On-line maintenance at nuclear power plants: History, implementation, and benefits

A white paper from the Electric Power Research Institute describes how on-line maintenance can increase plant reliability, reduce risks of component failure, and optimize work planning.

On-line maintenance can provide safety, economic, and performance benefits to nuclear plants. If properly designed and implemented and supported by an appropriate regulatory framework, on-line maintenance programs can enable nuclear plants to improve equipment reliability, reduce risks of component failures, extend fuel cycles, shorten refueling outages, and optimize work planning, all without compromising plant and personnel safety.

On-line maintenance practices for nuclear power plants are widely applied in the United States, and several other countries are now applying them as well. As more countries consider on-line maintenance, a greater awareness of its history, evolution, and application in the United States could help guide the implementation process.

This white paper provides an overview of on-line maintenance as applied at nuclear power plants in the United States, discussing its origins, regulatory basis, implementation practices, supporting tools, and plant-specific application.

Benefits of on-line maintenance

On-line maintenance refers to maintenance performed while the main electric generator is connected to the grid. Nuclear power plants can realize many benefits from performing maintenance activities during power operation. The U.S. Nuclear Regulatory Commission, for example, in Regulatory Guide 1.182, attributes the following benefits to on-line maintenance:

- Increased system and plant reliability.
- Reduction of plant equipment and system material condition deficiencies that could adversely affect plant operations.
- Reduction of work scope during plant refueling outages.[1]

Nuclear plants are also able to achieve longer fuel cycles and shorter refueling outages through on-line maintenance.[2] In the United States in the 1980s and early 1990s, most nuclear power plants operated with a refueling cycle of 12 months and an average refueling duration of three months. Today, U.S. nuclear units operate on an 18- or 24-month refueling cycle, with average outages of just over one month, as shown in Fig. 1.[3] The relationship between on-line maintenance and outage length reduction, operating interval extension, and plant economics is well documented.[4,5]

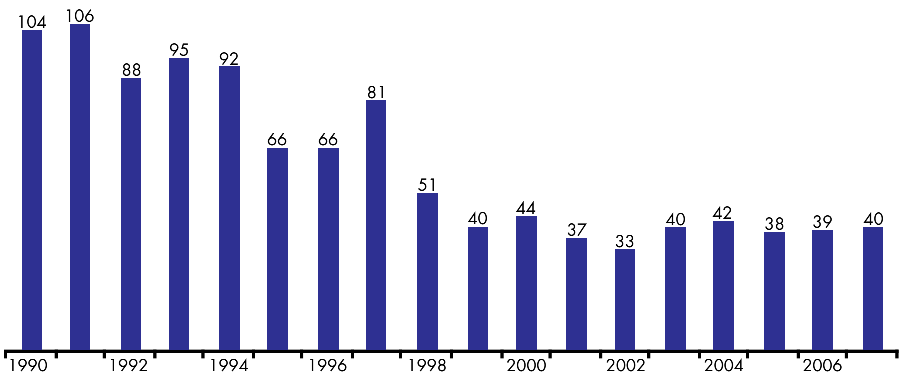

Fig. 1. U.S. refueling outage reductions (average refueling outage days) (Graph: NEI)

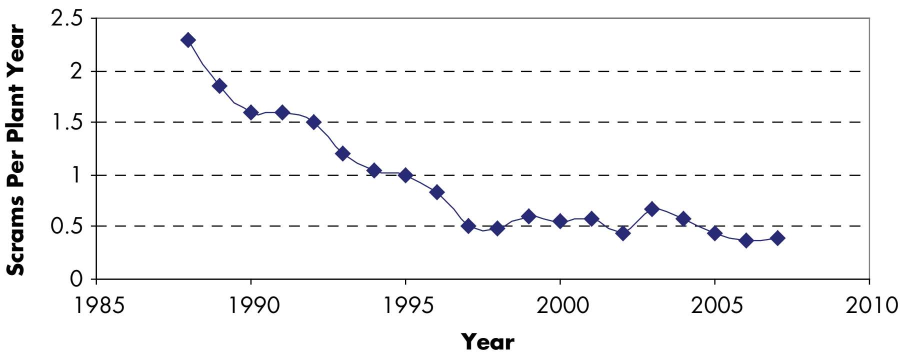

Fig. 2. U.S. scram rate reduction

On-line maintenance can also contribute to improved plant safety by allowing equipment and system issues to be resolved before they can have an adverse impact on operations. Operational and reliability improvements have resulted in a factor of three reduction in forced outages[6] and a factor of five reduction in the automatic scram rate[7,8] at U.S. nuclear power plants, as shown in Fig. 2. Both measures are indicative of improved plant safety.

