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The Role of Instrumentation and Control Systems in Power Uprating Projects for Nuclear Power Plants

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THE ROLE OF INSTRUMENTATION AND CONTROL SYSTEMS IN POWER UPRATING PROJECTS FOR NUCLEAR POWER PLANTS

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IAEA NUCLEAR ENERGY SERIES No. NP-T-1.3

THE ROLE OF INSTRUMENTATION AND CONTROL SYSTEMS IN POWER UPRATING PROJECTS FOR NUCLEAR POWER PLANTS

REPORT PREPARED WITHIN THE FRAMEWORK
OF THE TECHNICAL WORKING GROUP ON
NUCLEAR POWER PLANT CONTROL AND INSTRUMENTATION

INTERNATIONAL ATOMIC ENERGY AGENCY
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FOREWORD

The IAEA's activities in nuclear power plant operating performance and life cycle management are aimed at increasing Member State capabilities in utilizing good engineering and management practices developed and transferred by the IAEA. In particular, the IAEA supports activities focusing on the improvement of nuclear power plant (NPP) performance, plant life management, training, power uprating, operational licence renewal, and the modernization of instrumentation and control (I&C) systems of NPPs in Member States.

The subject of the I&C systems' role in power uprating projects in NPPs was suggested by the Technical Working Group on Nuclear Power Plant Control and Instrumentation in 2003. The subject was then approved by the IAEA and included in the programmes for 2004–2007. The increasing importance of power uprating projects can be attributed to the general worldwide tendency to the deregulation of the electricity market. The greater demand for electricity and the available capacity and safety margins, as well as the pressure from several operating NPPs resulted in requests for licence modification to enable operation at a higher power level, beyond the original licence provisions. A number of nuclear utilities have already gone through the uprating process for their nuclear reactors, and many more are planning to go through this modification process.

In addition to mechanical and process equipment changes, parts of the electrical and I&C systems and components may also need to be altered to accommodate the new operating conditions and safety limits. This report addresses the role of I&C systems in NPP power uprating projects. The objective of the report is to provide guidance to utilities, safety analysts, regulators and others involved in the preparation, implementation and licensing of power uprating projects, with particular emphasis on the I&C aspects of these projects.

As the average age of NPPs is increasing, it is becoming common for power uprating in a plant to be implemented in parallel with other modernization activities in the I&C systems. Any modernization project, including a power uprating project, provides a good opportunity to improve areas where the I&C design is judged to be deficient or where the equipment is becoming obsolescent or unreliable.

There are many technical issues associated with the implementation of I&C modifications in NPPs. As several other IAEA reports have already covered the relevant areas, it is not the intention of this report to repeat such guidance. However, I&C issues that are either specific to, or particularly important for, the successful implementation of power uprating projects are covered here.

As time passes and more NPPs operate at uprated power levels, lessons learned from power uprates accumulate. Some units, for example, have operated beyond their licensed power levels because of errors in reactor thermal power calculations. Therefore, this report also provides a review of the relevant lessons learned and gives information on potential concerns.

This report was prepared by a group of experts from Canada, Hungary, the Republic of Korea, Slovenia, Sweden, the United Kingdom, and the United States of America. The chairperson of the report preparation group was J. Eiler from Hungary. The IAEA wishes to thank all participants and their Member States for their valuable contributions. The IAEA officer responsible for this publication was O. Glöckler of the Division of Nuclear Power.

EDITORIAL NOTE

CONTENTS

1. INTRODUCTION TO POWER UPRATING

1.1. BACKGROUND

Increasing plant output is the cheapest source of power when compared to adding new capacity. In addition, gaining public acceptance to increasing existing nuclear power plant (NPP) capacity has proved to be significantly less controversial than constructing a new NPP. The greater demand for electricity, and the available capacity and safety margins in some of the operating NPPs are prompting nuclear utilities to request a licence modification to enable operation at a higher power level, beyond the original licence provisions. Currently, a number of nuclear utilities have already gone through the uprating process for their nuclear reactors, and many more are planning this modification process.

Additionally, in a deregulated electricity market, there is a need for flexibility in the mode of reactor operation. It is of importance to increase plant output when the demand is high and to allow the flexibility to make savings when the demand is low. There is also a need to make use of extra margins gained by backfitting and safety improvements done already for other purposes. Replacement of equipment can be required, as an example, for plant lifetime extension or for other reasons, and it is usually feasible to optimize the new equipment for possible higher power levels.

To increase the power output of a reactor, typically a more highly enriched uranium fuel is added. This enables the reactor to produce more thermal energy and, therefore, more steam, driving the turbine generator to produce more electricity. In order to accomplish this, plant components, such as pipes, valves, pumps, heat exchangers, electrical transformers and turbine generator sets must be able to accommodate the conditions that exist at the higher power level. In smaller scale power uprating activities, the reactor thermal power may remain at its original level, and fewer and less significant changes may be required.

In addition to mechanical and process equipment changes, parts of the electrical and I&C systems and components may also need to be altered to accommodate the new operating conditions and safety limits. The power uprating may, for example, require more precise and more accurate instrumentation, faster data processing, modification of the protection system set points, and/or more sophisticated in-core monitoring systems. It is also common that power uprating in an ageing plant is implemented in parallel with other modernization activities in the I&C systems. Therefore, it is essential to find ways to synchronize these parallel tasks in the I&C field to perform a cost efficient and properly scheduled series of activities serving all the major plant goals.

Any power uprate project is clearly motivated by economic reasons, where the focus is to increase the output power at the lowest possible cost. It is, therefore, important to realize that the project might face a need to include a larger portion of I&C changes than first expected. The existing I&C might be obsolete, or the intended supplier does not have the necessary skills with the equipment, or the components' (printed circuit card, relays, etc.) cost can be equal to or higher than a new, modern digital I&C.

All of these factors must be analysed by the licensee as part of a request for a power uprate, which is accomplished by amending the plant's operating licence. The analyses must demonstrate that the proposed new configuration remains safe and that measures continue to be in place to protect the health and safety of the public.

1.2. DEFINITION OF POWER UPRATE

The process of increasing the maximum licensed power level, at which a commercial nuclear power plant may operate, is called a power uprate.

1.3. TYPES OF POWER UPRATES

The three categories of power uprates are:

— Measurement uncertainty recapture power uprates;
— Stretch power uprates;
— Extended power uprates.

1.3.1. Measurement uncertainty recapture power uprates

Measurement uncertainty recapture (MUR) power uprates are those which seek to take advantage of a more accurate measurement of the reactor thermal power in order to operate closer to, but still within, the analysed maximum power level. They are achieved by implementing enhanced techniques, such as the improved performance of plant equipment both on the primary and secondary side, protection and monitoring system, operator performance, etc. These uprates are less than 2% measured in electrical output power. An example of the applicability of MUR uprates can be found in the following paragraphs.

At the time of the issuance of initial operating licences to the majority of NPPs in the USA, Title 10 of the Code of Federal Regulations (10 CFR) Part 50, Appendix K, required licensees to assume a 2.0% measurement uncertainty for the reactor thermal power and to base their transient and accident analyses on an assumed power level of at least 102% of the licensed thermal power level. The 2% power margin was intended to address uncertainties related to heat sources and measuring instruments. Appendix K to 10 CFR Part 50 did not allow for any credit for demonstrating that the measuring instruments may be more accurate than originally assumed in the emergency core cooling system (ECCS) rule making. It was not demanded that one should be able to demonstrate that the uncertainty in the calculation of thermal power was equal to or less than 2% either.

On 1 June 2000, the United States Nuclear Regulatory Commission (NRC) published a final rule (65 FR 34913) that allows licensees to justify a smaller margin for power measurement uncertainty when more accurate instrumentation is used to calculate the reactor thermal power and calibrate the neutron flux instrumentation.

The amount of the power increase is equal to the difference between the original 2% margin established by the NRC in 1973 and the justifiable accuracy of the instrumentation being used. For example, if the instrumentation can be demonstrated to measure thermal power to within 0.6%, then a 1.4% power increase could be obtained.

1.3.2. Stretch power uprates, effective margin utilization

Stretch power uprates are within the design capacity of the plant. The actual value for percentage increase in power which a plant can achieve and within which the stretch power uprate category can stay is plant specific, and depends on the operating margins included in the design of a particular plant, but typically remains within 7%. Stretch power uprates usually involve changes to instrumentation set points, but do not involve major plant modifications. This is especially true for boiling water reactor (BWR) plants. In some limited cases, where plant equipment was operated near capacity prior to the power uprate, more substantial changes, such as refurbishment or replacement of equipment contributing considerably to plant power without violating any regulatory acceptance criteria, may be required. A detailed cost–benefit analysis needs to be performed, considering implications on various aspects such as safety analyses, both deterministic and probabilistic.

1.3.3. Extended power uprates

Extended power uprates are greater than stretch power uprates and are usually limited by critical reactor components, such as the reactor vessel, pressurizer, primary heat transport systems, piping, etc., or secondary components, such as the turbine or main generator. To cope with these limitations, extended uprates usually require significant modifications to major balance of plant equipment, such as the high pressure turbines, condensate pumps and motors, main generators, and/or transformers. Extended power uprates have been approved for increases as high as 20%.

1.4. SCOPE FOR POWER UPRATE

Early generations of NPPs are likely to have included substantial design margins due to conservatism on the part of: (a) the designer; (b) the utility; and (c) the regulatory authority. This is particularly relevant for plants that were 'first of a kind' since there would have been no operating experience to substantiate the various safety and performance claims. Such plants may, therefore, include a significant scope for power uprating without the need for replacement of major plant items.

Later generations of NPPs are more likely to have been optimized (i.e. major plant items designed to operate closer to their limits), thereby reducing the potential for power uprating without the need for the replacement of major plant items (i.e. providing less opportunity for 'stretch' power uprating).

1.5. CURRENT STATUS OF POWER UPRATES, INTERNATIONAL TRENDS

Many of the operating NPPs in the world have already completed, or are in the process of, power uprating. Examples of a successful power increase can be found among different types of reactors, such as pressurized water reactors (PWRs), boiling water reactors (BWRs), the Russian types of PWRs (WWERs) and others. The Loviisa NPP in Finland, for example, increased thermal power by 9.1% between 1998 and 2000. Two of the Hungarian Paks WWER-440 units are now operating at 470 MW(e), while the other two at 500 MW(e), compared to the original 440 MW(e), due to significant modifications to relevant process components and the introduction of a new type of fuel.

Much experience has been gained in Belgium on power uprates of NPPs. Out of the seven Belgian nuclear units in operation, power uprates have been performed for three of them (Doel 3, Tihange 1 and Tihange 2), while a power uprate is under way for a fourth plant (Doel 2). For Tihange 2, the power uprate occurred in two steps of about 5%. For Doel 3, Tihange 1 and that planned for Doel 2, the single step power uprate is also coupled with a steam generator replacement. To allow a final uprate value of 10%, core design evolutions, major equipment modifications and changes of instrumentation set points were needed. Also, new methodologies were introduced to take advantage of unnecessarily large safety margins in some safety analyses.

A gradual increase in reactor thermal power began in the German pressurized water plants of the 1300 MW series roughly a decade ago. In this way, operational experience with a power uprate of approximately 5% of the original nominal power has been gathered. Examples of German PWRs with the mentioned uprates are Philippsburg 2, Emsland, Isar 2 and Unterweser.

In Switzerland, three utilities have requested and received regulatory authorization for power uprates. The Gösgen plant was permitted to undergo a 6.9% power uprate in 1985. In 1992, the Mühleberg power plant also received permission for a power uprate of about 10%. On the other hand, the Leibstadt power plant twice requested and received permission to uprate. This included an uprate of 4.2% in 1985 and subsequently, in 1998, the plant was permitted to uprate by an additional 14.7%.

During the 1980s, seven out of eight BWRs in Sweden were uprated between 5.9% and 10.1%. One of the PWRs was uprated as well. Most of the Swedish reactors are planning further uprates in the coming years; a few of them have already been given a first approval by the Swedish Government and the regulatory body.

In the Republic of Korea, the first power uprating projects are ongoing for 4 units out of 20 operating ones. The two affected plants are Kori Units 3 and 4 and Yongwang Units 1 and 2, which are PWR type reactors. The NSSS supplier was Westinghouse and the original electrical output was 950 MW(e). Uprating will result in the thermal power increase from 2775 MW(th) to 2900 MW(th) (4.5%). The category of this uprating is a stretch power uprate.

In the USA, the NRC has reviewed and approved 105 power uprates for a total of 13 250 MW(th) (or estimated 4417 MW(e), equivalent to four new reactors) from 1977 to 2005 (Fig. 1). These power uprates have been implemented for both BWRs and PWRs, and fall into all three categories. There have been 34 measurement uncertainty recapture power uprates ranging from 0.4% to 1.7%, typically achieved by using more accurate techniques for measuring feedwater flow. The number of stretch power uprates which have occurred is 58, ranging from 0.9% to 8.0%, typically achieved by changing instrumentation set points with few major plant modifications, and 13 extended power uprates have been reached, ranging from 6.3% to 20.0%, achieved

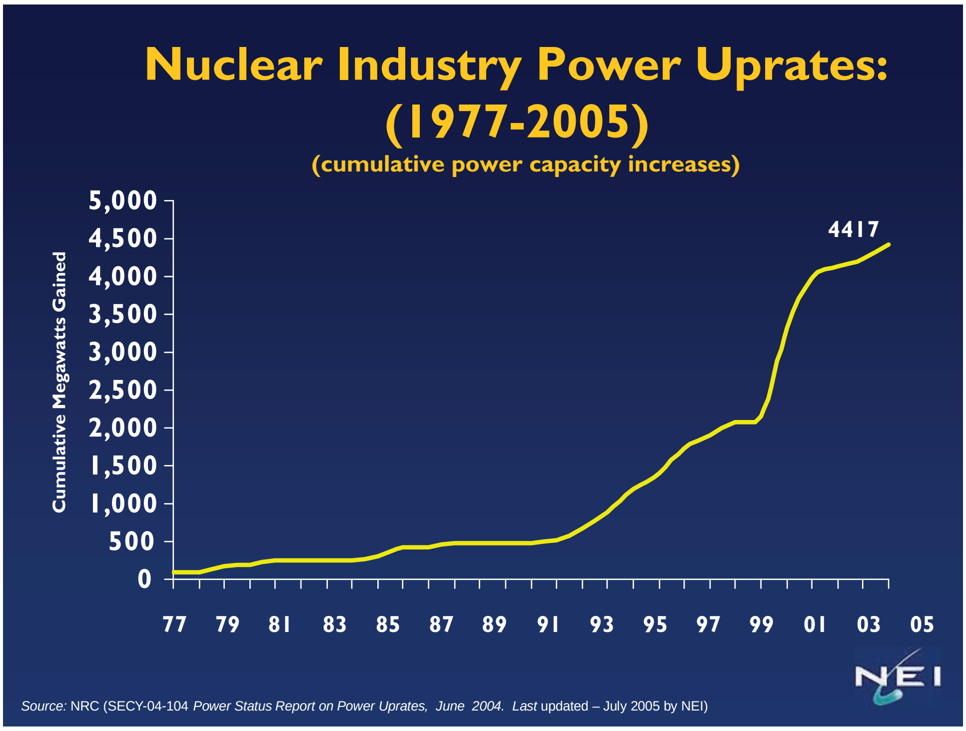

FIG. 1. Cumulative power capacity increases in the USA from 1977 to mid-2005 (NEI).

through advanced core design and by significant modifications to major plant equipment. These power uprates have had a dominant impact on the amount of electrical output produced by NPPs in the USA.

As of mid-2005, 12 power uprate submittals were under review by the NRC. These represent 2972 MW(th) (estimated 990 MW(e)) additional capacity. Based on a survey done in early 2005, 26 more power uprates are expected through 2010. These represent 4643 MW(th) (estimated 1548 MW(e)) additional power.

1.6. SCOPE AND OBJECTIVES OF THE REPORT

The report addresses the role of I&C systems in NPP power uprating projects. It applies to all reactor types and power levels used for commercial power production. It includes all projects starting from those aimed at increasing the efficiency and, hence, the electrical power generated at the same reactor thermal power through those associated with a minor increase in the thermal power of the reactor to those that constitute a major extension of the NPPs capacity. However, it excludes consideration of projects aimed at reducing the duration of the regular planned reactor outages or increasing the cycle time between these reactor outages.

The objective of the report is to provide guidance to utilities, safety analysts, equipment suppliers and regulators involved in the preparation, implementation and licensing of power uprating projects, with particular emphasis on the I&C aspects of these projects. While concentrating on a general treatment of I&C aspects, it also includes specific appendices and country reports to provide a comprehensive coverage of the potentially needed modifications.

1.7. ORGANIZATION OF THE REPORT

The report contains nine main sections and three appendices referred to as the body, as well as an annex. This major part of the report introduces the topic in Section 1 by describing the background to power uprating, the different types of power uprates, the current status of power uprating across Member States, and the scope and objectives of the report.

A good understanding of limits and margins, including their impact on I&C and the calculation of reactor thermal power, are crucial to power uprating, and these aspects are described in Sections 2 and 3.

Section 4 considers the impact of power uprating on plant I&C. It discusses the interaction with the safety analysis and operating procedures, the suitability of instruments, I&C systems of special interest, calculations and algorithms, set point changes, and many other I&C aspects related to power uprating. It constitutes the main section within the report.

Section 5 addresses human and training aspects with emphasis on the important role of the operating and maintenance staff following a power uprate and, hence, on the actions required during the uprating project to ensure that they are suitably equipped for that role.

Section 6 addresses regulatory aspects and, in particular, discusses those issues which a regulatory authority would expect to be considered in a power uprating licensing submission.

Section 7 provides implementation guidelines for the I&C aspects of power uprating projects and discusses the importance of having both a sound basis for the design activities, and a plan that is integrated with other modification activities. It also provides an example of the steps to undertake for a MUR uprating project.

Section 8 summarizes the additional benefits of plant uprating on the plant I&C and discusses some of the lessons learned in relation to I&C by those Member States which have undertaken power uprating.

Section 9 provides a few key recommendations based on the body of the report.

Appendix I illustrates the heat balance sensitivity to input parameters and sources of measurement errors; Appendix II describes the operating principle of ultrasonic flow measurement; and Appendix III summarizes training needs for design changes.

The References and Bibliography provide additional detailed information on topics relevant to the role of I&C in power uprating projects in NPPs.

Some Member States have provided independent reports to describe their own practices and experience related to the role of I&C in power uprating activities in NPPs. The Annex comprises these country reports.

2. LIMITS, MARGINS AND THEIR RELEVANCE TO INSTRUMENTATION AND CONTROL

2.1. DEFINITION AND APPLICATION OF LIMITS AND MARGINS

2.1.1. Introduction

There is a general tendency for utilities to take advantage of unnecessarily large conservatisms in safety analyses and margins, and to utilize them for reactor power uprates. Before they are used, however, there should be a discussion about why they were originally built in and what margins might be acceptable to use in a power uprate. The following section is to be seen only as a general basis for these discussions, since each case has its own prerequisites and, therefore, has to be handled separately.

Different limits can be identified that are related to nuclear safety, and in turn related to the built in margins. For every limit there is also a tolerance area, where an output signal from the limit supervision equipment should be activated so that the corresponding margin will not be exceeded.

A limit can be seen as a dot, position or line, where exceeding this value might cause a material or function to be used more than its intended purpose in the upcoming sequence of events. The limits are set so that the characteristics of a material or function are not exceeded eventually, from the reactor safety perspective.

TABLE 1. EXAMPLES OF DIFFERENT LIMITS IN A NUCLEAR POWER PLANT

Limits	Comment
Damage limit	If exceeded, the integrity of existing barriers cannot be demonstrated with analytical methods. The damage limit normally comes from a best estimate calculation, and is not an absolute limit due to material and manufacturing variations and operating history.
Safety limit	Set so that the probability of reaching the damage limit during a shutdown event sequence is acceptably low.
Limit for initiating reactor protection via the reactor protection system (RPS)	Supervised by the RPS equipment, and that initiates a shutdown of the reactor. This is one of the areas where instrumentation uncertainty (RPS uncertainty, in this example) plays an important role (Fig. 2).
Operating limit	Defines the normal area for operation such that no safety limits are exceeded during various types of transients or design basis events, provided the reactor protection system action occurs as intended.

2.1.2. Limits

To illustrate the reactor safety aspect for an NPP, different design events are used to demonstrate how the integrity barriers are satisfied. In connection with these analyses, various limits can be identified. As an example of the various approaches, Table 1 lists some of the conceivable limits applicable for NPP equipment.

The main principle is that the NPP should not exceed the safety limits under any circumstances. By doing so, good and verified margins to the damage limit are kept. The analysis to demonstrate the integrity of the barriers will also give the required response time, from detection of a limit being exceeded to initiation and activation of barrier protective equipment. For some parameters, there might be both an upper and lower limit.

The relationship between these limits and the design event categories defined in the deterministic safety analysis are illustrated in Fig. 2.

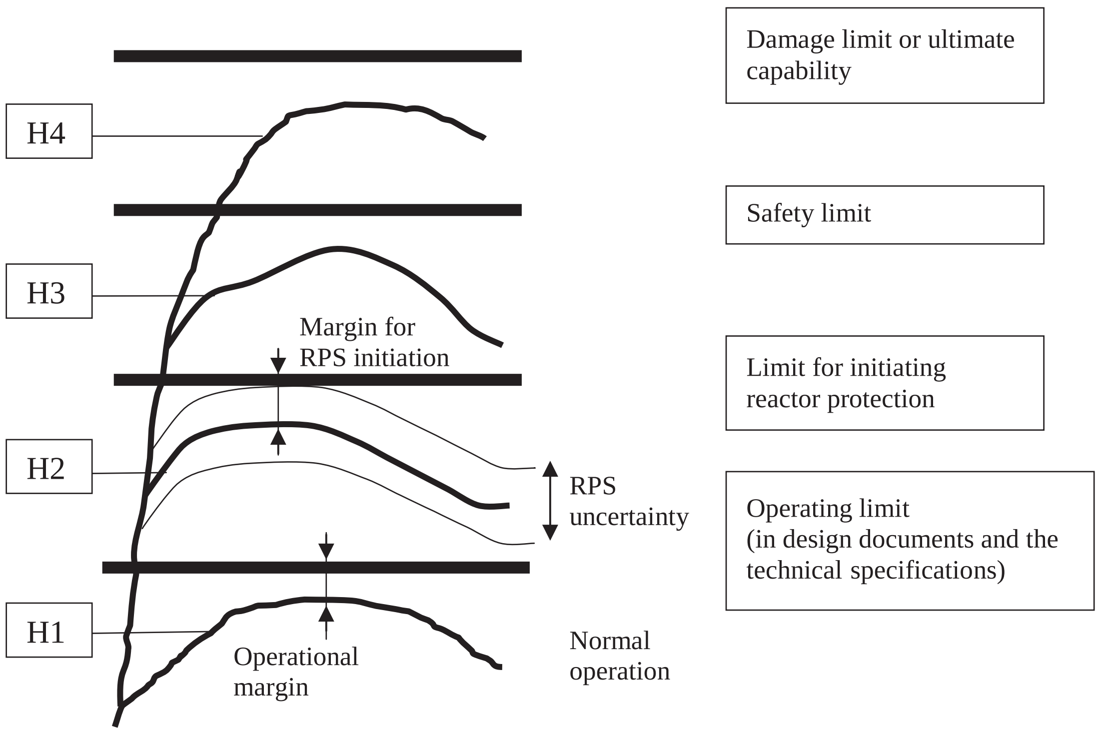

FIG. 2. Limit values and margins.

2.1.3. Margins

Note that in Fig. 2, the limits are not set to represent the calculated maximum value of the studied parameter; instead, they are set so that the maximum value of the process parameter — even keeping some room for various uncertainties — does not exceed the corresponding limit during the event sequence.

Margins are defined as the difference between the acceptance criteria (different limits in Fig. 2) and the conservative calculation of the upper bound of the design basis occurrences or the upper bound of the calculated uncertainty range (the maximum value of the H1–H4 curves in Fig. 2). The existence of such margins ensures that NPPs operate safely in all modes of operation and at all times.

One basic prerequisite for defining margins is that the characteristics of the studied functions are known with confidence, and that different aspects of the event sequence are well known.

The width of the margins is dependent, among others, on the:

— Knowledge about damage limits;
— Manufacturing uncertainties;
— Calibration uncertainties;
— Capacity decay due to operation and use of equipment.

With increased knowledge about physical phenomena and/or with improved analysis tools, it might be possible to demonstrate that some margins are larger than necessary. These 'extra' margins could arise, for example, from a reduction in the uncertainties previously used in the analysis.

