Long-Term Optimization of Outage Performance

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Abstract

Deregulation of the power markets and the accompanying pressure on electricity prices have forced all electric utilities to reduce their power generating costs in order to be able to hold their own in the new market environment. This has also particularly affected the operators of nuclear power plants since they have to compete against the lower power generating costs of fossil-fired combined-cycle power plants and, in Germany, are faced with a difficult political climate. The areas identified as having the greatest cost-cutting potential were fuel costs, operating costs and measures to increase plant availability. The main objective behind increasing plant availability was not only to improve the already high standard of operational reliability and plant safety even further, but also to significantly shorten the downtime needed for annual refueling outages. A variety of measures aimed at shortening scheduled plant outages have thus been developed and successfully implemented by nuclear plant operators. At the same time, process improvements and new technologies have been introduced by the service providers. Both initiatives together have contributed towards substantially reducing outage time and cost.

Introduction

At a German konvoi PWR, refueling outages which generally took around 30 days in the early 1990s now last only between 10 and a maximum of 22 days, depending on the scope of work involved.

The main contributions made by the plant operator towards this success have consisted of long-term outage planning and the shifting of maintenance activities out of the refueling outage and into the plant operating phase. Other key factors have included the introduction of modular maintenance and a general move towards condition-based maintenance with all of the savings in maintenance effort and cost that this entails.

The service provider, meanwhile, contributed the necessary diagnostics and data analysis equipment. Furthermore, the duration and cost of activities carried out by the service provider which have a major impact on the critical path – such as removing and re-installing the reactor pressure vessel (RPV) closure head, discharging and reloading the fuel assemblies, and performing in-service inspections (ISIs) on the RPV, reactor coolant system and steam generators – have also been able to be greatly reduced thanks to process improvements and the introduction of innovative technologies.

Long-Term Outage Planning

Apart from actual refueling of the reactor, the scope of an outage is mainly determined by the necessary maintenance work. Another key factor in this connection is the large number of ISIs that have to be carried out. ISI intervals are stipulated in various codes and standards and are also recommended by manufacturers. In Germany, for example, ISIs required by the KTA Nuclear Safety Standards have to be performed at intervals of 1, 2, 4 and 8 years. ISIs specified in the German Pressure Vessel Code, however, take place at 5- and 10-yearly intervals, whereas major turbine overhauls are recommended by the manufacturers after every 100,000 operating hours.
If one plots all specified ISIs according to their stipulated performance intervals over a long period of time, the result is a highly irregular pattern of the kind shown by the figure below.

The effect of ISIs on actual outage length can be determined by integrating the different packages of activities and their interdependencies into the critical path. As part of long-term outage planning, long-duration activities such as those listed below are then assigned to various outages:

- Reactor coolant system inspections
- Reactor coolant pump overhauls
- Turbine overhauls
- Work on redundant subsystems
- Integrated containment leakage rate tests
- Pressure tests on major components
- Upgrades and non-urgent repairs.

The objective of long-term outage planning is to re-arrange these activities in such a way as to optimize integral plant downtime over a long period of time. Often ISIs have been moved forward to give them a better position in the overall long-term strategy.
Based on these circumstances, four different types of outages of various lengths were thus defined (see also diagram below):

- "Short" outages of approximately 10 days recurring every 2 years (i.e. x+1, x+3, etc.)
- "Medium" outages of approximately 16 days recurring every 4 years (i.e. x+2, x+6, etc.)
- "Long" outages of approximately 18 days recurring every 8 years (i.e. x+4, x+12, etc.)
- "Very long" outages of approximately 22 days also recurring every 8 years but starting off in a different year (i.e. x+8, x+16, etc.).

This means, for example, that a "short" refueling outage with in-core shuffling of the fuel takes place every two years. There is no "low-loop" operation and all necessary ISIs can nevertheless be carried out with the plant in this condition.

"Medium"-length outages include not only reactor coolant pump maintenance but also ISIs on first shutoff valves, eddy-current examination of two of the four steam generators, and any work of a more extensive nature inside the turbine building that may also be possible within the allotted time span.

A "long" outage, which additionally includes ultrasonic examination of the RPV and a containment leakage rate test, takes place every eight years.

Then, also every eight years, theses activities are supplemented by a reactor coolant system pressure test and a major turbine overhaul during the longest – the "very long" – outage.