U.S. history

The U.S. nuclear industry has extensive experience with on-line maintenance of both safety- and nonsafety-significant equipment. Initial efforts related to safety-significant equipment focused on the on-line maintenance of components covered by plant technical specifications, which was addressed through limiting conditions for operation (LCO) and allowed outage time "to fix equipment or otherwise make it operable."[9] These were established under the premise

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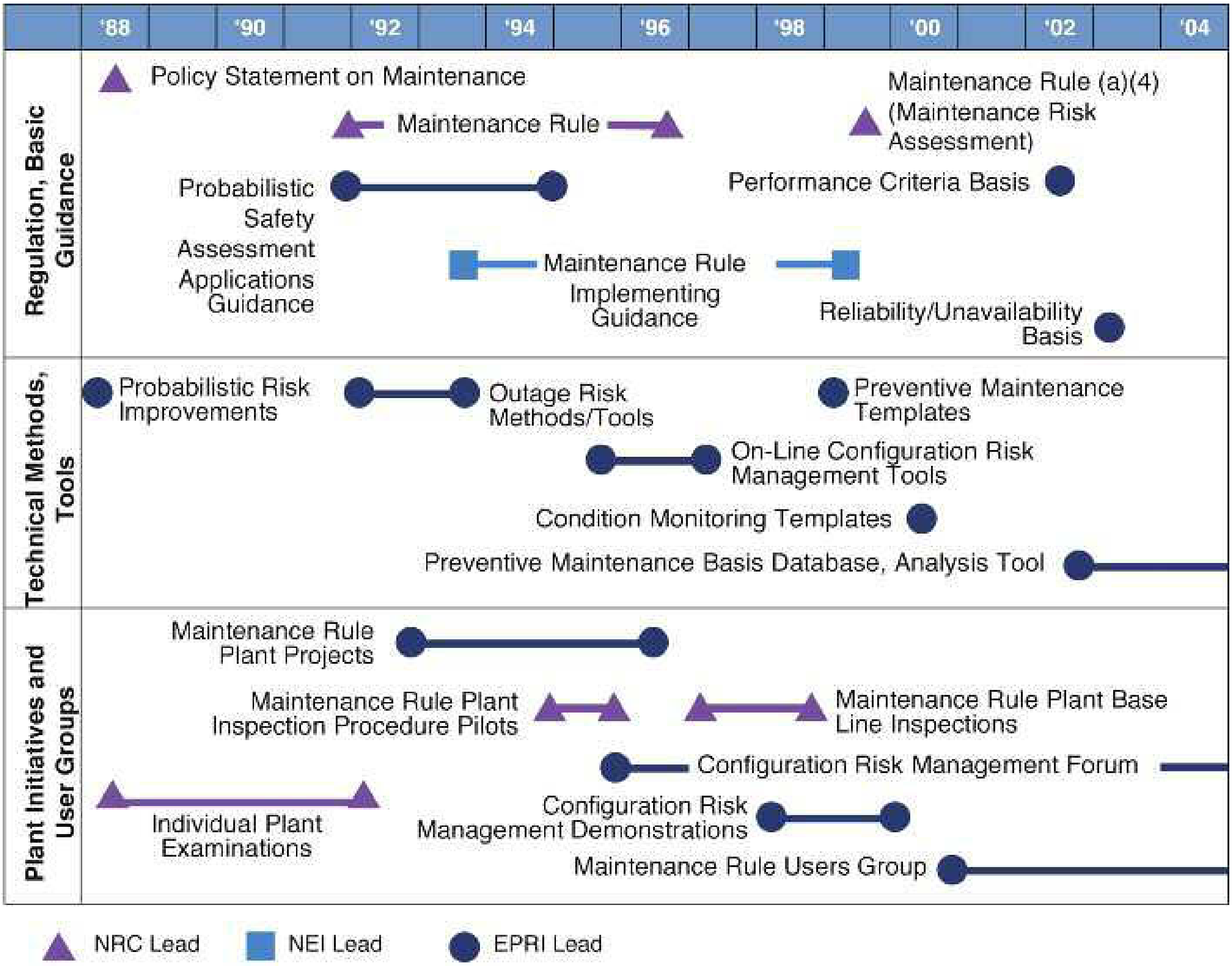

Fig. 3. The evolution of on-line maintenance at U.S. nuclear power plants

that only one LCO would be entered at a given time, because although not prohibited, multiple simultaneous LCOs were not viewed as desirable.

