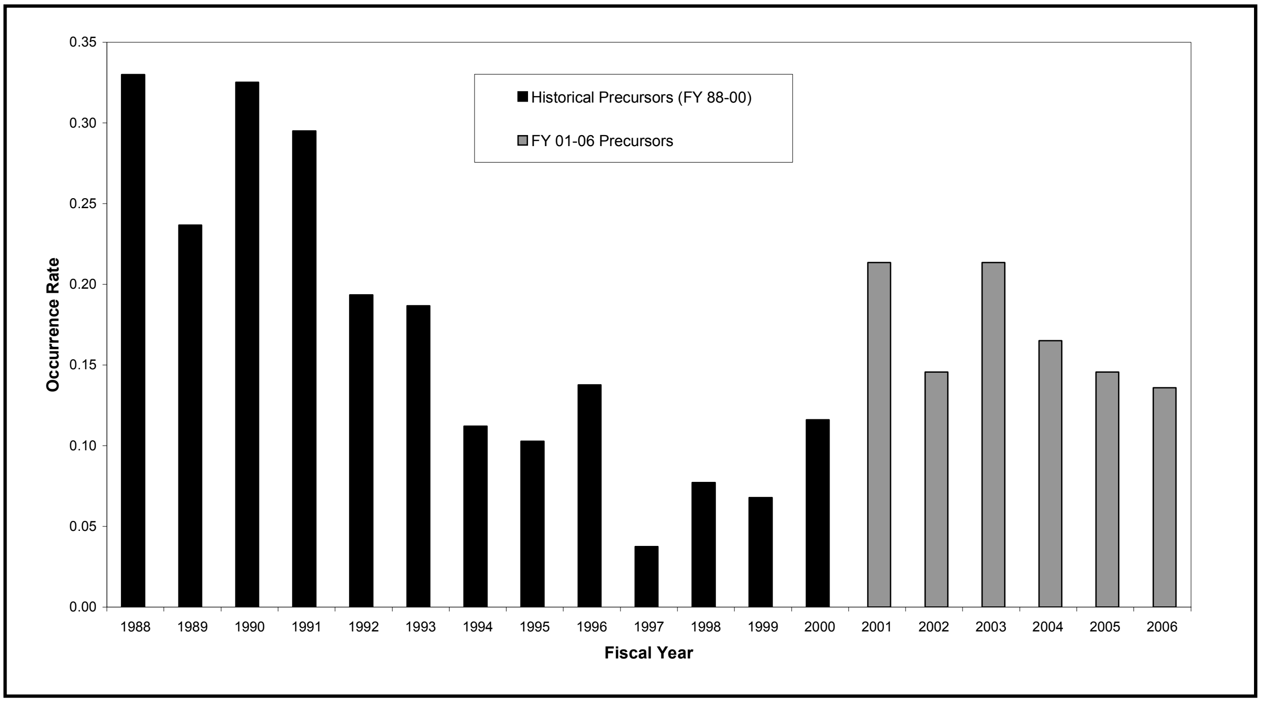

Figure 1. Total precursors—occurrence rate, by fiscal year. Data for FY 1988–2000 are shown for historical perspective. No trend line is shown because no statistically significant trend (p-value = 0.20) is detected for the FY 2000–2006 period.

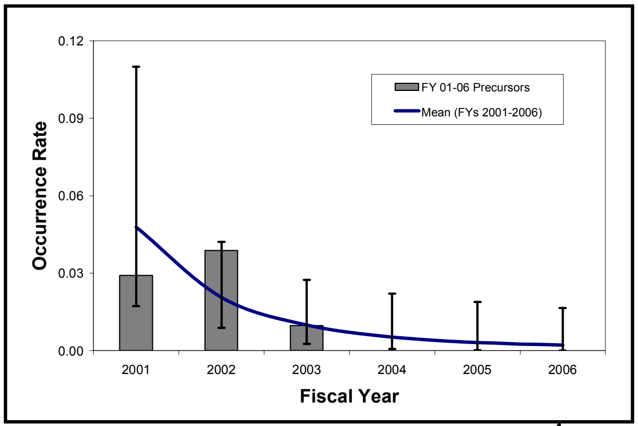

Figure 2. Precursors with a CCDP or ΔCDP $\geq 10^{-4}$—occurrence rate by fiscal year. A statistically significant decreasing trend (p-value = 0.002) is detected for the FY 2000–2006 period.

