POWER UPRATES IN NUCLEAR POWER PLANTS: INTERNATIONAL EXPERIENCES AND APPROACHES FOR IMPLEMENTATION

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The greater demand for electricity and the available capacity within safety margins in some operating NPPs are prompting nuclear utilities to request license modification to enable operation at a higher power level, beyond their original license provisions. Such plant modifications require an in-depth safety analysis to evaluate the possible safety impact. The analysis must consider the thermo hydraulic, radiological and structural aspects, and the plant behavior, while taking into account the capability of the structures, systems and components, and the reactor protection and safeguard systems set points.

The purpose of this paper is to introduce international experiences and approaches for implementation of power uprates related to the reactor thermal power of nuclear power plants. The paper is intended to give the reader a general overview of the major processes, work products, issues, challenges, events, and experiences in the power uprates program.

The process of increasing the licensed power level of a nuclear power plants is called a power uprate. One way of increasing the thermal output from a reactor is to increase the amount of fissile material in use. It is also possible to increase the core power by increasing the performance of the high power bundles. Safety margins can be maintained by either using fuels with a higher performance, or through the use of improved methods of analysis to demonstrate that the required margins are retained even at the higher power levels.

The paper will review all types of power uprates, from small to large, and across various reactor types, including light and heavy water, pressurized, and boiling water reactors. Generally, however, the content of the report focuses on power uprates of the stretch and extended type. The International Atomic Energy Agency (IAEA) is developing a technical guideline on power uprates and side effects of power uprates in nuclear power plants.

KEYWORDS : Power Uprates, Safety Margin, Design Phase, NSSS, BOP

1. INTRODUCTION

Currently, a significant number of nuclear power plants (NPPs) have plans for power uprates (PUs) of various amounts. In most cases, this is an economical way of producing more electricity in a NPP, which has attracted interest due to increased electricity prices, which are expected to continue to rise. The increase in the electricity produced in a NPP can be achieved in two ways.

- One way is to increase the thermal power in the reactor, and
- The other way is to improve the thermal conversion efficiency in the power plant by refurbishing or replacing the high-pressure or low-pressure turbine units or a combination of these actions.

In Boiling Water Reactors (BWRs), the increased core power is achieved by increasing the core feed water flows and steam flows. The degrees of re-circulation can be retained, with larger steam voids in the cores, or the steam volumes can be held constant by increasing the re-circulation flows. A combination of these measures can also be applied.

In Pressurized Water Reactors (PWRs), the increased power outputs call for an increase either in the core coolant flows or in the mean coolant temperature rise across the cores, or both. In all cases, secondary steam production increases, with increased electricity outputs being achieved by the turbo generators.[1]

Power uprates have been employed to enhance the output of US NPPs for over 27 years. During this period, advances in technology and the licensing environment have enabled the development and continued implementation of standard and new PU approaches and strategies.

In the US alone, over 100 PUs ranging from 1.3% to 20% have been approved by the Nuclear Regulatory Commission since 1977 for a total of about 4500 additional MWe to the nation's electrical grid. An additional 947 MWe is expected to be added to the grid from PUs through the year 2008. The benefits of PUs 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 plant life extension. See Table 1. [2, 3]

Table 1. Power Uprates Status in United States NPPs

Type	Total MWt	Approx MWe	%
EPU	4629	1543.00	33.55%
SPU	7695.2	2565.07	55.77%
MUR	1472.8	490.93	10.67%

Note:

- *EPU – Extended power uprate* – A term generally used to describe a large increase in licensed reactor thermal power above the originally licensed thermal power (OLTP). In the US, the Nuclear Regulatory Commission (NRC) has defined any uprate of 7% or higher to be an EPU.
- *SPU – Stretch power uprate* – A term generally used to describe 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 using existing design margins in the plant equipment. In the US, the NRC has defined a stretch power uprate as any uprate less then 7% of the OLTP of the plant.
- *MUR uprate – Measurement uncertainty recapture uprate* – A term applied to the regulatory process of reducing certain emergency core cooling system assumptions regarding reactor power measurement uncertainty from a standard assumption (typically 2-3%) to a specific value based on the use of more accurate ultrasonic feedwater flow measurement devices.

In Sweden, the nuclear operator OKG is to invest one billion Swedish kronor (130 million US Dollars, 110 million Euros) to increase the electrical power output of Oskarshamn-3 from 1,200 megawatts (MWE) to 1,450 MWE. OKG's owners, E.ON Sweden and Fortum, said the project would be carried out during 2008. The Swedish nuclear power inspectorate SKI approved the uprates last year, but OKG still needs a government permit. OKG called the planned uprates "the most significant industrial project" in southern Sweden since 1985, when Oskarshamn-3 was completed. On a yearly basis, the uprate would mean extra electricity production of about 20%, from 9 to 11 billion kilowatt hours [4].