The barrier protective functions are repeatedly (frequently) tested, and testing experience might show an 'extra' margin, or that more frequent testing provides a more secure way of verifying the margins.

Better knowledge about different circumstances or event sequences might permit a more detailed analysis, where new acceptance criteria or limits can be defined and will result in larger margins.

The above 'extra' margins can then be used for other purposes such as a power uprate (see also IAEA publications [1, 2]).

2.2. RELATIONSHIP BETWEEN LIMITS, MARGINS AND INSTRUMENTATION AND CONTROL

As can be seen in the previous paragraphs, instrumentation uncertainties play a key role in the identification of margins in Fig. 2. Consider, for example, measurement and controller ranges and tolerances while measuring feedwater flow rate, feedwater temperature, steam quality, fuel temperature, neutron flux, etc.

A typical example is the calculation of reactor thermal power in a more accurate manner. The reactor core thermal power is validated by a nuclear steam supply system (NSSS) energy balance calculation. The reliability of this calculation depends primarily on the accuracy of feedwater flow, temperature and pressure measurements. Because the measuring instruments have measurement uncertainties, margins are included to ensure that the reactor core thermal power does not exceed safe operating levels or, for that matter, does not exceed the licence value. Instrumentation enhancement may involve the use of state of the art feedwater flow or other measurement devices that reduce the degree of uncertainty associated with the process parameter measurements. Performing regular calibration and maintenance of instrumentation will also improve measurement reliability. These activities will, in turn, provide for a more accurate calculation of reactor thermal power. With this more accurate value, the corresponding margins may be narrowed and the extra space gained this way can be used for the safe increase of reactor thermal power.

3. CALCULATION OF THERMAL POWER

The operating licence for every NPP specifies the maximum amount of fission power that the reactor core is allowed to produce. Since the total fission power is very hard to measure accurately, it is usually estimated based on the readings of neutron flux detectors, which are time compensated by the power calculated by the reactor regulating system. However, to ensure that the reactor power is known as accurately as possible, and to satisfy licensing requirements, the reactor regulating system power is periodically adjusted to the power calculated by the heat balance around boilers/steam generators, sometimes also known as secondary calorimetric. The total fission power is then inferred from the boiler/steam generator power by adding or subtracting smaller terms, such as pump heat, piping and purification system losses.

An accurate and reliable calculation of reactor thermal power is essential both to make sure that the reactor stays within the limits of the safety analyses, and that the thermal power stated in the licence is not exceeded. Improvements in the calculation of thermal power through the increased accuracy of installed instrumentation or more sophisticated calculation algorithms may also provide opportunities to tighten uncertainty margins identified in the original licence and, in turn, to increase output power.

3.1. CALCULATION OF THERMAL POWER BY HEAT BALANCE

The heat balance program adds up all heat sinks and heat sources within a specified envelope to evaluate the amount of power produced by the reactor (see Fig. 3 for an illustration of the envelope). The heat balance program is run either in automatic or manual mode.

In the automatic mode, reactor thermal power is calculated in the plant process computer but with the fallback that this can be done manually should the automatic means be unavailable. The manual means typically involves the operating staff taking the relevant plant parameters from the control room displays and entering them into an off-line program such as a spreadsheet.

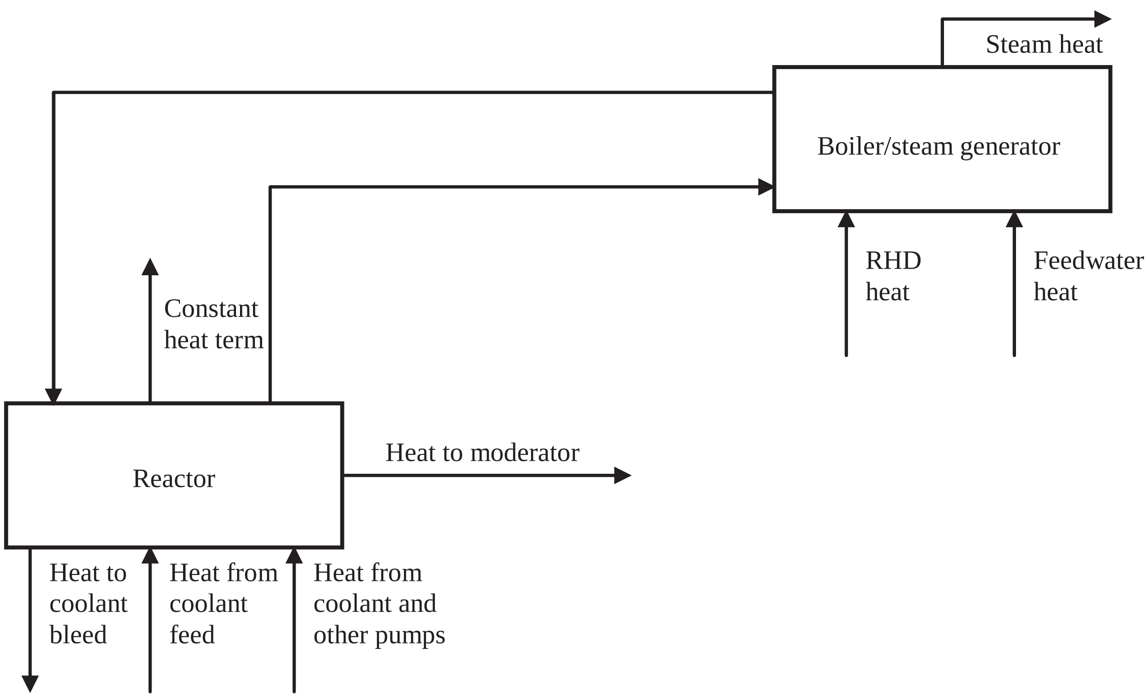

FIG. 3. Primary heat sources and heat sinks in a typical NPP arrangement.

The expression used for evaluating reactor thermal power normally is as follows:

$$Q_{RP} = Q_B + Q_M + Q_{PUR} + Q_{CONST}$$

where:

Q_{RP}: Reactor thermal power;
Q_B: Power to boilers/steam generators;
Q_M: Power to the moderator;
Q_{PUR}: Power to the heat transport purification (also called feed and bleed) system;
Q_{CONST}: Constant term.

The following discussion will consider each term in order of increased contribution to the total reactor power, with specific emphasis on the effect of improving the accuracy of measuring a particular term on maximizing the power uprate.

3.1.1. Constant term

This term usually incorporates contributions from various heat sinks and heat sources outside of the reactor core, and is about 1% of the total reactor thermal power. The biggest contribution to this term is from heat produced by the coolant circulation pumps. Other contributions include heat produced by smaller pumps and piping heat losses. Sometimes the power correction due to steam moisture content is also included in the constant term. As the name implies, the value of the constant term is fixed and is usually obtained from the plant design information. With the exception of steam moisture (ST_M) content, which can be measured directly using chemical tracer methods and is done several times over the lifetime of the reactor, accuracy of other contributions to the constant term can be improved only by improving the models used in design calculations.

3.1.2. Power to the purification (feed and bleed) system

This term accounts for heat losses due to a small flow of reactor coolant to the outside of the heat balance envelope in order to maintain the coolant chemical specifications. A typical value of this term amounts to a fraction of 1% of the total reactor thermal power. The accuracy of this term can be improved by improving the accuracy of the purification flow and temperature measurements but the net effect on the calculated reactor thermal power will be almost negligible.

3.1.3. Moderator power

This term accounts for the heat removed by the reactor moderator system. It is the second biggest contribution to the calculated reactor thermal power after power to the boilers/steam generators, and is usually a few per cent of the total reactor thermal power. Moderator power is normally obtained from design calculations and is assumed to be constant at a particular power level. However, those plants that use plant instrumentation to evaluate moderator power can increase the overall heat balance accuracy by improving moderator flow and temperature measurements.

3.1.4. Power to boilers/steam generators

This is by far the biggest contribution to the total reactor thermal power and comprises steam power, feedwater power, and some smaller contributions such as, for example, second stage reheat power. Each contribution is a product of the relevant flow multiplied by the enthalpy, which is obtained from the steam tables based on measured temperatures and pressures. This is summarized by the following equation (Σ implies summation over individual boilers/steam generators):

$$Q_B = \Sigma\, (W_{ST} \times H_{ST} - W_{FW} \times H_{FW} - W_{RHD} \times H_{RHD})$$

where:

Q_B:	Power to boilers/steam generators;
W_{ST}:	Steam flow from a boiler/steam generator;
H_{ST}:	Main steam enthalpy;
W_{FW}:	Feedwater flow into a boiler/steam generator;
H_{FW}:	Feedwater enthalpy;
W_{RHD}:	Second stage reheater drains flow;
H_{RHD}:	Second stage reheater drains enthalpy.

It should be noted that, instead of a direct measurement, steam flow is obtained in several NPPs by adding up the three flows into the boilers/steam generators, that is, feedwater flow, second stage reheat flow and boiler/steam generator blowdown flow.

Therefore, the equation for the boiler/steam generator power can be rewritten as:

$$Q_B = \Sigma\,[W_{FW} \times (H_{ST} - H_{FW}) - W_{RHD} \times (H_{ST} - H_{RHD}) + W_{BD} \times H_{BD}]$$

where:

W_{BD}:	Blowdown flow;
H_{BD}:	Blowdown enthalpy.

Table 2 summarizes typical values of flows, temperatures and pressures for selected reactor types. It should be noted that for any reactor type, steam and feedwater flow is very nearly proportional to the reactor thermal power.

3.2. CONTRIBUTIONS TO BOILER/STEAM GENERATOR POWER

This section deals specifically with contributions to the largest component of the heat balance: power to the boilers/steam generators, with particular emphasis on the relative importance of the accuracy of individual measurements.

The accuracy of different instruments used to measure the parameters included in the equation mentioned has a different effect on the maximum achievable reactor power and generator output. This notion is more conveniently expressed through sensitivities, defined as the change in reactor power per per cent change in the parameter being measured. Since by far the biggest contribution to the boiler/steam generator power comes from feedwater flow and enthalpy, and since enthalpy is strongly dependent on the fluid temperature but not on

TABLE 2. VALUES OF THE MAIN HEAT BALANCE PARAMETERS FOR SELECTED REACTOR TYPES

Reactor type	PWR	BWR	WWER-440	CANDU
Reactor thermal power at 100% FP – Q_{RP} (MW(th))	3300	2900	1375	2800
Reactor net electrical output at 100%FP (MW(e))	1200	1000	450	900
Main steam pressure – P_{STEAM} (kPa)	6000	5500	4500	5000
Main steam temperature – T_{STEAM} (C)	285	280	250	265
Feedwater temperature – T_{FW} (C)	235	180	140	170
Steam flow – W_{STEAM} (kg/s)	1500	1450	375	1300
Feedwater flow – W_{FW} (kg/s)	1450	1400	375	1250
Moisture content – M (%)	0.1	0.1	0.3	0.25

pressure, calculated reactor power will be very sensitive to the errors in feedwater flow and temperature measurements. Typical sensitivity values are summarized in Table 3.

Absolute sensitivity is expressed as the ratio of the contribution to the total reactor thermal power in per cent full power (%FP) per measurement unit of a particular parameter. Relative sensitivity is expressed as a ratio of %FP, divided by per cent error in a specific parameter. It is clear that the largest effect is due to errors in boiler/steam generator steam moisture content and in feedwater flow measurements, followed by the error in feedwater temperature measurements. However, since boiler/steam generator steam moisture content can be measured to within about ±0.1% accuracy, and it remains constant over long time periods, the effect on the reactor thermal power uncertainty is relatively small. In some cases, moisture carry-over tests were performed prior to an MUR uprate to ensure the most accurate possible value for the steam moisture content. In other cases, boiler/steam generator blowdown flow was measured ultrasonically to verify the value assumed in the heat balance program.

Additional examples of heat balance sensitivity to measurement uncertainty are given in Appendix I.

In general, measurement accuracy of a particular parameter is determined by contributions from:

— Errors in the primary measurement element, such as a venturi or nozzle in the case of feedwater flow, or an RTD in the case of feedwater temperature;
— Location of the primary element with respect to the heat balance envelope;
— Errors due to transmitter manufacturing specifications and transmitter calibration;
— Errors due to signal wiring;
— Errors due to analogue to digital conversion of the signal.

Examples of sources of instrumentation errors are also given in Appendix I.

Neutron flux instrumentation is calibrated to the core thermal power. As described in the previous sections, the core thermal power is determined by an automatic or manual calculation of the energy balance around the plant NSSS. An accurate measurement of feedwater flow, and main steam and feedwater temperature and pressure, will result in an accurate determination of core thermal power, and thereby an accurate calibration of the nuclear instrumentation.

In the next sections the focus will be, therefore, on the accuracy of feedwater flow and temperature measurements, with accurate flow measurements presenting a greater challenge.

3.3. FEEDWATER FLOW MEASUREMENTS

The instrumentation used for measuring feedwater flow is typically an orifice plate, a venturi meter or a flow nozzle. These devices generate a differential pressure proportional to the feedwater velocity in the pipe. Of the three differential pressure devices, a venturi meter is most widely used for feedwater measurement in NPPs. The major advantage of a venturi meter is a relatively low head loss as the fluid passes through the device.

However, nozzles and venturis are subject to a variety of problems, such as:

— Instrumentation drift;
— Feedwater pipe erosion;
— Cracked sensing tube;
— Bypass flow;
— Initial calibration problems;
— Fouling.

TABLE 3. SENSITIVITY VALUES FOR MAIN HEAT BALANCE PARAMETERS

Parameter	W_{FW}	T_{FW}	P_{STEAM}	M
Sensitivity (absolute)	0.09%FP/kg/s	0.25%FP/°C	0.0005%FP/kPa	0.1%FP/0.1%
Sensitivity (relative)	0.9%FP/%	0.5%FP/%	0.1%FP/%	1%FP/%

Some of the same problems are also encountered in the case of orifices, which are in addition subject to edge deterioration. Therefore, in general, to ensure that the claimed total feedwater flow measurement accuracy of better than ±0.5% is satisfied, it is essential to implement a regular surveillance and calibration program.

The major disadvantage of the venturi device is that the calibration of the flow element shifts when the flow element is fouled, which causes the meter to indicate a higher differential pressure and, hence, a higher than actual flow rate. This leads the plant operator to calibrate nuclear instrumentation high. Calibrating the nuclear instrumentation high is conservative with respect to the reactor safety, but causes the electrical output to be proportionally low when the plant is operated at its thermal power rating. On the other hand, undiagnosed defouling will lead to an underestimate of the measured feedwater and may result in the reactor thermal power licence limit being exceeded. This is particularly important if the plant has been power uprated.

To eliminate the fouling effects, the flow device has to be removed, cleaned and recalibrated. Due to the high cost of recalibration and the need to improve flow instrumentation uncertainty, the industry assessed other flow measurement techniques and found the ultrasonic flow measurement (UFM) to be a viable alternative. The UFM does not replace the currently installed plant venturi, but provides the licensee an in-plant capability for periodically recalibrating the feedwater venturi to adjust for the effect of fouling. Since the UFM technique is based on a totally different concept of flow measurement from that of a more standard pressure drop based flow measurement, it is not only free from the problems mentioned previously, but also provides a second, totally independent set of flow readings, which results in increased surveillance capabilities. A more detailed introduction of the applied UFMs is provided in Appendix II of this report.

3.4. FEEDWATER TEMPERATURE MEASUREMENTS

Plant temperature measurements are normally done by resistance temperature devices (RTDs). When installed properly, including the correct compensation for the lead wire resistance, RTDs can be as accurate as ±0.25% of the total measurement range, or better than ±1°C. However, experience has shown that often this is not the case and the resulting bias can significantly reduce RTD accuracy. Possible feedwater stratification downstream of high pressure feedwater heaters and the RTD location can add to the bias.

Some of the plants that have implemented MUR uprates have also improved the accuracy of feedwater temperature measurements by replacing existing RTDs and/or installing ultrasonic temperature measurement devices. These steps resulted in an improvement in feedwater temperature measurement accuracy from about ±1°C to better than ±0.5°C.

More information on instrument uncertainties can be found in the IAEA report on on-line monitoring [3].

3.5. SOURCES OF ERROR IN THE REACTOR THERMAL POWER CALCULATION

The total error in the reactor thermal power calculation is comprised of the contributions from different sources. In addition to errors arising from random and systematic measurement uncertainties, there are errors or uncertainties that are due to departures from the reactor steady state, changing constant terms such as main steam moisture content, or errors in design calculations such as in the total pump heat.

These faults or uncertainties could lead to an underestimation as well as an overestimation of the actual thermal power.

As mentioned previously, there are two methods for undertaking the reactor thermal power (heat balance) calculation — an automatic method using the plant computer and a manual method. The uncertainties associated with the two methods are unlikely to be the same and should be assessed individually. Aspects such as: (a) the way in which redundant measurements are averaged; (b) the use of instantaneous readings or readings averaged over time; and (c) any additional inaccuracies associated with the use of the displayed readings, should all be taken into account.

A change from automatic to manual means is also required when instrumentation drift is observed, such as in the form of a discrepancy between the original plant instrumentation and any add on instrumentation installed to improve the accuracy of the reactor thermal power calculation. An example of add on instrumentation is an ultrasonic flowmeter installed for on-line calibration of the feedwater flow instrumentation. When changes in the calibration factors are observed that are outside of the normal acceptance range, reactor power is usually reduced by an appropriate amount and manual means are used until the reason for the drift is identified.

3.6. THERMAL POWER, SAFETY ANALYSES AND LIMITS IN THE OPERATING LICENCE

The reactor thermal power limit is one of the most important quantities specified in the plant operating licence. The reactor thermal power limit is normally expressed in MW(th), corresponding to 100% full power (FP), and is based on the safety analysis performed at between 102% and 103% FP to account for the uncertainty in reactor power measurements. In certain cases, a safety analysis is performed at even higher power levels (e.g. 106% FP) to account for the reactor regulating system allowing the reactor to operate at up to 103% FP for short periods of time. Practical implementation of the compliance with the reactor thermal power licence limit depends on the specific safety margin and on specific regulatory requirements, and varies somewhat from country to country or even from plant to plant.

The most common options are:

— Instantaneous reactor power must be below 100% FP at all times;
— Power is allowed to drift above 100% FP by a few tenths of 1% and stay at that level until the value is verified by a repeated run of the calorimetric program;
— Power is allowed to drift above 100% FP by even 2% for a very short time, provided the average power over a specific period of time (usually between 2 h and 24 h) stays below 100% FP.

For stretch and extended power uprates, the safety margin normally remains the same, and, therefore, the reactor power compliance strategy can also remain unchanged. However, the essence of MUR uprates is a reduction in the margin between the licence limit and the value assumed in the safety analysis, based on the increased accuracy of reactor thermal power measurements. It is clear, therefore, that for MUR uprates the reactor power compliance strategy may have to be revised to ensure that the assumptions of the safety analysis are not violated.

For a typical MUR uprate of between 1% and 1.5%, the remaining margin is as little as 0.5%. It needs to be emphasized once again that, in this case, exceeding the margin may not only result in a violation of the operating licence but, more importantly, may invalidate the assumptions of the safety analysis. Therefore, the following steps are taken to ensure that a reactor that has undergone the MUR uprate is operating below the reactor thermal power limit:

— Reactor thermal power uncertainty analysis is redone to include instrumentation upgrades that were implemented as part of the MUR uprate application;
— Additional capability for on-line monitoring of the upgraded instrumentation, such as the installed ultrasonic flowmeter for feedwater flow calibration, is provided;
— Continuous comparison between the two methods for feedwater flow measurements (a nozzle and an ultrasonic flowmeter) is performed;
— The calorimetric program is run in the plant process computer and the output is available in the control room;
— Operating procedures clearly state that the reactor must be derated by a specified amount if there is any suspicion that the measurement uncertainty assumed in the application for the MUR uprate is in question.

Since by far the biggest effect on the reactor power measurement uncertainty comes from feedwater flow measurements, close attention has to be paid to justifying the validity of the measurement uncertainty, particularly transferring validation of the ultrasonic flowmeter calibration performed under laboratory conditions to field installations. It is also good practice to critically compare changes in feedwater readings of the installed ultrasonic flowmeter to the existing plant instrumentation, and to reconcile the revised value of the feedwater flow and of the reactor thermal power with other plant indications.

4. IMPACT OF POWER UPRATING ON PLANT INSTRUMENTATION AND CONTROL

The opportunities for power uprating will vary depending on: (a) the reactor type, nominal power rating and generation; (b) the margins inherent in the original design of the reactor and its major plant items; and (c) other factors specific to each NPP unit.

As for any licensing application, the uprated plant configuration will need to be supported by detailed analyses that demonstrate acceptable plant behaviour under normal operation, anticipated operational occurrences and design basis events. In order to achieve such demonstrably acceptable plant behaviour for the increased power level, it may be necessary to change specific algorithms or set points within the plant control, limitation or protection systems. Equivalent changes may be required to the set points for the alarms associated with the monitoring of the plant parameters.

An increase in output power will inevitably give rise to different conditions in the plant (temperature, pressure, flow rate, neutron flux), which could in turn potentially give rise to increased ageing or other phenomena. There may be, therefore, a need for monitoring of different parts of the plant, or surveillance activities at an increased frequency, to ensure that any appreciable deterioration is noted and appropriate action taken.

Any significant changes to the plant control, limitation or protection systems, or to the plant monitoring, will necessitate corresponding changes to the human system interface (HSI) in the main control room (and possibly also in other control rooms). It could also lead to changes being required in any plant simulator.

The I&C system functions in an NPP comprise protection functions, limitation functions, control functions, monitoring/display functions (including alarms), and testing/diagnostic functions. These include functions important to safety and functions not important to safety. All of these function types are potentially affected by a power uprating project.

Modifications in the instrumentation and control systems in relation to power uprating are, however, not necessarily very substantial. The following preconditions, in terms of sufficiency, must be fulfilled in the frame of I&C:

— Measurement ranges;
— Calculation algorithms to indicate credible reactor thermal power;
— Accuracy of process parameter measurements;
— Possibilities for setting new limits in the reactor protection system, limitation systems and other control systems.

I&C can feature in power uprating projects in the following three ways, where:

— Changes to specific I&C systems constitute a direct means by which an increase in output power can be engineered (or maximized), subject to a successful licensing application (I&C as enabler);
— Other changes to specific I&C systems are also required to enable the increase in power to be implemented;
— Further changes to I&C systems are necessary, for safety or operational reasons, as a consequence of the planned increase in thermal power (I&C as follower).

Referring to the first I&C role identified previously, several I&C capabilities and activities may be needed in order that a power uprate project can be implemented. By way of example, these may include the following:

— Modification of specific control systems to enable operation under different primary or secondary circuit conditions (e.g. higher primary circuit temperatures and flow rates) with the analytical justification to make the changes;
— Faster and more accurate three dimensional core analysis software program for the new fuel and to provide adequate representation of the core power in a timely manner for operational decisions;
— Changes in the pressurizer pressure control system to provide finer control under reduced operating margins;

— More accurate temperature control or monitoring, permitting ‘stable’ operation closer to the temperature limits for the fuel;
— Optimized calculation of the measurement uncertainties, permitting a reduction in the margin applied to the measurement of reactor thermal power.

Examples of the second I&C role may similarly include the following:

— Modification of the reactor protection system set points to permit operation under the new primary or secondary circuit conditions resulting from control system changes;
— Changes in the appropriate HSIs to accurately assess the current state of the plant and to take appropriate manual control actions under the new conditions resulting from the power uprate;
— Changes in alarm set points to reflect the new conditions resulting from the power uprate;
— Changes in the instrument calibration procedures to accurately measure process variables in the appropriate ranges after the power uprate.

Referring to the third I&C role, consider also by way of example that a power uprate project has been done and it results in increased feedwater and steam flow rates. In this proposed case, the increased flows raise several concerns, such as increases in the following:

— Vibration — leading to potential equipment damage or faster ageing through fatigue induced problems — and flow accelerated corrosion (FAC);
— Likelihood that small changes in the plant could result in overstepping power limits, since the operating margins have been reduced.

For both of these and other concerns, there are I&C solutions to help better understand the current state of the plant and equipment. Among others, but not limited to the list below, the following changes may be foreseen in a specific plant:

— Inclusion of vibration sensors;
— Increase in the frequency of vibration and FAC monitoring;
— Inclusion of additional process sensors;
— Replacement of sensors by ones with improved accuracy/reliability;
— Revision of instrument calibration procedures;
— Provision of additional information and tools (controls, displays and alarms) to the operator to help ensure that power limits are not exceeded even during transients;
— Adjustment of the plant computer and safety parameter display system (SPDS) software for the new operating conditions (higher power level, steam flow, etc.);
— Implementation of additional control capabilities;
— Inclusion of a scaling adjustment for ex-core and in-core neutron flux detector circuits to ensure that they read correctly at the uprated power level;
— Implementation of additional monitoring for flow induced ageing affects;
— Development of additional instrument validation processes.

