International overview: Good practices at nuclear power plants

A summary of findings from two IAEA studies on the reasons behind the good performance of nuclear power plants

by F. Calori and J. Dular

Positive trends on the performance of the world's nuclear power plants have been noticeable over the last decade. During 1990, a total of 231 nuclear power plants — or nearly two-thirds of the world's non-prototype nuclear power reactors larger than 100 megawatts-electric (MWe) — achieved high levels of performance. They operated with an energy availability factor (EAF) of between 70% and 90%, based on statistics from the IAEA's Power Reactor Information System (PRIS). Thirty-three of these plants reported an EAF (the percentage of time the plant is available to produce electricity) above 90%. These numbers represent a definite achievement for the nuclear industry. *(See graph.)*

At the same time, however, significant variances can be observed at plants run by different operating organizations. Forty-eight nuclear plants, for example, reported EAFs below 50% in 1990.

To determine and analyse the reasons for such differences, the IAEA initiated two studies covering a number of nuclear electricity plants.* The studies were different in scope and nature and were conducted independently. One study —which generally might be referred to as the "good practices" study — was directed at a restricted population of selected known good performers. The other study — referred to here as the OSART study — was a byproduct of the IAEA's Operational Safety Review Team programme. Through it, international experts at the request of national authorities conduct on-site reviews of nuclear power plants to assess the adequacy of those practices supporting operational safety.

This article reviews the key purposes and aims of these two studies, and summarizes their major findings, including the identification of the main factors contributing to the good performance of a nuclear electricity plant.

The "good practices" study

Initiated in the late 1980s, the IAEA's "good practices" study aimed to identify the main reasons for large variations in the performance of the world's nuclear power plants.

It focused on the efforts of operating organizations that go beyond requirements mandated by regulatory authorities. These organizations typically strive to establish, maintain, and improve the reliability of plant equipment, the accountability and proficiency of staff, and the way in which work is planned, executed, and controlled.

The study included visits to eight nuclear power stations in seven countries selected for their consistently good performance, as indicated primarily by their availability factors. Additionally, a number of operational support groups and three independent organizations providing support to multiple utilities were visited.

The stations visited had a total of 22 operating nuclear units that together had accumulated approximately 130 reactor-years of commercial experience at the time the study was performed. These units were representative of the world's nuclear plants in terms of size (445 to 1248 MWe); type (PWR, BWR, PHWR); and in-service vintage (1973-1986). The selection was based on the following criteria:

- the cumulative nuclear operating experience of the associated utility (greater than 10 years);
- number of operating units (two or more);

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* See *Good Practices for Improved Nuclear Power Plant Performance*, IAEA TEC-DOC 498, Vienna (1989), and *OSART Good Practices, 1986-89*, IAEA TEC-DOC 605, Vienna (1991).

Aerial view of Takahama nuclear power plant in Japan.

● the energy availability factor, as recorded in PRIS (consistently above the average world performance and consistent improvement for at least 2 years before the study began).

The OSART study

The second study — done under the OSART programme — was an outgrowth of regularly conducted IAEA missions to review the operational safety of nuclear plants.

During the course of their missions, OSART teams take note of good practices that are related to the operational safety and performance of the nuclear plant they are visiting. The teams began identifying good practices in 1986 and they have been systematically compiled since 1988.

The OSART programme itself was set up in 1982, growing from the recognition that a plant's safety depends ultimately on the ability and conscientiousness of the operations personnel and on their tools and work methods. Through technical exchanges between the OSART reviewers and their counterparts at the plant, problems are identified and discussed in detail, and possible solutions and options are elaborated.

Specific observations of each OSART mission are documented in technical notes. These are then used as source material for the official OSART report submitted to the government of the host country. The technical notes contain proposals for improvements and descriptions of commendable good practices. Good practices identified in the course of each review are communicated to the plant itself, and also checked for possible applicability elsewhere. They are intended for wide distribution to all organizations constructing, operating, or regulating nuclear power plants.

