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Non-baseload Operation in Nuclear Power Plants: Load Following and Frequency Control Modes of Flexible Operation

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NON-BASELOAD OPERATION IN NUCLEAR POWER PLANTS: LOAD FOLLOWING AND FREQUENCY CONTROL MODES OF FLEXIBLE OPERATION

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IAEA NUCLEAR ENERGY SERIES No. NP-T-3.23

NON-BASELOAD OPERATION IN NUCLEAR POWER PLANTS: LOAD FOLLOWING AND FREQUENCY CONTROL MODES OF FLEXIBLE OPERATION

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FOREWORD

One of the IAEA's statutory objectives is to "seek to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world." One way this objective is achieved is through the publication of a range of technical series. Two of these are the IAEA Nuclear Energy Series and the IAEA Safety Standards Series.

According to Article III.A.6 of the IAEA Statute, the safety standards establish "standards of safety for protection of health and minimization of danger to life and property". The safety standards include the Safety Fundamentals, Safety Requirements and Safety Guides. These standards are written primarily in a regulatory style, and are binding on the IAEA for its own programmes. The principal users are the regulatory bodies in Member States and other national authorities.

The IAEA Nuclear Energy Series comprises reports designed to encourage and assist R&D on, and application of, nuclear energy for peaceful uses. This includes practical examples to be used by owners and operators of utilities in Member States, implementing organizations, academia, and government officials, among others. This information is presented in guides, reports on technology status and advances, and best practices for peaceful uses of nuclear energy based on inputs from international experts. The IAEA Nuclear Energy Series complements the IAEA Safety Standards Series.

This report in the Nuclear Energy Series provides collective guidance for decision making in and implementation of non-baseload (flexible) operation in Member States. This guidance is intended to address relevant aspects of non-baseload (flexible) operation of nuclear power plants, as well as to share knowledge on the challenges and reasons for such operation, based on current knowledge and operational experience.

For commercial, technical and regulatory reasons, most existing nuclear power plants are optimized to operate at steady full power, known as baseload operation, because it is generally considered to be the most efficient use of capital investment. However, in a few Member States, the nuclear units are operated flexibly, and in several Member States, there is an increasing need to operate nuclear units flexibly, especially in those installing a nuclear power plant for the first time. The primary reasons for this are a large nuclear generating capacity relative to the total capacity, growth in renewable energy generation, and deregulation or structural changes of the electricity supply system and the electricity market during the long operating lifetime of a nuclear power plant. These necessitate technical and regulatory changes, and also operational, economic and financial rearrangements, to maintain the efficiency of capital investment.

The feasibility of flexible operation and a resultant decision that is agreed to by all stakeholders as to whether the nuclear power plant should be operated in a flexible or baseload mode can be influenced by several factors. Technically, newly built nuclear power plants have an advantage in that the planning and design of a plant have generally had flexible operation in mind. However, these systems need to be validated during initial startup testing, and any limitations have to be determined at the beginning of operations. Additionally, the operating licence application (safety case) could be developed to support flexible operation.

Conversely, the nuclear power plants that have previously operated only in a baseload mode, and are now considering flexible operation, face a more complicated situation. Depending on the plant design and the extent of flexibility requirements, modifications to the plant may be required to support frequency control and load following operations. Licensing changes may also be required, and existing operation and maintenance philosophies may need adjustment to support flexible operation. Commercially, the deviation from baseload operation has to be considered within the electricity market framework, to minimize, eliminate or compensate for the impacts of flexible operation on the efficient use of capital investment while serving the overall energy structure needs. This publication discusses all these aspects of design or operation of nuclear power plants in flexible mode based on existing knowledge and experience.

The IAEA expresses its appreciation for the generous contributions from many Member States, and is grateful to all contributors listed at the end of this publication, particularly, P. Clifford, N. Kumar, P. Lebreton, H. Ludwig, T. Salnikova and D. Ward, in addition to V. Alexeeva of the IAEA. The IAEA officer responsible for this publication was A.N. Kilic of the Division of Nuclear Power.

EDITORIAL NOTE

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

At present, there are no direct and economical methods for storing electrical energy on a large scale; therefore, all electrical power systems currently require the generation of electrical energy to be adjusted continuously so that it closely matches the variable demand, in order to stabilize system frequency. If the electricity generated is insufficient to meet the demand, the system frequency will decrease; if the electricity generated exceeds demand, the frequency will increase. This balancing is achieved by increasing or decreasing the electrical output of individual generating units, so that the total electricity generated matches the variation in total electricity demand. Some generating units need to be able to change electrical output rapidly (within a few seconds), and others may only need to change electrical output slowly (from a few minutes to a few hours). This adjustment of electrical output under the control of the grid system operator will depend on the variation in the mismatch between energy generation and demand. The adjustment may be required frequently (several times a day) or rarely (from once or twice a year to a few occasions in the lifetime of a power plant). It may also be necessary to change the electrical output of certain generating units to control power flows on the transmission system. In particular, in countries that have an electrical power transmission system that is connected to those of other countries, it is necessary to adjust the electrical power generated in order to control electrical power flows across the interconnections.

In balancing the generation and demand and controlling power flows, it is customary, in electrical power systems consisting of a spectrum of units utilizing different fuel sources for electrical generation, to operate the generating units in commercial/financial merit order, to minimize the overall operating costs. The generating units with the lowest marginal cost (generally the lowest fuel cost) are therefore operated at full power as much as possible. Generating units with higher marginal costs (higher fuel costs) are operated with reducing/ceasing electrical output at times of low electrical demand, or operated partially loaded, to increase or decrease generation when requested. Such units change power either automatically on signal or manually on instruction, as needed, thus providing ‘reserves’. In this balancing, some generating units in an electrical system are operated continuously at steady full rated power as much as possible, and are available 24 hours per day, 7 days per week. This mode of operation is termed ‘baseload operation’. In this publication, the term ‘flexible operation’ is used to describe any mode of operation that is not baseload, specifically focusing on changing electrical output to match generation with demand on the electrical grid system. In flexible operation, the electrical output of a generating unit can be adjusted, either automatically or manually, to meet the technical requirements and/or commercial agreements in order to control the frequency and power flows of the electrical system. In flexible operation mode, a nuclear unit may spend prolonged periods operating at less than full load. It is not necessary for all the generating units to operate ‘flexibly’, or to have the same capability for flexible operation, provided that there is sufficient aggregate ‘flexibility’ among all the generating units on the electrical system to allow electricity generation and demand to remain matched at all times.

Nuclear power plants have relatively low marginal costs, and so, in most Member States, nuclear generating units are operated in baseload mode. Consequently, the majority of existing operating plants do not have the need for or experience of operating flexibly, because they have been operated at steady and continuous full rated power, except when it is necessary to reduce power or to shut down for maintenance and refuelling, or for other operational or safety reasons. In the electrical systems where nuclear power plants are operated in baseload mode, other generating units (e.g. hydroelectric, coal, oil or gas fired) operate flexibly as required, to balance generation and demand.

In the early years of nuclear power, some owners/operators of nuclear units considered and requested designs with capabilities, and performed tests, for flexible operation. They also carried out a limited amount of load following operation, as reported in the literature [1–5]. Nevertheless, since that time, the majority of nuclear power plants have operated at baseload, and have optimized their plant and equipment for operation in that mode. However, there is a recent and increasing need in some Member States for nuclear power plants to operate flexibly. This need has arisen primarily either because nuclear generation has become (or will soon become) a large percentage of the total energy generation or because there has been the introduction and significant growth of other forms of energy generation that are not readily controllable (or have lower marginal costs), including the variable and intermittent forms of renewable energy such as wind turbines and solar photovoltaic panels.

Some Member States, such as France and Germany, have already needed to design or convert the majority of their nuclear power plants for flexible operation. Plants in those Member States have been designed or modified and have operated flexibly, and many reactor-years of experience and knowledge of flexible operation have been collected. This experience and knowledge is a beneficial resource for the nuclear industry in understanding the requirements, needs, challenges, solutions and lessons learned in order to make an informed decision on whether to build nuclear power plants for flexible operation or to convert existing plants from baseload to flexible operation.

1.2. OBJECTIVE

This publication aims to address all relevant aspects of flexible operation of nuclear power plants, specifically focusing on changing electrical output to match electrical demand and controlling the frequency of the electrical system, termed 'load following' and 'frequency control', respectively. It is intended to provide collective guidance, based on current knowledge and operational experience, for decision making in and implementation of flexible operation in Member States which are considering future flexible operation of their nuclear power plants.

1.3. SCOPE

This publication describes possible reasons why flexible operation of nuclear power plants may be required, and the various types of flexible operation that may be needed. These considerations would apply to any form of energy generation, including nuclear, independent of the technology involved. Further guidance is provided on what selection criteria to consider, what steps to take for feasibility studies and the decision making process, and what operational experience is available in the planning, design, licensing and operation phases. The technical issues that have been identified during flexible operation and any other foreseen plant challenges related to flexible operation of current reactor technologies are also discussed. Brief discussions of potential alternatives to flexible operation are included, as well as considerations of economic factors.

Technical issues that might arise with flexible operation of developing reactor technologies, such as fast breeder reactors, or novel small modular reactors (SMRs) are not within the scope of this publication. Flexible operation of SMRs will be discussed in a future document.

Nuclear reactors are used as the power source in many submarines and some large ships. These reactors necessarily need to change power output rapidly when required, and there are many reactor-years of experience worldwide of such flexible operation. However, the design of such reactors is different from those used for electrical power production, and that experience is not discussed here.

This publication is not intended to endorse or to invalidate the non-baseload mode of operation; rather, it is intended to provide Member States with an understanding of the reasons for operating nuclear units flexibly in a safe and efficient manner with quality and reliability — and of the challenges with, and solutions for, doing so. It is intended to lead to informed decisions on whether nuclear power plants need to operate flexibly, and to guide Member States in implementation of flexible operation in their plants, or in preparation of remedial actions for when the need for flexible operation arises, including the technical, operational and economic changes necessary.

The intended users of this publication are organizations involved in decision making regarding flexible operation of nuclear power plants or in implementing it in the Member States which are considering flexible operation. This includes Member States designing or building plants, and those considering flexible operation of existing plants that do not currently operate flexibly. Thus, the users of this publication may include the entities that are designing, providing, constructing, installing, maintaining, modifying and operating the nuclear power plants and the grid or are performing licensing and oversight of nuclear and grid governance. The following are foreseen as users:

— Utilities and plant owners/operating organizations;
— Architect–engineers/designers and technical support organizations;
— Regulatory bodies (nuclear and grid);
— Grid system operators;
— Energy planners (at governmental or utility levels).

This publication can be used as general guidance on understanding the characteristics of flexible operation and on determining whether nuclear power plants need to operate in non-baseload mode. It also can be used as a road map for deciding on and achieving necessary flexible operation in plants if that is deemed a necessity. This guidance and road map include considerations for new plant projects and also transition of existing baseload plants, and provide key aspects of plant design and configuration for flexible operation.

Users who are deciding whether to switch to flexible operation at their nuclear power plants could refer to Sections 2–4 to establish plant and grid needs for flexible operation. Section 5, for which the main intended audience is technical and operational staff, describes the technical and operational aspects of implementing a certain degree of flexibly operating plants.

As the implementation of flexible operation involves costs and benefits, the economic considerations in Section 6 may provide basic elements and models for financial and economic analysis. It is recommended that users refer to the sources of the information provided in this publication to expand on and utilize the topics discussed herein.

The aspects associated with the flexible operation of plants considered in this publication are not comprehensive of all needs, challenges and possible solutions, but are rather key concepts that could be taken into account, based on the current operational experience and technical and administrative fundamentals. Further, this publication is not intended as detailed and prescriptive implementation guidelines for achieving flexible operation in nuclear power plants. It is rather descriptive, covering major technical, managerial and economic topics, important milestones, and roles and responsibilities of stakeholder involvement in the process. The guidance provided is supplemented by specific examples of plant flexible operation from operational experience, as well as good practices and lessons learned. The IAEA, however, does not attest to the completeness and applicability of the examples of specific cases, which require validation and verification by users.

1.4. STRUCTURE

The main body of this publication is divided into seven sections. The annexes supplement the main text with examples, illustrations, case studies and specific discussions.

Section 2 defines and describes the various types of flexible operation that might be employed to meet electricity system needs. Section 3 explains why it may be necessary for some generating units to operate flexibly, why the majority of existing nuclear units presently do not operate flexibly and why they might need to do so in future. It also reviews some potential alternatives to flexible operation.

Section 4 provides a comprehensive discussion on whether to implement flexible operation in nuclear generating units and how to determine the feasible type and extent of flexibility. The roles of stakeholders in the decision making process are also discussed.

Section 5 discusses the main technical and operational issues that are important for flexible operation as they affect the common nuclear power plant design and technologies and operational programmes and procedures. It describes, from operational experience and fundamentals, aspects of flexible operation implementation in nuclear power plants.

Section 6 discusses the economic considerations related to flexible operation, focusing on associated costs and benefits at the plant, generation portfolio, grid and economy wide levels.

Annexes I and II provide details of practised methods and associated impacts, issues and possible solutions, with specific examples, for original design for flexible operation (German case study) and baseload to flexible operation conversion (French case study), respectively. These case studies illustrate the operational experience regarding various aspects of accomplishing specific levels of flexible operation or unique approaches to management of nuclear power plant flexibility. However, these do not endorse or suggest applicability to all cases, which require users to validate, verify and adapt them to their specific conditions. Annex III, therefore, gives some examples from the experiences of Member States concerning whether (or how) to operate nuclear units flexibly and the evolution of their decision making processes to illustrate methods of validation, verification and adaptation to accomplish or manage flexible operation of nuclear power plants. Finally, Annex IV provides a preview of the IAEA economic model to quantify the cost–revenue aspects for nuclear power plant operation in mixed energy systems, including flexible operation.