On-line validation of the instruments that are used to determine thermal power is very important to ensure that the plant is operating within its operating power limit. The key is to make sure that all of the instruments are operating in accordance with their documented accuracy basis for the power uprate. It is also important that the control room operators should be alerted immediately if any instrument is operating outside its bounds. This on-line validation applies to instrumentation including:

— Feedwater flow;
— Feedwater temperature and pressure;
— Steam moisture or, for superheat conditions, temperature and pressure;
— Blowdown flow and temperature;

— Other cycle gains and losses, such as pump heat input and heat radiation.

Experience with power uprates so far has shown that, in order to maximize the uprate, every plant needs to evaluate the need for upgrading or replacing existing instrumentation based on the amount of the proposed uprate and the associated cost–benefit analysis.

4.1. EFFECTS OF THE ANALYSES AND OPERATING INSTRUCTIONS ON INSTRUMENTATION AND CONTROL CHANGES

Any increase in reactor thermal power (RTP) will necessitate either an increase in the temperature difference across the reactor core or an increase in flow through the reactor core under normal steady state reactor operation, in order to transmit the additional power to the turbine. If the uprated plant is then subjected to an anticipated operational occurrence or design basis event, the resulting transient would invariably be different from that for the plant prior to uprating. This will potentially affect the conditions arising within the primary circuit of the reactor, and in the event of a breach of the primary circuit boundary, also that external to the primary circuit (e.g. the containment environment).

For a MUR power uprating, the changes in conditions due to the small increase in RTP are likely to be minimal. For a stretch and extended power uprating, however, they could be significant. Irrespective of the extent of the power uprating, an analysis should be undertaken to demonstrate acceptable plant behaviour for the maximum permitted RTP.

The analysis undertaken should demonstrate that the:

— Plant control system will maintain the plant in a steady state in normal operation, and will respond as intended to demands for an increase or decrease in power;
— Plant control (or limitation) system will respond as intended under anticipated operational occurrences to prevent unnecessary demands on the protection system;
— Protection system will respond as required to prevent, or mitigate the effects of, anticipated operational occurrences and design basis events.

The analysis undertaken should also establish:

— The most onerous environment (e.g. temperatures, pressures, radiation levels) arising in different parts of the plant under a design basis event;
— Whether any different (additional or amended) actions are required of the operating staff in support of normal or emergency operation.

For a power uprating project, changes such as the following may therefore be required to the I&C as a result of the analysis:

— Optimization of the plant control algorithms and constants;
— Introduction of new limitation or protection parameters and/or changes to the limitation or protection set points;
— Replacement or additional qualification of any I&C equipment that would otherwise be required to operate outside its qualified operating environment;
— Changes to the existing, or introduction of additional, monitoring, control and/or alarm circuits as necessary to support any different actions required of the operating staff.

In addition, changes may also be required to the ‘conditions of operation’ for specific I&C equipment items, such as if the power uprating leads to increased reliance on these items.

4.2. SUITABILITY OF INSTRUMENTS

As stated in the preceding section, an increase in RTP will lead to changed conditions in the plant, both during normal operation and following a design basis event. The suitability of the existing instrumentation for such changed conditions will need, therefore, to be assessed as a part of any power uprating project. This assessment should include, but not necessarily be limited to, consideration of the following aspects:

- Range, such as for instrumentation used for purposes from normal operation to post-accident monitoring;
- Accuracy, including consideration of the effects of drift, particularly if MUR is being implemented as part of the power uprating;
- Safety classification and numerical reliability, particularly if specific instrumentation is to be assigned an additional or a different duty following the power uprating;
- Response time, such as for instrumentation used for control and protection, particularly if the transients arising from anticipated operating occurrences or design basis events are more severe (steeper) than previously assumed;
- Equipment qualification, such as where the instrument environment is analysed to be more demanding following a design basis event than previously assumed;
- Vibration and other environmental resistance, such as for instrumentation associated with primary circuit areas, where harsher ambient conditions may result from the power uprating.

4.2.1. Transmitters

Operating conditions at the new, higher power level may encompass higher or lower values for key physical variables. A decrease in maximum process values will not cause any adverse effects on the transmitter, but care should be taken if there is an increase in maximum process values. Depending on the type of reactors and the method of uprating, the following variables may exhibit relatively large increases in their new steady state operating values: primary and secondary flow, temperature, pressure, level and neutron flux.

The existing transmitter's capacity and the newly required range and span should be evaluated. Transmitters, detectors and sensors measuring these variables may need to be replaced, or adjusted to the new operating range, in order to indicate the correct values in per cent of full power operation. This may require span adjustment in the transmitters' output range or a recalibration. If the measuring devices are not replaced, only adjusted, their calibration procedures will need to be revised, too. The changes in the measuring range and span may also affect the transmitter uncertainty.

Adjustments in the dynamics of the measuring devices may also be necessary in order to meet new response time requirements stipulated by a safety analysis performed for the uprated state. The requirements on allowable uncertainties of these response times may also be more stringent at the new operating conditions.

4.2.1.1. Temperature

In general, an RTD or a thermocouple has its own characteristics determined by the sensor type. Checking the new temperature ranges in conjunction with the sensor type and recalibration of the signal converters are required if necessary.

4.2.1.2. Pressure

Pressure is a directly measured variable. Checking the new pressure ranges and recalibration or replacement of the transmitters may be required. Response time and accuracy requirements need to be considered carefully prior to transmitter replacement.

4.2.1.3. Flow and level

The signals from differential pressure type sensors measuring flow and level are affected by the process pressure and temperature in addition to the actual flow or level measurements. Checking the new range and span, recalibration or replacement of the transmitter may be required. A power uprate involving higher flow rates could in some plants lead to increased divergence between the level measurement channels.

4.2.1.4. Neutron flux

The linearity of the neutron flux detector output should be kept within the acceptable limit at reactor power levels. The sensitivity of the neutron flux detector should be checked to establish whether replacement of the detector is necessary or not.

4.2.1.5. Activity measurements

The normal activity level may be somewhat higher in, for example, the steam flow, which means the settings may need adjustment.

4.2.2. Sufficient accuracy and response time of measurements

The performance of process instruments, such as temperature and pressure sensors, is normally described in terms of accuracy and response time. Accuracy is an objective statement of how well the instrument may measure the value of a process parameter, while response time specifies how quickly the instrument would reveal a sudden change in the value of a process parameter. Accuracy and response time are largely independent and are identified, therefore, through separate procedures.

The deterioration of accuracy is called calibration drift or calibration shift; the deterioration of response time is referred to as response time degradation. Accuracy can generally be restored by recalibration.

For power uprating, accuracy of field sensors and transmitters, as well as instrument loop components, is a vital precondition. Based on the requirements arising from the analyses undertaken, all the existing and possible new transmitters and instrumentation components should be carefully designed and/or evaluated to comply with the new process conditions. If replacement is required, span calibration and response time testing should be done on the new transmitter in a 'bench test' before installation.

The performance of the existing signal processing equipment is normally not affected by the change of process conditions at uprated power. Verification should, nevertheless, be undertaken to confirm that the total loop (or channel) uncertainties from sensor to final instrument are within the allowable limits.

4.3. INSTRUMENTATION AND CONTROL SYSTEMS OF INTEREST

At higher reactor power levels, specific I&C systems assume an increased importance for either safety or operational reasons. However, the I&C systems in question will differ for different reactor types and generations. The following subsections provide a few examples.

4.3.1. NSSS pressure control system

Primary circuit pressure control for PWR plants with a pressurizer typically involves:

— Switching on banks of heaters to increase the pressure;
— Opening injection valves to introduce a cooling spray to decrease the pressure.

The original controllers were only able to maintain 'coarse' control about the desired value under normal, full power operation. However, in order to achieve higher power levels, a controller that is able to maintain much finer control about the desired value may be necessary. The provision of such a system is, therefore, of increased importance.

4.3.2. Steam generator level measurement and control

The conditions within the steam generator of a PWR make measurement and control of the water level inherently difficult. Steam generator water level is also typically used as one of the reactor protection parameters.

At higher power levels, the feedwater–steam interface will be more agitated and, hence, the measurement and control of the water level within the steam generators will be even more difficult. Accurate measurement and stable control of the water level both, therefore, assume an increased importance in order to prevent unwanted protection actions.

4.3.3. In-core monitoring system

Monitoring the conditions within the core is generally required for many reactor types. This enables the operator to detect any asymmetry or other abnormalities and to take action before these develop sufficiently to place demands on the limitation or protection systems.

With higher average power densities, any abnormality within the core is likely to be amplified and to develop more rapidly, and hence to be potentially more serious (e.g. peak power densities or temperatures reached more easily). It is of increased importance, therefore, that the operator is provided with an accurate and detailed core monitoring capability.

4.4. CALCULATIONS AND ALGORITHMS

Calculations and algorithms support many of the automatic control, limitation, protection and complex monitoring functions. These both underpin the physical behaviour of the plant and incorporate an interpretation of this behaviour into the corresponding I&C logic.

For a power uprating where the emphasis is most probably on increased stability of the plant and better understanding of its status by the operator, more accurate and detailed calculations and more complex algorithms are likely to be required.

Typical examples of the need for more advanced calculations and more complex algorithms can be found in various sections of this report.

4.5. MODIFICATION OF SET POINTS

Set point values for control systems, limitation systems (interlocks) and protection systems, and for the associated alarms in a plant subject to power uprating, should be based on and shown to be acceptable by the analysis undertaken for the plant. The analysis undertaken to establish these values should be no different in concept from that undertaken for a new plant.

The applied set point changes associated with the power uprate are intended to maintain margins between operating conditions and the reactor protection (i.e. trip) set points, and so they do not significantly increase the likelihood of a false trip or failure to trip upon demand. Therefore, the existing licensing basis should not be adversely affected by the set point changes implemented to accommodate the proposed power uprate.

4.6. EFFECTS OF TRANSIENTS — HOW INSTRUMENTATION AND CONTROL CAN HELP

As discussed in several preceding sections, new analyses will be required to establish the transient behaviour of the plant in response to anticipated operational occurrences and design basis events occurring from the steady state conditions applicable to the new RTP level.

The implications are that the control algorithms may benefit from optimization for the new conditions, that the protection system may require new parameters or earlier initiation (revised set point values) for existing parameters, and that various instruments used for protection and post-accident monitoring may require qualification for a more demanding environment.

One of the consequences of power uprates is that the plant is operating closer to its licence limit, and equipment may be operating closer to its maximum capacity. Therefore, it is important that the modifications are well analysed for both normal operations and transient conditions to make sure that the limits are not exceeded. It is even more important to make sure that the operators have suitable information and tools to help them keep the plant within the operating limits. This includes several aids and controls.

Appropriate plant information is needed to ensure that the operator has a correct understanding of the plant state. The information must also be accurate to ensure that the control systems get the correct input for their actions. The control systems will need to support operator actions so that transients do not put the plant over the power limits. Appropriate alarms to alert the operator and HSIs to provide the operator with information and control interfaces are needed. Information validation tools are also necessary to make sure that the information is accurate.

4.7. INDIRECT IMPACT OF POWER UPRATING

Any major power uprating, by definition, will lead to operation closer to the absolute limits for the plant. The regulatory authority, therefore, may view the licensing application in a similar way to that for a SAR ‘revalidation’ or periodic safety review (see the Safety Guide in the IAEA Safety Standards Series No. NS-G-2.10 [4]).

With regard to the I&C, this may be assessed from the point of view of whether it meets current safety standards (e.g. as given in the IAEA Safety Standards Series Nos NS-R-1 [5], NS-G-1.3 [6] and NS-G-1.1 [7]), in addition to those in place at the time of the original plant design.

Though it would be unrealistic to expect an older plant to fully comply with all aspects of the current guidance, any major power uprating project could be expected to address the following broad questions:

— Are the normal operating systems (e.g. automatic control systems) and limitation systems arranged to minimize the demands on the protection systems?
— Are the protection systems able to provide adequate protection against all DBEs?
— Does the I&C maximize the opportunity for the operator to understand the safety status of the plant, particularly under DBE conditions?
— Does the I&C minimize the likelihood of human error on the part of the operating and maintenance staff (as an initiating event or in response to a requirement for action)?

The possible indirect implications of the licensing of a power uprating on the I&C, therefore, could include (but not necessarily be limited to) the need to:

— Automate the testing and calibration procedures (to the extent practicable);
— Introduce more stable control characteristics (in addition to any directly related to the power uprating);
— Introduce additional limitation functions (unrelated to the power uprating);
— Introduce additional protection functions (unrelated to the power uprating);
— Introduce additional monitoring of the status of the plant safety functions and the barriers to the release of radioactivity (if there are any gaps in the existing provisions);
— Introduce additional surveillance monitoring/failure identification of the plant’s safety systems (to the extent practicable);
— Provide additional guidance in support of operator decision making.

4.8. INTEGRATION OF THE ORIGINAL AND MODERNIZED SYSTEMS FROM A HUMAN ASPECT

I&C modifications, including those associated with power uprating, will result in a mix of old and new I&C systems with their corresponding HSI. From the point of view of the operating staff, the HSI in the MCR is of particular importance, since this can either enhance their effectiveness or, if badly arranged, be a contributor to human error. In this regard, it is generally accepted that a non-uniform interface be avoided.

A change from traditional desks and panels to a screen based interface, for example, may be sought as part of the I&C modification that comes together with power uprating. However, such a change could have a significant impact on the operators' situation and ability to perform their tasks. In particular, it would require a different approach to both communicating and working as a team within the MCR.

A change in interface type and the implementation of a major power uprating would each individually place significant demands on the operating staff. For a stretch or extended power uprating project, consideration should be given to whether these activities may be undertaken in a single step or whether they should be decoupled.

The HSI for new I&C systems provided in connection with power uprating projects should be integrated into the existing HSI in the MCR. Where this existing HSI is traditional, any screen based display provided as the 'normal' interface to the new systems could then be retained in the relevant I&C equipment rooms for system monitoring/maintenance.

4.9. IMPACT OF INSTRUMENTATION AND CONTROL CHANGES ON PLANT PROCEDURES

All changes made to I&C systems, or to the way in which they are to be operated, tested and maintained, should be fully reflected in the relevant plant procedures.

The following provides a few examples of features potentially associated with power uprating that would need to be addressed in the procedures:

- Changes to limitation and protection system set points;
- Changes to alarm set points and actions on receipt of alarms;
- Automation of I&C system testing and instrument calibration;
- Any cautions associated with the use of modified or new control systems;
- Any restrictions in the event of unavailability of specific I&C systems or subsystems.

4.10. BENCHMARKING FOR UPRATED OPERATING CONDITIONS

Major plant items, which either have an important role in safety or constitute a significant financial investment, are typically monitored for signs of deterioration. This is usually accomplished by comparison with a benchmark established early in the life of the plant. If the monitoring, and hence the benchmark, applies to the full power situation, then any change in the operating conditions arising from the power uprating could potentially affect the benchmark.

One benchmark that clearly needs to be addressed is the actual reactor thermal power level prior to the uprate. A benchmark that is outdated or is based on insufficiently accurate instrumentation may lead to either an underestimate or an overestimate of the increase in plant output, and could result in exceeding the reactor thermal power licence limit. There are documented cases of plants that, in doing benchmarking prior to an uprate, discovered their calculated reactor thermal power was in error by as much as 2%.

In addition to benchmarking individual instrumentation loops, the best way of getting an accurate value of the increase in plant output is to perform a full or at least a simplified turbine performance test before and after the uprate. If the cost of this is deemed prohibitive, then at least more accurate feedwater flow and temperature measurements should be performed.

5. HUMAN AND TRAINING ASPECTS

The personnel at any NPP play a vital role in the productive, efficient and safe generation of electric power. Operators monitor and control the plant to ensure it is functioning properly. Engineering and maintenance personnel help ensure that plant equipment and systems are functioning properly and restore them when malfunctions occur.

Personnel performance, and the resulting plant performance, is influenced by many aspects of plant design, including the level of automation, personnel training and the interfaces provided for personnel to interact with the plant. As part of the power uprate implementation, it is important that the appropriate HSIs are implemented in order to provide the user with both the proper information to have a good understanding of the current state of the plant, as well as the proper capabilities to interact appropriately with the controls.

While the proper implementation of HSIs during power uprate projects can greatly improve personnel and plant performance, it is important to recognize that, if poorly designed and implemented, the potential exists for there to be a negative impact on performance, for errors to increase and for human reliability to be reduced, resulting in a detrimental effect on safety and cost effective power production. Human factors engineering (HFE) is needed to ensure that the benefits of the power uprate are realized and problems with its implementation are minimized.

Power uprate projects may affect the HSI to different degrees. A small scale project might only affect different operating values and limit values, but it can also include new indicators, and push buttons for displaying additional process parameters and manoeuvring new equipment. Larger projects might also include rearranging the existing push buttons and readers, etc. Other projects might have an even bigger impact on the HSI where there is a change in technology, from panels and desks with push buttons and readers to a screen based interface. The amount of changes in the HSI will have a direct impact on the needed education and training, verification and validation of the HSI, and the updating of operating and disturbance procedures, etc.

As part of the specification phase of the power uprating program, functional analyses should be performed in order to determine the testing needs of all end-users in different modes of operation, such as steady state, normal transients (such as startup and shutdown), abnormal operation, emergency operation and maintenance.

5.1. HUMAN ERRORS

Experience has shown that human errors have led to some of the reported events after power uprates have been implemented. Some of these are related to an inadequate understanding of the new or modified system. Others are related to control systems, set points and control capabilities that did not meet all the needed abilities to respond to normal and transient conditions, especially where the operating margins were smaller or the system was more sensitive. Others still are related to situations where the information — including alarms — provided to the operator or maintenance staff was inadequate to support the user in the desired manner.

Sections 5.48–5.56 of Ref. [5] identify the human factor requirements in the design of NPPs, including that for the HSI in the control rooms.

5.2. CHANGES TO CONTROL ROOM CONTROLS, DISPLAYS AND ALARMS

Power uprate projects will most likely lead to some changes in the controls, displays and alarms in the control room. The following discussion focuses on some of the human factor issues and concerns that should be addressed when control room changes are being considered.

5.2.1. Controls

The power uprate project should evaluate what controls may need to be added or modified to allow proper control of the plant under the new conditions, functionalities, response times, etc. The uprate project may provide the opportunity to go to soft controls for some. Minor modifications and additions would fit better in the original control environment (whether conventional or soft control). If the power uprate project comes together with more significant I&C system replacements or extensions, the new controls will most likely have their own, new control environment. This, however, will raise new concerns with regard to human factor issues.

This report does not provide detailed requirements for controls; more information on this area in provided in the IEC reports (see Refs [8, 9]).

5.2.2. Displays

Understanding information is at the centre of human performance, and therefore of plant performance in complex systems. The introduction of power uprates may change both what information is obtained by personnel, and how some of it is obtained about plant systems, equipment, processes and conditions. For these reasons, an important aspect of the power uprate project is to develop an appropriate presentation of information that can be used by the operation, engineering and maintenance staff to efficiently and effectively perform their jobs. These displays, whether hardwired or computer based, should follow good human factor engineering practices and requirements. Some of the important things to define or consider for new or modified displays, based on the operational, engineering and maintenance needs, include the following:

— Identification of tasks and associated needs;
— Identification of information needed and to be presented;
— Organization of the information to be presented;
— Content of the individual displays;
— Display format (text, mimics, lightbox, trends, graphs, etc.);
— Navigation within the display hierarchy with computer based displays;
— Design for task performance;
— Design for teamwork, operator coordination and collaborative work;
— Coding and highlighting of information;
— Use of icons and symbols, abbreviations and acronyms;
— Data quality and data update;
— Response time to events.

The design of the displays should be done with input from the users. The IEC reports (see Refs [8, 10]) give more detailed requirements for displays.

5.2.3. Alarms

The operators' task of monitoring the operating condition of NPPs and detecting problems can easily be overwhelming due to the large number of individual parameters and conditions involved. Therefore, operators are supported in these activities by alarms. I&C offers the opportunity to ensure that any new alarms necessitated or desired as part of the power uprate project provide appropriate information. Although alarms play an important role in plant operation, they have also posed challenges to the users. Common problems include:

— Too many alarms (including 'avalanching');
— Too many spurious or nuisance alarms;
— Poor distinction between alarms and normal status indications.

I&C capabilities offer the opportunity to develop effective alarms that provide the desired capabilities and avoid the common problems to support operation and maintenance activities related to power uprates. Alarm procedures need to be augmented and/or new procedures need to be developed for the potential new or modified alarms resulting from the power uprate project.

The IEC reports (see Refs [8, 11]) give detailed requirements for alarms.

5.3. CHANGES TO THE SAFETY PARAMETER DISPLAY SYSTEM

After the accident at the Three Mile Island (TMI-2) NPP, the NRC and the nuclear industry required the installation in NPPs of a system that would provide a better support to the plant personnel during normal and accident conditions. This includes a safety parameter display system (SPDS), a post-accident monitoring system (PAMS) instrumentation and bypassed and inoperable status indication (BISI). The regulations, however, provided little guidance on how these systems, functions and capabilities were to be implemented.

Changes deriving from the power uprate project to the safety parameter display system (SPDS) and other special displays, such as post-accident monitoring, should follow all of the human factor engineering good practices and requirements that are used for displays in general, as discussed previously. However, these special displays have additional regulatory requirements that must be included. As an example, in the USA, the SPDS requirements are specified in NUREG-0737 [12] and NUREG-1342 [13]. The review criteria for the human factor aspects of the SPDS are contained in NUREG-0700, Rev. 2 [14].

In addition, NUREG-1342 [13] recommends that parameters, also a point of focus in a power uprate project, reflect the following safety functions:

— Reactivity control;
— Reactor core cooling/primary system heat removal;
— Reactor coolant system integrity (e.g. steam generator pressure, containment sump level);
— Radioactivity control (e.g. stack, steam line and containment radiation);
— Containment conditions (e.g. containment pressure, temperature and isolation status).

The above correspond approximately to the fundamental safety functions given in Ref. [5].

Changes made for the power uprate project should be evaluated to determine any effects on the safety functions. If there are any changes, the SPDS should encompass these into a modified SPDS following the appropriate regulations and the human factor engineering practices for displays.

5.4. TRAINING AND SIMULATION ISSUES

Training and the use of simulation for other activities, such as design evaluation, acceptance and procedure development, are important aspects of the power uprate project. Training is needed for both operations staff and maintenance staff for the new and modified systems, equipment and HSIs that result from the power uprate project.

A power uprate project will create a need for education and training among the utility personnel. The main target groups are within the operations and maintenance departments, but some groups within the design department might also be in focus.

All personnel should have some theoretical knowledge of the scope of supply and of the operation of the new equipment. This should also include what equipment will be removed, and how the interfaces to the new and retained original equipment are intended to interact with each other.

Appendix III shows examples of potential training needs related, among others, to the power uprating project with changes in controls, HSIs, functionality and performance.

5.5. CRITICAL TIME SCHEDULE FOR THE FULL SCALE SIMULATOR

The plant simulator and other simulation capabilities must be modified to reflect the changes made in the plant. These simulation capabilities play an important role in familiarizing and training the operators on the new systems, equipment and HSIs. This leads to a need to modify the simulator well before the changes are made in the actual plant.

The time schedule for power uprate projects is often influenced by the utilities' possibilities to earn additional money. This implies that if it is possible to increase the output power one year earlier, the utility will start earning more money one year earlier. This means that a drive exists to make tight time schedules for most power uprate projects.

In general, the needed input to the simulator comes from the output of the system design. Therefore, as part of the power uprate project, a plan should be established for the modification of the plant simulator and other simulation capabilities related to the power uprate project. This plan should include a schedule that addresses the simulation needs for the project. These include:

— Design and evaluation support;
— Operating procedure development;
— Engineering evaluation and verification of the I&C logic and HSI — simulation can allow closed loop testing of control algorithms to help ensure desired functionality, and facilitate demonstration and testing of operating displays to obtain the input and review of operations;
— HFE evaluations of the HSIs;
— Familiarization and training of operators;
— Familiarization and training of maintenance staff;
— Factory acceptance tests or other testing of the I&C and HSI designs.

This schedule must incorporate sufficient lead time prior to the implementation of the power uprate to allow the needs mentioned to be satisfied.