2. OVERVIEW & GUIDANCE FOR POWER UPRATES

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

- a feasibility study to establish the achievable level of uprate,

Table 2. Power Uprates Status in Sweden NPPs

BWR Plant name/unit	Previous power increase (%)	Planned power increase (%)	Date of application	Date for application of trial operation	Rector Type
Forsmark 1	8.0	12	Sept 2005	Jan 2008	BWR
Forsmark 2	8.0	12	Sept 2005	Jan 2008	BWR
Forsmark 3	9.3	15	Sept 2005	Dec 2009	BWR
Oskarshamn 3	9.3	19.9	Oct 2004	June 2007	BWR
Ringhals 1	10.1	1.6	March 2004	March 2006	BWR
Ringhals 2	-	8	March 2004	Dec 2005	PWR
Ringhals 3	-	5.5	March 2004	March 2007	PWR
Ringhals 4	-	13.5	April 2007	2011	PWR

- project mobilization,
- design work,
- licensing work,
- field implementation,
- post-uprates testing and
- power ascension to the new power level.

Although the potential benefits of PUs have been clearly demonstrated, it is important to recognize that the benefits are accompanied by associated limitations, and to manage those limitations in terms of technical, financial, and licensing benefits that can be gained by a PU.

Proper selection of PU parameters and the use of improved analysis and design approaches can result in the best combination of benefits, including increased MWe production while maintaining plant safety and avoiding risk consequences. In setting design conditions for a PU, the effects of several physical factors have to be recognized and evaluated as a basis for making the tradeoffs necessary to capitalize on the available benefits. Technical issues include tradeoffs among coolant temperatures, corrosion concerns, and steam pressure; core loading pattern efficiency and irradiation effects on the reactor vessel and internals; increased fluid flow rates and flow induced vibration margins; and several other issues [5].

2.1 Feasibility Study of PU

The primary purpose of a PU feasibility study is to develop the range of possible PUs with the risks, modifications, and costs associated with each target level. On this basis, recommendations can be made as to the optimum power uprate levels. The final decision on a particular target level and proceeding with the PU would be made by the utility management based on their assessment of the optimum balance of the risks, costs, and benefits associated with the project.

2.1.1 Feasibility study overview

A PU feasibility study requires a significant amount of work and a broad range of expertise. A variety of study contracting models can be used successfully. For example, where the original nuclear steam supply system (NSSS) designer has successfully supported PU projects, a significant part of the study work can be contracted to this organization. Whatever the chosen organization and contracting model, there must be:

- Knowledge of the original design intent for both NSSS and balance of plant (BOP) systems and components,
- Knowledge of the operating history and current status of NSSS and BOP systems and components,
- Knowledge of the reactor licensing process, the current status of the operating licence, and any currently open issues,
- Input from control room operating staff in the unit being uprated and those staff responsible for staff training,
- Input from staff experienced in making field modifications in 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 to 20 person years of effort. The precise time and effort depend on the degree of PU being assessed and the number of precedents for a similar level of PU on reactors of that type.

For measurement uncertainty recapture uprates (MUR), such studies are typically not required or performed. For stretch PUs (SPU), the study would be at the lower end of the time and expense range. Such a study 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. For extended PUs (EPU), there are more requirements for design changes specific to a particular plant, particularly in the BOP. Therefore, these studies are the most complex and expensive to do. [6]

Generally, a PU feasibility study will consider a number of PU scenarios to establish an understanding of which one offers the best alternative based on considerations of cost, benefit, and risk. Higher levels of PU will require more changes to equipment and procedure and will possibly have a higher risk of either not meeting the target power output or having loss of capacity factor after the changes are made. [7]

2.1.2 Review initial conditions for PU

The additional electrical output achievable by a station is generally a function of the capacity of the reactor core to generate power, while maintaining acceptable fuel and thermal performance, and the capacity and efficiency of the process 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 PU 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 (TSs), or the design documentation. On this basis, one can estimate the current design margin in each system and component, and decide which parameters, systems, and components are critical in determining the potential uprate level.

The margin has two important aspects, as follows [8]:

- Safety margin,
- Production margin:

Figure 1 shows the Institute of Nuclear Power Operations (INPO) margin model for the design and operational margin concept.