A glossary of specific terms and a list of abbreviations used are also provided in this publication.

2. NUCLEAR POWER PLANT BASELOAD AND FLEXIBLE OPERATION CONCEPTS

It is necessary for some generating units to vary their electrical output, to allow total generation on an electrical system to match the changing electrical demand. In doing so, some generating units contribute at constant output at their full rated power, while others vary their electrical output. In simple terms, the baseload operation of a generating unit refers to operation at steady full rated thermal power (RTP) and full rated electrical output (REO), while flexible operation refers to any change from baseload operation in interfacing with the grid (to meet the requirements of the electricity system in balancing generation and demand).

For reasons that are discussed in Section 3, electrical grid systems require the output of generating units to be adjusted so that total generation increases/decreases to match variations in electrical demand during the day, not only hour by hour, but also minute by minute, even second by second (Fig. 1).

Figure 2 illustrates the definitions of baseload and flexible operation for nuclear power plants and also possible types. The following sections describe these in detail.

2.1. BASELOAD OPERATION OF NUCLEAR POWER PLANTS

Baseload operation of a nuclear power plant refers to operation at steady full RTP/REO. Power is reduced or shut down only when required for refuelling and/or periodic maintenance (i.e. planned); urgent maintenance to correct plant equipment issues (i.e. unplanned); or unexpected design and/or safety constraints. In other words, in baseload operation mode, reduction in power output is induced by the plant operator's needs, rather than the grid system operator's needs. Most nuclear power plants in Member States are operated in this way, where the grid system operator is able to balance electricity generation with demand and control the electrical system frequency without the need for plants to deviate from full RTP and REO.

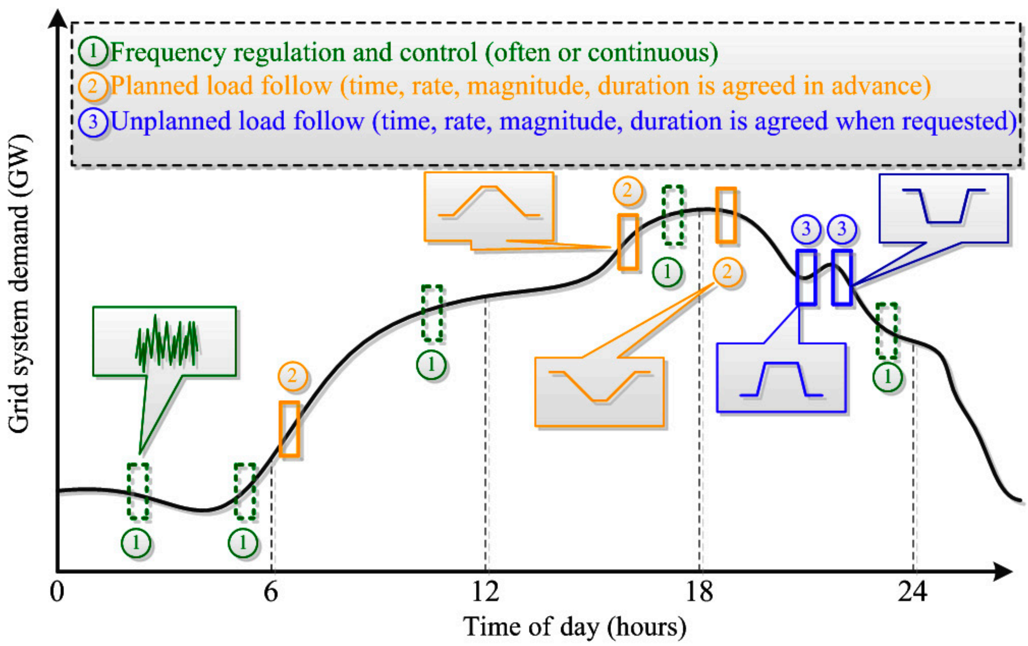

FIG. 1. Basic concept of daily flexible operation.

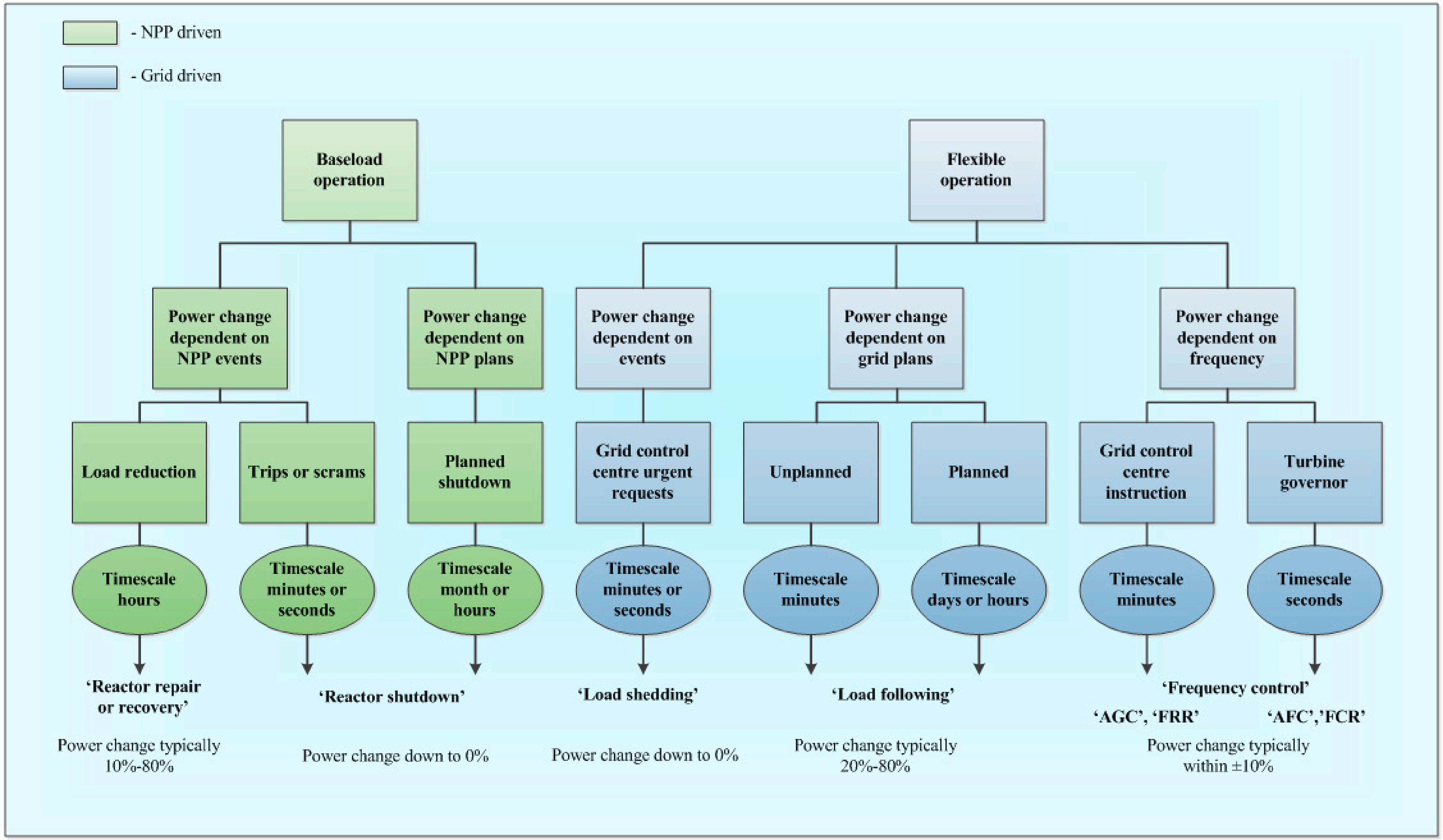

FIG. 2. Definition of load changes under baseload and flexible operation. AFC — automatic frequency control; AGC — automatic generation control; FCR — frequency containment reserve; FRR — frequency restoration reserve; NPP — nuclear power plant.

From the perspective of the plant owner/operator, it is usually preferable to operate in steady full load (full RTP/full REO, i.e. baseload) mode as much as possible, and not to operate flexibly [3], because it is generally considered the most efficient use of capital investment. There are several reasons for this, including:

- Constant thermal/electrical power operation is easier with fewer changes in plant condition.
- Nuclear power plants have high capital costs, but relatively low variable costs (fuel costs), so operating plants at full load minimizes the average operating cost of nuclear generation.
- Baseload operation may lead to more efficient utilization of nuclear fuel as the thermal output during a fuel cycle is better predicted and core design is optimized.
- Design and licensing of plants are simpler for operation at constant load, as degradation in design and safety margins as plant ages vary more predictably and can be better anticipated during the design.
- Non-baseload operation may require increased maintenance and monitoring, and may complicate the reliability and ageing assessments of some systems, structures and components (SSCs).

However, from the perspective of the electricity system as a whole, and also the grid system operator, it may be preferable for nuclear power plants to operate flexibly, when needed by the system, for the reasons discussed in Section 3.

2.2. FLEXIBLE OPERATION OF NUCLEAR POWER PLANTS

In this publication, flexible operation of a nuclear power plant refers to any change from baseload operation to meet the needs and requirements of the electrical grid system. Operating any generating unit flexibly implies operation with power manoeuvres at levels less than the RTP, so the total amount of electrical energy output is less than if the unit operates at baseload.

Flexible operation mode may include load following, frequency control or other actions to voluntarily change the power output of the plant, based on the duration and periodicity of power changes. The extent of the plant's response may vary for each mode, as well as the operating parameters associated with the power change and its duration and periodicity.

2.2.1. Load following

Load following means to change the generation of electricity to match the expected electrical demand as closely as possible. A generating unit is said to be load following when its output is varied, either in a planned way, or in response to instructions or signals from the grid control centre, to allow generation to match demand. The variations in output may be large or small, and may be frequent or infrequent. References [1, 2] compare planned or unplanned load following for generating units, and discuss the advantages and disadvantages of both modes.

A nuclear generating unit providing a load following service of either type (as described below) must be able to operate stably at constant power at any power level between RTP/REO and a defined minimum power level. It also needs to be able to ramp power up or down at a defined rate between any two power levels within this range.

2.2.1.1. Planned reduction or increase in power

Planned load following might include reducing the electrical output and associated thermal power when electrical demand is low and increasing generation when the demand increases. The operator of a nuclear generating unit may choose to operate in this way, based on plans prepared by generation planners. Such changes in electrical generation may be planned weeks or days in advance. The planned changes in electrical output must be within the plant capabilities in terms of number, speed and size of power manoeuvres. They are executed and controlled by the plant reactor operators, who have direct control of the magnitude and speed of any changes in thermal power and electrical output.

2.2.1.2. Unplanned (instructed or requested) reduction or increase in power

Unplanned load following requests may come from the grid system operator or from the generation planner of the owner/operating organization. This would normally mean starting to respond within a few minutes of a request, and achieving a significant change in electrical output (and associated thermal power) quickly, typically within 10−20 minutes. Sometimes, the grid system operator may give advance warning of the need for a power change, or specify a slower or faster change in electrical output. Plant reactor operators initiate, execute and control the change in power output based on the request. A plant operator could also refuse a request if it could place the plant outside its accepted capabilities and agreed envelope of operational parameters, or if it is precluded by the plant equipment conditions. More importantly, the plant operator would reject the request if it could place the unit at risk for safety and reliability.

Actions in response to instructions/requests from the grid system operator may occur several times per day. Reactor operators do not know in advance the amount and magnitude of power manoeuvres that they will be requested to make, although these can be estimated to a certain degree, based on the known typical behaviour of the electrical system. Nuclear generating units that can change power in this way contribute to the ‘replacement reserves’, ‘ancillary services’ and ‘balancing mechanisms’ [6, 7], which are defined in the glossary.

2.2.2. Frequency control

Frequency control means to adjust the electrical output to contribute to the control of the frequency of the electrical system within a predefined range. The minimum and maximum output limits for providing frequency control are different and much less, usually within ±10% of RTP, than the limits for the load following ranges. A nuclear unit that is providing frequency control could do this either when operating at constant power or while ramping.[1]

For the various modes of frequency control operation described in Sections 2.2.2.1–2.2.2.3 below, the reactor operators may not be in manual control of the changes of load if the reactor protection and control systems are designed and set for limiting the magnitude and rate of changes of electrical output to acceptable levels (except for the frequency control outside a specified frequency range, described in Section 2.2.2.2, where the change is initiated by the reactor operator). However, the reactor operator is, and has to be, able to manually intervene in any of these modes of operation if the behaviour of the plant becomes unacceptable.

It should also be noted that the nuclear regulatory bodies in some Member States may only permit changes of reactor power that are initiated and controlled by a licensed reactor operator. In these Member States, frequency control might be permissible only outside a specified frequency range mode of operation, described in Section 2.2.2.2. Under these regulations, the other modes of frequency control described below may not be permitted, or they may be strictly constrained.

The frequency control function can include any or all of the following.

2.2.2.1. Continuous frequency control

Controlling the frequency continuously means controlling the reactor power output automatically and continuously, so that the generated electrical output increases when the system frequency falls, and decreases when the system frequency rises. This is termed automatic frequency control (AFC) or automatic frequency responsive operation.

The variation in system frequency normally comprises continuous, small and gradual changes and infrequent, abrupt large changes when a large generating unit trips or a fault on the grid system disconnects a large generating unit or a substantial amount of electrical demand. The likely magnitude of power (load) changes that will be required when operating in AFC mode can be estimated in advance, based on the known typical behaviour of frequency on that electricity network.

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[1] Depending on the design and operational requirements and margins, there may be technical or procedural restrictions on performing frequency control while ramping (e.g. a restriction to have one power manoeuvre at a time) or while operating at reduced power (e.g. restricted manoeuvres to avoid perturbations in the reactor parameters to stay within the operational limits).