6. REGULATORY ASPECTS

6.1. LICENSING EVALUATION

The nominal value of the reactor thermal power is one of the most important safety parameters. The most important task for the regulatory body concerning power uprates is to ensure that the licence conditions are satisfied at the higher power level. In most cases, the maximum allowed thermal power is specified in the operating licence. This implies that if the thermal power is to be increased, the licensee has to apply for a change in the licence, that is, a licence amendment.

Any changes must be approved by the regulatory body, thus, the licensing analysis that demonstrates the safety of the plant must be performed when planning the power uprate. The essential part of the analysis is the demonstration that the plant structures, systems and components can support safe plant operation after the power uprate and/or associated plant modifications, and that the results of the safety analysis remain within regulatory limits.

The utility that operates the plant is responsible for the safety of the installation. It is the responsibility of the operator to submit an application for a modification of the plant to the safety authority and to demonstrate, by consideration of the analysis results, that this modification is feasible, while keeping sufficient licensing or safety margins.

One of the main tasks for the regulatory body is to ensure that the internal quality control at the plant, of necessary analyses and plant modifications, for example, is managed properly. A power uprate entails changes in the technical specifications and in the SAR, which must be approved by the regulatory body. At some point in the process, a testing program for operating at the higher power would probably be developed by the licensee and reviewed by the regulatory body. The process of regulatory review for a power uprate will be plant specific and may also vary from country to country, since the requirements differ. The NRC has developed a few guidelines and review standards concerning the review and assessment processes (see Refs [15, 16]).

The regulatory approach to evaluation and acceptance of proposed power uprates is based on the following general principles:

— All safety impacts of the proposed change should be evaluated in an integrated manner. If several changes are implemented, then the cumulative effect on safety margins should be considered in the decision making process. If reductions in margins are predicted for certain events, the safety benefits from the proposed change should outweigh the anticipated safety margin reductions.
— The scope of design verification and safety analysis activities in support of the proposed change should be appropriate for the nature and scope of the change. Data, methods, acceptance criteria and assessment results in support of the change must be verified, validated, documented and available for review.
— Programs of surveillance and compliance activities should be established to monitor the effect of changes on plant operation and the performance of systems and equipment.
— Any new challenges to safety caused by changes in design or operating conditions should be identified, evaluated and shown to meet all applicable requirements.

6.2. POTENTIAL REGULATORY CONCERNS

6.2.1. General concerns

The detailed implications for I&C systems may differ significantly, depending on the type of power uprate. Some general concerns are discussed in the following sections.

6.2.1.1. Adequate resources

Planning and implementation of a power uprate is usually a resource intensive project. A large part of the personnel at the plant and other resources are probably involved in the process. It is important to make sure that the licensee manages to handle the realization of the power uprate in a safe way and at the same time maintain day to day safety work at a high level.

6.2.1.2. Project management structure

Management of I&C related issues is dependent on the project management structure as a whole. As seen in previous sections, the changes concerning I&C directly related to power uprates, in many cases, could be minor in comparison with the overall magnitude of a power uprate project. As a consequence, a necessary modification might be overlooked.

6.2.1.3. Systematic evaluations

Power uprating may result in changes in some parameters that, in turn, affect I&C systems. This could involve changes in operating ranges and acceptable response times. Hence, the licensee has to perform high quality systematic analyses and reviews, and be able to demonstrate that the I&C systems will either cope with these changes and new demands, or that needed modifications are carried out.

6.2.1.4. Human factor issues

If changes in I&C systems entail modifications in the main control room or at other working stations, human factor issues should be taken into account already in the design phase. As seen in previous sections, uprating could result in reduced operating margins and faster transients and, consequently, could affect the working conditions for the operators. This could require the introduction of more automated I&C systems and/or functions which, in turn, requires adequate operator training.

6.2.1.5. *Relevant benchmarks*

It is recommended that adequate 'fingerprints' are made of the reactor unit prior to uprating, using both the normal instrumentation of the plant and also special instrumentation to be used during testing at the new power level, so that changes may be detected and dealt with.

6.2.1.6. *Vibrations*

Vibrations is one area where 'fingerprinting' could be beneficial. The feedwater and steam flow rate may increase as a consequence of a power uprate. Hence, more instrumentation and monitoring of vibrations in pipes and internal parts of both the reactor pressure vessel and other components may be needed. If adequate instrumentation is fitted and used before the uprate is realized, possible future problems regarding vibrations may sometimes be predicted and prepared for, or at least understood afterwards. In any case, the risk for vibration problems connected to power uprating should not be overlooked.

6.2.1.7. *Interruptions in the project*

It is advisable, both for the licensee and the regulator, that a plan be produced to address how unexpected interruptions in the power uprate project should be handled. For example, if changes in settings or other modifications necessary for the uprate are implemented during the outage, but it is then not possible to complete the uprate at that time for some reason, a contingency plan is essential.

6.2.1.8. *Testing program*

An important task for the regulator is to assess and approve the test program that is to be conducted by the licensee during the trial operation at intermediate power steps and at the new power level. This testing process represents an opportunity to ensure that the instrumentation and control systems are working properly, that the settings are correct and that the plant behaves as anticipated. For these reasons, a well developed test program is essential. It should be carried out with caution to avoid conflict with reactor safety.

6.2.1.9. *Experience feedback*

The regulatory body will also closely follow national and international experiences from power uprates and how they impact on I&C, and should make sure that the licensee does this as well.

6.2.2. MUR type uprates

As described earlier in this report, the so-called 'Appendix K' or MUR type uprates are based on the fact that in most countries, the majority of the safety evaluations are done at an assumed thermal power, which generally is about 2% higher than the licensed power. Under certain circumstances, which basically involve showing that the uncertainty of specific measurements is lower than anticipated or could be reduced, a part of this margin could be allowed to be used for power uprating.

The regulator should take into consideration questions regarding the general applicability of this kind of uprate, as well as the techniques used to reduce the uncertainty of relevant measurements.

The practice of doing safety analyses at a thermal power of 102% of the licensed thermal power originates from Appendix K of 10 CFR Part 50, where it was stated that it should be done "to allow for such uncertainties as instrumentation error". The phrase "such as" has led to some discussion about what uncertainties this 2% margin should account for, since in the original rule making it was not required that the uncertainty in the power measurement should be demonstrated. Finally, the NRC concluded that the 2% margin should probably solely account for instrumentation uncertainties. At the same time, the NRC decided that if a licensee could prove the uncertainty in the thermal power measurement to be less than 2%, this reduction in uncertainty could be used to justify a power uprate.

It should be noted, however, that by doing so, the 2% margin is interpreted as a margin for random uncertainties and not a margin for possible systematic uncertainties or faults in the calculation of thermal power. An increase in the number of overpower events, in which the power level for which the safety analyses have been performed is exceeded, could therefore be anticipated, since the margin for unidentified systematic uncertainties or faults in the calculation of thermal power will be as low as 0.4–0.6%. A renewed evaluation of the way the thermal power is calculated, as well as more stringent demands on quality control and calibration procedures, may be recommended.

Similarly to the situation in the USA, the safety case in the United Kingdom was changed from one that assumed a 2% uncertainty at full power to one where it is possible to take credit for a lower calculated uncertainty in a corresponding power uprate.

The practice in other countries may vary. In those countries that use best estimate techniques for safety assessment, the reactor power may be one of the statistical parameters that should be considered. This is to say that a MUR uprate implies a change of perspective and possibly a need to update or change certain regulatory requirements to be applicable.

It has been determined that the most significant part of the uncertainty in reactor thermal power measurement is due to the flow measurement of the feedwater. Feedwater flow is typically measured by venturi tubes, flow nozzles or orifice plates. Typical uncertainties for these measurements are shown in Section 3.3, together with a description of how the measurement of different factors affects the evaluation of the thermal power. Techniques to reduce the uncertainty of this measurement have been developed and may be used as justification for a power uprate.

The most common way of trying to reduce the uncertainty is to install an ultrasonic flowmeter. Below is a description of some issues, both general and ultrasonic flowmeter specific ones, in which the regulatory body may show an interest.

An application for a MUR uprate should include a justification with an estimation of the total uncertainty of the power measurement, stating in detail all the different factors contributing to the uncertainty. This justification should be done using a proven standard for an evaluation of the uncertainty, which should include an evaluation of the confidence level in the calculation. The justification should be plant specific since, for example, the uncertainty of the flow measurement is dependent on the profile of the flow and, therefore, on the piping configuration.

The licensee should also give a detailed description of the usage of the instrumentation in question. This includes information about maintenance, calibration and a technical basis for an allowed outage time for the instrument. Since the increase in power is justified by a decrease in uncertainty, the power should be reduced if the instrument does not work as intended. The way this is managed should be explicitly described and documented. Ultrasonic flowmeters are commonly used as a means to adjust the measurements in the original feedwater measurement instrumentation, which leads to an interest in the way the adjustment of the original measurement is handled. It is both a question of how often the correction factor is updated and how the acceptance of a correction factor is managed.

Due to the reported experiences from the USA (see Section 8.2), some specific issues related to the installation of ultrasonic flowmeters have to be sorted out and discussed with the regulator. Anomalies and discrepancies in the measurements have been observed and, in some cases, the plants have exceeded the licence power. Noise has disturbed the measurements, which makes it important to investigate if vibrations at relevant frequencies could occur. It also pinpoints the importance of monitoring the performance of the flowmeters to make sure that interference between the measurements does not occur.

Experience reported from the USA also stresses the need for stringent and adequate quality assurance. This need applies, for example, to the installation of the instrument as well as the software used. Thus, awareness is essential, both on the part of the vendor and of the plant personnel.

6.2.3. Stretch and extended power uprates

As described earlier in this report, the improvement in the fuel design has made it possible to carry out stretch and extended power uprates. For these kinds of uprates, the general concerns regarding I&C described previously are all valid. It is essential that the potential impact of the uprate on all plant systems (including the service systems) has been fully assessed and reflected in the licensing submission. The assessment should take into account the actual performance of the plant systems, as established from operating experience, rather than being based solely on the original design assumptions. The general advice from a regulatory perspective is, therefore, that a comprehensive baseline of signatures of the NPP be established prior to the uprate in order to assess the resulting plant behaviour.

In general, it can be concluded that if there are problems at the current power levels, they will tend to increase at higher power levels. For example, the higher steam flow rates at higher power may increase the magnitude of vibrations. Similarly, the reliability of the level measurements in BWRs, which is crucial to safety, may be affected by the higher flow rates. The amplitude of the noise will normally increase, a fact which has to be taken into account when new set points are introduced. Examples of measurement settings or measurement ranges that may have to be changed are activity measurements and neutron flux measurements. Appropriate handling of all the aspects mentioned previously has to be demonstrated in a detailed way in the corresponding licence modification submittals.

6.2.4. Test programs

As mentioned earlier, a well thought out test program is essential for ensuring the further safe operation of the plant. It is during the test period that the behaviour of the I&C systems is put to the test to make sure that it behaves as intended and that the settings are correct.

A starting point for the design of the test program could be the original test program that was used when the reactor was first taken into operation. This original test program should be revised, however, to take account of the type of power uprate and the changes implemented. Operating experiences and experiences from earlier testing processes should also be taken into account. The regulator should make sure that the scope for the testing program is wide enough, a proper evaluation is undertaken after the different tests are performed, as well as that appropriate limit values are set, if applicable.

7. INSTRUMENTATION AND CONTROL IMPLEMENTATION GUIDELINES FOR POWER UPRATING

7.1. INTRODUCTION

The goal of power uprating is to maximize the output of the plant (by increasing the thermal power or increasing the efficiency/minimizing the losses incurred), while minimizing the likelihood of an inadvertent reactor trip and the impact on plant ageing. In general, this is not a simple task to achieve, and it is essential to weigh potential benefits against the associated potential risks.

There are many technical issues associated with the implementation of I&C modifications in NPPs, and some of them are addressed in other IAEA reports (Refs [17, 18]). It is not the intention of this report to repeat such guidance; instead, this section is restricted to those I&C issues that are either specific to or particularly important for the successful implementation of power uprating projects.

7.2. INSTRUMENTATION AND CONTROL DESIGN RELATED ISSUES

What often sets the time schedule for a project is the design process, and associated manufacturing and testing of equipment before shipment to site. A closer look at the design process helps identify three different phases: conceptual design, system design and detailed design. These phases are really parts of an iterative process, rather than a straight sequence process.

Power uprates represent a significant change that may necessitate modifications to many individual control systems. It is important that the basis upon which the power uprate design work is to be undertaken be established at an early stage. It is also important to start with the overall design so that the wider implications of the power uprating are understood and individual component questions do not take undue prominence.

Significant coordination effort is required in order to undertake the necessary analysis and to introduce the modifications in a safe and efficient manner. The project should be organized so that the responsibilities for this function are clear. Examples of coordination issues are:

— *Coordination within/between individual modifications:* Interaction analysis should be done. Modifications in individual support systems should be coordinated with other modifications.
— *Safety analysis:* All modifications that will have been introduced into the plant prior to the power uprate (even if they are not a part of the power uprate) should be included in the power uprate safety analysis.
— *Action analysis:* The project is responsible for ensuring that all requirements arising from the safety analysis are 'captured' and included appropriately in the planned modifications.
— *Licensing submission:* The project is responsible for ensuring that the technical solutions implemented comply fully with the requirements given in the licensing submission.

7.2.1. Existing documentation update

A power uprate could constitute a major modification of the plant that may affect many systems. Before starting the modification work, it is necessary to establish the correctness of the relevant documentation, for example:

— Documentation should be updated in a way that will form the basis for all power uprate modifications, that is, it will be the foundation upon which the modification activities are based. Larger modifications, and especially those that concern reactor safety, will be very hard to carry through if the documentation is not correct from the beginning. Therefore, documentation has to be revised to reflect the current plant configuration before starting work on the power uprate.
— SAR updates. The updates should be done considering, on the one hand, those completed projects that are not yet implemented in the SAR and, on the other hand, the power uprate. The first part normally can and should be done in the project in question.

Once up to date documentation is available, a project execution plan should be prepared that addresses the steps discussed in the following section.

7.2.2. Design and verification preparation

Design and verification preparation may involve the following:

— Preparation of an overall summary description of the planned power uprate.
— Producing a design rule on the plant level at which the design activities should be undertaken (e.g. at the system level or across the whole plant). There may be several areas where considering things across the plant can give valuable information and understanding. For example, a plant's interaction with the external power network is important for power uprating projects.
— Updating the design rule and reproducing it in logic form.
— Ensuring the general test instructions are clear.
— Ensuring the general control instructions are clear.

7.2.3. Administration and design process

The administration and design process involves the following:

— Planning the work and the way (method) of working.
— Identifying the parties concerned and getting them initiated with the work.

— Checking that the appropriate working processes are in place for the various different types of modification.
— Clarifying the functions that are to be undertaken jointly between design departments and jointly planning the associated design activities.
— Appointing the person responsible for all process systems in question, including mechanical systems, ventilation systems and other systems.
— Appointing the person responsible for all electrical and control systems.
— Appointing the system coordinator for all systems in question.
— Letting the person responsible for the process system begin the design work with system descriptions and flow descriptions for all systems in question.
— Letting the person responsible for the process system in the beginning of the design work produce component specifications for new and altered process components, and also for process components that will get altered conditions.

Particular care should be exercised when all the design modifications leading to the power uprate have been completed but there are discovery issues that delay the actual implementation of the uprate. In this case, the plant operator must ensure that the modifications have no negative licensing implications or a detrimental effect on the plant operation at the original power level.

7.3. SYNCHRONIZING ACTIVITIES IN AN INTEGRATED PLAN FOR POWER UPRATES

The complexity of the project and the scope of supply will affect the implementation time schedule. In order to ensure that safety and operational/economic performance of the plant are maximized, integration of all uprate related activities into a single logical and well structured plan is required.

Consideration of all possible requirements and options in an integrated plan will also help to ensure that individual modernization activities do not restrict the future options for other planned or potential modernization activities.

Power uprate activities are only one aspect of planned activities in the plant. In order to best satisfy the needs of the plant, there should be an integration of the power uprate activities into the overall long term plan for the plant. The integration of the power uprate project into the overall plant plan will most likely provide both guidance and constraints on the project.

As a subset of the overall long term plan for the plant, there should be a long term plan for the I&C equipment and systems. This plan should include maintaining or modifying existing I&C systems and equipment, and modernizing I&C systems and equipment. Again, it is best to integrate the I&C aspects of the power uprate projects into the overall long term I&C plan for the plant. This will ensure that the power uprate activities are consistent with its overall goals and objectives.

The disadvantage of not having an integrated plan is that the power uprate project will be done as a stand-alone project without taking into consideration the plant as a whole. Experience has shown that this often leads to isolated islands of functionality and information. This has frequently resulted in increased operational and maintenance costs, and unnecessary duplication of functions and information in the plant. The stand-alone approach has often led to the use of different equipment and systems from those currently used in the plant, leading to increased costs for spare parts, training and maintenance. This also leads to either disconnected systems and information access, or to the need to develop costly interfaces between systems or information sources.

It is important to make the decisions for the power uprate project based on the overall long term plan for the plant, in order to better integrate with other systems and equipment, share information as appropriate, and reduce operational, maintenance and capital costs. These operational, maintenance and capital costs are not only for the power uprate related systems and equipment, but also for any equipment or systems that interact with them.

Incremental power uprating at the plant also requires integrated planning. When considering a particular power uprate project, it is important to interface/integrate with other ongoing or planned power uprate activities. If a plant has an ongoing power uprate project, an evaluation should be made to determine if the subsequent power uprate projects should be combined and re-analysis should be done for the total uprate. Even if these power uprate projects are not combined, it is essential to have an integrated plan so that the new power uprate project performs the correct analyses and takes as much benefit from the other power uprate project implementation, instrumentation, baseline, etc., as possible. For example, certain stretch or extended power uprates may be planned in two or more stages due to core physics design/implementation considerations. Others may be done in stages to provide additional confidence in each new power level prior to going to the next level.

The implications of such incremental power uprating on the I&C can vary. In some cases, the existing design may be appropriate for the new power levels. In other cases, changes will be required, for example, to the protection system set points, control system algorithms and/or to the monitoring and display facilities. Furthermore, changes to different I&C functions may only be required at different stages of the incremental power uprating.

Irrespective of whether the power uprating is achieved in a single stage or several stages, the suitability of the I&C design has to be demonstrated for the maximum reactor thermal power applicable to that fuel cycle.

7.4. EXAMPLE: MUR SPECIFIC INSTRUMENTATION AND CONTROL ACTIVITIES

For a measurement uncertainty recapture power uprate project, the following steps should be completed:

(1) Feasibility study and cost–benefit analysis;
(2) Procurement and installation of approved flow measurement instruments (or analysis justifying existing instrumentation);
(3) Re-analysis of a subset of the NSSS accident and transient analysis;
(4) Evaluation that the balance of plant (BOP) has sufficient capacity, including the identification of necessary modifications;
(5) Assessment of grid stability issues;
(6) Regulatory approval;
(7) Implementation of changes and increase of power.

There are I&C specific activities that support several of these steps. The following are examples of some of the I&C activities (indicating the corresponding item number from the previous list):

— *From item (2), the procurement and installation of approved flow measurement instruments (or analysis justifying existing instrumentation):* The new flow or other measurement instrumentation must be evaluated and selected. The accuracy of the instrument needs to be determined in order to establish the amount of measurement uncertainty recapture that is feasible.
— *From item (3), re-analysis of a subset of the NSSS accident and transient analysis:* Although I&C is not related to the re-analysis of the NSSS accident and transient analysis, the results of the analysis may indicate the need for new plant measurements, modifications to control systems, or HSIs to support operation after the power uprate due to reduced operating margins.
— *From item (4), evaluation that the BOP has sufficient capacity, including the identification of necessary modifications:* Although I&C is not related to the evaluation of the BOP capacity, the results of the analysis may indicate the need for new plant measurements, modifications to control systems, or HSIs to support operation after the power uprate due to reduced operating margins.
— *From item (5), assessment of grid stability issues:* Although I&C is not related to the assessment of grid stability issues, the results of the analysis may indicate the need for new plant measurements, modifications to control systems, or HSIs to support operation after the power uprate.
— *From item (6) regulatory approval:* An essential part of obtaining regulatory approval is the evidence that the accuracy of the new instrumentation really supports the amount of power uprate requested. This accuracy argument needs to take into account the actual implementation.
— *From item (7), implementation of changes and increase of power:* Here, I&C is responsible for the actual implementation of the new flow measurement instrument and any other instrumentation, controls, alarms,

on-line validation of instruments used to determine thermal power, or HSIs needed to enable effective operation and maintenance of the plant after the power uprate is completed.

8. INSTRUMENTATION AND CONTROL BENEFITS AND LESSONS LEARNED FROM POWER UPRATING

8.1. MAIN INSTRUMENTATION AND CONTROL BENEFITS IN RELATION TO POWER UPRATING

Any modernization project, including a power uprating project, provides a good opportunity to improve areas where the I&C design is judged to be deficient against modern standards or where the equipment is becoming obsolescent or unreliable.

The introduction of more modern I&C then brings general benefits in terms of increased functionality, improved reliability, increased accuracy, increased testability, better failure diagnostics, ease of maintainability, lower maintenance costs, etc.

In addition, the introduction of more modern I&C helps to address the problem faced by many NPPs, that is, that new recruits to the operations and maintenance staff are generally not familiar with the older I&C technologies.

The utilities should consider these benefits when determining the scope of the power uprating project and should strive for the best utilization of them. This approach may result in higher short term costs associated with the power uprating project, but will lead to savings in the longer term considering operational, maintenance and other expenses.

8.2. CONCERNS

8.2.1. General lessons learned

The Institute of Nuclear Power Operators reported in the Significant Event Report SER 5-02, released August 2002, that:

> "More than 40 events have occurred over the past five years as a result of inadequate analysis, design, or implementation of plant power uprates. Many of the events involved equipment damage, unanticipated responses to plant conditions, or challenges for operating staff."

Some of these events can lead to opportunities for I&C to prevent similar types of event in the future.

The Institute of Nuclear Power Operators reported among the "Significant aspects of the events" — among others — the following:

> "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."

The Institute of Nuclear Power Operators did an analysis of the events and — among many more items — the following highlights I&C related system and component problems in power uprates:

— Main turbine control systems — changes to turbine controls or plant operating conditions have resulted in transients and challenged operators to control load or turbine speed;

— Feedwater flow and temperature measurements — incomplete understanding of a modification's impact on reactor thermal power measurements.

Power uprates are a viable way to increase the power output of NPPs. However, the conclusions from this analysis clearly point out the importance of doing a proper analysis, design and implementation of the power uprates to ensure that problems do not occur. Adequate reviews by plant personnel during all stages of the uprate project are needed to identify potential problems and obtain input. There must be enough time allowed to identify and develop procedure changes, incorporate changes into the simulator and provide training.

Experience indicates that there are opportunities to use I&C to help ensure that problems do not occur. In many cases, increased monitoring (and potentially more sensors), information access, analysis capabilities, additional alarms and information presentation (HSI) may be needed to support operational and maintenance decisions to avoid difficulties such as those that have been experienced. I&C plays a major role in all of these areas.

An example of the role I&C should play is given. Increased feedwater and steam flows can lead to equipment problems due to flow accelerated corrosion and vibration. Increased vibration in components in systems can cause fatigue induced failures. In order to better understand the current state of equipment and system components, the scope and frequency of vibration and flow accelerated corrosion monitoring should be increased as appropriate.

The first step is to identify whether adequate instrumentation exists to perform the scope and frequency of monitoring required. If additional instrumentation is required, either permanently or periodically attached, then it should be implemented and a means should be developed to provide the resulting output to the appropriate analysis capability. For the monitoring instrumentation that already exists, the output should also be provided to the appropriate analysis capability. The analysis capability to acquire the appropriate information, determine the current state of the equipment and systems, determine if problems are appearing, and create alarms or other information messages to operators, system engineers or maintenance staff, should be acquired or developed. Where appropriate, alarms should be developed and information should be added to the HSI to alert the relevant plant personnel to changing conditions as well as providing the current state. Appropriate procedures and training also need to be developed.

8.2.2. Lessons learned from the use of ultrasonic flowmeters

The Institute for Nuclear Power Operations issued Topical Report TR4-34, Review of Feedwater System Ultrasonic Flowmeter Problems, in March 2004. There were 14 reports from the Plant Events and LER databases from 2000 to 2003. There was one event report in 2000, two in 2001, six in 2002, and five in 2003. These reports cover both BWRs and PWRs, thus plant type does not appear to be a factor. Both flowmeter types used by plants experienced problems during this period.