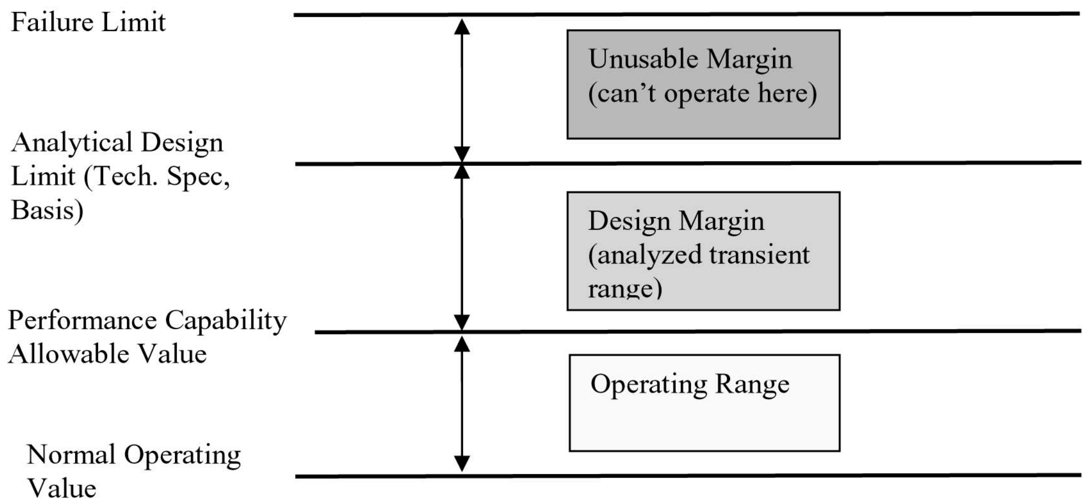

Fig. 1. Design and Operational Margin Concept Developed by INPO

2.1.3 Examination of potential PU range

Identification of critical constraints & margins

Having gone through the process outlined in section 2.1.2, 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 a PU 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. Some examples of such potentially life-limiting effects are corrosion or pressurized thermal shock in a PWR and corrosion or creep deformation in a pressure tube reactor.

Operation at a higher power level will require a change to either the fuel enrichment, frequency of refuelling outages, or higher batch fractions. However, the utility may want to push to a longer refuelling outage interval, and fuel performance may not allow both goals (uprating and longer intervals between outages) to be met simultaneously.

A PU could also potentially impact equipment capability or redundancy under certain operating conditions with 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, or where starting of a standby cooling water pump is required during hot weather to deal with the higher cooling water temperature and the higher heat output of the uprated unit.

Another consideration would be any plans for licence extension for the unit. There are opportunities for synergies between uprating and licence extension, but competition for scarce resources might occur and will have to be managed.

Identification of components & systems potentially affected by PU

A list of critical margins and constraints should suggest areas where changes to design, operating procedure, 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 PU scenarios can be constructed, each having a set of required changes (cost) and an achievable level of PU (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.

All changes should be categorized to facilitate understanding of their impacts. For example, changes may only have a one-time equipment upgrading cost. Other changes will have ongoing costs due to increased maintenance requirements, increased fuelling costs, or potential for increases in reactor unplanned 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 PU project. Typical categories of impact include the following:

- no impact,
- impact on margins,
- analysis change,

- design modification required,
- procedure modification required.

Cost of each category of change impact and the overall costs of each PU scenario can now be estimated, as shown in Figure 2. 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.

Review regulatory requirements

To operate a reactor at a higher power level than that for which it was originally licensed, permission will be required from the licensing authority. There may be additional permits required due to the need for more cooling water for a higher output, which could 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 a critical path in determining the PU project schedule. There will also be costs and possibly additional program requirements associated with such approvals, such as a need for a public information program or public hearings.

In order to obtain these approvals, technical analysis reports that support 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 of the project.

Margin review

For each PU scenario, the operating, safety, and uncertainty margins should be tabulated and compared. It is useful for such a table to include the original design margin, the current operating or safety margin, the predicted margin after the PU project is completed, and the projected uprated margin, including plant-ageing effects.

A proper PU scenario will also point out areas where design/operating and uncertainty margins are reduced and where the reductions will require justification to the regulatory body. In addition to the review of operating margins, any proposed changes to operating procedure need to be reviewed at the feasibility stage with qualified operations and training personnel to establish whether the proposed changes are truly practicable given current staffing levels and whether any additional risks are introduced by the proposed changes.

More generally, the feasibility team needs to review their data and conclusions with expert parties within the operating organization. Topic areas for such participation could include the following: design, construction, equipment performance, maintenance, operation, and finance. Figure 3 shows the relation between design/analytical margin and operating margin. [9, 10]

To decide the extended PU margin scope, each task was defined as follows:

- Task 1: Identify PU impacts on all plant systems
- Task 2: Define / quantify the post PU margin for plant systems
- Task 3: Ensure that actual system performance is consistent with predictions based on analytical models or engineering judgement

