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POWER UPRATE IN NUCLEAR POWER PLANTS: GUIDELINES AND EXPERIENCE

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IAEA NUCLEAR ENERGY SERIES No. NP-T-3.9

POWER UPRATE IN NUCLEAR POWER PLANTS: GUIDELINES AND EXPERIENCE

PREPARED WITHIN THE FRAMEWORK OF THE TECHNICAL WORKING GROUP ON LIFE MANAGEMENT OF NUCLEAR POWER PLANTS

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FOREWORD

It is in the interest of nuclear power plant owners to keep their plants operating at high levels and in service as long as they can be maintained safely and it is economically viable to do so. Implementing a power uprate programme is one method of achieving this goal. Specifically, a power uprate programme can assist nuclear power plant life management programmes for the long term operation and license renewal of water cooled reactors. A number of physical plant modifications are required and need to be implemented to allow operation at the increased levels of power and to ensure operation within the constraints and framework of the power plant.

A goal of a power uprate is to increase the gross electrical output of the nuclear power plant, while maintaining adequate safety, design and operating margins. It is important to ensure that there is a balance between the number of modifications installed and the attainable electrical power output. There are a number of options for uprating the power level and these are discussed in this report.

The power uprate process involves the consideration of a number of factors. These include the material condition of the plant, the plant's technical concept, and asset management/business planning. Power uprates, especially large uprates, have in some instances resulted in accelerated equipment degradation due to increased flows and energy levels in secondary systems. In some cases, there were latent effects that took weeks or even months to be detected after completion of the uprate.

This report provides information and guidance on current trends, licensing aspects, monitoring, lessons learned, verification technology, and the associated side effects. It discusses various types of power uprates, from small to large, for pressurized and boiling water reactors. A successful power uprate may involve utilizing a portion of the existing design margins, using improved analytical techniques, improving material conditions, and developing advanced fuel management techniques.

The process of power uprates varies among countries due to differences in reactor design and type, regulatory processes, and plant life management programmes. To ensure that a wide range of information is presented, country reports are provided in the appendices. These are intended to promote the exchange of experience and lessons learned from the various countries who have implemented power uprate programmes.

The IAEA wishes to thank the participants for their contributions, especially P. Bystedt (Sweden), who also chaired the technical meeting. The IAEA officers responsible for this publication were K.-S. Kang and L. Kupca of the Division of Nuclear Power.

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

The process of increasing the licensed power level of a commercial nuclear power plant is called a power uprate. Power uprates are generally categorized based on the magnitude and the methods used to achieve the power increase.

Power uprates have been implemented at a number of nuclear power plants (NPPs) in many countries. Currently, there are also a significant number of NPPs that have plans for larger or smaller power uprates. Such uprates are an economical way of producing more electricity at an NPP and have attracted interest due to increased electricity prices, a situation that is expected to remain. The increase in the electricity produced at an NPP can be achieved in two ways:

— Increase the thermal power in the reactor;
— Improve the thermal conversion efficiency in the secondary side of the power plant by refurbishing or replacing the high pressure or low pressure turbine units, by feedwater heater refurbishment/replacement, or by a combination of these actions.

1.2. INCREASES IN THERMAL OUTPUT

One way of increasing the thermal power from a reactor is to increase the amount of fissile material in use. Optimization of the reactor operating conditions can also be done. The amount of fissile material is increased either by increasing the degree of enrichment or by increasing the density of the fuel. Optimization of the fuel reload focuses on increasing the output from the fuel bundles using less power without affecting the high power bundles. It is also possible to increase the core power by increasing the performance of the high power bundles.

Safety margins for fuel can be maintained by either using fuels that are designed to perform at a higher level or through the use of improved methods of analysis to demonstrate that the required margins are retained even at the higher power levels.

In BWRs, the increased core power is achieved by either optimizing the control rod pattern or by increasing the reactor recirculation flow. The degrees of recirculation flow can be retained, with larger steam voids in the cores, or the steam volumes can be held constant by increasing the recirculation flows. A combination of these measures can also be applied.

In PWRs, the increased power output requires an increase either in the steam flow or in the coolant temperature difference across the core, or both. In all cases, the steam production to the main turbine increases with increased electrical output being achieved by the turbogenerators.

1.3. OBJECTIVE

This report provides guidance and describes experience related to the reactor thermal power uprate of NPPs. It is intended to give a general overview of the major processes, work products, issues, challenges, events and experience in a power uprate programme, as well as to provide lessons learned and recommendations.

1.4. SCOPE

This report provides information on current trends, licensing aspects, monitoring, verification technology after a power uprate, and the associated side effects. It reviews the type of power uprates, from small to large (for

PWRs and BWRs). Where appropriate, the differences between smaller (MUR)[1], or stretch uprates (SPU)[2], and the larger, extended uprates (EPU)[3] are discussed. Generally, however, the content of the report focuses on uprates of the stretch and extended types and covers the following topics:

— Basis for power uprate — types of uprate;
— History of power uprate in various countries;
— Scope and execution of feasibility study — areas of analysis, types of analysis, results of analysis;
— Lessons learned from feasibility studies — missed scope, augmented reviews;
— Typical schedule, resource requirements of power uprate;
— Lessons learned from power uprate;
— Ongoing power uprate issues — steam dryers, fuel reliability, secondary plant effects;
— Procedure to verify the design of a power uprate;
— Startup and test programme after a power uprate;
— Training programme for a power uprate;
— Project management for implementation of a power uprate;
— Licensing aspects of a power uprate;
— Warranty tests to verify the balance of the plant (BOP);
— Performance test programme.

1.5. STATUS OF THE POWER UPRATE PROCESS

Power uprates have been employed to enhance the output of NPPs for over 30 years in many countries (for further details see Appendix VII). During that period, advances in technology and the licensing environment have enabled the development and continued implementation of standard and new uprate approaches and strategies.

For example, in the USA alone, over 100 power uprates ranging from 1.3 to 20% have been approved by the Nuclear Regulatory Commission (NRC) since 1977, adding a total of 4222 additional MW(e) to the nation's electrical grid. The benefits of power uprating to the industry and to individual plant owners can be highly significant in the near term and even more substantial in the long term, when combined with the plant life extension programme.

In Sweden, several BWRs implemented a power uprate some years (5–10 in most cases) after startup. The uprates were feasible without, or with minor modifications to the plants, using the margins that were included in the original design. Levels of power increase were up to 10%, which is typical for a stretch power uprate. Important parts of the engineering work and the licensing efforts used approaches similar to those established during the original design and commissioning phase. To some extent also, the experienced staff that was engaged in the commissioning could be relied upon.

Additionally, in Sweden, after about 25 years of operation, some of the units were approaching needed renovation of some main components in the BOP[4], such as turbine rotors and generators. The issue of extended power uprates then came into focus as a replacement of components to correspond to larger capacities, and using the potential for increased power density in the reactor cores for power uprate turned out to be very favourable. Modernization of the design of the BWR fuel was essentially what enabled the core power increase. A power

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[1] *Measurement uncertainty recapture (MUR) uprate.* A term applied to the regulatory process of reducing certain emergency core cooling system (ECCS) assumptions regarding reactor power measurement uncertainty from a standard assumption (typically 2–3%) to a specific value based on the use of more accurate feedwater flow measurement devices. The reduction in the uncertainty assumption can result in an increase in reactor licensed thermal power of 1.2–1.7% above currently licensed thermal power.

[2] *Stretch power uprate (SPU).* A term describing an uprate that uses the original plant design excess margin to accommodate an increase in reactor thermal power. Conceptually, such an uprate would not require significant plant modifications since it is ostensibly using existing design margin in the plant equipment. In the USA, the Nuclear Regulatory Commission (NRC) has defined a stretch power uprate as any uprate less then 7% of the originally licensed thermal power of the plant.

[3] *Extended power uprate (EPU).* A term generally used to describe a large increase in licensed reactor thermal power above the originally licensed thermal power. In the USA, the NRC has defined any uprate of 7% or higher to be an EPU

[4] *Balance of the plant (BOP*): The non-safety systems, structures and components (SCCs) of an NPP — these are usually referred to as the power production side of the power plant.

increase, in addition to what was implemented by the stretch, of 15 to 20% is under implementation. In most cases, changes to some plant systems are integrated to the power uprate in order to meet enhanced safety requirements.

In the case of PWRs in Sweden, the replacement of steam generators has enabled a power increase. The main purpose has been to cope with steam generator tube degradation due to corrosion. The replacement steam generators were specified to have a larger heat transfer surface area. This enabled the production of higher steam flows by a reactor with increased power. Several large components of the BOP were replaced, which, as in the case of BWRs, led to some additional gains in output as a direct result of the higher cycle thermal efficiency.

1.6. GENERAL DESCRIPTION FOR PUBLIC ACCEPTANCE

Explaining the safe implementation of a power uprate in technical and economical terms is usually straightforward. The preparations and associated investments are, in most cases, seen as minor in relation to the value of the increased power production of the plant. In cases where an uprate is connected with more substantial investments, the technical modifications are to a great extent motivated by plant modernization that is related to plant life management[5]. The extra investments needed specifically for the increase of power are generally seen favourably. However, a general public acceptance should not be taken for granted based merely on the arguments above. Some people may feel that changing the allowable power level of an ‘old’ operating reactor will lead to decreased safety in the operation of that power plant.

It is therefore important that suitable information is collected and made available to the public while implementing an uprate. This should be commenced at the early phase of the project and updated at suitable times when needed. Efforts should be undertaken to present to the public subjects such as: (1) the principles of nuclear legislation; (2) the responsibilities of the licensee together with the role of the licensing authority; and (3) the safety regulations. The aim should be to make clear what is meant by “acceptable safety” in terms of its interpretation in the assessment process as a basis for changing a licence and for issuing necessary permits for the uprate. The timing and sequence of such information should be adapted to the established licensing process and the involvement of different authorities in the assessment of nuclear safety, environmental impact and in relevant exchange of information according to agreements.

The technical solutions that enable the uprate together with the need for changes of the plant operating procedures should be made available as information that is presented in an understandable manner for the general public. The basis for evaluating that safety margins already may be available in the current design and operation that could be used for uprating should be communicated. The manner in which safety margins that may be impacted by the uprate can be compensated for by a combination of technical and administrative efforts should be clearly explained. Acceptance by the public can only be sought after an understanding is arrived at that these aspects are the basis for the uprate assessment and that the uprated plant will be operated within acceptable safety margins. Information should be open and cover a wide range of aspects, including possible impacts on operational safety, accident sequences, the environment and also on more general aspects of nuclear safety such as its impact on the production of radioactive waste.

1.7. USERS

This report is intended for use by the staff, managers, engineers, operations, maintenance and licensing personnel of organizations involved in power uprating projects, including:

— Utilities;
— Project management team organizations;
— Supplier organizations for power uprating and commissioning services;

[5] *Plant life management* (PLiM) is the integration of an ageing programme and economic planning to: (1) maintain a high level of safety; (2) optimize the operation, maintenance and service life of SSCs; (3) maintain an acceptable level of performance; (4) maximize return on investment over the service life of the NPP; and (5) provide NPP utilities/owners with the optimum pre-conditions for achieving long term operation.

— Technical support organizations;
— Vendors and equipment suppliers.

The report also includes information that may be useful for decision makers (e.g. regulators) and advisors for power uprating in NPPs.

1.8. STRUCTURE OF REPORT

This publication covers four major areas. Section 2 provides information related to the major phases of a power uprate initiative, from the overview of the power uprate programme to its completion, along with significant issues and guidance. In Section 3, operating experiences and lessons learned are introduced to provide a review of significant challenges and events related to power uprates from which specific guidance can be provided and recommendations may be made. In Section 4, conclusions and recommendations are provided. In the appendices, country reports on power uprates from Canada, Hungary, the Republic of Korea, Switzerland, Sweden, and the USA are given.

2. OVERVIEW AND GUIDANCE FOR POWER UPRATE

This section provides an overview of a typical power uprate project and provides guidance on the overall project elements that should be included for a successful programme. A power uprate project will typically have several parts:

— Feasibility study to establish the achievable level of uprate;
— Analysis and design work;
— Project mobilization;
— Licensing work;
— Field implementation;
— Power ascension testing to the uprated power level.

Although the potential benefits of power uprates have been clearly demonstrated, it is important to recognize that the benefits can be accompanied by associated limitations. Therefore, it is essential to manage those limitations in terms of technical, financial and licensing benefits [1].

Proper selection of uprate parameters and the use of improved analysis and design approaches can result in the best combination of overall benefits (including increased MW(e) production), while maintaining plant safety and avoiding risky consequences from incidents or accidents. In setting design conditions for a power uprate, the effects of several physical factors have to be recognized and evaluated as a basis for making the trade-offs necessary to capitalize on the available benefits. Technical issues include trade-offs among coolant temperatures, corrosion concerns; core loading pattern efficiency and irradiation effects on the reactor vessel and internals; increased fluid flow rates and flow-induced vibration margins; along with several others [1].

2.1. THE POWER UPRATE PROCESS

2.1.1. Principal safety related effects from the increase of power

An increase in plant output can affect an NPP in various ways. Reduction of margins in system capacities and redundancies may affect plant operational stability and therefore could have implications on plant safety. The main parameters and conditions that are affected by a power increase and that can call for compensatory actions to ensure that the required margins and capabilities (in both normal and emergency operating conditions) are maintained include:

Normal operation

The steam flows from BWR pressure vessels or PWR steam generators will increase, resulting in increased pressure drops and greater dynamic loadings on some components and systems. This can call for increased surveillance and renewed analysis. An example is the risk of increased vibrations in the internals of certain systems, vessels and steam generators.

The temperatures in the primary system of a PWR are dependent on power levels. The temperatures affect the local stresses and corrosion properties. Analysis must show that adequate margins are maintained, and that the surveillance and inspection programme is adequately reviewed. Shutdown margins may be reduced with power uprates, and this has to be considered during refuelling.

Neutron irradiation in the core region will increase, resulting in different requirements for radiation embrittlement and radiation-induced stress corrosion monitoring programmes.

Mean value of power density in the core, which will be increased with a power uprate, needs to be taken into account in the core design. This can be addressed by resorting to core re-optimizing or the use of improved fuels, or more modern methods of analysis. Modern fuel designs (e.g. with intermediate spacers) often have larger margins to film boiling or dryout than earlier designs.

The power plant environment will be subjected to larger amounts of waste heat to the water recipient. Furthermore, plant wastes will contain greater amounts of radioactive substances. The release of radioactive substances may increase. Also more uranium and chemical products will be used. The consumption of fissile material (^{235}U) increases in direct proportion to the power level increase, as do the quantities of certain chemicals.

Anticipated operational occurrences

Certain transient phenomena may occur more rapidly. Pressure transients in the pressure vessels of BWRs and in the steam generators of PWRs may occur more rapidly and be potentially larger than before. In BWRs, the core power response that accompanies a steam line closure may change the resulting pressure transient. Set values for vessel protection systems can be affected, and all this can result in the need for renewed analysis, and possibly other actions, in order to demonstrate that set requirements can still be met.

Emergency: Transients with initiation of safety systems

Decay heat will be increased, leading to an increased duty for the safety systems. In certain situations, the time available for operator intervention may be shorter. New safety analyses will be needed to demonstrate that required margins can be retained. Technical specifications and instructions may have to be modified as well as training and instruction programmes.

The loads on certain electrical systems and components will increase at the increased power levels, calling for a review of the capacities of the power supply systems (diesel generators, accumulators, rectifiers, etc.) for dealing with transient and severe accident situations.

Accidents

Mass and energy releases into the reactor containment in the event of steam line or primary system leakages (LOCA) will be larger than before. The resulting pressure transients depend mainly on the thermal power levels and the primary system operating temperatures. In the short term, it is the mass release that dominates, and in the longer term, it is the decay heat which is linked to the power increase. Renewed stress analyses will have to be performed together with safety reviews to demonstrate again that relevant margins are maintained.

Severe accidents (beyond design basis)

Certain severe accident sequences (like ATWS with loss of boronation system) will be influenced by a power uprate, calling for a review of severe accident management procedures (SAMG).

PSA assessment

In addition to assessment of margins resulting from deterministic analysis, probabilistic analysis should also be included in the safety analysis. An uprate could result in changes related to the success criteria or, in critical time frames, for intervention that might require updating the probabilistic assessments.

2.1.2. Processing a power uprate application

As shown in Fig. 1, the process flow chart describes each step involved in processing a power uprate application.

The utility should perform several steps for the power uprate such as feasibility studies, project mobilization, design work, licensing work, field implementation and startup testing. The licensing authority also has various responsibilities according to the license amendment process. Frequent and early communications between the

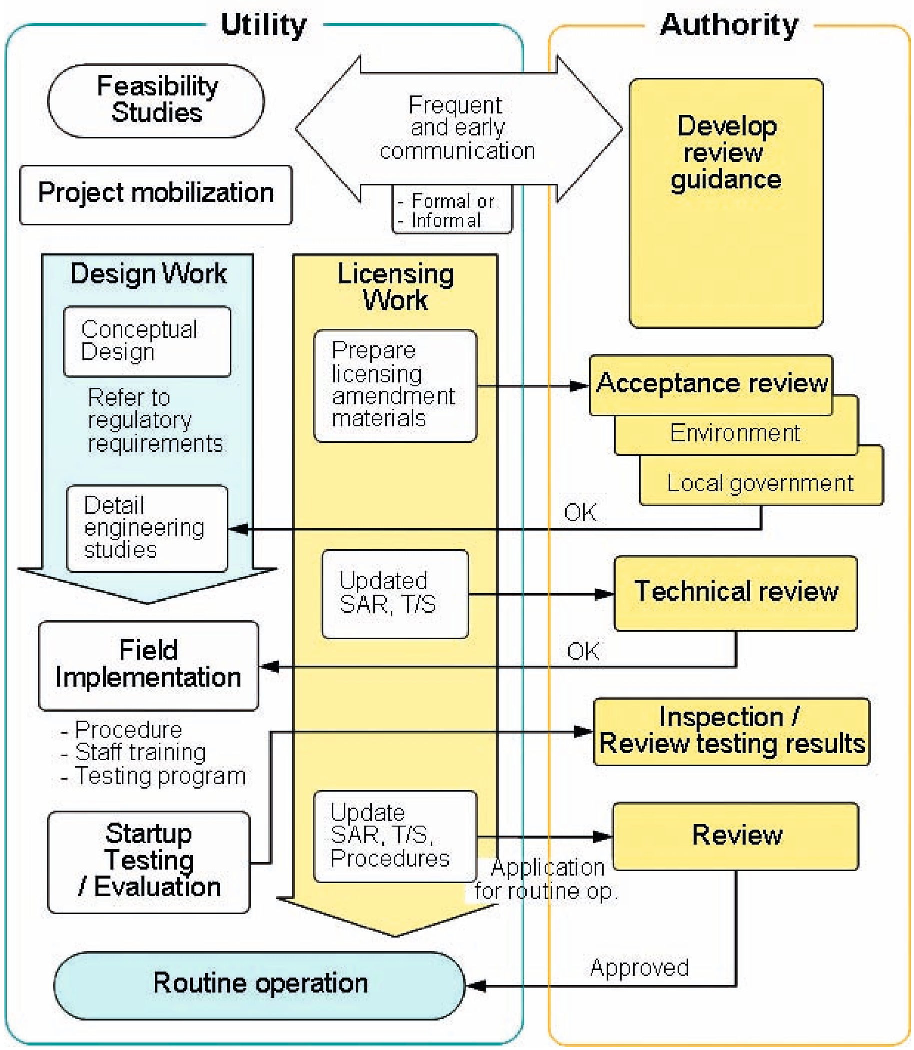


FIG. 1. General process of a power uprate.

licensing authority and the utility can help avoid problems later in the process. The exchange of information on technical and/or resource issues is also encouraged.

For feasibility studies, the range of possible power uprates is determined and the cost/benefit analysis is performed. The range of thermal power level increases could be confirmed through sustaining the existing safety margins. For project mobilization, the management plan, including staffing, resources and schedules, is settled upon. The design work consists of a conceptual design and detailed engineering studies. Compliance with current regulations should be verified in a conceptual design. The analysis of transient and accident conditions is performed to verify that the safety limits are not exceeded at the uprated power level.

Field implementation includes the completion of all remaining work as well as revision of design, licensing and operating documentation affected by the power uprate. The implementation also includes a review and analysis, as necessary, of any remaining safety issues, mechanical design and systems operations that may be affected by the change in operating conditions.

For licensing work, the utility has to determine what licensing activities must be completed to gain regulatory approval of the power uprate application. The utility should determine which documents need to be prepared. The safety analysis report, including technical specifications and procedures, is one of the major documents that must be updated.

Operating procedures, staff training programmes and testing programmes must be reviewed and analysed in order to properly implement the power uprate. Upon the receipt of a power uprate application, the regulatory body/licensing authority will conduct the acceptance review to ensure that the application meets regulatory requirements. The acceptance review checks for the completeness of submitted documents for the application.

The technical review represents the bulk of the licensing effort that is expended in processing a power uprate application. The regulatory guidance should be used in determining the appropriate scope and depth of the review. Thus, a careful identification of what is addressed in this review is central to effective planning.

Any issues identified as a result of independent calculations should be resolved with the utility. If necessary, the utility should be requested to update and resubmit any affected analyses.

2.2. FEASIBILITY STUDY OF A POWER UPRATE

The primary purpose of a power uprate feasibility study is to develop the range of possible power increases with the necessary modifications, as well as the costs and risks associated with each targeted increase. On this basis, recommendations can be made as to the optimum uprate level. The final decision on the target level and whether or not to proceed with the uprate would be made by the utility management based on their assessment of the optimum balance of the costs, benefits and risks associated with the project.

2.2.1. Feasibility study overview

A power uprate feasibility study requires a significant amount of work and a broad range of expertise. Ideally, a person with broad responsibility and experience within the utility organization will be assigned the job of leading the study team and delivering the final report as his main task. A variety of contracting models can be used successfully. For example, where the original nuclear steam supply system (NSSS)[6] designer has successfully supported power uprate projects, a significant part of the study work can be subcontracted to this organization. Whatever the chosen organization and contracting model, there must be:

- Knowledge of the design/current licensing basis for both an NSSS and a BOP systems and components;
- Knowledge of the operating history and current status of the NSSS and BOP systems and components;
- Knowledge of the licensing amendment process, the current status of the operating license and any currently open issues;

[6] *Nuclear steam supply system (NSSS).* The systems, structures and components (SSCs) of an NPP that constitute the ‘nuclear island’ of a commercial NPP. This typically consists of the primary reactor systems, cooling and decay heat systems, energy transfer systems and safety systems.

— Input from operating staff in the unit being uprated, and those staff members responsible for staff training;
— Input from staff experienced in making field modifications for the unit being uprated.

A schedule and budget should be established for the study along with the deliverables to be produced. Typically, such studies can take anywhere from six months to two years and require on the order of 5–20 person-years of effort. The precise time and effort depends on the degree of uprating being assessed and the number of precedents for similar levels of uprating reactors of that type. The following provides information as it relates to the complexity of the feasibility study associated with each of the three types of uprates:

— **Measurement uncertainty recapture uprates (MUR).** Note that for MUR, feasibility studies are typically not required or performed.
— **Stretch power uprates (SPU).** For SPU, the feasibility study would be at the lower end of the time and expense range and would often depend primarily on vendor assessments of the NSSS issues that have been performed on a generic basis for that series of plant and the built-in margins in BOP equipment.
— **Extended power uprates (EPU).** For EPU, there are more requirements for design changes specific to a particular plant, particularly in the BOP. Therefore, these feasibility studies are the most complex and expensive to do. The division of responsibility in these studies will depend on the capabilities of the utility organization in terms of staff time availability to work on the study and knowledge level. It is important to consider whether similar power uprates have been done elsewhere and by whom.

For measurement uncertainty, recapture uprates and stretch power uprates, reactor vendors and other suppliers often have the required knowledge and experience from doing similar uprates elsewhere on the same plant series.

Generally, a power uprate feasibility study will consider a number of power uprate scenarios to establish an understanding of which one offers the best alternative based on consideration of cost, benefit and risk. The attainment of higher power levels than that shown by the best alternative will require more changes to equipment and procedures. This may have a higher risk of either not meeting the target power output or having a lower capacity factor after the changes are made (lower capacity is associated with equipment reliability). This must be carefully considered to ensure that reliability and efficiency of the plant components are maintained as high as possible.

2.2.2. Review initial conditions for the power uprate

The additional station electrical output achievable is generally a function of the capacity of the reactor core to generate power while maintaining acceptable fuel and thermal performance as well as the capacity and efficiency of the mechanical and electrical equipment in converting the nuclear heat to electricity. Additionally, there may be limits in safety-related equipment, which could be impacted by higher reactor power output.

Therefore, feasibility of a power uprate project starts with consideration of the actual plant operating data at the current power level and a comparison of this data with any limits established in the Safety Analysis Report (SAR), technical specifications or the design documentation. This must also include a thorough review of the turbine, main generator, condenser, etc. On this basis, the current design margins in each system and component can be assessed, and the systems and component parameters that are critical in determining the potential uprate level will become apparent.

The margin has two important aspects:

— Safety margin: to have room for unanticipated transients;
— Production margin: to have room for equipment degradation so that there will not be an impact on normal, daily operations and anticipated operational occurences.

Once the critical parameters, systems and components are listed, then a more detailed study of the current capacities, operating data and operational events are required to better establish the margins available for uprating. For situations where the uprating will potentially impact the capacity of safety related equipment to respond to accidents, safety analysis work will be required to establish the available margins and to study design options.

2.2.3. Determination of potential power uprate range

Identification of critical constraints and margins

Having gone through the process outlined in Section 2.2.1, a list of design, operating and safety margins that are critical to the unit power output will be generated. It is essential to consider the overall strategy for station operation at this stage to ensure that all constraints relevant to power uprate have been understood. One example of such considerations relates to the planned unit operating lifetime. It may be the case that operation at a higher power level will reduce the length of time that the unit can be operated and this reduction may not be acceptable given all of the constraints that the utility is facing. The pressurized thermal shock (PTS) phenomenon in the case of PWRs is one of the examples of potentially power uprate-limiting effects.

Operation at an uprated power level will require a change to either the fuel enrichment, frequency of refuelling outages or higher batch fractions. Dependent on the specific goals of the utility, these need to be reviewed to determine which combination would lead to the most optimum and reliable performance.

A power uprate could also potentially impact equipment capability or redundancy under certain operating conditions, and this could have an impact on overall unit reliability. Some examples of such considerations would be situations where the turbine steam condenser is capable of the higher output for only part of the year or where starting a standby cooling water pump is required during hot weather to deal with the higher cooling water temperature and the higher heat rejection of the uprated unit.

Another consideration would be any plans for licence extension for the unit. There are opportunities for synergies between power uprate and licence extension, however this will require additional resources that have to be managed. The impact of power uprate on plant life management for long term operation is an important issue. Plant ageing issues may be aggravated by power uprate as a result of existing plant material conditions. This may result in a need for more inspections and installation of monitoring systems for certain critical components to ensure extended plant operational life.

The examples outlined in this section point to a need to consider more broadly the impacts of power uprate on overall utility strategic needs for the NPP under consideration.

Identification of components and systems potentially affected by a power uprate

The listing of critical margins and constraints should suggest areas where changes to design, operating procedures or safety analysis will be required in order to attain higher output. It is helpful to associate these changes with the power level at which the change is required to be implemented. By doing so, a number of power uprate scenarios can be constructed, each having a set of required changes (cost) and an achievable level of power uprate (benefit). Each scenario will also have a set of technical and economic risks, which will depend on the scope and degree of innovation associated with the changes.

Review of regulatory requirements

In order to operate the reactor at a higher power level than originally licensed, a license amendment will be required from the reactor licensing authority. There may be additional permits required due to the need for more cooling water for a higher output, which could have an impact on environmental approvals or water permits previously granted. Therefore, it is essential to review what changes to licenses, permits and approvals will be required to reach a target power level increase and the process to be followed in obtaining these approvals. Quite often, the time taken to obtain such approvals can be critical in determining the power uprate project schedule. There will also be costs and possibly additional programme requirements associated with such approvals, such as a need for a public information programme or public hearings.

In order to obtain these approvals, the safety evaluation report that supports the existing regulatory approvals will need to be revised. Therefore, it is important to establish early on the required scope of analysis work to assist in understanding the work scope and schedule. If there are no clear precedents, then discussions with the regulatory bodies would be advisable to help determine the scope and schedule.

In many countries, one also needs to consider the costs charged by regulatory bodies to perform their review of the uprating application, which in some cases may be a significant portion of the project costs.

Margin review

For each uprating scenario, the operating, design and analytical margins should be tabulated and compared. It is useful for such a table to include the original margins prior to the uprating project and the projected uprated margin available post-uprate (including plant ageing effects).

Such a tabulation will assist in determining whether the proposed uprate may have impacts on future operation (e.g. capacity factor). It will also point out areas where margins are reduced, and the reductions will require justification to the regulatory body or plant changes. The impact of proposed design changes should also be reflected in such tabulations. These tables provide information for ongoing review and management of plant margins as the feasibility study progresses and they provide valuable input and insight into the decision making process.

In addition to the review of operating margins, any proposed changes to operating procedures needs to be reviewed at the feasibility stage by qualified personnel in the operations and training departments. This will help to establish whether the proposed changes are truly practicable given current staffing levels and whether any additional risks will be introduced.

More generally, the team responsible for the feasibility study needs to review their data and conclusions with expert parties within the operating organization. There is also value in assessing whether external parties have relevant knowledge and experience that would add to the study by their participation in such reviews. Topic areas for such participation could include design, construction, equipment performance, maintenance, operation and finance.

Figure 2 provides an example of the relationship between the operating, design and analytical margin ranges.

To help ascertain the extended power uprate margin scope, the following is an example of various tasks that could be utilized:

— Task 1: Identify power plant systems that were affected by a power uprate;
— Task 2: Define/quantify the post-power uprate operating and design margins for plant systems;
— Task 3: Ensure that existing system performance is consistent with predictions based on analytical models or engineering judgement;
— Task 4: Confirm that the planned changes are adequate and also check to ensure that the future changes needed will help ensure long term reliability.

To quantify the safety margin, the OECD/NEA established an international working group, the Safety Margin Action Plan (SMAP). The group issued a comprehensive document [2] in which the concept of the margins for the

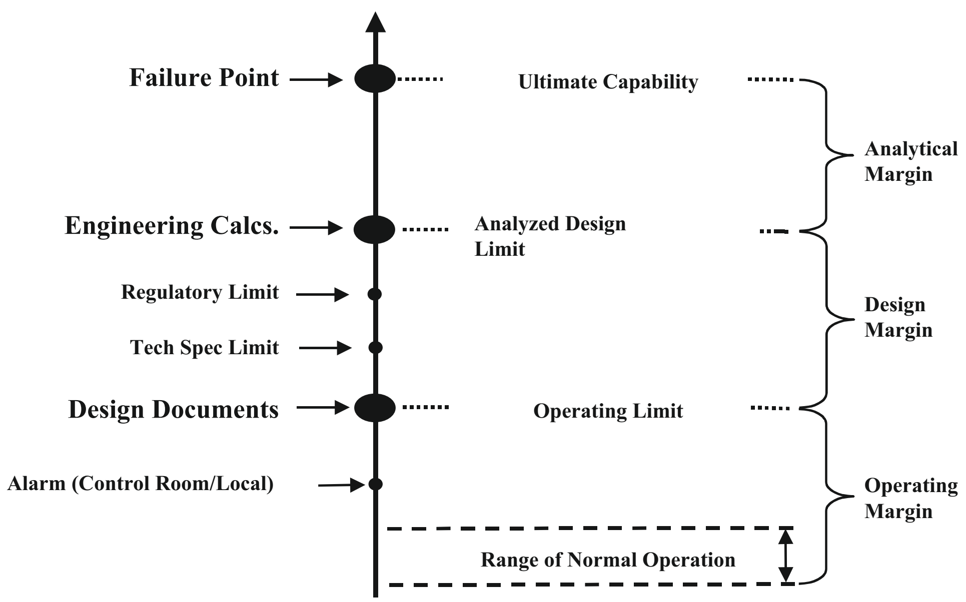


FIG. 2. Design and operating margins.

safety assessment of operating NPPs is widely discussed and analysed. The document described in detail the assessment process for the safety margin in connection with the definition of the risk space. It is assumed in this process that the failure occurs discretely when the safety limit is reached.

Design margin quantification

The design margin is linked to safety limiting values imposed on safety variables. The existing design margin could be changed due to power uprates. Total margin consisted of analytical margin and design margin stems in load-strength interference work as shown in Fig. 3.

Preliminary economic analysis

Once the impacts of the various power uprate scenarios have been listed, estimates of costs can be generated. It is important in estimating the costs to consider not only the costs of the design changes and required analysis but also to consider any increase in outage times required to accomplish the changes as well as any potential impacts on plant or component operating life. Estimates of the benefits in terms of increased output should also be made.

An important complementary activity is an assessment of the potential risks of a proposed power uprate project. This is particularly important when the project is planning on technical innovations that have not been previously proven. In those cases where the technical solution has been proven, one needs to consider the risk of problems in the implementation phase or commissioning/operations phases after implementation, which could lead to unexpected costs. It is advisable to estimate the potential costs and their probability and to propose measures that will be taken to reduce the risks where the risk (product of probability and cost impact) is significant to the financial success of the proposed power uprate project.

Once the preliminary technical requirements for the range of potential uprate power levels is completed along with an estimation of associated costs, a comparison is made between the cost and benefit (in additional, MW(e) generating capability). Based on the technical risks and economic value, an optimum uprate power level can be selected.

All changes should be categorized to facilitate understanding of their impacts. For example, changes may only have a one time equipment uprate cost. Other changes will have ongoing costs due to increased maintenance requirements, increased fuel costs or potentially for increases in unplanned reactor outages. Some changes will be one-time investments in changing a safety analysis or an operating procedure. Categorization of the change impacts is fundamental to understanding and properly calculating all of the costs associated with a power uprate project. Typical categories of impact include:

— No impact;
— Impact on margins;
— Analysis change;

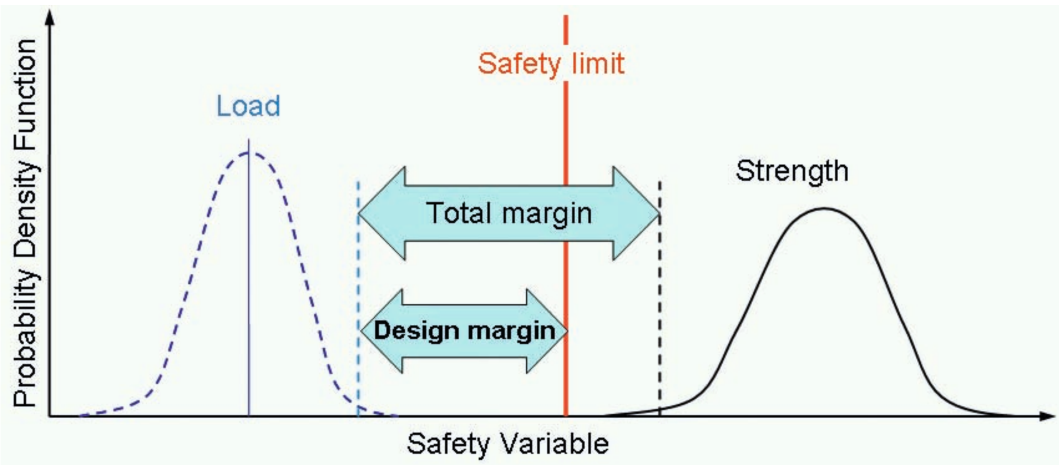


FIG. 3. Safety margin in the nuclear industry.

— Procedure changes required;
— Design modification required.

Costs associated with each category of change and the overall costs of each power uprate scenario can now be estimated. Other impacts that do not have a direct cost (e.g. effects on operation or project risk) need to be considered (at least qualitatively) and listed for each scenario. Once costs, benefits and risks are estimated, in most cases, the preferred choice of uprating scenario will be clear.

Staffing and resource considerations

For each power uprate scenario, once the overall target schedule and required work scope is estimated, there needs to be consideration of the resources required (budget, qualified staff and equipment) and whether such resources are available or can be acquired either within the corporation or through subcontracting. If not, there could be impacts on feasibility or the implementation schedule that affect the preliminary economic analysis. Therefore, staffing and resources are also risks that should be managed within the overall risk management framework for the project.

2.2.4. Selection of target power uprate level and implementation approach

On the basis of the preliminary economic analysis (both the cost/benefit analysis and the technical and economic risk analysis), it will be possible to choose the most desirable power uprate project scenario. This choice is usually a matter of choosing the scenario with the most favourable cost/benefit ratio and an acceptable risk level. Before making the choice, the feasibility study team needs to ensure that the key assumptions and analysis that have gone into each scenario have received adequate review by qualified independent experts. A one step or multi-step approach can be utilized to achieve the full uprate dependent upon the preliminary results.