Reactor power indication was directly affected in 10 of the 14 reported events over this period. Reactor power limits (100%) were exceeded during seven events. The primary causes of these seven events were instrumentation problem or malfunction, unknown biases or incorrect calibration assumptions. One plant operated slightly in excess of its 102% analysed limit. The potential to exceed reactor power limits existed in three events, with the primary cause being software error or fluid leakage.

Six of the 14 events involved software and/or programming issues with the primary causes being undetected instrument biases or software problems.

Nine of the 14 reported events involved human errors. Seven of the nine involved some type of error, oversight or lack of knowledge on the part of the vendor. The primary causes that were identified were:

— Inadequate verification of flowmeter system corrections;
— Flow measurement system installed without adequate air conditioning;
— Vendor error in software assumptions;
— Inadequate vendor hardware fabrication;
— Post-repair test plan omitted steps for testing transducer functionality;
— Non-conservative calibration assumptions combined with a pipe measurement error after flowmeter system upgrade;

— Lack of questioning attitude when installing a new system, as well as vendor failure to document use of its diagnostic tool.

One conclusion from the analysis of the events related to measurement uncertainty recapture power uprates using ultrasonic flowmeters is that there is a need to carefully monitor instrument output and closely oversee the installation of new systems. Another is that more detailed review and questioning by plant personnel pertaining to the basis for software programming and post-modification testing, as well as acceptance of post-installation test results, is needed.

8.2.2.1. Issues with cross-correlation flowmeters

Most of the issues with cross-correlation flowmeters related to the reactor power limit can be classified as belonging either to the existence of undetected correlated noise, which results in a bias in the measured transit time, or to the incorrect value of the flow profile correction factor used in calculating the feedwater flow.

The Advanced Measurement and Analysis Group (AMAG) Inc., the vendor of Crossflow, the cross-correlation flowmeter approved by the NRC for power uprating, has developed a methodology to identify and remove the bias due to the correlated noise. The methodology has been applied to most of about 35 Crossflow installations, and for 25 of these, the effect of noise was found to be negligible. For the remaining ten installations, the effect varied from a fraction of 1% to as much as about 2%. The current Crossflow installation and commissioning procedure now includes testing for the presence and removal of in-phase noise.

The behaviour of the flow profile correction factor for Crossflow has been obtained in calibration laboratories for a number of common pipe geometries, for example, a single elbow, two out of plane elbows, a T-junction, a flow straightener, etc. Based on the early calibration work, it was assumed until recently that the effect of the upstream disturbance disappears after 15–20 pipe diameters. However, recent comparison of Crossflow readings with the results of chemical tracing tests performed in a few plants with complicated piping geometry seems to indicate that additional tests should be performed prior to plant uprating to verify the value of the flow profile correction factor used.

These tests include:

(1) Moving the transducer along the pipe to verify stability of the flow reading;
(2) Reactor power reduction to ensure that there is no dependence of the flow profile correction factor on the value of the feedwater flow.

The NRC has reopened critical examination of the Crossflow topical report in order to establish if the claimed measurement uncertainty is justified for non-fully developed flow.

8.2.2.2. Issues with transit time flowmeters

Transit time meters have a much longer history than the cross-correlation flowmeter and, therefore, a larger number of reported issues. The only transit time meter approved for power uprating is a leading edge flowmeter (LEFM) manufactured by Caldon Inc., and known as Check+. Unlike a strap-on Crossflow meter, Check+ uses a transducer mounted on a spool piece, which is installed in feedwater pipe. The strap-on version of the Caldon LEFM meter has been used extensively for power recovery, particularly in those plants where feedwater nozzles were subject to fouling.

There has been a number of reactor power violation events reported for the strap-on LEFM. Most of them were identified when the Check+ meter was installed prior to implementing the power uprating. However, instead of increasing power by the predicted amount, it was found that the assumed 100% FP level, based on the strap-on meter calibration, was in fact underestimated by as much as 2%. The reported issues with Check+ meter include loss of the transducer path and leakage around spool piece flanges. Although the latest reports indicate that this particular problem has been overcome, the NRC has reopened critical examination of the Caldon topical report to establish that hardware reliability issues do not translate into reduced measurement uncertainty.

9. KEY RECOMMENDATIONS

The following is a list of specific recommendations in addition to those given in the body of this report.

For MUR power uprates or other power uprates in which the measurement uncertainty associated with the calculation of the reactor thermal power is claimed to be small (i.e. less than 2% RTP), it is important to:

— Fully understand the safety and technical bases for the claimed margins and limits;
— Fully evaluate the areas of potential measurement uncertainty, to implement all design and operational improvement options for minimizing this uncertainty, and to establish suitable means for on-line validation of the relevant instrumentation.

Power uprates involving a significant increase in reactor thermal power (i.e. most stretch and all extended power uprates) will result in an appreciable change in the reactor operating conditions (flows, temperatures, etc.), and this could potentially lead to various unwanted effects. Prior to initiating any power uprate project, it is necessary, therefore, to undertake a comprehensive impact assessment to ensure that the benefits are not outweighed by the negative effects (e.g. accelerated fatigue, ageing or corrosion effects, or excessive vibration). This also means that, for such a power uprate project, it will almost certainly be necessary to add new instrumentation to ensure that the operating conditions at the higher power level are adequately monitored and controlled.

Most NPPs will have long term plans for equipment modernization or plant life extension. Power uprating plans should be integrated into such long term plans, both in terms of the plant as a whole and for the I&C systems. Integral to such plans, a power uprating could provide the opportunity for a wider modernization of the plant I&C systems. This would then bring other benefits in terms of increased functionality, increased reliability, etc., and greater familiarity for any new recruits with the newer I&C technology.

For the implementation of significant power uprate projects, it is necessary that:

— A comprehensive analysis be undertaken covering all aspects of plant behaviour under normal, abnormal and accident conditions (as for the original SAR), and that the results be included in the updated SAR;
— All effects of the uprating be addressed by the analysis and then reflected in modifications to the design, operation and maintenance of the plant.

As part of the issues mentioned, it is important to thoroughly analyse the external impacts caused by or affecting the power uprate. These should include the impact:

— On grid stability due to the additional power generated;
— Of operating closer to high temperature limits, increasing the vulnerability to equipment problems during high seasonal ambient temperature conditions.

Since operation of the plant will inevitably be closer to the ‘real’ safety limits, it is also important for such projects that:

— There is an increased emphasis on ensuring that the operating staff are able to maintain the plant within its new operating limits;
— Particular attention is paid to the design of the HSI for the new systems, and of integration of this with the existing HSI, to ensure that operating staff performance is enhanced rather than degraded;
— All affected instructions and operating and maintenance procedures are updated and reflect the new conditions;
— Operating and maintenance staff are adequately trained in the new systems and, additionally, in any new working methods associated with their introduction.

In terms of the licensing application for a significant power uprate project, it should be noted that the regulatory authority:

— Will want to be sure that the utility has the necessary organization and resources to implement the project while maintaining safe day to day operation of the plant;
— Will require the licensing submission to positively demonstrate that the existing safety level has been maintained or, preferably, increased;
— May assess the licensing submission in the same way as for a periodic safety review (i.e. for compliance with ‘current’ in addition to the ‘original’ standards). In some aspects, the assessments may be comparable to the review of a new plant;
— May require comparison of the actual plant performance before and after the power uprating, thereby leading to a need for establishing a ‘benchmark’ and, hence, the implementation of a surveillance program before any uprating can be initiated.

Experience feedback from past power uprate projects has shown that some plants have incurred serious problems with their implementation (e.g. equipment damage or degraded performance, unanticipated responses to plant conditions, challenges to the operating staff, or inadvertent violation of licensed power limits). These problems have mainly arisen from an insufficient analysis and/or understanding of the full implications of the proposed uprating on the plant, or from insufficient attention to detail during the design and implementation of the modifications to the plant and to the associated operating and maintenance procedures.

Appendix I

HEAT BALANCE SENSITIVITY TO MEASUREMENT ERRORS

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A discussion of the relative importance of measurements accuracy for different parameters entering reactor thermal power calculation is given in Section 3.2 of the body of this report. A further illustration of the effect of instrument errors on the accuracy of reactor power calculation is given in this Appendix.

From the heat balance/process diagram in Section 3.1, and from the sensitivity values summarized in Table 3, it becomes clear that failure to compensate for process parameters corrections due to the variation in fluid conditions from the measurement location to the location of interest would introduce unexpected reactor power calculation errors. This is the first source of uncertainty discussed in this Appendix.

The second potential source of uncertainty in the calculated reactor power considered in this Appendix is due to a reduction of instrument loop errors by using more modern instruments.

The third source of uncertainty addressed in the Appendix is due to instrument calibration.

I.1. EXAMPLES OF POSSIBLE ERRORS

I.1.1. Effect of instrument location

I.1.1.1. Feedwater temperature

Main feedwater heat dissipates to the atmosphere, from the location of measurement to the entrance of the reactor/steam generators. While this loss could account for just a fraction of a degree, the accumulated power loss through the operating life of the plant could be substantial.

For an estimated 0.125°C temperature loss, the impact in the calculated heat balance shown in Table 4 can be evaluated.

TABLE 4. TEMPERATURE LOSS IMPACT ON HEAT BALANCE

Parameters	@ Point of measurement	@ Steam generator entrance
Temperature	233.33°C	233.205°C
Main feedwater sensitivity	0.25% FP/°C	
HB error	0.031% RP_{rated}	

I.1.1.2. Main steam pressure

Main steam pressure losses can be due to the following factors:

- Piping losses, which is the pressure difference due to friction losses from the steam generator to the place of measurement;
- Velocity effect ($v^2/2g$), which is the portion of pressure in the form of steam velocity;
- Static head, which is the pressure due to the column of steam, $\rho \times h = kg/m^3 \times m$, and is the additional pressure due to the height of the column of steam from the reactor/steam generator drum elevation down 'h' metres to the elevation of the place of pressure measurement.

The observation of the process diagram indicates that while in a BWR reactor, the steam pressure is sensed at the reactor dome; in some PWR steam generators, the pressure is sensed just upstream of the main steam line isolation valves, where pressure:

- Reduction due to friction losses has occurred;
- Increase is added due to the steam column;
- Reduction exists at the pressure tap due to the steam velocity effect present.

An estimated pressure difference between the PWR steam generator and the location of measurement at the isolation valves could be approximately 40 kPa. Thus the impact on the calculated heat balance shown in Table 5 is observed.

TABLE 5. PRESSURE DIFFERENCE IMPACT ON HEAT BALANCE

Parameters	Steam generator pressure	Pressure @ MSI valves
Pressure	5640 kPa	5600 kPa
Main steam pressure sensitivity	0.0005%FP/kPa	
HB error	0.02% RP_{rated}	

I.1.2. Instrumentation loop error

Table 6 shows instrumentation loop error values.

TABLE 6. INSTRUMENTATION LOOP ERROR VALUES

Instrumentation loop span		Instrumentation loop error (%)	Error value
Main steam pressure loop span	8200 kPa	1.5	123 kPa
Feedwater temperature span	83°C	1.0	0.83°C

I.1.3. Heat balance calculation impact

Table 7 shows heat balance error values.

TABLE 7. HEAT BALANCE ERROR VALUES

Heat balance error due to main steam pressure loop error		
HB_{PST}	$= S_{PST} \times$ ST pressure error	$= 0.06\%\ RP_{rated}$
Decreasing the loop error by half the impact would be: $RP_{ST\_press\_err} = 0.03\%\ HB_{rated}$		
Heat balance impact due to feedwater temperature loop errors		
$HB_{FW\_temp\_err}$	$= S_{FWtemp} \times$ FW temperature error	$HB_{FW\_temp\_err} = 0.21\%\ RP_{rated}$
Decreasing the loop error by half the impact would be: $HB_{FW\_temp\_err} = 0.10\%\ RP_{rated}$		

I.2. HEAT BALANCE CALCULATION IMPROVEMENT BY THE USE OF MORE ACCURATE INSTRUMENTATION

Since the accuracy of the instrumentation has a direct impact on the calculated reactor power error, the importance of using accurate instrumentation cannot be overstated. This section demonstrates the degree of heat balance calculation accuracy improvement, by using up to date instrumentation, as compared to instrumentation from previous generations.

I.2.1. Main steam pressure transmitter accuracy improvement

As an example, Table 8 illustrates the case of an improved main steam pressure transmitter accuracy by comparing an older Rosemount 1151 series transmitter and a new generation smart transmitter.

TABLE 8. TRANSMITTER ACCURACY COMPARISON

	Rosemount 1151GP9		Smart LD301A5	
Range	20 000 kPag		25000 kPag	
span	8000 kPag		8000 kPag	
accuracy	0.25% span	20 kPa	0.10% span	8 kPa
Drift	0.25% range/6 months	50 kPa	0.1% range/24 months	25 kPa
Temperature effect	Zero error = 0.2% range/40°C	10 kPa (for ΔT=10°C)	–	–
	Total error (0.2% range + 0.2% span)/40°C	50 kPa (for ΔT = 10°C)	0.02% range + 0.1% span/20°C	15 kPa (for ΔT = 10°C)
Power supply effect	Less than 0.005% span per volt	Same	Less than 0.005% span per volt	Same
	Rosemount 1151GP9		Smart LD301A5	
Total error	100 kPa		25 kPa	
Main steam pressure sensitivity	0.0005% FP/kPa		0.0005% FP/kPa	
HB error	$0.06\%\ RP_{rated}$		$0.02\%\ RP_{rated}$	
		3 × higher		

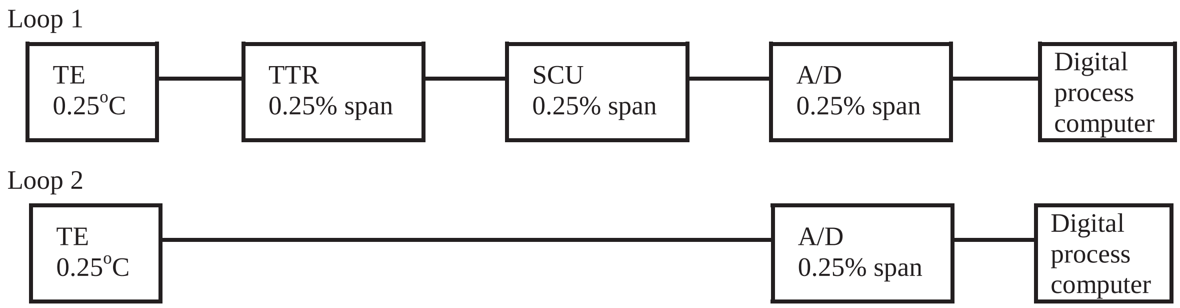

FIG. 4. Complex and simple temperature measurement loops.

I.2.2. Feedwater temperature measurement loop

In the example shown in Fig. 4, a comparison is made of an old temperature loop comprising a temperature sensing element, a transmitter, a signal conditioning instrument and the main plant computer A/D card, to a simple loop comprising the temperature element directly connected to the computer A/D card.

Table 9 shows the features of complex and simple temperature measurement loops.

It should be noted that: (1) typical accuracy values have been used in Table 9; and (2) the second loop arrangement, in addition to providing better accuracy, needs less maintenance due to fewer loop components and a simpler calibration/accuracy check. Evaluating the total error in quadratures gives the values shown in Table 10.

TABLE 9. FEATURES OF COMPLEX AND SIMPLE TEMPERATURE MEASUREMENT LOOPS

	Loop 1		Loop 2	
Span	83°C		83°C	
TE accuracy	0.25°C	0.25°C	0.25°C	0.25°C
TTR accuracy	0.25% span	0.2075°C	n/a	n/a
SCU accuracy	0.25% span	0.2075°C	n/a	n/a
A/D accuracy	0.25% span	0.2075°C	0.25% span	0.2075°C
Calibration instrument accuracy	0.125% span × 3 + 0.25°C	0.56°C	0.25°C	0.25°C
Calibration tolerance	0.125% span × 3	0.311°C	n/a	n/a

TABLE 10. TOTAL ERROR OF THE COMPLEX AND SIMPLE TEMPERATURE MEASUREMENT LOOPS

	Loop 1	Loop 2
Total error	0.78°C	0.41°C
Feedwater temperature sensitivity	0.25% FP/°C	
HB impact	0.2% RP_{rated}	0.1% RP_{rated}
	2 times higher	

I.3. CALIBRATION PROCEDURES/CALIBRATION INSTRUMENTATION

Calibration procedures shall be written to achieve maximum practical accuracy, specifying accurate calibration instrumentation at the same time. The following shall be considered when developing the necessary calibration procedures.

I.3.1. Calibration tolerances

It is often found that calibration tolerances are set to values larger than the rated accuracy. For example, a Rosemount transmitter of the 1151, 1152, 1153, 1154 series with a rated 0.25% span accuracy shall be set to a calibration tolerance of no higher than ±0.25%. Additionally, the procedure should require the technician to calibrate as closely as feasible to the desired calibration value.

I.3.2. String versus individual loop instrument calibration

To obtain the best loop calibration accuracy, string calibration should be performed. String calibration normalizes all instruments towards the desired value, rather than leaving more than one instrument on a 'one side calibration offset' when performing individual instrument calibration. Additional benefits can be obtained by performing an initial string calibration check, when the instrument loop is found to be within the required calibration tolerance, by terminating the procedure at the first steps, thus avoiding unnecessary time and cost commitments by performing individual instrument calibration activities.

I.3.3. Cross-calibration

Cross-calibration should also be used as much as possible. The following are benefits of cross-calibration:

— Ensuring that loop instruments measuring the same process parameter are calibrated close to each other and to the highest accuracy achievable;
— Reduced maintenance.

For example, in the case of a feedwater temperature heating system, there are two trains in which the feedwater temperature for all practical purposes is very similar. This statement can be easily corroborated by review of plant performance through loop calibration results and plant computer history.

I.3.4. Calibration instrumentation

Test instrumentation must be at least twice as accurate as the accuracy of the instrument being calibrated. While some standards have specified a ratio of 10 to 1, it is not until recent years that a ratio better than 2 to 1 has been achieved. For example, a Heise Handheld Calibrator PTE-1, with a QS2 module, having a rated 0.1% accuracy with temperature compensation, achieves a true accuracy equivalent to its posted rated accuracy. However, when the calibrator is used with a QS1 module, its rated accuracy becomes improved several times when affected by a temperature change in the calibration temperature. Also, the use of a high accuracy temperature block calibrator with an approximate 0.25ºC as compared to 0.75ºC calibrator provides significant loop calibration improvements.

I.4. RELEVANT KNOWLEDGE AND EXPERIENCE

The scope of knowledge and experience of I&C engineers should go beyond instrumentation and control systems knowledge. Knowledge of the process systems, of their engineering basis and their interface with the instrumentation used to measure parameters for reactor power calculations is also of utmost importance.

Appendix II

PRINCIPLES OF THE ULTRASONIC FLOWMETER OPERATION

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All of the MUR uprates implemented so far have been based on installed ultrasonic flowmeters for continuous feedwater flow monitoring. The only ultrasonic flowmeters used for MUR uprates are the Caldon LEFM Check+ multipath transit time meter based on a spool piece installed in each feedwater pipe and the AMAG/Westinghouse strap-on cross-correlation flowmeter known as Crossflow. Topical reports produced by both vendors have been accepted by the NRC for MUR uprating. Both meters claim a total feedwater flow measurement accuracy of better than ±0.5%, similar to that of the calibrated venturi or nozzle but without potential drift problems.

The general arrangement of the transit time flowmeter installation is shown in Fig. 5. The spool piece has four pairs of ultrasonic transducers mounted on chordal paths at a certain angle. The spool piece may either be welded or flanged into the piping.

The electronic unit (EU) is connected to the spool piece transducers via shielded cables. The fluid velocity is calculated by measuring the transit times of ultrasonic pulses of energy travelling upstream and downstream. Based on the transit times of the ultrasonic signals from different fluid paths and on the measured sound velocity, the radial fluid velocity distribution is determined. The average axial velocity is then calculated to determine the volumetric feedwater flow rate. Mean fluid temperature can also be calculated from the mean sound velocity. The integrated average temperature is used, along with an input feedwater pressure value, to determine fluid density and, in turn, the feedwater mass flow rate.

The general arrangement of Crossflow installation is shown in Fig. 6. The Crossflow UFM consists of four ultrasonic transducers mounted on a metal support frame which is clamped on the feedwater piping. There is one upstream and one downstream transducer station, each station consisting of one transmitting and one receiving transducer.

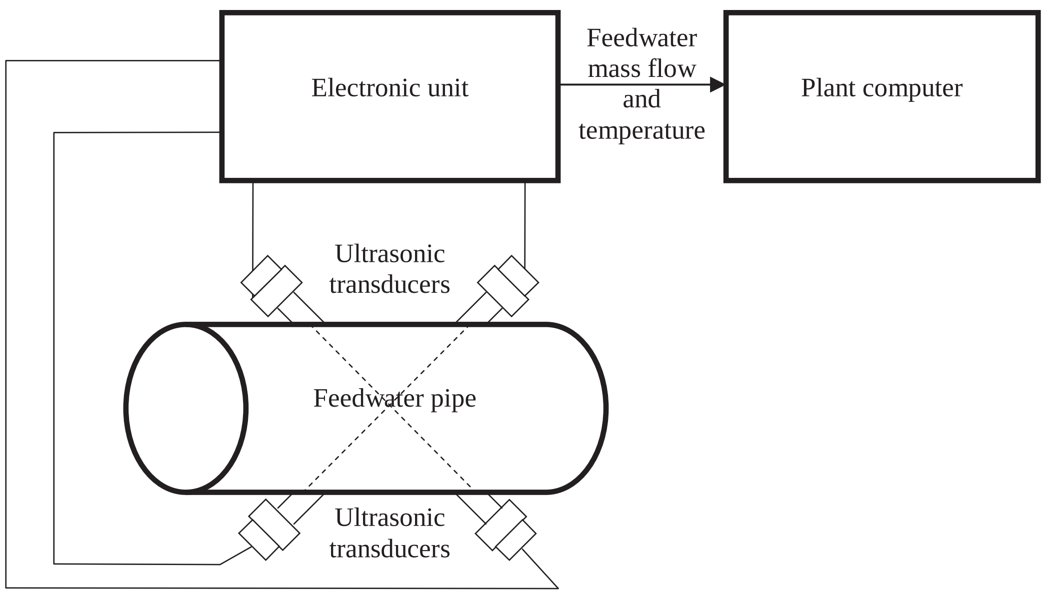

FIG. 5. The general arrangement of the transit time flowmeter.

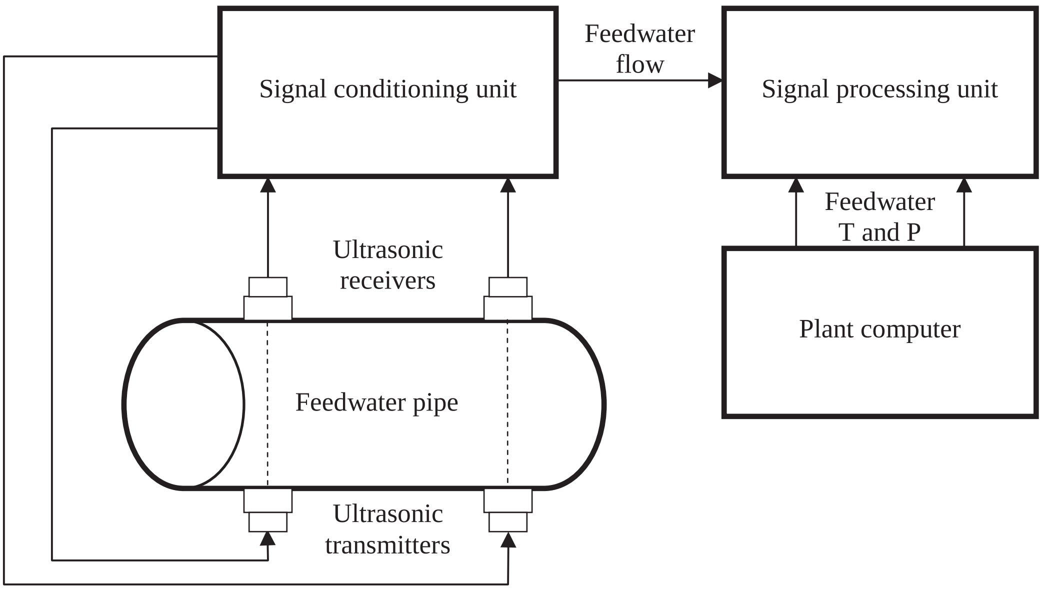

FIG. 6. The general arrangement of the Crossflow flowmeter.