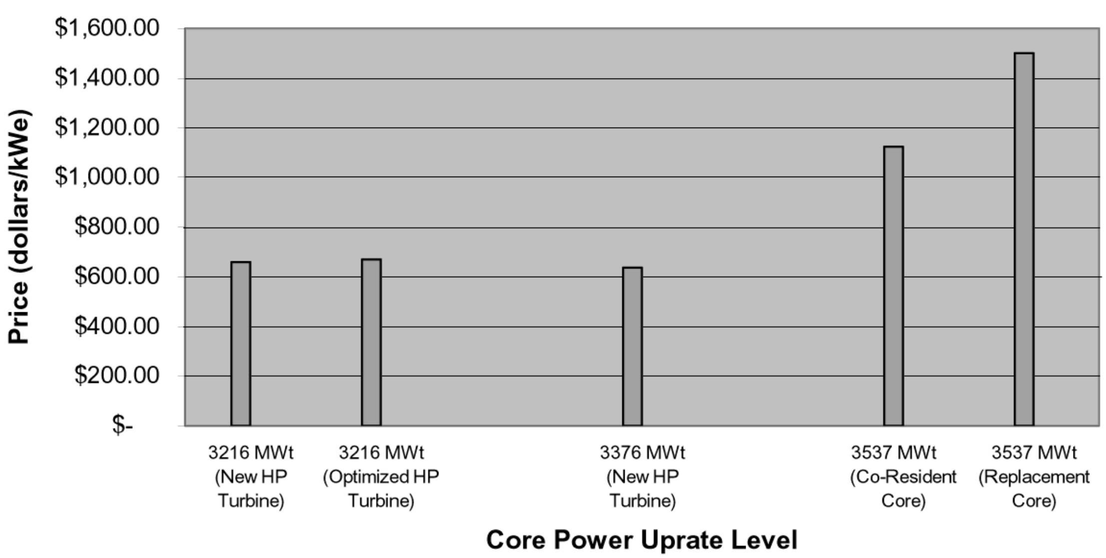

Fig. 2. Cost and Benefit Analysis for Indian Point Unit 3 NPP According to Level of Reactor Power Uprates

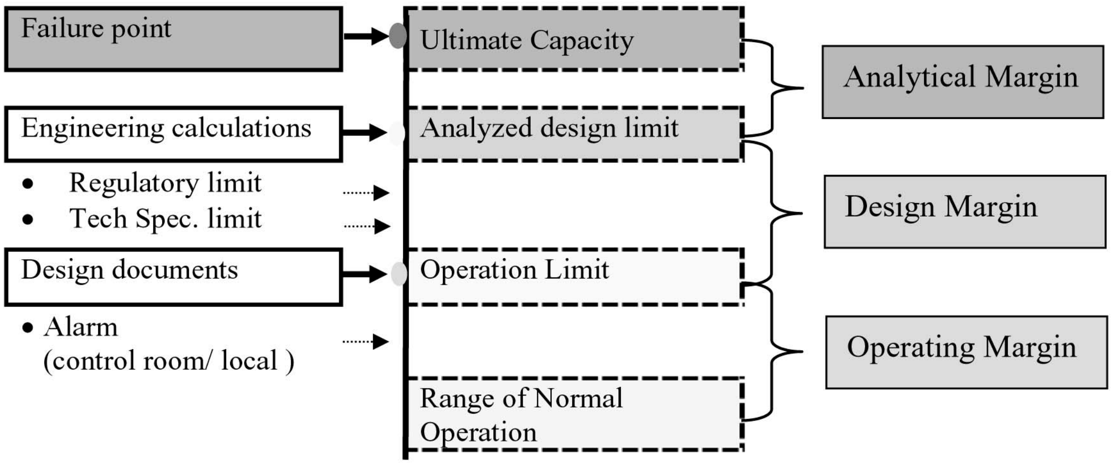

Fig. 3. Design and Operating Margin

· Task 4: Confirm the planned changes are adequate and check the future changes needed to ensure long-term reliability for the following systems:
  - Feedwater heaters
  - Feedpump/condenser booster pump
  - Condenser
  - Condensate polisher

Preliminary economic analysis

Once the impacts of the various PU 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 and any potential impacts on station or component operating life. Estimates of the benefits in terms of increased output should also be done. For these estimates, it can be useful to calculate the net present value (NPV) of the costs and benefits for a range of discount rates to ensure that the benefits are sufficient to meet whatever investment criteria are established for the utility. These requirements are typically provided by the owner/company.

An important complementary activity is an assessment of the potential risks of a proposed PU project. This is particularly the case where the project is planning on technical innovation that has not been proven elsewhere. Even where the technical case is 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 to propose measures that will be taken where the risk (product of probability and cost impact) can significantly affect the financial success of the proposed PU project.

2.2 Design Phase

2.2.1 Perform analyses

Initially, a set of plant parameters will be established as a basis for the PU 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 available, and limitations of components and systems that would not be practical to replace or modify. The following key parameters should be analysed to decide the level of PU [11, 12]:

· reactor power
· core flow rate
· reactor coolant pump flow rate
· steam flow rate
· feedwater flow rate
· steam generator outlet pressure
· reactor vessel inlet temperature
· reactor vessel outlet temperature
· steam generator feedwater temperature
· moderate temperature coefficient (MTC)
· containment pressure
· heat balance
· mass/steam flows to turbine
· generator capacity
· cooling requirements
· condenser limits
· effects on probability safety analysis / core damage frequency
· structural analysis limits

Accident analyses

A reference analysis is normally established as part of the initial licensing effort as documented in the safety analysis report. This is supplemented by reanalyses required for reload fuel or plant equipment or system changes. For a PU, a safety evaluation should be performed to confirm the validity of applicable reference analyses. If the reference analyses do not bound within the uprated conditions, reanalysis using currently approved methods and appropriate input parameters will be performed.

The safety design bases to be met for the uprated core are listed as follows:

- design basis of departure from nucleate boiling,
- design basis of fuel temperature,
- design basis of loss of coolant,
- pressure of reactor coolant system.

The objective of the uprating safety evaluation is to verify 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 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 as the basis to determine whether the reference safety analysis remains valid.

For an uprating, values of these safety parameters are determined for the core during the nuclear, thermal, and hydraulic, and fuel design process. Each of these parameters is compared with the reference analysis value to determine if any parameter is not bounded. If all of the parameters are bounded, the reference analysis remains valid and no new analysis is needed to verify that the safety limits are not exceeded. If one or more of the safety parameters are not bounded, a re-evaluation of the accident is performed.