U.S. nuclear plants began applying on-line maintenance consistently after risk-based approaches were introduced to the industry through the Maintenance Rule, 10CFR50.65.[10] The Maintenance Rule, published in July 1991, with an effective date of July 1996, allowed two years for the development of industry guidance and three years for plant implementation.[11] The Maintenance Rule was one of the first risk-informed, performance-based regulations in the United States.

The Maintenance Rule requires nuclear plant licensees to identify risk-significant structures, systems, and components (SSC), to establish performance criteria for selected SSCs (generally based on reliability and/or unavailability), and to evaluate the safety implications of equipment removed for maintenance.[12]

Figure 3 provides a timeline of key events led by the NRC, the Electric Power Research Institute (EPRI), and the Nuclear Energy Institute (NEI) in the evolution of on-line maintenance in the U.S. nuclear power industry. Other industry organizations, including the Institute of Nuclear Power Operations, the reactor owners groups, and individual companies and plants, also contributed to this evolution, but recognition of all such activities is beyond the scope of this paper. Figure 3 also illustrates the integration of regulations, technical tools, and utility actions that drove implementation.

The Maintenance Rule broadened regulatory control on overall SSC performance by encompassing all risk-significant SSCs. This change was intentional, as discussed in Regulatory Guide 1.160: "In addition, good maintenance is also important in providing assurance that failures of other than safety-related structures, systems, and components (SSCs) that could initiate or adversely affect a transient or accident are minimized."[13]

The Maintenance Rule initially addressed on-line maintenance in paragraph (a)(3): "In performing monitoring and preventive maintenance activities, an assessment of the total plant equipment that is out of service should be taken into account to determine the overall effect on performance of safety functions."[13]

After reviewing each plant's Maintenance Rule implementation activities through on-site assessments, the NRC in 1999 revised the treatment of on-line maintenance to include a "stand-alone" paragraph commonly referred to as (a)(4): "Before performing maintenance activities (including but not limited to surveillance, post-maintenance testing, and corrective maintenance), the licensee shall assess and manage the increase in risk that may result from the proposed maintenance activities. The scope of the assessment may be limited to structures, systems, and components that a risk-informed evaluation process has shown to be significant to public health and safety."[14]

The direction contained in the Maintenance Rule was the basis for conducting on-line maintenance on multiple safety-related systems (functions) simultaneously.

The U.S. nuclear industry developed overall implementing guidance in parallel with the introduction of the Maintenance Rule. This general guidance, contained in NUMARC 93-01, "Industry Guideline for Monitoring the Effectiveness of Maintenance at Nuclear Power Plants," has been revised three times. The most significant revision, in 2000, was made to reflect changes associated with assessing risks resulting from maintenance activities.

Probabilistic safety assessments have contributed to U.S. efforts in implementing the Maintenance Rule and on-line maintenance. Prior technical work on probabilistic safety analysis (PSA) methods and managing risks associated with equipment out of service during refueling outages facilitated the effective use of the implementing guidance issued in 1993. For example, individual plant examinations completed by utilities in 1992 resulted in the creation of 74 probabilistic risk assessments (PRA) representing 106 U.S. nuclear plants. These studies verified plant safety and identified accident vulnerabilities using risk assessment criteria, such as core damage frequency and large early release frequency.[12]

The U.S. nuclear industry proposed a series of risk-informed applications to investigate the further use of these tools, with EPRI and NEI playing active roles in discussions with the NRC. EPRI's PSA Applications Guideline is considered the technical foundation for assessing the risks associated with on-line maintenance.[15] A key element provided in the guideline is the basis for determining acceptable and unacceptable risk.