The operation of a cross-correlation UFM is based on the fact that an ultrasonic beam travelling across fluid flowing in a pipe is affected (modulated) by the turbulence (eddies) present in the flowing liquid. When this modulated signal is processed, a random signal which is a signature of the flowing eddies can be obtained. The Crossflow UFM calculates the time a unique pattern of eddies takes to pass between two sets of ultrasonic transducers, and divides the known distance between the two sets of transducers by the calculated time to obtain the flow velocity. This measured velocity is not an average velocity over the pipe cross-section but the velocity corresponding to the maximum turbulent viscosity of the flowing fluid. This velocity has to be multiplied by the velocity profile correction factor (VPCF) to obtain the average velocity of the fluid flowing in the pipe.

The Crossflow UFM system consists of a mounting/transducer support frame with ultrasonic transducers, a signal conditioning unit (SCU), and a signal processing unit (SPU). The SPU receives a feedwater flow signal from the SCU, and feedwater pressure and temperature input from the plant computer. Using a built-in signal processing algorithm, the Crossflow SPU calculates fluid velocity and converts the fluid velocity to a mass flow using flow, temperature and pressure as calculation inputs. The Crossflow feedwater mass flow is periodically compared to the feedwater venturi mass flow to determine the correction factor that must be applied to the venturi mass flow to obtain the corrected mass flow. This corrected mass flow is used in calculating core thermal power and, thereby, calibrating nuclear instrumentation in accordance with the plant technical specification requirements.

Appendix III

TRAINING NEEDS FOR DESIGN CHANGES

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Table 11 shows the training needs for design changes, and describes the training focuses involved.

TABLE 11. TRAINING NEEDS AND FOCUS OF TRAINING

Training need/objective	Focus of training
Gain an understanding of the change, its purpose and basic differences between the old and new system	Differences in the hardware and the system configuration versus the old system; any differences in basic functionality (e.g. in level of automation); any changes in operator roles or responsibilities.
Gain familiarity with basic operation of the new plant systems (I&C and other equipment) and their HSIs	How tasks are performed on the new system; basic organization and functionality of the interface (e.g. display structure, user interface management features, the alarm system and any operator aids that are provided).
Gain familiarity with operating screens, important displays and their content	General layout of screens, symbols and colours; content and arrangement of specific displays for monitoring and control; basis for high level displays, their information content and how to interpret them and query for additional detail.
Gain familiarity with user defined features of the HSI	Basic understanding of the configurable and user definable aspects of the interface, their purpose, restrictions on their use and configuration control impacts.
Develop skills in operating the system using the new interface and new/modified procedures	Details of the user interface; developing individual skills in navigating through displays, menus and other selections; skills in performing basic control operations, obtaining information to support tasks; understanding and using any decision aids that are provided.
Develop skills in normal and abnormal operations with the new system and HSI in a crew environment in the control room	Normal and emergency operations (e.g. plant startup, shutdown, post-trip, design basis events); hybrid issues such as the use of both analogue and digital interfaces to perform tasks.
Understand system failure modes and develop skills in distinguishing between and managing I&C/HSI system failures versus plant equipment malfunctions	Effects of plausible I&C and HSI failures; interpreting alarms; recognizing specific failure modes; proper response to these failures; use of backups for HSI failures; alarm response procedures and other procedures related to failures and malfunctions.
Develop skills in operator coordination, communication and teamwork with the new system and new HSI	Impact of the change on teamwork or ability to maintain operator coordination; working as a team; peer checking; supervision; responding as a crew to major plant malfunctions.

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Annex

COUNTRY REPORTS

This part of the report comprises country reports, listed in Table A–1. These country reports are included here in alphabetical order and are as received from the countries listed.

Table A–1. LIST OF COUNTRY REPORTS

Country	Title
Hungary	Power Uprating Activities in the Paks NPP
Republic of Korea	Evaluation of NSSS Process Measurement Channels
Sweden	Power Uprating Activities in Swedish NPPs
United Kingdom	Power Uprating at the NPPs in the United Kingdom

POWER UPRATING ACTIVITIES AT THE PAKS NUCLEAR POWER PLANT, HUNGARY

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Abstract

The original design output power of the Paks NPP was 440 MW(e). Early uprating activities took place in the late 1990s. These modifications were related to the turbines and did not involve very significant I&C changes. After this first uprating, the new nominal power was 465 MW(e)/unit. A further uprating from 465 MW(e) to 500 MW(e) is under way at present. This second step requires several I&C systems to be upgraded and some set points to be altered. This country report provides a general overview of the uprate and detailed descriptions of the I&C related changes. As is described earlier in this report, the accuracy of the feedwater flow measurement is one of the critical I&C issues in power uprating. The problems usually come from venturi fouling. It needs to be noted that in Paks venture, elements are not used for feedwater flow detection. The applied orifices may suffer from different types of problems, such as from edge deterioration. Therefore, the originally welded orifices have been changed to flange mounted ones and can be removed for size checking periodically. Currently, this is done every four years and the orifices are replaced whenever necessary. Hence, feedwater measurement accuracy does not play a critical role in the Paks power uprating process and, therefore, is not described in this report.

1. POWER UPRATING IN THE PAKS NPP

1.1. Early activities

The power plant's original 440 MW(e)/unit capacity was increased in the first step to about 465 MW(e), keeping the reactor thermal power unchanged. This modification took place between 1997 and 2001, and introduced changes to the turbines and condensers. Instrumentation and control did not play a significant role in this alteration. The first phase power uprating comprised changes mainly in the Kharkiv made K-220-44-3 type turbines. Relevant modifications consisted of the replacement of the blades of all stages of the high pressure rotor, as well as some diaphragms and sealing in the HP housing. In addition, rotor blades in the low pressure turbine were also exchanged, together with diaphragms and the labyrinth sealing.

To facilitate the refurbishment of the K-220-44-3 type turbines, the NPP purchased all rotors of the turbines from the EWN Greifswald (KKW Nord). These rotors were then rebladed at the site of OAO Turboatom (Kharkiv Turbine Factory), then balanced at nominal speed in the same factory. These German rebladed rotors were then installed into the turbines of one Paks unit, and the rotors demounted from that unit underwent the same reblading and balancing process. This chain went through all the units and the project finished in 2001. In parallel with these activities, the condensers of all the turbines were replaced. One of the primary reasons for this change was to provide a higher heat exchange rate in the condensers. However, the ultimate goal was to introduce a different material in the heat exchange tubing to provide for an increased pH water regime.

1.2. The feasibility of a further 8% reactor power uprate in Paks

When completing the safety enhancement measures, as well as the turbine refurbishment described in the previous section and the secondary circuit modifications (mainly measures to enhance the efficiency), the Paks NPP began to examine the possibilities of further power enhancement, taking into account the international trends and economic aspects. By this time, the Finnish 'sibling' units at the Loviisa site had already reached 500+ MW electrical power.

To reveal the possibilities of increasing power and define the optimum strategy, the Hungarian Atomic Energy Research Institute (AEKI) prepared a feasibility study. This study was completed at the end of 2001. The study was then sent to the Finnish Fortum Nuclear Services for comments and remarks. The study overviewed the potential modes of power uprating and their impact on the plant systems, indicated the bottlenecks, and provided a proposal for the main steps of the programme.

Safety assessments accomplished in the feasibility study showed that transients starting even from the increased (108%) power level will not cause any significant change in the level of safety. Higher power level means no safety risk for the normal operational, or the safety equipment.

1.3. Modifications enabling the power uprating

For the purpose of the additional power increase, modifications are implemented in the following areas:

- Fuel;
- Primary circuit;
- Core monitoring (VERONA);
- Secondary circuit;
- Electrical systems;
- I&C systems.

These modifications serve for:

- Increase of the reactor thermal power;
- Utilization of the available spares;
- Safety of the operation at the enhanced power level;
- Improvement of efficiency, energetic optimization;
- Operation at an enhanced power level.

The essential features and reasons for the modifications are summarized in Table A–2.

Set values and dynamic behaviour have been assessed for certain I&C systems and control circuits as follows:

- Secondary circuit level controllers dynamic and leakage evaluation;
- Reactor power controller dynamic evaluation;
- Examination of adjustability of the turbine power controller;
- Verification of the settings of some protection circuits.

(Eliminating the orifice type fresh steam mass flow measurement was included in the feasibility study and in the project plan. However, as a result of the cost–benefit analysis, the task aimed at removing these instruments was cancelled.)

1.4. Implementation of the power uprating

One third of the modified fuel was introduced in 2005 in Unit 4. Further on, implementation of the uprating stages was influenced by the timely progress of licensing and the realization of the needed modifications. In 2006, when the Unit 4 reactor contained two loads of modified fuel, the 108% new thermal power was attainable. The stepwise increase of power required a medium term test run at about 104%, thus, the further increase up to 108% was realized several months after the restart of the unit from refuelling. Currently, the unit is suitable to provide the 108% nominal power. The necessary modifications for power uprating of Unit 1 were done during the refuelling outage in 2007. After the unit restart, the stepwise increase of power from the original level to 108% is under way at the time of writing this report.

As for Units 2–3, the implementation of the power uprating steps is significantly influenced by the situation arising from a former fuel incident in Unit 2. Operation with the fuel assemblies that are suspected to suffer from deposits will end in the upcoming years. Power uprating in a core loaded with fuel assemblies with possible deposits is not considered. As a result, the last unit is foreseen to reach 108% power in 2009.

TABLE A–2. MAIN PLANT MODIFICATIONS AND THEIR REASONS

Systems, components	Essential features of the modification	Reasons for the modification
Fuel development	Increased lattice pitch, hafnium inserts in the upper part of control fuel assemblies.	Required for utilizing the contingencies, to attain the 108% reactor power.
Primary circuit	Improvement of the primary circuit pressure control.	Required for utilizing the contingencies and safe operation at the enhanced power level.
	Increasing the primary coolant circulation in Unit 2.	Required for utilizing the contingencies and safe operation at the enhanced power level.
	Modification of hydro-accumulator parameters.	Required for safe operation at the enhanced power level.
	Modifying the lowest boric acid concentration in the emergency cooling systems.	Required for safe operation.
Core surveillance system (VERONA)	Phase 1: designing a new structure and operation of the system, establishment of new reactor physics calculations needed for attaining the enhanced power level, their implementation in the system, selection of fundamental hardware and software tools, development and preparation of the design and drawings.	Required for utilizing the margins, and support safe operation at the enhanced power level.
	Phase 2: commissioning systems in the units, completion of software development.	
Turbine, secondary circuit	Exchange of turbine nozzle ring. Modification of turbine control.	Provides support for improving the efficiency and operation at the enhanced power level.
Electrical systems	Improving the generator cooling. Exchange of encased bus bars in Units 1 and 2. Reduction of the asymmetric load on the 6 kV household supply.	Provides support for operation at the enhanced power level.
I&C systems	Modification of reactor protection system set point values. Modification of set values of control and protection systems and interlocks.	Needed for the safe operation at the enhanced power level.

1.5. Unit operation at the uprated power level

The implementation of power uprating does not lead to changes in plant operational modes. Modifications result in changes of some system/component parameters. The parameter changes shown in Table A–3 occur in the primary circuits of Units 1–4.

TABLE A–3. PRIMARY CIRCUIT PARAMETER CHANGES

Parameter	Value before power uprating	Value at 108% power level
Reactor thermal power	1375 MW	1485 MW
Primary circulation	39 400–40 300 m^3/h	40 300–41 000 m^3/h
Cold leg temperature	265.0–265.5°C	266.0–266.5°C
Hot leg temperature	295.2–295.7°C	298.4–299.5°C
Shutdown boric acid concentration	12.0 g/kg	13.5 g/kg

TABLE A–4. FRESH STEAM PARAMETER CHANGES

	Parameter	Value before power uprating	Value at 108% power level
Intake fresh steam parameters at the turbine	Pressure	43.15 bar	43.15 bar
	Mass flow	1350 t/h	1467 t/h
	Temperature	254.9°C	254.9°C
	Moisture content	~0.3%[a]	~0.5%[a]

[a] Estimated data.

By maintaining the pressure in the main steam collector unchanged, the power could be increased basically by increasing the volume of direct steam. The extent of the steam volume increase is nearly the same as that of the power (8.6%), and nearly the same increase could be expected through the whole turbine, while the amount of bleeding increases by an even higher extent (Table A–4).

2. SPECIFIC INSTRUMENTATION AND CONTROL RELATED MODIFICATIONS FOR POWER UPRATING

Besides a few minor I&C changes, the three most significant, I&C related modifications comprise the improvement of the primary circuit pressure control, the modernization of the VERONA in-core monitoring system and the change of some reactor protection and other set points. The following sections provide a detailed description of these activities.

2.1. Improvement of the primary circuit pressure control

2.1.1. Cause and justification of the modification

The primary circuit and reactor core pressure is controlled through interactions to the water and steam areas of the pressurizer. Pressure increase can be achieved by turning on the electrical heaters at the lower part of the pressurizer vessel, while the pressure can be reduced by ‘cold’ water injection to the steam area of the pressurizer. This water is taken from the cold leg of one of the main circulation loops.

The pressurizer pressure control system has the following outputs:

— Increase in pressure: five electrical heaters altogether with a 1620 kW capacity;
— Reduction in pressure: four injection valves altogether with a 25 t/h capacity.

The static characteristic of the original pressure controller is shown in Fig. A–1.

In the original system, a constant 325°C saturation temperature was considered, which corresponded to the 120.6 bar (abs) pressure. According to the technical specification, an uncertainty of 7.5°C had to be taken into account at the highest core subchannel outlet temperature.

This pressure control system had the following major drawbacks:

— The I&C devices reflected the Russian technology of the 1970s. The long term stability of these devices was not satisfactory, they were sensitive to ambient temperature changes and they were ageing;
— The controller had discrete characteristics for both the electrical heaters and the injection valves. After crossing a set point, the output stepped to the next range and — due to the large uncertainty band and the integration feature — the output pressure could be kept only in a relatively wide range. According to the operational experience, the primary circuit pressure in the actual units varied between the limits of 121 and 123 bars (over)pressure.

The former values of the primary circuit pressure at a regular weekend can be seen in Fig. A–2.

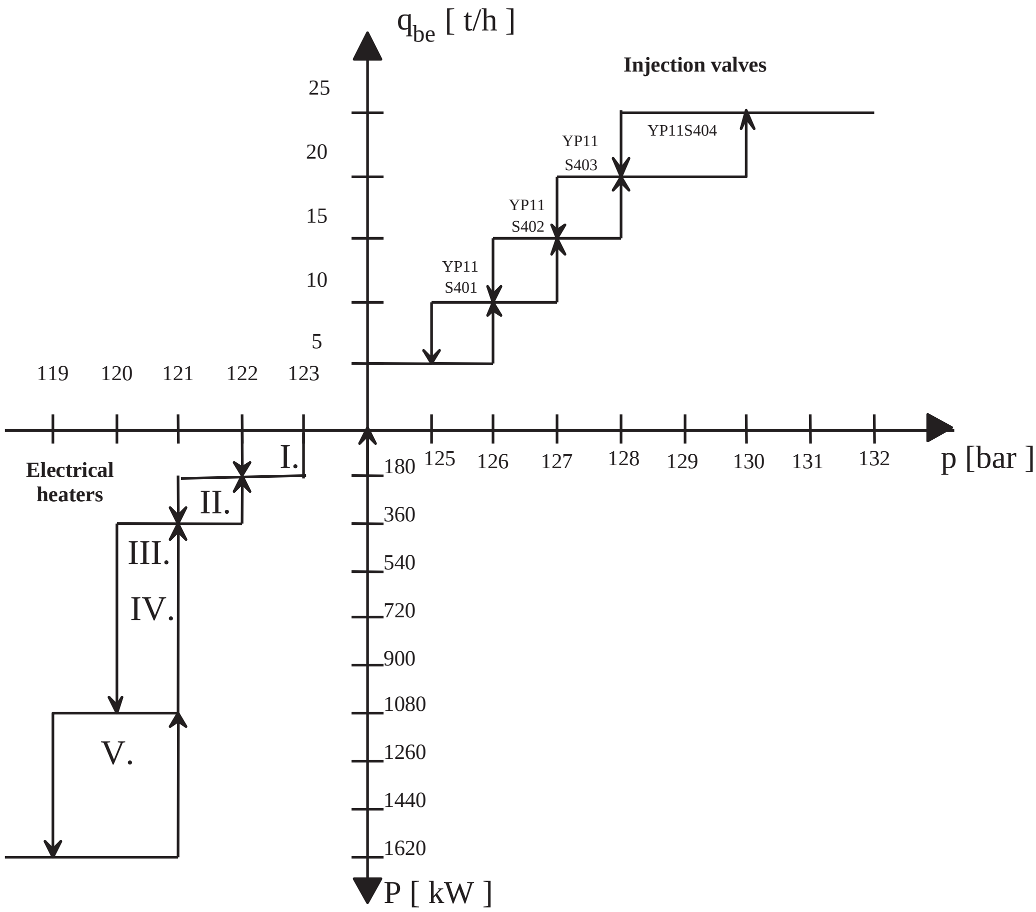

FIG. A–1. Static characteristic of the original pressure controller.

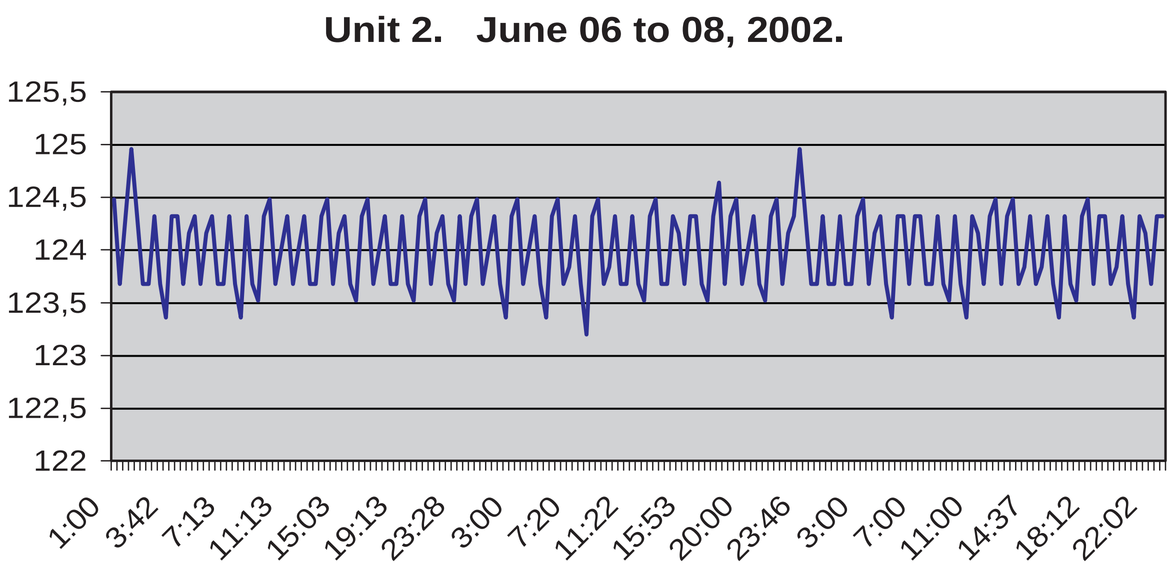

FIG. A–2. Primary circuit pressure values before modernization.

The alternating characteristic mentioned previously can be observed in Fig. A–2. The period time is approximately 1.5 h.

As a result of power uprating, the core outlet temperature increases with the power increase, thus, it gets nearer to the saturation temperature. However, if the primary circuit pressure control system can ensure a finer maintenance of the primary circuit pressure, the margin of saturation can still be kept at the required level.

2.1.2. Modification

One of the preconditions of power uprating is to maintain the operating pressure at a stable 123.0 bar with an accuracy of ±0.25 bar.

To fulfil this requirement, the NPP has decided to build a new pressure controller. In the design of the new loop, the basic concept of a future Paks I&C system was taken into consideration:

— Application of distributed (in function and in space) programmable controllers (PLCs);
— Integrated system architecture, meaning that the same equipment performs all the I&C tasks required in the system (i.e. control, information provision, diagnostics, etc.);
— Application of an industrial Ethernet communication system between the PLCs and towards the plant computer;
— Application of field buses (PROFIBUS-PA);
— Application of a simulation development environment (ProfiSim) to verify the software.

The new controller builds on the basics of the original system. Below 119 bars, all electrical heaters are on, and as the pressure increases up to about 124 bars, they will gradually turn off. If the pressure increases further, the injection valves start to open at about 125 bars and at 130 bars all four of them will be fully open. When the pressure decreases, the same process follows the reverse way.

The novelty of the new pressure controller is in the 122.25–123.75 bars range, where the discrete control is replaced with a continuous analogue control with an electrical heating capacity of 360 kW (out of the total 1620 kW).

The modified characteristic of the pressure controller is shown in Fig. A–3.

The algorithm is based on an inverse control algorithm. This is an equation that is calculated in every cycle of the controller. The input to it is the actual, measured pressure of the primary circuit, while the output is the required electrical heating power.

Figure A–4 indicates the primary circuit pressure stability after the modernization. It may be observed that the overall fluctuation of the pressure dropped to less than 0.1 bar as compared to the original, more than 1 bar band.

2.1.3. The structure of the new system

The controller consists of four main components, as follows:

— High precision pressure transmitter;
— SIMATIC intelligent controller (Main PLC);
— WAGO intelligent controller (Field PLC);
— Ethernet switch.

The structure can be seen in Fig. A–5.

There is a TCP/IP based Ethernet communication between the components, which makes it possible to install the devices at a relatively large distance from each other.

Input pressure is provided by a dedicated pressure transmitter. The transmitter sends the measured absolute pressure value to the controller through its Profibus PA interface, periodically. The controller performs the hydrostatic and environmental pressure correction on the input value and forms the simple average of the last ten measurements. The calculated primary circuit pressure is then used to compose the output commands

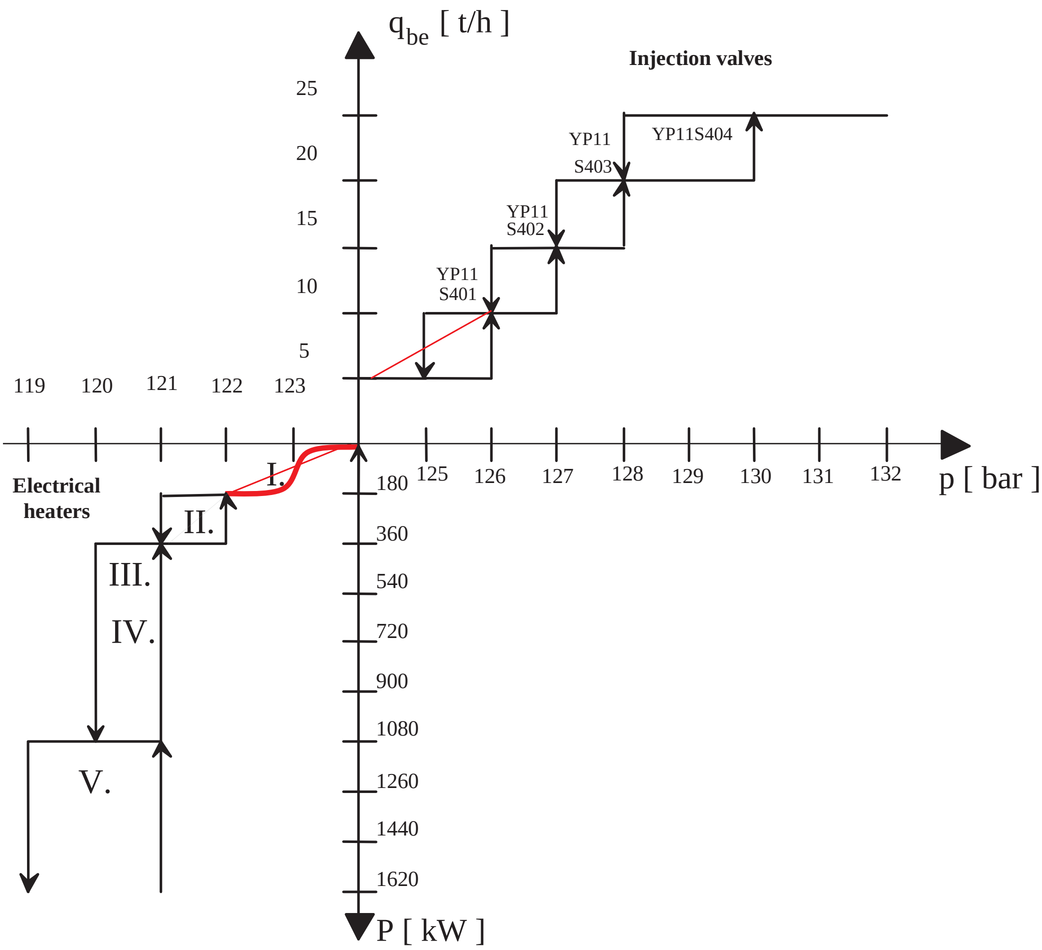

FIG. A–3. Static characteristic of the new pressure controller.

for the heaters and injection valves. These output devices are driven through the WAGO intelligent terminal blocks at the left side of Fig. A–5.