The behaviour of system frequency varies among networks. The range and speed of variation of frequency is generally significantly greater on isolated small electricity networks than on large interconnected electricity networks. Generating units that are operated in AFC mode contribute to the frequency containment reserve (FCR), which is discussed in Section 3 and defined in the glossary, and need to be able to respond to changes in frequency in timescales of seconds (for smaller electricity networks) or tens of seconds (for large electricity networks).

2.2.2.2. Frequency control outside a specified frequency range

Controlling the frequency outside a specified frequency range refers to reducing the generated electrical output at a defined rate when the system frequency goes above a maximum limit, or increasing the output at a defined rate when the system frequency goes below a minimum limit. This change in output could be instead of, or in addition to, AFC, as described above. The change in output could be initiated automatically, or it could be initiated manually by the plant operator in response to a frequency deviation, usually indicated by an alarm.

Depending on the set limits of frequency, these actions could be frequent or rare events. Generating units providing this form of frequency control may need to be able to start to respond within a few seconds of the frequency limit being exceeded. Generating units that are operated in this way also contribute to the FCR.

2.2.2.3. Frequency control within a power range

Controlling the frequency within a power range refers to reducing or increasing the power output automatically, within a limited range, in response to a signal from the national or regional grid control centre or from the plant generation planner. This form of operation is also termed ‘automatic generation control’ (AGC). The operation of a nuclear unit in this way contributes to the frequency restoration reserve (FRR), as discussed in Section 3 and defined in the glossary. The timescale to initiate such changes of output is likely to be a few minutes (depending on the time for the signal to come from the grid control centre).

2.2.3. Other forms of flexibility

There are other modes of flexible operation, in addition to load following and/or frequency control, that are usually considered and provided for in the original design of existing technologies. These capabilities of flexibility are, however, based on predicated baseload operation with anticipated power transients/manoeuvres in the lifetime of a baseload plant. Although this design predication does not explicitly include the load following or frequency control that are defined above, some existing plant designs may have an implicit capability for a limited range of non-baseload operation that is not currently exercised. For example, most current plant technologies are designed to perform power manoeuvres in the range of 50−100% RTP, and can ramp power as fast as 5% RTP/min. However, these evolutions are not a part of normal daily operations, as the design philosophy is to have normal operations as baseload at 100% RTP.

In addition, depending on the design of the plant control and reactor protection systems, changes in electrical output may be decoupled from the reactor thermal power output, so that flexible changes in electrical power can be achieved while maintaining thermal power (or without shutting down the reactor). This feature may be inherent in the plant design, as explained in the following subsections.

2.2.3.1. Load shedding

Load shedding refers to a rapid power reduction required by the occurrence of a grid disturbance or a request by the grid system operator to prevent such a grid disturbance. The operators of the plant will not know in advance when such actions will be necessary, although the likelihood of such events can be estimated, and their occurrence is anticipated and incorporated in the design. Overall, such actions should be in response to rare events. For example, if one or more transmission circuits near a nuclear generating unit are switched out of service following a fault (e.g. a lightning strike), then power flows will increase on the remaining circuits. If this causes any of the circuits to exceed their rating, the grid system operator may require the plant operators to take immediate action to reduce output, to prevent overloading to avoid cascade tripping of other circuits, which could otherwise lead to a local or regional blackout. In some cases, when a circuit is switched out of service, there is a dynamic instability that leads to loss of synchronism between different parts of the transmission system, which may lead to a partial blackout of the system. Attempts by the grid system operators to avoid such losses of synchronism may include requesting generating unit operators to rapidly trip a generating unit or quickly reduce (cut back) the thermal/electrical output to a compensating level.

The nature of immediate actions that may be required (e.g. how much and how quickly to reduce output) and the circumstances under which they may be needed could be agreed in advance between the grid system operator and the plant owner/operator, taking into account the design and operational limitations. Whether there might be a need for such immediate actions following grid faults and disturbances also depends on the design and configuration of the transmission system around the plant, and may only arise following a fault during particular planned transmission circuit outages.

A cutback in electrical output still may be accomplished by maintaining thermal power or without tripping the reactor, depending on the design of plant control and reactor protection systems.

2.2.3.2. Design power transients

By design, nuclear power plants are generally able to stay in operation and connected to the grid during particular failures of grid or plant components. In these cases, plant control systems coordinate and adjust the relevant physical parameters (power, voltage, flows, etc.) to keep the generator synchronized and avoid tripping the reactor. These adjustments in response to design transients do not meet the definitions of load following or frequency response as provided above; however, they provide flexibility in electricity generation. Some examples of these designed flexibility features are:

— Most existing plants are designed to respond to and stabilize a limited magnitude of rapid ‘load rejection/reduction’ by reducing (cutting back) reactor power without a reactor trip, even if they do not have the capabilities for load following or frequency control as defined earlier. This could be acceptable and within the plant design basis, usually with a provision that such an event is rare (i.e. not a normal operation scheme).
— Most current technologies are able to withstand temporary dips in the high voltage on the grid (generally about 100–250 milliseconds long, corresponding to the duration for the grid protection to clear electrical faults on transmission lines). The unit returns to normal operation in a few seconds.
— When one redundant component of the plant’s conventional island fails (e.g. a train of a feedwater pump or a condensation pump), reactor controls rapidly reduce the reactor (thermal) power to an appropriately preset level (e.g. 50% RTP for loss of a feedwater pump) and continue power operation without a reactor trip. If the failed component/system can be returned to service within the allowable time limits for operation at an intermediate power level, then the unit can progressively return to full power operation.
— A quick and short duration of reduction in electrical output without changing the thermal power of the plant could be accomplished by ‘dumping’ (bypassing the turbine and directing some steam to the main condenser or to the atmosphere), if permitted. The net result is a reduction in electrical output, while remaining at or near full reactor power. This method requires that the SSCs are designed and configured for such situations (e.g. the main or auxiliary feedwater system with adequate capacity, the condenser with the capacity and capability to accept the dumped steam and valves to realign steam paths). These requirements are assessed during design, and any limitations in operation of SSCs in such configurations are established and incorporated into the plant design basis and the operating procedures.

2.2.3.3. Reactive power control

In order to control the grid system voltage, it is necessary for generating units to be able to control the reactive power (measured in megavars), either upon instruction from the grid system operator or automatically. The range of reactive power control that is required will depend on the design of the transmission system and the extent to which it uses other forms of reactive compensation such as controlled capacitors or inductors. The ability of a generating unit to control reactive power and voltage depends on the design of its generator (alternator), the generator’s excitation control system and the high voltage transformer connecting it to the transmission system. The range of reactive power control that a generator can provide is mainly specific to the design of the generator. The specifications of a generator, including the relationship of active and reactive power limits, are represented in a ‘generator capability diagram’ or ‘generator performance chart’, which is typically available to the operators in the main control room of the plant or indicated in standard documents (see, for example, the code provided in Ref. [7]).

The range of reactive power control that a generator can provide generally increases as the active power (measured in megawatts) is decreased from full load. The grid system operator may wish to utilize this relationship between the active and reactive power of the generator, and may instruct the operators of a generating unit to reduce the active power in order to provide a greater range of reactive power when this is needed. This can effectively be considered a specific additional form of flexible operation[2] due to local grid conditions.

As the reactive power control does not depend on the design of the nuclear island of a plant, it has no material effect on the operation of the nuclear reactor. It also does not affect nuclear safety unless the voltage supplied to the auxiliary equipment in the plant goes outside the permitted range for the equipment. Consequently, the capability of existing and new nuclear power plants to control reactive power and voltage flexibly is generally similar to that of large fossil fuel or hydroelectric generating units.

From the economic perspective, the cost of reducing the active power output on a few occasions per year may be cheaper than the cost of additional reactive compensation equipment; however, this needs to be considered on a case by case basis and confirmed by case specific cost–benefit analysis.

It should also be noted that one consequence of changes in electricity systems, such as the introduction of a large amount of new generation sources, is that there can be large changes in power flows. This can cause a large change in the reactive power that individual generating units have to provide. Operation at maximum lagging reactive power, which corresponds to maximum excitation current on the rotor and maximum stator current, could lead to increased vibration of the generator rotor and of the stator end windings. Hence, a generating unit that has previously only provided small amounts of reactive power may experience new operational problems, emphasizing that this is a potential commercial risk, and not a nuclear safety issue.

2.2.3.4. House load operation

For a generating unit, house load operation is a mode in which the unit is not connected to the grid system, and a small part of the rated capacity is generated to supply only the auxiliary loads of the plant. This operating mode is mostly triggered by a transmission system or by a power substation failure (e.g. a low voltage detected at a high voltage grid connection point or a line protection fault) or an equipment failure (e.g. a pump trip due to a frequency perturbation). The ability of a nuclear unit to reduce to house load operation allows the reactor to stay at power during temporary grid issues.

In this mode of operation, when a small fraction of the RTP is adequate for providing electrical power to plant loads, a typical nuclear unit reduces the thermal power to low levels, at around 20−30% RTP, without shutting down the reactor, and the excess thermal energy is discharged, for example, to the condenser (or atmosphere, if permitted) without conversion to electricity. House load operation capability is useful for performance and for safety aspects because:

— It provides an alternative electrical source different from the grid system and from the internal (on-site) sources (e.g. emergency diesel generators or batteries);
— It keeps the reactor at power mode (i.e. without a hot or cold shutdown), so it can return to full power operation fairly quickly once the transmission system connection is restored.

Some existing nuclear power plant technologies have this capability, while others do not. Even for the plant technologies with house load operation capability, there may be a time limit, generally of a few hours, for a house load operation period due to constraints on the plant design and operation parameters of systems and components, such as the condensation system capacities, reactor power distribution limitations or protection system restrictions.

[2] This is not a common practice, but nuclear power plants in at least one Member State have occasionally been requested by the grid system operator to reduce active power in order to increase the reactive power capability, although the plant is not load following as defined in Section 2.2.1.

3. REASONS FOR FLEXIBLE OPERATION OF GENERATING UNITS

As mentioned previously, all electrical grid systems require the output of generating units to be adjusted so that the total generation changes to match variations in demand during the day. Controlling the total generation is equivalent to controlling the system frequency, as any imbalance between generation and demand will cause the frequency to rise or fall. A stable system frequency is a common good for all users of the electricity system — although it is presently not a traded commodity.

Large system frequency variations (caused by large imbalances between generation and demand) may jeopardize electrical equipment, including equipment at the nuclear power plant, in terms of maintaining stable and reliable operating conditions. For example, when the frequency decreases or increases, it may change the reactor coolant pump speed, which then affects the coolant flow through the core and the core power distribution, together with the temperature variation along the core. This may cause the power distribution limits in the reactor core to be reached, resulting in an automatic reactor shutdown (i.e. a reactor trip). Therefore, as discussed in detail in Ref. [4], a stable and reliable electricity system is very important for plant safety equipment and systems.

An unstable and unreliable 'weak' grid system may also increase the number of reactor trips and the probability of loss of off-site power directly affecting plant safety evaluations. Hence, it is essential to continuously adjust generation and power flows to balance the electricity system and to control the frequency, in order to maintain stability and reliability. As such, the amplitude and duration of system frequency deviations must be limited.

In most electrical grid systems, the control of generation, to balance it with demand, and the control of system frequency, is ultimately the responsibility of the grid system operator. This entity monitors the system and issues instructions from the grid control centre in order to control generation, power flows and system frequency. Thus, the grid system operator needs to continuously monitor and also properly forecast the variations in electricity generation and demand at all times, in order to maintain a stable electricity system. However, in this process of forecasting and monitoring, variations continuously occur in the system mainly due to errors in the electricity generation–demand forecast; abrupt variations/cessations in the electricity generation–demand, including unexpected tripping or disconnection of generating unit(s), connection of small generating units at the distribution level or as an impact from a public event; or transmission system perturbations.[3]

Stabilization of the grid system is mostly achieved by control of the generation (although it can also be enhanced by additional management of demand, when possible). This necessitates that a sufficient number of generating units are available to change the electrical output (i.e. to operate flexibly), either automatically or on request (verbally or by signalling) from the grid system operator to control the system frequency. Such flexible operation generating units contribute to the FCR, FRR and replacement reserve.

3.1. REASONS FOR FLEXIBLE OPERATION OF ANY GENERATING UNIT

3.1.1. Electricity demand variation

The electricity demand on an electrical power system varies for several reasons. The particular details of the demand variation may be different in each Member State, but there are a number of common characteristics and behaviours for all grid systems.

The main variations in electricity demand depend on the time of day, day of week, time (season) of year and weather conditions:

[3] Based on experience with predicted and actual imbalances in some Member States, approximately two thirds of the difference in generation and demand is due to forecast errors, while the other third is mainly due to random technical issues on generation and to the design of the balancing mechanism.

— *Time of day.* Electrical demand is lower at night than during the day; in many Member States, the minimum electricity demand at night is typically in the range 60–80%[4] of the maximum electricity demand during the day. Figure 3 illustrates a typical example: daily electricity demand in Great Britain. As shown, there is a large increase in demand over a couple of hours in the morning after sunrise, and a similar but slower decrease in demand in the late evening. There may be one or more peaks in demand during the day.

— *Day of week.* Variation in demand also depends on the day and, especially differs between work and non-work days. Demand is generally lower on weekends and public holidays than on working days, as illustrated in Fig. 4, based on UK data. In some Member States, the demand is particularly low on certain public holidays.