On-line maintenance can reduce refueling outage work scope and improve plant reliability. (Photo: Entergy)

Between 1993 and 1996, EPRI coordinated two full-scale and two limited-scale pilot applications of the Maintenance Rule, one of which addressed on-line maintenance. Lessons learned from these pilots informed the development of technical tools

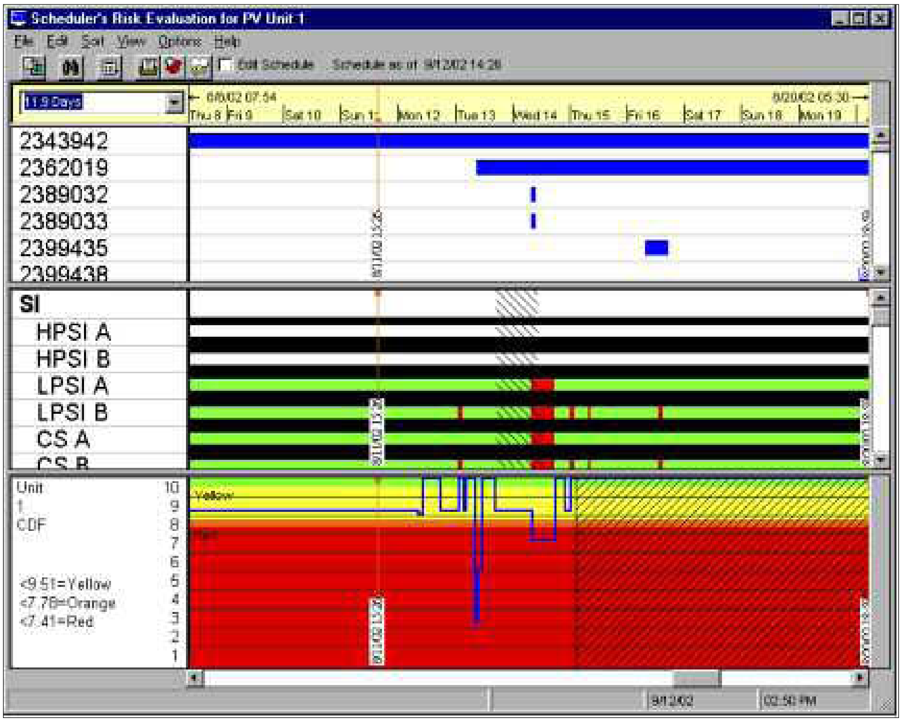

Fig. 4. A computer monitor display of EPRI's equipment-out-of-service (EOOS) configuration risk management tool

to support on-line maintenance, such as configuration risk analysis. The functionality included in these tools helps users confidently evaluate on-line maintenance work plans. Figure 4 illustrates how the equipment-out-of-service (EOOS) configuration risk management tool developed by EPRI can concisely convey integrated physical, temporal, and risk information.

Planning processes also evolved to take advantage of these tools' capabilities, resulting in closely coordinated efforts between work planners and configuration risk analysts. By the end of the utility implementation period in 1996, most plants were applying or planning to apply software-based configuration risk management tools.[16]

To help utilities define appropriate maintenance activities, EPRI developed component-specific templates that provide the technical basis for component preventive maintenance. These templates contained reliability-based tasks, as well as task intervals to help plants determine whether maintenance tasks should be performed during refueling outages or on line to maximize component reliability. EPRI also developed condition-monitoring templates to identify degrading conditions and the need for maintenance.

Industry operating experience with the templates led EPRI to develop an electronic tool, the Preventive Maintenance Basis Database, to collect the templates and to accommodate the growing number of components included. The database tool enables users to perform sensitivity analyses to optimize maintenance strategies on individual components.

As industry activities related to on-line maintenance increased, utilities needed venues in which to share best practices, discuss lessons learned, and inform future tool development. EPRI responded by creating the Configuration Risk Management Forum and the Maintenance Rule Users Group in the mid- and late 1990s, respectively.

The Configuration Risk Management Forum brings together industry configuration risk experts to improve processes and to expand the use of risk-informed applications beyond outage and on-line risk assessment (for example, into areas such as flexible technical specifications). The Maintenance Rule Users Group interfaces with the NRC and other industry organizations on key technical issues. The group also develops guidelines, evaluations, and white papers to help members deal with the subtleties that may arise in applying the Maintenance Rule and on-line maintenance.

Application and extent of use

Because not all maintenance tasks can be performed on-line, plants often employ screening methods to assess which tasks are most suitable for on-line maintenance. Such screening considerations, described in several references,[11,17] provide specific practical and regulation-based criteria for determining the situations that are most suitable for on-line maintenance.