The feasibility team will also need to establish what approval process will be used by utility management to review and approve a decision for the proposed power uprate project. Once the approval process is agreed upon, a business case that meets the requirements of the approval process can be assembled based on the feasibility study work.

Business case

One of the first steps in assembling a business case will be to determine which organizations will be assigned to the work. As an example, use of the original reactor vendor to perform an analysis will likely result in cost savings and synergies in assigning the NSSS portion of the work. There may be similar considerations in the BOP due to the experience and expertise that the BOP designer or a contractor can provide. One also has to consider the current and projected staffing level in the utility and the likely workload in the coming years. Each of these inputs will help to determine what part of the power uprate project that is expected to be performed by the utility staff or by personnel that can be hired in the immediate future.

Whatever division of responsibility is eventually agreed upon, it is vitally important to have a common understanding of which organization will be doing what work scope to ensure that no tasks are left unassigned. This will ensure that all work is identified and avoid misunderstandings about work not being performed.

Development of high-level schedule

An overall schedule (Level 1) should be developed with sufficient detail to show the major activities and milestones expected in the programme. Estimated durations can be assigned based on the preliminary work scope assembled as part of the feasibility study and the expected staffing levels developed during the division of responsibility and staffing plan steps.

Major milestones typically include:

— Start of approvals process for the project;
— Project approval;

— Deadline for ordering of long lead items;
— End of design engineering;
— All equipment and material delivered to site;
— Licensing process, including approval to proceed with installation and to operate;
— Outage dates, etc.

Final economic analysis/funding approval request

The proposed power uprate project scenario can now be developed to a greater level of detail. The level of detail needs to be adequate to meet the requirements of the approvals process, and additionally the overall uncertainty in the cost estimate should be low compared to the net benefit (benefit minus cost). It can be beneficial at this stage to develop a list of project deliverables with associated manhour estimates. Engineering and equipment cost estimates can be confirmed with vendors.

2.3. POWER UPRATE PROJECT MOBILIZATION

Once approval of the power uprate project is granted, there will be a project mobilization phase to acquire and organize the resources.

2.3.1. Staffing, resources and expertise

The first step in the project mobilization will be to assemble the personnel needed for the project. This will require appointment of a project manager who can then develop the project organization and acquire the people to fill the vacant positions in the team. Steps will likely be required early on to establish project infrastructure such as office space, financial controls, schedule control, document control, as well as any unique process procedures and controls. It is also necessary to establish job requirements for key positions and ensure that incumbents have the proper training to cover any gaps between job requirements and personal capabilities.

During this stage, the human resources organization will play a key role in ensuring that the best qualified and most appropriate personnel are assigned to the power uprate team. During the early stages of the power uprate project, the area of technical analysis will demand the majority of the resources while later in the project (implementation stage), resources in the area of planning, scheduling, operations and field implementation personnel will be important. To support the requirement for technical analysis early in the project, expertise in the areas of power plant operation, mechanical engineering, electrical engineering, instrumentation and controls, nuclear plant licensing and nuclear engineering are needed to ensure the functions of design reviews, licensing impacts and plant modifications are properly and thoroughly addressed.

2.3.2. Supply chain, procurement and contracts

Once the basic project infrastructure and staffing are in place, any contracts for engineering services or equipment that are required for the project can be initiated and put in place. As with any contracts of this type, clarity is required in stating the expectations for the contractor, including a specific list and description of deliverables, quality assurance requirements, schedule, cost and warranty as well as deciding on the degree of oversight of the contractor’s work to be done by the utility.

2.3.3. Detailed schedule development

As managers, staff and contractors start work on the project, it will become possible to develop, review and finalize the list of project deliverables and confirm the tasks to be done, along with the estimate and schedule for each. These tasks should all be assembled into a detailed project schedule showing resources assigned to the tasks and any interfaces or dependencies between tasks. It is recommended that there be one common schedule (Level 1) that drives the entire project. The utility should control the schedule, and it should not be fragmented among the parties involved. With this concept in place, everyone is held responsible for one common goal, expectations are clear and responsibility rests with the utility.

Monitoring of the schedule should be performed at a specified interval (a recommendation is to have weekly schedule review meetings). Techniques such as the calculation of the schedule float in each task can be helpful in judging the schedule criticality of each task. Any gaps between actual and required performance should be addressed by reassignment of resources or other changes to the plan.

2.4. ANALYSIS PHASE

The analysis is performed to ensure safe and reliable operation of the nuclear power plant at the uprated power levels. This analysis consists of reviews of capability, capacities and characteristics of plant systems to ensure that an adequate margin to safety is maintained and to guarantee long term equipment reliability.

The full scope of the analysis is guided by the SAR. Many systems and functions important to plant safety (e.g. radwaste treatment, grid stability, equipment qualification, I&C systems) should be addressed from the point of view of:

- Plant safety;
- Performance;
- Reliability.

Initially, a set of plant parameters will be established as a basis for the uprating evaluations. These parameters will be established by the utility in conjunction with the NSSS supplier and architect engineer based on knowledge of replicate plants operating at higher power levels, available system/component margins, potential hardware/system improvements and limitations of components and systems that would not be practical to replace or modify. The following list provides typical key parameters that should be analysed to decide on the level of the power uprate:

- Reactor pressure;
- Core flow;
- Steam flow;
- Feedwater flow;
- Reactor vessel inlet/outlet temperature (PWR);
- Steam generator — outlet pressure and feedwater temperature (PWR);
- Turbogenerator capacity;
- Main condenser limits.

2.4.1. Safety analysis

Operational transients

Operational transients must be analysed to ensure that their occurrences do not lead to safety transients or unanticipated reductions in power or other undesirable outcomes.

An example of a transient could be the additional flow required during a backwash of the condensate polishing system in a BWR. The additional flow required by this backwash must be taken into consideration to ensure that adequate suction pressure is maintained for the feedwater pumps to remain at the desired power level.

Accident analyses

A reference analysis is normally established as part of the initial licensing effort as documented in the SAR. This is supplemented by reanalyses required for reload fuel, plant equipment or system changes. For a power uprate, a safety evaluation should be performed to confirm the validity of applicable reference analyses.

The objective of the uprating safety evaluation is to verify the compliance with the currently established safety limits for the specific unit with the uprated core and plant system design. This is accomplished by examining each accident presented in the SAR to determine if the reference analysis remains valid for the uprating. In the performance of an uprating safety evaluation, each accident is examined, and the bounding values of the key safety parameters that could be affected by the uprating are determined based on the reference analysis. These parameters will be used for the basis to determine whether the reference safety analysis remains valid.

Nuclear steam supply system analyses

In parallel with the review of the design limiting accidents and transients, an analysis of the NSSSs and components will be performed to determine their capability for operation at the uprated power. These analyses and evaluations will be either to:

- Verify compliance of existing systems and operating procedures with applicable plant design bases and regulatory requirements; or
- Identify those areas where revisions and/or modifications are required.

This review will include all of the classical NSSS fluid system components as well as any components provided by the NSSS supplier in areas as follows:

- Nuclear steam supply system parameters. The NSSS design parameters provide the reactor coolant system (RCS) and secondary system conditions for use in NSSS analyses and evaluations.
- Reactor coolant system (PWRs). The changes in the NSSS design parameters that impact the RCS design basis functions include the increase in core power and decrease in core inlet temperature.
- Engineered safety features (ESF). The required volume, duration and heat rejection capability of the safety injection system and containment spray system should be determined in the event of a postulated accident based on analytical models that simulate reactor and containment conditions subsequent to the postulated RCS and main steam system breaks under power uprate conditions.
- Residual heat removal (RHR) system. Operation at a higher power level increases the amount of decay heat being generated in the core, which results in a higher heat load to the RHR system for plant cooldown.

The impact of the uprated parameters on the functional design requirements and structural integrity of these components will be reviewed. NSSS operating transients are also to be considered during this review. Where the uprating requirements are not bounded by current component design, revisions and modifications will be made as necessary to demonstrate compliance with applicable codes and standards. The plant technical specifications will be reviewed to identify required revisions to protection set points and/or limiting conditions for operation.

Fuel design

The analyses performed in support of the uprate in the nuclear fuel and fuel related areas are fuel thermal-hydraulic design, fuel core design, fuel rod performance, heat generation rates, neutron fluence and source terms. The impacts of power uprate on the thermal and mechanical integrity of fuel rods will be evaluated to show that all fuel rod design criteria have been met for uprated conditions. Also, the impacts of power uprate on the fuel assembly mechanical design criteria will be evaluated. Primary design features of concern with respect to fuel design include: power density in leading fuel assemblies, core peaking factors and material corrosion. New fuel products, core loading patterns and analysis methods have been employed to enable plants to safely and economically achieve power uprates.

2.4.2. BOP analysis

Engineering evaluations for the power uprate demonstrate that the BOP systems, components, and structures are either adequate for the uprated parameters or may have to be modified. The BOP plant systems and components impacted by the predicted changes will be reviewed to obtain an initial assessment of the extent of change required to their existing operating parameters. Also consideration will be given to assessing any potential impacts on structures and on the existing licensing bases contained in the Final Safety Analysis Report (FSAR), including transient and accident analyses resulting from the predicted changes to the BOP systems.

To perform the assessments, the potentially impacted design base and licensing base documentation that supports the pre-uprate operation of the plant systems, components and structures will be identified, collected and reviewed. The proposed uprating will be analysed in accordance with the design and regulatory codes, standards and criteria that constitute the existing design and licensing bases of the plant. The assessments and detailed evaluations will focus on addressing the impacts expected as a result of power uprate parameter changes.

2.4.3. I&C system analysis

Instrumentation and control systems are provided to control plant processes having a significant impact on plant safety, to initiate the reactivity control system (control rods), to initiate the ESF systems and essential auxiliary supporting systems, and to achieve and maintain safe shutdown conditions of the plant.

To meet the above safety functions, the reactor protection system, the engineered safety feature actuation system, safe shutdown systems, control systems, and diverse instrumentation and control systems should be reviewed to ensure that the systems and any changes will function per design at the uprated power level.

The measurement uncertainties are considered at the uprated power level to avoid exceeding the power levels assumed in the design basis transient and accident analysis. Furthermore, the safety trip set points are calculated to ensure that sufficient allowance exists between the trip set point and the safety limit to account for instrument uncertainties. The range of set points related to relative power levels may be scaled to reflect the uprated conditions.

2.4.4. Further studies

Grid impact study (grid stability)

The impact of the additional electrical output on the electrical distribution system must also be considered and analysed to ensure that the electrical grid remains stable should a fault occur on the grid at the higher output levels and also to ensure that the stations output breakers can and will respond to any disturbance in order to protect the station equipment and the electrical grid. Increasing the size of the major electrical generating equipment, such as the main generator or exciter, to accommodate the increased power from the power uprate will require that a grid stability study be performed. These studies review various scenarios on the grid such as electrical disturbances, ground faults and other generators being out of service. Each of these scenarios are carefully analysed to ensure that the plant output breakers as well as the grid equipment can respond to disturbances in a timely manner to avoid blackouts and/or catastrophic events.

Equipment qualification

The equipment qualification (EQ) programme for the power uprate should be reviewed. The review will be performed for the new accident temperature, pressure, humidity, submergence and radiation dose associated with the uprate and environmental conditions in the EQ programme. The power uprate has little effect on the qualification of equipment inside containment (for constant pressure power uprates) with respect to the temperature and pressure, but does have an effect as it relates to qualification with respect to radiation dose. For the auxiliary systems, which may not necessarily be part of the EQ programme, it is very important to ensure that the component reliability is unaffected by change of process parameters and environmental parameters.

The power uprate has little effect on the qualification of equipment outside containment with respect to the temperature, except for equipment in the main steam line penetration area. The following high energy line breaks (HELBs) for EQ equipment outside containment should be reviewed:

— The main steam line break (MSLB) in the steam and feed line penetration area;
— The main steam supply line to the turbine drive of the auxiliary feedwater (AFW) pump in the AFW pump room;
— The steam generator blowdown line break in the pipe penetration area.

In the case of a PWR, the equipment that is required to respond to these HELBs should be re-evaluated using thermal lag analysis of the equipment response to the break environment for the spectrum of breaks. The equipment in the steam and feed line penetration area will also be qualified through thermal lag analysis. All equipment outside containment required for accident response should be justified as qualified [1, 3].

2.5. MODIFICATION PHASE

2.5.1. Development of design modification packages

After the analysis phase, a detailed design can be initiated. Revisions of plant design and operating documents are required to ensure that they reflect the parameters for the uprated power. In order to determine the documents and drawings that require changes, a review of the design and operating document baseline is required to identify documents that contain data, design requirements or descriptions of the design that will change. Release of the documents for the purposes of procurement, development of training plans and materials or construction planning can occur as needed during the project. However, release for use by operations will only occur as the changes are implemented in the plant.

In addition to the required changes in design documents and drawings, a set of field drawings and instructions must be prepared for the field modification staff to use during installation of the modifications. These instructions need to clearly set out the steps of work to be done by these staff, the reference documents and drawings as well as the points at which work approvals and quality surveillance will be required. These very important activities are sometimes done by designers and sometimes by “field engineering” or Operations. It is important to decide who has this responsibility and include time and effort in the project plan to complete this work. When these actions are completed, the plant is ready for component and system testing/commissioning prior to being operated at the uprated power.

Contracts

Typically, an SPU or EPU will require a number of minor or major plant modifications to accommodate operation at the increased reactor thermal power level. For significant modifications (e.g. generator rewind, high-pressure turbine replacement, main transformer upgrade), many NPP owners will issue a contract to an architect/engineering firm to prepare the design modification package(s). One of the key challenges in managing an uprate programme is ensuring a proper and consistent understanding among the many parties involved of their responsibility and the quality and content of their deliverables. In the preparation of modification packages, variations in expectations regarding the final deliverables from contractors has proven to be a project management issue and must be given attention.

Procurement documentation

Given that for SPU and EPU projects a large number of vendor-supplied drawings, manuals and other information will be added to the plant design basis, it is critical that the project establish clear guidance for contractors regarding expectations for the format and content of this information.

Design document updates

As with any major change to the plant design basis or physical plant construction, it is critical to maintain proper configuration control. One of the issues that has affected power uprate projects in this regard is the discovery of existing design basis inadequacies [4].

Because a typical SPU or EPU affects essentially every major system and underlying analysis in the plant, it is common to identify the update of the design basis through the power uprate project. These issues should be identified, tracked and corrected in accordance with plant procedures and established processes. This is sometimes referred to as design basis reconstitution and should be implemented in a timely manner with respect to the power uprate project.

2.5.2. Procedure changes

The operation and maintenance groups of the NPP should be involved in the power uprate project (or programme) from the very beginning. After all of the parameter changes are determined, the utility has to prepare documentation of the modification, including the operation and maintenance procedures.

Operation

To ensure that the effects of the power uprate are well known and understood, it is important that personnel from plant operations are involved in the process. These personnel have to view the entire list of operating procedures, surveillance test procedures, emergency operating procedures, plant modifications and process parameter changes, then determine which procedures must be modified, taking into account the changing parameters. These procedures must then be revised, validated and approved to support the power uprate.

The changes needed will be made in accordance with current procedure change control processes. The changes to the emergency operating procedures (EOPs) reflect the increased power level and associated set point changes. For example, for PWRs, the EOP regarding the addition of supplemental feedwater to the SGs after a reactor trip will be changed to provide specificity for the flow and time requirements.

Maintenance

It is also important that personnel from plant maintenance are involved in the process to review the maintenance procedures and ensure that they reflect the effects of changes from the power uprate (including modifications). The procedures need to be reviewed from the standpoint of increased frequency of maintenance on components, revised maintenance practices, additional maintenance that may need to be implemented and any additional inspections that may need to be performed. Examples of this may include increased frequency of valve maintenance, revising a maintenance procedure associated with a pump teardown to look for any signs of abnormal wear, and/or revision to the inspection frequencies to understand the effects of erosion/corrosion on the plant systems.

2.5.3. Training requirements

Classroom and simulator training for the operating personnel and other personnel must be considered due to hardware changes, including changes to the operating procedures and set points contained therein. The training for the site personnel can be a time limiting constraint for the project and needs attention early on to ensure that all personnel have been trained in advance of the power uprate. It is important that the simulator be updated to reflect the effects of the power uprate well in advance of its implementation at the power plant, making it possible for the operating staff and other site personnel (as needed) to receive this training and fit it into their daily schedules. If it is not possible to upgrade the simulator in time to support the power uprate, this must be factored into the overall implementation plan (i.e. consideration to run the non-uprated simulator in parallel).

Classroom training for the operations staff should be completed in advance of the implementation phase. A detailed lesson plan should be developed by the operations training department that specifies (at a minimum) the following:

— Before and after set points;
— Expected changes to gauges/alarms in the control room;
— Technical specification changes;
— Surveillance procedure changes;
— Detailed impacts on equipment as a result of modifications in the plant and the expected changes as a result of these modifications.

Additionally, 'just-in-time' (JIT) training should be performed for each shift of operations personnel just prior to startup and after the implementation of the hardware changes in the plant. JIT training should encompass scenarios in the plant simulator as well as classroom discussion to ensure that the operations staff has a fresh view of what the plant will look like in the control room and how it will behave after the uprate.

It is equally important that maintenance, engineering and radiation protection personnel are given training on the changes made as a result of the power uprate programme. The engineering staff must be aware of the engineering calculations that were changed, and the analysis of system differences must be clearly communicated and understood to ensure that future changes/impacts are fully analysed with the power uprated parameters. Maintenance personnel need to be made aware of the changes in the plant as it will affect the maintenance schedules and type of maintenance performed, and these in turn will have an effect on the needed skills from the maintenance staff. Radiation protection personnel also need to be aware of the changes made in the plant as the new power levels will affect the radiation doses in various areas of the plant, and changes to the normal transit path may be required and/or changes to shielding in various areas.

2.5.4. Testing plan development

A power uprate programme leads to modifications of systems and components and also to changes of many plant process parameters. All of these changes have to be tested to ensure proper response at the uprated power level. Major emphasis is placed on ensuring that the integrated plant response fulfils the predefined acceptance criteria. For that purpose, a test specification needs to be developed.

Nuclear steam supply test specification

The NSSS test specification identifies the minimum recommended NSSS tests necessary for the confirmation of acceptable plant performance for operation at uprated power levels. The specification is based on the original startup test specification amended to reflect the needs for the power uprate of the plant. The tests included fall into the following categories:

- Performance evaluations for mechanical and electrical equipment that will be operating near maximum design capacity;
- Demonstration of expected performance for modified systems;
- Verification of acceptable characteristics of control systems for power uprate transient testing and for operational considerations;
- Verification of SCRAM avoidance capability.

The tests contained in this specification are not the only evaluations that will need to be performed to document plant compliance with the power uprate but are, in general, the most involved and hence justify increased attention in the form of individual procedures to verify their performance. The other evaluations can be satisfied by completion of existing surveillance or functional tests, or through steady state data collection as part of normal system monitoring.

The power and flow conditions for the tests contained in this specification should be selected in a manner consistent with the approach utilized for initial plant startup. In addition, they also take into consideration the plant modifications required for implementing the power uprate.

Individual test abstracts define the purpose of the test, the appropriate test conditions and the associated test criteria. Detailed test instructions will be prepared in a predetermined format to implement these requirements.

The test criteria have up to two levels of importance. The criteria associated with plant safety are classified as Level 1. The criteria associated with design expectations are classified as Level 2.

Level 1 criteria. If a Level 1 criterion is not satisfied, the plant must be placed in a hold condition that is judged to be satisfactory and safe based upon prior testing. Plant operating test procedures, or the technical specifications may guide the decision on the direction to be taken. Other testing may continue as long as the tests are independent of the hold conditions. Resolution of the problem leading to the hold condition must be immediately pursued by equipment adjustments or through engineering evaluation, as appropriate. Following resolution, the applicable test portion must be repeated to verify that the Level 1 requirement is satisfied. A description of the problem must be included in the report documenting the successful test.

Level 2 criteria. If a Level 2 criterion is not satisfied, plant operating or startup test plans would not necessarily be altered. The limits stated in this category are usually associated with expectations of system transient performance, and characteristics can be improved by equipment adjustments. An investigation of the related adjustments as well as the measurement and analysis methods would be initiated.

Confirmation of component and system performance

The activities to prove the performance of mechanical and electrical components and systems are the same as would be done after each modification to confirm they meet system requirements.

Testing a component is therefore not an isolated activity but is embedded into many other dependencies and operating states. Therefore, the sequence of testing is important to fulfil all the testing activities in a short time and requires thorough planning. Some examples are turbine performance, pump performance of the condensate system (for both normal operation and during transients), steam dryer performance at full power by use of a N24 tracer and the performance of preheaters.

Monitoring system

A comprehensive monitoring system is necessary for testing BOP systems and components. An existing process computer with a sufficient number of signals for main process parameters and a time resolution in the order of 1 second is recommended. This monitoring system will follow the whole power uprate programme, starting with base measurements before any power increases. For special tasks (e.g. mobile ultrasonic flow measurement), a local computer-based data acquisition system can be used.

Reactor thermal power

One key parameter for a power uprate is the determination of reactor thermal power. Traditional measurement techniques combined with the assumption of an uncertainty of 2% standard deviation (1σ) are not useful for the necessary degree of precision.

An isolated measurement campaign with tracer methods or other methods is expensive and delivers results only for the time of the campaign.

The implementation of permanent ultrasonic feedwater flow measurements seems to be a good hardware/software-based solution. This method has the pitfall of being a single isolated measurement with good performance at laboratory conditions but may drift and fail unexpectedly and unnoticed in field applications.

State of the art is the use of process data reconciliation according to the guideline [5]. This method uses all available (redundant) information of the entire heat cycle and is independent of the accuracy of a single measurement. Using this method, the reactor thermal power can be defined with a high degree of accuracy (better than 0.2% standard deviation (0.4% is the 2σ value)).

Verification of characteristics of control systems

The function of control systems is to keep the desired process operational values and to control disturbances by failures in a way that the process remains controlled and further damage is prevented.

For a BWR/PWR, three main control systems are to be tested before and after a power uprate.

— Pressure regulation should be tested for the whole operational range;
— Level regulation should be tested for all essential operational ranges;
— Flow control should be tested by flow demand steps.

Control system testing is also required per the power uprate programme, and this includes pressure control and feedwater level control system tests. Both tests insert small perturbations into the control system and verify that stable operation is maintained. These tests are performed during initial plant startup.

Verification of SCRAM avoidance capability

For a power uprate programme, the underlying principles should be defined at the very beginning. One principle is not to accept any impact on plant reliability. Therefore, the items that define reliability (not only failure free components) as SCRAM[7] avoidance capability should be carefully tested.

This capability can detect the absence of a SCRAM as a result of:

— Feedwater pump trip;
— Turbine trip;
— Generator load rejection;
— Two recirculation pump trip.

To verify this plant capability, various transients may have to be tested. The preparation of these tests consists of detailed transient analysis for predicting plant behaviour, specifying test procedures with clear Level 1 and Level 2 criteria and using a fast data acquisition system for post-evaluation of the tests. It should also be considered to prepare training for the shift personnel at the simulator. The effort for such tests should not be underestimated.

Startup and test programme after power uprate

Based on a variety of events in the industry's experience with uprating, more and more emphasis has been placed on the startup and test plans following the implementation of an uprate.

Significant emphasis has also been placed on establishing a very deliberate power ascension plan that contains numerous 'plateaus' between the previous 100% reactor power and the new, uprated 100% reactor power. Each power level change should be an approximate one and a half per cent increase in reactor thermal power. The plateaus typically range between 2 and 5%. The power ascension plan would require operation at each plateau for various lengths of time. The duration at each plateau would be established based on both the absolute power level and the plant response at the plateau power level (e.g. vibration, noise levels, other indications).

Additionally, scheduled dynamic tests should be performed, including control system testing as required by the test schedule. All data and test results need to be reviewed and analysed against pre-established limits and acceptance criteria. The results of the review should be presented to plant management, and the approval to proceed to the next higher power should be requested. This process is repeated until the maximum electric output is reached.

At each plateau, the plant staff is monitoring for abnormal or unexpected responses by plant systems and equipment. Increased noise levels, higher than expected vibration readings, and erratic indications would all result in a deliberate set of investigative steps to understand and satisfactorily explain the response prior to proceeding to a higher power level.

The tests selected for power ascension can come from a number of inputs and from numerous sources. In the case of BWRs, the license topical report (LTR) required pre-operational tests for systems that have revised performance requirements because of the uprate. A test plan is required to be submitted with the license amendment request, which specifies the required tests to be performed. Test requirements can also be added based on the system task reports to ensure that analyses are accurate or closely monitored and finally, test requirements can be added based on engineering judgement. The power ascension test procedure must be written to ensure that it accomplishes the power increases in controlled, conservative and well-monitored incremental steps [6].

Because of the increased incidence of flow-induced vibration problems after a power uprate, large uprates have established the practice of adding both permanent and temporary vibration instrumentation to various systems with intense monitoring during and sometimes after power ascension.

[7] SCRAM: Emergency shutdown of an NPP.

2.6. LICENSE AMENDMENTS

Because the licensing authority controls any change to the plant technical specifications, the utility may only change these documents after the approval of a license amendment for change. Therefore, no matter how small, the application of a power uprate must be approved by the licensing authority in advance.

The utility, usually through a contract with the NSSS supplier and an architect–engineering company, works to analyse existing plant systems to determine if they can accommodate the proposed uprate. It usually takes the utilities about a year to complete the upfront work for a license application of power uprate. It then takes the licensing authority about a year to approve the application.

The utility has to discuss with the licensing authority the startup programme and the tests to be carried out during the startup. The utility must determine who will prepare all of the necessary operating documentation and what role the utility will play in the preparation and verification of documentation.

In some countries, the regulatory licensing authority demands an opinion from an independent expert organization about the planned modification. The utility should decide who is qualified and, if necessary, get approval from the regulatory authority.

The utility must also understand the requirements of the licensing authority regarding revisions to the FSAR to reflect the changes to the plant and supporting analyses, and in which project phase the utility has to submit the modification of the FSAR.

2.6.1. Identification of required licensing amendments

In each national practice, the application of a power uprate will depend, in part, on whether the licensing amendment process regarding the power uprate is already determined in domestic practice or whether the regulatory rules contain precise instructions regarding the licensing process.

The utility has to determine what licensing activities must be done to gain approval for power uprate implementation. It may be that the licensing process depends on the value of the power uprate. For this, the utility and technical support organizations should review what documents and rules prescribe the licensing activities.

The utility should determine what documents need to be prepared for each licensing process and what the scope of each document is. In the case where the licensing process is complicated or not every aspect is clear enough, the utility should communicate with the authorities to elaborate the process of the licensing and to clarify what additional demands the licensing authority will have.

Environmental licenses/permits

In the case where environmental licensing is needed, the utility should determine what kind of documentation must be prepared and what the acceptance criteria are. If there is a need for any additional environmental monitoring programmes, it should be determined when they should start and how long they should last.

The environmental approval process may require that other authorities be involved in the licensing process. The utility needs to determine what their requirements are. Also, the utility must understand and be knowledgeable regarding if public hearings are necessary and when they must be held.

2.6.2. Development of licensing amendment requests/submittals

After the licensing authority demands are determined, the utility should prepare the licensing document. The responsibilities must be determined and clearly documented for all required scopes. In the case where the licensing documentation will be prepared by another organization, the utility has to determine in which way the documentation will be reviewed and approved by the utility.

In order to keep the power uprate schedule, the utility has to inform the licensing authority about the schedule for submitting the application. It may be that, during the period of licensing of the power uprate, it is reasonable to decrease the other licensing activities.

Codes and standards

The process for power uprate applications is the license amendment process; therefore, the application for the power uprate is submitted to the licensing authority as a license amendment request. For example, in the USA, the NRC used the following regulations and guidance:

- Change to license and technical specifications;
- License amendment process;
  - 10 CFR 50.90 — Application for Amendment;
  - 10 CFR 50.91 — Notice for Public Comment/State Consultation;
  - 10 CFR 50.92 — Issuance of Amendment;
  - Other regulations that form licensing basis of the plant;
- Environmental impacts — 10 CFR Part 51;
- Review guidance of power uprates;
  - Existing standard review plan;
  - Template safety evaluations;
  - Regulatory issue summary 2002–03 (MURs);
  - Review standard RS-001 (EPUs).

2.6.3. Management of the regulatory process

Meetings with regulators

The licensing authority and licensees should be in regular contact to discuss the authority's ongoing reviews and other regulatory matters requiring review and approval. Frequent and early communications between the licensing authority and the licensee could help avoid unnecessary delays in the processing of the license amendment applications.

Acceptance review

Acceptance review is a preliminary screening of the application by the licensing authority to see whether the documents of the license amendment application contain enough information to establish compliance with the current regulations. This review does not judge the technical adequacy of the application but rather is an evaluation to determine whether the application documents would be sufficient to support granting a license amendment and whether the application is ready for the licensing authority to begin its detailed technical review. During the acceptance review, the licensing authority will have to ensure that the submitted information results in a full and complete license amendment application.

Technical review

The licensee should identify the specific area of change that the licensee indicates to need revision. If the licensee completely submits the entire application documents, the licensing authority should request that the licensee specifically identify the changes.

Technical review of the license amendment application can be characterized by the following sub-processes:

- Working planning;
- Public notification and comment resolution;
- Evaluation of proposed amendment;
- Documentation of safety evaluation;
- Amendment preparation;
- Review and concurrence;
- Issuance of amendment approval.

Requests for additional information (RAIs)

RAIs serve the purpose of enabling the authorities to obtain all relevant information needed to make a decision on a licensing action request that is fully informed, technically correct and legally defensible.

RAIs should be directly related to the applicable requirements related to the amendment application and consistent with the applicable codes, standards, regulatory guides, and/or the applicable standard review plan (SRP) sections.

During the licensing process, the authorities might have additional demands or remarks regarding the licensing documentation. Utilities should be ready to respond to questions. To ensure that a clear and prompt response is given, the utility should determine who is responsible for each part of the application documentation and, in the case where the documentation was prepared by a contractor, the contract should contain a condition about additional support during the licensing process.

For better understanding of the authorities' remarks, the utility should keep an ongoing dialogue with the authorities by arranging consultations and meetings.

Public hearings

The utility has to know if public hearings will be implemented and in which phase of the licensing. If hearings are required, then it needs to be determined who will be responsible for arranging the public hearings. Before any public hearings, it may be useful to know and understand the level of public acceptance of nuclear power plants operating in the country.

2.7. IMPLEMENTATION OF THE POWER UPRATE

2.7.1. Field engineering/implementation guidelines and procedures

Between the design basis documentation and the operating plant procedures are all the interim documents and procedures that will guide the implementation of the power uprate project. Field instructions, work orders, planning documents and field changes all represent a significant amount of documentation that must be created in order to properly implement the necessary changes to the plant for the power uprate. The project manager must ensure that design requirements and instructions are scheduled and completed such that adequate time is allowed for the craft, maintenance and engineering organizations to translate the design requirements and documents into implementation work packages.

2.7.2. Organization and management

The implementation of the power uprate programme will involve electricians, millwrights, mechanics, I&C technicians, engineers and other personnel. Having tight coordination with the companies and plant departments that will provide these personnel and manage these resources is essential to execute the technical scope of the power uprate in accordance with the plant operational requirements for implementation.

2.7.3. Quality assurance activities

Quality assurance is in a common sense linked to hardware modifications of safety-related components. During power uprate, quality assurance should accompany the whole process from concept to design to analysis, as well as modification and documentation. For this task, personnel have to be recruited, trained and motivated. All of the project team members should fulfil quality requirements at the highest level.

2.7.4. Power ascension/testing plan implementation

Implementation of a power ascension step requires additional personnel who should be integrated into the normal operating process. A recommended method is that normal operations are controlled by the shift in charge, and a test director with operating experience leads the implementation of the uprating.

There are many criteria to be observed, and the monitoring process includes all groups involved in the process. Before implementation of each step, a briefing is mandatory with all responsible personnel. After implementation of each step, an evaluation of the results should be performed to ensure that they meet requirements.

Before a power ascension step is implemented, a test programme should be developed and accepted by the authority. For each test, a test specification should be written with objectives, approach, criteria at different levels, personnel, data acquisition, caution conditions and hold or 'no-go' criteria.

Test specifications should be transformed into test procedures, which are similar to normal operating procedures. Shift personnel are familiar with this type of guidance. A shift supervisor or higher should be designated to be the test director (this level of experience will ensure that proper and prompt plant response to plant conditions is made should deviations occur during the test.

The preparedness of the staff, auxiliary staff and supporting hardware/software has to be assured. It is critical to the success of the project to have computerized monitoring systems not only for the heat balance part but also as a fast transient recording facility for the evaluation of the test runs. It is very helpful if these recording systems are permanently installed and able to catch every disturbance, deviation or drift.

There are three types of tests:

— Performance;
— Control systems;
— Plant transients.

In the case of BWRs, steam dryer performance monitoring is required. Some NPPs may be able to utilize their on-line operational monitoring systems for areas such as:

— Main steam flow calibration;
— Feedwater flow calibration;
— Pressure controlling;
— Level controlling;
— Power controlling by recirculation system.

3. OPERATING EXPERIENCE AND LESSONS LEARNED

3.1. NSSS ISSUES

3.1.1. NSSS operating parameters

Power uprates are normally performed using constant pressure (i.e. pressure in the reactor is not changed). The reason for not increasing operating pressure is that if the pressure were increased, it would require substantial revision of structural verification as well as thermohydraulic analyses as compared to the relatively low benefit in terms of extra MW(e).

In the case of BWRs, the power flow map will inevitably change due to the higher thermal power. One manner of change is to prolong the rod line up to the uprated power level. This can often be used for SPUs together with the possible need to increase the maximum core flow. For EPUs, the operating range for reactor recirculation at full power will be none or will be so small that a more radical change to the power flow map may need to be considered. Examples of this include moving the rod line up (in parallel) and to the left all the way down to the knee and also to expand the core flow map to the left in the area from 90% and upward. Figure 4 shows a typical BWR power flow map with an example of an extended flow area(s). The analysis, which is reflective of this extended rod line and additional flow area, is known as maximum extended load line limit analysis + (MELLLA +). To avoid getting into the area where there is a high risk of instability, there are examples from ASEA BWRs of also increasing the minimum core circulation flow in connection to the power uprate.

3.1.2. Challenges for the NSSS

Challenges are plant-specific and can fall into either economic or physical limitation categories. The following are typical examples of the types of constraints that may be encountered.

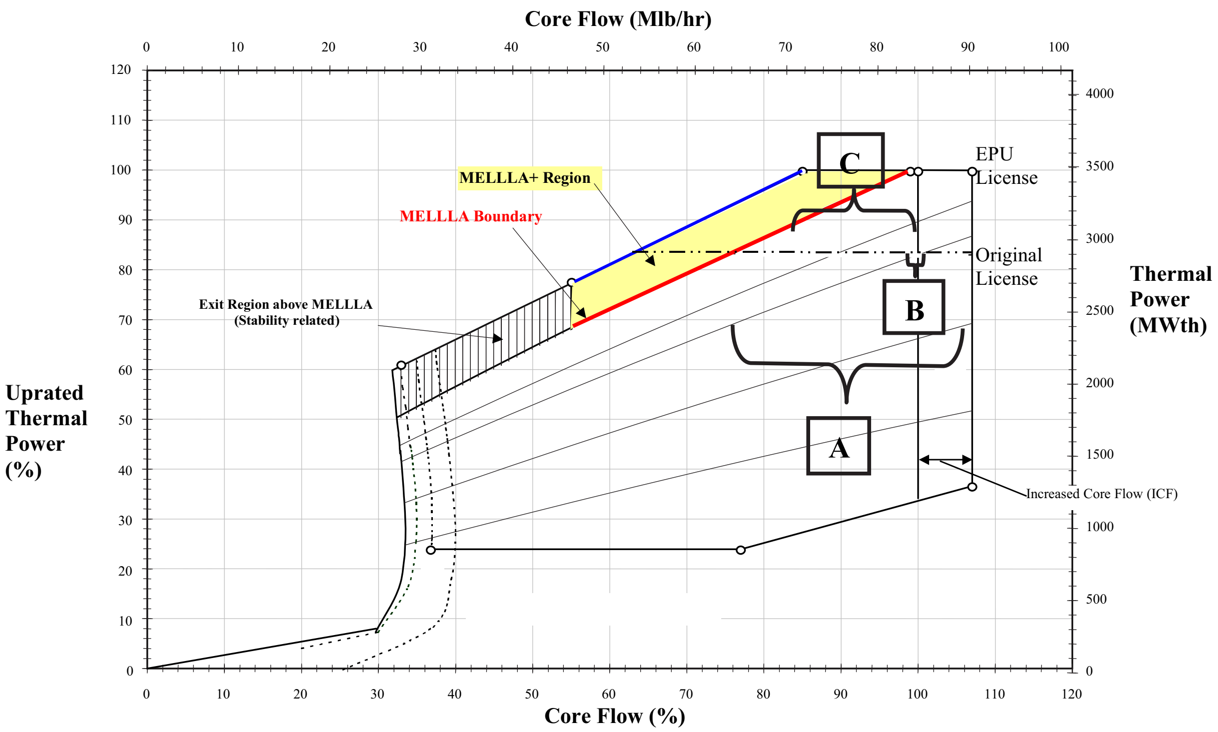
Increased flow will have an impact on flow-induced vibration in the steam/feedwater path; non-linear effects might occur. Vibration monitoring systems should be installed on the steam/feedwater path to check vibration. In addition, more frequent inspections may be required of components in the path with increased flow.