A number of points should be kept in mind in connection with the good practices identified by OSART teams. Since some practices were first identified some years ago, they may have become widespread and normal by now. Additionally, not all of the good practices are applicable to all nuclear plants because of the specific nature of each OSART review, as well as the subjective views of each team's individual members.

Main contributors to good performance

From the results of the two studies, a number of operating practices and procedures proved to be main contributors to good plant performance. They generally are related to:

General principles of quality management. The studies identified practices that reflect management's consistent involvement, promote staff accountability, and set high expectations for performance. To this end, effective management ensures that performance goals and objectives, which state clearly what is to be achieved, serve as a basis to develop work programmes and plans, allocate adequate resources, and com-

Nuclear power plants in the OSART study

UNIT	COUNTRY (OPERATOR)	TYPE	CAPACITY NET MWe	START OF COMMERCIAL OPERATION	CUMULATIVE EAF TO 1989	OSART REVIEW
BARSEBECK 1-2	SWEDEN (SYDKRAFT)	BWR	2 x 600	1975 - 77	Unit 1: 79.3 2: 84.5	1986
PICKERING 1-8	CANADA (OH)	PHWR	8 x 516	1971 - 86	58.2 - 89.6*	1987
CALVERT CLIFFS	UNITED STATES (BGE)	BWR	2 x 825	1975 - 77	Unit 1: 69.2 2: 74.2	1987
PHILIPPSBURG 1-2	GERMANY (KKP)	PWR	864 1268	1985	Unit 1: 65.6 2: 88.7	1987
ALMARAZ 1-2	SPAIN (CNAL)	PWR	2 x 900	1981 - 84	Unit 1: 70.1 2: 81.2	1987
TAKAHAMA 3-4	JAPAN (KEPCO)	PWR	2 x 830	1985 - 85	Unit 3: 84.0 4: 86.8	1988
ST. ALBAN 1-2	FRANCE (EDF)	PWR	2 x 1335	1986 - 87	Unit 1: 60.5 2: 68.1	1988
PAKS-3	HUNGARY (MWMT)	WWER	410	1986	87.5	1988
ROVNO-3	UKRAINE (MAPI)	WWER	950	1987	74.4	1988
KANUPP	PAKISTAN (PAEC)	PHWR	125	1972	25.7	1989
ANGRA	BRAZIL (FURNAS)	PWR	626	1984	24.9	1989
BYRON 1-2	UNITED STATES (COMED)	PWR	2 x 1120	1985 - 87	Unit 1: 69.0 2: 69.1	1989

* Minimum and maximim values among the eight units.

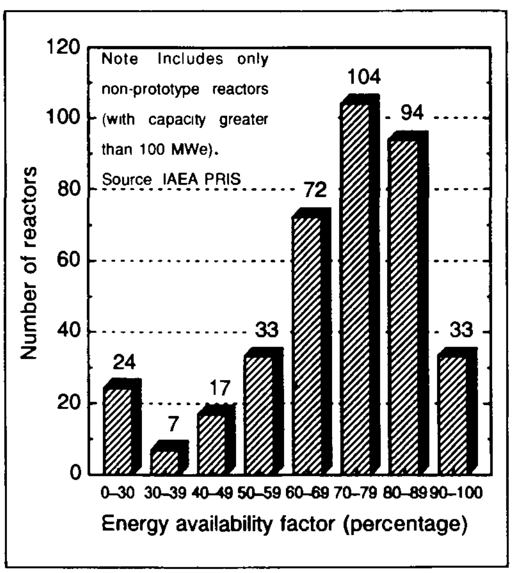
Notes EAF = energy availability factor Factors are calculated from the month following commercial operation.

Source IAEA PRIS

municate performance expectations to staff. Performance objectives are typically included in station policy documents and procedures, integrated into staff training and work programmes, communicated to contractors prior to work commencement, and reinforced by management staff in daily communications and meetings.