— *Time of year (season/climate).* The detailed shape of the daily and weekly changes in demand also varies during the year. In colder climates (e.g. northern Europe), electricity demand is significantly lower in summer than in winter (see also Fig. 5, which shows a comparison of the daily demand for winter and summer in Great Britain). The minimum night-time electricity demand during weekends in summer can be as low as one third of the peak daytime demand in winter (e.g. in 2013, the minimum electricity demand in the UK, which occurred at night-time in summer, was 33.7% of the yearly peak demand, which occurred in winter daytime). In warmer climates (e.g. southern Europe, southern USA or southern Japan), the seasonal variation is less; the demand in summer can be as high or higher than winter demand, with slightly lower demands in spring and autumn.

— *Weather conditions.* The variation in electricity demand with time of day, day of week and time of year is modified by changes in the weather conditions, including ambient temperature, wind speed, precipitation and cloud cover. The effects of weather conditions differ among regions and their climates. Generally, in winter or in colder climates, the demand tends to be higher than average on days that are colder than average, with the highest demand occurring on cold, wet, cloudy and windy days. By contrast, in summer or in warmer climates, the demand tends to be higher than average on days that are hotter than average, with the highest demand occurring on hot, sunny and windless days.

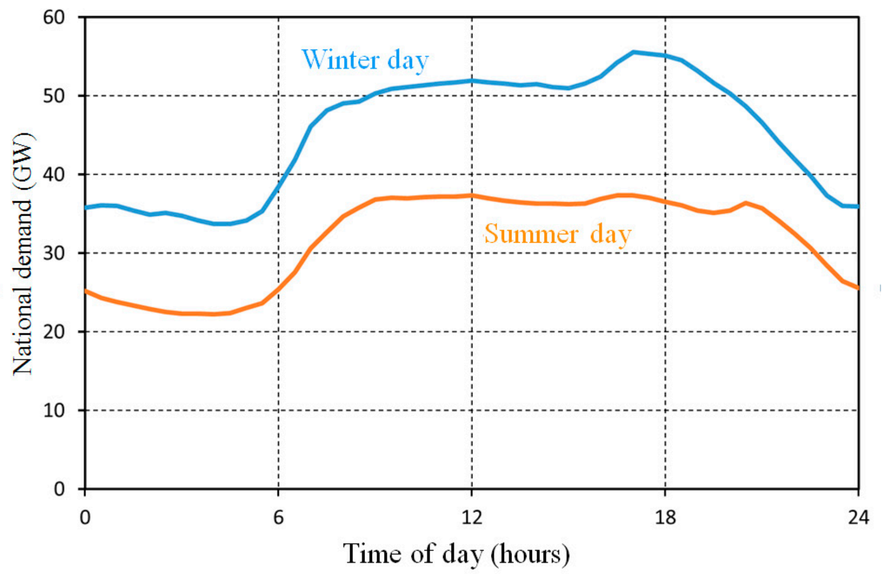

FIG. 3. Typical variation in electricity demand throughout a day in Great Britain. Data for Great Britain was used (excluding the data for Scottish grid) (courtesy of D. Ward, reproduced from Ref. [8]).

[4] A typical value in the UK is around 60%. In France, it is around 70−80%, and in Spain and Scandinavian countries, it varies over a range of 60−80%.

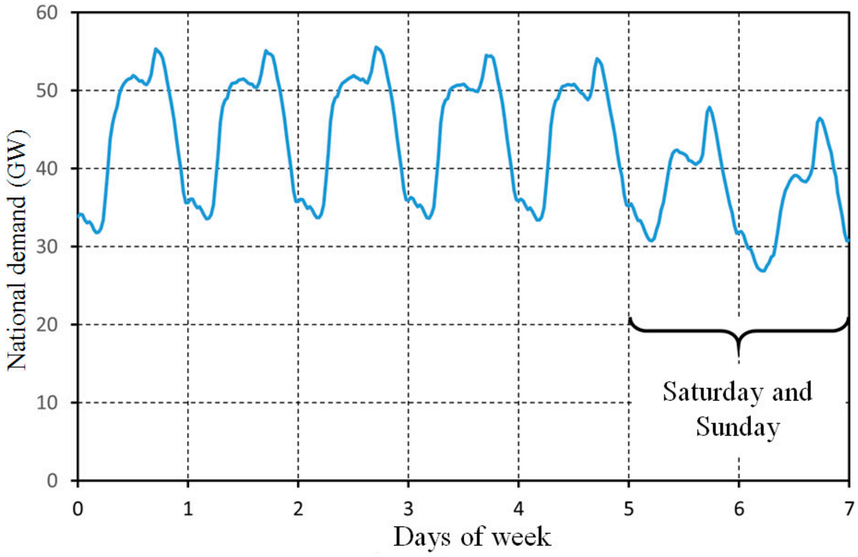

FIG. 4. Typical variation in electricity demand throughout a week in Great Britain. Data for Great Britain was used (excluding the data for Scottish grid) (courtesy of D. Ward, reproduced from Ref. [8]).

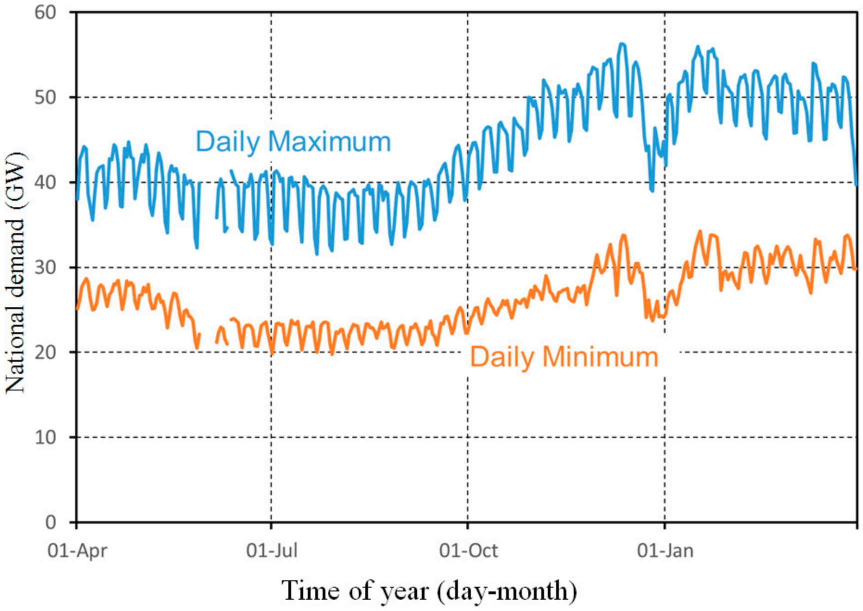

FIG. 5. Typical variation in electricity demand throughout a year in Great Britain. Data for Great Britain was used (excluding the data for Scottish grid) (courtesy of D. Ward, reproduced from Ref. [8]).

The magnitude of seasonal and weather related demand change also differs from one Member State to another within the same region or electricity grid system. Figure 6 illustrates the variation of monthly electricity consumption in various Member States in European systems in 2010. As can be seen, the electricity consumption variation was much more significant in France, ranging from just over 30 TW·h in summer to nearly 60 TW·h in winter, compared to, for example, that of Spain.

In response to these variations, the generating units in an electricity system are operated in various load modes in order to meet the daily or weekly variations in electricity demand, as illustrated in Fig. 7. Some generating units operate at constant full output throughout the 24 hours of every day of the year (baseload), while other generating units routinely reduce output or shut down at night or on weekends and start up or increase generation again in the morning (load cycling or load following), and some may only operate for short periods (peaking) at the times of highest demand. If the variation in electricity demand is well predicted, the main load cycling for generating units

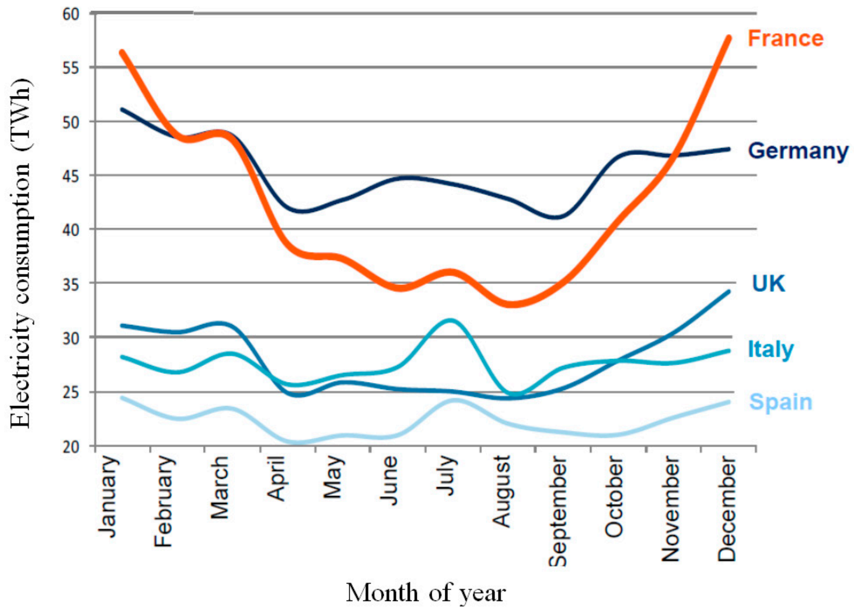

FIG. 6. Variation in electricity demand throughout the year in some European Union countries in 2010 (courtesy of F. Farruggia, Électricité de France, reproduced from Ref. [9]).

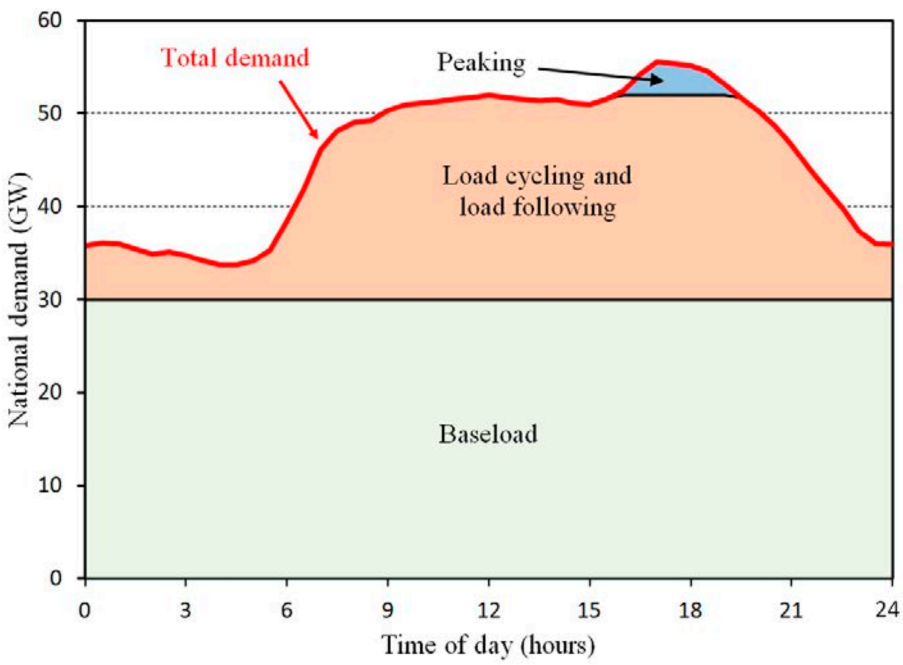

FIG. 7. Conceptual example of baseload, load following/cycling and peak generation.

can be planned and scheduled in advance. As such, the generating units doing load following do not necessarily need to change output rapidly, and a timescale of 1–2 to plan and execute power adjustments is often sufficient.

The time dependent and weather dependent variations in demand can be predicted; in many Member States, the grid system operators are able to forecast demand a day ahead to within 1–2% accuracy. However, in addition to those, largely predictable, time dependent variations in electricity demand, there are smaller random variations in demand that can be observed as unpredictable random changes in system frequency. Such smaller magnitude random variations, in timescales of minutes and seconds, are inevitable in a complex generation–transmission–demand network, and they are hard to quantify and to incorporate into the forecast. However, they can be monitored, and appropriate compensations estimated.

There may also be occasional, though rare, large magnitude random changes in system frequency caused by large and sudden imbalances between generation and demand. For example, a sudden trip of a generating unit, or a grid event disconnecting some generation or demand, will cause a rapid and usually large step change in system frequency (see Section 3.1.2). Those large scale random variations cannot be predicted in advance and thus incorporated into the forecast, but they are anticipated and the electricity system is operated with sufficient reserves (FCRs and FRRs) to ensure that the changes in system frequency are adequately controlled.

3.1.2. Electricity generation variation

In addition to the changes in electricity demand, the output from some generating units can also change. Such changes in generation can arise from a number of reasons:

- Generating units may change output for commercial reasons (e.g. to match contracts sold in advance), and these changes may not precisely match changes in demand.
- Generating units, including nuclear units, may trip off because of technical (e.g. equipment failure) or operational (e.g. exceeding operational limits) issues at the power plant.
- Generating units may be disconnected by faults on the grid system.
- Generation from wind turbines will increase or decrease as wind speed changes. Similarly, generation from solar panels will change during the day as the height of the sun changes, and will increase or decrease as cloud cover varies.
- Small generating units, including local generating units that are normally connected to low voltage distribution networks and sited at customer premises, normally change output without knowledge of the grid system operator as they are outside the control of the system operator.

In addition to planning for the changes in electricity demand described in Section 3.1.1, the grid system operator has to ensure that there are a sufficient number of generating units operating flexibly to provide adequate reserves to also allow for the additional effects of such changes in generation.