BWR case

The thermal limits of fuel can limit the possible power level that can be reached. Experience shows that the existing core flow regime can cover today's power uprate range.

If the plant design and construction is one where the recirculation pumps are installed internally in the pressure vessel, the installation of extra pumps is not possible. The only way to increase the core flow is to modify the pump and/or motor.

The capability of the steam separator and steam dryer can be another of the major constraints for an EPU in the upper bound.



A – Pre-EPU Operation Flow Margin
B – Post EPU Operation Flow Margin (Full Power – w/o MELLLA+)
C – Post EPU Operation Flow Margin (Full Power – w/ MELLLA+)

FIG. 4. Typical BWR core flow map.

PWR case

Moisture carryover is expected to be below the design limit for all uprating cases with proposed feedwater temperatures. The design limit of moisture carryover is threshold for erosion and corrosion of piping and valves downstream of the steam generator. The major challenge is the capacity of the steam generator.

3.1.3. Safety issues

The amount of safety analyses required depends on the level of the power uprate and on the complexity of the changes made to the plant. The status of the existing analyses also has an effect. On one end of the scale, only minor work is required while on the other end (e.g. an EPU analysis), a completely new set of safety analyses needs to be performed.

Safety analyses take a rather long time to perform. Depending on the status of existing analyses, an early start could be a success factor. Results from the safety analyses may also give necessary input to the design of the uprated plant.

The safety analysis (deterministic and probabilistic) is the basis for the verification of the safety and auxiliary system(s). The analyses will determine if the system needs to be strengthened or not. Additionally, if additional set points for the reactor protection system are needed, the verification of such points is done in the safety analysis.

3.2. EXPERIENCE WITH FUEL PERFORMANCE

The development of modern types of fuel that have better performance and are designed for higher and more efficient burnups has been driven by reasons other than potential power uprates. However, supported by improved analytical methods, this development has now made power uprate for a BWR possible with up to 30% (depending on the initial power density). For a PWR type reactor, fuel performance seems to be the major constraint.

3.2.1. Fuel reliability at uprated condition

There are no indications that power uprates would decrease the fuel reliability in the plant. However, during the power uprate, many modifications are installed, and the risk of foreign material entering plant systems increases. It is therefore recommended that the foreign material exclusion programme be reviewed and enhanced to minimize these occurrences. The power uprate may affect water chemistry that could lead to consequences related to the fuel reliability. Therefore it is recommended to monitor the fuel (including inspections) if any of these three areas are affected:

- Plant modifications;
- Fuel type;
- Change of water chemistry.

3.2.2. Constraints for operation at uprated conditions

Fuel performance can still be the limiting parameter for the maximum possible power level. In special cases, operating cycle-length in combination with fuel performance can set the limit. For PWR types of reactors, the fuel performance is definitely a major constraint. For a WWER reactor, an uprate of a maximum 8% seems possible; for a BWR reactor, an uprate in the range of 20–30% is possible.

3.3. SECONDARY PLANT ISSUES

Evaluations are conducted to assess the ability of the BOP SSCs and verify that they are structurally and functionally capable of safe, reliable operation at the power uprate conditions. This evaluation includes a review of the major components and systems typically impacted by a power uprate. Identification of the parameters and design inputs that will be used to evaluate the BOP SSCs is one of the initial tasks to be performed. A heat balance (sometimes known as a thermal kit) is usually developed by the turbine generator vendor. This identifies the operating parameters (based on design and performance conditions) expected for the uprated power level.

Pinch points for the BOP and turbine and generator (TG) systems normally exhibit themselves as a point in the uprate where large changes need to be made before the uprate can continue. Examples of these include changes to the main generator, main turbine changes, moisture separator/reheater tube replacement/chevron changes, and/or large valve changes. These changes are required to facilitate increases in power to the next step and are usually associated with large economic implications.

Experience has shown that equipment failures during normal operation will appear after a longer operating time post-uprate. Higher excitation/vibration of process lines (especially steam and sometimes feedwater lines) has led to accelerated wear of supporting structures and studs. Also, internal defects can be originated by higher vibration levels, which has led to impending failures that could only be detected during inspection periods associated with refueling outages. A partial plugging of the steam path as a result of a failed structure at a water separation elbow showed up during operation as only some minor changes in reheating steam distribution with no plant efficiency loss.

During normal operation, BOP component performance, in general, has enough margin to cope with operational disturbances. The performance during operational occurrences and transients may result in very low margins and unexpected behaviour (cliff edge effects). An example of this occurred at a BWR where a turbine trip led to instable flow (wave forming) in the wet well of the condenser due to insufficient apertures between the partitions of the delay path. The condensate control system could not control the waves, and it overshot, which led to an increased pressure drop in the feedwater tank. The feedwater pumps started cavitating for a short time and, after cavitation ended, the high speed of the pumps resulted in a high water level in the reactor with a SCRAM. Major analytical work revealed the causes of this unexpected physical behaviour and led to some major hardware modifications and control system adjustments.

Major awareness is performed on mechanical components because they are closely related to the process fluid. Effects on electrical components may sometimes be neglected or overlooked because of lack of knowledge or incorrect assumptions. One example of this is a generator failure by local overheating in the stator or failure in insulation of transformers (excitation or main) with unanticipated plant shutdowns.

Higher steam flows and associated feedwater flows can also result in valves not performing as they did per uprate. An example of this is associated with the feedwater heater drain valves (normal and emergency). Since there is now more condensate flowing through the secondary side of the plant, these valves will now be required to open further and operate at a different control point. If these valves are not calibrated correctly or if their valve trim is not changed out (if the analysis shows that there is loss of margin), feedwater heater levels will not be stable and control of the secondary side of the plant will be difficult to achieve.

3.4. TESTING AND OPERATIONAL ISSUES

Testing issues associated with power uprates have surfaced in a number of areas such as the effects of feedwater level control testing on the plant equipment. During the level regulation phase of testing in a BWR, the turbine-driven feedwater pumps are called upon to respond to changes resulting from a change in level demand.

The purpose of this testing is to ensure that the level control system will respond to changes in level under power uprate conditions. Since the plant is operating at higher power levels, these changes in demand could result in the feedwater pumps operating at a point where they have not operated before (i.e. speeding up to inject more water into the core in response to the demand signal).

It is important that this equipment is properly prepared from a maintenance standpoint to respond to these changes in demand. If this is not done, undesirable effects to level response can become apparent, up to and including a SCRAM of the reactor on level. Operational issues include areas such as valve operation, pumps operating at a different point on their pump curve and system responses to transients.

An example of a valve operational issue may be in the area of the feedwater control valves in that these valves will be operating at different positions than before power uprate. The valves must be properly prepared (maintenance performed) to operate in this range, and the operators must be aware of these “new” positions.

Power uprates, especially large EPUs, have in some instances resulted in equipment degradation and damage due to increased flows and energy levels in secondary piping systems and equipment. In some cases, these were latent effects in that the development and detection of the issue took weeks or even months after completing the uprate to become apparent.

Due to several significant events, primarily the US Quad Cities 2 steam dryer cracking problems, increased attention has been placed on vibration instrumentation (both temporary, during startup/power ascension, and permanent, during plant operation), test procedure rigor and detail, and power ascension plans. The US nuclear power industry has experienced over 60 events related to power uprates since 1997. From the Institute of Nuclear Power Operations (INPO) Significant Event Report (SER) SER-05-02: “Significant aspects of these events include the following:

- An extended, unplanned shutdown was required to retrieve several loose parts as a result of a flow-induced, high-cycle fatigue failure of a steam dryer cover plate.
- Operational transients and equipment damage have occurred as a result of weaknesses in identifying, communicating, and training the plant staff on expected changes to secondary plant operating characteristics.
- Unanticipated operating challenges and degraded equipment performance have resulted from reductions in operating and design margins.
- Some units have operated beyond their licensed power levels for extended periods because of errors in reactor thermal power calculations following uprates that changed secondary plant operating characteristics.”

Unanticipated problems caused by, or contributed to uprates have occurred in a wide variety of plant systems. However, main steam and feedwater systems, especially in piping and heat exchanger equipment, have proved especially susceptible to problems and therefore require increased focus during the evaluation and design phase as well as the testing and monitoring phase after uprate implementation. Main turbine controls, and main generator and isophase bus cooling systems have also experienced problems that may have been able to be avoided with increased analysis during the design phase to identify inadequate margins or operational considerations under the uprated conditions.

In addition to equipment problems, inadequate procedure review and revision has led to problems with both maintenance and operations personnel having inadequate understanding of the plant and its new responses under uprated conditions. Increased attention to procedure development, training, simulator modelling and careful evaluation during power ascension to verify actual plant response versus expected plant response in uprated conditions is critical to avoiding problems of this nature. This is especially true where uprates require a significant change to plant operational regimes such as moving from turbine control changes, from ‘full-arc’ to ‘partial-arc’ steam admission, transition from a one feed pump operation to a two feed pump operation, changes in feedwater heater train operations and hot summer operations conditions (more susceptibility to condenser backpressure variations).

For MUR uprates, some events have occurred where, due to software configuration issues with the ultrasonic feedwater flow measurement devices, the plant was operating above its licensed power level. Increased rigor in the design and analysis phase is required in these cases.

- Degradation detection and damage evaluation of some effected components;
- Flow-accelerated corrosion;
- Vibration.

A number of these concerns may become apparent through the use of plant simulator scenarios. It is important that the plant simulator be modelled and that various operational scenarios be run to help understand and identify potential effects.

3.5. MARGIN ISSUES

Increasing the electrical output of a plant requires a thorough understanding of the margins of the plant systems and components. Both the margin available prior to power uprate and the margin available after power uprate is implemented must be known and understood. This is vitally important to all plant personnel whether it be operations, maintenance, engineering, etc. Post-uprate margin issues exhibit themselves in the form of decreased operating margin (operational flexibility) and decreased design margins. As operational flexibility is reduced, negative effects such as increased occurrences of alarms in the control room and/or operation at the high end of control room indicators such as temperature, pressure and/or flow, begin to occur. Additionally, procedures may need to be revised to reflect this change in operational flexibility to ensure that this effect is documented and understood by the operating staff. Decreased design margins are usually resolved by the implementation of modifications to restore the design margin to acceptable values or in some cases, the decrease in design margin is accepted as is, and design documents are updated to reflect this decrease. From a maintenance standpoint, the reduction in margins could result in more frequent maintenance and/or additional maintenance. This could be a direct result of components being subjected to accelerated wear or components being subjected to a totally different wear pattern/phenomena than was apparent before power uprate.

It is very important that a trending programme be established and that the trending of parameters in the marginal systems/components be tracked and reviewed to ensure that the actual results are comparable to the predicted results in terms of margin reduction. Areas that do not compare favourably to the predicted results are candidates for further review to determine and understand the discrepancy. Corrective actions to resolve these discrepancies must be implemented.

3.6. LICENSING/REGULATORY ISSUES

During the power uprate licensing process, the SAR is one of the basic documents that is affected. Therefore, it is recommended that efforts be spent to update the SAR to ensure that it reflects the pre- and post-uprate conditions.

The experience from licensing reviews related to power uprate varies in large part depending on the size of the uprate. In the case of MURs, the issues are concentrated to a specific measurement technique, procedure, and the assessment and interpretation of safety margins. The licensing effort expended for MURs is therefore less than for EPUs. This is due in part to the fact that EPUs result in the implementation of several plant modifications and therefore are more complex, requiring more time and effort.

There are several stages in the licensing process where issues are reviewed. These include the principal assessment stage, the review prior to issuing the permit for raising power and the follow-up of possible long term effects. In order to have a basis for comparison of detailed data before and after the uprate, it is advisable to establish a programme for collection of before data or fingerprints. This might require setting up some additional equipment for measurements and for data acquisition.

In addition to the technical issues of potential impact on reactor safety, there are also broader issues related to public perception of power uprates. These include the potential changes of radioactive releases during normal operation, interpretation of analysis related to the risk, and the consequences of accidents and waste production. Certain sets of these issues are dealt with in the context of the environmental impact review during the licensing process. Public hearings may be one part of this process. Several bodies, supported by the licensee, need to be involved and prepare material to serve the public interests.

There are a variety of issues associated with power uprates. This leads to the need for a broad competence base within the licensing authority and must be supported by the licensee. For the licensing activities, the following disciplines should be involved: reactor physics (including core design, fuel and thermal hydraulics), structural mechanics, safety analysis, system design, issues related to barriers and defence in depth, human factors, reactor operation, operator training, environmental impact and radioactive waste.

4. CONCLUSIONS AND RECOMMENDATIONS

The economic incentives for low-cost electricity will continue to drive more and more utilities to identify safe and reliable methods of increasing the electrical power output of a nuclear power plant. Power uprate provides such a method for many operating NPPs.

It is essential to identify and analyse all the conditions and parameters that have an influence on plant safety. It must be shown that all required safety margins have been properly retained and that the existing safety level has been maintained or, preferably, increased.

A power uprate feasibility study will consider a number of scenarios to establish an understanding of which one offers the best alternative based on consideration of cost, benefit and risk. Because changing the power level of the reactor affects so many systems and analyses and often requires significant physical plant changes to implement, there are numerous opportunities to overlook potential problems. Thorough reviews, independent analysis and attention to detail, all must be carefully considered and implemented to ensure that safety, reliability and efficiency of the plant components are maintained as high as possible. All of the proposed changes are required to be tested to ensure proper plant response at the uprated power level.

While experience from power uprate projects is generally favourable, some plants have incurred problems with their implementation (e.g. equipment damage or degraded performance, unanticipated responses to plant conditions). These problems have arisen mainly from an insufficient analysis and/or understanding of the full implications of the proposed power uprate or from insufficient attention to detail during the design and implementation phase.

To implement a power uprate, it is strongly recommended that:

— The power uprate project plan should ensure that it accomplishes the power increases in controlled, conservative and well-monitored incremental steps.
— A comprehensive safety analysis should be undertaken, which covers all aspects of plant behaviour under normal, abnormal and accident conditions (as was done for the original SAR).
— A rigorous, disciplined approach focusing on multidisciplinary teams, including engineering, licensing, operations, maintenance and test implementation personnel, with appropriate skills is required to ensure success.
— The vulnerability to equipment caused by material degradation and vibration concerns needs to be considered and reflected in the power uprate process.
— Operating staff are adequately trained as it relates to how the plant will operate after the power uprate. It is equally important that maintenance, engineering and radiation protection personnel are provided training on the changes made as a result of the power uprate programme.
— All affected documentation, and operating and maintenance procedures should be updated and reflect the new conditions.
— Special attention should be paid to procedure development, training and simulator modelling. This will help to verify actual plant response versus expected plant response in power uprated conditions and avoid the unanticipated problems.

The impact of the power uprate on plant life management for long term operation is an important issue. Plant ageing issues may be aggravated by the power uprate due to plant conditions. This may result in a need for more inspections and installation of monitoring systems for certain critical components to ensure extended plant operational life.

Appendix I

EXTENDED POWER UPRATE PROJECT AT CLINTON POWER STATION, USA

I.1. INTRODUCTION

In the third quarter of 2000, the Clinton Power Station (CPS) made the decision to proceed with an extended power uprate (EPU) programme. This decision was made after a detailed economic analysis was developed and presented to the Board of Directors of the company. At that time, the General Electric Corporation (GE) had developed a detailed process for BWRs related to the engineering analysis surrounding EPUs. They had received approval from the NRC for a generic type analysis for EPUs using a “topical report” approach. BWR utility owners were then able to apply for a site specific license to uprate their plant up to 120% of the original licensed thermal power (OLTP). This topical report established the methodology and generic scope that would be the basis to be used in the analysis of the systems, structures and components (SSCs) when a utility applied for a site specific uprate license from the NRC. CPS entered into a contract with GE to perform the detailed engineering analysis to uprate the Clinton Station to 120% of OLTP in accordance with the NRC-approved topical report. Shortly after the decision was made to proceed, a team of personnel was assembled at CPS to concentrate on this effort. This team (hereafter referred to as the core team) consisted of seven people dedicated to extended power uprate. Supplementing this team were General Electric (NSSS supplier) personnel and Sargent and Lundy (Balance of plant archetict engineer) personnel as well as various subcontractors hired by each of these firms.

I.2. SYNOPSIS

The engineering analysis to support the EPU conditions of 120% thermal power for CPS was completed in 2001. The primary focus of this analysis was to ensure that Clinton Station would be able to operate safely and reliably at 120% of OLTP. Included were the following major focus areas:

- This was a cooperative effort between GE and Clinton Power Station;
- The analysis was based on the structured/standardized process (topical report) developed by GE and approved by the NRC;
- There was one common schedule that was controlled by Clinton Power Station;
- The analysis of the Clinton Power Station was divided into task reports (total of 82 tasks), which were performed in the following major areas:
  - Operating conditions;
  - Core and fuel performance;
  - Reactor coolant and connected systems;
  - Engineered safety features;
  - Instrumentation and control;
  - Electrical power and auxiliary systems;
  - Power converstion systems;
  - Radwaste systems and radiation sources;
  - Reactor safety evaluation;
  - NSSS initial power assessment;
  - BOP power cycle initial power assessment;
- The information reviewed in the 82 tasks was representative of all areas of the plant (i.e. the SSCs).

This analysis was conducted to ensure that the SSCs at Clinton would be ready to safely support the higher power levels that were planned for EPU operations. This analysis was initiated in August 2000 and was completed in June 2001. The review of the task reports was performed by the core team, and the 82 tasks were divided up among those personnel. Their primary job was to be responsible for the development of the scope, provide design details as required and perform reviews of the task reports. Final approval of the task reports from the Clinton

Power Station was the responsibility of the team leader (project manager). The development and analysis of each of the task reports was performed either by GE, SandL or a subcontractor. There were additional task reports (~10) developed and approved by the core team, and this work entailed mainly passive items such as environmental assessments and/or process reviews. The results of these reviews indicated that a number of changes (both non-hardware and hardware related) would be required before CPS would be able to achieve these higher power levels. CPS submitted the results of this analysis to the NRC in June 2001. In April 2002 (10 months later), a new operating license was received by the station, which allowed operation at an increased thermal power level of 120% of the OLTP (2894 MW(th) to 3473 MW(th)).

A plan was developed by the core team to implement the increase in power in two steps due to economics and the complexity of the changes involved. The first step would be an approximate 8% increase following C1R08 (known as interim power uprate (IPU)), and the second step (to the target power uprate (TPU) level, which is the rated condition for CPS) would follow in the next refuelling outage, C1R09. The first of these two steps was implemented post-C1R08 when CPS completed power ascension testing in accordance with an approved test programme, which indicated that the station SSCs were capable of operating at the higher power levels. EPU testing (post-C1R08) was halted at 92% power due to economic and schedule considerations. During the testing, a feedwater pump experienced a malfunction, and the plant experienced a SCRAM. As a result of this scram and the subsequent recovery efforts associated with bringing the plant back on-line and our commitment to supply electrical power to the grid, the decision was made to complete the remainder of the EPU testing after our next refuelling (C1R09). Plant operation following C1R08 supported this with electrical output of the station being at or higher than the projected output while generating approximately 1080–1095 MW(e) during the summer months.

As a result of the analysis performed, a number of physical plant modifications were identified, which were required to be implemented to allow operation at these increased levels of power. The design development of these modifications occurred after the submittal of the license amendment request (June 2001), and they were completed and ready for implementation by March 2002. This was the large refuelling outage where EPU modifications were installed. A listing/explanation of the major modifications that were installed at this time is discussed later in this report.

I.3. STEP 1 CHANGES — INTERIM POWER UPRATE (IPU), (IMPLEMENTED DURING C1R08–MARCH 2002)

To ensure that all of the required documentation was updated to support the refuelling outage in 2008, there was a large effort expended on the non-hardware changes. This work included the updating of calculations, revisions to vendor documentation and vendor manuals, as well as updates to licensing documentation. Attached are pictures of the non-hardware changes that were performed along with a picture of all of the hardware changes that were performed.

Plant operation within the constraints of the analysis and the modifications that were performed was a requirement of our new operating license, and therefore a number of operational limitations were placed on the plant. These limitations were reflected in the plant operating procedures. Finally, a review of the operating margins was conducted to ensure alignment with the analysis for operation in cycle 9 (post C1R08). Subsequently, in 2004, CPS also performed a comprehensive and very detailed review of the design and operating margins arising out of EPU to ensure that we understood the effect of EPU on all of the affected systems.

The second step of power increase was planned post-C1R09. During the course of preparations for this, CPS was also concurrently performing the necessary analysis to extend our operating cycle from 18 months to 24 months. As this proceeded, it became apparent from an economic standpoint relative to the fuel area that both of the projects could not be implemented in C1R09. As such, a business case was developed to determine which of the projects should be implemented during C1R09 (for cycle 10). This analysis yielded no distinct advantage to either project economically, and the decision was made in April 2003 to proceed with the implementation of the 24-month project and install only a few of the modifications needed for the second step of EPU. A listing/explanation of the major modifications that were installed at this time is discussed later in this report and entitled “STEP 2 CHANGES — INTERIM POWER UPRATE (IPU), (IMPLEMENTED DURING C1R09 — FEBRUARY 2004).” The remaining changes would be installed during the subsequent outage (C1R10) for cycle 11; hence, full implementation (to the guaranteed/rated output of 1138 MW(e)) was to be delayed for one cycle, and therefore no additional EPU testing was performed during this outage (C1R09).

During this same period, CPS was also pursuing the implementation of maximum extended load line limit analysis + (MELLLA+). This project (working in conjunction with and as a part of EPU and the asset enhancement programme) ensures that the reactor recirculation flow margin is regained in terms of operator flexibility at the high power levels of EPU. CPS had submitted a license amendment request (LAR) in April 2003 with a requested approval date of January 2004 for MELLLA+ implementation. In order for the NRC to issue a revised license to CPS, the first step in the process was for the NRC to approve a topical report submitted to them from General Electric (GE); this process was very similar to the approach that was used for EPU. As a result of the topical report submitted to the NRC, GE was resolving numerous comments on the submittal, and it became clear to CPS that the topical report would not be approved in such a time that would allow us to obtain a LAR to support C1R09 implementation of MELLLA+. In September 2003, a site decision was made to not pursue implementation of MELLLA+ for C1R09, and instead we would pursue this for C1R10 along with full implementation of EPU. Since an earlier decision had been made to not increase electrical power generation to the rated levels during C1R09, this decision had no effect on flow margin.

During 2004, while preparing for our tenth refueling outage (C1R10), GE and the NRC were still in constant communication regarding the topical for MELLLA+. In July 2004, it became apparent that the topical would not be approved in time to support implementation in C1R10. A monetary approval team known as the project review committee (PRC) met at CPS, and a decision was made to not pursue the modification development and subsequent implementation of those modifications during C1R10. Additionally, the decision was made to continue the actions in support of the request for a license amendment for MELLLA+. Progress was being made, however, there were no definite approval dates available at this time for the GE topical. To ensure that the site continued to concentrate on the correct priorities, the following decisions were made:

— CPS would operate cycle 11 at approximately the same thermal power level (as we had been operating in cycle 10).
— CPS would not implement MELLLA+ during C1R10. Without MELLLA+, the ability of operations to maneuver becomes limiting as power is increased since the flow window becomes smaller and the reactor recirculation margin is reduced.
— CPS would plan to implement MELLLA+ post-C1R11 (for cycle 12), and this implementation would then allow us to achieve full rated electrical power output of 1138 MW(e) with the additional reactor recirculation operator flexibility. This implementation would be tied to the NRC approval of the MELLLA+ topical submittal from GE.

An economic analysis was performed to determine which modifications (exclusive of those associated with MELLLA+) would be pursued in support of C1R10 in light of business considerations within Exelon. The results of this analysis yielded that we should pursue the modifications identified in this report as “STEP 2 CHANGES — TARGET POWER UPRATE (TPU) (TO BE IMPLEMENTED DURING C1R10 — FEBRUARY, 2006). Two larger modifications (exciter replacement and stator water cooling replacement) were moved to the subsequent refueling outage (C1R11) based upon economics.

CPS is currently operating at the limit of testing (in terms of reactor power) that we performed coming out of C1R08 as well as the limit of thermal power imposed by Operations pending the implementation of MELLLA+ (the flow control margin window has been reduced significantly without MELLLA+). During the C1R11 refueling outage, GE recommended that CPS not operate beyond 3365 MW(th) as a result of inspections performed on our steam dryer, and therefore this limitation was added as a restraint to operations.

As a part of the main exciter installation, a new grid stability study was required to understand the effect(s) on the grid of operating at 1265 MVa (1138 MW(e)). The previous grid stability studies had not been performed at the TPU output level since CPS did not have the capability to generate that level of MW(e), however, with the addition of the new exciter, this would allow generation at TPU conditions (1138 MW(e) @ 0.9Pf) pending the resolution of the items discussed above related to testing, margin, etc. The results of this study (entitled “Midwest ISO IP10 (36629-02) System Impact Restudy, dated September 2007”) was that a fault was identified which could potentially take CPS out of synchronism if operated beyond 1115 MW(e). The proposed “fix” for this potential grid concern is the installation of an additional breaker in the switchyard. The study results showed that below 1115 MW(e) CPS remained in synchronism after the fault, however, at an output of >1115 MW(e) gross, there would be problems if there was a fault and breaker 4518 did not respond in a defined amount of time. As a result, Clinton Station is limited to 1115 MW(e) gross. Additionally, other parameters such as steam flow and feedwater suction pressure are nearing their margin limitation. As such, prior to increasing power beyond the present limitations as noted in our operating procedures, CPS has made the decision to perform detailed studies as to the correct course of action surrounding the removal of these limitations. Pending results of those detailed studies (to be performed at a later date) and also pending the acceptance of the General Electric MELLLA+ topical report by the NRC, CPS will remain at its present power level.

The following provides the major modifications with a short explanation for each. The final guaranteed design power output of CPS is 1138 MW(e) at 0.9Pf or 1265 MVa.

I.4. STEP 1 CHANGES — INTERIM POWER UPRATE (IPU) (IMPLEMENTED DURING C1R08 — MARCH, 2002)

Isolated phase bus duct (Phase 1)

This change modified the isolated phase bus (IPB) outdoor ductwork to upgrade the IPB ratings, enabling higher currents for the EPU. The upgraded rating of the IPB will be 34 000 amps (forced cooling) for the main bus portion and 20 000 amps (forced cooling) for the delta bus portion. This change also modified the cooling capacity of the isophase bus (IPB) cooling system in order to meet the increased cooling requirements. The IPB cooling system provides cooling to the isophase buses (A, B and C). The system is a closed air-cooling and circulation system. It consists of two 100% capacity air-cooling units and ducts that are routed to surround the buses. The cooling units are composed of coils, fans and motors. Normally, one cooling unit is used, while the other is on standby. The fans blow air across the cooling coils and circulate it through the cooling loop at the rate of 14 600 cfm. Cooling is provided by water from the turbine building closed cooling water (WT) system, which pumps water through the cooler in use at the rate of 85 gal/min. The maximum design basis temperature of the WT water is 40°C. The cooling capacity is enhanced by this modification by:

(1) Using the two coolers simultaneously, in parallel, with a total airflow rate of 22 000 cfm;
(2) Increasing the WT water flow rate to 150 gal/min total through the two coolers;
(3) Cooling water flow through each cooler dropped to 75 gal/min from 85 gal/min.

With this new configuration, a loss of one operating unit may require Operations to reduce output from the generator. Operation procedures were also revised to limit the generator output, as required, to maintain the isophase bus temperature below the alarm set point of 180 °F.

Replacement of main power transformers

This change modified the existing four-single phase main power transformers (MPTs) with a new set of four-single phase MPTs. Previously, there were three-single phase, 310/347 MVA, 55°/65°C MPTs (1MP04EA, EB and EC) installed at CPS. The fourth MPT (1MP04ED) is a common spare. The new MPTs are rated at 475 MVA, FOA, 65°C for each phase, and sized to allow the full generator EPU output when the plant loads are fed from the reserve auxiliary transformer. This change replaced the main power transformer (MPT) 1A, 1B and 1C fire protection system. The new transformers are a larger design and a different configuration, and therefore a new fire protection sprinkler system was required to accommodate these transformers. This modification also included the installation of a new automatic deluge sprinkler system to three transformers (1A, 1B and 1C). Transformer 1D is a spare transformer, and a sprinkler system is not required.

HP and LP turbine rotor replacement

This change replaced the existing Clinton HP turbine to ensure that it had the capability to support EPU conditions. In addition, the LP turbines were converted from the conventional turbine rotors, which use shrunk-on

Clinton Power Station Extended Power Uprate - Non-Hardware Changes "Big Picture"

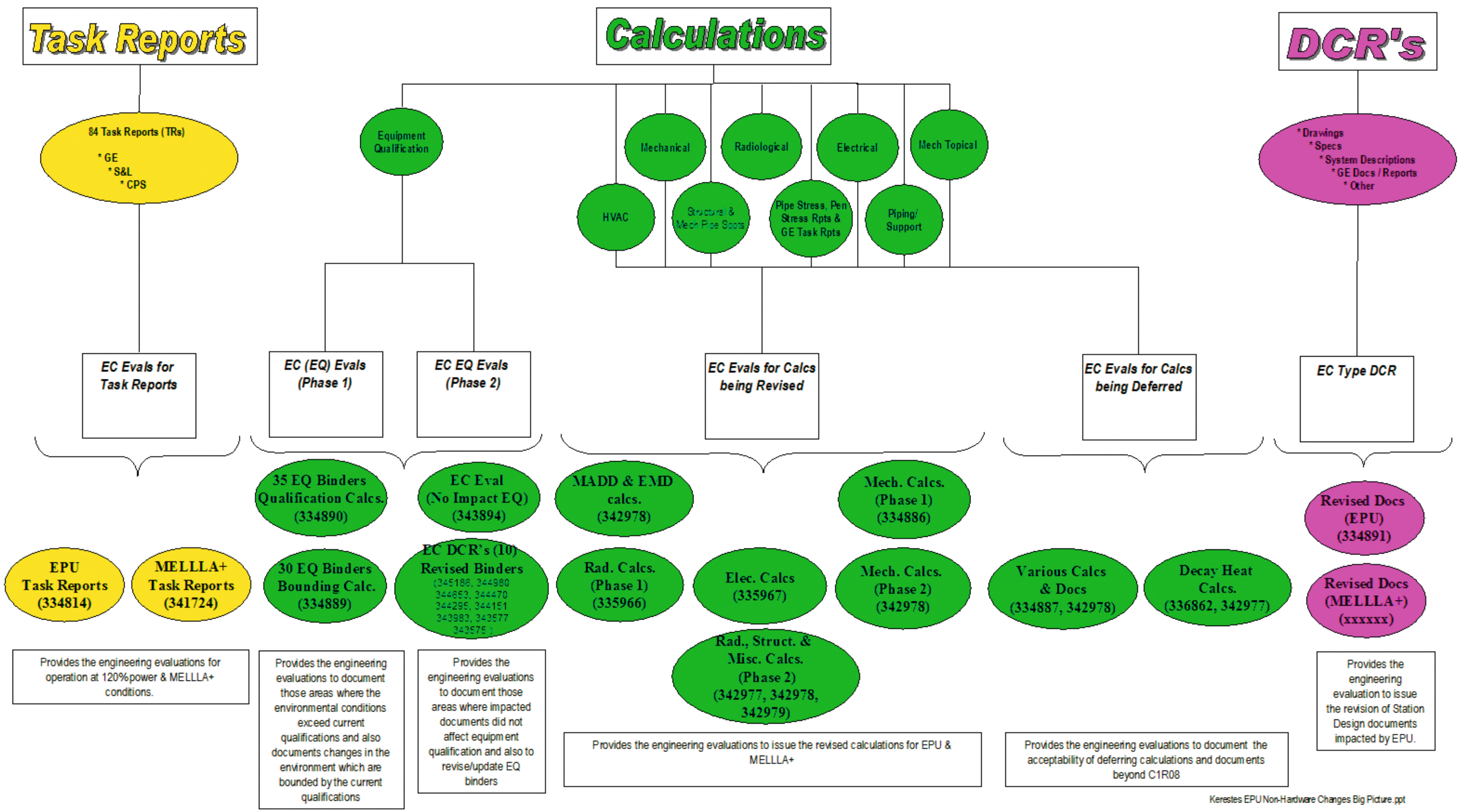


FIG. I.1. Clinton Power Station power uprate — non-hardware changes.

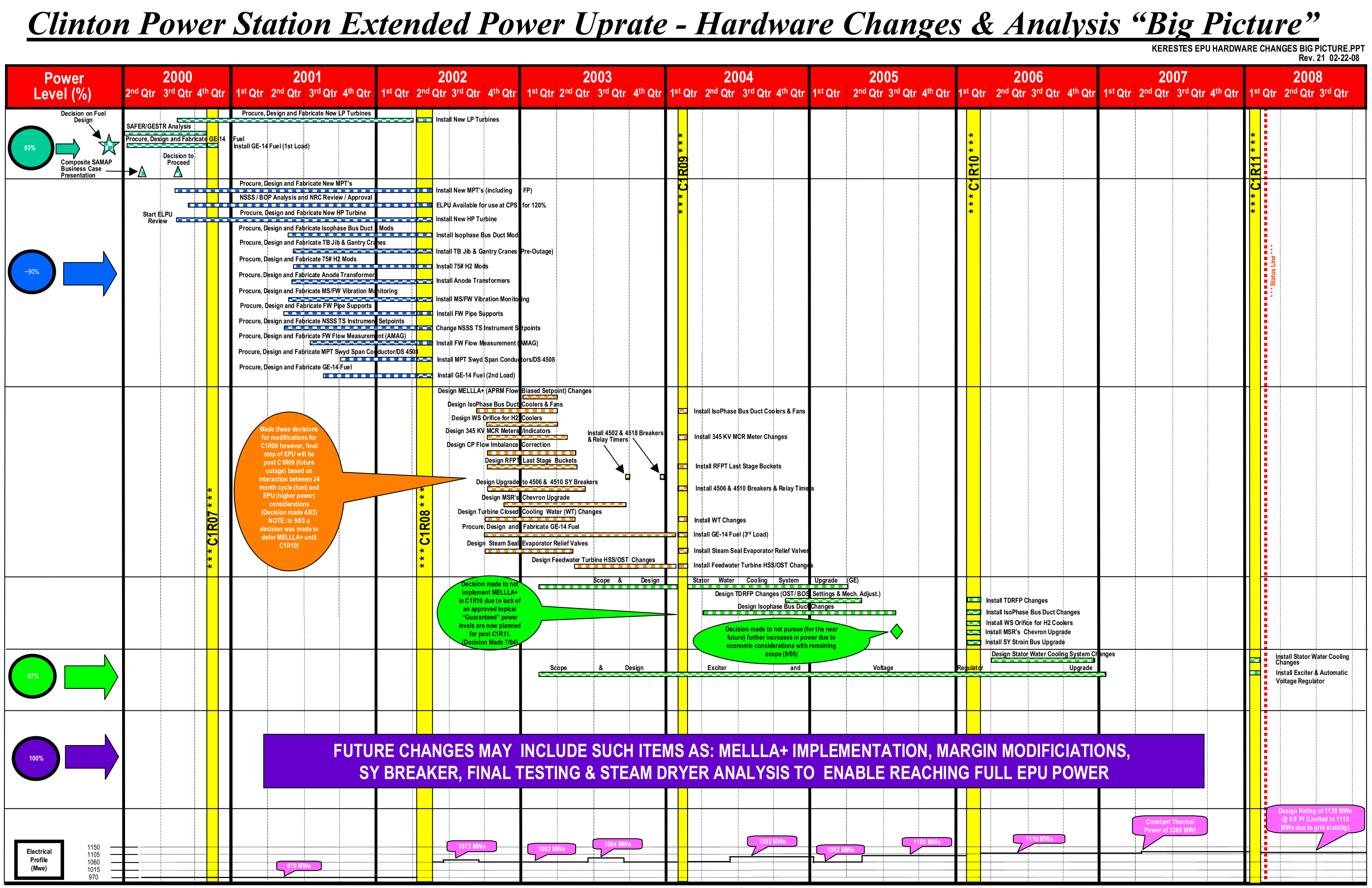


FIG. I.2. Clinton Power Station extended power uprate — hardware changes and analysis.

wheels and axial keyways; to new mono-block rotors that eliminated wheel key way and dovetail stress corrosion cracking concerns. The HP rotor is also of the mono-block variety. This change replaced a number of components within the turbine generator complex as identified in task report 700. The engineering evaluations to support these changes to the Clinton turbine were the scope of GE. This activity modifies the Clinton HP and LP turbines such that this equipment is capable of operating at the rated power levels.