An important element in this process is the definition of an organizational structure and associated authority and responsibility. The station manager ensures that directives for functional responsibilities and associated interfaces are defined in station documentation, communicated to staff, and understood and accepted by all. This includes relationships of plant staff with corporate management and external operations support groups.

Energy availability factors at nuclear plants in 1990



Particular attention is devoted to establishing effective reporting mechanisms which ensure that significant items are promptly brought to management attention by means of shift supervisor reports, event reports, on-call systems, or results of audits. The line organization is the primary source of information to senior management. If problems are identified through other sources, senior management staff are careful not to circumvent line management staff in implementing corrective actions.

Team-building is considered an important task of a good management. Teamwork is cultivated and reinforced through emphasis on the need for and benefits of co-operation, communication, and co-ordination. The following activities are good examples of management involvement which foster teamwork and reinforce staff accountability:

- daily "morning meetings" involving key operations, maintenance, technical, planning,

UNIT	COUNTRY (OPERATOR)	TYPE	CAPACITY NET MWe	COMMERCIAL OPERATION	EAF 1985-1987	CUMULATIVE EAF to 1987
BARSEBECK-1	SWEDEN	BWR	600	1975	89.3	78.3
BARSEBECK-2	(SYDKRAFT)	BWR	600	1977	91.5	84.2
BLAYAIS-1	FRANCE	PWR	910	1981	82.0	76.6
BLAYAIS-2	(EDF)	PWR	910	1983	85.7	81.3
BLAYAIS-3		PWR	910	1983	89.4	86.9
BLAYAIS-4		PWR	910	1983	81.5	80.9
FUKUSHIMA-DAINI-1	JAPAN	BWR	1067	1982	82.5	79.1
FUKUSHIMA-DAINI-2	(TEPCO)	BWR	1067	1984	74.5	79.8
FUKUSHIMA-DAINI-3		BWR	1067	1985	*	*
FUKUSHIMA-DAINI-4		BWR	1067	1987	*	*
GUNDREMMINGEN-B	GERMANY	BWR	1240	1984	84.3	85.3
GUNDREMMINGEN-C	(KGB)	BWR	1248	1985	83.3	83.3
LOVIISA-1	FINLAND	PWR	445	1977	92.7	81.6
LOVIISA-2	(IVO)	PWR	445	1981	89.0	86.3
PICKERING-5	CANADA	PHWR	516	1983	82.7	82.6
PICKERING-6	(OH)	PHWR	516	1984	78.5	79.9
PICKERING-7		PHWR	516	1985	87 6	87.6
PICKERING-8		PHWR	516	1986	*	*
PRAIRIE ISLAND-1	UNITED STATES	PWR	503	1973	83.9	78.4
PRAIRIE ISLAND-2	(NSP)	PWR	500	1974	90.7	83.2
TVO-1	FINLAND	BWR	710	1979	90.3	86.2
TVO-2	(TVO)	BWR	710	1982	92.3	90.9

* Commercial operation less than 23 months at time of study

Notes EAF = energy availability factor Factors are calculated from the month following commercial operation

Source IAEA PRIS

Nuclear power plants in the IAEA "good practices" study

and other support staff to review operational problems and their corrective actions;

- committees or review groups involving corporate/external support to address special problems requiring interdisciplinary competence;
- rotation of key staff between station departments and/or between station and corporate support groups to enhance staff knowledge and stimulate initiatives;
- use of system engineers to act as a focal point for activities relating to a particular plant system; and
- frequent management tours of the station that are visible to staff, take time for discussion, and display awareness of staff activities.

Moreover, effective management is attentive to performance data and their trend analysis. To this effect, a set of selected, plant-specific performance indicators is used as an efficient tool to detect slipping standards promptly and alert management to incipient problems. It is important that performance trends and achievements be promptly communicated to the staff by means of display on station bulletin boards, distribution of performance reports, and reviews of trends at staff meetings.

These practices are important as they convince the staff that:

- performance deficiencies and associated root causes are systematically identified and corrective action taken to prevent recurrence;
- performance improvement objectives and programmes are developed, prioritized, and adequately resourced; and
- work progress is monitored to completion.