**Maintenance during Power Operation**

Since 1999, following approval by the German licensing authorities, this plant has been able to carry out safety system maintenance while the unit is on line. The work is restricted to a single period of 14 days and may be performed on one major redundant system along with its dedicated emergency core cooling and residual heat removal chain. It covers all requisite maintenance work on the systems' electrical, instrumentation and control (I&C) and, in particular, mechanical components.
Shifting such work into the plant operating phase brings the following advantages for plant outages:

- Fewer system and equipment tagouts
- Reduced scope of maintenance work
- Improved plant condition during outages (more redundant subsystems available)
- Outages shortened by approximately 1 day
- Reduced stress for specialists assigned to perform such activities.

In addition, maintenance can also be carried out during power operation on the following components which are important in terms of plant availability:

- Feedwater pumps
- Main condensate pumps
- Mechanical circulating water cleaning systems.

Normally this work is carried out immediately before an outage and extends into the outage itself.

Modular Maintenance

Modular maintenance was also introduced with the objective of taking activities off the critical path and avoiding the need for unscheduled repairs. Modular maintenance consists of the complete replacement of a component or of parts of a component. The replaced part is subjected to maintenance and repair after the plant has gone back on line and is then re-installed during the next outage. As already mentioned, this avoids the necessity for performing time-consuming repair work of possibly indeterminate length while an outage is in progress. Of course, an adequate stock of spare parts is essential for modular maintenance.

This type of maintenance is currently being applied to the safety valves in the main steam valve station.

Apart from reducing the volume of outage work, modular maintenance also has the benefit of reducing stress for the specialists performing this work since it can be carried out under "normal" working conditions – i.e. without the pressures of the outage time schedule – while the plant is in operation.

Revision of Maintenance/ISI Intervals and Reduction of Maintenance Effort

While revising previous maintenance and ISI intervals on the basis of past experience, plant operators have found opportunities for extending the intervals or even eliminating them altogether by applying a different strategy.

As mentioned earlier, the interval for major turbine overhauls, for example, has been extended from 50,000 to 100,000 operating hours in agreement with the turbine manufacturer, enabling this work package to be scheduled every eight years in line with the long-term outage planning strategy.

Corrective maintenance is now performed on more than 60% of a nuclear plant's pumps and valves since this proportion is not important for safety or availability.

For some safety-related components, maintenance intervals have been able to be extended from four to eight years thanks to the use of substitute techniques – which mark a general trend towards condition-based maintenance – such as regular vibration measurements in the plant in conjunction with in-depth analyses of long-term component performance. The resulting trend analyses enable changes in component conditions to be determined using automated monitoring and diagnostics systems. If a need for maintenance should be identified, the corresponding activities can then be planned in good time for the next outage on the basis of concrete information, thus making preventive maintenance totally unnecessary.

Diagnostics systems of this kind are being successfully deployed in various fields of plant engineering thanks to specially developed hardware and software. Measurements taken on rotating machines (pumps, fans and turbines), stationary components (reactor coolant system and RPV internals, steam generators and connected piping) and motor-operated valves using diagnostics systems installed in or designed for Siemens/Framatome ANP plants have supplied valuable reference data for the above-mentioned substitute techniques. Actual condition monitoring is carried out using both mobile and fixed measuring instruments. The frequency of these measure
ments is based on the behavioral trend exhibited by the component in question and, with today's PC-based monitoring systems, can automatically be adapted to changes in performance.

New developments in this area can be expected to open up additional potential for reducing maintenance effort in the next few years. These new developments will not be focused so much on the installation of more or new monitoring systems but rather on a more in-depth analysis of the data already provided by existing systems. This will require the involvement of hardware specialists who not only have the requisite component know-how but also are capable of correctly diagnosing the data supplied. In addition, cross-comparisons between the diagnostic data and inspection results from various plants will also become a necessity.

Information from component inspections can help reduce re-assembly work during an outage by, for example, avoiding the need for a component – such as a valve – to be disassembled at all. Instead of taking the valve actuator apart, borescopic examinations can be carried out through inspection openings in the valve body. The areas to be subjected to a borescopic examination are determined from experience with damage in the past and cover a component's entire condition.

The experience which forms the basis for this approach is not just built up from experience gained at one's own plant, but is also supplemented by data from other plants of an identical design (in this case, the German Convoy series of PWRs), experience from manufacturers and information from non-plant-specific databases such as that run by Germany's Technical Association of Large Power Plant Operators (VGB).

Now that the above-mentioned measures are in place, the next step is to consider extending ISI intervals for reactor coolant system components. Current proposals include extending the frequency of ultrasonic examination of the RPV and reactor coolant system from four to five years, and that of pressure testing from eight to 10 years.