Nuclear Steam Supply System analyses

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

1) verify compliance of existing systems and operating procedures with applicable plant design bases and regulatory requirements, or
2) identify those areas where revisions and/or modifications are required.

The impact of the uprated parameters on the functional design requirements and the 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.

Instrumentation and control system

To achieve safety levels above those required the reactor protection system, the engineering safety features actuation system, safe shutdown systems, control systems, and diverse instrumentation and control systems should be reviewed to ensure that the systems and any changes required for the proposed PU are adequately designed.

The measurement uncertainties are considered at the proposed power level to avoid exceeding the power levels assumed in the design basis transient and accident analysis. Furthermore, the safety trip setpoints are calculated to ensure that sufficient allowance exists between the trip setpoint and the safety limit to account for instrument uncertainties.

Fuel design

The analyses performed in support of the PU in the fuel and fuel-related areas examine fuel thermal-hydraulic design, fuel core design, fuel rod performance, heat generation rates, neutron fluence, and source terms. The impacts of a PU 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. In addition, the impacts of a PU on the fuel assembly mechanical design criteria will be evaluated. Primary design features of concern with respect to fuel design include the following: 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 PUs

BOP analysis

To perform the assessments, the potentially impacted design bases and licensing bases documentation that supports the pre-uprated operation of the plant systems, components, and structures will be identified, collected, and reviewed. The proposed PU will be analyzed in accordance with the design and regulatory codes, standards, and criteria that constitute the existing design and licensing bases of the plant. Assessing the significance of the predicted changes on the existing bases documentation is a key element of the feasibility study. The assessments and detailed evaluations will focus on addressing the impacts expected as a result of PU parameter changes. The BOP evaluations included the following general topics:

- BOP systems and components
- BOP radiological review
- Instrumentation and Controls
- Electrical systems
- Structures
- Environmental considerations

- Pipe stress and supports
- Generic issues and programs
- Plant procedures

Electrical Systems

The electrical equipment qualification (EQ) program for the PU should be reviewed. The review will be performed for the new accident temperature, pressure, humidity, submergence, and radiation dose associated with the PU to environmental conditions in the EQ Program. The PU has no effect on the qualification of equipment inside containment with respect to the temperature and pressure, but does have an effect with respect to qualification to radiation dose.

The PU radiation doses have increased as a result of the increased power, the associated allowance for instrument error, and the fuel cycle extension to 24 months. Final evaluation of the exposure of the radiation sensitive parts should be determined in accordance with the EQ Program.

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

- Main steam line break in the steam and feed-line penetration area,
- Main steam supply line to the turbine drive of the auxiliary feed water (AFW) pump in the AFW pump room, and
- Steam generator blow-down line break in the pipe penetration area.

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 also will be qualified considering the thermal lag analysis. All equipment outside containment required for accident response should be verified as qualified.

2.2.2 Procedure changes

The operation and maintenance specialist of an NPP should be involved in the PU project from the very beginning. After all parameter changes are determined, the utility has to prepare documentation of any modifications, including operation and maintenance procedures

Operation

The utility has to organise a group to change the operational documentation to include specialists from operations and technical support sections. The specialists have to review the entire list of existing documents (emergency operating procedures, system procedures, test procedures, etc.), taking into account the changing parameters, to determine what procedures must be modified. After this, they have to prepare, validate, and approve modifications in a proper way.

Maintenance

The utility has to organise a group to change maintenance documentation to include specialists from maintenance and technical support sections. The specialists have to review the entire list of existing documents, taking into account the changing parameters and their effects, and determine what documents need to be changed. After this, they have to prepare, check, and approve modifications in a proper way.

2.2.3 Training requirements

Training for the operating personnel and other personnel must be considered due to changes to the operating procedures and set points. The training for the operating personnel can be a time-limiting constraint for the project. This is due to the fact that changes to the simulator need to be done well in advance of implementation in the real plant, making it possible for the operating staff to train and to fit the training into their working schemes. In addition, the difficulty with having the non-uprated simulator running in parallel must be considered.

2.2.4 Testing plan development

Procedure to verify the turbine power

As part of the PU program, the main turbine generator will typically require modifications to accommodate the increased mass steam flow. These modifications range from minor high-pressure turbine inlet nozzles being widened to entire high-pressure turbine rotor/blading replacement, depending on the limitations and margins of the current turbine design and the size of the uprate.

Typically, such modifications are designed and implemented by a specialised turbine-generator company. As part of the contract for the performance of this work, the PU project will expect the delivery of a targeted increase in megawatt output from the main generator based on the design analysis and heat balance of the PU program. The contract to the turbine-generator company will typically contain specific warranty requirements regarding the final main generator output megawatt capacity after uprating.

Start-up and Test Programme after PU

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

Signification emphasis has 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. The plateaus typically range between 2-5%. 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, and other indications).

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

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

2.3 Licensing

2.3.1 Identification of required licensing changes

According to each national practice, the difficulty of licensing a PU will depend, in part, on whether the licensing process regarding the PU is already determined in domestic practice or whether the licensing authority rules contain precise instructions regarding the licensing process.