As a result of the modification, the pressure of the pressurizer steam space can be maintained at 123 ±0.25 bar (abs).

The new regulator was installed in 2004 in Unit 3 in an open loop mode in order to gain experience. It then entered real, closed loop operation in the summer of 2005, after the successful commissioning tests. Modification in two other units was completed in 2006, and the last unit will come in 2008.

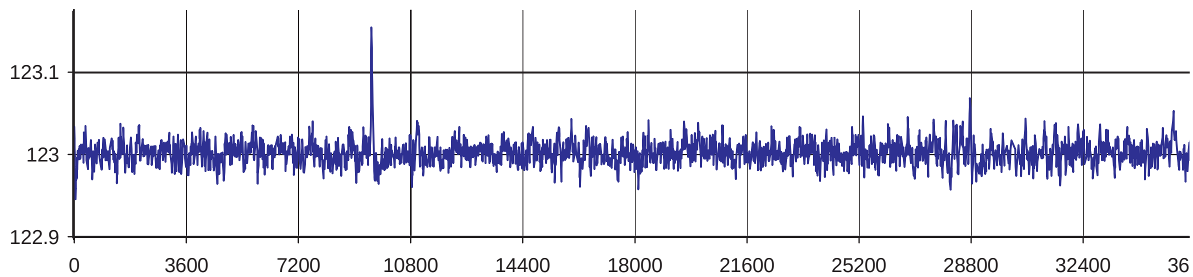

FIG. A–4. Primary circuit pressure values after modernization.

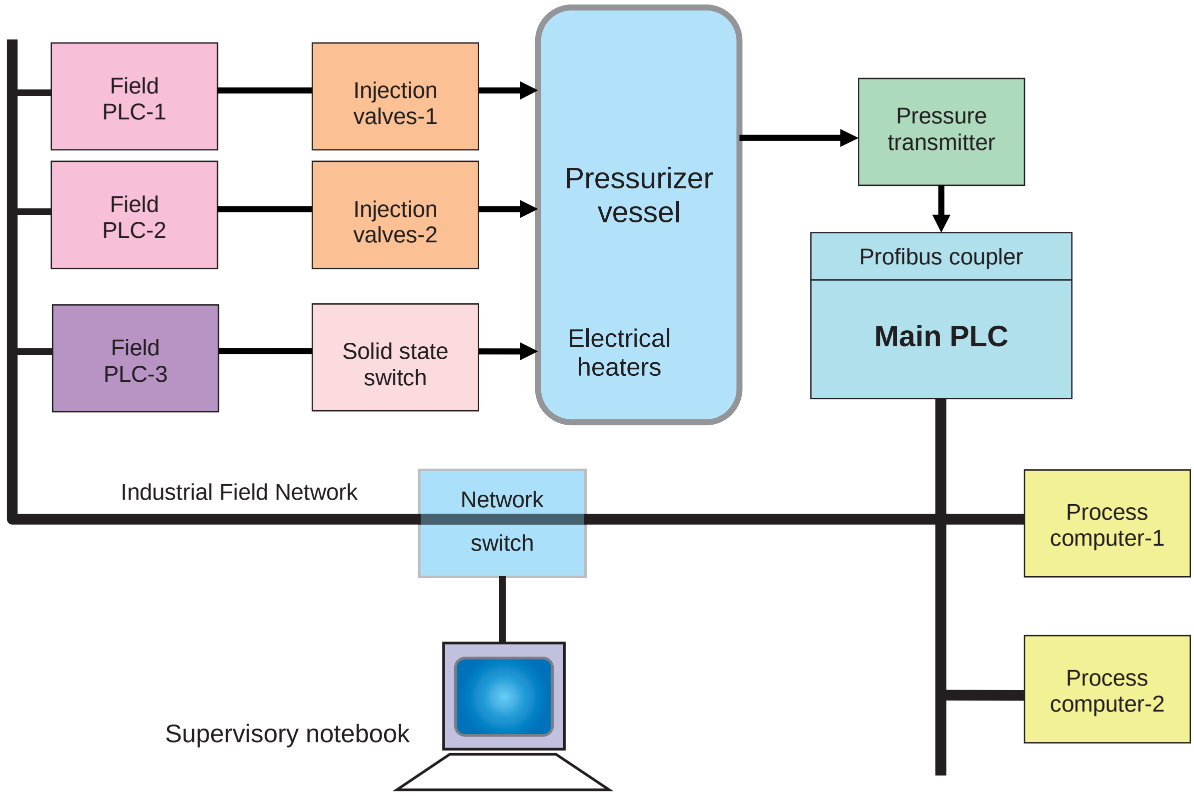

FIG. A–5. The structure of the new pressure controller.

2.2. Modification of the VERONA in-core monitoring system

2.2.1. Overview of previous VERONA versions

The WWER-440/213 type units of the Paks NPP have extensive in-core instrumentation: 246 fuel assemblies out of a total of 349 are equipped with measuring devices in the core. Self-powered neutron detector (SPND) strings are located at the central tubes of 36 assemblies and the outlet temperature of the coolant is measured by thermocouples in 210 assemblies. This relatively dense in-core instrumentation offered the opportunity to develop and operate a comprehensive core monitoring system in the early 1980s.

One of the main targets was to replace the original HINDUKUS in-core data acquisition and monitoring system. The data acquisition part was replaced with a modern, high precision system consisting of standard VME modules. Data processing and core calculations were performed in dual redundant MicroVAX host computers, under the system name of VERONA. The application software running in the VERONA host computers has been changed several times, in order to cope with the ever changing operational and safety requirements. However, no major architectural changes were required until most recently (see Fig. A–6). The goal was achieved through the following architectural and functional solutions:

— Input sensor scanning interval of 2 s;
— Application of a partly redundant data acquisition hardware (PDA system);
— A dual redundant host computer configuration (MicroVAX);
— A continuous, periodic archiving of all measured data for off-line analysis;
— An improved core analysis (‘pinwise’ core calculations);
— A user-friendly human–machine interface.

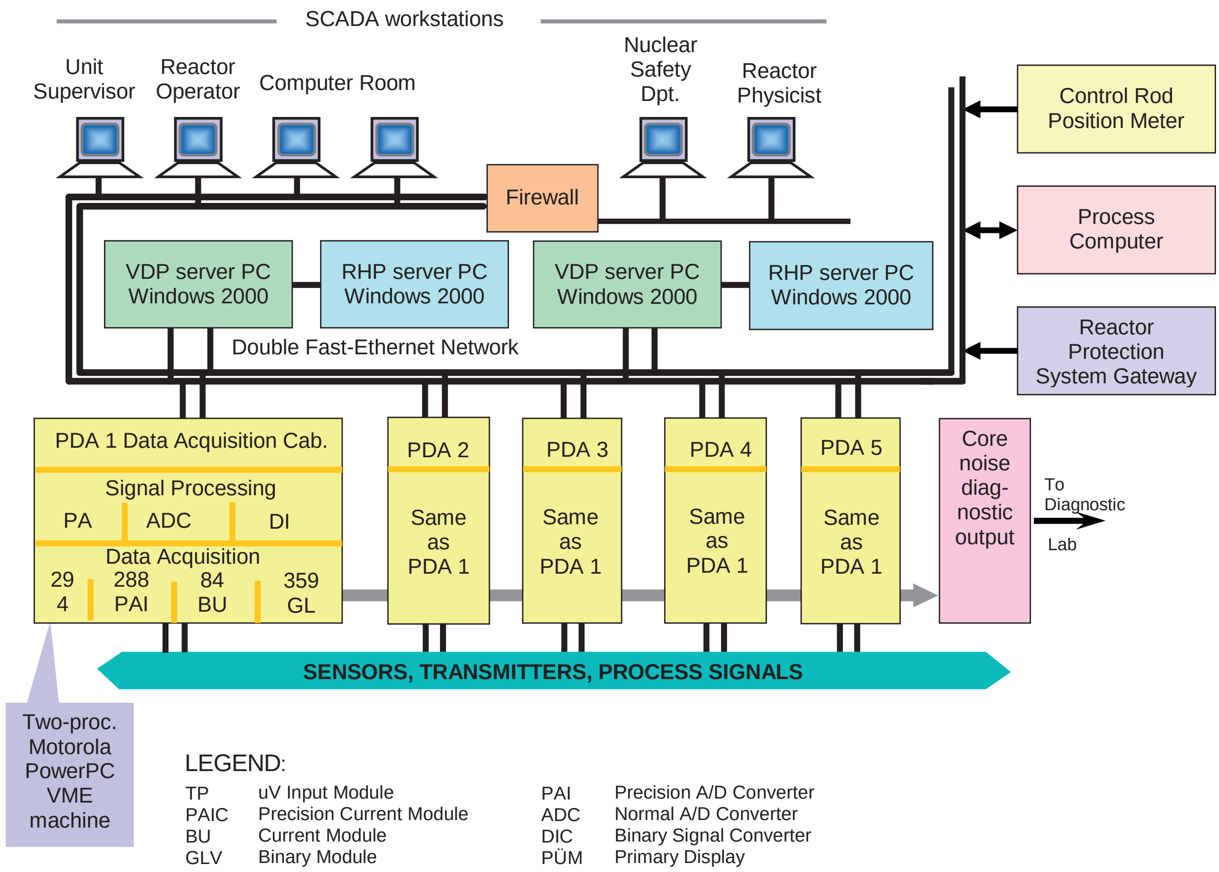

FIG. A–6. Architecture of the new, distributed VERONA system.

2.2.2. *Main reasons for the ongoing VERONA upgrade*

As previously mentioned, several important software changes were introduced during the past ten years and the original MicroVAX-3100 Model 96 machines became gradually overloaded.

Other important reasons for the modernization came from the reactor power uprating program. Feasibility studies have shown that increasing the reactor power to 108% can be accomplished only by using a new type of fuel (radially profiled assemblies with burnable poison). The on-line analysis of the new fuel requires higher accuracy and a more detailed modelling, which cannot be achieved using the old core analysis algorithms and computing resources. Another important project is the plant lifetime extension programme, which is in the preparatory phase at present. If the lifetime of the Paks units is extended, they will need core monitoring systems running reliably far beyond 2010. In order to meet these requirements a new, fully ‘open’ system architecture had to be designed. This open architecture should support an easy system extension and the addition of new functions and services.

Considering the requirements mentioned, the NPP decided to create a new system with higher accuracy and with advanced services. The medium term system upgrading phases contain the following major items:

— Modernization of the system architecture and software;
— Partial upgrading of the PDA data acquisition computers;
— Development of a new version of the reactor physics calculation modules.

In the following subsections, details of the ongoing upgrading will be outlined.

2.2.3. *New system architecture and new software tools*

One of the main architectural changes of the upgrading is the introduction of a ‘distributed’ system architecture. The originally redundant (1 + 1) host configuration was changed to a divided and dual redundant (2 + 2) configuration. The software of the host computer was split into two major parts: the reactor physics calculation system was separated and moved to a separate, powerful RPH server. In order to create the RPH server, all reactor physics calculation modules had to be ‘ported’ to Windows from OpenVMS. It was quite a straightforward operation and no major problems were encountered (the Linux version of the RPH system had already been created successfully some years before, for off-line analysis). Another pair of Windows based personal computers (the VDP servers) was dedicated to the primary data processing and data presentation tasks. New, SCADA based workstations were installed for mimic and data displaying. This approach was successfully used at the Paks NPP before, for the modernization of the process computers, where old systems were totally replaced with distributed, Windows based systems.

The new architecture was tested in the framework of a pilot system installed at Unit 3 in 2003. Fully parallel tests were run in order to check the performance and reliability of the Windows based system. Test results have shown that one can obtain a remarkable core analysis capacity at reasonable cost: the applied commercial industrial personal computer performs a full on-line core calculation (i.e. a three dimensional pinwise power determination followed by a thermohydraulic analysis to obtain maximum subchannel outlet temperature), approximately 40 times faster than the Model 96 MicroVAX. Long term operation of the divided system did not reveal stability or reliability problems.

Major software items marked for modernization were as follows:

- Process database and data archive management tools: application of standard relational database management tools and SQL compatibility;
- Data visualization: application of a professional mimic editor and a dynamic mimic displaying system. In addition, serving of remote users are accomplished by using a web server and standard hypertext browser in the users’ machines;
- System management: reliable system supervision programs and the application of graphic management tools;
- System expansion: the new architecture supports seamless system expansion by providing ample reserves and built in expansion possibilities;
- Modification of the off-line and on-line core calculation modules for the new fuel (designed for the increased 108% reactor power);
- Integration of the C-PORCA core design code into the VERONA and run it on-line. This is a general tendency for core surveillance systems and this approach is also used for WWER reactors at Loviisa (RESU-98), Temelin (BEACON) and Dukovany (SCORPIO).

The following system design principles were taken into consideration:

- The system should be of high reliability and high (99.98%) availability;
- No data loss should occur during data acquisition, processing and archiving. The system should preserve the consistency of data in case of incidental stoppage and restarting, as well as in normal shutdown and restart;
- Operational functions should be realized in a redundant way, and the basic functions in a paralleled manner;
- The system should automatically recognize degradation of the application software and some hardware failures, and should indicate them univocally and in a well recognizable manner to the users.

2.2.4. *Advanced core analysis*

In general, the VERONA core analysis can be considered as a combination of measured and off-line calculated information. The two dimensional and three dimensional extrapolation algorithms use precalculated core distributions determined by the C-PORCA core design code. Calculated information is essential for the 37 control rod positions, where no measurements are available. Off-line core calculations are performed before each fuel cycle: the whole fuel cycle is 'simulated' in given T_{eff} (full power day) steps. For every T_{eff} step, a lot of calculations are made, with different reactor power, control rod position and boric acid concentration as input. The resulting two dimensional and three dimensional distributions are stored in a large file: on-line algorithms use this file to read in the distribution closest to the actual reactor state.

The two dimensional extrapolation provides reliable ΔT estimates for the fuel assemblies not having outlet coolant temperature measurement. The extrapolation is carried out by a combination of the measured and pre-calculated information, within a least-squares fitting procedure. The fitting takes the neutronic coupling between neighbouring assemblies into account: 'microsectors' (i.e. an assembly + its six neighbours) are treated as coupled entities during the procedure. Three dimensional extrapolation means the determination of the fast neutron flux and linear power distributions in 349 × 20 core nodes. The method can be considered as a three dimensional synthesis algorithm: the two dimensional assembly power distribution is taken from the result of the two dimensional extrapolation and the axial distribution is determined from measured SPND currents. Currents are converted to local fast flux values by using conversion factors calculated by the transport code. When having the three dimensional fast flux distribution available, the distribution of the thermal flux and the power can be determined, as well.

For a radially profiled fuel assembly, one must determine the pinwise power distribution in a much more detailed manner, for example, for all the 126 fuel rods, if required. The number of axial nodes also needed to be increased to 20 (originally it was 10), in order to achieve higher accuracy around the control rods. Having the three dimensional pinwise linear heat rate distribution available, one can determine subchannel outlet temperatures by using an appropriate thermohydraulic model. Another important new feature is that the system is able to take into account the pressure dependence of the primary circuit saturation temperature when calculating actual subchannel outlet temperature reserves. In general, this increases minimum subchannel outlet temperature reserve by approximately 0.7–0.8°C compared to the previous method, when a constant (pressure independent) limit of 317.5°C was used. This way, the new algorithm provides more space for power uprating of the core.

2.3. Modification of reactor protection system set points

Due to the changing process parameters, it was also necessary to modify some set points in the safety I&C system. The goal was to keep the number of altered set points at a minimum. According to this approach, all the ECCS signals and interlocks remained unchanged after the power uprating. The correctness of these set point values had already been justified in the former analyses.

As for the reactor shutdown signals, only three set points needed to be altered as a consequence of the power uprating. These were:

— Turbine trip related signal;
— Limitation signals for neutron flux increase;
— Reactor power limitation signal that evaluates the number of running reactor coolant pumps.

EVALUATION OF NSSS PROCESS MEASUREMENT CHANNELS

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Abstract

When the process conditions are changed by power uprating, it is necessary to check the measuring range of process variables to find whether the existing instruments can be reused or new instruments are necessary. Different process conditions can affect the measurement channel performance. Therefore, the effects on the sensor performance by the changes in process condition for 4.5% thermal power uprating were evaluated.

The target plants and conditions were:

Plants:	Kori Unit 3 and 4, Yonggwang Unit 1 and 2
Reactor type:	PWR
NSSS supplier:	Westinghouse
Capacity:	950 MW(e)
Uprating power:	2775 MW(th) → 2900 MW(th) (4.5%)
Uprating method:	Stretch power uprate

1. EVALUATION METHODOLOGY

1.1. Evaluating the maximum range capability

Maximum range capability is related to process sensors (transmitters). The main variables evaluated are as follows:

— Primary side temperature;
— Pressurizer pressure and level;
— Channels for low temperature overpressure protection;
— Main feedwater flow;
— Main steam pressure and temperature;
— Steam generator level control channels;
— RCS flow and temperature;
— Channels for residual heat removal system;
— Channels for chemical and volume control system heat exchanger;
— Channels for plant protection system;
— Channels for engineered safety features actuation system.

The evaluation result shows that the operating process conditions are changed but do not exceed the sensor design limit. Therefore, the power uprating does not affect the sensor operating range and replacement of the existing sensors is not necessary.

1.2. Evaluating the effects on calibration

It is confirmed that the changes in the operating condition affect the transmitter calibration. The pressure indicating channels are not affected, but those channels for which the fluid density has an influence suffer changes to the calibration range according to the different static pressure and temperature conditions.

As a result of evaluating Kori Unit 3 for the case of PCWG 3, 6, 9, two variables, notably SG level and main feedwater flow, were found to require recalibration as the SG pressure and temperature decreased and the feedwater temperature increased by the power uprating. The pressurizer level measurement channel is not affected because the pressurizer pressure and its saturation temperature have the same values as before power uprating. Table A–5 shows typical calibration data for the Kori Unit 3 SG level.

TABLE A–5. TYPICAL CALIBRATION DATA FOR THE KORI UNIT 3 SG LEVEL

		Before power uprating	After power uprating		
			Case 3[a]	Case 6[a]	Case 9[a]
SG operating condition	Temperature	287.2°C	278.7°C	278.1°C	274.4°C
	Pressure	1036 psia	912 psia	904 psia	855 psia
Transmitter calibration data	0%	128.67 inH_2O	129.28 inH_2O	129.33 inH_2O	129.58 inH_2O
	100%	38.70 inH_2O	36.75 inH_2O	36.61 inH_2O	35.81 inH_2O
	Span	89.92 inH_2O	92.53 inH_2O	92.72 inH_2O	93.77 inH_2O

[a] SG tube plugging rate: 7% at normal T_{avg} (307.8°C).

The SG level reading difference is ~3–4%. The feedwater temperature increases about 6°C by the power uprating, which causes 0.52% difference in differential pressure on the feedwater flow transmitter according to the calculation based on the ASME PTC 19.5–1971. Those differences should be compensated by recalibration.

1.3. Evaluating channel uncertainty

Channel uncertainty evaluation for the major NSSS measurement channels was conducted to estimate the effect on the operating limit conditions which were defined in the plant technical specification. The following table contains the evaluation results. It shows that the calibration value and static pressure are the uncertainty factors which are affected by power uprate.

The uncertainties are expressed by per cent span, and a larger calibration (span) value causes a bigger channel uncertainty. The static pressure effect on the SG level becomes smaller as the steam generator pressure is decreased by the power uprate. The combination of the influences shown in Table A–6 on the channel uncertainty allows the total channel uncertainties to remain within the present margin after power uprate.

2. CONCLUSION

The NSSS major process measurement channels were evaluated for the influence of the different process conditions caused by power uprate.

It was found that the increased or decreased process conditions do not exceed the existing sensor design limits. Therefore, the existing sensors can still be used after power uprate.

Evaluation of the effects on the calibration found that the measurements of SG level and main feedwater flow are affected by the operating conditions. The reading errors, ~3–4% for SG level, 0.52% for main feedwater flow should be compensated by recalibration.

Consequently, the overall channel uncertainties for major NSSS process measurements remain within the present margin after power uprate.

TABLE A–6. COMPONENT UNCERTAINTIES AND THEIR EFFECTS

Components	Uncertainty factor	Effects
	Drift	Possibly can be affected by the As–found/As–left methodology
	Environmental temperature	No
	Calibration value	Yes
Transmitter	Static pressure (DP Tr.)	Yes
	Radiation	No
	Power source, reference accuracy, calibration tools	No
Signal processor	Environmental temperature	No
	Drift	No
Process dynamics	Process velocity	No
	Ref. leg temperature	No
	Boron concentration	No

POWER UPRATING ACTIVITIES IN SWEDISH NUCLEAR POWER PLANTS

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Abstract

About 50% of the energy production of Sweden originates from nuclear power. There are in total ten reactors in operation, seven BWRs and three PWRs, located at three different sites. The BWRs are of Asea-Atom design and the PWRs are of Westinghouse design. The last one of two reactors at the Barsebäck plant on the south-west coast of Sweden was closed down in May 2005. The commercially operating research plant at Studsvik was, for commercial reasons, closed down in the same year. Governmental approval for nuclear power production includes a value of the maximum allowable thermal power that the reactor may produce. Power uprating is, therefore, mainly used as a term when talking about thermal uprates. If the licensee wishes to uprate the power, a change in the licence must be applied for. The application should be addressed to the Swedish Government but is handled by SKI, the Swedish Nuclear Power Inspectorate. The ultimate decision, however, must be taken by the Government. The application must also go through an environmental court process.

1. PERFORMED POWER UPRATES

In the 1980s, all but one of the Swedish BWRs were uprated. These uprates were possible to carry out without any substantial modifications in the plants because of margins in the original design of the Swedish BWRs. For the PWRs, uprates were possible after the exchange of steam generators. Table A–7 provides an overview of the thermal uprates already performed.

TABLE A–7. OVERVIEW OF THE THERMAL UPRATES ALREADY PERFORMED

Reactor	Original thermal power (MW(th))	New thermal power (MW(th))	Uprate (MW(th))	Uprate (%)	Year of thermal uprate
Oskarshamn 2	1700	1800	100	5.9	1982
Barsebäck 2[a]	1700	1800	100	5.9	1985
Forsmark 1	2711	2928	217	8.0	1986
Forsmark 2	2711	2928	217	8.0	1986
Forsmark 3	3020	3300	280	9.3	1987
Oskarshamn 3	3020	3300	280	9.3	1989
Ringhals 1	2270	2500	230	10.1	1989
Ringhals 2 (PWR)	2440	2660	220	9.0	1989
Total	26 513	21 216	1644		

[a] Barsebäck 2 was closed down in May 2005.

In addition to these thermal power uprates, the NPPs have continuously taken measures to increase the efficiency of the plant performance and thereby produce more electrical power.

* K. Johansson was the author of this paper, excepting Section 4.1–4.3.

2. PLANNED POWER UPRATES

After a period with a very moderate interest in investments in energy production, possibly due to low energy prices and uncertainty concerning the political agenda of the Swedish Government, the interest in power uprating has grown in recent years. Most Swedish NPPs are now planning for power uprates. Table A–8 demonstrates their plans in late 2006.

As seen from Table A–8, different kinds of power uprates are planned — from a small 1.6% uprate to an extended uprate for Oskarshamn 3. The planned small uprate for Ringhals 1 is not a MUR uprate, as originally planned, but rather an uprate based on a renewal of the safety analyses for the higher power level. The uprates are planned to be carried out roughly during the period 2006–2012.

During the same time frame as the uprates are supposed to be realized, new requirements from SKI have to be implemented. These requirements are not connected to power uprating formally, but their practical implementation, in several cases, will be intermingled with actions taken due to the power uprates and end of life replacements.

3. EXPERIENCES AND FUTURE PLANS CONCERNING INSTRUMENTATION AND CONTROL, AND POWER UPRATES

The following discussion reflects information provided by the Forsmark NPP site, and describes some of the issues, including I&C issues, connected to their planned power uprates.

3.1. Forsmark

Forsmark has three units. Together, they generate between 20 and 25 TW h/a of electricity, and this is about one-sixth of Sweden's electricity production.

The original reactor power rating for Forsmark 1 and 2 was 2711 MW(th), and for Forsmark 3 it was 3020 MW(th).