Here, it is useful to introduce the concept of ‘residual demand’ for electricity systems that have a significant amount of generation from renewable energy sources or small generating units (Fig. 8). In such systems, the grid

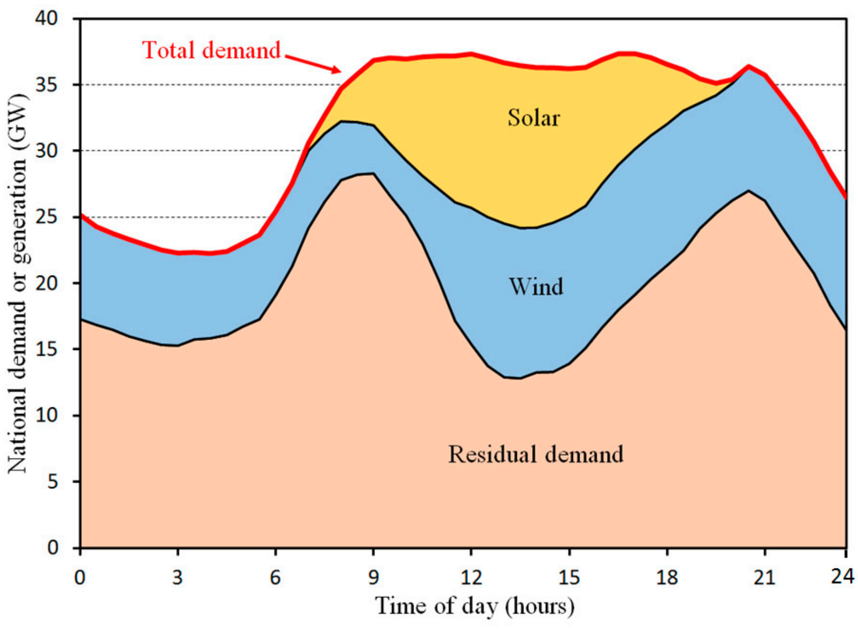

FIG. 8. Conceptual example of residual demand in an electricity system with renewable energy generation.

system operator has to control large generating units, including nuclear generating units, to balance changes in the residual demand, and not just the demand.

3.1.3. Generation management and optimization

In any system that has a mix of generating technologies, the commercially sensible method that minimizes overall operational costs is to operate the generating units according to merit, so that the output from generating units with the lowest marginal cost is maximized, and generating units with higher marginal costs are operated flexibly. Figure 9 illustrates an example of merit ordering of different generation technologies of an energy mix based on their generation cost, as a hypothetical case to demonstrate the merit order concept. However, in real markets, the 'least cost' stacking of the generation sources is only one part of the equation between generation cost and demand price, as demand response may lower the marginal cost. This requires the management and optimization of generation technologies.

Optimization of a generation plan of an electrical system aims to minimize, for a defined period of time, the cost of the generation. However, in almost all cases, the merit order is built on factors, including:

— The generation technologies having dispatch priority either for technical reasons (e.g. in the case of 'run of the river' hydropower) or for regulatory reasons (e.g. in the case of wind or solar power);
— The units that must operate in baseload mode (i.e. the units that are limited to only baseload operation due to technical reasons);
— The operational limitation/availability of SSCs in particular generation plants;
— The request for provision of FCR or FRR to control frequency deviations.

Typically, basic considerations include the following:

— Nuclear generating units have high fixed costs and low marginal costs (low fuel costs) when compared with generating units powered by fossil fuels such as coal and oil, which have relatively lower fixed costs but

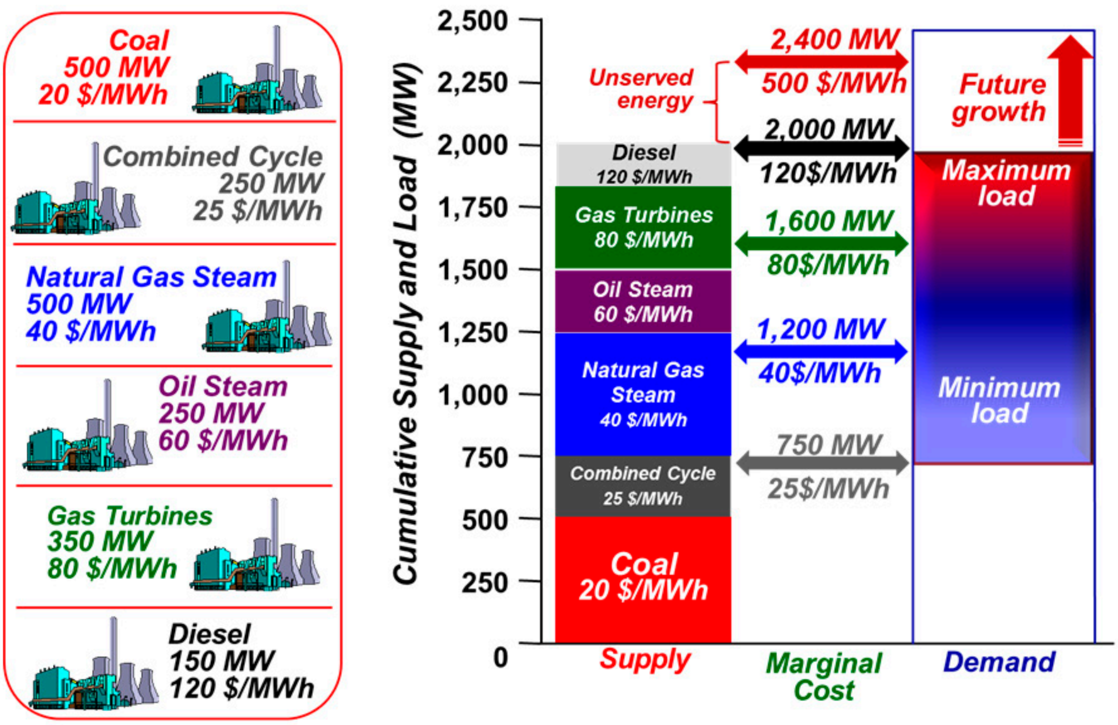

FIG. 9. Concept of merit order of generation sources that are loaded into the grid based on electricity production costs to meet demand. Note that the values are for illustration purposes only (courtesy of B. Hamilton, reproduced from Ref. [10]).

typically higher marginal costs. Hence, in any system that has a mix of nuclear and fossil fuel generating units, the overall lowest cost method of operation is generally for the nuclear units to run at full load (i.e. baseload) as much as possible, and for the fossil fuel generating units to provide frequency control and engage in load following. This is true even if the nuclear generating units have the design and operational capability to operate flexibly. On the other hand, if the percentage of nuclear generation is large, it could be necessary for some nuclear generating units to contribute to the electricity balancing services.

- Hydroelectric generating units, on the other hand, have effectively a zero fuel cost, but in many Member States with hydroelectric units, there is not enough water to operate them continuously at full load.[5] Where this is the case, the owners or operators of hydroelectric units with storage (not run of the river units) will prefer load following to baseload, and allocate their limited supply of water to be utilized at high power price periods (i.e. increase generation at periods of higher demand (higher price)) and reduce generation at lower demand (lower price) periods.[6] In addition, many hydroelectric units are more efficient at 80–85% load than at full load, so it is commercially beneficial for them to operate at reduced output and to provide frequency control and reserves, especially if they are financially compensated for doing so. In this case, it can be beneficial to use the stored water hydroelectric units to provide load following and frequency control, while operating the nuclear generating units at baseload, even though the marginal cost of the hydroelectric units is lower than the marginal cost of the nuclear units.
- It would not be desirable to operate nuclear generating units flexibly, provided that the other generating units can offer the necessary flexibility. Even though a lower variable cost generating unit alternative exists, its share in the generation and constraints in the capabilities/capacities may promote nuclear generating units to operate in baseload mode. Such is the case in Sweden, which has a high percentage of 'low variable cost' hydroelectric generation.
- In some cases, the grid system operator might prefer to instruct a nuclear unit operator to perform frequency control because the power provided by a large nuclear generating unit due to a frequency deviation (i.e. governor average gain in megawatts per hertz) is significant in volume due to the size of the unit. Hence, it may be more economical to provide the frequency control from a nuclear unit rather than by bringing numerous smaller fossil fuel units on-line just to provide this frequency control.
- Some Member States have thermal power plants that form part of an industrial combined heat and power system. These units need to operate at baseload in order to provide a constant source for heat.
- Nuclear generating units may not be able to achieve the high level of flexibility of other types of generating units that are specifically designed to maximize flexibility, such as gas turbine, hydroelectric or pumped storage plants. A sample set of flexible capacities for various generating units is indicated in Table 1, noting that the capability of individual power plants in other Member States may vary from the values shown [11], but these values are typical.

TABLE 1. SAMPLE RANGE OF FLEXIBILITY CAPABILITIES OF VARIOUS GENERATING UNITS

Generating unit type	Maximum power (MW)	Minimum power (MW)	Ramp rate (MW/min)	Frequency control for a 50 mHz deviation (MW)
Nuclear	900/1300	300/400	30	25/34
Coal	600	280	7	15
Combined cycle gas turbine	400	200	22	40
Open cycle gas turbine	70	40	7	0
Hydro	250	0	25	5

[5] To be on the merit order, hydroelectric generating units are generally considered based on the 'value of water' rather than the 'fuel cost'. This value of water is based on the potential price at which hydro energy may be sold to the market at a specific future time.

[6] In addition, for pumped storage hydroelectric plants, there may be revenue due to the spread between pumping and generating prices.

— The capability of some non-nuclear generating units for flexible operation may be restricted for technical and regulatory reasons. In some Member States, increasingly strict environmental legislation may further restrict flexible operation of non-nuclear units, as discussed in Section 3.2.5.

Furthermore, technical and economic considerations that affect the merit order differ from one electrical system to another. Figure 10 illustrates this merit order and the interrelationship of the generation cost and electricity demand. In this figure, wind and nuclear energy take the first and second places in the merit order because of their low marginal costs. Note that this figure is a simplification because the merit order can be affected by technical considerations. For example, it may be necessary to use a few higher cost generating units that are very flexible in preference to lower cost but inflexible generating units, in order to provide sufficient frequency control and reserves.

Figure 11 depicts the generation variation and merit order in Belgium on 3 November 2014, and illustrates how generation is managed when the factors mentioned above are considered. At this time, two nuclear units were in outage (2051 MW(e)) and the other nuclear units were operating at baseload. Wind and nuclear energy were first in the merit order, and system balancing was performed mainly by gas and hydroelectric generation.

Another example, illustrated in Fig. 12, demonstrates the influence of wind generation on grid management in Germany. In this case, when wind generation was low, the electrical system was balanced using coal, gas, oil and hydroelectric generating units. When wind generation was high, the electrical system was balanced by stopping lignite generating units and varying nuclear generation while maintaining fast start gas fuelled units as backup for reserves.

3.2. REASONS FOR FLEXIBLE OPERATION OF A NUCLEAR GENERATING UNIT

In the previous section, the fundamental reasons for requiring any generating unit to be operated flexibly were provided, as well as the specific considerations in management of a mixed generating portfolio, including nuclear generation. In addition to those reasons, there are specific reasons that would necessitate nuclear units to operate flexibly.

As a general rule for nuclear generation flexibility needs, if the total output capacity of the nuclear generating units in a grid system is: (a) a small fraction of the total generating capacity, and (b) significantly less than the minimum residual demand, then the grid system operator should be able to balance electricity generation with

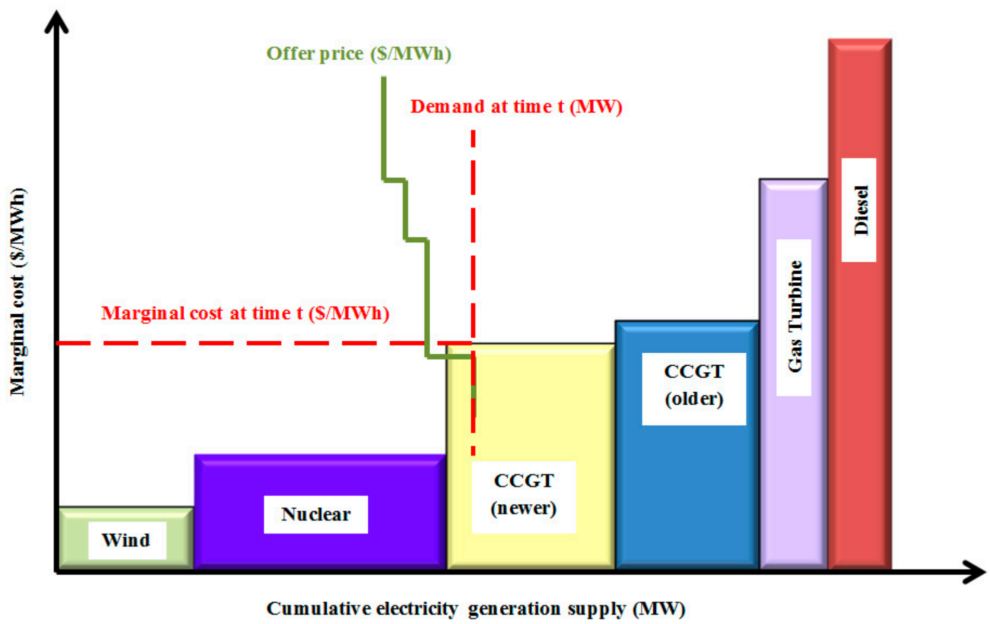

FIG. 10. Concept of merit order of generation sources in relation to the electricity price. CCGT — combined cycle gas turbine.