The utility has to determine what licensing activities must be done to gain approval for the PU implementation. For this, the utility and technical support organizations should review what documents and rules prescribe the licensing activities.

The utility must also determine what types of licences will be affected (environmental, nuclear, or other special authorities should be involved). In the case where several licensing processes are necessary, there is a need to determine the sequence of the process, taking into account the time necessary for each process.

The utility should determine what documents need to be prepared for each licensing process and the scope of each document. In the case where the licensing process is complicated or where aspects of the process are unclear, the utility has to consult with the authority to clarify the process of the licensing and to clarify what additional demands the authority will have.

Environmental licenses/permits

In the case where environmental licensing is needed, the utility has to determine what kind of documentation must be prepared and what the acceptance criteria are. The need for any additional environmental monitoring program, the time it should be started, and the duration of such programs needs to be determined.

The environmental approval process may require that other authorities will be involved in the licensing process. The utility needs to identify these authorities and determine their requirements. The utility has to know if public hearings are necessary and when they must be held.

Operating licenses

The utility has to know the position of the regulatory body regarding acceptance criteria and safety margins. The utility must determine whether the raising of the power and modifications necessary for this will be licensed together in one complex licensing process or whether they will be licensed separately. It may be that some modifications to be done for a PU will be implemented before the PU outage.

The utility should determine in how many steps the PU program will be executed from the point of view of power increases and what is the approach if the PU will be done in several steps. There needs to be agreement with the authority if a separate permission must be gained before every PU step or if one permission for the maximum power increase is sufficient.

It must be determined what documentation (deterministic and probabilistic safety analyses, computer codes used in analyses, strength, fatigue analysis, modification description, procedures modification, maintenance practice, etc.) should be prepared and what the scope of the documentation is. It should be determined what kind of training is necessary, classroom training or simulator training, and what are the regulatory body requirements regarding the simulator model modification.

The utility has to discuss with the authority the start up program and the tests to be carried out during the start up. The utility must determine who will prepare all of the necessary operating documentation and what the utility roles are in the documentation preparation and verification process. In some countries, the regulatory body 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 body.

The utility must also understand the requirements of the regulatory body regarding revisions to the final safety analysis report (FASR) 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.[13]

2.4 Implementation of PU

2.4.1 Field engineering/implementation guidelines and procedures

Between the design basis documentation and the operating plant procedures are all the interim, temporary documents, and procedures that will guide the implementation of the PU project. Field instructions, work orders, planning documents, field changes, etc. represent a significant amount of critical information that must be created in order to properly implement the necessary changes to the plant for the PU. 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 field engineering organizations to translate the design requirements and documents into implementation work packages.[14]

2.4.2 Organization and management

The implementation of the PU program will involve dozens, if not hundreds, of electricians, millwrights, mechanics, I&C technicians, engineers, and other personnel. Having tight coordination with the companies and plant departments that will supply these personnel and manage these resources is essential to execute the technical scope of the PU in accordance with the plant operational requirements for online implementation and in accordance with outage management.

3. OPERATING EXPERIENCE/INDUSTRY EXPERIENCE/LESSONS LEARNED

3.1 Nuclear Steam Supply System Issues

3.1.1 NSSS operating parameters

In a BWR, operating pressure is seldom changed, even if there are examples of this. The reason for not changing or increasing operating pressure is still within the conservation involved with doing so. It brings into structural verification compared to the relatively low benefit in terms of extra MWe. The power-flow-map will inevitably change due to the higher thermal power. One way to keep the power-flow-map is just to prolong the rod-line up to the new power level. This can often be used for SPUs sometimes together with increased maximum core flow. For EPUs the operating range at full power will be none or too small with this strategy, necessitating a more radical change to the power-flow-map.

<u>*Example of Steam Dryer Broken in Quad Cities Unit 2*</u>

Quad Cities Unit 2 completed an 18% EPU in the first quarter of 2002. On June 7 2002, operators noted a reactor vessel pressure decrease from 1,001.1 psig to 998.8 psig and a tenfold increase in moisture carryover to the turbine from 0.028 percent to 0.27 percent.

On June 20 2002, the A channel of the reactor vessel water level indicator showed a level 4 inches lower than the other channels, while moisture carryover peaked at 0.735 percent. On June 30, operators observed a decrease in the A main steam line flow and a 6 psi increase in reactor pressure. During the next week, steam pressure reached 15 to 20 psi above the initial pressure. Plant