General scenarios in which on-line maintenance is likely to be used include the following:

- *Systems and components that do not have safety functions and are not essential to power generation.*—For example, non-power block work on buildings or structures (offices, storage structures) that support station staff, and the heating, ventilating, and air conditioning and support systems for those structures.
- *Systems and components required to maintain shutdown safety margins.*—For example, work on systems and components that are utilized during refueling outages for functions such as decay heat removal, inventory control, reactivity control, and containment closure.
- *Systems and components that may be called upon to provide a safety function or generation function where the risk associated with unavailability for maintenance is low.*—For example, work on systems and components with redundant backups, such as auxiliary feedwater, instrument air, and control room ventilation.

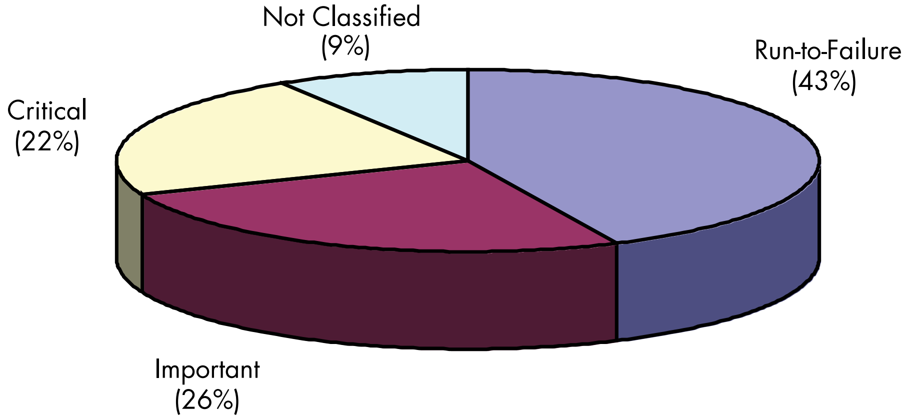

Fig. 5. Classification of components for optimization of plant reliability

About one-half of the equipment in U.S. nuclear power plants is maintained through preventive maintenance programs. This equipment is contained in categories designated as "critical" or "important," as shown in Fig. 5.[18] Although these categories are subject to individual plant interpretation and some level of periodic industry redefinition,[19] they represent the most likely candidates for on-line maintenance.

In the United States, nuclear utilities classify components into three categories to optimize equipment reliability:

- *Critical components* are those that are critical to safety or electricity production.
- *Important components* are those that are not critical to safety or electricity production, but whose failure would cause significant economic consequence.
- *Run-to-failure components* are those that are not critical to safety or electricity production and whose failure would not cause significant economic consequence.

Although this paper was developed based on U.S. experience, on-line maintenance in nuclear power plants has been successfully applied elsewhere, including in France, Spain, Brazil, Switzerland, and Canada. Nuclear plants in a number of other countries, as well as other sectors of the power industry, have expressed interest in on-line maintenance as well.[5,20,21]

To assess the degree to which on-line maintenance is applied in the nuclear power industry, EPRI surveyed its Nuclear Maintenance Applications Center (NMAC) participants in 2008.[21] The survey data primarily reflect U.S. plant experience. International respondents indicated that they apply on-line maintenance to the extent allowed by their regulations, including safety-significant systems and components.

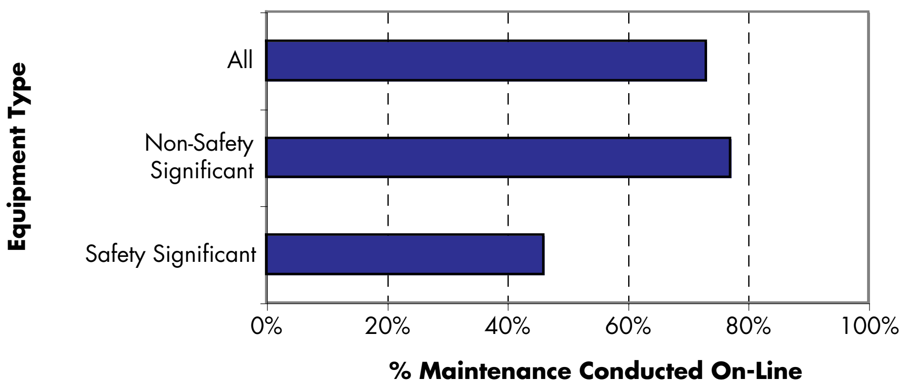

Fig. 6. Implementation of on-line maintenance at U.S. nuclear plants (Graph: NMAC survey)