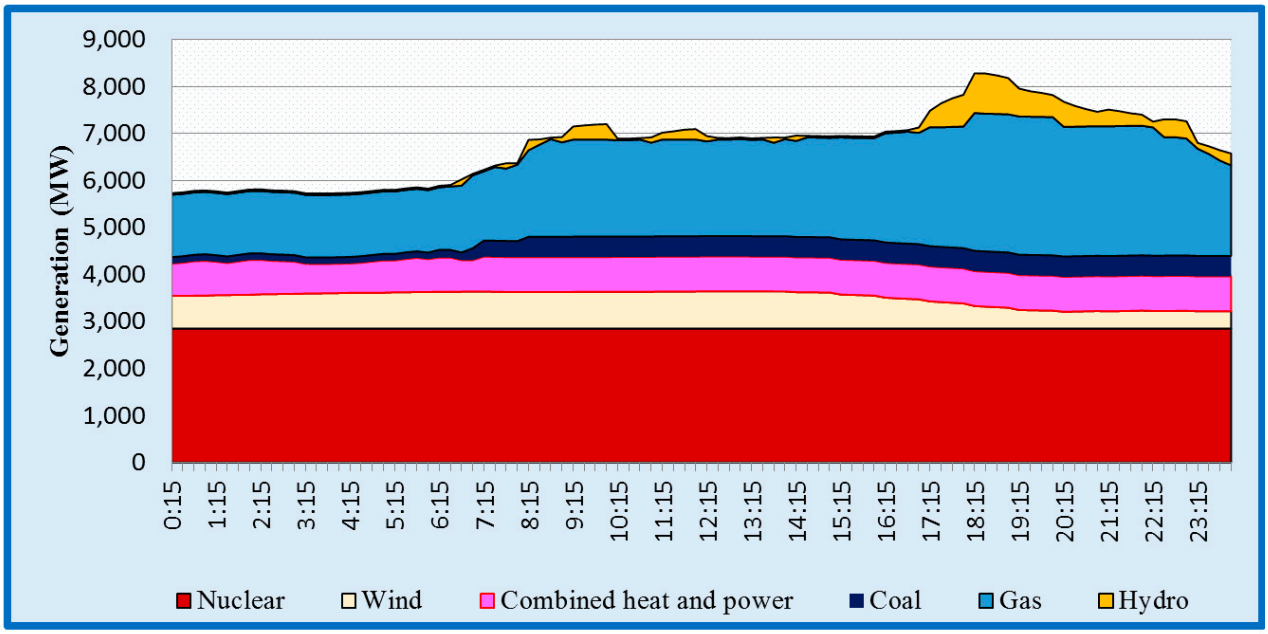

FIG. 11. Electricity generation in Belgium on 3 November 2014 (courtesy of P. Lebreton, reproduced from Ref. [12]).

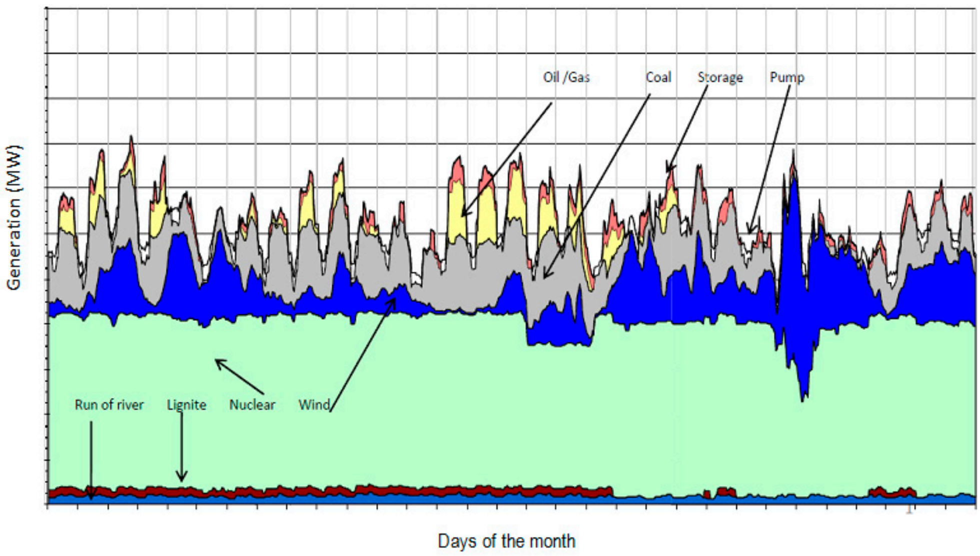

FIG. 12. Electricity generation in Germany in a winter month in 2009 (courtesy of P. Lebreton, reproduced from Ref. [13]).

demand and to control the system frequency without requiring nuclear generating units to operate flexibly. However, the definition of ‘small fraction’ and ‘significantly less’ depends on the structure, conditions and control methods of the grid system.

Moreover, it will become necessary and inevitable for nuclear generating units to operate flexibly under one or more of the particular conditions described in the following subsections.

3.2.1. Large share of nuclear generation capacity

If the total capacity of nuclear generation in an electricity network increases so that it approaches or exceeds the minimum electricity demand in the network, then it will not be possible for the grid system operator to match generation with demand or to provide sufficient reserves to allow adequate control of frequency using just the non-nuclear generation, particularly during periods of low electricity demand. Hence, it will be necessary for the nuclear generating units to operate flexibly, to reduce electrical/thermal output and to provide frequency control at times of lowest demand.

This consideration applies to an electricity network that may be national, regional or international in extent, and is not necessarily limited to the share of generation within a country. It is possible for the percentage of nuclear generation in a country to be very large, without the need for flexible operation, if that country is connected strongly to a much larger system.[7] Conversely, nuclear units may contribute a large percentage of generation in one region of a country, even if it is a small percentage of the total generation in the whole country; this can be especially significant if that particular region has weak grid connections to the rest of the country.

3.2.2. Growth in renewable energy or non-dispatchable electricity generation

In many Member States, there is currently significant growth in generation from renewable energy sources, such as wind turbines and solar photovoltaic systems because of strategies to reduce carbon emissions in order to meet government policies. There is also likely to be future growth in solar thermal systems and in tidal or wave power systems. These electricity generation sources have effectively zero fuel cost, and in some Member States, have priority status by legislation. However, they also have output that varies with time and weather conditions; these variations have limited predictability and are not always correlated with variations in electricity demand. Such forms of generation are not readily dispatchable in comparison with conventional generation sources.

There is also a growth in the number of other small generating units connected at distribution voltage levels and sited at customer premises, such as small wind turbines and domestic generating units. These units may have variable output and cannot readily be dispatched by the grid system operator.

If the minimum residual demand in a Member State (electricity demand minus generation from renewable energy sources and non-controllable sources) falls to a level that approaches the installed capacity of nuclear units, then the nuclear generating units would need to start operating flexibly.

The approach for nuclear power plant operations is also changing in Member States, due to increases in renewable energy generation in addition to possible retirement of older fossil fuel generating units, as described in Section 3.2.5, which has resulted in rapidly growing needs of nuclear power plants to reduce power during times of low demand and/or high renewable energy generation output. For example, in the United States of America and Canada, nuclear power plants have historically operated as baseload, because this has been the economically and technically preferred mode of operation. The growth in such forms (renewable and non-dispatchable sources) of generation displaces conventional generation sources, such as fossil fuel units, that previously provided reserve, while increasing the amount of reserve that is required. This causes a greater need for generating units that previously operated at baseload (including nuclear generating units) to operate flexibly to assist in balancing generation with demand. Figure 13 shows nuclear power plant load following in Ontario, Canada, in July 2015. Note that the early morning (04:00–08:00) demand on 4 July and on 5 July was low, resulting in load following dispatch of the plant. On Monday, 6 July 2015, with the anticipated increase in wind resources, the plant output was reduced by about 1000 MW(e), requiring deviation from typical baseload operation.

Additionally, the initial rate of change of system frequency after a trip of generation or demand depends on the inertia of the system (see Appendix II of Ref. [4]). This inertia is provided mainly by the rotors of the operating turbogenerators. Large wind turbines and solar panels do not directly provide inertia to the system, nor does the converter of a high voltage direct current link. Consequently, a growth in such generation sources that displaces turbogenerators will reduce the system inertia. A consequence of such growth is that it may be necessary for more generating units, including nuclear units, to operate in AFC mode and to respond more quickly to changes in frequency, in order to adequately control the system frequency.

Hence, there might be a need for nuclear generating units in a Member State to start operating flexibly because of increases in variable renewable energy generation, if the minimum residual demand falls to a level that approaches the installed nuclear capacity, or if the system inertia falls too low.

[7] For example, this is the case for Slovenia and was formerly the case for Lithuania.

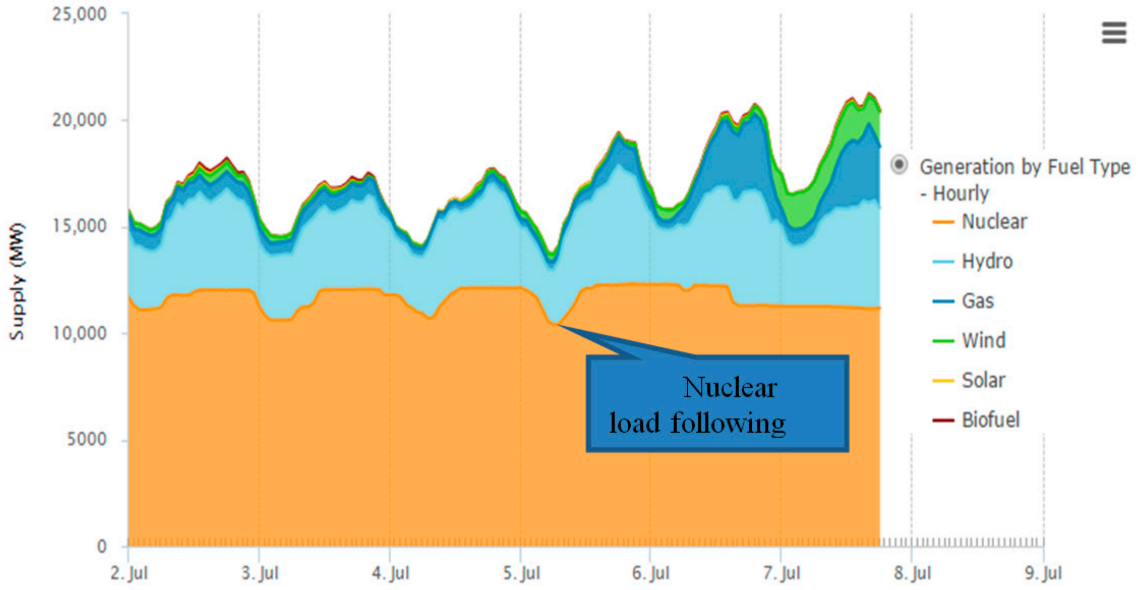

FIG. 13. Nuclear generation load following in Ontario, Canada, in the first week of July 2015 (courtesy of R. Kothe, reproduced from Ref. [14]).

3.2.3. Large nuclear generating unit on a small electrical system

With currently available nuclear power plant designs, it is likely that a new plant will be a large, if not the largest, generating unit in the system to which it is connected. If that is the case, then it is necessary to consider the effect of an unplanned trip of that unit on the system frequency. It becomes difficult to adequately control the frequency and to avoid a system blackout following the trip of a large generating unit, if the output of that generating unit is more than about 10% of the system demand at the time [4]. Therefore, this consideration may apply at times of minimum electricity demand in:

— Member States after they connect their first nuclear power plant to the grid (newcomer countries);
— Member States with existing nuclear units after they connect a new nuclear power plant that has an output capacity much larger than the existing nuclear units (expanding countries).

In such Member States, it will be necessary to consider operating the new nuclear power plant flexibly to reduce its thermal power/electrical output whenever demand on the electricity system is low.

In many Member States considering the introduction of nuclear power based on the rapid growth in electricity demand, and basing their first nuclear power plant technology selection on the energy forecast for 30−40 years ahead, this reason for flexible operation may potentially apply for the early years of operation until the long term electricity demand reaches levels that would allow baseload operation of the nuclear units.

On the other hand, as explained in Section 2.2.2, system frequency is generally more variable on small electricity systems than on large interconnected networks. Therefore, it should be noted that for a Member State that is installing its first nuclear power plant in a relatively small system, the plant can greatly improve the stability of system frequency if it is able to provide good AFC.

3.2.4. Transmission system constraints

The capacity of the transmission network to which the nuclear power plant is connected may be limited so that it is not possible for the nuclear unit to operate at full RTP under certain system load conditions or during some planned or unplanned transmission circuit outages. This situation may arise if additional generation sources, such as large wind farms, are connected near the plant and if the transmission network is not strengthened at the same time. If this is the case, it may be necessary for the nuclear unit to operate flexibly to reduce thermal power/electrical output under those conditions. From the perspective of the plant owners/operators (or energy planners/policy makers of a country or a region), it is preferable that the transmission system is designed with sufficient capacity and operated so that such restrictions would not apply.

A low degree of interconnectivity among neighbouring power systems can also force nuclear units to provide the required flexibility to the power system grid when faced with fluctuations in energy demand. Where neighbouring power systems have weak interconnections, it may be necessary for a nuclear power plant to operate flexibly to allow the required power flows across the interconnection. In this case, flexible operation of the nuclear unit may reduce transmission constraints.

3.2.5. Constraints on non-nuclear generating units

Increasingly strict environmental legislation in some Member States is starting to affect the operation of power plants that burn fossil fuels (e.g. coal or lignite). This may reduce or limit the ability of such plants to operate at much less than full RTP, or to change output rapidly or frequently if they are to remain within the environmental limits.[8] In addition, as in the cases of North America and Europe, the legislation may cause older fossil fuel generating units that previously operated flexibly to be retired, as a result of being economically unfeasible, in order to comply with the new rules. A reduction in the capacity of such generating units that previously operated flexibly will increase the need for other generating units, such as nuclear power plants, to operate flexibly. For example, in the United States of America, proposed greenhouse gas limits under ‘clean coal’ initiatives have brought forward the need for flexible operation of nuclear power plants. This means that operators with mixed generation assets may prefer to utilize nuclear generating units, for example, before clean coal generating units, in order to ensure they are operating catalytic conversion systems efficiently, because these conversion systems are not efficient at low power.