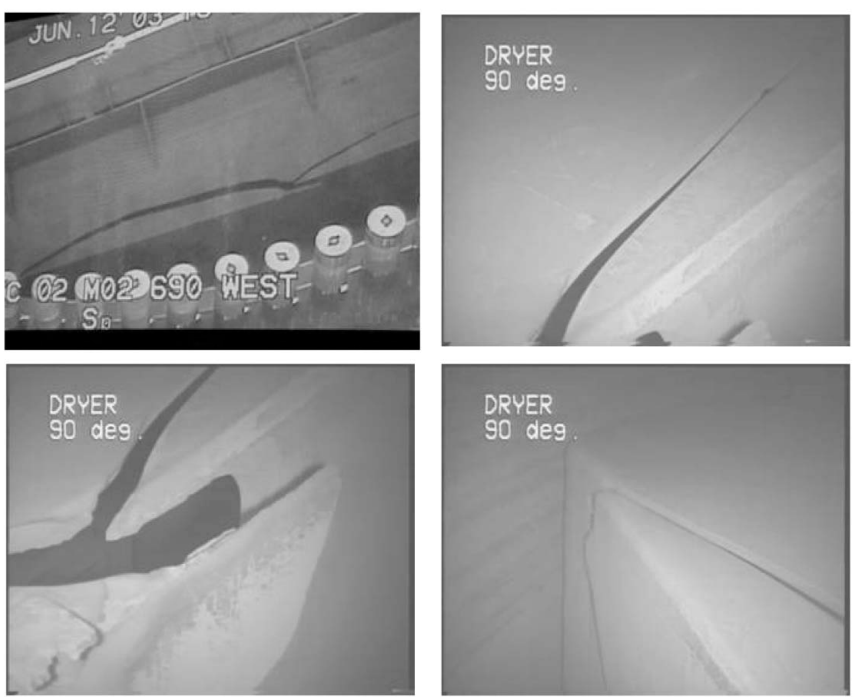

Fig. 4. Steam Dryer Broken in Quad Cities Unit 2

management directed that the plant be shut down on July 11 because of the concern that loose parts may have exited the reactor vessel and traveled into the main steam lines (see Figure 4).

Upon inspection, a section of the steam dryer outer bank hood cover plate was found to be missing. The cover plate, 10 feet long by 16 inches wide and ¼ inch thick, had separated into three large sections and several small pieces. One section was found on top of the steam separator; another section was partially separated, but still attached to the steam dryer; and the third section was lodged in the A main steam line venturi nozzle. This piece was about 12 inches wide and 18 inches long. One small piece was found downstream of the venturi, and several small pieces were found in the turbine stop valve strainer. Visual inspections identified impingement damage to the A main steam line nozzle, minor surface damage on steam line piping, and minor damage to the A main steam line flow venturi nozzle. [15]

3.1.2 Constraints for NSSS

In a BWR, the total core flow driven by the main circulation pumps can be a constraint on the achievable power level. This is due to the need of higher core flow with higher power to keep the thermal margin for the fuel with respect to critical power ratio. As the pumps are installed internally in the reactor vessel, an installation of extra pumps can not be possible. The only way to increase the core flow is to modify the pump. The capability of the steam separator and steam dryer is one of the major constraints for an EPU in the upper bound.

3.1.3 Safety issues

The number of safety analyses to be done depends on the level of the PU and the complexity of the changes made to the plant. In addition, the status of the existing analyses has an impact. On one end of the scale, only minor work needs to be done; on the other end, a complete new set of safety analyses needs to be performed.

Safety and auxiliary systems verification

A safety analysis using deterministic and probabilistic approaches is the basis for the verification of the safety and auxiliary system. Such analyses show if the system needs to be strengthened or not and if extra set points for the reactor protection system are needed. Verification of completed changes is also included in the safety analysis.

3.2 Fuel Issues

Development of modern fuel types that have better performance have been driven by other reasons than potential PUs. For a BWR, this development has now made a PU possible of up to 30% in some plants. For a PWR and PHWR type reactors, fuel performance seems to be more of a constraint.

3.2.1 Fuel reliability

There are no indications that PUs would decrease the fuel reliability in the plant. On the contrary, there are indications of increased fuel reliability in uprated plants. However, the reason for this is rarely the PU itself but merely other measures taken in connection with the PU.

3.2.2 Constraints

Depending on the power level for the uprate, fuel performance can still be the limiting parameter for the achievable power level. In special cases, operating cycle-length in combination with fuel performance can set the limit. For PWR and PHWR types of reactors, the fuel performance is definitively a constraint. For example, a WWER reactor is limited to an uprate of 8%, due to fuel restrictions, and a BWR reactor is limited to an uprate in the area of 20-30%.

3.3 Secondary Plant Issues

Evaluations are conducted to assess and verify that the BOP structures, systems, and components (SSCs) are structurally and functionally capable of safe, reliable operation at the power uprated conditions. Such a study will include a review of major components and systems typically impacted by a PU. The first task will be to identify the parameters and design inputs to be used to evaluate the BOP SSCs. Heat balance usually generated by turbine generator vendor will be used to identify the operating parameters based on design and performance conditions expected for the uprated power level. To date, evaluated impact of PUs on BOP SSCs has shown SSCs generally falling into three areas:

- Bounded by existing analyses and design conditions, with no further evaluation or analysis required.
- Bounded by design with reanalysis. This category required evaluation or reanalysis (calculations or revision to existing calculations) to demonstrate the existing design is adequate with no modifications.
- Not bounded by analysis or design. This category required evaluation and/or analysis to justify operation of the SSCs at conditions beyond the existing design basis to accommodate the PU.