NSSS tech spec instrument set point changes

This change modified the tech spec. allowable values (AVs) for the NSSS instrument set points as well as the instrument set point analytical limits (ALs). These modifications incorporated the changes, ALs, AVs and nominal trip set points (NTSP), into the design documents.

The scope of this DCP consisted of the following changes for division 1, 2, 3 and 4:

(1) Average power range monitor (APRM) flow biased STP high scram and APRM flow biased STP rod block (Two loop operation (TLO) and single loop operation (SLO);
(Note: The APRM flow biased set points needed to be revised since the flow changes with power.)
(2) Turbine first stage pressure scram bypass permissive;
(3) Low power set point rod control block (LPSP);
(4) High power set point rod control interlock (HPSP);
(5) Main steam line high flow group 1 isolation.

Main generator hydrogen cooler upgrade and pressure increase

This change replaced the existing four generator hydrogen coolers with new units in accordance with the recommendations of EPU task report T0700. General Electric designed and supplied the new coolers, which required an increase in service water (WS) flow from 3000 gal/min to about 3053 gal/min. This change also implemented an increase in the operating pressure of the generator hydrogen system. The hydrogen operating pressure was also increased by 15 psi, to 75 psig as recommended by GE in task report T0700.

Alterrex anode transformer upgrade

This change replaced the three-phase anode transformers with larger units (42.7 KVA) in order to operate the controls and rectifiers at the higher excitation field currently required for EPU. The ALTERREX excitation system controls the voltage (or reactive volt-amperes) of the main generator by controlling its excitation. The input for the silicon controlled rectifiers (SCRs) is taken from the exciter output through the anode transformer, providing a source voltage that will allow the SCR circuit to provide a controlled DC voltage for the exciter field.

Feedwater support changes

This change modified various supports as a result of an analytical assessment in support of EPU, which resulted in increases in both feedwater temperature and feedwater flow rate.

Calculation IP-M-0652, Rev. 0 evaluated the impact of these parameter changes on pipe support loading. The increase in temperature affects thermal expansion loads, and the increase in flow rate affects the feedwater pump trip transient loads. The impact of these parameter changes was that for the 77 supports on feedwater subsystems 1FW03A, 1FW03B and 1FW03C, five supports required modification as the increased loads following EPU implementation would otherwise have exceeded the capacity of the support(s). The following changes were required.

Subsystem no.	Support no.	Description of change
1FW03B	1FW03035S	Replace snubber
1FW03C	1FW03052X	Add plate between rear end bracket and embed plate
1FW03C	1FW03064X	Add plate between rear end bracket and embed plate
1FW03C	1FW03070X	Add kicker and embed plate
1FW03C	1FW03097S	Replace snubber

Startup testing vibration monitors

This change installed vibration monitoring equipment in the plant to monitor piping systems for the effects of the higher flow rates resulting from EPU. Implementation of EPU significantly increased flow rates in the main steam and feedwater piping. General Electric (GE) prepared project task report T0316 (GE-NE-A22-00110-21-01) to assess the effects of the increased flow rates on flow-induced vibration. The GE task report concluded that main steam and feedwater piping vibration levels could increase by at least 48% as a result of EPU from those levels corresponding to currently licensed thermal power. The GE task report recommended that a vibration-monitoring programme be implemented to show that the main steam and feedwater piping vibrations are acceptable at EPU operating conditions. Since EPU was implemented in two stages, the changes from this modification remained in place until after full power implementation was achieved.

The four main steam lines inside containment from the reactor vessel nozzles to the penetrations and outside containment from the penetrations to the turbine were monitored for steady state vibration. The two feedwater loops inside containment from the reactor vessel nozzles to the penetrations and outside containment from the penetrations to the feedwater pumps were also monitored for steady state vibration. The main steam and feedwater piping that was monitored is considered to be inaccessible, and therefore, as discussed in GE task report T0316, remote vibration monitoring was required.

The approach to obtaining the vibration measurements was to use LVDT transducers that were hardwired to a remote, stand-alone digital data acquisition system (DAS) that was located outside the containment. The DAS consisted of a self-contained microprocessor-based unit that performed the analog-to-digital conversion, provided transducer signal conditioning, and stored the collected data. A PC was also located on the DAS table and connected to the DAS. The PC contained software used to control the data acquisition process, monitor the live piping vibrations and review stored vibration data. Data stored in the DAS was downloaded to the DAS PC.

Reactor feedpumps low suction pressure alarm set point revision

CPS has three reactor feedpumps. Two of these are turbine driven reactor feedwater pumps (TDRFPs) and one is a motor driven reactor feedwater pump (MDRFP). Each of these RFPs requires a minimum suction header pressure to prevent cavitation, which could result in possible pump and downstream pipe damage. This change revised the reactor feed pump (RFP) low suction header pressure alarm and trip set points, and rescaled the RFP suction header temperature transmitter. These changes were made as a result of EPU task T0701.

The RFP suction header pressure alarm set point was lowered from 400 psig to 375 psig while the suction header pressure alarm set point was increased from 290 psig to 320 psig as per revised calculations shown in CPS calc MAD-88-0175. The TDRFP suction temperature also increased due to implementation of EPU. This resulted in the need to rescale the RFP suction header temperature transmitter to a higher range due to increased heat. In order to bound this increased temperature range, this modification rescaled the RFP suction header temperature transmitter from 60–390°F to 60–410° F. The scaling for the corresponding computer point 1FW-BA200 for RFP suction header temperature was changed to reflect this.

I.5. STEP 2 CHANGES — INTERIM POWER UPRATE (IPU) (IMPLEMENTED DURING C1R09 — FEBRUARY 2004)

Isolated phase bus duct cooling (Phase 2)

This change replaced the isolated bus duct coolers 1MP01AA and 1MP01AB with larger capacity coolers. The purpose here was to restore redundant cooling capacity of the IPBC cooling system at EPU conditions. This resulted in replacing the IPB coolers with much larger bus duct coolers and also with larger capacity fans and coils to support the additional cooling requirements. The new fan/coil cabinet units consisted of redundant 100% capacity coils, fans, and motors. Each new fan was designed to supply 32 000 CFM. Each new coil was designed to remove 1.473 MBTUH with 200 gal/min of water supply. Each new motor is 125 Hp. In addition, redundant air temperature and flow switches were added. Instrument set points associated with the IPBD coolers were revised along with the turbine building closed cooling water (WT) HX outlet header alarm.

Switchyard breaker replacements

This change replaced the subject breakers, their bushings and the current transformers (CTs) in the switchyard as a result of an EPU. The new breakers have a rating of 3000 amps and were replaced to ensure that the power output of 1138 MW(e) and 1265 MVA could be reliably delivered to the grid. The breakers in the 345 KV switchyard were additionally very expensive to maintain both in terms of time and money. These breakers were no longer fully supported by the vendor and obsolescence was an issue with these breakers.

The switchyard is owned and maintained by Ameren with the Clinton Power Station, and they are responsible for maintaining the 345 kV switchyard main generator circuit breakers 4506 and 4510. There were two additional breakers replaced as part of EPU (4502 and 4518) however, these two breakers did not interface directly with CPS, and thus they were replaced under Ameren internal design control, and no ECs were issued by CPS.

Reactor feedpump turbine last stage bucket upgrade

This change upgraded the material in the seventh or last stage bucket and diaphragms of the unit #1A and #1B reactor feed pump turbines. The buckets and diaphragm were replaced based on the GE study entitled, Turbine-Generator Evaluation Study ~115% Core Thermal Power Extended Power Uprate as part of the EPU study. CPS had imposed a steady state limit of 5200 rev./min on the turbines until this change was implemented. Increasing power output to 1138 MW(e) results in the turbine speed nearing this RPM level. In addition, GE technical information letter (TIL) #1206-3, Impact of Modern Design Methods on Calculated Mechanical Stresses on Reactor Feed Pump Turbines discusses this also. In addition to the bucket and diaphragm change out, the coupling on the turbine was replaced with a new coupling, half with tighter heat-shrink tolerances. A relief groove was machined on the turbine shaft, and the keyway area was shotpeened for stress relief. This change is recommended by GE report (TIL) 1129-3.

Turbine building closed cooling water upgrade

This change replaced the existing turbine building closed cooling water (TBCCW) pumps (1WT01PA and 1WT01PB) with pumps of the same model number (Goulds Model 3405M) and the same materials of construction, with the difference being that the impeller diameter was increased from 16 1/8 in to 17 in. This change increased the design flow rates by approximately 10 gal/min from 1034 gal/min. In order to accommodate the increased horsepower requirements resulting from the increased impeller size, the motors were also replaced with 100 horsepower motors. The larger size motor required a change to the breaker settings while the power feed cables did not need to be changed.

Feedwater pump turbine high speed stop/over-speed trip set point

These changes modified the high-speed stop and the over-speed trip settings for the unit 1A reactor feed pump (RFP) turbine, ETN 1FW01KA and the unit 1B reactor feed pump (RFP) turbine, ETN 1FW01KB. The high-speed stop (HSS) and the over-speed trip were changed based on a GE evaluation entitled Engineering Evaluation of Reactor Feedwater Pump Turbines per TIL 1206–3, Impact of Modern Design Methods on Calculated Mechanical Stresses on Reactor Feed Pump Turbines, Revision 2, dated 31 March 2003. GE recommended these modifications to meet current GE new unit design criteria. The existing trip assembly (for the over-speed trip) for both “A” and “B” FWT was removed and sent to the factory for readjustment to the new over-speed trip set point. Associated with the changes to the HSS and the over-speed trip settings, the over-speed stop setting (OSS) and the backup over-speed device setting were also changed.

The high-speed stop (HSS) settings for the “A” and “B” feedpumps were changed from 5457 rpm to 5570 (±1%) rev./min. The low-speed stop setting was not affected. The over-speed stop (OSS) settings for the “A” and “B” feedpumps were changed from 6.04 VDC to 6.29 VDC (6290 rev./min). The over-speed test (backup over-speed device) trip setting for the “A” and “B” feedpumps was changed from 5617 to 5700 rev./min.

I.6. STEP 2 CHANGES — INTERIM POWER UPRATE (IPU) (IMPLEMENTED DURING C1R10 — FEBRUARY 2006)

Moisture separator reheater Chevron upgrade

This change upgraded the moisture separator reheaters (MSR) 1TG01AA and 1TG01AB by removing the existing chevrons and replacing them with new chevrons of higher efficiency. This involved reconstruction of the MSR to install high-performance Chevron vanes as designed by Thermal Engineering International (TEI). This allowed the MSR to handle increased flow of steam from the HP turbine, while increasing the efficiency for moisture removal as part of the extended power uprate programme (EPU). This upgrade will improve the moisture removal efficiency to approximately 95%. As a result of this modification, more and dryer steam is being sent to the low-pressure turbine, and the condensate flow through the heater drain system will be increased.

Feedwater pump turbine high-speed stop/over-speed trip set point

This change revised the over-speed trip settings for the unit 1 reactor feed pump (RFP) turbines, ETN 1FW01KA and 1FW01KB, and made mechanical adjustments to valve linkages for the control valves of these turbines.

As part of the EPU changes during C1R09, the high-speed stop (HSS) and the over-speed trips were modified in EC 342321/342322 based on the GE evaluation entitled, “Engineering Evaluation of Reactor Feedwater Pump Turbines per TIL 1206-3 “Impact of Modern Design Methods on Calculated Mechanical Stresses on Reactor Feed Pump Turbines”, Revision 2, dated 31 March 2003. GE recommended the above modifications to meet current GE new unit design criteria. Associated with the changes to the HSS and the over-speed trip settings, the over-speed stop setting (OSS) and the backup over-speed device setting were also changed. As part of this modification, the over-speed trip set point (OST) was changed from 5870 rev./min for 1FW01KA and 5960 rev./min for 1FW01KB to the new range of 6011–6132 rev./min per guidance from GE.

I.7. STEP 2 CHANGES — INTERIM POWER UPRATE (IPU) (IMPLEMENTED DURING C1R11 — FEBRUARY 2008)

Main generator exciter upgrade

This change replaced the main exciter and modified various support areas (systems) to re-rate the main generator to a rating of 1265 MVA/0.9 PF, 1138 MW(e). These changes are needed to support the next phase of the EPU.

The following physical changes were made:

- The AC and DC bus duct within the exciter “doghouse” were altered;
- Piping changes, including cooling water supply, lube oil and drain lines;

— Modification of the rectifier panel doors;
— Installation of new equipment anchors for the collector pedestal;
— Replacement of meter dial banding;
— Replacement of the main generator nameplate.

Automatic voltage regulator replacement

This change replaced the exciter automatic voltage regulator (AVR) in support of the next phase of EPU. The following major changes were made as part of this modification:

— The existing GE exciter voltage regulator cabinet 1MP05S was replaced with a new ABB AVR;
— Two 480 V AC feeds for AVR power from adjacent MCCs 1AP56E (TB MCC 1I) and 1AP57E (TB MCC 1J) were added;
— A second three-phase PT input source from existing generator PTs was added;
— A second three-phase CT input source from existing generator CTs was added, and the present generator CT input source from single-phase was changed to three-phase;
— Existing cables and conduit was removed, and larger conduit was installed and additionally a new 350 kcmil cable for the main field discharge circuit was pulled;
— The main generator field instrumentation cables were replaced with 1 kV rated cables;
— Changes were made to the 1H13-P680-09C exciter control pushbuttons for interface with the AVR control system.

Stator water cooling system upgrade

This change upgraded and replaced stator water cooling system components and revised GC system instrumentation set points and rebalanced WS flow requirements to support EPU operations at the uprated generator level of 1264.777 MVA, 0.9 power. This EC also replaced the WS GC cooler inlet valves 1WS008A/B, which were replaced to provide a tighter shutoff to the GC cooler.

Appendix II

EXECUTION OF THE POWER UPRATE ON UNITS 1–4 OF THE PAKS NUCLEAR POWER PLANT, HUNGARY

II.1. INTRODUCTION

The Paks Nuclear Power Plant used to be viewed as the cheapest power plant in the Hungarian power generation market in terms of electric power generation costs. With Hungary joining the EU and the liberalization of the markets, the Paks NPP will have to comply with new market challenges in the future. The NPP will have to be competitive not only domestically, but also with the other European power plants. In order to achieve this, the company set forth the target of decreasing production costs, and one element of this is the execution of the power uprate. Taking into account the high load factor, the power plant is intending to achieve the power uprate by increasing the reactor power.

II.2. JUSTIFICATION OF THE FEASIBILITY

Following the commissioning of the Paks NPP units in the mid-1990s, a re-evaluation of their safety was performed, resulting in the decision to implement a number of modifications affecting the technology of the power plant units (safety uprate measures). The purpose of this series of measures was to increase the safety level of the units to match or even exceed the safety levels of western PWRs of similar age. Furthermore, the turbines were reconstructed, and a number of modifications in the secondary circuit were made, mainly to increase efficiency.

Following these modifications, the Paks NPP started to consider a potential power uprate, taking into account economic issues.

In order to further explore the possibilities of a power uprate, the Nuclear Power Research Institute of the Central Research Institute of Physics (KFKI-AEKI) performed a feasibility study, which was completed in December 2001.

The study reviewed the potential methods for the power uprate, effects thereof on the power plant systems and bottlenecks. It also provided recommendations for the power uprate programme.

The study stated that:

- In the Paks NPP, the execution of the power uprate is possible without major modifications;
- The margins of the power uprate are strongly limited with the presently used fuel assemblies, and a significant (more than 3–4%) power uprate is achievable only with a new fuel type;
- Further development of the fuel provides the possibility to increase the power to 108%;
- It is possible to increase the thermal power of the reactor without significant decrease of the safety margins;
- The secondary circuit systems are capable of handling the increased steam and water flow rates without essential modifications. The conduction of the surplus steam is possible even if the primary circuit capacity increases by 8%, in the case that the inlet wheel of the turbines will be replaced.

Following completion of the feasibility study, the power uprate concept was updated at the company level, within which the finalization of the modifications necessary for the power uprate and the elaboration of the execution schedule were incorporated. With the aim of realization of the two main strategic targets of the company, the lifetime extension and power uprate projects were launched.

In accordance with the set-up targets, the activities of the power uprate project and of the lifetime extension project shall be harmonized, and the performance of the power uprate shall not be an obstacle to or a negative influence on the execution of the LTE project. In this regard, the Electric Power Research Institute (VEIKI Rt) has prepared an analysis titled “Effect of power uprate of the power plant on the ageing processes of the main equipment of the units.” It was stated in the analysis that the planned extension of the operational lifetime of the Paks NPP by a maximum of 20 years is not significantly influenced by the surplus ageing effects arising from the circumstances changed due to the planned power uprate option. The postulated effects due to the power uprate might be securely minimized by means of the ageing management measures already completed, those in the process of being completed and those to be carried out in the future.

II.3. LICENSING ISSUES

Nuclear licensing

The authority procedures and licensing criteria are set forth in the Nuclear Safety Regulations. There were no licensing procedures for complex modifications similar to a power uprate in the Hungarian practice, therefore, the power plant elaborated the approach for the process of licensing based on consultations with the authorities. As agreed with the authorities, the licensing will be performed in several steps. The licensing of the modified fuel and of all necessary modifications will be performed in separate procedures, and the licensing of power uprate will be started by a facility level principal modification licensing applicable to Units 1 to 4. Afterwards, individual modification licenses will have to be applied for in the case of every unit prior to the power uprate.

Following completion of the power uprate, it will be necessary to apply for an operational license.

The following special authorities will participate in the procedures: the Lower-Danubian Environmental Protection and Water Inspectorate (ADvKTVF) and the Hungarian National Public Health and Medical Officer Service (ÁNTSZ OTH).

Following completion of the power uprate programme, it will be necessary to request the modification of the operational license from the Hungarian Power Authority (MEH).

The Paks NPP submitted the application for the principal modification to the authorities in May 2005, the procedure lasted six months, and the Nuclear Safety Directorate of the Hungarian Atomic Energy Agency (OAH NBI) issued the license in late November 2005.

The licensing of the fuel was completed, and the first charge was loaded in on Unit 4 in 2005. The application for the modification license related to the power uprate of Unit 4 was submitted to the authorities in early 2006. The licensing of the modifications necessary for the power uprate of Unit 4 is in progress.

Water utilization licensing

In order to achieve the power uprate, the water utilization licensing procedure shall be completed as well. During the water utilization licensing procedure, the power plant will have to demonstrate how the power uprate will impact the water utilization from the Danube river and the heat loading thereof. The procedure was started by obtaining the principal water utilization license. Within the licensing documentation, it was demonstrated that the limits applicable to the present water utilization from the Danube river will stay in force following the completion of the power uprate, and furthermore that there is no need for water management investments in connection with the power uprate or for modification of the system assuring the cooling of water. On the basis of the justification documentation, the water management authorities declared that there was no need for obtaining an execution license for the power uprate, and thus the water utilization licensing procedure was deemed as completed.

II.4. MODIFICATIONS NECESSARY FOR THE POWER UPRATE

The actual feasibility of an increase of the nominal power (i.e. reactor power) is determined by the characteristics of the core fuel load. The maximum potential power is determined by the actual values of the characteristics — subchannel outlet temperature, pin-wise power and linear pin-wise power — compared to the local limits. In the feasibility study, these characteristics were investigated, and it was determined that the critical parameter regarding the increased power level is the outlet temperature from the subchannel.

Thus, the most important issue is how we are able to ensure the margins related to the increased nominal power level in case of a given subchannel outlet temperature. Sources for exemption of the reserves are as follows:

Introduction of the new fuel type

The uprate of the power is possible by utilizing modernized fuel assemblies. The fuel development is performed in two phases.

In the first phase of development, the purpose of the planned, small scale modification of the fuel is to make the operation of the fuel assemblies more secure. In the course of introducing the modified fuel assemblies, the presently valid pin-wise and subchannel-wise limits will not change, while the allowed power level of the fuel assemblies will be slightly increased.

The pin grid distance is increased from 12.2 mm to 12.3 mm, enabling a more even subchannel outlet temperature distribution. The present geometry of the fuel assemblies is not optimal from this point of view; the outer pin row is cooled by a relatively large water volume, while the inner pins are cooled by a smaller amount of water. The increase of the pin grid distance by 0.1 mm will effectively achieve the more even subchannel outlet temperature distribution.

The use of the welded-on hafnium absorption plate in the upper section of the follower fuel assembly will practically cease by means of neutron absorption of hafnium and the power peak, arising in the outer fuel pins of the fuel assemblies located next to the follower assemblies, allowing for a more even distribution of the axial neutron flux and of the power.

The modified fuel assemblies might be utilized together at the present nominal power level, resulting in a flatter axial distribution of the neutron flux and a radial distribution of the outlet temperature.

The introduction of the modified fuel is sufficient to reach the 108% reactor power level, however this alone would not achieve optimum fuel efficiency. In fact, by using this type of fuel at the increased power level, the specific fuel use would be worse by 4–5%.

The second phase of development is the optimization of fuel efficiency as a result of the further development of the fuel, enabling operation at the increased power level with optimum fuel utilization. To achieve this, the enrichment shall be increased and the burning of poisons shall be used as well. This fuel is called (for reactor power of 108%) optimized fuel. By using this type of fuel, it will be possible to introduce a more efficient five-year fuel cycle. This power uprate programme will be completed by introducing the optimized fuel, which alone will not result in further power uprate, but will improve the specific fuel utilization.

Modernization of the primary circuit pressure regulation and resulting improvement of pressure maintenance in the primary circuit

In the original condition of the core control system limits, a constant 325°C saturation temperature value was taken into consideration, which corresponds to a pressure value of 120.6 bar (absolute). According to the technical specifications, 7.5°C of uncertainty shall be taken into account at the maximum subchannel outlet temperature. According to the operational experiences on the units, the primary circuit pressure varied from 123 to 121 bar (overpressure).

In comparison to the pressure corresponding to the saturation temperature in the core control system, there is a temperature margin (1.2°C) corresponding to approx. 2 bar. This margin might be used without function degradation of the core control system in such a way that the core control system will treat as the saturation temperature not the constant value of 325°C, but rather the actual value of the pressure measurement gained from the new, reliable and more precise primary circuit pressure measurement system installed as a part of the reactor protection system.

As a result of the power uprate, the outlet temperature of the core will increase more or less proportionally to the value of the power increase. This means it will get closer to the saturation temperature, however, if the primary circuit pressure regulation system is capable of ensuring the more fine pressure maintenance of the primary circuit (will not get closer to the presently experienced lower primary circuit pressure value), the saturation margin might be even greater. The modification of the instrumentation and control (I&C) system of the pressure regulation shall then be performed, the aim of which will be to keep the value of the primary circuit pressure within a narrower uncertainty range.

The modification of the primary circuit pressure regulation means the complete replacement of the regulation system and will not cover the intervention systems. The principle of regulation will also be modified; instead of position-based regulation, continuous regulation will be applied. As an outcome of the modification, the pressure within the pressure chamber of the pressurizer under normal operational conditions will be kept at an overpressure level of 123.0 ± 0.4 bar. The pressure over the active core in accordance with the hydrostatic conditions will be 123.6 ± 0.4 bar at the nominal level of the pressurizer.

Reconstruction of the core control system and updating of its algorithms

The upgraded system will be able to serve the reactor power uprating requirements as well as the planned lifetime extension. Major objectives of the uprate project were the follows:

- Replacement of the present hardware and local area network architecture and devices;
- Full software modernization and porting to Windows;
- Partial uprate of the in-core data acquisition computers;
- Development of a new version of the reactor physics calculation modules;
- Modernization of the man–machine interfaces.

The new system contains professional HP Proliant DL585 servers running the Windows 2003 server operating system. The man–machine interface is realized on powerful Windows XP workstations with 19 in TFT monitors. The MS SQL Server 2000 relational database is used for storing data and as a long term data archive.

One of the main developments was the introduction of a distributed architecture; the original, dual-redundant host configuration was changed to a divided and dual-redundant (2+2) server configuration. The software was split into two major parts; the reactor physics calculation system was fully separated and moved to a powerful Windows 2003 server. The rest of the software (i.e. data communication and standard processing, data storage) was extended and fully recoded to be able to run under Windows 2003.

The primary function of VERONA is to provide continuous core surveillance with a two second cycle time (actually 349 × 20 × 72 core nodes are treated in the core calculations). The modifications in the reactor physics calculations focused on increasing the accuracy of off-line and on-line core calculations, and the main targets were as follows:

- Integration of the standard Paks core design programme (C-PORCA code) into the VERONA system and run it on-line (with five-minute cycle times);
- Modification of off-line and on-line core calculation modules in order to handle the new fuel (designed for the increased 108% reactor power) accurately and reliably;
- Modification of the subchannel outlet temperature calculation module by applying a new model based on a validated thermohydraulic code (this is needed to achieve a more accurate handling of coolant mixing between subchannels).

The new architecture and high-speed network made the introduction of a new form of reactor physics analysis possible. The Paks NPP Reactor Physics Department will make use of a so-called expert system (VERONA-e) consisting of dedicated workstations running local core analysis programmes. On-line and archive process data can be transferred to these computers via the network, and experts can perform their own core calculations locally. The expert system can be used for testing new models, to perform special core calculations and for report generation. These workstations can host additional software modules (i.e. modules that are not present in the unit configuration) for performing other important tasks such as long term trend monitoring and statistical analysis of in-core measurements (for signal validation purposes), and application of a detailed core hydraulic model for core anomaly interpretation. It is believed that this new, open system architecture combined with built-in data server functions will support reactor physics experts to a great extent by providing convenient tools for off-line analysis.

Change of the parameters of the hydro-accumulators — Instead of 58 bar and 40 m^3 of stored cooling water, 35 bar and 50 m^3 of cooling media

Due to the new parameters of the large cross-section ruptures, which are deemed to be critical in the maximum design basis accident, the highest cladding temperature of the increased power will be lower than the present value, thus having a favourable effect on the cladding oxidation as well. Furthermore, the integrated mass volume and energy escaping through the rupture — during the time period when there is overpressure within the containment — is lower in the case of 108% reactor power than 100% reactor power. In other words, the maximum pressure that will be generated within the containment as well as the activity values released to the environment will be more favourable.

Changes of the minimum boric acid concentration of the emergency systems

The cores characterized with identical cycle length will have more reactivity reserve, and this might be during the early phase of the campaign bonded only by a higher concentration of boric acid. The value of the maximum critical boric acid concentration will be increased to 12 g/kg, while the shutdown period boric acid concentration will increase from 12 g/kg to 13.5 g/kg, and the minimum boric acid concentration of the emergency system will be increased to 13.5 g/kg.

Replacement of the turbine nozzle crown

Due to the increase of the fresh steam mass flow, the flow-through capability of the turbine shall be increased, constituting a necessary implementation of an inlet wheel with a bigger cross-section.

Increase of the flow rate assured by the main cooling pumps on Unit 2

At the present time on the units, the primary circuit flow rates assured by the MCPs are deviating from each other. Regarding the operational security of the core, the subchannel outlet temperature is a limiting factor, and furthermore, the power uprate will cause the outlet temperature of the core to further increase. As this temperature depends on the primary circuit flow rate, it is reasonable to increase the flow rate of the unit with the lowest flow rate. We intend to achieve an increased flow rate by replacing the impellers.

The original designer, who is also the manufacturer of the prototype, will deliver the impeller manufactured in accordance with a new technology, containing dimensions based on the original impeller and adjusted to the desired characteristics. The other purpose for installing the modernized, forged and welded impellers is that because of the improved manufacturing quality, the operational security will also be increased. In the case of forged and welded construction, the defects characteristic for impellers manufactured by casting are not present — the pores, the shrink holes and shrink cracks.

II.5. SAFETY EVALUATION OF POWER UPRATE

Due to the increase of the nominal power to 108%, in the majority of the emergency situations investigated in the FSAR, the critical parameters will likely be closer to the limit values determined as acceptance criteria. Therefore, the calculations related to the FSAR will be repeated. The purpose was to investigate to what degree these changes were within the design basis emergency conditions of the power plant, while on the other hand to investigate whether the new values are still in compliance with the acceptance criteria.

Within the calculations, the modifications necessary for the power uprate were already taken into account.

Within the analysis, the justification of the set values of the reactor protection signals was investigated, and in the course of the surveillance, one of the main targets was to modify the set values only in those cases where it was really justified. Accordingly, all the ECCS signals and interlocks will be operated with unmodified set values even after the power uprate, and the appropriateness of these was justified by means of the performed emergency analysis. The signals of the reactor protection system were modified in a minimum range.

The effect of the power uprate was evaluated in such a manner that on the basis of the new analysis results, it was checked whether the key parameters (DNBR, fuel temperature and enthalpy, pressure in the primary and secondary circuits, the cladding temperature and oxidation, loads of the containment, releases) got closer to the allowable limit values.

The results of the analyses have proven unambiguously that the power uprate can by no means lead to violation of the acceptance criteria. Thus, neither an exceeding of the limits, nor a significant decrease of the margins available to the limits are anticipated, and the power uprate will by no means lead to violation of the acceptance criteria.

Beyond recalculation of the design basis emergency cases, the effect of the planned power uprate on the safety of the Paks NPP units was investigated by means first-level probabilistic safety analyses and evaluated in a quantitative manner. Considering the postulated power uprate, the frequency of the core damage for nominal power operation, taking into account the effects of all the related modifications, will be 1.09×10^{-5}/year. The value constitutes a 1.4 % (i.e. 1.56×10^{-7}/year) increase in comparison to the present reference PSA result value, which does not incorporate the power uprate. The value of the increase is negligible both in absolute and in relative terms.

II.6. EXECUTION SCHEDULE

The scheduling of execution is determined by the deadline for introduction of the new fuel, by the licensing procedure and by the performance of the modifications linked to the long outages. Furthermore, this schedule is influenced by the situation that arose following the Unit 2 emergency, which occurred on 12 April 2003, and elimination of the consequences of the incident.

Taking into account what has been written so far, the power uprate might be performed in the following way:

- Unit 1: in 2007 103%, in 2008 108%;
- Unit 2: in 2008 103%, in 2009 108%;
- Unit 3: in 2008 103%, in 2009 108%;
- Unit 4: in 2006 104%, then 108%.

Appendix III

IMPLEMENTATION OF THE EXTENDED POWER UPRATE AT THE LEIBSTADT NPP, SWITZERLAND

III.1. INTRODUCTION

The Leibstadt NPP is a BWR/6 238–648 with a Mark III containment. It started commercial operation in December 1984 at a licensed reactor thermal power of 3012 MW. In 1985, the first power uprate (stretch type) to 3138 MW (+4.2%) was implemented, which was already considered in the original licensing analyses. In 1990, the decision for further uprating was taken. Feasibility studies of the turbine island show a possible range of 10 to 15%. It was decided to go for a license of the maximal possible level and to use it as far as it is economically achievable. A round number of 3600 MW reactor thermal power was defined. In 1992, the first EPU license documentation was submitted to the authorities. The implementation of the power uprate started in 1998 with an initial 6% step. The final stage of the extended power uprate was successfully reached in September 2002 at a reactor thermal power rate of 3600 MW.

Further uprates of reactor thermal power will be possible with extended (and expensive) modifications of ECCS and turbine island systems, including power transmission to the grid. An increase of electrical output is still possible by implementing turbines with higher efficiency and improving the “cold end” (main cooling system, including main condenser and cooling tower).

This report gives an overview of:

- Project organization;
- Major licensing items;
- Major plant modifications;
- History of the EPU implementation;
- Test programme and results;
- Warranty measurements;
- Inspection programmes;
- Six years of experience at EPU conditions;
- Lesson learned.

III.2. PLANT DESCRIPTION

The Leibstadt NPP is a GE BWR/6 238-648 with a Mark III containment. It started commercial operation on 15 December 1984 at a reactor power level of 3012 MW. General Electric was the supplier of the nuclear island and Asea Brown Boveri the supplier of the turbine island. The core design consists of 648 fuel elements and 149 control rods. The main steam energy is converted by 1 HP and 3 LP turbines at 3000 RPM; the condenser heat is rejected by a natural draft cooling tower. Since 2002, KKL is operating at 3600 MW of reactor power with a gross electric power rate of 1220 MW and a net electric power rate of 1165 MW.

III.3. PROJECT ORGANIZATION

The project organization on the vendor side consists of a GE (nuclear island) and ABB (turbine island) project organization, each responsible for their specific areas. On the KKL side, there were only a small number of engineers handling the technical items, project management and the liaison work with the authorities. Most of these engineers were also involved in plant operations and technical support.

The advantage of a aproject organization such as this is that knowledgeable people with specific plant technical and organizational expertise provide a strong link between the vendors groups, the plant personnel and the authorities. The disadvantage is the heavy workload, which can lead to the personnel missing some important issues. A balanced distribution between people assigned solely to the project and people supporting the operation should be targeted in order to cover all plant-specific issues.

III.4. PRINCIPLES FOR POWER UPRATING

At the beginning of the EPU project, the KKL staff agreed on the following principles for uprating. The highest priority is that all safety criteria be fulfilled with conservative enough margins, and that the ALARA principles be considered. Further on, there should be no negative impact on the already existing high plant reliability. More challenging was the principle of providing efficiency and operational flexibility while maintaining an economic approach with low costs. Some reduction in plant life seemed to be acceptable, but it should be limited to a controllable extent. These agreements provided a baseline of clear principles, which saved many discussions during the project.

III.5. MAJOR LICENSING ITEMS

There is a good report already available about the licensing aspects at KKL written by the authority [1], therefore the following is provided as a summary.

Emergency cooling

KKL had the advantage that the emergency cooling systems (ECCS) were designed according to the large vessel size and therefore for higher reactor power. In addition, there was a special emergency heat removal (SEHR) system built at KKL on request of the authority during the construction phase. With this addition, KKL has to this day a sound technical concept as proved by PSA. Licensing analysis of design basis accidents was not a problem.

Fuel

KKL followed the fuel development from GE 8 × 8 to SVEA 10 × 10 elements. Together with progressive fuel analysis, licensing was not a problem. The higher reactor thermal power was delivered by a broader radial power distribution. Only a few bundles showed a controlled higher heat generation than before.

KKL uses Zn injection for dose rate reduction at the recirculation system inside the drywell. Because of a very low Fe fraction in the reactor water, KKL experienced some enhanced shadow corrosion below the fuel spacers in 1996. The clarification of that effect delayed the granting of the power uprate license by the authorities for two years.

Stability

Stability is an issue for BWRs and is effected by a power uprate. Therefore, several actions were taken to avoid the occurrence of instability. The exclusion regions in the power flow map were extended to maintain the existing margins to instability. Automatically or manually selected rod insertion (SRI) was built in for rapid power reduction, especially to leave the exclusion regions. A core stability monitoring system (COSMOS) was added to indicate an upcoming instability situation. There are no automatic actions for stability events.

PSA

The regulatory body requested a state of the art PSA level 1 and level 2. At that time, PSA methods and knowledge had just emerged, and developing new analyses was the hardest issue. The studies for PSA level 2 were used to establish an interactive core melt simulator based on the MELCOR code and the KKL plant configuration, including logics. This tool provides useful insights into severe accident management issues, which were used to adopt SAMG procedures accordingly.

ATWS

For EPU, ATWS was a concern for the authorities. KKL decided not to install an automatic boronation initiation because there was appropriate time (more than five minutes) for operator actions. The plant capability to cope with an anticipated transient without scram (ATWS) was improved by installing an automatic feedwater pump runback initiated by an ATWS alarm. This reduces the water level and power level, thereby providing additional time of up to 10 minutes for the operator to start the boronation system. In addition, an inhibition of automatic depressurization (ADS) as a precondition for the start of low pressure emergency cooling systems was built in to avoid dilution of the boron.

III.6. MAJOR PLANT MODIFICATIONS

Reactor pressure

KKL decided to keep the reactor pressure at the same level and raised only the steam mass flow to the turbine. There was more than one reason for that. KKL already operated at a high reactor pressure for BWR (73.1 bar). The effort to raise that pressure would have been determined by a new design analysis of the pressure boundary and a new adjustment of the set points of the SRVs, losing the ability to adjust the SRV with nitrogen in a test facility at KKL. There was a substantial amount of money and unknown follow-ups to be expected. On the other hand, KKL had to change all of its turbines, and therefore keeping the reactor pressure meant only some minor adjustments for the turbine supplier.

Turbine building

The major plant modifications were in the turbine island mostly due to higher mass flows of steam and condensate not only during normal operation but also during operational and emergency transients. All turbines were replaced with remarkable efficiency. For normal operation and transients, the turbine control valves and bypass valves were enlarged. The drain and condensate pumps were enlarged. The feedwater pumps had a higher than necessary capacity and proved to be sufficient for transients with some small margin. The generator switches and power connectors were improved, and the generator and transformers had an acceptable margin according to the responsible engineers.