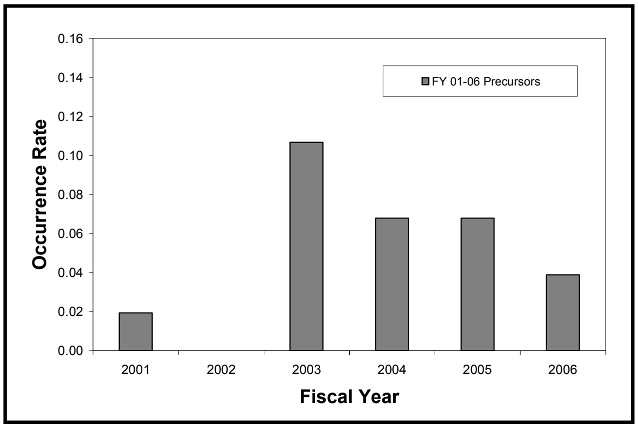

Figure 3. Precursors involving initiating events—occurrence rate by fiscal year. No trend line is shown because no statistically significant trend (p-value = 0.15) is detected for the FY 2000–2006 period.

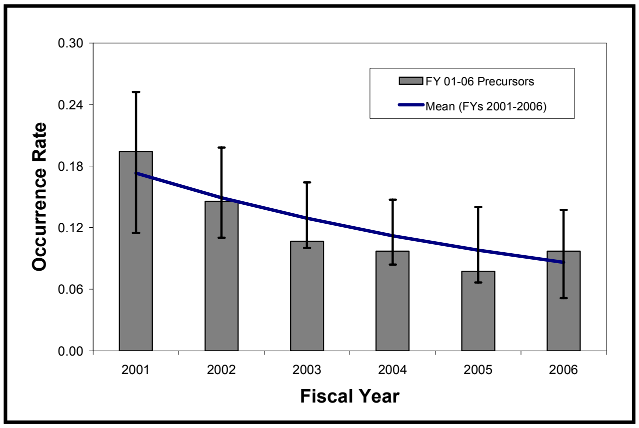

Figure 4. Precursors involving degraded conditions—occurrence rate by fiscal year. A statistically significant decreasing trend (p-value = 0.01) is detected for the FY 2000–2006 period.

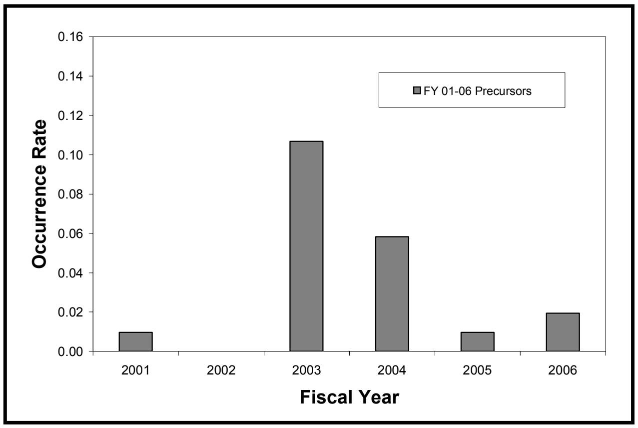

Figure 5. Precursors involving LOOP events—occurrence rate by fiscal year. No trend line is shown because no statistically significant trend (p-value = 0.85) is detected for the FY 2000–2006 period.

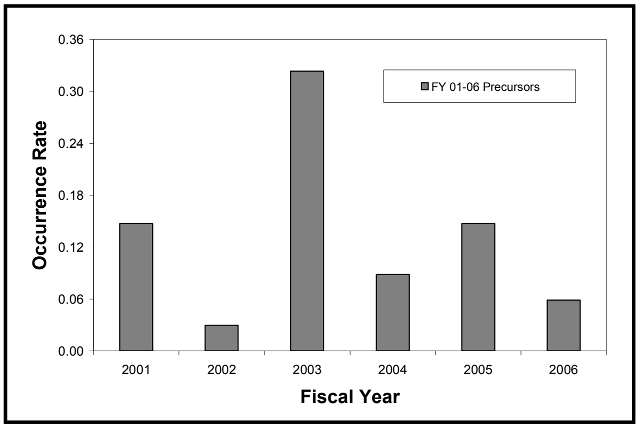

Figure 6. Precursors involving BWRs—occurrence rate by fiscal year. No trend line is shown because no statistically significant trend (p-value = 0.54) is detected for the FY 2000–2006 period.