The evaluations will be performed based on the existing design and licensing basis documented in the FSAR and technical specification basis. When either the existing basis could not be met following a PU, or a revised basis was used to demonstrate compliance to new criteria, justification for compliance and/or the revised basis should be provided for the PU evaluation. In addition, calculations could be performed in areas where existing documentation did not demonstrate capability at the power uprated conditions. To date, BOP PU evaluations have included the following general topics:

- BOP systems and components
- BOP radiological review

- Instrumentation and controls
- Electrical Systems
- Structures
- Environmental considerations
- Pipe stress and supports
- Generic issues and programs
- Plant procedures

When the original design requirements are not met under power uprated conditions, then alternatives will be considered, including system/component modification, change to the design basis, or change to plant operating procedures, and the resolution will be coordinated with the utility.

For a turbine generator system, an engineering evaluation of the retained and reused components to verify their capability with the uprated conditions of best estimated operating parameters will be performed. The following areas will be analyzed to determine the current situation [16]:

- Existing turbine and generator
- Thermodynamic cycle for pre and post –uprating
- High pressure steam path mechanical analysis
- Low pressure steam path mechanical analysis
- High pressure cylinder assessment
- Low pressure cylinder assessment
- High pressure and low pressure valves and interconnecting pipe work
- Turbine generator shaft dynamics
- Moisture separator reheater & drain system performance evaluation
- Turbine auxiliary systems assessment
- Generator assessment

3.4 Testing & Operation Issues

Power uprates, especially large EPUs, have in some instances resulted in equipment degradation and damage due to increase flows and energy levels in piping systems and equipment. In some cases, the development and detection of the issues took weeks or months after completing the uprating to detect.

Due to several significant events, primarily the US Quad Cities 2 steam dryer cracking problems, significantly increase attention has been placed on vibration instrumentation, test procedure and power ascension plans. The US nuclear power industry has experienced over 60 events related to PUs since 1997. From the Institute of Nuclear Power Operators (INPO) Significant Event Report 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."

Main turbine controls, main generator, and bus cooling systems have also experienced problems that could likely have been avoided by 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.[17]

For MUR uprates, some events have occurred where, due to software configuration issues with the ultrasonic feed-water 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.

3.5 Licensing/ Regulatory Issues

An increase in output can affect a reactor plant in a number of ways and to varying degrees. The main parameters and conditions that are affected by a power increase, and which can call for remedial actions to maintain the required safety margins or to ensure that they are unaffected are as follows:

- Mean value of power density in the core, which increases with a PU. This can result in smaller margins to film boiling/dryout. By resorting to core re-optimising, or the use of improved fuels or more modern methods of analysis, this problem can be avoided. Modern fuel designs, e.g., those with intermediate spacers, often have larger margins to film boiling or dryout than earlier designs.
- The steam flows from BWR pressure vessels or PWR steam generators will increase. This will result in increased pressure drops and greater loadings on some components and systems. This can call for better surveillance and renewed analysis, for example, for the risks of vibrations in the internals of certain systems, vessels, and steam generators.
- Certain transient phenomena will occur quicker. Pressure transients in the pressure vessels of BWRs and in the steam generators of PWRs will both occur quicker and be potentially larger than before. In BWRs, the core power surge that can accompany a steam line closure will amplify 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.

- Certain severe accident sequences will be influenced by a PU, calling for a review of severe accident management procedures.
- Decay heat will be increased, leading to an increased load on the safety systems. In certain situations, the time available for operator intervention will be shorter. New safety analyses will be needed to demonstrate that required margins can be retained. Technical specifications and instructions will have to be modified, as well as training and instruction programmes.
- Mass and energy releases into the reactor containment in the event of steam line or primary system leakages 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 that 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.
- The temperatures in the primary system of a PWR are dependent on power levels. The temperatures affect the local stresses and corrosion properties. Again, renewed analysis must prove that adequate margins are held and inspection routines are validated. Shutdown margins are reduced with PUs, and this has to be considered during refuelling.
- The loads on certain electrical systems and components will increase with the greater 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.
- Neutron irradiation in the core region will increase, resulting in different requirements for radiation embrittlement and radiation induced stress corrosion monitoring programmes.
- The power plant environment will be subjected to greater releases of waste heat to the water recipient. Furthermore, plant wastes will contain greater amounts of radioactive substances. The release of radioactive substances will increase. In addition, more uranium and chemical products will be used. The consumption of fissile material (U- 235) increases in direct proportion to the power level increase, as do the quantities of certain chemicals.

4. CONCLUSIONS

The economic drivers for low cost electricity will continue to drive more and more plant operating companies to seek safe, economic methods of increasing reactor power. The PU provides such a method for many operating NPPs. However, these projects, even the small uprates, represent a significant change to the plant operation, design, and licensing basis documents and practices. 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.

Recent increased focus on multi-discipline teams (including maintenance and operations), post-uprate testing, power ascension processes, and vibration monitoring is a result of the failure of earlier uprates to fully anticipate the wide-ranging effects of power uprating. A rigorous, disciplined approach, based on a thorough feasibility study, with appropriate staffing and skills, and adequate oversight and support is required to ensure a successful power uprate.

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