III.7. HISTORY OF THE IMPLEMENTATION OF THE EPU

The history is shown in Fig. III.1, where all milestones according to thermal and electrical power are shown. In 1994, it started with the replacement of all three LP turbines, which resulted in plus 45 MW of generator power. In 1996, the license was expected for a power uprate. Therefore, a new HP turbine and larger control and bypass valves were built in. Because the license was not granted until 1998, two years of operation were only at partial load, resulting in a loss of efficiency. The start of the EPU was in October 1998, with an initial 6% step done in three 2% steps over a three-day period. It was agreed with the authority to run at least six months without major failures before going to the next higher power level with the exception of a short period (two weeks) at the next higher power level.

The intended steps were 106%, 109% and 112%. For the 112% power level, the new HP turbine had to be adjusted for capacity reasons. After successfully having reached 112% in October 2000, management decided to go to the final license level of 114.7% = 3600 MW. To reach this power level, some modifications of the first stages of the HP turbine were necessary.

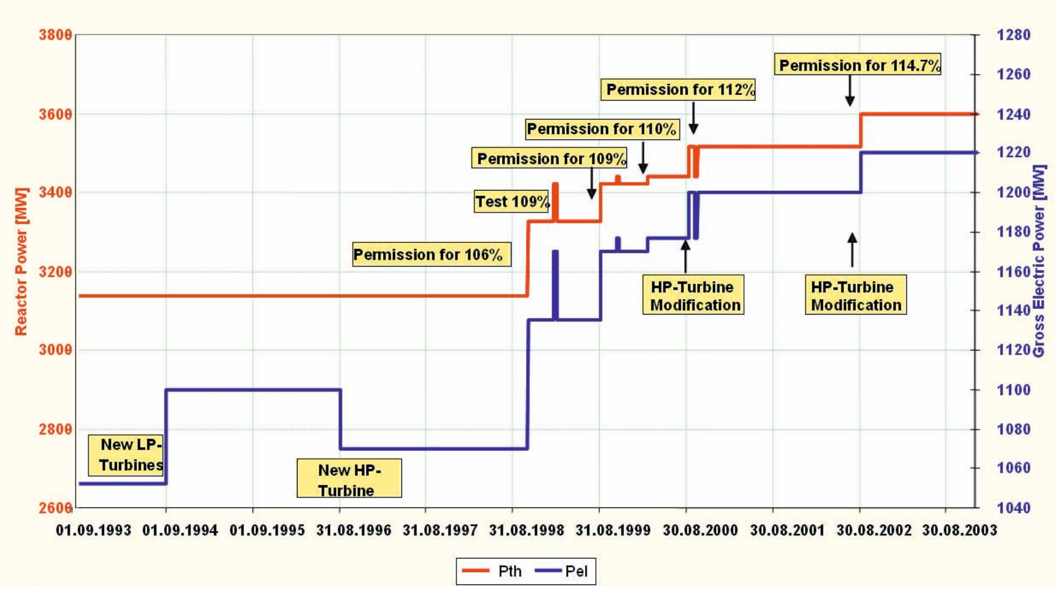


FIG. III.1. History of the EPU of KKL.

III.8. TEST PROGRAMME AND RESULTS

All EPU activities were accompanied by an appropriate test programme, which contained the most important parameters and features according to the agreed upon principles. It was organized similar to the original startup tests with some enhancements of data acquisition and analytical capabilities. Table III.1 shows the total programme. It can be divided into three major objectives:

- Component and system performance;
- Control system characteristics;
- SCRAM avoidance capability.

All tests were performed successfully. All SCRAM avoidance verification tests were especially analysed before testing. Thus, there were very few situations (e.g. turbine trip) whereby a hold on testing occurred because of too much uncertainty of the expected test results.

III.9. WARRANTY MEASUREMENTS

For a thermal engineer, it was a challenge to go to different power levels never experienced before with new components such as turbines and preheaters. At KKL, all this was very easy by using process data reconciliation software.

This method is based on Gaussian compensation calculation, including fulfilment of all auxiliary constraints (conservation of mass, energy and material). The applied software VALI is certified according to the German guideline VDI 2048. The model contains the total balance of the plant with all available (including redundant) information. The result is a non-contradictory image of the heat cycle with complete results, including the value of the process parameter and its uncertainty. The mathematics also deliver an integrated quality control of the overall and single results. Using this method makes it independent of the accuracy of single parameters such as feedwater mass flow.

TABLE III.1. TEST PROGRAMME

Year	1995	1996	1998	1999	2000	2002
% RTP:	100	100	106	109	112	114.7
Test (Number, title) MW(th):	3138	3138	3227	3420	3515	3600
PUT-1 Dryer/separator performance					99/080	99/080 Rev 1
PUT-22 Pressure regulator		96/191	98/123 [95-051] [95-081] [95-005]	99/124	00/106	02/088
PUT-23A Feedwater control		96/192		99/125		02/089
PUT-23C Feedwater pump trip		96/193	[97-174]	99/126		
PUT-23D Max feedwater runout	95/268	96/194				
PUT-24 Turbine valve surveillance		96/195		99/128	00/110	02/119
PUT-25C Main steam flow element calibration		96/196	98/124 [96-179]	99/129	00/111	02/093
PUT-27A Turbine trip		[a]	[b] [97-024] [98-072] [95-016]	[c] 99/123 [99-025]	[d] 01/107	[d,e] 02/115 [02/041] [01/325] [01/162]
PUT-27B Generator load rejection		96/197				
PUT-29 Recirculation flow control		96/198		99/132		02/090
PUT-30A Single recirculation pump trip		96/199				
PUT-30B Trip of both recirculation pumps	95/237 [94-027]			99/133		

The test report numbers document the testing performed. The reports are numbered as BET/Year/Number. Associated plant modifications are numbered as [Aae/Year/Number].

[a] GENE-A13-00400-02, Engineering Evaluation of KKL Turbine Trip Test 65% Power (2040 MW(th)) 9 September 1996.

[b] Engineering Evaluation of KKL Revision 98 Turbine Trip Test, 65% Power (2040 MW(th)), 27 August 1998.

[c] GENE A13-00413-01-01, Engineering Evaluation of KKL Revision 99 Turbine Trip Test, 65% Power (2040 MW(th)) — 3 September 1999.

[d] BET/01/107 (112%), BET/02/115 (114.7%) Turbine Trip tests were performed in 2001 and 2002 but not as part of the power uprate programme.

[e] [01/162] was implemented in 2001.

At the beginning of the power uprate programme, there were some normal warranty measurements with a lot of additional instrumentation. At the last implementation steps, the supplier could be convinced that this effort is not necessary. To get the same results as an expensive warranty measurement, KKL uses operational instrumentation plus data reconciliation.

III.10. INSPECTION PROGRAMMES

The long term effects of the power uprate could only be detected by a thorough inspection during outage. Therefore, the effort during outage was extended after each step of the power uprate. There were only a few items revealed such as bolts of the main steam line supports and some vibration-induced surface rubbing of the SRV bearings. The major failure was the broken shell of a pre-separator after the HP turbine. Water chemistry is excellent for fuel with a higher iron content in condensate as expected. Inspection programmes for erosion/corrosion did not result in any drastic change.

III.11. FOUR YEARS OF EXPERIENCE WITH EPU CONDITIONS

There were both positive and negative experiences for KKL. The positive ones included:

— Optimum (minimum) plant modifications;
— No increase of reportable events;
— Minor (no) impact on health protection (all-time low cumulated dose rate reached at the end of the EPU: about 60% of previous values);
— Minor (no) impact on release/waste (amount of raisin waste reduced by partial no-raisin filters for condensate polishing);
— No impact on maintenance (for EPU-related work);
— No fuel failures caused by the higher power level;
— System margins are equally distributed for normal operation;
— Steam dryer performance excellent (< 0.005% moisture content);
— Plant response to deviations and transients is perfect, including under real operating conditions;
— Plant response experienced as expected for real events like LOOP, load rejection, generator trip, turbine trip and feedwater pump trip.

The negative ones included:

— Vibration-induced failures at pipe supports of main steam line found (Comparison of analytical results and measurements showed some ‘cliff-edge’ effect). The cause could be the steam line resonance oscillation, which was enhanced by higher steam flow.
— Fatigue damage at internals of preseparator (Poor design showed up when challenged by higher vibration loads; problem is solved).
— Tribological phenomenon at bearing of some SRVs due to vibration (no functional loss; hint to different kind of vibration).
— FW pump cavitation during transients (Problem expected but due to different actions now at an acceptable level).
— Operation of generator has to be limited to 50 MVAr capacitive and 450 MVAr inductive to prevent local overheating of compression plate (Five months of repair time in 2005).
  • Problem temporarily solved by testing, advanced monitoring and administrative limitations of generator operation.
  • New generator stator ordered.
— Some operational/emergency procedures had to be adjusted to the new power level (e.g. fast depressurization of reactor, where inventory balance and energy dissipation are challenging).
  • Problems showed up at training simulator after power uprate.

III.12. LESSON LEARNED

The major lessons learned include:

— Do one major step for licencing to save time (Several years for licensing is needed);
— Do several appropriate steps for implementation of higher power levels to gain experience (by doing that, most cliff-edge effects may be found early);

- Set clear criteria in advance for modifications and operation objectives (Should be good practice for any large project);
- Safety margins for nuclear technology significantly improved over the last decades (e.g. decay heat uncertainties, fuel design); use them for power uprate;
- Risk will decrease during a power uprate programme due to the improvements and increased know-how made possible by the higher energy content;
- Closest margins found in turbine systems;
- Do not neglect local effects in electrical components and power distribution (Largest backstroke due to the generator failure in 2005, resulting in five months of repair time).

Appendix IV

APPLICATION OF ULTRASONIC FLOW MEASUREMENT FOR POWER UPRATES BASED ON MEASUREMENT UNCERTAINTY RECAPTURE

IV.1. INTRODUCTION

The largest source of uncertainty in the calculation of reactor power can be attributed to the limited accuracy and potential for undetected degradation of conventional flow nozzles and venturis used for feedwater flow measurement. UFM installations have been carried out with regulatory approval in PWRs and BWRs in the USA, regulatory approval is being progressed for trial installations on commercial nuclear units in Japan, and installations are being considered for PHWRs in Canada.

Installations use permanently mounted chordal measurement transducer arrays in laboratory calibrated pipe spools to achieve a measurement accuracy of ±0.28%. In addition to high accuracy, measurement systems have evolved to be highly reliable, with redundancy and self-checking features built in to eliminate failures and the potential for drift and inadvertent overpower conditions. Outputs can be used for thermal power measurement and for feedwater flow process control. Measurement frequency can be set to be compatible with existing systems for thermal power measurement and process control.

Contributors to thermal power measurement uncertainty are examined, and the range of potential measurement uncertainty recapture (MUR) is identified. Using industry-accepted practices to carry out MUR calculations, the available thermal power uprate can be predicted. Based on the combined uncertainty of all of the process parameters used in on-line thermal power calculations and the uncertainty assumed in the original licensing basis, available thermal power uprates vary between 1.5 and 2.5% of full power (FP).

As the year-to-year power demand in Canada increases, nuclear energy continues to play an essential role in providing secure, stable and affordable electricity. Nuclear energy remains cost-competitive compared to other energy resources while eliminating greenhouse gas emissions.

In the last decade, great progress has been achieved in developing new technologies applicable to NPPs, especially in the field of computer based instrumentation and control. An ultrasonic flow meter (UFM) is one of these technologies, which enables a significantly more accurate flow measurement compared to the traditional flow meters. In addition, the UFM has no fouling issues due to ageing, thereby retaining its accuracy through the life of the plant.

Hitachi and AECL have initiated a feasibility study on UFM applications to enhance CANDU performance, focussing especially on the MUR reactor power uprate for CANDU. Hitachi has developed the UFM application over the last ten years in Japan and AECL has widespread CANDU technology and licensing experience. Thus, the collaboration of these two companies provides a good fit for introducing this technology into CANDU.

IV.2. MUR USING UFM IN LWRs

In the USA, the original 10CFR50 Appendix K required that safety analyses be performed at 102% of FP to allow for a 2% margin for instrument uncertainty in thermal power measurement based on traditional flow meters.

In 1999, a group of partner utilities and Caldon proved that actual calorimetric uncertainties could be reduced from about 2% to 0.6%. With this more definitive knowledge of 100% operating power, the NRC agreed that safety could actually be increased, even while increasing the licensed thermal power level to an amount equal to the safety analysis levels minus the uncertainty of the power calculated. Subsequent improvement in UFM systems led to justified power uprates of up to 1.7%.

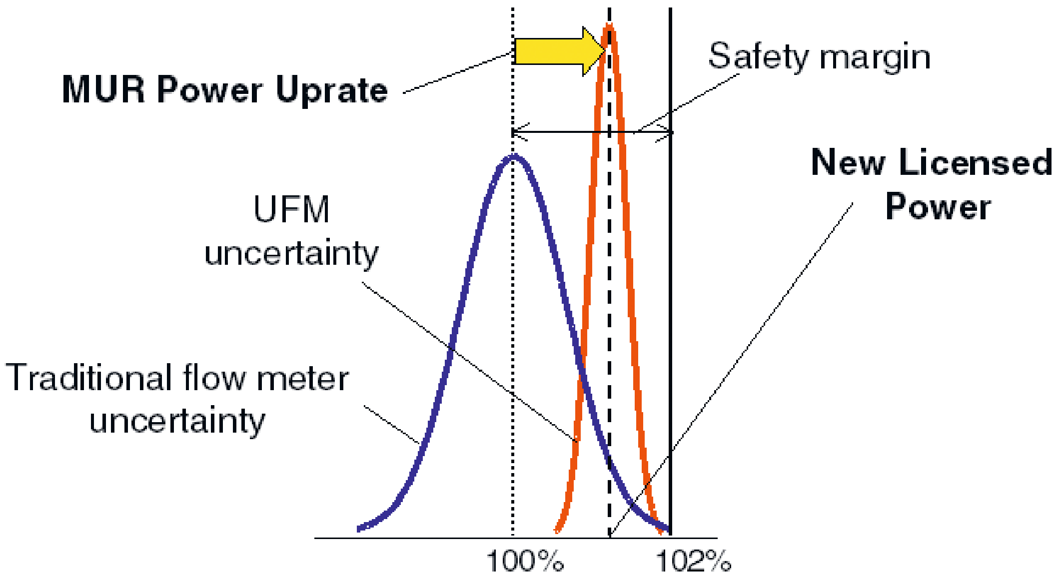


FIG. IV.1. Mur power uprate concept.

IV.3. MUR STATUS

Status in the USA

The modest cost of a measurement upgrade and resultant attractive cost per MW for this type of licensing action led to a large surge in MUR uprates in the first decade of the 21st century. Since Comanche Peak 2 received the first approval for an MUR application in 1999, 25 MUR applications for PWRs and 10 for BWRs have been reviewed and accepted by the US NRC.

To date, these uprates have created an additional 1533.8 MW(th) in the operating US NPP fleet. Altogether, the MW generation gained has been equivalent to building a large new nuclear plant at an installed cost of approximately US $63 000 000. This investment represents only a small fraction of the $1–2 billion price tag of an equivalent new plant.

The latest MUR power uprate approval received was for Seabrook (May 2006). This application for a MUR power uprate was the first to be accepted after an NRC Task Force on UFM technologies (after completing an additional two years of rigorous investigations) reconfirmed its approval for the use of the Caldon LEFM in MUR power uprate applications.

Status of Hitachi plants in Japan

Prior to 2000, the Japanese regulator had allowed utilities to generate electricity from NPPs only by the rated electric power. Since 2000, Japanese utilities have been allowed to operate their NPPs by the rated reactor power. This change to plant operation policy required the utilities to monitor and manage thermal power output with more accuracy and higher reliability.

TABLE IV.1. MUR STATUS IN THE USA

	Approved	Gained MW(th)
PWR	25	1050.8
BWR	10	483.0
Total	35	1533.8

Originally, UFM technology was applied for the recalibration of feedwater flow measurement instruments that have fouling issues when operating at rated electric power. In addition to this recalibration issue, Hitachi also investigated the possible future use of UFM technology for MUR power uprating and to meet the requirements of thermal power management under operation by rated reactor power. In the late 1990s, Hitachi R&D on UFM applications to feedwater flow measurement in NPPs identified Caldon's technology as superior to all other UFM models then available.

Hitachi has led several other R&D efforts as well as joint studies with Japanese utilities. Hitachi conducted LEFM external performance field tests for the purpose of recalibration of feedwater flow nozzles. LEFM chordal performance tests were also conducted, aimed at future MUR applications based on the LEFM chordal technology. Currently, LEFM chordal systems are permanently installed and working at one ABWR NPP and three PWR NPPs in Japan. Hitachi is now planning to install the LEFM chordal system at three other Japanese units.

In 2004, the Japanese nuclear regulatory board and the Atomic Energy Society of Japan (AESJ) established a working group to develop the power uprate roadmap for Japanese NPPs, including application of MUR. This working group has made a performance assessment of several UFMs for MUR applications, and they have confirmed LEFM chordal's superiority to the other UFM technologies.

IV.4. CANDU FW FLOW MEASUREMENT

CANDU feedwater (FW) flow measurements are currently being done using traditional methods such as venturis, flow nozzles and orifice plates. Periodically, the FW instruments are calibrated using externally mounted clamp-on ultrasonic flowmeters. There has been no application of the leading edge chordal UFM on any CANDU station to date. AECL has examined the feasibility and has concluded that the leading edge chordal UFM provides enough capabilities to replace the traditional flow meter.

IV.5. DESCRIPTION OF LEADING EDGE UFM TECHNOLOGY

The leading edge UFM technology is a transit-time ultrasonic flowmeter. Velocities are determined by measuring the precise time of travel of ultrasonic pulses going upstream and downstream across the fluid. Velocities are then numerically integrated using a Gaussian-Quadrature integration formula to make a precise measurement of volumetric flow. The unique configuration of the LEFM ensures almost total insensitivity to hydraulic effects, typically less than ±0.1%. Temperature calculations derived from ultrasonic fluid velocity is added to calculate mass flow rates to better than ±0.28%.

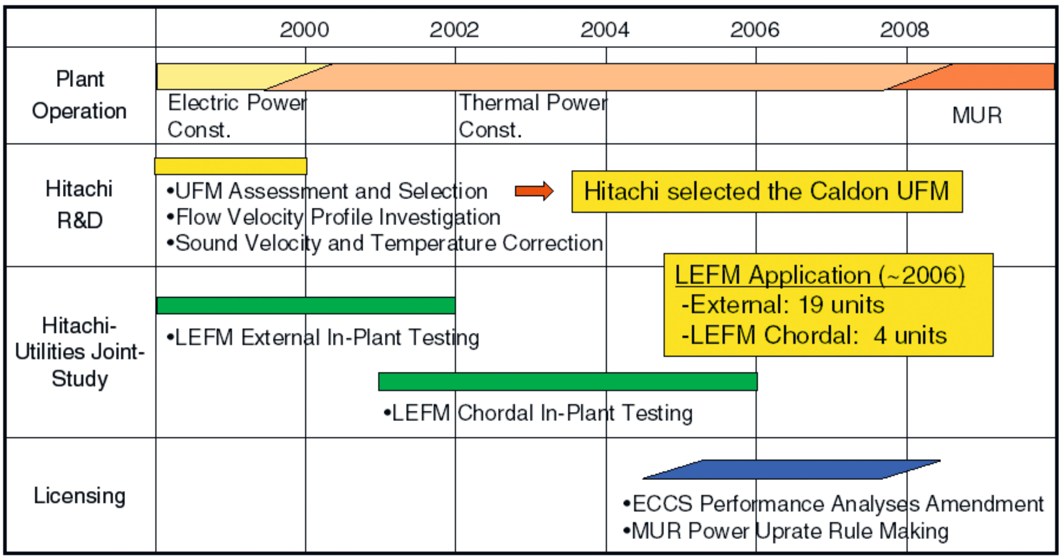


FIG. IV.2. Hitachi experience and status in Japan.

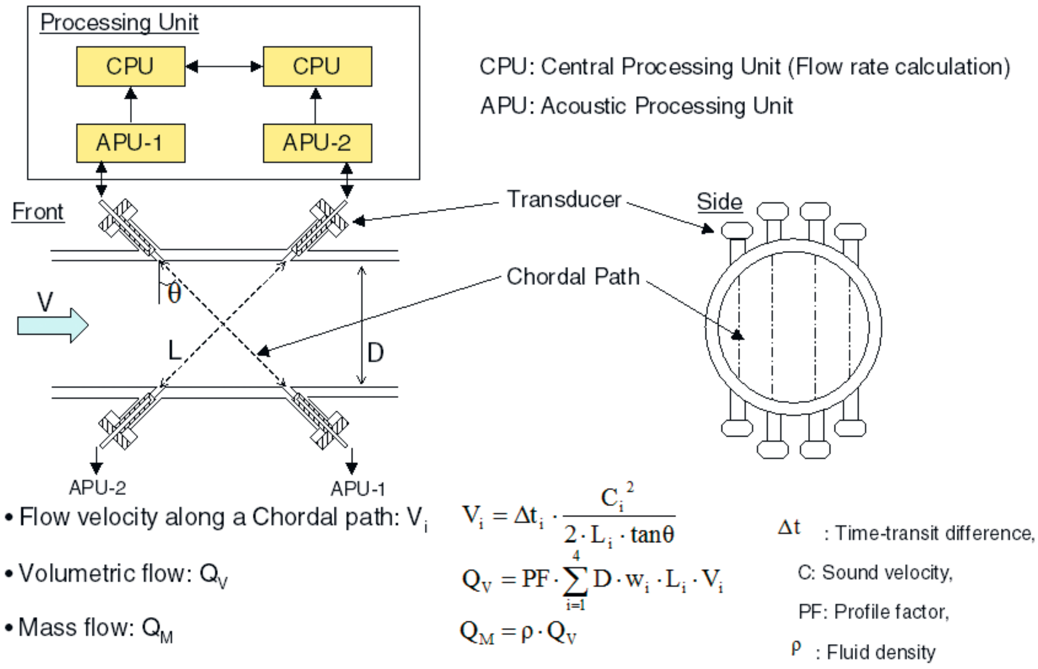


FIG. IV.3. Time-transit method and eight chordal paths.

IV.6. CONFIGURATION IN GENERIC NPP

A typical installation in a PWR nuclear plant would involve an LEFM CheckPlus measurement section, or spool piece, installed in each of the steam generator loops. Mass flow and temperature is calculated by the LEFM and fed to the plant computer, where on-line thermal power is calculated. Alternative solutions have called for single header measurement configurations or the addition of measurements for bypass flow paths.

IV.7. LEFM CHORDAL FEATURES

The critical parameters of the LEFM CheckPlus meters are time measurement, path lengths and path angles. These parameters are relatively easy to control with precision machining and by using available high frequency oscillators and timing circuits. Careful control of these critical parameters enables high-accuracy velocity measurements.

The high accuracy of the calculated volumetric flow is a function of both the accuracy of the velocity measurements and the numeric integration of each 4-path plane. This integration provides unique insensitivity to axial profile shape. The eight path arrangement in two orthogonal planes eliminates errors from radial (cross) velocities and tangential (swirl) velocities.

To further enhance accuracy and reduce errors, each meter is calibrated in a 100% scale model of the installation piping constructed in a flow calibration facility with complete traceability to international standards. Parametric testing provides traceable data with which to bound the effects of installation geometry or roughness, which cannot be modeled precisely.

Once installed in the plant, the meter's self-checking function provides real time monitoring of all possible sources or error, alarming the user if errors are detected outside of acceptable tolerances as defined in the uncertainty analysis.

Feedwater mass flow and temperature can be monitored and averaged over any desired interval to match the plant thermal power calculation needs and procedures. Typical average intervals are 1–2 min, updated every 5 s.

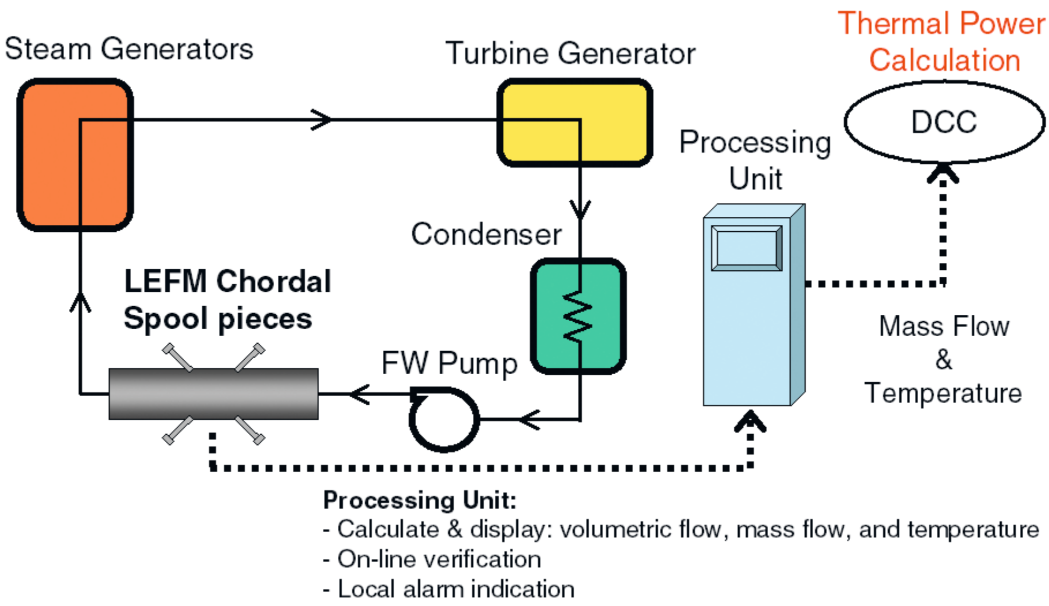


FIG. IV.4. Leading-edge chordal system.

FIG. IV.5. Leading edge chordal for PWR in Japan.

The system is designed for complete redundancy, including volumetric flow measurements from two four-path planes, two processors, and two separate sets of power supplies. Outputs for control can be made even with only one of eight paths functioning, providing a redundancy factor of 8 for transducers.

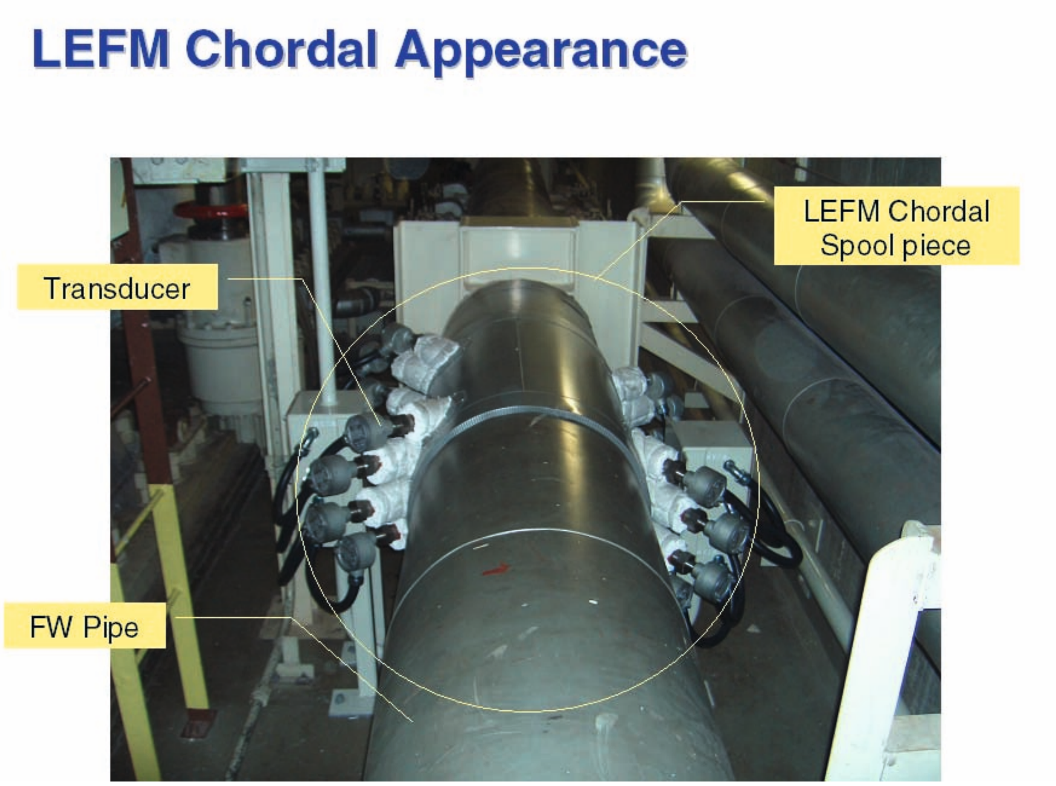


FIG. IV.6. Leading edge chordal appearance.

Fast response time constants as short as 0.5 s are available for steam generator level control (SGLC) in addition to very precise thermal power calculation inputs. In new construction applications, because the LEFM provides both of these functions, the flow nozzles become obsolete and are not needed, saving significant pumping power and capital investments.

IV.8. TYPICAL INSTALLATION

Conventional rules for the location of measurement sections do not apply to the LEFM. The LEFM inherently cancels the effects of radial and tangential velocities that can affect other types of meters. The integration of multiple velocity measurements over the whole velocity profile make the LEFM insensitive to axial profile shapes, wall roughness, Reynolds Number, and upstream effects. As a result, the LEFM has been and may be installed in very small spaces, immediately downstream from elbows and disturbances, with very good results.

IV.9. APPLICATION TO SGLC AND THERMAL POWER CALCULATION IN CANDU

A new build CANDU 6 with four steam generators is assumed in the following discussion. In addition, a distributed control system (DCS) used for data acquisition and control functions is assumed. DCS control functions are divided into a number of independent partitions through a probabilistic safety analysis, so that the resultant partitioning prevents functions in one partition from being affected by failures in another partition. All partition stations use dual-redundant controllers. According to a preliminary study, five control partitions are identified, in which the SGLC in the steam and feedwater partition and the thermal power calculation in the reactor partition are independently implemented in the DCS.

The LEFM chordal system with eight APUs and two CPUs in the processing unit is proposed for the four-loop feedwater flow line configuration. Having a dual transmitter for the steam flow meter, the proposed system provides the fully redundant configuration in terms of the SGLC. A mass flow rate (four-chordal based) calculated at an APU is used as an input signal to SGLC and a mass flow rate (eight-chordal based) calculated at a CPU is used

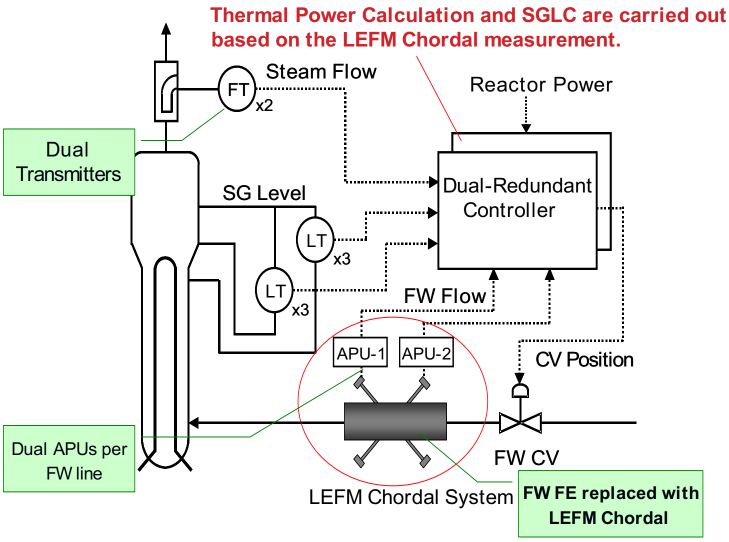


FIG. IV.7. Proposed system for a new build.

as an input signal to thermal power calculation. For example, APU-A1 calculates a mass flow rate at feedwater line A by the four pairs of transducers on the one measurement plane in SPMS-A, and it sends the mass flow rate to a dual-redundant controller used for the steam and feedwater partition and CPU-1. At the same time, APU-A2 calculates a mass flow rate at feedwater line A by the other four pairs of transducers on the other measurement plane in SPMS-A, and it sends the mass flow rate to the dual-redundant controller and CPU-2.

For the other three feedwater lines, B to D, the mass flow rate calculations using the dedicated APUs are similarly executed, and the results are sent to the dual-redundant controller, and CPU-1 or CPU-2 in the same way. The dual-redundant controller executes each of the four SGLC programmes using their respective mass flow rate and produces output signals to position each of the four feedwater control valves.

The LEFM chordal system can execute the feedwater flow calculations within 50 min. Taking 20 samples for smoothing the calculation result from the LEFM chordal system, for instance, the smoothed data of feedwater flow rate can be updated every one second. Since the SGLC programme is required to execute every 2 s, the LEFM chordal system has the capability to provide more than enough response performance required for the feedwater flow measurement input to the SGLC.

The LEFM chordal system can provide the feedwater flow measurement with an uncertainty of ±0.28%, and it has no fouling issues that can lead to increased uncertainty because of the measurement principle it uses. Even in the four-chordal based case, the feedwater flow measurement can achieve ±0.5% uncertainty. On the other hand, the traditional flow meter typically achieves a total uncertainty of around ±1.0%, including the flow element calibration error of ±0.25%. In addition, the traditional flow meter may experience some fouling over time, thereby requiring maintenance and recalibration on a regular basis to maintain and ensure the initial accuracy of the device.

As for the thermal power calculation, all the APU calculation results are shared with CPU-1 and CPU-2 by means of the communication network between CPU-1 and CPU-2. The two CPUs independently calculate the mass flow rate in each of the four feedwater lines. Finally, the outputs from CPU-1 and CPU-2 are used as input signals to the thermal power calculation performed by the reactor partition every two seconds, instead of the traditional flow meter inputs. As mentioned above, the LEFM chordal system exceeds the response performance and accuracy required for the thermal power calculation.

Because of the dual-redundant configuration described above, the LEFM chordal system can be available to maintain the SGLC function and thermal power calculation function even following a single component failure and still provide more reliable feedwater measurements compared to the current CANDU 6 design using the single traditional flow meter. For example, in the case of an APU-A1 failure, the dual-redundant controller retains its function using the input signals form APU-A2, and the thermal power calculation function associated with feedwater line A is performed based on the four chordal paths.

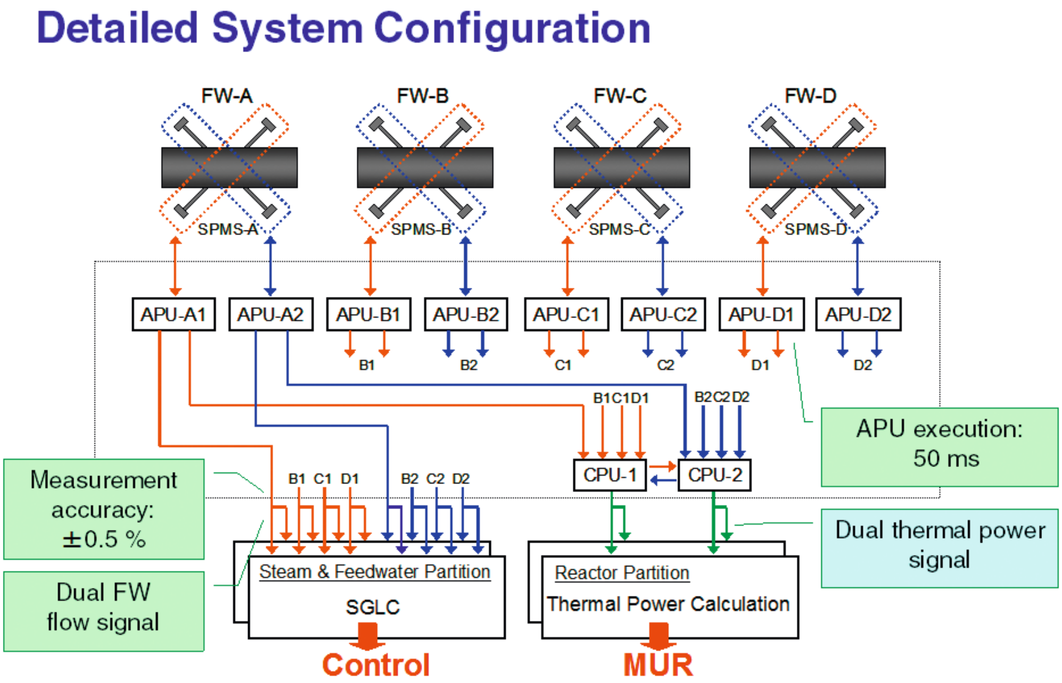


FIG. IV.8. Detailed system configuration.

IV.10. MEASUREMENT OF UNCERTAINTY RECAPTURE

NRC process

The MUR power uprate has been developed in the USA, and the NRC provides all utilities with a standard guidance issued on 3 July 2000. NPPs are licensed to operate at a specified reactor thermal power. The regulator requires the licensees to assume that the reactor operates continuously at some power level beyond the licensed power when performing safety analysis. This assumption is required to ensure that thermal power measurement uncertainty is adequately accounted for in the safety analyses. The assumed power margin in the safety analyses is based on considerations associated with the thermal power measurement. If the licensees can justify a smaller margin for thermal power measurement uncertainty by using more accurate instrumentation to calculate the reactor thermal power, then a small thermal power uncertainty may be assumed in the safety analysis, and the 100% licensed thermal power limit may be increased accordingly.