**What Service Providers Have Done to Reduce Outage Lengths**

As described above, plant operators have focused their outage optimization efforts on implementing a long-term planning strategy, on shifting certain outage activities into the plant operating phase and on applying their experience from day-to-day plant operation.

Service providers, however, have pursued three main avenues in their efforts to help shorten outage lengths:

1. Development and manufacture of monitoring and diagnostic equipment for recording data on system and component conditions, followed by the development and manufacture of expert software for analyzing these data.
2. Process improvements for those services which are closely linked to activities carried out by the customer, these improvements being achieved through joint analysis and planning as well as the deployment of new technologies.
3. Reductions in the time and cost of those services carried out autonomously – i.e. separately from the customer – these reductions being achieved once again through process improvements and the use of innovative technologies.

Re: 1: Most of the development work that has been carried out in the last few years on diagnostics systems which have an impact on power plant maintenance has been concentrated on the following systems:

- Loose parts monitoring
- Vibration monitoring of reactor coolant system components and rotating machinery
- Comprehensive monitoring of motor-operated and solenoid-actuated valves.

Loose parts monitoring has currently reached a level of development which assures the accurate detection and location of loose and detached parts and their assessment in terms of further damage potential. Latest advances have led to a significant improvement in detection sensitivity. In recent years typical cases of damage have provided striking proof of these systems' great worth, with the prompt location of loose parts enabling plant operation to continue on a controlled basis until the next scheduled outage despite clear signs of damage. This accuracy in detection enabled efficient planning and performance of the necessary repairs.

Vibration monitoring has now gone beyond the status of a simple plant monitoring system, as originally required by Germany's DIN Industrial Standards and KTA Safety Standards. Further development of hardware and software components, coupled with the increased power of state-of-the-art computer systems, have raised these
monitoring systems to the level of genuine expert systems. Based on plant know-how available from the past, recorded changes in the condition of a component are converted directly into diagnoses along with maintenance recommendations based on action catalogs (either already in existence or in development), thereby enabling the scope of maintenance activities to be reduced.

The monitoring systems that have been developed for motor-operated valves (ADAM/SIPLUG) enable the performance of these valves to be monitored on-line with only a small need for equipment backfitting. Data on component conditions are obtained by recording electrical parameters when the valve is actuated. By linking the various modules in a PC network, the recorded data can be continuously stored in a central on-site database and retrieved by plant personnel at any time.

Re: 2: These services mainly concern all activities on the reactor service floor, many of which dominate the critical path of an outage. Plant operation such as shutdown and startup, along with all of the operating conditions that these entail, goes hand-in-hand with the progress of these activities. The first step for making improvements in this area is detailed planning of all job sequences together with the plant operator. Timely preparation of a master time schedule which identifies the main elements of the outage work scope is an essential prerequisite for this.

Potential areas for improvement were identified step by step by carefully analyzing all sequences of activities. For example, this approach enabled the time span from removal of the first reactor cover slab to the start of core unloading to be reduced from around 120 hours to just 48 hours.

The following aspects contributed to this considerable time saving:

- Improvement of reactor coolant system purging to remove aerosols.
- Improvement of RPV closure head cooling, enabling detensioning of the RPV closure head studs to be started much earlier.
- A total time of only approximately 3 hours is now required for stud detensioning, including removal of the studs and nuts.
- An additional gantry crane permits lifting operations in the reactor well while the reactor building crane is being used elsewhere.
- The RPV closure head is transferred to its laydown position immediately after stud detensioning, without waiting for the reactor well to be flooded. A tarpaulin stretched over the reactor well prevents aerosol release.
- The reactor well and setdown pool are flooded in less than 2½ hours using two high-pressure safety injection pumps.

The same aspects also save time when the closure head is replaced.

A similar approach has been used to improve the processes involved in core unloading and reloading. Whereas each of these operations used to take approximately 120 hours, they are now completed in just around 48 hours. This was achieved by optimizing the processes of fuel assembly discharge and fuel assembly insertion using a number of dummy assemblies. The refueling machine was upgraded, its speed was increased by 10% and it was provided with capability for transverse travel. In addition, all fuel assembly grappling and transfer operations are monitored using a submersible inspection vehicle, enabling prompt response to offnormal conditions such as fuel assembly bow. This submersible vehicle is also used to perform the last core loading verification check.

Great benefits have also been gained from the deployment of highly trained outage personnel who perform these activities several times each year, and from a pool of mechanical and I&C specialists who were permanently on standby for troubleshooting while the refueling machine was in use, an activity which lies on the critical path of the outage.