All survey respondents indicated that they apply on-line maintenance, and more than 80 percent reported that they apply it to safety-significant systems and components. Overall, the survey showed that more than 70 percent of maintenance is performed on-line (see Fig. 6). It also showed that on-line maintenance of nonsafety-significant equipment is more common than on-line maintenance of safety-significant equipment. These results are consistent with industry screening criteria for selecting on-line maintenance activities.[11,17]

Implementation

Effective implementation of on-line maintenance depends on coordinated efforts between configuration risk management, work management, and maintenance.[16]

Configuration risk management—A plant's configuration risk management process is used to assess the risk impact of equipment out-of-service and to maintain plant risk at desired levels.[22] Specific to on-line maintenance, configuration risk management can help in determining whether the unavailability of a system or component is more significant during on-line or shutdown conditions, whether a system or component has a safety or essential generation function in specific plant configurations, and the increased risk associated with the

ON-LINE MAINTENANCE FRAMEWORK

Regulation and Regulatory Guidance	Regulation Interpretation	Programmatic	Major EPRI Implementing Tools and Methods
10CFR50.65, Maintenance Rule Reg Guide 1.160 Reg Guide 1.174 Reg Guide 1.182	NUMARC 93-01	Configuration Risk Management	• Risk & Reliability Workstation • ORAM-Sentinel: All Modes Safety Function Advisor
		Work Management	• Guidance for Development and Implementation of an On-Line Maintenance Strategy • Maintenance Work Package Planning Guideline
		Maintenance	• Preventive Maintenance Basis Database • Preventive Maintenance Program Implementation Assessment Guide

unavailability of a system or component that may serve a safety or essential generation function.

When performing on-line maintenance on safety or generation risk-significant equipment, utilities must carefully control the plant configuration and the systems and functions that are available. Such control is provided through close coordination of configuration risk management and work management.

Work-management process—The work-management process, and the work-planning activity in particular, ensures that resources to support on-line tasks are properly scheduled to maximize effectiveness. The work management process also helps ensure that unintended plant configurations do not occur that could change the risk significance of equipment that is unavailable.

Maintenance process—Familiarity with the technical basis for equipment maintenance tasks and the time intervals between repetitive tasks (task intervals) is critical. This technical basis determines the amount of maintenance work necessary to ensure adequate equipment performance and whether the maintenance task intervals are appropriate. Also, timely and successful completion of maintenance tasks becomes more important when these tasks are performed while the plant is on line because of the potential impact of maintenance task completion delays on plant operations. Nuclear power plants must have high confidence that the work scope of tasks can be completed within the allocated time windows. Plants typically take extra measures to ensure success, such as additional advanced planning and work area walkdowns, pre-task briefings, contingency parts procurement, staff selection, technical support resources, and management staff attention.

These maintenance practices often carry over to other maintenance activities and additional maintenance staff resources. For example, U.S. nuclear plants often create "Fix it Now" teams, equipping them with the necessary resources and expertise to address emergent issues that could arise and interfere with on-line activities.

A supporting framework has evolved in the United States for implementing on-line maintenance. This structure, and how it translates into plant implementation, is depicted in the accompanying table, although each plant's implementation methods may vary. Major tools, methods, and information documents developed by EPRI are included to illustrate the flow from regulation to practice. Additional resources are listed in Appendix A.

Continued

On-line maintenance trends at nuclear power plants

Results of NMAC survey

1. About one-half of the equipment in a plant requires preventive maintenance.
2. All plants apply some form of on-line maintenance.
3. A majority of plants apply on-line maintenance to some safety-related equipment.
4. Nearly one-half of the safety-significant equipment in a plant is maintained on line.
5. Most nonsafety-significant equipment in a plant is maintained on line.