Typical gains in the USA

The average gain in the licensed power level for MUR uprates in the USA is 1.5% with maximum values of 1.7% achieved. Since the actual pre-uprate thermal power is uncertain due to instrument uncertainties stemming from the potential errors in the dP instrumentation, the net thermal power uprate that a plant will achieve due to a licensed thermal power uprate is also uncertain. However, because the uncertainties in both the LEFM and the original venturis have proven to be normally distributed, the average net power gain achieved through MUR uprates is essentially equal to the average licensed power gain. A slight conservative bias of 0.1% has been found in the dP based measurements. These data are summarized in Fig. IV.9.

UFM overpower events in the USA

There have been 21 reported overpower events associated with UFMs in the past six years. All of the overpower events have been associated with externally mounted ultrasonic flowmeters — 15 associated with a cross-correlation type technology and six with a transit-time type technology. Reported root causes included noise,

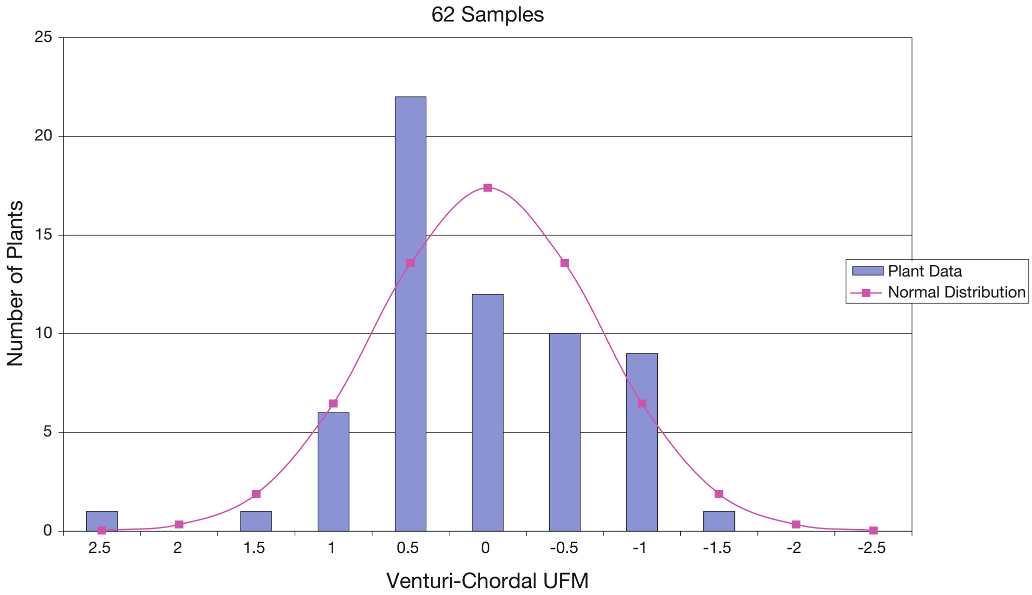


FIG. IV.9. Distribution of Venturi–chordal differences.

velocity profile effects, errors in hydraulic model calibrations, errors in in situ calibrations, improperly selected meter locations in consideration of meter sensitivities and poor monitoring of the UFMs.

There have been no reported overpower events associated with the type of meter that is the subject of this appendix. Insensitivity to velocity profile effects and complete self-checking features have prevented overpower events from occurring.

Potential gains in CANDU

The safety analyses in typical CANDU 6 design is carried out at 103%. The current 3% margin represents a measurement uncertainty associated with reactor thermal power, most of which comes from the feedwater flow measurement uncertainty based on using a traditional flow meter.

By introducing the LEFM chordal system for the feedwater flow measurement, the thermal power measurement uncertainty can be reduced to about 0.5% (2 sigma). Thus, reactor thermal power could be raised theoretically by as much as 2.5% without compromising the safety margin and the licensing basis of their facility. Even allowing for a 1% uncertainty for power fluctuations during refuelling against the current 3% margin, the thermal power could be increased by 1.5% by taking credit for the improved accuracy of the LEFM chordal system flow measurement.

Phased approach in implementing MUR in CANDU

CANDU owners are looking at life extension of their stations. Retubing, in which the fuel channels of a CANDU station are removed and replaced will extend the life of the station for another life cycle. A retube project, such as the one already underway at Lepreau NPP, represents an opportunity to install the LEFM into the feedwater lines once the reactor is defuelled and installation of the LEFM on all feedwater lines can proceed simultaneously.

For installation into existing plants either in conjunction with a retubing project or during a maintenance outage, the proposed approach would entail retention of SGLC by the existing venturis. This approach has the least impact on the already proven control systems. The calorimetric calculation for thermal power would utilize the LEFM technology, and the lower uncertainty would be the basis for the licensing application to increase reactor thermal power.

For new build opportunities for CANDUs, such as the CANDU6E (enhanced CANDU 6) and the ACR (advanced CANDU reactor), the LEFM technology will be utilized for both SGLC as well as for thermal power calculation, and the older technology of FW venturis will no longer be required. Therefore, the introduction of UFM into the new build CANDU provides two benefits at one time — cost reduction by eliminating the traditional flow meter and increased power by the MUR power uprate.

Appendix V

SYSTEM EVALUATIONS FOR THE POWER UPRATES OF THE KORI 3 AND 4 NUCLEAR POWER PLANTS IN THE REPUBLIC OF KOREA

V.1. INTRODUCTION

Power uprates for Kori units 3 and 4 and Yonggwang units 1 and 2 have been ongoing since September 2002 with a target value of 4.5% in core thermal power. The power uprate work is being implemented in three phases. Phase I consists of feasibility evaluations, phase II consists of detailed evaluations, and licensing approval is acquired during phase III. Systems and components of NSSS, BOP and turbine-generator have been analysed. The thermohydraulically important design and operating parameters were reviewed through the phase I feasibility study. The existing systems and components were evaluated at phase II with the uprated operating conditions. The potential licensing issues such as interface with periodic safety review were also investigated.

A goal of power uprate is to increase the gross electrical output without making significant modifications to the existing main components such as the steam generators, reactor coolant pumps and the turbine generators while remaining within the boundaries of the existing safety analyses and operating margins for the plant. There are many options for uprating the power level. A successful uprate, for example, may include a combination of capturing a portion of the design margins, using improved analytical methods, and developing improved fuel management techniques.

The first uprates in nuclear power plants in the Republic of Korea have been ongoing for Kori units 3 and 4 and Yonggwang units 1 and 2. The power uprate work is being implemented in three phases. Feasibility evaluations are conducted in phase I and detailed evaluations are conducted in phase II, while phase III is dedicated for licensing approval. The results of the feasibility study provided an estimate of the areas that might have difficulty in meeting any regulatory acceptance criteria or design limits at the uprated power conditions and identified potential component and system ‘pinch points’ that require further technical evaluations and detailed analyses during the phase II engineering work. The feasibility study was completed on 30 November 2003, and the detailed evaluations of phase II were finished on 30 April 2005. The licensing amendments were submitted to the regulatory body on 1 September 2005, and the power uprates of Kori units 3 and 4 were approved on 14 December 2006. During the licensing review for the power uprates of Kori units 3 and 4, about 500 issues were successfully resolved. Now the licensing of the power uprates of Yonggwang units 1 and 2 are expected to be approved within the first half of 2007.

The NSSS, fuel, core, turbine-generator (TG) and BOP system and components have been analysed, and the thermohydraulically important design and operating parameters, as well as the safety and operating margins, were reviewed through the phase I feasibility study. The evaluations performed at phase II compared the existing design conditions with the estimated operating conditions required for the power uprate, and assessed whether these conditions will be bounded by the existing system and component design capabilities. Based on the results, the targeted uprating power of 4.5% in thermal rated power was determined.

Some BOP and TG items were identified not to have sufficient capacity to accommodate the predicted power uprate conditions. When possible, recommendations were made on what changes might be needed to the plant design or analysis assumptions in order to satisfy the acceptance criteria.

V.2. GENERAL OVERVIEW OF THE UPRATING PROCESS

The general process of a typical power uprate programme is shown in Figure V.1, which consists of three phases. Phase I as a conceptual study is performed to identify major barriers or potential technical challenges to the power uprate for a preliminarily assumed operating point. A major barrier is an issue for which a cost effective technical solution is not known or should be developed through the power uprate programme. A technical challenge is an issue for which a solution based on engineering judgment should be developed in time to support the power uprate.

In the case of the current power uprate project in the Republic of Korea, phase I identified the margin for the determination of target power through review of the design and operation data of Kori 3 and 4 and Yonggwang

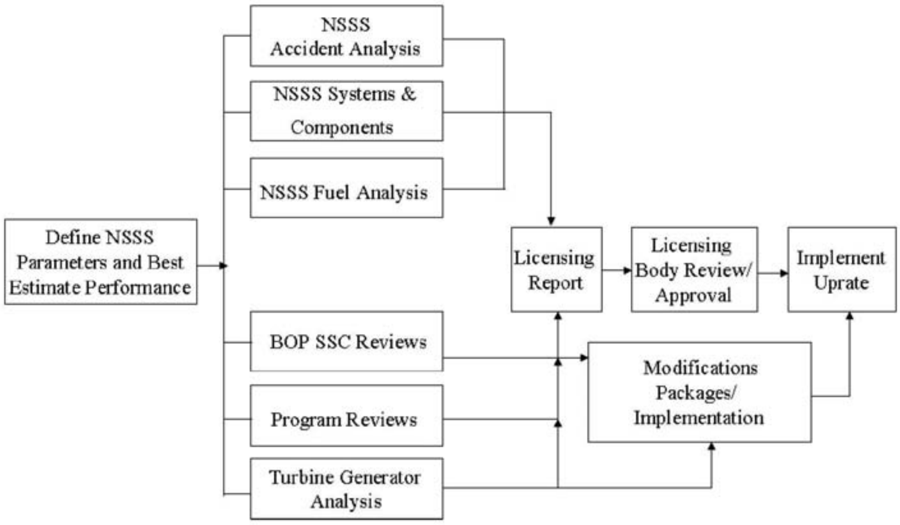


FIG. V.1. General overview of a typical power uprate process.

units 1 and 2. It also determined the amount of uprated power and the scope of design and operation through preliminary evaluation of performance, safety and integrity of systems and components in a limiting way. Phase II, as a detailed scoping study, checked and confirmed the performance, safety and integrity of systems and components in an uprated condition through safety analysis, set point evaluation, performance analysis of NSSS and auxiliary systems, structural analysis of NSSS components, performance analysis of BOP and TG, etc. Products of this stage include a licensing report, proposed changes to technical specifications and the safety analysis report, revisions to plant procedures, plant modification packages, simulator upgrades and startup test requirements. The approval for the licensing amendment for power uprating has been planned in phase III.

V.3. TARGET DESIGN PARAMETERS

The target or preferred design values and operating ranges of the NSSS parameters for the uprated conditions were defined. The target design parameters include NSSS power levels, the reactor coolant loop temperature, steam generator tube plugging levels and reactor coolant system flow rates to be considered in the power uprate. The targeted NSSS power level is 2912 MW(th). This value was selected because it was the typical value considered as the maximum calculation or safeguards systems rating at which other Westinghouse plants have secured stretch power uprate licenses.

The targeted design parameters provided in Table V.1 were established based on the following assumptions:

(1) The power level for the uprating is 2912 MW(th), which is approximately 4.5% higher than the current NSSS power of 2785 MW(th).
(2) The coolant T_{avg} ranges from 304°C to 308°C. The plant is assumed to be operated at any temperatures within the range.
(3) The thermal design flow (TDF) is reduced by 1.5%, from the current value of 95 600 gal./min/loop to 94200 gal./min/loop. The purpose is to widen the allowable operating range of the reactor coolant system (RCS) coolant flow rate and thus accommodate the currently measured low RCS flow rate at the sites.
(4) Design core bypass flow is 6.7%, including an uncertainty of 1.5%.
(5) The parameters are applicable to the Model F steam generators.
(6) Feedwater temperature is increased from 226°C to 230°C.
(7) The steam generator tube plugging (SGTP) rates are 0, 5, and 7%.
(8) The 17 × 17 robust fuel assembly (RFA) is installed in the core.

TABLE V.1. TARGET DESIGN PARAMETERS FOR THE POWER UPRATE

Parameter		Original design value	Uprated value (by T_{avg}, °F)		
			580	586	587
Core thermal power, % (MW(th))		100 (2775)	104.5 (2900)		
T_{hot}, °F		620.5	614.4	620.0	621.0
T_{cold}, °F		556.4	545.6	552.0	553.0
TDF per loop, gal/min		95 600	94200		
SG pressure, psia		964.0	912.0	918.0	926.0
Steam flow rate × 10^6, lbm/hr		12.29	12.91	12.93	12.94
Electrical output (MW(e))	Kori 3, 4	999.1	1033.2 (3.40% increase)		
	Yonggwang 1, 2	996.5	1046.2 (5.0% increase)		

In addition to the design parameters discussed above, the best estimate of NSSS performance parameters were generated. These parameters were used as input for TG vendors to develop the secondary side heat balance, which is later used for the BOP evaluations. They are based on the full power calorimetric data measured at the sites. From the calorimetric data, best-estimate values were determined for the steam generator fouling factor and RCS flow rate.

The best estimate parameters are based on the expected operating conditions, such as the following:

(1) Operating T_{avg} is assumed to be 308°C;
(2) The RCS flow rate is assumed at the best estimate, not at the TDF;
(3) The moisture carryover (MCO) is assumed to be 0.25%, the same as the design value;
(4) The SGTP level is assumed to be the same as currently measured.

V.4. POWER UPRATE EVALUATIONS

Some of the efforts done in the first and second phases of the three-phase uprate programme were accomplished, including the development of design parameters, the evaluations of NSSS and BOP system performance, and the mechanical evaluations of the TG system. The following presents the evaluations for the adequacy of the 4.5 per cent thermal power uprate.

NSSS performance analysis

The NSSS systems performance analysis includes the RCS performance, NSSS/BOP interface requirements, NSSS main component performance. The NSSS main components reviewed are reactor, pressurizer, reactor coolant pump (RCP) and steam generator (SG). The NSSS/BOP interface requirements were also reviewed on the main steam system, main feedwater system, auxiliary feedwater system, and SG blowdown system. It is concluded that the flow and pressure distribution at the core inlet would not be impacted by power uprate.

The steam generator components would be acceptable as installed. The MCO is expected to be below the design limit of 0.25% for all cases with the proposed feedwater temperature of 230°C. Therefore, the MCO for the proposed design parameters is expected to be below 0.25%, which is considered a threshold for erosion and corrosion for the piping and valves downstream of the steam generators. Pressurizer sizing criteria were satisfied enough to control the insurge and outsurge of the coolant during design transients at uprated power condition. The RCP motor loading was reviewed for the expected effects of a 4.5 per cent power uprate with a range of T_{avg} values and a range of steam generator tube plugging. RCP evaluation resulted in the conclusion that there would be minimal impact on the motors for the power uprate.

NSSS auxiliary system performance analysis

The power uprate impacts on the existing system design and performance capabilities of the NSSS auxiliary system were evaluated. The NSSS auxiliary system includes the chemical and volume control system (CVCS), residual heat removal system (RHRS), emergency core cooling system (ECCS), spent fuel pool cooling system (SFPCS), auxiliary feedwater system (AFWS), component cooling water system (CCWS), and containment spray system (CSS).

The CVCS, RHRS and ECCS could perform functional requirements with some minor impacts on those requirements, which, however, would not exceed their existing capabilities. It was evaluated that the spent fuel pool cooling requirement would be satisfied for the uprated power condition. The evaluations of the AFWS, CCWS and CSS showed that the design bases and criteria remain applicable for the power uprate.

System structural integrity evaluation

The main parameters for the power uprate that impact the NSSS components and supports are the operation pressure, temperature and mass flow rate under the full power and transient operations. The changes in the temperatures of the hot leg and cold leg pipes under the power uprate conditions are expected to result in very small changes in displacements of the reactor coolant loop (RCL) piping.

The fracture toughness of ferritic materials is reduced due to the neutron embrittlement of material, and the structural integrity of the reactor vessel during the plant lifetime is verified by re-evaluating the fast neutron fluence during the plant operation. The maximum fast neutron fluence of reactor vessel materials of target plants was calculated based on the design and operation data. Based on the evaluation results, the impacts on the structural integrity of NSSS components and supports due to the uprated power conditions were expected to be insignificant.

Also evaluated were the auxiliary pumps, heat exchangers and valves for the impacts by the thermal transients and maximum operating temperatures, pressures and flow rates resulting from the uprated power conditions. The evaluation consists of a structural and flow capacity review of the component pressure boundaries. It was shown that the auxiliary equipment continues to meet the design pressure and temperature requirements, and the allowable limits, such as the fatigue usage factors according to which the equipment had been designed.

Also assessed and evaluated were the piping systems and structural elements of the NSSS auxiliary equipment and critical components within these systems under the uprated power conditions. The changes in the NSSS and BOP process parameters (i.e. pressure, temperature, flow and their effects on the applicable piping systems) were assessed and evaluated. Margins in stress levels, penetration loads and nozzle loads were reviewed, and the effect on pipe break locations was investigated. As a result of the evaluations, there would be no physical changes required to any of the components. These systems were determined to be capable of accommodating the uprated power conditions within the bounds of existing design bases.

BOP system evaluation

The selected BOP systems, structures and components (SSC) were evaluated to determine whether or not the existing plant could accommodate the proposed uprated power conditions. The evaluations focused on the effects of the uprated power conditions on BOP safety and hazard protection, radiation shielding and dose analysis, containment integrity and equipment qualification. The impacts on the existing containment pressure and temperature analyses were evaluated, which were due to the changes in the mass and energy releases by the main steam line break (MSLB) and loss of coolant accident (LOCA). The analysed MSLB and LOCA cases resulted in the peak containment pressure being less than the current containment design pressure.

Turbine generator evaluations

Turbine generator system evaluations were performed with a best-estimate condition of 4.5% thermal power (T_{avg} 586D). Primarily, evaluation was performed focused on the effects on the turbine-generator system performance and the mechanical integrity at the predicted uprated power conditions. A baseline heat balance diagram was established by using the original design data and current equipment performance data. Based on the SG outlet pressure and final feedwater temperature at uprated power conditions, steam path optimization was fulfilled, and equipment performance and mechanical integrity was evaluated. The study results indicated that the present high-pressure (HP) turbine could not accommodate increased steam volume flow at decreased steam pressure conditions. To accommodate the increased steam flow, a high-pressure turbine needs partial modification.

V.5. PLANT MODIFICATIONS

There were no modifications for the NSSS hardware, while some set points, such as turbine runback set points, were changed. According to recommendations based on the BOP system evaluations, the component cooling water heat exchanger will be replaced to restore the heat transfer capability, and the steam generator blowdown control valves will be replaced to increase the flow rate.

The FIP turbine modification was also recommended as follows:

— Kori 3 and 4: Replacement of the diaphragms for stages 1 through 4;
— Yonggwang 1 and 2: Replacement of the internals such as rotor, nozzle block and blade rings.

V.6. LICENSING APPROACHES AND LESSONS LEARNED

Some licensing approaches were suggested at the initial phase of the project for successful licensing approval of the first power uprate project in the Republic of Korea. Early contact with the regulatory body was typically proposed and several presentations were held. In particular, it was directed that all analyses should be based on current licensing practices with some exceptions. Those include natural circulation cooldown and some that are beyond design bases, such as total loss of feedwater, mid-loop operation and anticipated transient without scram. In addition, potential licensing issues such as leak-before-break, environmental qualification and periodic safety reviews are covered.

Some lessons learned from the project are: (a) It is recommended to establish contact with the regulatory body at the beginning of the project; (b) Current equipment performance data should be correctly identified for the analysis; (c) Early performance of NSSS-related activities is recommended for better interface with BOP-related activities; (d) The work scope should be well defined so that no task is omitted.

V.7. CONCLUSIONS

The evaluations have been performed to assess whether the uprated power conditions would be bounded by the existing system and component design capabilities. The targeted power uprate level was determined at 4.5% in thermal rated power, and the capabilities of existing systems and components in the NSSS scope were identified. Some pinch points were found in certain BOP items to accommodate the predicted uprated power conditions, and minor hardware changes are required in the BOP components to maintain acceptable margins. In addition, high-pressure turbines require modifications to accommodate the increased steam flow. Finally, the 4.5% power uprate of Kori units 3 and 4 successfully received the licensing approval, and it is expected that Yonggwang units 1 and 2 will soon be granted the licensing approval as well.

Appendix VI

EXPERIENCE FROM POWER UPRATES IN SWEDISH NPPs

VI.1. REVIEWING THE APPLICATIONS FOR POWER UPRATES

Introduction

Reviewing an application for increasing the thermal power of a nuclear reactor is a process that stretches over several years and requires competence from many of the professional disciplines within the Swedish Radiation Safety Authority[8]. Current plans for power uprates in Swedish nuclear power plants will lead to significant increases in seven units and a lesser increase in one unit as shown in Table VI.1 below. Earlier uprates from original power levels are also shown.

A power uprate process is initiated by the application to the Government by a licensee. This application is addressed to the Government and is forwarded to SSM for a preliminary safety review. The result of the review is then provided by SSM as a basis for a governmental decision.

If the licensee's application is approved by the government, deeper analyses and studies are required in order to modify the plant and update the safety analysis report and the associated technical specifications. SSM reviews this material on a continuous basis in four stages prior to test operation and routine operation at the increased power level.

TABLE VI.1. POWER UPRATES IN SWEDISH NUCLEAR REACTORS

Reactor	Type	Startup year	Original power MW(th)/MW(e)	Implemented uprate			Planned uprate		
				MW(th)/MW(e)	Year	%	MW(th)/MW(e)	Year	%
Barsebäck 1	BWR	1976	1700/580	1800/630	1985	6	/Closed in 1999/		
Barsebäck 2	BWR	1978	1700/580	1800/630	1985	6	/Closed in 2005/		
Forsmark 1	BWR	1980	2711/900	2928/1014	1986	8	3253/1134	2011	20
Forsmark 2	BWR	1981	2711/900	2928/1014	1986	8	3253/1134	2010	20
Forsmark 3	BWR	1985	3020/1100	3300/1190	1989	9	3775/1360	2012 2015	18 7
Oskarshamn 1	BWR	1972	1375/460	1375/490 (modernization)	2003				
Oskarshamn 2	BWR	1975	1700/580	1800/630	1982	6	2300/805	2011	35
Oskarshamn 3	BWR	1985	3020/1100	3300/1200	1989	9	3900/1450	2009	29
Ringhals 1	BWR	1976	2270/750	2500/880 2540/895	1989 2007	10 1.5			

[8] Nuclear power in Sweden has, since 1 July 2008, been supervised by the Swedish Radiation Safety Authority (SSM). SSM was formed by merging the two previous authorities the Swedish Nuclear Power Inspectorate (SKI) and the Swedish Radiation Protection Institute (SSI).

TABLE VI.1. POWER UPRATES IN SWEDISH NUCLEAR REACTORS

Ringhals 2	PWR	1975	2440/820	2660/910	1989	9			
Ringhals 3	PWR	1981	2783/915	3000/1010	2007	8	3160/1110	2009	14
Ringhals 4	PWR	1983	2783/915				3300/1160	2011	19

— Stage 1: Review of the application to the Government for approval to power uprate. SSM prepares a proposal for decision by the Government.
— Stage 2: Review and approval of the preliminary safety analysis report (PSAR).
— Stage 3: Review and approval of the application for test operation at uprated power.
— Stage 4: Review and approval of routine operation at uprated power.

Review of the application to the Government

A request to the Government for approval of power uprate has to include the following:

— A description of how the power uprate project is to be managed, controlled and supervised;
— A summary description of the plant design and the modifications necessary to accommodate the uprate;
— A presentation of a systematic review and evaluation of the impact of uprated power on the current safety analysis report;
— An environmental impact statement, which includes information required according to the environmental code.

At this stage it is important that the licensee has identified those parts of the plant and its operation that are influenced by the proposed power uprate. The SSM review of the application aims at assessing the premises for the implementation of the uprate and the operation of the plant within the necessary safety margins.

Comments from authorities and the general public

According to nuclear power legislation, SSM is to ask, in its review of the application, for comments from relevant authorities and bodies. SSM forwards the application to

— The authorities in the counties and communities concerned;
— The local safety board for the power plant;
— The Swedish Environmental Protection Agency;
— The Swedish Rescue Services Agency;
— The Swedish Board of Fisheries;
— The Swedish Grid.

To meet the requirements of the environmental legislation, the matter is publicized in the relevant local press and in the official “Post- och Inrikes Tidningar”, providing information on the environmental impact statement and making it available for review by the general public.

The Espoo Convention includes the agreement on exchange of information between the Nordic countries on matters of possible cross-border environmental effects, giving the individuals the right to participate in the decision making process in other countries. In line with this agreement, the application is sent to the authorities in Denmark, Finland and Norway.

SSM recommendations and the Government’s decision

Based on the review, SSM documents its opinion together with a suggestion for a decision to be taken by the Government. The suggestion together with the comments and opinions from other authorities and the general public is sent to the Government. SSM also suggests conditions to be associated with an approval of the application. The conditions are, typically, that approval by SSM should be required before start of test operation at the uprated power level and before entering into routine operation. SSM also suggests it be authorized to issue any other requirements necessary for safety.

This review process is estimated to take between six and nine months, depending on the magnitude of the power increase envisaged.

If the Government decides to approve the application, the licensee can then proceed with the preparations for uprating. The next phase includes the preparation of a preliminary safety analysis report (PSAR) by conducting the deeper studies and analyses that will be required for the uprate of the plant and its future operation. The PSAR has special relevance in the case of major increases of thermal power and is thus, in accordance with SSM regulations, a prerequisite for further action by SSM in the matter.

Review of the preliminary safety analysis report

This PSAR is based on the existing SAR with the addition of:

— Information on the actual or planned plant configuration modifications;
— Information on the envisaged method of plant operation, including operational limits;
— Description of and reference to engineering and safety analysis that covers the systems and functions to be changed, but also those areas presumed to be influenced by such changes.

The requirements on the PSAR are thus that it covers the updating and changes, and complements the existing SAR. The review of the PSAR done by SSM is to check that the proposed changes to the design principles are correct, and that the quoted studies and analyses concerning the safety-related aspects of the power uprate were conducted in a correct manner. The review is also to establish that the safety requirements are met with necessary margins.

It should be noted that deterministic analyses will need to be backed up by probabilistic analyses in order to get the complete picture of plant safety. Furthermore, a check is done to see that loadings on, and fracture mechanics analyses of, pressurized components and building structures covered by the SSM requirements have been verified by an accredited inspection body.

In the case of minor power uprates, e.g. measurement uncertainty recapture (MUR), no approval is required by SSM of a comprehensive safety report — only the parts involved need to be covered.

The time required for review of the PSAR can be between three and 12 months, depending on the magnitude of the power uprate involved and the measures called for.

Review of the application for approval of test operation

In order to meet the conditions attached to a power uprate approval, it is necessary for the licensee to submit an application for entering into operation at the higher power level. Such an application should include:

— A renewed SAR that has been updated to reflect the plant modifications presented in the PSAR together with deviations from the PSAR that might have occurred;
— The updated technical specifications for operation (STF) that apply for the new operational and safety limits;
— Updated instructions suited to the higher power level;
— Supplementary operator training for operation at the higher power level;
— The test programme regarding extent and aim.

Test operation normally extends over one operating season. Also, the maintenance period to follow is included in the test period in order to verify that the operation has elapsed as expected.

The review done by SSM of this material aims at seeing that all necessary measures have been taken to ensure that current safety requirements are met with necessary margins, and that the safety report, in its entirety, together with the STF and operator instructions meet all applicable requirements. The process should take between four and six months.

Modifications in the plant are to be followed up by SSM with respect to how they are done and to what extent the process follows the assumptions made in the analyses presented. This is done by a combination of spot checks of reported modifications together with in-plant inspections.

The latter focus on how well the licensee controls and follows up on its own work, together with that done by external contractors on-site. This supervision is carried out during the entire time that plant modifications are being made but especially at the start of the work period.

The application is to be submitted together with the material listed above. Before the time planned for the test operation, this is then supplemented by a renewed SAR and details of any last minute modifications not previously documented.

Review of the application for routine operation

Meeting the conditions associated with uprating permit, the licensee should submit an application to the SSM for entering into routine operation.

To this application the following must be appended:

— A comprehensive safety report that has been updated to also reflect the results of the test operation period and other experiences gained;
— The technical specifications for operation (STF) that have been similarly updated to reflect the experience gained during the test operation;
— Operational instructions that have been updated in a similar manner;
— A presentation of any possible changes that have been made to operator training in light of the operational experience gained during the test operation.

The SSM review of this material aims at checking that necessary measures have been taken in light of the results of the test operation period to meet safety requirements during routine operation, and that the safety report, in its entirety, together with the STF and the instructions, meets the requirements stipulated.

The time needed for this review should be between four and six months, depending on the actions called for from the test operation period.

Competence for carrying out the reviews

The work at SSM of reviewing the applications for power uprates is organized and carried through as a project spanning a number of years. Project groups are staffed with competencies from several fields of expertise (e.g. thermohydraulics, material properties, fracture mechanics, project management, human–machine technology).

Experience from the licensing process

One set of experiences from the licensing process for power uprates described above and implemented so far is that it raises the level of competence of the regulatory authority as well as the other actors involved. Another experience is that the licensing of a power uprate brings attention to many old issues that need to be addressed. Furthermore, informal communication with the licensee is important without compromises to his own safety review and responsibilities.

VI.2. EXPERIENCE FROM THE POWER UPRATE OF UNIT 3 AT OSKARSHAMN

Introduction

Project Puls was started in 2003 in order to make a pre-study for the power uprate of unit 3 at Oskarshamn. The analyses showed that it was technically and economically feasible to uprate unit 3 at Oskarshamn with a reasonable risk profile. In early 2006, contracts were signed with Westinghouse (reactor scope) and Alstom (turbine and electrical scope), and the start of installation was planned for the end of 2008.

To secure the short time schedule for the project — 30 months from the contract signing to the start of installation — analyses required for the SAR was started long before the contractors were chosen. Measures were taken to secure big components early in the process, such as forgings, valves, etc. In addition, a number of analyses were started regarding time schedules, interoperability and project execution processes.

Project Puls pinpointed very early in the project's life cycle the need for close cooperation with the contractors to manage all requirements and to integrate the experience from operating the plant for 20 years into the new design.

Our experiences have clearly shown that a megaproject such as Puls needs the competencies, experiences and full engagement from all involved parties. The contractors are fully competent when it comes to the design and manufacturing as well as the functioning of their respective scopes. The owner, OKG, has an important task to ensure plant interoperability, interface engineering, operating and maintenance instructions and plant documentation. This means that OKG has to have a well staffed and competent project organization.

Background

OKG owns and operates three nuclear power plants at the Simpevarp site, located in the southeastern part of Sweden. The three plants produce 10% of Sweden's total consumption of electricity. In early 1990, the electricity market was deregulated after the shock of decreasing prices for electricity; on the market, the prices have stabilized at a higher level than before the deregulation. There are several reasons for this higher cost: the shutdown of Barsebäck, the cost for producing green electricity, which is passed on to the consumers and a lack of production capacity on the Nordic market place (i.e. "Nordpool").

In 2003, the board of OKG decided to start a pre-study for power uprate of unit 3, called the Project Puls. Project Puls is short for power uprate with licensed safety. The objectives were set to:

— Improve reactor safety;
— Enhance staff competence;
— Increase power output;
— Increase the units availability.

The pre-study showed a good return at a reasonable risk profile. The cost of the power uprate was about 25% less compared to a new nuclear power plant. The decision was taken in late 2005 to start implementation of Project Puls in late 2008.

The installation was scheduled for 91 days, and the startup of installation planned for August 2008.

The prerequisite for the short outage was an extensive cable pulling, installation of new cooling water screens and installation of a new cooling water system independent of the existing one.

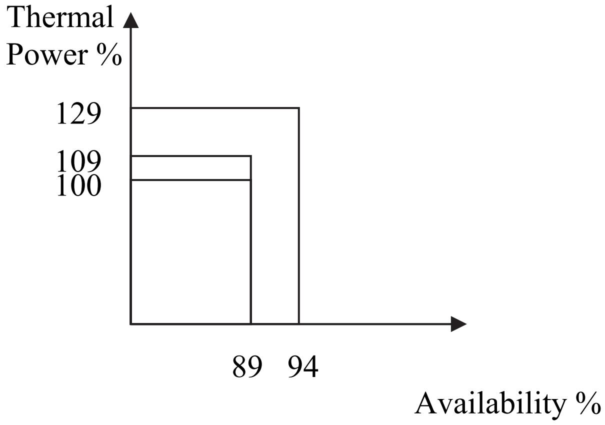


FIG. VI.1. Project objectives in a graph (thermal power and availability).

The thermal upgrade is one of the largest performed in the world and will increase the thermal power by approximately 20% to a total of 129% of the original thermal power (the unit was uprated in 1989 to 109%). At the same time, OKG and Project Puls aim to increase the availability to 94 %. This will be achieved through a new and improved design, exchange of old equipment and OKG's outage philosophy of two short and one long outage.

The increase of availability put extensive demands on the integration between the project/operations department and the maintenance department.

Project Puls is now approaching the end of its project time. Due to delays mainly in the manufacturing of big components, the initial time of 30 months has increased to approximately 40 months. The contract was signed in early 2006 with Westinghouse for the reactor scope and Alstom for the electrical power and turbine scope. Another important contractor is KSU who is responsible for building the new simulator and providing training for the operators on the uprated unit.

KSU is a subsidiary of all nuclear companies in Sweden and provides all training for nuclear operators in Sweden.

The simulator is built in close cooperation with OKG, Westinghouse and Alstom. The timeframe for the project is very short, and the need for concurrent engineering is crucial.

By mid-2009, the project execution had run for a little more than 40 months. During this phase, approximately 50 000 documents had been sent to the contractors, and 20 000 of them had been sent for review.

For the full design phase, Project Puls expects approximately 25 000 documents for review and a total of 100 changes in unit 3. This volume puts a lot of pressure on the project's administrative routines. The project is currently a "paper mill," processing reports and integrating knowledge from different parts of the OKG's organization into the contractors' design process.

The challenge is to manage the requirements from the SSM, the norms, criteria and requirements from the OKG operation, as well as the maintenance and engineering to be taken care of in the design, installation and commissioning done by the contractors Westinghouse and Alstom. All this has to be done in close cooperation with Project Puls. All changes have to be fully integrated within the OKG organization that, for 20 years, has experience in operating and maintaining the unit.

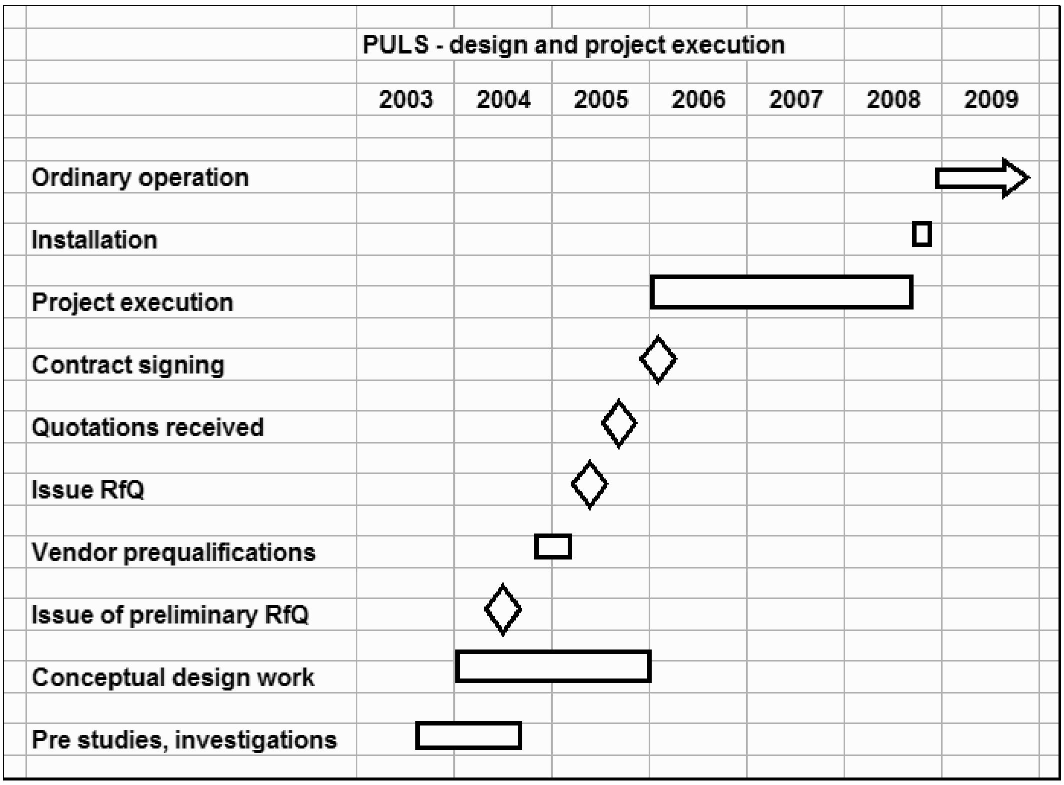


FIG. VI.2. Project Puls life cycle.