A strong, rigorous quality culture is recognized as an important element of good station management.* This concept rests on the following practices:

- Quality Assurance programmes are extended to all power production-related systems in the plant, not just safety-related systems.
- Responsibility to achieve quality, and to verify its achievement, remains with those performing the task and their associated line management.
- Plant modifications of a temporary or permanent nature are prepared, reviewed, and approved by staff knowledgeable of the design intent of the affected systems who would ensure the operability and maintainability of the proposed modifications.

* See "Quality assurance at nuclear power plants: Basing programmes on performance," by F. Hawkins and N. Pieroni, *IAEA Bulletin*, Vol.33, No. 4 (1991).

- A mechanism is in place to ensure that approved modifications are communicated to sister units in the utility for implementation.
- Plant documentation, including drawings and procedures, are promptly updated in accordance with the revised configuration, obsolete documentation is withdrawn, and provisions are made to ensure staff awareness of changes.

Competent station management further understands the importance of establishing and maintaining long-term working relationships with the original architect-engineer and major vendor and supplier organizations. Major benefits can be derived from a good relationship.

This plant management/supplier interaction is supported by regularly providing vendor/supplier organizations with feedback on performance of their equipment/components. For active and expeditious exchange of experience, vendors/suppliers are encouraged to appoint a resident representative at the station site. The practice of establishing long-term contracts, and agreements for research and development initiatives in order to supply special inspection/maintenance/engineering services and special tooling development, has proved an important contributor to a plant's high level of availability.

Similarly, the maintenance of good and open professional relationships with government regulatory authorities goes a long way toward resolving licence-related issues, avoiding unnecessary delays, and expediting in-plant regulatory inspections during plant outages. This contributes to increased station availability.

Well-established and clearly defined plant programmatic procedures are the key elements of a well-functioning quality management system that govern safe and reliable plant operation. A rigorous and systematic approach to preparing, approving, and ensuring compliance with procedures is an important task of the station manager.

Plant operations control. In well-performing nuclear stations, operations activities are carried out in a disciplined manner with the objective of achieving a prompt identification of and appropriate response to equipment problems while minimizing human-related errors.

The quality of supporting documents for operating staff is a significant factor in minimizing human-related errors and achieving good plant performance. Operating procedures are clear, concise, and formated for easy usage. They are prepared by operating personnel, reviewed, and field-validated by senior management staff prior to authorization for use in order to ensure conformance with the station design intent. They are promptly updated to reflect new information and lessons from the experience. In case of major plant modifications, the procedural changes are promptly integrated in classroom/simulator training programmes. Utmost care is taken to minimize the number and duration of temporary operating instructions which supersede normal procedures. This is controlled through frequent review of outstanding temporary instructions by senior staff, operations committees, and/or station safety review committees.

One prerequisite for good plant performance is that operating crews remain aware of the conditions of the equipment and systems under their responsibility. This is done through a rigorous and strictly disciplined plant status control, which is monitored on a continuing basis.

This control is effected through routine panel inspections and scheduled surveillance tests by qualified control-room staff to confirm that components and systems are in an appropriate state of readiness. Clear procedures and reporting lines are established to document deficiencies and bring them to the attention of supervisory staff for initiation of corrective action. A log-keeping which is timely, accurate, and reflects fully the station activities is an important element of the plant status control. High quality log-keeping supports effective continuity between shifts, ensures that problems are followed through to completion, and helps reviews by senior staff in their operations surveillance activities. Formal procedures are established to ensure effective transfer of information on station status during shift turnovers. The process includes agreement by incoming and outgoing staff on transfer and acceptance of responsibilities.