APPENDIX A

Programmatic	Additional Implementing Tools and Methods
Risk Management	• Survey on the Use of Configuration Risk and Safety Management Tools at Nuclear Power Plants • Sentinel Technical Basis and Demonstration Reports • Qualitative Risk Assessment Methods for Shutdown Risk Management • Risk-Informed Integrated Safety Management Specifications Implementation Programs • Risk-Informed Configuration Based Tech Specs Implementation Guide • Option 2, 10CFR50.69 Special Treatment Guidelines • Development of Probabilistic Risk Assessment Qualification and Curriculum • Review of Current Practices for Configuration Risk Management at Nuclear Power Plants • Reliability and Risk Significance
Work Management	• Work Planning Assessment Guideline • Clearance and Tagging • Guideline for Addressing Contingency Spare Parts at Nuclear Power Plants • Guidelines for Balancing Reliability and Availability • Risk Based Maintenance Guidelines
Maintenance	• Freeze Sealing of Piping • Guideline for Application of the EPRI Preventive Maintenance Basis Database • Predictive Maintenance Program Development and Implementation • Predictive Maintenance Self Assessment Guideline for Nuclear Power Plant Personnel • Guideline for Assessing Maintenance Effectiveness

Plant demonstrations

Plant-specific applications of on-line maintenance are the final proof of success. In the late 1990s, EPRI coordinated demonstrations of its Configuration Risk Management (CRM) Tool at a number of plants.[23,24,25,26,27,28] These demonstrations showed how the use of electronic CRM tools could replace manual CRM assessments. They also led to the integration of CRM methods and tools into utility processes and ongoing activities.

Following the 1998 and 1999 CRM Tool demonstrations at the FitzPatrick and Indian Point-3 nuclear plants, the host utility documented a number of process and performance benefits.[29] The utility traced these benefits to improved staff efficiencies and incremental outage length reduction.

Staff efficiency benefits resulted from reduced planning and scheduling labor requirements. The reduction of the duration of outages resulted from the decreased number of tasks performed during outages (more were performed on line) and an increased number of tasks performed in parallel.

The utility estimated quantitative savings on the order of $750 000 per year. Because these savings would extend for multiple years, the total savings was estimated at $6 million.

The work planner at the host utility summarized the value of the EPRI CRM Tool as follows: "The ability to make dependable, repeatable, and risk-informed decisions with confidence plays a key role when striving for long-term economic viability through shorter, safer outages coupled with an aggressive but safe on-line maintenance program."

Performance and safety benefits

Some have questioned whether the industry's efforts to improve plant performance have compromised plant safety. The concern is that actions to shorten refueling outages and extend fuel cycles could reduce safety. U.S. industry data prove otherwise, demonstrating that performance and safety are not mutually exclusive objectives.

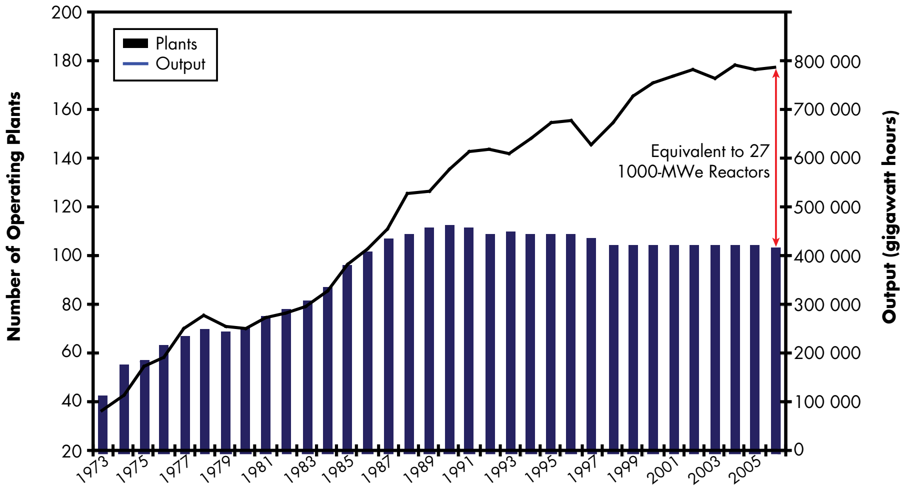

Fig. 8. Performance improvements at operating U.S. nuclear power plants over the past 20 years have provided the equivalent electrical production of 27 new 1000-MWe plants. (Graph data: NEI and EIA)

Through actions including on-line maintenance, the average capacity factor at U.S. nuclear power plants increased from roughly 70 percent to about 90 percent between 1992 and 2002. It has remained at this level ever since. Over a similar time period, from 1992 to 2005, studies using the NRC's PRA models from NUREG-1150 show that calculated core damage frequencies have been reduced by a factor of four.[30] This relationship is illustrated in Fig. 7.