Environmental legislation may also restrict the flexible operation of some hydroelectric units because of the need to maintain water flow rates to conserve fish stocks, for irrigation or for flood control. Run of the river hydroelectric plants (i.e. those without significant water storage) are generally treated as being inflexible.

3.2.6. Changes in electricity market rules

Some Member States have deregulated their public electricity supply systems, and more Member States are considering deregulation. The technical or commercial rules in the deregulated market may require all generating units to be treated similarly, and hence, require all generating units to have at least a defined minimum capability to operate flexibly. This requirement for capability may apply to nuclear units, even if there is rarely a need for them to operate flexibly.

In some Member States that have deregulated their public electricity supply system, there is a payment to generating units when they operate flexibly at the request of the grid system operator to change output or to support grid frequency control. Such incentives provide a potential commercial opportunity, as well as compensation, to nuclear units that are operated flexibly.

In other Member States, electricity trading is based around a spot market; therefore, the electricity price can become negative if a time of low demand coincides with high output from renewable generating units such as wind turbines and solar photovoltaic units. With such market arrangements, there would be a commercial incentive for nuclear units to reduce output at such times, to avoid the financial debit of negative prices.

3.3. ALTERNATIVES TO FLEXIBLE OPERATION OF A NUCLEAR POWER PLANT

In some circumstances, the need for flexible operation by a nuclear power plant could be avoided by using alternative technologies and means to provide balance or adjustment of the generation and demand. Application of these technologies and means depends on their economic and technical feasibility, and needs to be evaluated on a case by case basis. Some methods and facilities that may be alternatives to flexible operation of a plant, or reduce the need for its extent, may include the following:

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[8] For example, gas fired generating units may be unable to comply with nitrogen oxide emission limits when operating below 60% rated power.

— On an electricity network, where periods of lowest electrical demand are confined to a particular time of year, it is sensible to schedule the planned shutdown of the nuclear units for maintenance and refuelling for this time. This could avoid the need for flexible operation of nuclear generating units that would be necessary if they were in operation during these periods. A pumped storage power station will purposely increase electrical demand on the electricity system at low demand times, typically during the night, when it is in pumping (charging) mode. At other times, it provides additional generating capacity, and can operate flexibly to provide load following and frequency control. Hence, a pumped storage power plant may allow nuclear units to continue to operate at baseload, as it provides the capability for flexible operation that would otherwise have to be performed by nuclear units. This alternative has been implemented in some Member States where the specific geography is suitable. For example, it was utilized for the first nuclear units built in China [3]. Other forms of energy storage that could provide a similar function are under development (e.g. flywheels or flow batteries). Figures 14 and 15 show the utilization of pumped storage for managing demand and maintaining baseload generation, respectively, in the Czech Republic on 5 March 2016.
— Where the electricity network in a country or region has suitable electrical interconnections with neighbouring countries or regions, it may be possible to develop commercial arrangements for the import/export of surplus generation during low demand periods (e.g. on weekends or at night), to reduce or avoid the need for flexible operation of nuclear units. The differences in the price of electricity among neighbouring countries or regions may provide a commercial incentive for building or increasing the capacity of such interconnections.
— It may also be possible to operate a nuclear unit at steady full thermal power while varying the electrical output, if other technologies could make use of the excess thermal power from the reactor (e.g. in forms of heat) that would otherwise be wasted [16]. This could include district heating, desalination of sea water or process heating (e.g. industrial steam, coal liquefaction/gasification or hydrogen production). As discussed in Ref. [17][9], a proper assessment of the technical and economic feasibility has to be performed to justify the alternatives being considered.

  Some nuclear power plants in Member States are currently using part of their thermal power to provide heat for industrial or district usages. In this principle, as illustrated in Fig. 16, the heat transfer can be adjusted, allowing the electrical power to be varied while leaving the thermal power extracted from the nuclear core

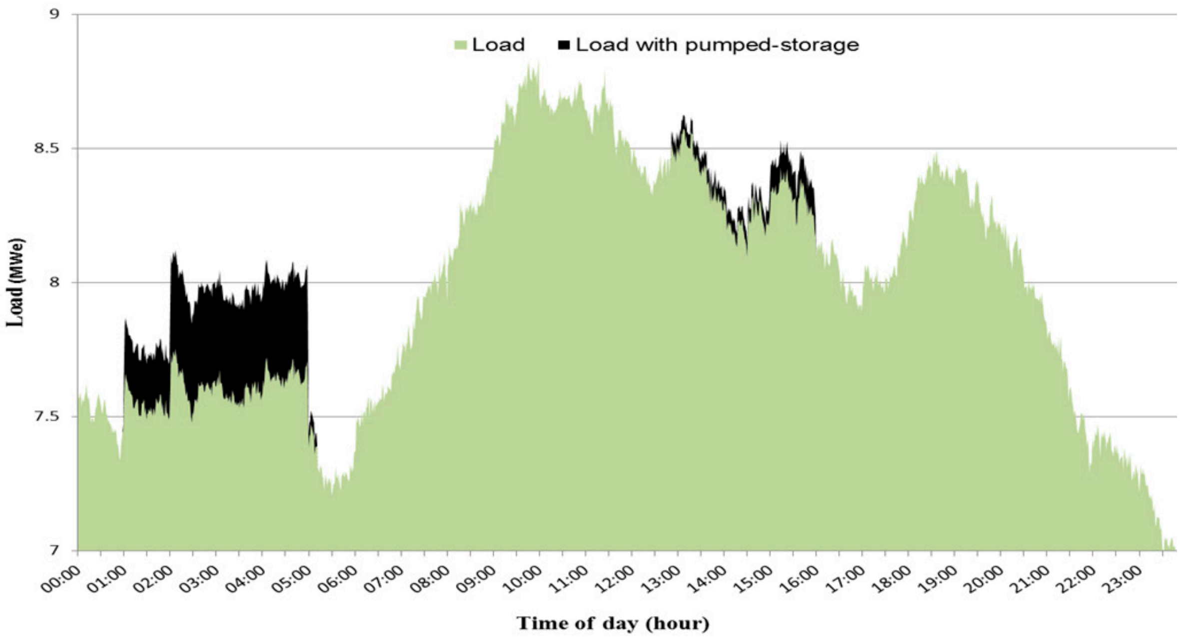

FIG. 14. Increased demand by pumped storage in the Czech Republic on 5 March 2016 (reproduced from Ref. [15]).

[9] Reference [17] discusses SMRs as a representative case; however, the basic economic principles apply to any technology.

unchanged. The provision of sufficient energy storage via hot water storage tanks would allow the varying heat demand to be met, independent of changes in the power supplied to the heating system by the reactor. In this application, the economic models of heat and electricity generation have to be compatible. Use of the derived heat from reactors for district heating has been practised in several Member States, particularly in Northern, Central and Eastern Europe. In these plants, 5–15% of the thermal power is used for district heating [18, 19].
— Demand side management and load management, as well as other commercial arrangements, can be used to encourage electricity consumers to alter their electrical usage from periods of high electrical demand to periods of low electrical demand, including arrangements to increase night-time electricity demand. For

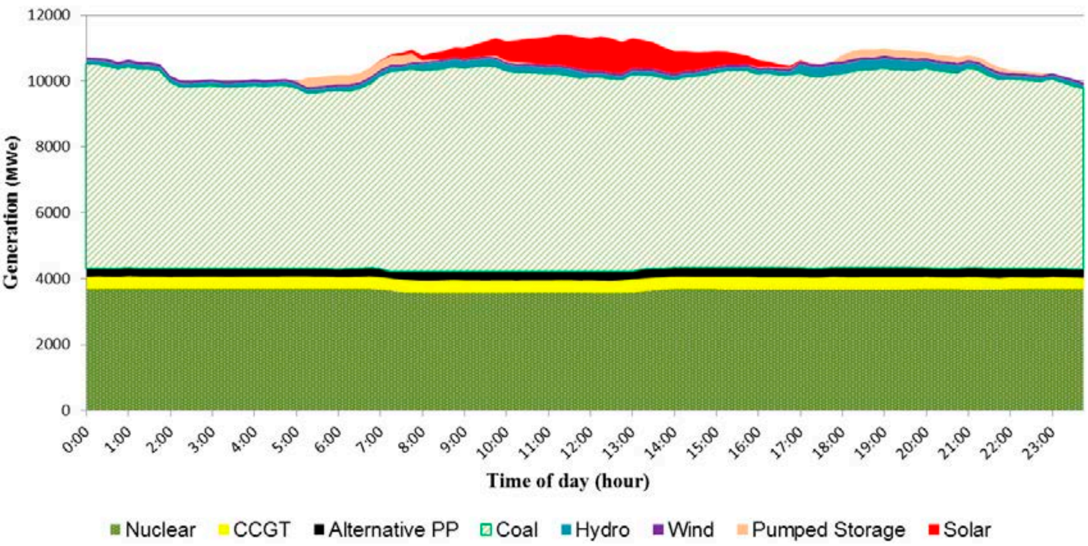

FIG. 15. Maintaining baseload generation with use of pumped storage in the Czech Republic on 5 March 2016 (reproduced from Ref. [15]). CCGT — combined cycle gas turbine, PP — power plant.

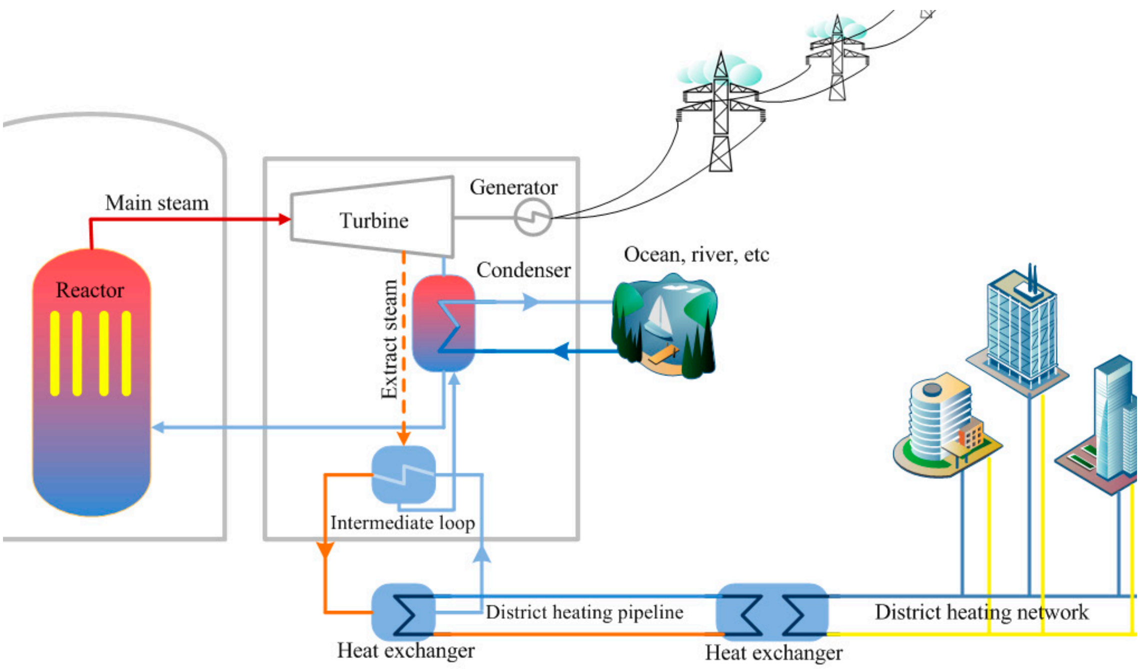

FIG. 16. District heating with constant reactor power and variable electrical output.

example, with the emergence of smart grid technology and electric vehicles, there may be more opportunities in the future for innovations in demand side management.

Commercial arrangements can also be used to persuade large industrial users of electricity to reduce demand on request when reserves are low, or to automatically disconnect demand in response to a low system frequency. That is, large demand users may be willing to control their demand to provide ancillary services. One specific instance is in Indiana, United States of America, where services have been provided by an aluminium smelting plant [20, 21]. This would reduce the amount of frequency response and reserve that must be provided by generating units.

4. FEASIBILITY EVALUATION OF AND DECISION MAKING ON FLEXIBLE OPERATION OF A NUCLEAR POWER PLANT

The decision on flexible operation of a nuclear power plant is driven by a business case based on the necessity or probability of having to periodically reduce the thermal/electrical output of the plant during its operational lifetime, due to the commercial or grid operational reasons presented in previous sections. During the entire decision making process, the business case and the alternatives need to be updated and reviewed, giving the owner visibility on costs and possible benefits of flexible operation.

This feasibility evaluation is mainly focused on identifying the technical, financial or operational impacts rather than on making a decision to operate flexibly or not. Subsequently, the decision will be made by integrating the impacts, associated costs and benefits, including the potential payments for providing balancing services, an overall energy policy, and legal and regulatory aspects. This fundamental decision making process by the nuclear power plant owner/operating organization on whether to operate flexibly is illustrated in Fig. 17, which also depicts the key aspects to consider when deciding on the desired extent and form of plant flexible operation.

When deciding whether a nuclear power plant should be operated flexibly, many factors within a Member State’s energy policy and technical, economic and legal constraints or incentives have to be taken into account systematically and in an integrated manner. The decision involves many stakeholders, ranging from energy planners to plant owners/operating organizations (Fig. 18).

Although the roles, as well as the amount and timing of stakeholder participation in decision making, may vary due to the economic, energy, financial and legal frameworks of each Member State, a fundamental process to describe important processes and to define the roles of the entities in decision making with a step by step approach can be established.

The key elements of decision making and interaction among the stakeholders are described in this section.