Well-disciplined administrative controls are implemented for operation of field equipment, including its isolation for maintenance purposes. Field operations are performed in accordance with operating orders, and prepared and authorized by qualified staff. These orders prescribe individual component positions and the correct sequence of operation. Exceptions are defined in station procedures and if a field device is found in an unexpected condition, the execution of the operating order is suspended pending review with control-room staff. Close communications are established between operations and maintenance staff regarding the nature of work to be performed, adjacent worker safety hazards, the specifics of the equipment isolation, and the proposed testing after maintenance. Extensive provisions are made for signatures which record activities performed and responsibilities accepted. Responsibilities for review prior to resumption of normal operation are clearly established and decision-making authority for restart is well defined. This approach reflects an underlying philosophy that station safety precedes production objectives.

Particular attention is given by good operators to the reduction of personnel exposure, monitoring of radioactive effluents, and volume reduction of solid radioactive waste. The following is noteworthy:

- Analyses are performed of radiation work to be carried out, monitoring of work execution, and of its results. Well-designed systems for entry to control areas are in operation.
- Special attention is given to monitoring radioactive effluents. Mobile laboratories for environmental monitoring exist, continuous measuring of radionuclides in the stack are carried out, and monitoring of radionuclides in the primary coolant is regular (daily).
- Attention is paid to reduction of radioactive waste volume by cleaning and clearance of large components, among other measures.

In well-operated plants, sufficient attention is given to chemistry, especially to water chemistry. To this effect, on-line surveillance of the water-steam circuit is carried out, analysis of each event that affects plant chemistry is regularly performed, and chemist training books are developed based on this. Additionally, special corrosion investigation programmes are carried out.

Maintenance organization. Performance of maintenance activities which are carefully prepared, strictly controlled, and timely executed has a strong impact on plant availability.

To maximize equipment reliability and thus improve plant performance, good operators perform an increasing amount of preventive maintenance. This also helps to decrease maintenance costs by systematic planning of actions, restriction of work interruptions, and more uniform utilization of maintenance resources. In order to monitor the condition of operating equipment, a number of predictive maintenance techniques are in use. These techniques alert operators to incipient degradation in equipment, thus reducing forced outages and facilitate scheduling of preventive and corrective maintenance.

Good operators perform corrective maintenance expeditiously and closely monitor the outstanding backlogs. An up-to-date list of work requiring unit shutdown is maintained and a priority work list is prepared to make maximum use of unscheduled outages. Equipment history files, containing complete records of maintenance work, are kept. They summarize work performed, radiation exposures involved, time spent on tasks, observations on "as-found" component conditions, and suggested improvements for future execution of work. For crucial maintenance jobs, rehearsals are performed on mock-ups prior to actual field work. Tool inventories are kept and strict control applied in specialized maintenance areas to prevent foreign items from being inadvertently introduced into systems/components. Extensive use of automated tooling is made to reduce radiation exposure to workers, reduce time and labour to complete tasks, and perform high-quality work. Effective conduct of maintenance is supported by a well-stocked inventory of spare parts on the site. Their storage is subjected to effective material management practices, which include computerized inventories, quality checks of condition upon receipt, and attention to storage conditions to prevent degradation, and proper labelling of parts. Access to inter-utility pools for major spare components provides an excellent way to facilitate major inspection/refurbishment programmes with minimum impact on plant down-time.

On-site maintenance support facilities also are important. These may include chemical, electrochemical, or ultrasonic decontamination tanks to immerse components — such as primary coolant pump impellers and valve internals — for ease and speed of refurbishment; special workshops to accommodate overhaul of contaminated components; and rehearsal facilities with mock-ups for training and tool testing. Special care for specialized maintenance tooling storage includes procedures ensuring that tools are properly labelled for easy retrieval, and that they are effectively decontaminated or repaired after use, thereby ensuring their readiness for future usage.