The first power uprate was done in the 1980s. This was mainly done by modifications to the core, HP turbine, reheater system, pressure relief system and scram. Instrumentation and control did not need any significant alteration, but some scales on instruments and printers, scaling factors, limit values, and some software had to be modified.

The current reactor power rating for Forsmark 1 and 2 (108%) is 2928 MW(th), and that for Forsmark 3 (109%) is 3300 MW(th).

Presently, a retrofit of LP turbines is ongoing. The three LP turbines at Forsmark 3 were replaced during the outage in 2004. The six LP turbines at Forsmark 1 were replaced during the outage in 2005, and were replaced in Forsmark 2 during the outage in 2006. Table A–9 summarizes the Forsmark power uprates.

TABLE A–8. OVERVIEW OF THE PLANNED THERMAL UPRATES

Reactor	Present thermal power (MW(th))	Planned new thermal power (MW(th))	Uprate (MW(th))	Uprate (%)
Forsmark 1	2928	3253	325	11.1
Forsmark 2	2928	3253	325	11.1
Forsmark 3	3300	3775	475	14.4
Oskarshamn 2	1800	2300	500	27.8
Oskarshamn 3	3300	3900	600	18.2
Ringhals 1	2500	2540	40	1.6
Ringhals 3 (PWR)	2783	3160	377	13.5
Ringhals 4 (PWR)	2783	3300	517	18.6
Total			3159	

TABLE A–9. FORSMARK POWER UPRATES

Reactor	Original electrical output (MW(e))	Electrical output (MW(e)) before uprate	New net electrical output (MW(e))	Uprate (MW(e))	Total uprate % from original power	Uprate (%)	Year of thermal uprate
Forsmark 3	1050	1155	1190	35	13.3	3	2004
Forsmark 1	900	961	1010	49	12.2	5.1	2005
Forsmark 2	900	951	1010	59	12.2	6.2	2006
Total	2850	3067	3210	143			

A third power uprate is planned (second thermal power uprate). The pre-study showed that at Forsmark 1 and 2, the technical limitations can be found in the turbine facility rather than in the reactor facility. At the start of the pre-study, it was estimated that the new low pressure turbines could cope with a power level at 118%. More detailed studies, however, have revealed that the LP turbine is not the limiting factor. The limiting factor is, instead, the connection between the LP turbine and the generator (123%) and the major electric power components.

At Forsmark 3, the technical limitations are more evenly distributed among the various parts of the power plant.

The above reasoning constitutes the basis for the selection of power levels:

— 120% for Forsmark 1 (F1), which gives a power output increase of 120 MW(e);
— 120% for Forsmark 2 (F2), which gives a power output increase of 120 MW(e);
— 125% for Forsmark 3 (F3), which gives a power output increase of 170 MW(e).

3.1.1. Background for selected power levels

When market and political conditions are favourable, the addition of new power generated through power uprates of existing NPPs is a very attractive alternative, both with respect to economic and environmental considerations. If a plant lifetime of 50 years is assumed, it is profitable to raise the power level as much as possible.

In the pre-study for the power uprate, analysis and previous experience have been combined to identify problems and propose measures to prevent or solve them. Experience from other power uprate projects and other major plant modifications shows, however, that surprises are to be expected. Typically, surprises can derive from mistakes in judgement rather than complete ignorance of the problem. In the Forsmark pre-study, the goal has been to constrain power levels and technical solutions to be within the experience base defined by previously performed power uprates. This approach should mitigate the risk level considerably.

Power uprates have been implemented at more than 100 plants worldwide. Most uprates have been to power levels less than 110%. A handful of reactors have raised the power to levels exceeding 120%, with Olkiluoto 1 and 2 in a lead position with its uprates to 125%. Of course, a simple comparison of percentage raise is not necessarily relevant, since the conditions with respect to technical details may vary considerably. An example of this variation is that the containments at Olkiluoto 1 and 2 are identical to the containments at Forsmark 1 and 2, although the original nominal thermal power is considerably higher at Forsmark 1 and 2 (2711 MW(th) at Forsmark versus 2000 MW(th) at TVO). Another example is that the average power density at Leibstadt (120%) is higher than the power density at Forsmark 3 operated at 125%. The general impression is that politics, licensing environment, authorities, market situation and policy within the utilities are at least as important as technical limitations when it comes to selecting power levels.

It is quite clear that a successful and cost effective implementation of a power uprate is profitable. However, the existing plant with its excellent performance is potentially at stake. This fact and the reasoning mentioned previously are behind the strategic project focus stated in the pre-study.

The overall goal is to guarantee the profitability and the plant's overall performance with respect to availability and lifetime. A solution that is robust with respect to various scenarios is emphasized rather than a solution optimized to a specific scenario. Risks with respect to cost, availability, premature ageing, implementation and deliveries should be identified. These risks should be quantified and treated in a probabilistic manner to support an integrated economic analysis. Thus, the keyword is robust rather than optimal.

3.1.2. *Basic decisions on plant design*

The basic decisions on plant design include:

- Reactor pressure will be kept at the present level (70 bar);
- Recirculation pump capacity will not increase;
- New core shroud cover will be needed for large power uprates;
- Maximum power for F3 125%;
- Maximum power for F1/F2 120%;
- Minimum speed on circulation pumps is kept at the present level. Partial scram on two scram groups are implemented and initiated on fast pump runback;
- Inner isolation valves are replaced on F1/F2;
- Moderate reactive power capacity on the generator.

3.1.3. *Reactor systems*

In the reactor, a basic consideration is that the internal circulation pumps are kept unaltered since a new design may have an adverse effect on plant availability. Experience from the early days is that proper operation of the internal pumps requires substantial in situ testing and adjustment. To be able to handle pressure drops in the main loop and moisture content, new core shroud head and steam separators are required. Moreover, at Forsmark 1 and 2, the obsolete design of the steam dryer cannot deal with the higher steam velocities resulting from the power uprate. At Forsmark 3, steam dryer baffles must be installed to mitigate steam line vibrations.

The nuclear fuel and reactor core can fulfil the safety requirements with good margins, especially at Forsmark 1 and 2, where power density will be approximately 10% lower than at Forsmark 3. The specific fuel cost will increase marginally during a transition period, but will be undetectable in the long run. Since the main recirculation pumps will not be modified, the power must be increased upwards in the power/flow map. The stability problem that arises will be dealt with by introducing double partial scram that limits the operating region. The power density in the core is lower than existing power levels in other BWR power plants.

The steam main line inner isolation valves will be replaced. The existing valves are of the same type as those that inadvertently closed in January 2004 at TVO. The problem with these isolation valves has been an issue for several years and the margin to undesired closure of the valve decreases with higher power, which is why it is reasonable to replace the valves prior to power uprate.

The inner isolation check valves and pipe break check valves (the check valves in direct connection to the reactor) in the feedwater system need to be replaced at F3, since the higher water flows may lead to erosion problems. For the same reason, the pipe break check valves need to be replaced at F1/F2.

The control valves in the pressure relief system require modification in order to be accredited in the safety analysis.

A plant modification to increase the capacity in the residual heat removal system was carried out at Forsmark 1 in 2005 and Forsmark 2 in 2006. This modification satisfied the need for capacity increase required by the power uprate.

To cope with residual heat removal at Forsmark 3, the capacity needs to be increased. Capacity increase of residual heat removal during outage is needed for all three units.

3.1.4. *Turbine systems*

The high pressure valves need to be replaced, since they are too small, which results in an unacceptably high pressure drop.

The high pressure turbine must be replaced or modified to cope with the higher steam flow. The recommendation is to replace the high pressure turbine. The main reasons for this are twofold: firstly, the efficiency will be higher with a new turbine; secondly, there is a risk for stress corrosion cracking on the old turbine.

The modification already planned in the present reinvestment programme in the steam reheat system will be adjusted in order to cope with the higher power. It is assumed that the planned modifications on the condenser at Forsmark 3 will be carried out prior to the power uprate.

To maintain efficiency and margins to disturbances, an increase in the main cooling water flow is required.

To resolve the problems with feedwater and condensate, different solutions have been proposed at F1/F2 and F3. The main issue is to maintain two-pump operation on all three units, since the feedwater pumps are relatively sensitive to disturbances.

At Forsmark 1 and 2, forward drain pumping will be applied to the last HP preheater, which will result in a lower load on the feedwater pumps and the entire preheater chain. This solution will also give an improvement in efficiency.

At Forsmark 3, three-pump operation will be applied for the condensate pumps, since these have an excellent availability track record. The low pressure drain will bypass the condensate polishing systems. This is the original solution at F3. Improved water chemistry and experience from Oskarshamn 3 constitute the basis for this modification. The HP drain pumps need to be modified to cope with the higher flow. The capacity of the feedwater pumps will be increased through replacement of the impellers. The consequence is that two-pump operation can be maintained with the existing control system. The electrical motors for the feedwater pumps must be replaced in order to fulfil the design requirements.

3.1.5. Electric power systems

A prerequisite for the power uprate is that the planned replacement of G21 at Forsmark 2 will be carried out.

Depending on the system design solution for the cooling systems, the load on the diesel supported power system may increase so that the requirements cannot be met. This problem can be resolved by moving non-safety loads from the diesel supported power system to the normal power system.

To ensure the status of the main transformers at F1/F2, the surveillance system will be improved.

The generator must be replaced at Forsmark 3. Studies have revealed that the optimal voltage level is higher than the existing voltage level and, consequently, new transformers are needed.

3.1.6. Instrumentation and control

The basic decision regarding I&C is that those modernizations that are not mandatory for the power uprate will not be done during the implementation.

The biggest impact on I&C is expected to come from modifications of:

— Feedwater and condensate system, all three units;
— Improved partial scram, all three units;
— Reactor power control, all three units;
— Reactor protection, all three units;
— Change of HP turbine and HP valves, all three units.

3.1.7. Safety and licensing issues

A prerequisite for the power uprate is that it has been authorized by the government and the authorities. The power uprate has to proceed in accordance with the Nuclear Act as well as the Environmental Act.

The safety analysis is a central part of the application. Existing applications of the safety requirements have been used. Salient safety aspects in the uprate are fuel margins, pressure relief and residual heat removal.

As a result of the fuel development during the last 20 years, loading a core that fulfils the requirements for an uprated plant is a minor problem. Core stability is the most challenging problem. By limiting the operating region through partial scram, the stability problem can be managed.

An analysis of tests and occurrences shows that the pressure can be predicted with good accuracy. In addition to this, conservatism in accordance with guides and norms is applied in the pressure relief analyses. The analyses in the pre-study show that the installed pressure relief capacity is adequate. However, the control relief valves at F1/F2 need to be modified so that they can be accredited in the analysis. Maximum pressure in the containment is mainly dependent on the reactor pressure and will be affected only marginally by the power uprate.

A variable that will be affected by an increase in reactor power is the maximum temperature in the wet well after a pipe break in containment. Passive safety in terms of water volume in the wet well in relation to the thermal power will decrease. To fulfil the requirements, capacity increase of the cooling systems is required (replacement of heat exchanger and flow increase).

In general terms, the formal safety requirements can be fulfilled with good accuracy and with reasonable margins. There are other potential problems, which may not be explicitly formulated in terms of quantified limits. These may be vibration or erosion problems stemming from the higher steam flows. These phenomena may be difficult to analyse theoretically with good accuracy. Experience from other BWR plants, such as Leibstadt, which already operates at high power density, can be utilized. Nonetheless, analysis and experience from other plants must be complemented with tests to ensure adequate operation.

Some of the modifications needed to meet new Swedish regulations are appropriate to incorporate in the power uprate. The planned modifications will increase safety in the following areas:

— Improvement of long term cooling (installation of tube heat exchangers in system 322);
— Pool cooling system;
— Pressure relief system;
— Improvement of the scram system in order to provide independence between the pressure relief system and the scram system.

Considering the extensive and time consuming process to license in accordance with the Environmental Act, it would be desirable to conduct the environmental assessment for a somewhat higher power level in order to facilitate future minor power adjustments. However, the close interaction between the Nuclear Act and the Environmental Act precludes this approach. The Environmental Court will require a statement from SKI supporting the environmental assessment. SKI would have difficulties in issuing a statement relating to a higher power level that is inconsistent with the application to SKI.

3.1.8. *Implementation*

The implementation will be done in packages, described as follows:

— *Feedwater and condensate system F1/F2:* Forward pumped HP heater drain, change of feedwater pump impellers installation, power supply to feedwater pumps, adjustment of the reactor water level control system.
— *Feedwater and condensate system F3:* Change of impellers and motors on feedwater pumps, LP and HP heater drain pumps.
— *Power generation F1/F2:* Change of generator stator 21, measuring transformer, upgrade of generator cooling system 719–718.
— *Power generation F3:* Change of generator to 24 kV, excitation transformer, generator cooling, step up transformer and local power supply transformer.
— *Main cooling:*
  • F1/2: Change of main cooling pumps;
  • F3: Adjustment of main cooling pump impellers, removal of cooling water outlet hose.
— *Reactor control:*
  • F1–3 Improved partial scram;
  • F1–3 Reactor power control;
  • F1–3 Reactor protection.

— *Reactor internals:*
  - Core shroud head and steam separators in Unit 1–3 and change of steam dryer in Unit 1–2;
  - Cooling systems.

— *Core related issues:*
  - Upgrade residual heat removal system;
  - Upgrade fuel pool cooling and cleanup system;
  - Valves in containment;
  - F1/2: Change inner steam pipe isolation valves;
  - Redesign against vibrations on pilot safety relief valves;
  - F3: Inner feedwater pipe isolation valves.

— *Turbine related issues:*
  - F1–3: Change of HP turbine and HP valves;
  - Process heat exchangers;
  - F1/2: Change of steam reheater;
  - F3: Change of tubes in steam reheater, change of HP heater, retubing in condenser.

UPRATING AT THE NUCLEAR POWER PLANTS IN THE UNITED KINGDOM

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Abstract

The first commercial Magnox NPPs were commissioned in the mid-1950s. Until the early 1970s, 24 reactors of that type were commissioned progressively. A substantial number of these reactors have since been shutdown.

The advanced gas cooled reactor followed on from Magnox and 14 reactors of that type were commissioned progressively from the mid-1970s to the late 1980s. These were all twin unit sites, and all are still in commercial operation, though several have now reached their original designated lifetime.

Since that time, a single pressurized water reactor was commissioned in 1995.

This country report addresses the situation for the 14 AGRs and PWR outlined previously (Table A–10).

TABLE A–10. OVERVIEW OF THE NPPs IN THE UNITED KINGDOM

Power plant	Type	No. of units	Commercial operation	Original thermal capacity/unit (MW(th))
Hinkley Point B	AGR	2	1976, 1978	1500
Hunterston B	AGR	2	1976, 1977	1496
Hartlepool	AGR	2	1984, 1985	1500
Heysham 1	AGR	2	1984, 1985	1500
Dungeness B	AGR	2	1985, 1988	1550
Heysham 2	AGR	2	1988, 1989	1555
Torness	AGR	2	1988, 1989	1555
Sizewell B	PWR	1	1995	3411

1. DECISION ON POWER UPRATING

A decision on power uprating has to take account of several factors, including:

- Potential impact on plant safety;
- Potential impact on overall plant lifetime;
- Potential impact on stable plant operation;
- Outage implications (of implementation);
- Cost implications (of implementation).

2. OVERVIEW FOR AGRs

For the AGRs, a specific concern has been the potential impact on the life of the reactor core and other key components, and so the emphasis has generally been to maintain or extend the overall plant lifetime rather than increase the power rating.

Notwithstanding the mentioned issues, work has been undertaken to permit an increase in power for the majority of the sites and, by way of example, a safety case was successfully submitted for an increase to 1700

MW(th) at Torness. This falls into the category of a stretch power uprating. The implications for the design and operation of the plant are discussed further in the following section.

2.1. Stretch power uprating for AGR

The underlying philosophy for the licensing application was to move from a fixed set of plant operating conditions to an 'envelope for safe operation'. The possibilities for increasing the thermal power were judged to involve:

— Primary side: increasing the core gas mass flow and/or the outlet temperature;
— Secondary side: increasing the boiler feed flow and/or boiler temperatures.

A detailed review and revision of the fault studies was undertaken to include reactor thermal powers up to 1700 MW(th). This allowed relaxation in certain operating limits while still maintaining the existing operating margins. The principal operating limits affected were:

— Channel power limit redefined (increased from 6.6 MW(th) to 7.25 MW(th));
— Bulk channel gas outlet (CGO) temperature limit introduced (635°C);*
— Peak CGO temperature limit increased (from 675°C to 680°C);
— Boiler gas volumetric flow limit introduced for reheater inlet (15.97 m^3/s);*
— Boiler steam outlet pressure limit increased (from 166 bar(g) to 170 bar(g));
— Boiler steam outlet temperature limit increased (from 541°C to 546°C).

Other limits (e.g. primary circuit pressure, gas baffle dome differential pressure, upper transition joint (UTJ) superheat margin, UTJ gas temperature, UTJ weld temperature, reheater steam outlet pressure) were not affected, though in some cases, the margins to these limits were reduced and some of them have subsequently been changed for other reasons.

The strategy for achieving the increase in power was to: (a) increase the core mass flow by increasing the gas circulator inlet guide vane (IGV) angle and motor power; (b) increase the bulk CGO temperature; and (c) increase the circuit pressure, in that order of preference.

The direct changes in design arising from the issues mentioned were:

— CGO temperature trip set point maximum limit redefined;
— Gas circulator motor thermal overload protection set point increased;
— Boiler safety relief valve set points increased;
— Alarm set points for several parameters redefined.

A possible direct change in operation arising from the issues mentioned was the need to run a startup/standby boiler feed pump and a second condensate extract pump in parallel with the normal design provision.

In addition, monitoring for any increase in ageing or associated affects assumes greater importance following a power uprating. For the AGRs, the impacts of the following are of specific interest:

— Primary circuit operating conditions (i.e. temperature, neutron dose, flow and pressure) on core life;
— Gas mass flow rate on core vibration;
— Bulk CGO/reheater gas inlet temperature on component life;
— Bulk CGO temperature on carbon deposition in the boilers;
— Peak CGO temperature on thermal shock during on-load refuelling;
— IGV angle on the inception of gas circulator instability (vibration);
— Boiler outlet pressures on the 'life' of steam pipework.

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* Note: These limits replace limits on other plant variables.

3. OVERVIEW FOR PWR

For the PWR at Sizewell B, the original intent was to seek a 5% power uprating early in its operation, and a safety case was prepared in anticipation of this. However, other significant changes were being sought on a similar timescale (change in fuel, 50% increase in cycle length, change to automatic frequency response operation), and the regulatory view was that too many changes were being proposed at the same time. These other changes were considered more beneficial by the utility and so the 5% power uprating was deferred.

Advantage has since been taken for introducing a minipower uprating to 101%. This falls into the category of a measurement uncertainty recapture (MUR) power uprating. The implications for the design and operation of the plant are discussed further in the following section.

3.1. MUR power uprating for PWR

A mini-uprating was achieved for Sizewell B by treating the uncertainties in a different way in the safety case. The basic safety case was developed for 102% rated thermal power (RTP), assuming 2% calorimetric uncertainty. The revised treatment then enables statistical methods to be used in order to operate closer to the 'absolute' safety case limit.

A more detailed explanation of the original safety case, the revised safety case and the impact on the design and operation is as follows:

3.1.1. Original safety case

The original safety case:

— Reactor operated such that the 1 h rolling average power ≤ 100% RTP;
— Safety analysis assumed 2% RTP uncertainty at full power;
— Safety analysis assumed an initial power level of 102% RTP.

3.1.2. Revised safety case

The revised safety case:

— Rolling average power ≤ 102% RTP less assessed uncertainty in reactor power;
— Improved (statistical) method used for calculating the uncertainties.

3.1.3. Licensing application

The licensing application for the improved (statistical) method successfully demonstrated:

— Multiple levels of conservatism in the assessment of uncertainties;
— Multiple lines of defence against miscalibration of nuclear instrumentation.

3.1.4. Impact on design and operation

Impact on design and operation:

— Cold leg temperature held at the scheduled value; hot leg temperature rises slightly;
— The RTP is measured automatically by the secondary calorimetric calculation (SCCAL), which calculates the average over periods from 1min to 24 h;
— The main input parameters are feedwater flow, feedwater temperature, feedwater pressure and steam pressure;
— The nuclear instrumentation (power range flux, N16) is calibrated daily against the results of the SCCAL;

— If SCCAL is unavailable, readings are taken manually using the control room displays and entered into a spreadsheet application. An increased uncertainty is assumed for the manual calculation in comparison with the automatic calculation.

GLOSSARY

This glossary provides definitions for technical terms used in the report or otherwise applied to power uprating.

acceptance criterion. The acceptance criterion is the quantitative limitation of a selected parameter or a qualitative requirement set up for the results of accident analysis. Specified bounds on the value of a functional or condition indicator used to assess the ability of a system, structure or component to perform its design function.

accuracy. In process instrumentation, a number or quantity that defines a limit that error should not exceed when a device is used under specified operating conditions. Error represents the difference between the measured value and the standard or ideal value.

analytical margin. An analytical margin contains an estimate of individual modelling or overall code uncertainties, representation uncertainties, numerical inadequacies, user effects, computer/compiler effects and data uncertainties on the analysis of an individual event. This shall be determined either by a conservative calculation or by a best estimate calculation plus uncertainty evaluation.

anticipated operational occurrence (AOO). An operational process deviating from normal operation which is expected to occur at least once during the operating lifetime of a facility but which, in view of appropriate design provisions, does not cause any significant damage to items important to safety or lead to accident conditions.

benchmark. A set of parameters that can be measured for a plant or plant item under a defined set of circumstances which are representative of the condition or performance of the plant or plant item. Subsequent measurements can then be taken under the same set of circumstances to determine any change (deterioration) in condition or performance.

calibration. The process of adjustment, as necessary, of the output of a device such that it responds within a specified tolerance to known values of input.

Crossflow. Trade name of an ultrasonic cross-correlation flowmeter manufactured by AMAG Inc. and distributed by Westinghouse. This is one of the two, and the only non-intrusive type of flowmeters, approved by the NRC for MUR uprating.

design basis event (DBE). Conditions against which an NPP is designed according to established design criteria, and for which the damage to the fuel and the release of radioactive material are kept within authorized limits.

design margin. Variations in parameters (or additional performance capability) above required system parameters, specified by a system designer to account for uncertainties in design details, and for the inherent limitations of analytical methods that are employed in the design process. Design margins are managed throughout the design process and documented in the engineering calculations.

drift. An undesired change in output over a period of time, which is unrelated to the input, environment or load.

event sequence. A combination of events starting from a postulated initiating event and including any additional failures which may occur.

instrument channel. An arrangement of components and modules as required to generate a single protective action or indication signal that is required by a power plant condition. A channel loses its identity where single protective action or indication signals are combined.

leading edge flowmeter (LEFM). Transit time ultrasonic flowmeter manufactured by Caldon Inc. The multipath, spool piece model known as Check+ has been approved by the NRC for MUR uprating.

licensing margin or safety margin. Licensing margin is the difference, in physical units, between a threshold that characterizes an acceptance criterion and the result provided by either a best estimate calculation or a conservative calculation. In the case of a best estimate calculation, the uncertainty band must be taken into consideration.

margin. An additional allowance added to the instrument channel uncertainty to allow for unknown uncertainty components. The addition of a margin moves the set point further away from the analytical limit or nominal process limits.

operational limits and conditions. A set of rules setting forth parameter limits and other constraints that ensure the functional capability and the performance levels of equipment for the safe operation of an NPP.

postulated initiating event. An event identified during design as capable of leading to anticipated operational occurrences or accident conditions. (It is the starting point of an event sequence. It may be a direct plant fault or an event caused by an internal or external hazard or by human action.)

safety limit. A limit on operational parameters within which a licensed nuclear facility has been shown to be safe.

safety margin. The safety margin is the distance between an acceptance criterion and a safety limit. If an acceptance criterion is met, the available safety margin is preserved.

set point. A predetermined value at which a device changes state or interacts to indicate that the quantity under surveillance has reached the selected value.

shutdown event sequence. An event sequence for which reactor shutdown is the required safe state.

span. The region for which a device is calibrated and verified to be operable.

steady state. A characteristic of a condition, such as a value, rate, periodicity or amplitude, exhibiting only a negligible change over an arbitrary long period of time.

surveillance. The activity of checking a system or device to determine if it is operating within acceptable limits.

uncertainty. The amount to which a parameter of interest is in doubt (or the allowance made) due to possible errors either random or systematic that have not been corrected for. The uncertainty is generally identified within a probability and confidence level.

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