In addition to the gantry crane mentioned earlier and the submersible inspection vehicle, a wide variety of different tools have been developed to help improve work procedures. For example, a gripper and vacuum extraction system for retrieving foreign objects and a dosimeter have been added to the submersible vehicle to enable cleaning operations to be performed only at those locations where they are actually necessary.

The RPV flange seal face is cleaned automatically during draining of the reactor well, thus taking that activity off the critical path. The threaded stud holes in the RPV flange are automatically cleaned and prepared for retensioning of the closure head studs from the auxiliary bridge.
All of these measures have not only helped to improve the sequence of outage activities but have also enhanced the overall quality of outage performance.

Re: 3: As far as autonomous work by the service provider is concerned, careful linking of innovative technologies with consistent process improvements aimed at reducing outage lengths is of key importance, as are the downsizing of inspection teams and person-rem reduction. These last two items can also make an important contribution towards cutting outage costs. Tools and techniques available for this include:

- Ultrasonic examinations using the innovative phased-array technique which provides for precise, electronically-controlled steering of the sound beam, allowing one search unit to do the work previously done by several and nevertheless supply more ultrasonic data than ever before.
- The corresponding ultrasonic examination systems SAPHIR and Saphir\textsuperscript{plus} which ensure optimal deployment of any desired combination of phased-array and conventional search units.
- The consistent application of state-of-the-art robotics has led to an array of modular manipulator designs whose mechanical and control equipment can be easily and quickly assembled for rapid deployment.

Some key examples are given below to illustrate the progress made in the past five years in the field of ISI:

- The current state of the art in RPV internal inspection (140 such inspections have now been carried out worldwide) can be characterized by the following figures:

  - At a Convoy-series PWR, vessel occupation time for a complete ISI of the lower section of the RPV now totals 3.5 days, while the same scope of work used to take a total of 10 days a decade ago.
  - At Framatome reactors and pre-Convoy plants, vessel occupation time is around 5 days, unlike 12 to 15 days in the past.
  - Over the same period of time, the 3-shift inspection crew has been able to be downsized from 22 to 13 persons.

- The innovative phased-array technique has now become a firmly established method for examining the circumferential weld and nozzle ligaments of the RPV closure head. Its greatly simplified search unit system considerably reduces equipment setup and inspection times in this high-dose area.

  - The phased-array system also enables areas that previously had to be examined separately, with repeated interruptions for relocating the equipment, to now be covered in a single scanning pass.

- Techniques for eddy-current steam generator tube inspections have also been optimized over the past five years.
Advances in inspection equipment design, together with a much larger number of data channels, paved the way for the development of a dual probe pusher with which it is now possible to inspect two tubes at a time with only one set of equipment.

Steam generator inspection manipulator with dual probe pusher
The following figures give an idea of what this has meant for eddy-current steam generator tube inspections in German plants.

Using four manipulators and a total of eight probes in two steam generators (700 tubes per steam generator and 10-hour shift), component occupation times of 60 to 70 hours have been achieved for 100% inspections of the steam generator tubes over their entire length. This means that tube inspection efficiency has increased by a factor of 2, thereby shortening the critical path.

A further increase in inspection efficiency to reach a total of 800 tubes per 10-hour shift will be possible in the near future thanks to the introduction of a new manipulator which will no longer be hindered by having to be mounted on the tubesheet.

Formation of the joint venture Framatome ANP has had a highly positive impact in this area of work due to the considerable expansion of resources and the use of similar inspection and data analysis equipment.

As far as the topic of ISI is concerned, it is certainly true that RPV and steam generator tube inspections, which used to have a major influence on the critical path of an outage, have now been improved to such an extent that their potential for prolonging an outage has been minimized.

1. Conclusion

In conclusion it can be said that all of the measures introduced by plant operators and service providers with the aim of optimizing outage performance have indeed enabled the goal of short, lower-cost outages that can be reliably planned in advance to be achieved.

As far as we can tell today, the outage concept described in the introduction with its durations ranging between 10 and 22 days already seems to have exploited most of the remaining potential for optimization in terms of technology and licensing. Further variations in outage length do, however, exist at some other plants where, for example, two short outages of 7 days each might be performed every year to make additional savings on fuel costs.

Certainly, new technological advances will enable further areas for improvement to be exploited in the future. However, the large savings in cost and time achieved in the past will not be seen again. The objective today must be to maintain and consolidate this high standard of outage performance in the long term.