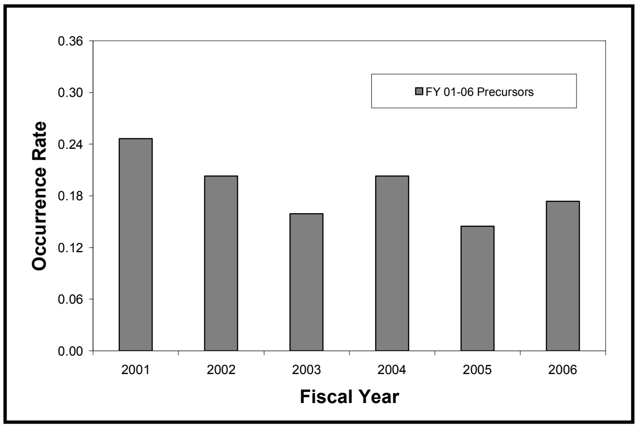

Figure 7. Precursors involving PWRs—occurrence rate by fiscal year. No trend line is shown because no statistically significant trend (p-value = 0.26) is detected for the FY 2000–2006 period.

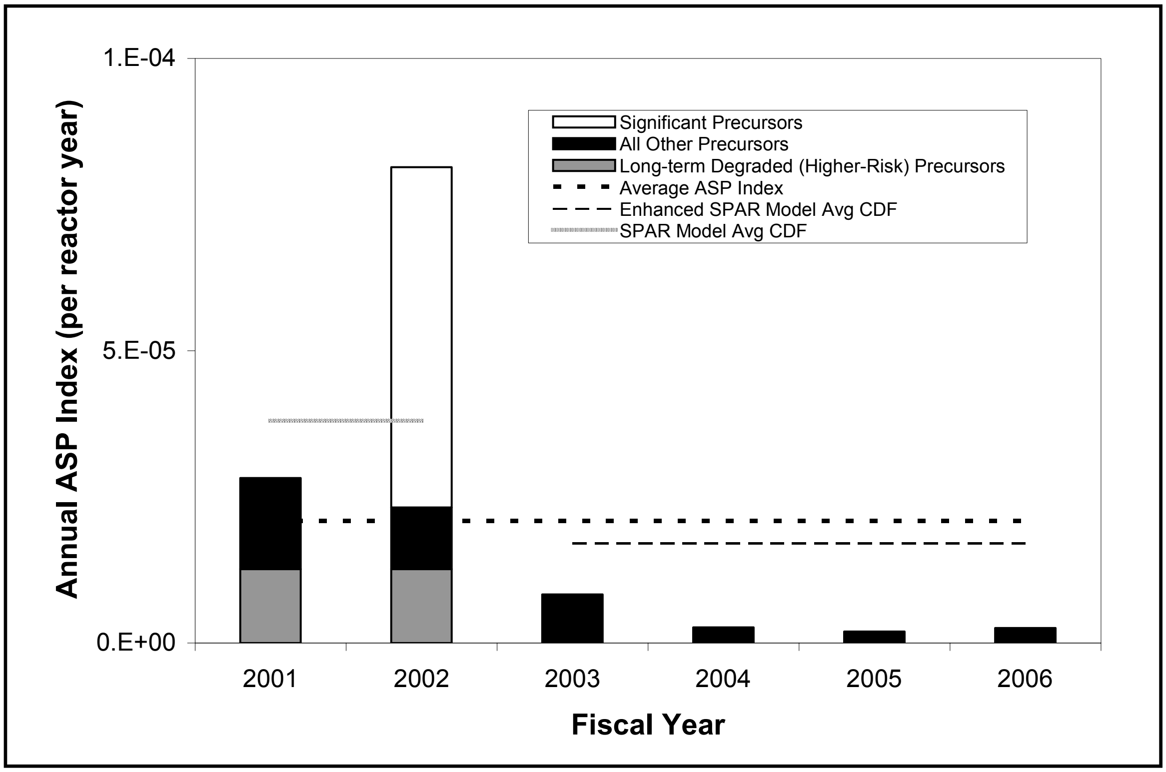

Figure 8. Integrated ASP index—risk contribution from precursors per fiscal year. The risk contribution from precursors involving degraded conditions is included in all fiscal years when the degraded condition existed. The risk contribution from precursors involving initiating events is included in the fiscal year in which the event occurred.