EPRI reviewed the observed rate of significant safety events over the same time period to validate the calculated core damage frequency results. The analysis found the relative rate of significant safety events and the relative calculated core damage frequencies to be consistent.[31]

The improvement shown in Fig. 7 can be attributed to several factors associated with risk analysis, as follows:

- Improved understanding of the relative significance of various plant events based on risk analysis.
- Identification of plant-specific sources of risk and of relatively inexpensive changes to reduce risk.
- Improved understanding of which safety equipment is truly important in event prevention or mitigation.
- Reduction of failure rates for key equipment identified as risk-significant through PRA studies.

Several less-technical elements also support these improvements. These include regulatory understanding and support, cross-utility sharing of information and benchmarking, application of performance measures to gauge progress, and corrective action programs to drive improvement.

Looking forward

On-line maintenance—and risk-informed initiatives in general—have played a large part in the confidence that underpins the "nuclear renaissance" in the United States. As of September 2009, the Nuclear Regulatory Commission was actively at work on applications for 23 new power reactors. The reactor designs these applications are based on, informed by U.S. operating experience, are expected to benefit from risk-informed applications such as on-line maintenance.

Despite the heightened level of current interest in the nuclear renaissance, many believe that the renaissance actually began several years ago, when operating plants began demonstrating sustained excellence. The U.S. nuclear industry has significantly improved safety and performance over the past couple of decades, due in large part to individual plant accomplishments, industry-led initiatives, and changes in regulatory requirements and processes.[31] Included

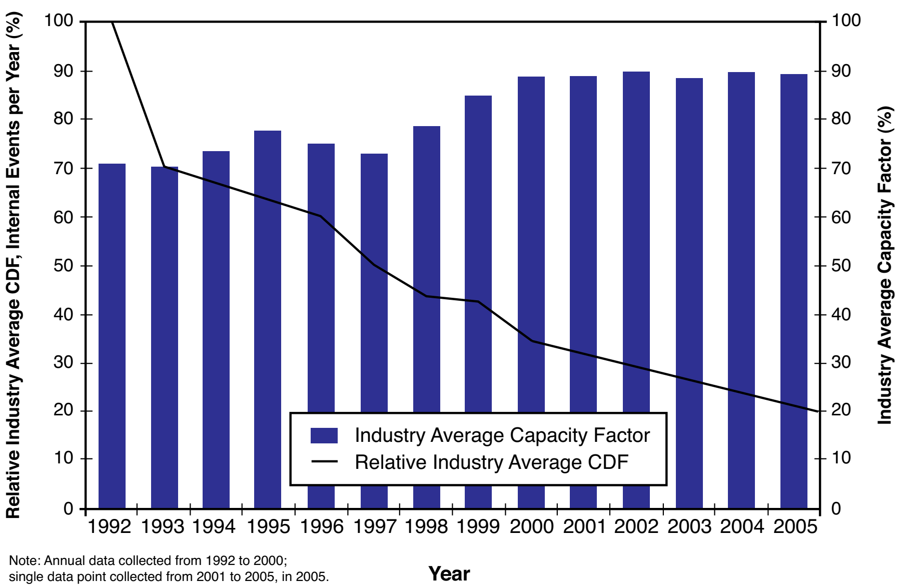

Fig. 7. Plant capacity factor performance versus core damage frequency risk levels

in these improvements are on-line maintenance and other risk-informed and performance-based techniques. Together, these improvements have enabled the nuclear power industry to increase plant reliability and capture efficiency gains, substantially increasing electricity generation output without adding new capacity. As shown in Fig. 8, performance improvements over the past 20 years at operating U.S. plants have provided the equivalent electrical production of 27 new 1000-MWe plants.[32]

This performance has significantly increased the value of operating plants and has led to about 90 percent of these plants electing to pursue the renewal of their initial 40-year operating licenses. The remaining plants are expected to follow,[33] and plants are now beginning to discuss research in support of longer-term operation.[34]

The saying "A journey of a thousand miles begins with a single step" is particularly appropriate in the context of on-line maintenance. While on-line maintenance was not the only step in the U.S. nuclear industry's journey toward sustained high-performance levels, it was certainly one of the first.

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