Planned outages for refuelling inspection and maintenance contribute to a major portion of unavailability of well-performing nuclear plants. Thus, an effective outage management is considered a major reason for good overall performance and high plant availability factors.*

Factors that are important contributors to good outage management include:

- an efficient organization in charge of outages, which is committed fully to achieving outage objectives while minimizing outage extensions;
- establishment of a long-term outage strategy which meets the utility requirements for long-term safe and reliable operation in the most cost-effective manner;
- detailed and comprehensive outage planning and preparation, which ensures availability of qualified on-site and off-site manpower resources and specialized tooling to perform outage-related work;
- attention to selection, briefing, and supervision of contractor personnel;
- systematic post-outage review which identifies the lessons learned and directs thorough

*See *Good Practices for Outage Management in Nuclear Power Plants*, IAEA TEC-DOC 621, Vienna (1991).

and lasting corrective actions to prevent recurrence of shortcomings for continued improvement.

A rigorous and systematic outage review process, which solicits possible improvement initiatives from all staff, has a major underlying benefit. Each person is provided with another opportunity to contribute to the achievement of plant goals which enhances individual accountability and ownership. This process is one of the methods which reinforces an ethic in staff for the station's continuous improvement.

Technical support. A strong and competent on-site and corporate technical support is essential to reliable plant operation consistent with high standards of operational safety.

Effective technical support is provided by establishing and implementing a technical surveillance programme for all plant systems essential to safety and reliability. It includes provisions to ensure that clear procedures and assignment of responsibilities are in place to periodically perform routine reviews of operating parameters and plant systems performance in order to assess their changes with time. This is accomplished systematically by reviewing deficiencies through analysis of operating logs and maintenance reports and prompt assessments of routine and special system tests and their trends. Plant procedures are regularly examined to ensure that they remain up-to-date with respect to plant modifications and that operating experience is appropriately incorporated.

Significant events, including "near-miss" situations, are promptly reported to senior management. To this effect, guidelines are developed that specify the type of events to be reviewed, the methods for conducting the review, and the responsibility for identifying and implementing the associated corrective actions.

A competent and systematic analysis of operating experience is essential for performance improvement. This analysis is an important task of the technical support staff assisted by central utility groups, senior management, and "ad hoc" multi-disciplinary review committees. The station/utility operating experience is complemented by reviewing the experience of other stations/utilities. To this end, a well-managed technical support department establishes methods to obtain external experience feedback through nuclear network information systems. These may include the Institute of Nuclear Power Operations' Significant Operating Event Report; the Incident Reporting Systems of the IAEA and Nuclear Energy Agency of the Organisation for Economic Co-operation and Development; vendor/supplier bulletins and newsletters; and inter-utility groups, such as the World Association of Nuclear Operators or the Union of Producers and Distributors of Electrical Energy.

Findings and results of the technical surveillance activities of the technical support are periodically submitted to the station manager through formal reports on key safety, environmental and performance parameters. These include a summary of the operating histories of equipment or components, together with an appraisal with respect to their long-term implications on the safety and reliability of the plant.

Training and qualification. At nuclear power plants and training centres, attention is focused on training of the instructors and the use of simulators for training operating staff.

The technical competence of instructors is maintained by periodic involvement in plant activities. Instructors, as licensed personnel, keep their operator license and participate in the operator requalification programme. Well-developed simulator training programmes for operators were noted at some training centres established for new power plants. They are equipped with full-scope simulators as well as compact and part task simulators. The latter two types are used also in the plants to supplement the theoretical training. Also, special training groups, covering different disciplines, are facilitating the exchange of the job-related experience during training.

Another area for which particular efforts were noted is the training of maintenance personnel, and special care that is given to the training facilities. Special training courses and rehearsals for outages and training for refuelling operations also were noted. Training covers the lessons learned during previous outages, quality assurance, industrial safety, radiation protection, waste reduction, and analysis of new tasks.

The systematic approach to training general employees noted in some plants contributes to the development of the safety culture.

Keys to good operation

Of interest to note from results of these two independently conducted IAEA studies is their close convergence with respect to the identification of good operating practices at nuclear electricity plants. Indeed, those practices that improve plant *performance* were found to be the same as those that ensure the plant's operational *safety*.

One of the most important conclusions is that top-quality management which supports disciplined operation is the key to achieving overall plant safety, reliability, and economic performance objectives.❐