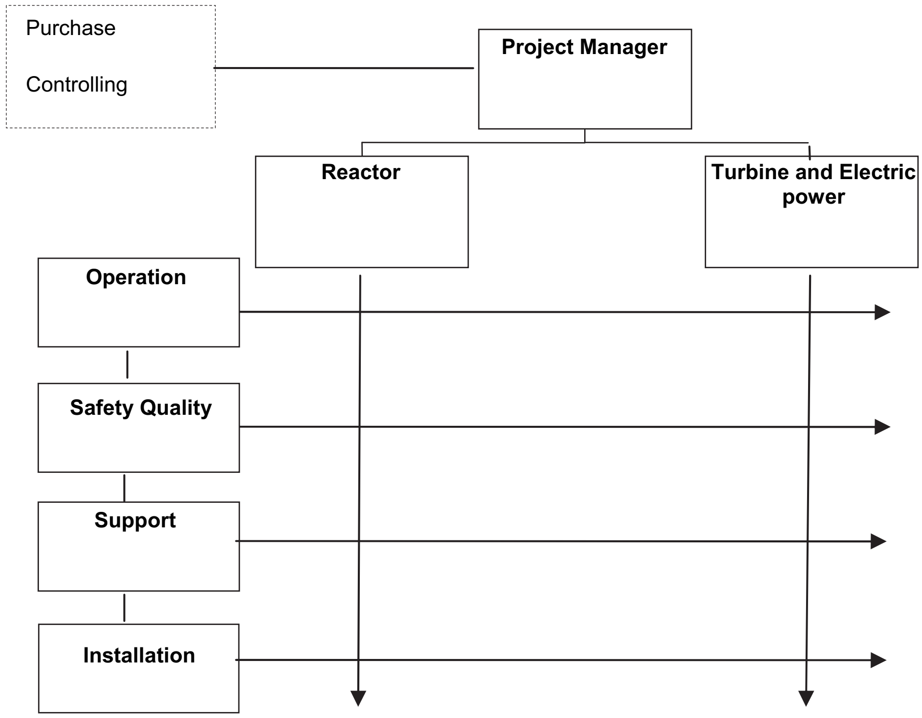


FIG. VI.3. Organization of Project Puls. When changing to the installation phase, the project was reorganized to ensure full support of the suppliers.

Engineering

The full scope of Project Puls reaches beyond the whole unit 3 configuration. The scope starts with the SAR that will be updated. This work was started early and had a large impact on design as well as future operation and maintenance. A lot of decisions regarding technical solutions were made early so that all prerequisites of the SAR analysis were clear before the actual design started. This approach has been successful, and now design and analysis are being integrated as a normal review process. Without this early start of analysis, the execution time schedule would not have been possible. The normal time frame for a power uprate/modernization is almost double in comparison with Project Puls (compare Olkiluoto, Ringhals unit 2 (twice), and Borssele).

The main purpose of this organization is to create close cooperation with our main contractors and to ensure full compliance with the requirements. This organization enables a keen focus on the contractors' work and, at the same time, focus on the full complexity of safety, operation, installation and quality.

All experiences from similar engineering, manufacturing and installation activities show that all competencies from the owner must be used to support the contractors in their work. OKG is responsible not only for the final product but also for any shortcomings arising from the contracted suppliers.

This also changes the way the owner must act in cooperation with the contractors. The key is to be proactive; the contractors are not always aware if the blind spot and to mitigate the risk of loosing time or quality, the OKG must stand close to the contractors in all phases of project execution. The challenge lies in balancing the contractors' responsibility with the necessity of interfering as the owner.

The OKG uses lead engineers in Project Puls. These experienced engineers have written delegations and are assigned from different organizations within the functional organization with the task of ensuring full compliance with all requirements. This approach has the advantage of obtaining quick responses, initiating formal review and design review processes and gaining approvals from the engineering, operations and maintenance departments. The functional organization is consulted for review on crucial or very specific issues when the lead engineer judges it necessary. The specialist resources are then allocated to reviewing the contactors' work. This relationship is of great importance when it comes to building trust and allocating OKG's staff only when it is relevant. The OKG is

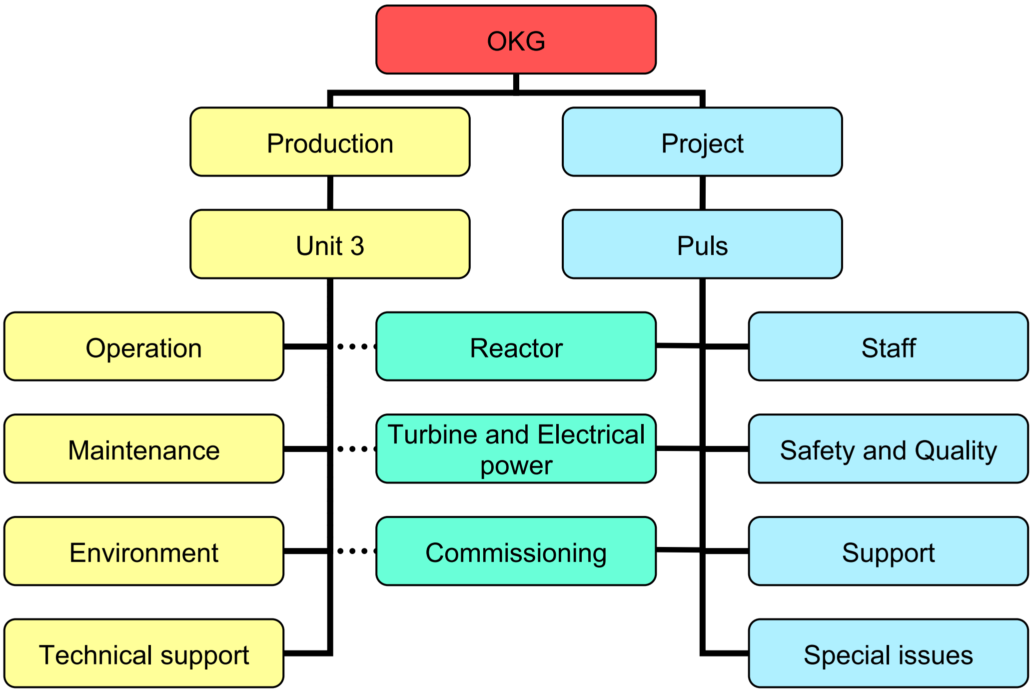


FIG. VI.4. Project Puls and integration with OKG organization.

currently experiencing the largest workload to date with normal operations and megaprojects such as the Puls Project, the power uprate of Oskarshamn unit 2 and the implementation of a new system for physical protection.

The formal system for approval of work in unit 3 is used for Project Puls. The purpose is to create a well known environment for decision makers, engineers, operators, maintenance staff, and independent review staff (i.e. safety and regulator staff).

This means that normal routines and responsibilities are used in order to create barriers to designs not fulfilling the requirements. The decision making process is well established and known to all staff.

The key document used is called a "project report." This report describes the full scope of change for a specific part of the plant (i.e. a process system) together with the requirements. There will be approximately 200 project reports to cover the full Puls scope.

Together with the project report, a "X-list" is developed. This checklist contains all documents relevant to the change.

Another important topic is the fingerprint and its implications on the design and follow-up of the uprated plant.

The fingerprint work started early in the project, and the foundation is experiences from the operation of unit 3 and other nuclear plants, both normal and uprated. The objective of the fingerprint is to ensure that the uprated plant conforms to all requirements and to show that the behaviour of the power station before and after the power uprate is well-known with respect to:

- Power consumption of components;
- Water chemistry;
- Erosion corrosion (Flow accelerated corrosion);
- Vibrations and cracks in the building;
- General measurements and capacity of cooling chains;
- Disturbances in the power station;
- External and internal environment;
- Vibrations in components and system parts.

As mentioned before, the increased availability is one of the main objectives of Project Puls. This creates a need for analyses of the maintenance system as well as for deterministic and probabilistic analyses. The nuclear business is used to the deterministic and probabilistic analyses. These analyses are not sufficient to show when a

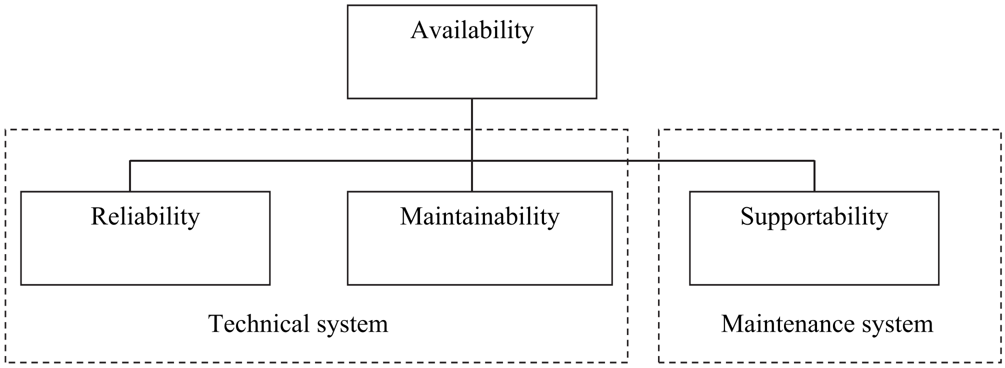


FIG. VI.5. Availability model used as a base for the LCC analyses.

new design ability satisfies availability requirements. OKG has used a methodology (LCC) for availability analyses that was used in the procurement process; the very same method is used for analyses of the new design as well as a baseline for the warranty period analyses of both preventive as well as corrective maintenance. This method takes into consideration FMEA as a tool to evaluate demands on maintenance staff as well as the need for spare parts and components for fast replacements in the unit 3 preventive maintenance programme.

Experience with this work shows that the suppliers are not well prepared for this kind of requirement. The knowledge and capability of taking an overall responsibility for a complex delivery is not a strength with suppliers.

Another important task in Project Puls is the interoperability analyses, which aim to identify areas where the plant’s robustness may be diminished and propose corrective measures with the purpose of maintaining present operational and safety margins. These analyses show that the units respond to a wide array of disturbances as well as normal operation. These analyses reach beyond the different scopes provided by each contractor and include non-affected systems. Depending on experiences and engineers’ judgment, approximately 60 different analyses have been chosen to prove the uprated unit’s ability to operate safely, reliably and predictably.

During a project that runs over several years, such as Project Puls, new requirements or incidents do occur, affecting previously taken decisions within the project. For instance, the Swedish regulator issued new requirements on how the power station should handle and declare to the authorities the presence and work of these suppliers. Also the so-called Forsmark event, where a grid disturbance entered the power station and put safety objects out of operation, occurred during the lifetime of the project.

Both are good examples of how unpredictable the boundary conditions can be. This experience contains both engineering aspects of design and testing as well as how to meet the challenge of how to control changes in the plant and administration. The project must therefore have preparedness for so-called special issues that might arise during the course of the project. OKG is responsible for the outcome of the contractors’ work, putting the focus on the methods and efficiency of our review process as well as the management of requirements.

Close cooperation at all levels within and especially between the involved organizations is a necessity, and it requires common understanding of system performance, operation and maintenance demands. The contractors and OKG engineering staff amount to approximately 300 persons at present, and there has been one technical or administrative meeting per working day on average, all with the purpose of ensuring a common understanding of the detailed requirements as well as the plant’s overriding requirements.

Configuration management

Challenges in a project like Puls are enormous and fascinating. Not only shall short term objectives such as thermal power and availability be fulfilled, or rather be exceeded, the long term objectives must also be met; sustainability in the operability and maintainability of the plant must be secured not only in the plant’s physical appearance but also in the design requirements and documentation for another 40 years, reaching a total lifetime of 60 years. The project must consider all aspects of long term operation of the plant. One area that is stressed is configuration management or the equilibrium between the design requirements, the plants physical appearance and the way it is documented. The objective of configuration management is the conformance of these three elements.

There are severe risks for this equilibrium to be broken when large changes are implemented in a short time. Project Puls has put a lot of effort into ensuring that this equilibrium is maintained all the way from analyses through design and into the documentation system as well as the different IT systems supporting operation and maintenance. Examples of activities carried out to ensure this equilibrium are OKG’s review process, verification and validation, and the structured documentation process in line with the standards of unit 3.

A prerequisite for plant documentation control is a well-structured and well-defined updating routine for new/updated documentation. OKG has three major systems, databases, for handling documentation or better plant status information.

The first is OKG’s plant management system or “ODU Oskarshamn Drift och Underhållsystem”. This system is used for component and system registering as well as for work orders and purchases. The contractors in Puls are responsible for updating this system as part of their scope.

The other is a database called Alladin, which is used for the operational plant. And finally, for the project execution time until the new decimation will be valid for the power station, the documents are handled in a database called Projdok. Both systems allow for controllable updating and a review process.

As mentioned above, the review process is one way to ensure the equilibrium, but as stated earlier, close cooperation between OKG and the contractors is needed to ensure the right interpretation of the requirements and understanding of OKG’s documentation system. Without this close cooperation the full scope of equilibrium cannot be met.

The supervision of the equilibrium is done in review teams and as a part of the formal decision making process where every change is validated not only technically but also regarding documentation. All changes in design and scope have a formal process that controls the conformance with requirements. After commissioning and testing, the project will update “as built” documentation to ensure the equilibrium.

The project uses a “deviation” routine together with change management routines to control deviations. This deviation routine is used when a suspicious deviation is identified. This is one of the main tasks for the QA function.

As a part of the normal project work in Puls, a group called engineering management is used to identify changes and deviations that might have an effect on Project Puls or unit 3. OKG is responsible for this equilibrium, and the contractors are responsible for delivery of analyses and documentation as well as hardware.

This team of very skilled engineers met with the project management team monthly to raise questions about the design for the uprate. This process ensured that the plant’s total requirements were continuously in focus, even after the scope was fixed in the contracts.

In the projects, the safety analysis scope was identified very early and decided to be executed outside the hardware contracts. This approach made it possible to stat the analysis work very early, which was also a prerequisite for the timely execution of the project.

For the control of this early analysis, the project introduced so-called project binding technical decisions (PSTB), where assumptions on the design were documented. These decisions were checked against the actual outcome of the design to ensure that the analyses were made with the right input.

The approval of the preliminary SAR was obtained two weeks before the start of the installation. This was a requirement to start the installation. The SAR is of course the basis for commissioning, verification and validation work.

In addition to the built-in process of verification and validation of the changes introduced to the power station as described in the KG review and testing procedures, project Puls had introduced an additional work with this purpose. The credited functions in the safety analysis report will be broken down into separate testable functions of components. The functions are then compared to the actual test plans and validated.

The margin of the new configuration has been thoroughly examined as part of the updated analysis report. The results of the analysis of the new configuration are then compared to the old one, and the impact is documented. The conclusion is that the margins have decreased in only a few cases, but not under an acceptance level. In all other cases, the margins have increased.

Implementation

Installation of Project Puls is planned for 91 days in the 2009 outage. This short time frame calls for careful planning with full use of the experiences from the contractors as well as from OKG. Pre-installations will be made during operation and the ordinary outages in 2007 and 2008 as preparation for the final installation. There will be approximately 100 changes in the Puls scope, of course with differences in scale. Project Puls and the management team from unit 3 have agreed on an organization for the outage in 2007 and 2008 that is similar to the outage organization of today. This will give OKG the opportunity to use operation and maintenance staff for the surveillance and guiding of contractors in the plant. It will also be a good foundation for work order review and pre-job briefing. The plant and contractor staff will be divided into functional groups during installation. These groups are well-known to OKG staff and provide a good way to focus on each system change in 2008. Examples of functional groups include:

— Turbine systems;
— Auxiliary systems;
— Recirculation pumps and converters;
— Generator systems;
— Primary systems;
— Cooling train system;
— Cooling water systems.

Unit 3 operation and maintenance will not perform any work in the plant that is not coordinated with Project Puls. The scope management is of crucial importance during the life cycle of the project. With changes outside the control of Project Puls, the successful implementation is jeopardized. Therefore, the project management team and the unit 3 management team work close together during the entire 40-month execution period to control the project scope and activities that might affect the scope.

The contractor is responsible for all preparations, including work orders. The contractor and Puls will perform pre-job briefings when deemed necessary. This pre-job briefing will be used to ensure that work orders are correct and that the contractor staff has the knowledge required to manage the work at the site. It will also be valuable practice before the “real” work begins on-site. Experiences have shown that this training is of great value when applied to other OKG activities.

A smooth installation requires experienced staff in the field of electrical safety, industrial safety and work order preparation. The unit as we know it is dismantled in one way, but the reverse is not applicable when the unit will be different at the time of testing. This puts emphasis on work order management, where all aspects of installation, commissioning and testing have to be taken into consideration when the work order is prepared.

To ensure OKG has the right competence for all work provided by the contractors, competence issues are one of the key areas for auditing. All contractors are open to OKG audits, and we perform audits on all “first line” contractors. A list of all sub-suppliers is sent to OKG together with their certificates and, if applicable, licenses for welding, etc.). OKG experiences from other projects, works and reviews may indicate that an audit ought to be initiated. This is done to ensure compliance with all requirements stated in the contracts as well as overriding laws and norms.

Around the time of the outage in 2008, an integrated education of all staff working at site will take place together with Westinghouse and Alstom. This will ensure a highly competent and knowledgeable on-site staff.

This education is a part of the OKG campaign “safety culture” but is extended to include work practices and clean systems at the site.

The OKG routines are used to guarantee the correct level of competence when work is carried out on-site by contractors.

Comparison of a SPU and an EPU in the case of Swedish NPPs

The comparison below is for the Oskarshamn 3 plant where an SPU was made in 1989, five years after first startup. The EPU has been contracted, and implementation is planned for 2008. TVO has undergone approximately the same steps with some variation in the approach. Forsmark 1, 2 and 3 are heading for the approximately the same area with approximately the same scope.

The medium/high risk with EPU must be seen in the contrast to the risk of not taking any measures due to ageing. If a decision is taken to go for plant life extension, measures need to be taken. Then only the extra risk of increasing the power is the risk to be considered when considering the risk/benefit decision.

Training and startup testing

Classroom material presented:

— Technical specifications and updated safety analysis report changes;
— Plant limits and operating condition changes;
— Design changes for EPU;
— New power/flow map;
— Operating procedure revisions;
— Uprate operating experiences.

Simulator training:

— Observed EPU full power conditions;
— Normal operation scenarios;
— Dynamic scenarios selected to highlight both similarities and differences in plant responses at EPU versus current power level to transients and accidents;
— Operator re-qualification training covered two cycles of classroom and simulator training;
— Just in time training planned prior to power ascension.

TABLE VI.2. COMPARISON OF SPU AND EPU OF NPPs IN SWEDEN

Compared area	SPU	EPU
The rate of the power uprate	+9.3% to 109.3% (3300 MW)	+19.8% to 129.1% (3900 MW)
Modifications in the plant	Few: Power flow map, Some other minor changes.	Many: replacements: core shroud head, steam separator, steam dryer, main steam isolation valves, HP-turbine, LP-turbine, generator, main transformer modifications: main circulation pumps, main feedwater pumps, power flow map modifications due to plant life extension are included but not due to new requirements.
The cost	1	Factor 10
Design work needed	Very little and medium level.	Much work and very high complexity
Safety analyses	Re-analysed 10–20% Assessed 30%	Re-analysed 90% Assessed 10% typical value would be 40% and 60% if every analysis were up to date.
Licensing	Low–medium	High
Implementation	Easy	Very complex. To make the implementation in steps would reduce the complexity but increase the cost.
Resources needed	Medium level	Highest level
Number of contractors and subcontractors needed	2	>15
Number of staff in own project organization	<10	80
Training to be considered	Easy to handle	Time critical event
Risk analysis needed	Simplified model good enough	Structured methodology needed
Instructions affected	Low number	Large number

TABLE VI.2. COMPARISON OF SPU AND EPU OF NPPs IN SWEDEN

Documents to handle	Many	Huge
Total complexity	1	>10
Total risk	Low	Medium/high

Startup test overview:

— Careful and deliberate approach to uprated power levels;
— Startup test programme in accordance with ELTR;
— 2% incremental power test programme;
— Power increases along constant rod line to maximum achievable power level;
— Steady state data collection and testing, beginning at 90% of current power;
— Dynamic testing begins at approximately 70% OLTP;
  • Pressure control system;
  • Feedwater level control system;
  • Turbine valve surveillances.

Non-hardware changes:

— Calculations;
— Drawings;
— Technical specifications.

What are operating envelopes?

— Operate the plant to maintain 1179 MVA;
— Do not exceed the licensed power level;
— Do not exceed 97% of thermal power;
— Operate with reactor thermal limits;
— Do not exceed 13.6 million/lb/h of steam flow.

Lessons learned:

— Define operational envelope early;
— Ensure systems are ready to operate where they have never been before;
— Solicit/insist on departmental input;
— System manger, maintenance, operations, OEM;
— Communicate at all levels;
— Works, supervision, management, senior management, vice president;
— Identify and understand margin early;
— Pay close attention to TG and auxiliaries.

EPU effects on margin:
How does it present itself?

— Operational considerations: reduced operator flexibility;
— Design considerations: modification.

Appendix VII

PROCESS DATA RECONCILIATION IN ACCORDANCE WITH VDI 2048 — USE FOR MEASUREMENT UNCERTAINTY RECAPTURE, POWER UPRATE, PROCESS MONITORING, COMPONENT MONITORING AND ACCEPTANCE TESTS IN NPPs

VII.1. INTRODUCTION

The determination of thermal reactor power is traditionally done by establishing the heat balance:

- For a BWR, at the interface of reactor control volume and heat cycle;
- For a PWR, at the interface of the steam generator control volume and turbine island on the secondary side.

The uncertainty of these traditional methods is not easy (impossible) to determine, and it can be in the range of several per cent. Technical and legal regulations (e.g. 10CFR50) cover an estimated instrumentation error of up to 2% by increasing the thermal reactor power for emergency analysis to 102% of the licensed thermal reactor power.

Basically, the licensee has the duty to warrant at any time operation inside the analysed region for thermal reactor power. This is normally done by keeping the indicated reactor power at the licensed 100% value. A better way is to use a method that allows for a continuous warranty evaluation. The quantification of the fulfilment level of this warranty is only achievable by a method which:

- Is independent of single measurement accuracies;
- Results in a certified quality of single-signal values and for the total heat cycle analysis;
- Leads to complete results, including 2σ deviation, especially for thermal reactor power.

This method allows us to determine the true process parameters with a statistical probability of 95% by considering closed material, mass and energy balances following the Gaussian correction principle. The amount of redundant process information and complexity of the process improves the final results. This represents the most probable state of the process with minimized uncertainty according to VDI 2048.

Hence, calibration and control of the thermal reactor power are possible with low effort yet high accuracy, and independent of single measurement accuracies. Furthermore, VDI 2048 describes the quality control of the process parameters. Applied to the thermal reactor power, the statistical certainty of warranting the allowable value can be quantified. This quantification helps to maintain a safety margin in agreement with the authorities.

The determination of thermal reactor power is traditionally done by heat balance. The uncertainty can be in the range of several per cent caused by instrumentation errors. Technical and legal regulations (e.g. 10CFR50) cover an estimated error of up to 2% by increasing the analysed area for emergency cooling analysis to 102 % of the licensed thermal reactor power (see Fig. VII.1).

Figure VII.2 shows that an uncertainty (2σ) of ±2% leads to a probability of 97.5% for the thermal reactor power to be inside the analysed area. It is easy to show that larger uncertainties increasingly fail the warranty to be inside the analysed area. For an uncertainty of 3%, there is only 90% warranty for being inside the analysed area.

Until today, the common strategy of determination of thermal reactor power is based on single parameter measurements with the highest possible (but unknown) accuracy. This can be achieved by the state of the art calibration of flow nozzles, including tracer measurements for total feedwater mass flow or implementation of ultrasonic measurement devices with a sophisticated software evaluation. The disadvantage of all these methods is the unknown absolute accuracy of the field measurement and the unknown development of the accuracy of measurement devices including sensor characteristics, amplifiers, cable links, digitizing circuits and so on.

This method is independent of all of these unknown and uncontrollable influences. The heat balance is done by use of multi-redundant information of operational measurement devices, including the whole heat cycle. The fulfilment of energy and mass balance includes a quality control of the results. Thus a contradiction-free heat balance is warranted with continuous accuracy of about ±0.5% (2σ) for thermal reactor power.

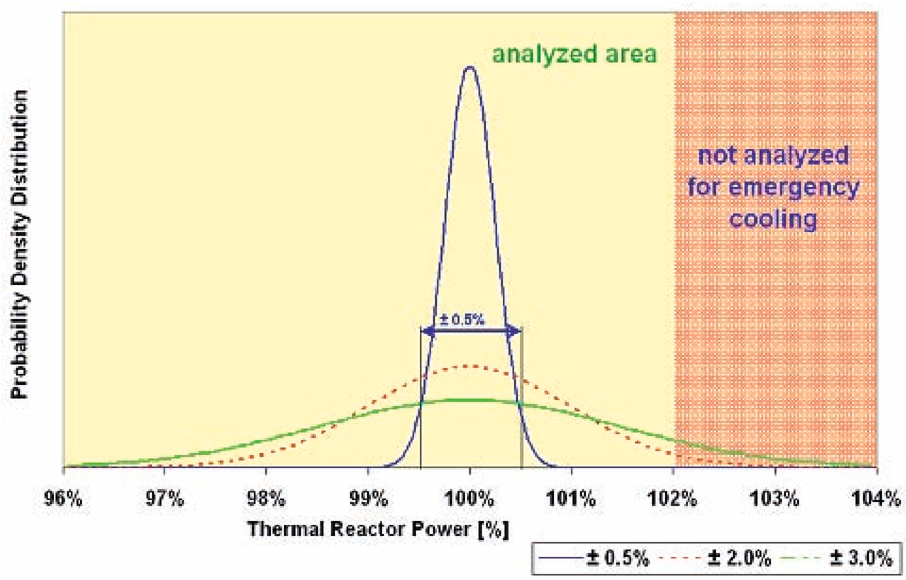


FIG. VII.1. Probability density distribution for different uncertainties.

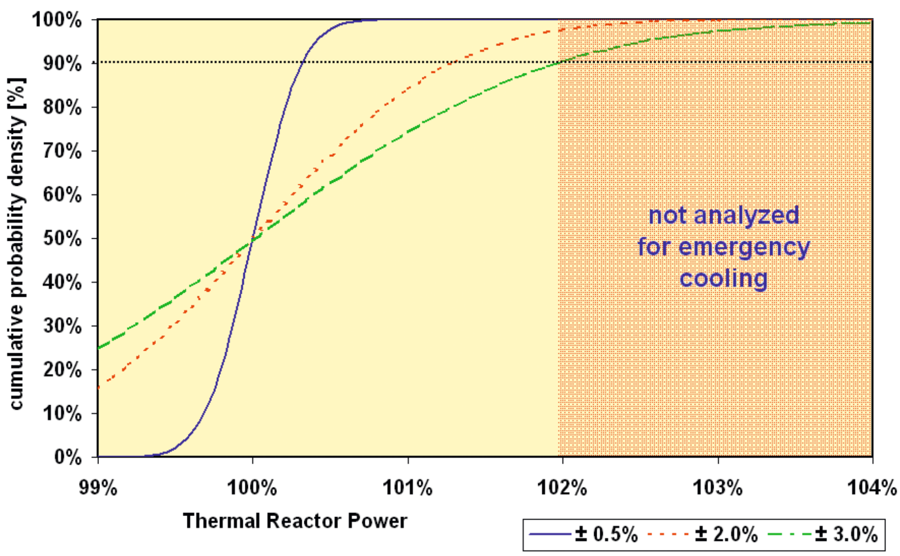


FIG. VII.2. Cumulative probability density distribution.

VII.2. APPLICATION FOR POWER UPRATE

The authors propose a license method for the evaluation of thermal reactor power based on data reconciliation according to VDI 2048 by which the operator has to demonstrate to what extent he is outside the un-analysed area. It is according to present practice that the operator should be able to prove at any time that he is inside the analysed area, with a probability of greater than 97.5%.

The evaluation of thermal reactor power by process data reconciliation is a task comparable to a continuous warranty measurement with a quantified high accuracy, which could easily be verified by the authorities.

VII.3. BENEFITS FOR THE OPERATORS

The smaller the uncertainty of the thermal reactor power is, the more margin the operator can use for operating at a higher reactor power level, maintaining, at the same time, the committed level of safety. This method is known as measurement uncertainty recapture (MUR) in the USA.

MUR pays for itself and assures a high level of safety. There is no longer a need for expensive calibration procedures or other expensive and dose rate related tests.

VII.4. PRINCIPLE OF PROCESS DATA RECONCILIATION BASED ON VDI 2048

All measured values are subject to distortions caused by avoidable, systematic or random errors. For more than 200 years, the Gaussian correction principle that is complemented by taking boundary conditions into account has been available as an estimation method in the statistical–mathematical sense that allows measurement errors to be detected.

The basic idea of this method is to use not only the minimum quantity of measured variables required to obtain a solution but to record all accessible measured variables along with the respective variances and covariances. Additionally, the true values of the measured variables must meet the boundary conditions of:

- Mass balances;
- Energy balances; and
- Material balances (stoichiometric laws, phase separation).

This method is described in VDI 2048 [5] and is the best possible quality control method available to detect serious measurement errors. This methodology allows consistent estimations of the true values of the measured variables to be derived from conflicting measured values. The consistently estimated values thus obtained correspond to the true values with a 95% probability.

Gaussian correction principle

Corrections ν are made to the measured values x in accordance with Eq. (VII.1) in order to obtain estimated values (reconciled values) $\overline{x}$.

$$\overline{x} = x + \nu \qquad \text{(VII.1)}$$

The corrections ν must be determined in such a manner that the quadratic form

$$\xi_0 = \nu^T \cdot S_x^{-1} \cdot \nu \Rightarrow \text{Min} \qquad \text{(VII.2)}$$

ξ_0 = square form of errors
S_x^{-1} = inverse empirical covariance matrix

becomes a minimum. The empirical covariance matrix S_x is the estimated value for the uncertainty of the measured variables X. This general formulation also covers the existence of covariances (i. e. the interdependencies of the measuring points). The improved covariance matrix $S_{\overline{x}}$ is calculated from the empirical covariance matrix S_x and the covariance matrix of the improvements S_v as follows:

$$S_{\overline{x}} = S_x - S_v \qquad \text{(VII.3)}$$

Quality control

As a quality control measure, two criteria must be fulfilled for process data reconciliation based on VDI 2048. For one thing, the square form of errors ξ_0 contained in Eq. (VII.2) must be smaller than $\chi^2_{95\%}$ (95% quantile of χ^2).

$$\text{VDI 2048 criterion 1: } \xi_0 < \chi^2_{95\%} \tag{VII.4}$$

The 95% quantile of χ^2 is a statistical measure for the number of model redundancies. The number of model redundancies is dependent both on the number of equations contained in the model and on the number of embedded measured values and reflects the overdetermined character of the system. The relationship between the square form of errors and χ^2 is referred to as reconciliation quality (see Eq. (VII.5)). Generally, the following applies: The smaller the reconciliation quality, the better is the quality of the measured values.

$$\text{Reconciliation quality} = \xi_0 / \chi^2_{95\%} \tag{VII.5}$$

Additionally, the value of the individual penalty must be smaller than the statistical coefficient of 1.96. The value of the individual penalty of a measuring point is the ratio of the square of the improvement ν_i to the difference between the estimated uncertainty of the measured value $s_{x,ii}$ and the calculated standard deviation of the reconciled value $s_{\bar{x},ii}$ (see Eq. (VII.6)).

$$\text{VDI 2048 criterion 2: } \frac{|\nu_i|}{\sqrt{s_{x,ii} - s_{\bar{x},ii}}} = \frac{|\nu_i|}{\sqrt{s_{\nu,ii}}} \leq 1.96 \tag{VII.6}$$

This criterion must be complied with for all measured values i. If it is not complied with, a serious fault exists for the corresponding measuring point i or for the estimated value of the associated uncertainty.

In this case, the reconciled value as well as the measured value itself is questionable. If both of the above criteria are complied with, the reconciled measured values $\bar{x}$ correspond to a 95% probability of the true physical state variables.

Benefits for an industrial process

When process data reconciliation based on VDI 2048 is applied to any industrial process, measured temperatures, mass flows and pressures lose their singular character. The physical relationships between the measured parameters generated via secondary conditions such as mass balance and energy balance result in a process image that corresponds to the physical basis of the process as closely as possible. The relationships thus generated can be represented via the correlation coefficients that result from the improved covariance matrix. A typical process model for a nuclear power plant generated with VALI 4 usually consists of:

— 150 to 350 measurements as input values;
— 600 to 1200 equations;
— 80 to 200 redundant pieces of information.

Use for MUR

Currently, in some German and Swiss nuclear power plants, the method of monitoring and evaluating thermal reactor power is embedded in a total quality management (TQM) process with clear criteria for action. There are two ways to implement the reconciliation results into the real process:

(1) The correction of the measurement (mainly feedwater and temperature) is done directly at the transducer with a potentiometer (after reaching 100% load);
(2) Insert a new process value, which is based on a correction factor calculated with reconciled values.

Both methods can be used during the operation of the plant. The proceedings for the implementation are:

Method 1

— Calculation of the differences between the reconciled value and measurement;
— Setting up with a potentiometer;
— After some iterations, the final setting is adjusted (Fig. VII.3).

Method 2

— Definition of a new process value within the process control system;
— Continuous calculation of a correction factor (ratio of reconciled value to measurement);
— Implementation of a static correction factor into the process control system (Fig. VII.4).

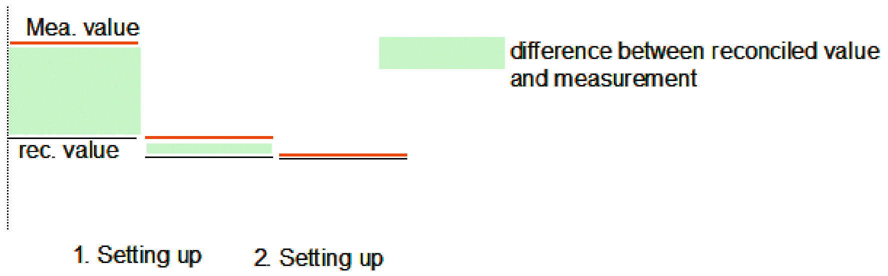


FIG. VII.3. Correction procedure with Method 1.

Standard calculation

$P(\text{thermal reactor power}) = f(\dot{m}, T)$ with $\dot{m}$, T raw measurements

With process data reconciliation and correction factors

$P(\text{thermal reactor power}) = f(\dot{m}_{corrected}, T_{corrected})$ mit

$\dot{m}_{corrected} = \text{correction factor1} \times \dot{m}$ and

$T_{corrected} = \text{correction factor2} \times T$

and

$$\text{Correction factor1,2} = \frac{\text{Reconciled value}}{\text{measurement}}$$

Example: $T_{measurement} = 217\ °C$, $T_{reconciled\ value} = 218°C$

$$\text{Correction factor2} = \frac{218\ °C}{217\ °C} = 1{,}0046$$

FIG. VII.4. Correction procedure with Method 2.

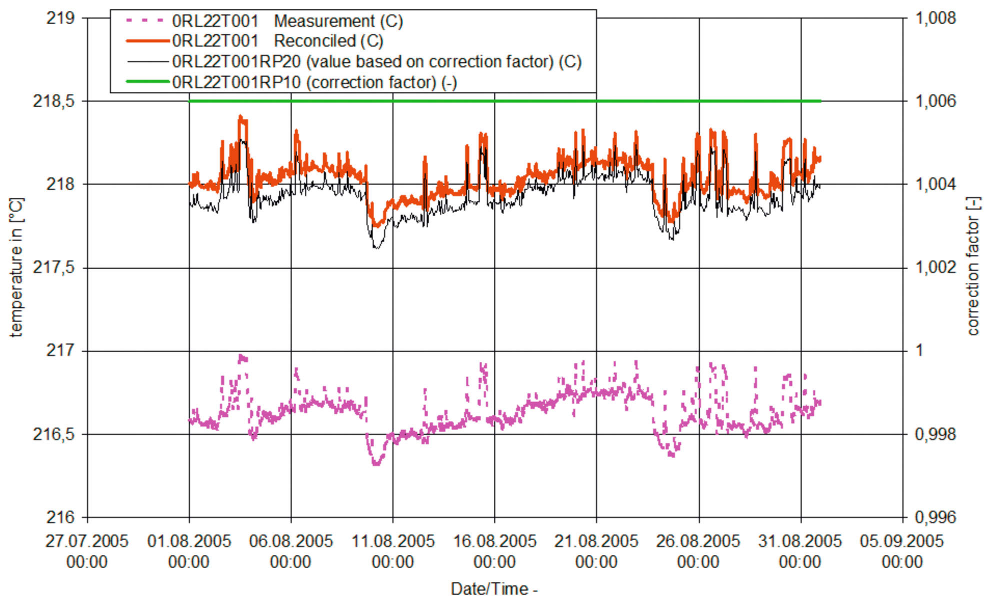


FIG. VII.5. Real correction of feedwater temperature.

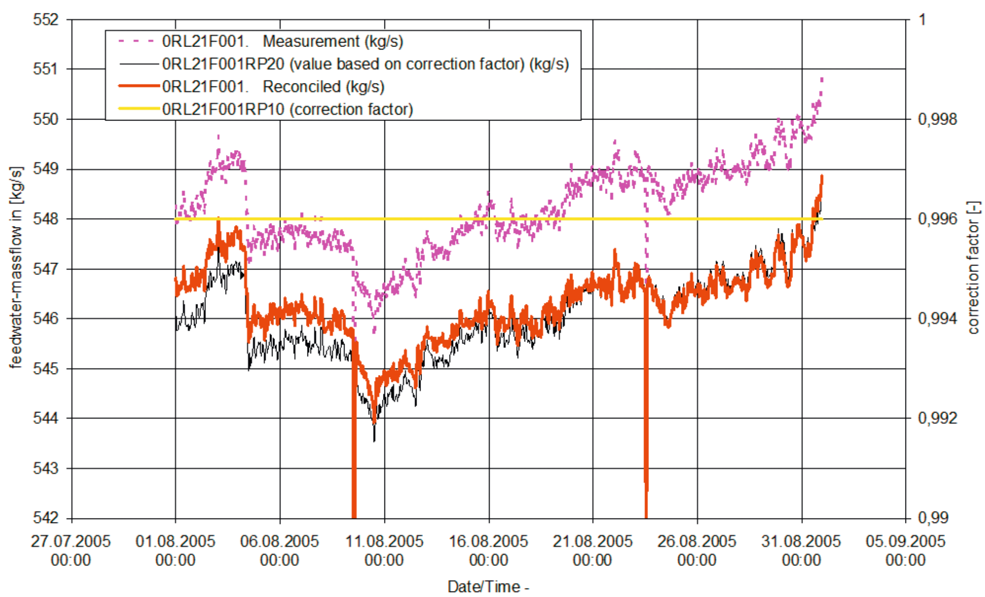


FIG. VII.6. Real correction of feedwater mass flow.

VII.5. ADDITIONAL USE OF PROCESS DATA RECONCILIATION

Process data reconciliation described in VDI 2048 [VII.1] is used for:

— True process monitoring;
— Component monitoring system;
— Process optimization;
— Maintenance optimization;
— Acceptance tests.

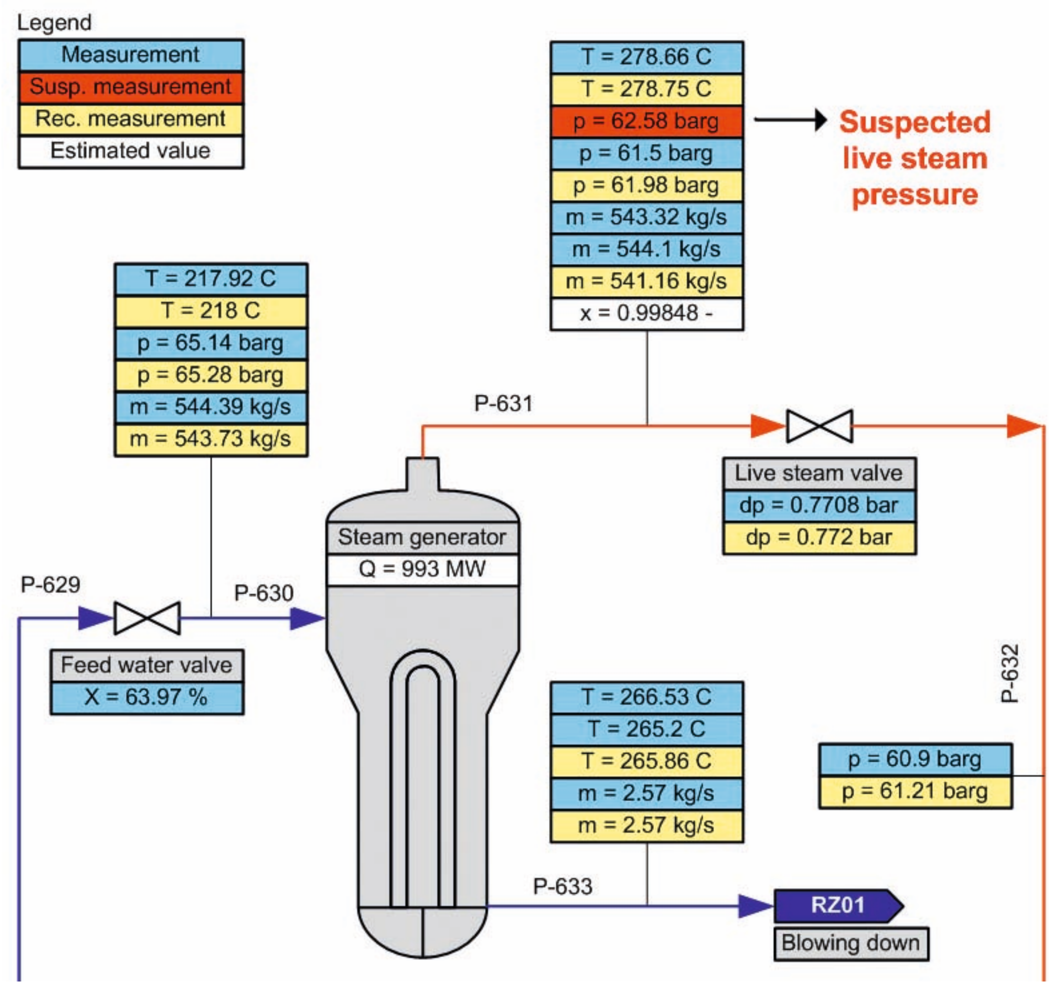


FIG. VII.7. Process flow diagram (section steam generator).

Process monitoring

ProcessPlus™ is a pre and post processing tool based on Microsoft Visio and Visual Basic. The modules of the *ProcessPlus*™ process monitoring system are:

— Event file;
— Tree view;
— Process flow diagram (Fig. VII.7);
— Component monitoring system;
— Value field information and functions.

VII.6. PROCESS FLOW DIAGRAM

Figure VII.8 depicts a steam generator of a pressurized water nuclear power plant. In addition to the measured values, the process flow diagram of the monitoring system presented here includes the reconciled values as well as additional parameters calculated by the reconciliation process.

Using the link to the database that contains the original measured values and the reconciliation results, the reconciliation run was read into the process flow diagram with a time stamp of 31.08.2006 23:00 hours. After reading in the reconciliation run, targeted searches can be performed for the suspected tag that has occurred, and the relevant process area will be displayed.

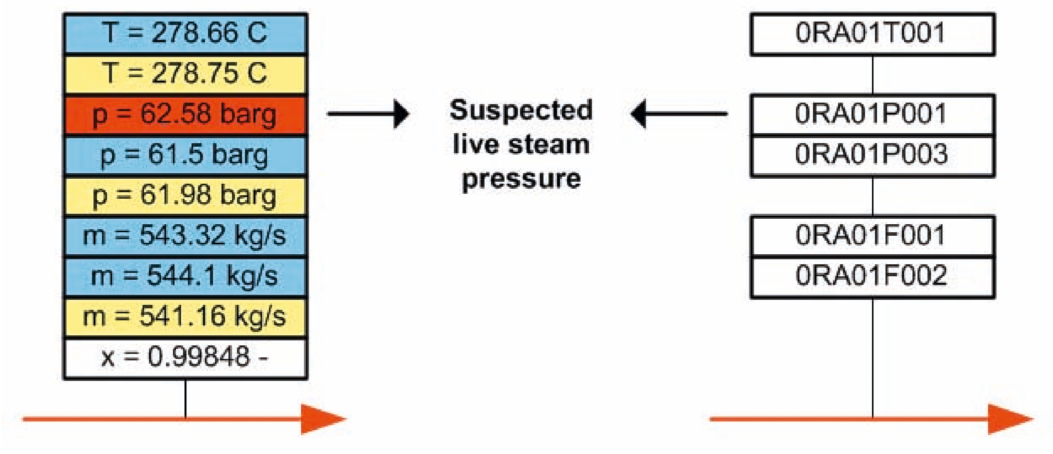


FIG. VII.8. Process flow diagram ↔ measuring points diagram.

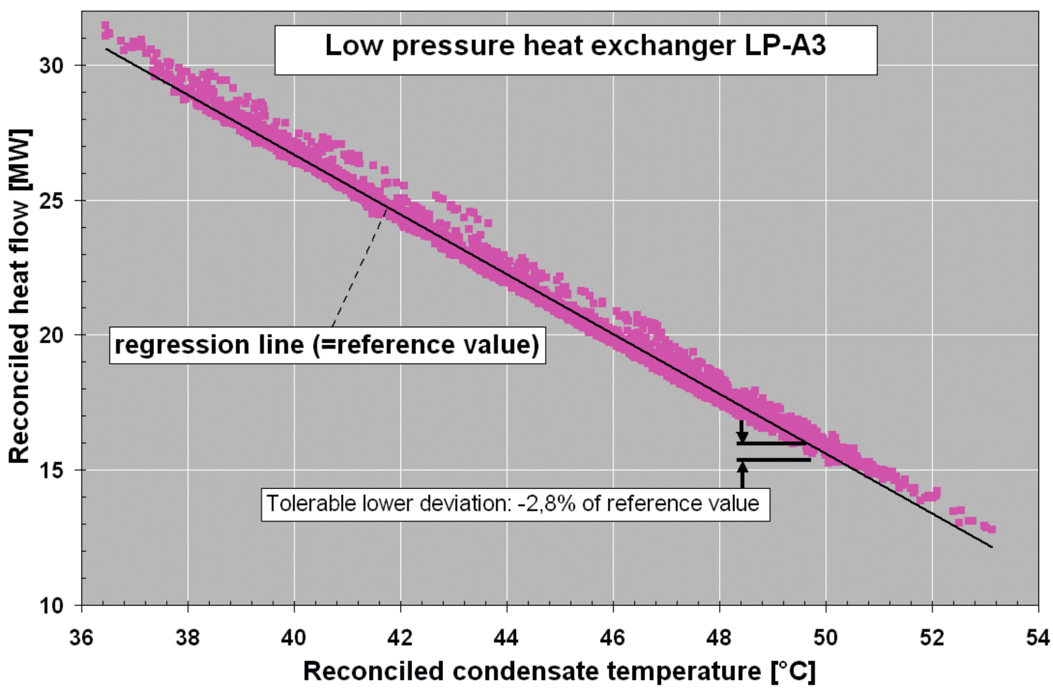


FIG. VII.9. Characteristic curve of a heat exchanger.

As shown, the live steam pressure is marked as a suspected tag (i.e. VDI 2048 criterion 2 is violated). Its single penalty is calculated as follows (cf. Eq. (VII.6)):

$$\text{single penalty} = \frac{|v_i|}{\sqrt{s_{x,ii} - s_{\bar{x},ii}}} = \frac{|x_i - \bar{x}_i|}{\sqrt{s_{x,ii} - s_{\bar{x},ii}}} = 2.39 > 1.96 \qquad \text{(VII.7)}$$

The individual parameters in the above Eq. (VII.7) are the results of the measured value and of the results of the reconciliation run:

x_i = 62.58 barg (measured value)
$\bar{x}_i$ = 61.98 barg (reconciled value)

Loads of low pressure preheaters							
Component	Part	Reconciled value	Unit	Reference value	Tolerable deviation to reference value [%]		Dev. to reference [%]
Low pressure preheating	LP-A1	1.3	MW	1.33	-5.8 %	+10.0 %	-2.09 %
	LP-B1	1.18	MW	1.23	-5.8 %	+7.5 %	-3.87 %
	LP-A2	6.5	MW	6.73	-13.4 %	+6.4 %	-3.36 %
	LP-B2	6.84	MW	7.08	-13.4 %	+6.4 %	-3.39 %
	LP-A3	22.54	MW	22.2	-2.8 %	+6.4 %	1.52 %
	LP-B3	19.87	MW	20.18	-4.2 %	+6.4 %	-1.5 %
	LP-A4	89.48	MW	91.87	-9.3 %	+4.5 %	-2.61 %
	LP-B4	93.22	MW	96.74	-9.3 %	+4.5 %	-3.63 %
	LP-A5	96.22	MW	94	-2.5 %	+11.9 %	2.36 %
	LP-B5	98.69	MW	99.36	-2.5 %	+2.5 %	-0.67 %

FIG. VII.10. Excerpt from the component list.

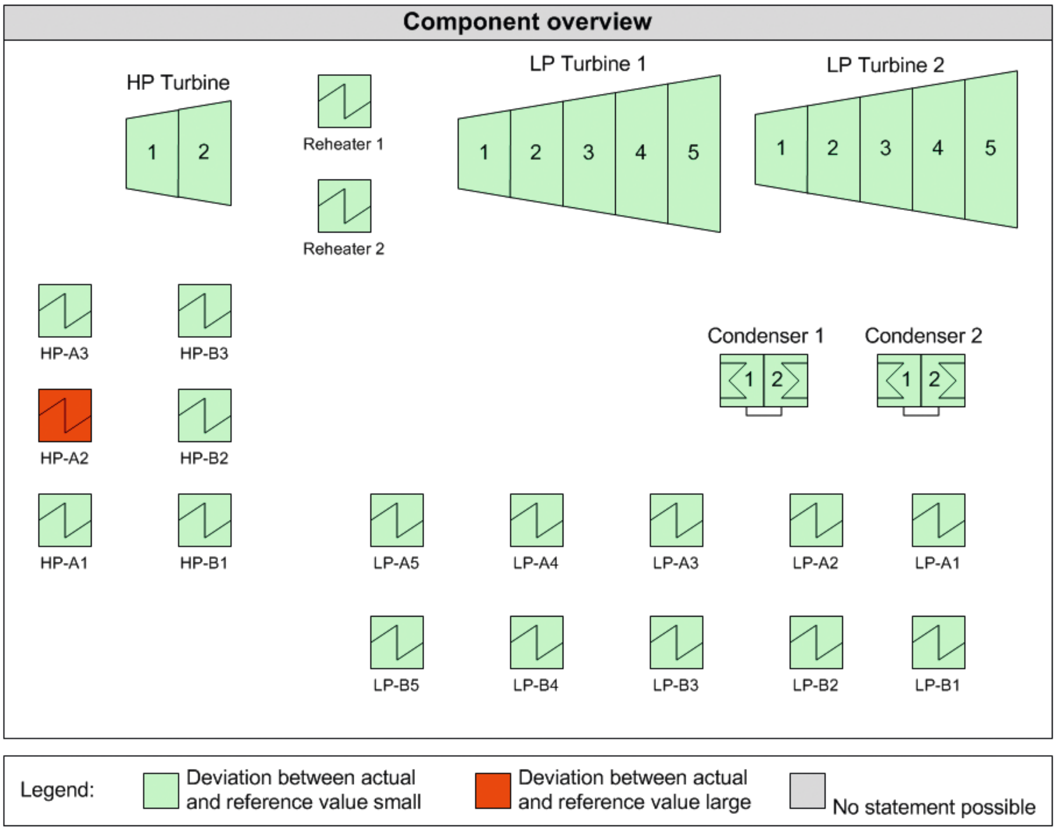


FIG. VII.11. Component overview.

$s_{x,ii}$ = 0.105 (variance of the measured value)
$s_{\bar{x},ii}$ = 0.042 (variance of the reconciled value)

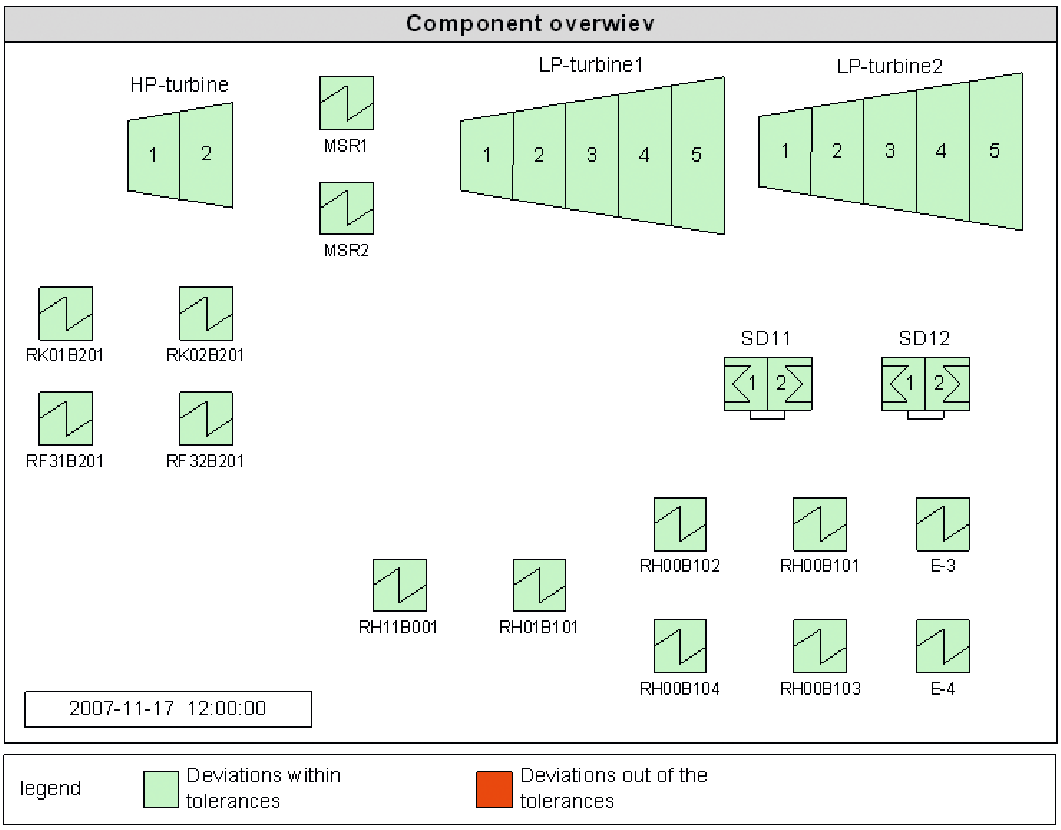
In case a measuring point diagram is to be generated from the process flow diagram of Fig. VII.11, the signal names can be shown instead of the original measured values (see Fig. VII.9). Optionally, the reconciled measured values and the calculated parameters can be masked out. Using the “measuring points diagram”, the signal names can be identified. The signal name will also be displayed when it is clicked with the mouse cursor (Quick info).

VII.7. COMPONENT MONITORING SYSTEM

The component monitoring system is intended to make the user aware of any deterioration of the heat transmission of each heat exchanger at an early stage. This application is based on reconciled data, which is used to build characteristic curves for each component. Figure VII.10 is an example of such a characteristic curve of a heat exchanger. It depends on the condensate temperature. For all cases, the dots of Fig. VII.10 fulfil the overall mass and energy balance of the process.

In the component monitoring part of the *ProcessPlus*™ system itself, the regression line and the tolerable lower and upper deviations of Fig. VII.10 are defined. In Fig. VII.11, a part of the component list is shown. The actual reconciled values and the reference values of each heat exchanger are displayed. Also the deviations and the tolerable deviations are displayed. The tolerable deviations and the reference value are derived from the characteristic curve distribution (see Fig. VII.10).

In Fig. VII.12, these results are shown in a schematic display of the process with each heat exchanger and turbine stages. The turbine stages are monitored by comparing the actual isentropic efficiency, and the corresponding isentropic efficiency of the past (reference value). The reference value for the isentropic efficiency is a function of the condenser pressure. The component behaviour is displayed at a glance. “Green” means that the component lies within the tolerable deviations, “Red” indicates that something has changed and further analysis needs to be conducted.



Heat rates MSRs							
component	part	Reconciled value	unit	Nominal value	Tolerable deviation to nominal value[%]		Dev. In [%]
MSRs	MSR1	78.02	MW	77.98	-3.0 %	+3.0 %	0.05 %
	MSR2	79.24	MW	79.24	-3.0 %	+3.0 %	0 %

FIG. VII.12. Situation before the accumulation (2007-11-17).

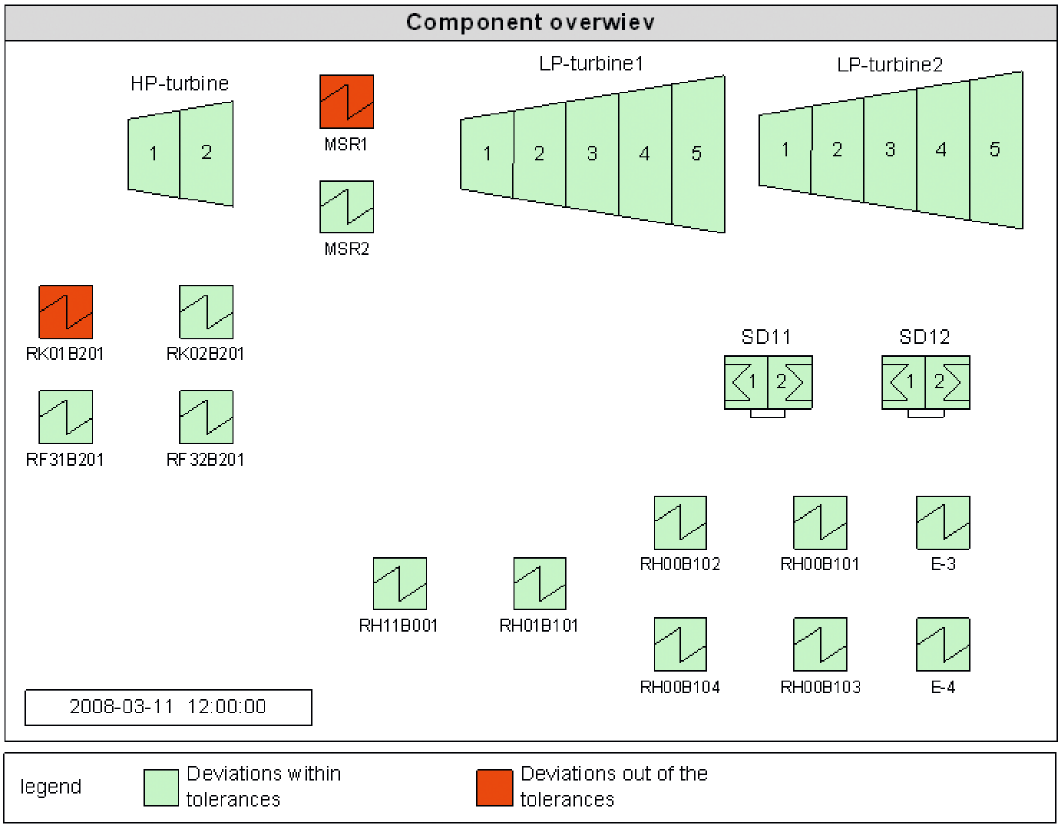
Benefits for plant operation

The benefits for thermal performance engineers can be found by an early stage of differentiation and detection of:

— Erroneous measurements and drifts;
— Physical deviation of equipment performance;
— Inner leakages of preheaters or drain lines;
— Accumulation of non-condensable gases;
— Condenser fouling;
— These are all events that have an impact on safety, availability, reliability and performance of the plant.

Safety

In the case of a feedwater mass flow measurement drift on an erroneous measurement which has an influence on the thermal reactor power calculation, *ProcessPlus*™ serves as a system that detects a possible overpower event at a very early stage. In addition, the detection of non-condensable gases (e.g. radiolysis gases) in boiling water reactors is also a safety-related motivation for using this system. In the past, *ProcessPlus*™ has detected non-condensables in low-pressure preheaters and in moisture separator reheaters (MSR). In this case, the MSR was taken out of operation. In Fig. VII.13 the situation before and in Figure VII.14 after, the accumulation of the non-condensables in the MSR is displayed.



Heat rates MSRs							
component	part	Reconciled value	unit	Nominal value	Tolerable deviation to nominal value[%]		Dev. In [%]
MSRs	MSR1	69.84	MW	77.98	-3.0 %	+3.0 %	-10.43 %
	MSR2	77.05	MW	79.24	-3.0 %	+3.0 %	-2.76 %

FIG. VII.13. Situation after the accumulation (2008-03-11).

VII.8. ACCEPTANCE TESTS

The results of acceptance tests with highly accurate measurements (conventional acceptance test) and with VALI 4 (only data of operational instrumentation were used) for a low-pressure turbine retrofit in an NPP is shown in Table VII.1.

VII.9. UNCERTAINTY OF REACTOR POWER DETERMINATION

Table VII.2 shows the status of reactor power uncertainty at various nuclear power plants in 2007, only achieved by use of operational instrumentation and process data reconciliation according to VDI 2048.

VII.10. CONCLUSION

With process data reconciliation, NPPs could hold the true thermal reactor power in a very narrow range, thereby avoiding production losses, easily detecting minor changes in the heat cycle and keeping a quantified margin to the designed safety limits. In addition, the same process data reconciliation model can be used for acceptance tests, component diagnosis and for evaluation of necessary maintenance activities.

TABLE VII.1. COMPARISON OF THE RESULTS OF A CONVENTIONAL ACCEPTANCE TEST AND WITH PROCESS DATA RECONCILIATION

Activities	Power uprate	Uncertainty
Agreed of power uprate based on DIN 1942/1943	30 MW	±0.5% of the measured generator output (ca. 7 MW)
Result of the conventional test	30.86 MW	
Result of the VALI III acceptance test	30.96 MW	±9.3 MW

TABLE VII.2. UNCERTAINTY OF REACTOR POWER 2007

Type	Plant	Licensed thermal reactor power [MW_{th}]	Reconciled uncertainty (2σ) [%]
PWR	GKN 1	2497	0.59
	GKN 2	3850	0.38
	KKP 2	3950	0.53
	KKG	3002	0.35
BWR	KKP 1	2575	0.69
	KRB B	3840	0.59
	KRB C	3840	0.59
	KKL	3600	0.4

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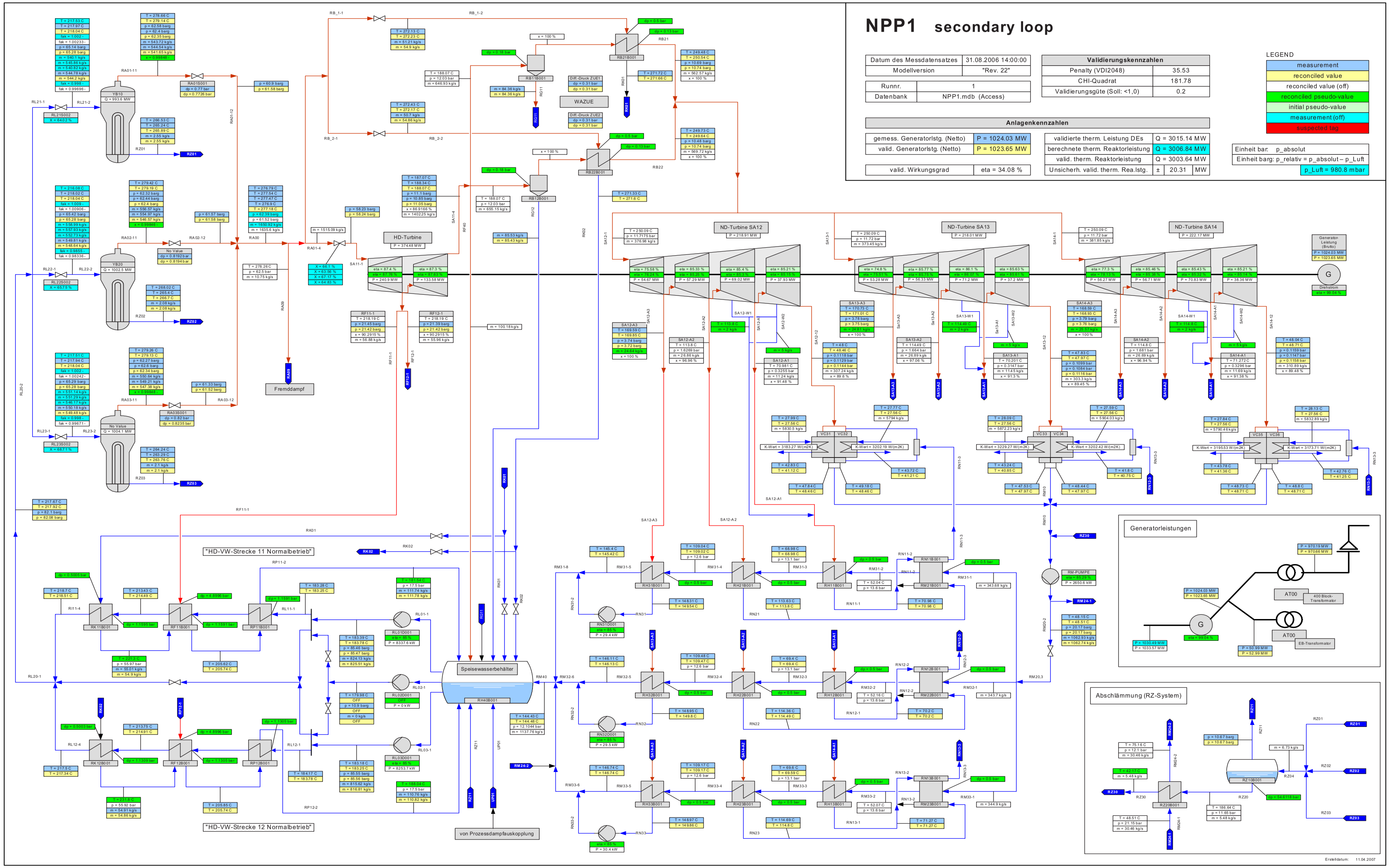
Annex I

PROCESS FLOW DIAGRAM (SECTION SECONDARY CIRCUIT)



ABBREVIATIONS

AECL	Atomic Energy of Canada Limited
AFWS	auxiliary feedwater system
APRM	average power range monitor
APU	active processing unit
ASME	American Society of Mechanical Engineers
ATWS	anticipated transients without scram
AVR	automatic voltage regulator
BOP	balance of the plant
CCWS	component cooling water system
CFR	Code of Federal Regulations (USA)
COSMOS	core stability monitoring system
CPS	Clinton Power Station
CSS	containment spray system
CVCS	chemical and volume control system
DAS	data acquisition system
DNBR	departure from nucleate boiling ratio
ECCS	emergency core cooling system
EFPY	effective full power years
ELTR	extended power uprate licensing topical report
EOP	emergency operating procedures
EPU	extended power uprate
EQ	equipment qualification
ESF	engineered safety features
FMEA	failure modes and effects analysis
FP	full power
FSAR	Final Safety Analysis Report
GE	General Electric Corporation
HELB	high energy line break
HP	high pressure
HPSP	high power set point
HSS	high speed stop
I&C	instrumentation and control
INPO	Institute of Nuclear Power Operations
IPB	isolated phase bus
IPU	interim power uprate
KKL	Leibstadt Nuclear Power Plant (Switzerland)
LAR	License Amendment Request
LEFM	linear elastic fracture mechanics
LOCA	loss of coolant accident
LP	low pressure
LPSP	low power set point
LVDT	linear variable differential transformer
MCO	moisture carryover
MDRFP	motor driven reactor feedwater pump
MELLLA	maximum extended load line limit analysis
MPT	main power transformer

MSLB	main steam line break
MUR	measurement uncertainty recapture
NEA	OECD Nuclear Energy Agency
NRC	Nuclear Regulatory Commission (USA)
NSSS	nuclear steam supply system
NTSP	nominal trip set point
OLTP	original licensed thermal power
PLiM	plant life management
PRC	Project Review Committee
PSAR	Preliminary Safety Analysis Report
PTS	pressurized thermal shock
PU	power uprate
RAI	request for additional information
RCP	reactor coolant pump
RCS	reactor coolant system
RFP	reactor feed pump
RHRS	residual heat removal system
RPV	ractor pressure vessel
RTP	eactor thermal power
SAMG	severe accident management guidelines
SAR	Safety Analysis Report
SCRAM	emergency shutdown of a nuclear power plant
SEHR	special emergency heat removal
SER	significant event report
SFPCS	spent fuel pool cooling system
SG	steam generator
SGLC	steam generator level control
SGTP	steam generator tube plugging
SLO	single loop operation
SMAP	safety margin action plan
SPU	stretch power uprate
SRP	standard review plan
SRV	safety/relief valve
SSC	systems, structures and components
SSM	Swedish Radiation Safety Authority
STF	technical specifications for operation
TDRFP	turbine driven reactor feedwater pumps
TG	turbine and generator
TIL	Technical information letter
TLO	two loop operation
TPU	target power uprate
TQM	total quality management
TRS	Technical Reports Series (IAEA)
UFM	ultrasonic flow meter
WWER	water cooled and moderated energy reactor
WT	turbine building closed cooling water

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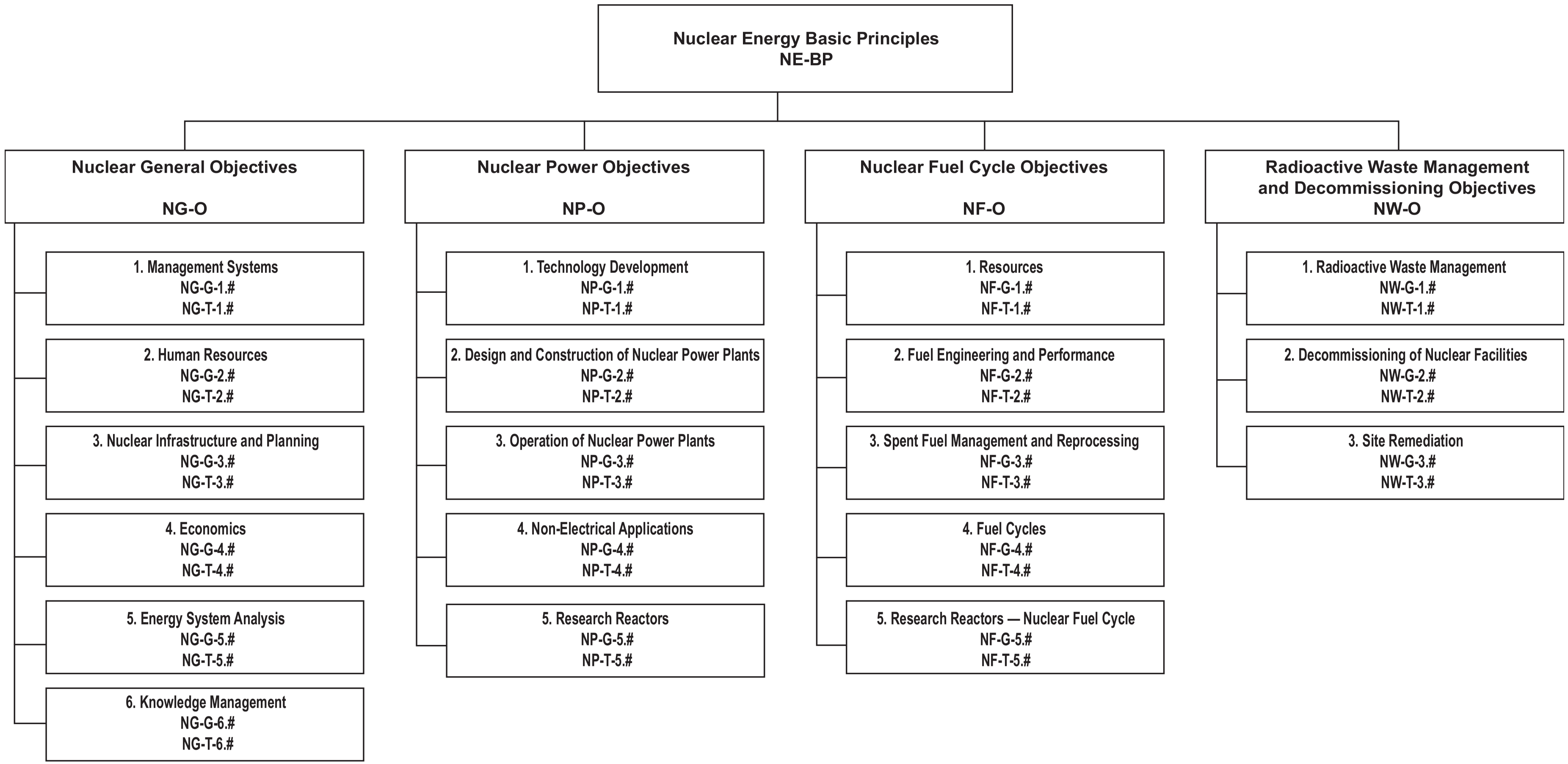

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