4.1. ENERGY PLANNING AND ASSESSMENT OF NEEDS FOR FLEXIBLE OPERATION OF GENERATING UNITS

The main consideration in assessing the feasibility of flexible operation of a nuclear power plant is whether the combined capacity of the nuclear generating units will always be significantly less than the minimum demand (or the minimum residual demand) on the electricity system when the plant is first connected to the grid and subsequently during its operational lifetime, as planned and forecast. If that is the case, it may not be necessary for the plant to operate flexibly. In all other cases, there would be a need for some nuclear power plants to operate flexibly, as explained in Section 3. Hence, energy planning is the main input to the decision making process on the necessity of flexible operation of a plant.

If the energy planning reveals the necessity for nuclear power plants to operate in a mode other than baseload, then it is necessary to consider and implement the capability for the plants to operate flexibly. In this case, the flexibility needs have to be characterized to identify the ranges for frequency control, the minimum stable power and power ramping, how often the unit will need to do load following and how often there will be significant frequency deviations to control.

For a new nuclear power plant project, this capability is analysed at the feasibility stage because it affects the design, operation and business case of the new plant. For existing nuclear power plants, this capability is analysed considering the needs for flexibility until the end of life of the plant, the existing capability of the plant and the additional capabilities that may be available or may need to be added.

This identification is performed stepwise by analysing a predefined time horizon (e.g. present time and present time+5, +10, +20, +30 years), including the commissioning dates of the plants and other generation sources/projects implementation.

4.1.1. Analysing the evolution of electricity demand

As explained earlier, electricity demand varies on a daily, weekly and yearly basis, and is influenced by weather factors such as temperature, sunshine and wind. It can also be affected by social events, power management activities, power exchanges with neighbouring countries and electricity demand management. Using the known past variation of electricity demand, combined with scenarios for economic and electricity sector development, the future magnitude and shape of electricity demand can be forecast.

The variation is quite repeatable in most Member States, and the main variations in future demand can be forecast with reasonable accuracy [22]. The additional effect of variations in weather conditions can also be modelled based on past experience and records, to allow good forecasts of electricity demand once a reliable weather forecast is available. The grid system operators in many Member States are able to predict consumer demand typically within 1−2%, including the expected effects of weather conditions, 1 or 2 days in advance.

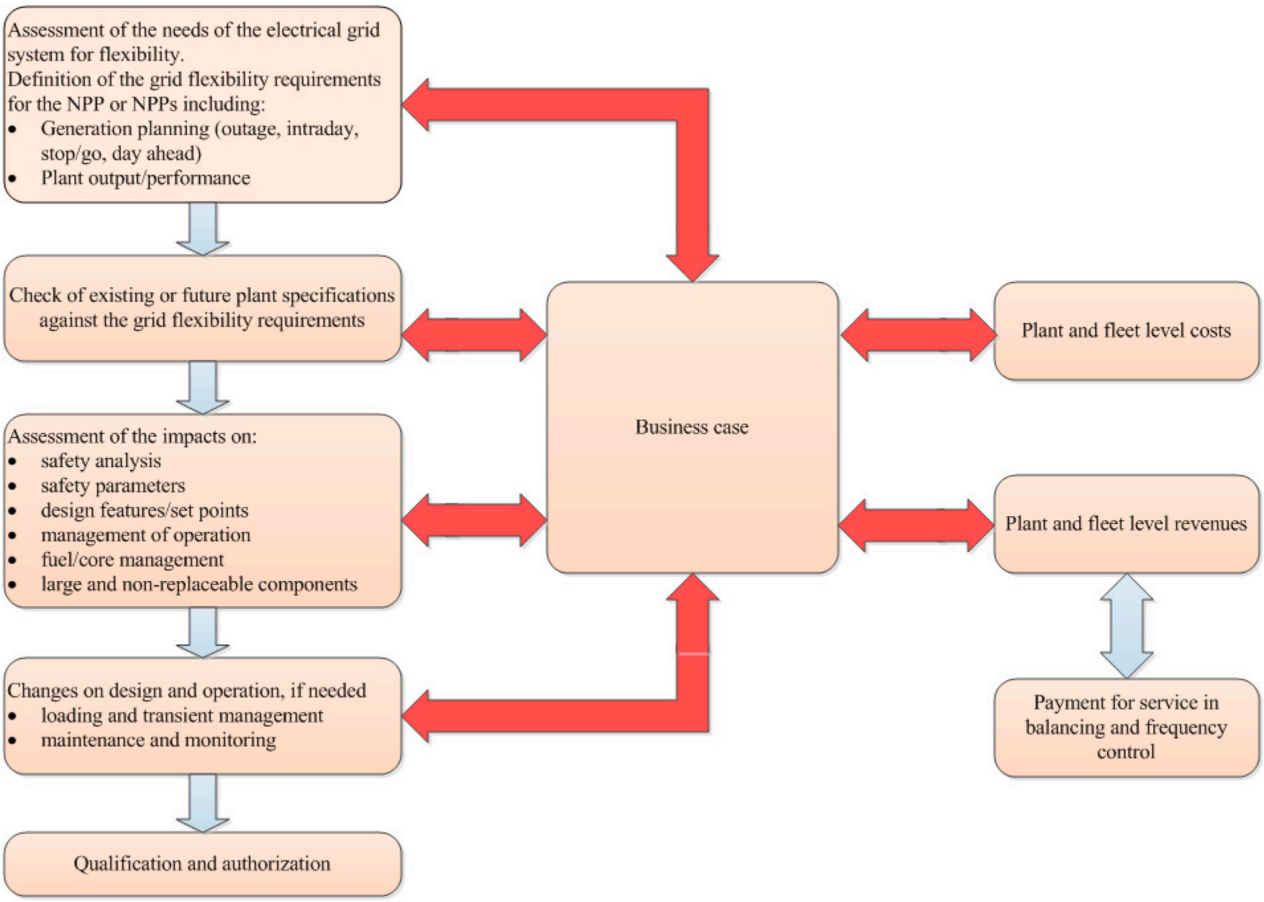

FIG. 17. Simplified process of a nuclear power plant (NPP) owner/operating organization considering flexible operation.

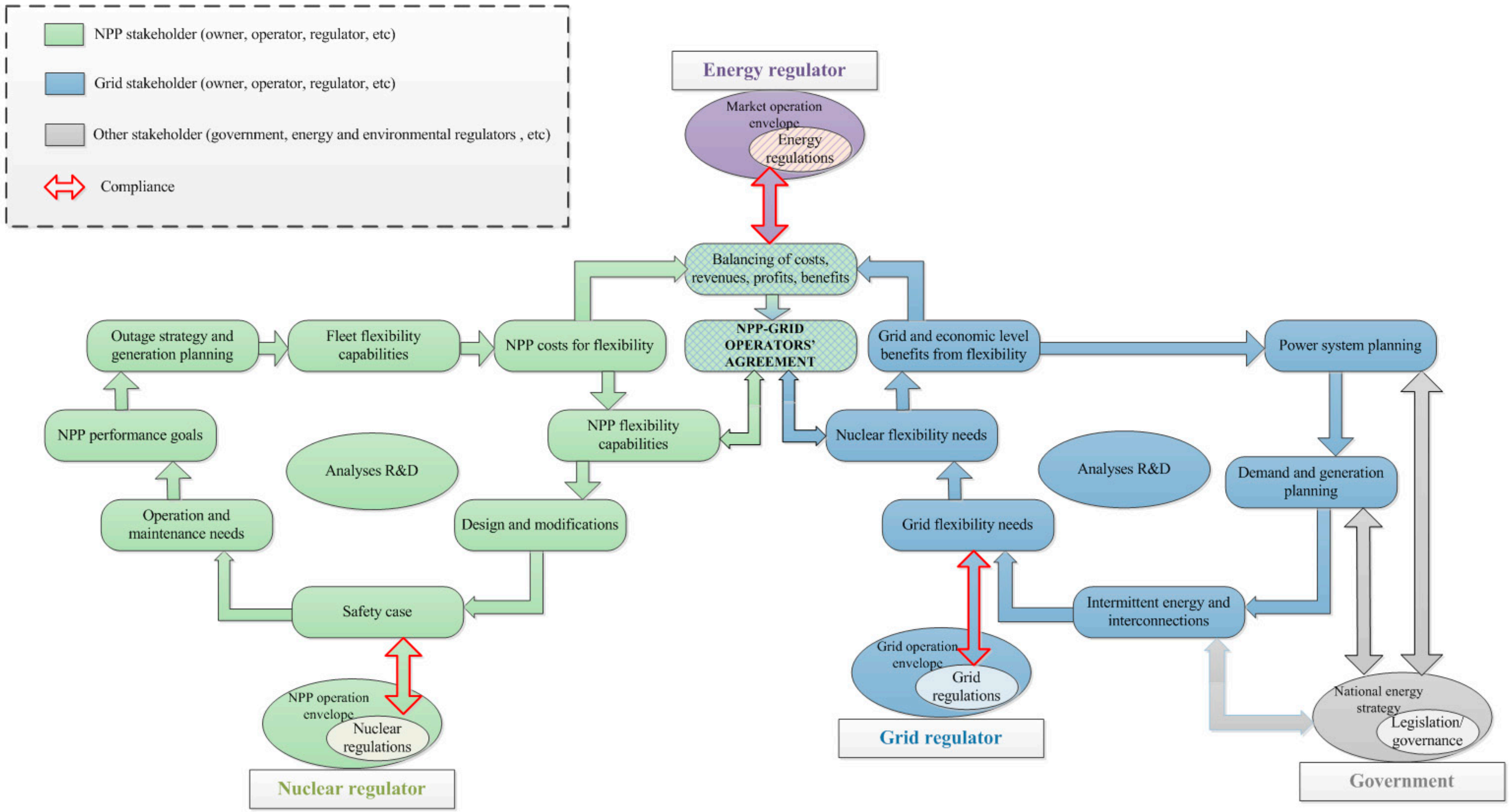

FIG. 18. Interfaces among flexible operation and plant management activities. NPP — nuclear power plant; R&D — research and development.

It is necessary to consider several different economic scenarios, depending on the energy policy of the Member State, to set the boundaries for future energy use. The scenarios include a range of forecasts of electricity demand for different time periods (year, week, day, etc.) for various times into the future (present time and present time+5, +10, +20, +30 years). The outcome of this analysis of electricity demand evolution is often published in 'energy forecasts', 'power studies' or 'power master plans'.

4.1.2. Analysing the evolution of electricity generation

Starting from the installed capacity, electricity generation forecast analysis integrates the evolution of different generation technologies and the main factors affecting their development: the cost of primary energy; environmental constraints; Member State governmental plans for development of renewable forms of energy, clean energy sources, etc.; and associated economic and technical plans for existing generating units, including future life extension, uprating or retirement/decommissioning. This analysis provides a forecast of installed capacity for each year up to the planned time horizon (present time and present time+5, +10, +20, +30 years).

This yearly installed capacity is then scaled down to include a predicted/proven capacity factor that is specific to each generation technology, to better estimate the overall availability of the generating units.

In the analysis of electricity demand described in Section 4.1.1, the renewable energy generating units connected at distribution levels are generally treated as a decrease in electricity demand accounted for at transmission levels.

The outcome of the analysis of the evolution of the electricity generation is published in 'generation master plans'.

4.1.3. Modelling power flows and power exchanges

Power flows and power exchanges are analysed to model current and future evolution of power exchanges within an electrical system and, if applicable, the power exchanges with other electrical systems.

If relevant, the power flows and exchanges with the electrical networks in neighbouring countries or regions[10] are included in the energy planning based on the transmission capacity that is available either for commercial exchanges of power or to provide reserves. In accounting of the power flows between electrical networks, power exports are treated as variations of demand and power imports are considered variations of generation.

Grid systems are required to deliver the power from generating units to the centres of demand within acceptable voltage and stability limits while meeting the regulations established to prevent overloading the grid system components. The expected power flows in the electrical network(s) are modelled to ensure the effectiveness of the transmission and distribution system, to assess the electrical losses and to determine any need for reinforcement of the systems and equipment (power lines, power stations, transformers, etc.) in future grid plans.

The results of the grid development studies and power system simulations are published in 'grid master plans', which describe the structure of future stable and efficient electrical grid systems.

4.1.4. Assessing the electricity generation–demand balance

For different time horizons (present time and present time+5, +10, +20, +30 years) and different timescales (yearly, weekly, daily), the balance between electricity generation and demand needs to be assessed to identify the risks on security of electricity supply. The power margins are calculated using probabilistic methods. The risks of lack of energy or reserves are also in these probabilistic methods. Sensitivity studies on gross domestic product, primary energy prices and development of renewable energy may complete this step of assessment to provide a better understanding of the 'system adequacy study', which is often the name of the document reporting this assessment process and its results.

[10] In some cases, the power flow and exchanges may include regional electricity networks (e.g. North America, Scandinavia or the regional electrical systems within the same country, such as in China or the USA).

4.2. ASSESSMENT OF NEEDS FOR FLEXIBLE OPERATION OF NUCLEAR GENERATING UNITS

Based on the analysis and forecasts performed for electricity generation and demand on a specific time horizon, sufficient input would now be available to calculate the probability of nuclear generation/output to be reduced due to low electricity demand, and to determine the fraction of a given year (or of a given fuel cycle length) when it would be necessary to use nuclear power plants in a flexible mode to balance the electricity system.

It is recommended to integrate the stakeholders, such as plant and grid system owners/operators, vendor organizations or design authorities of the plant, technical support organizations, as well as nuclear and grid regulatory authorities, at this stage in the consideration process. Their assistance and agreement are needed for the next steps in the decision making process.

4.2.1. Assessing the requirements for nuclear generation to be flexible

4.2.1.1. Load duration curve

As a common tool, a typical load duration curve (LDC) illustrates the relationship between generating capacity requirements and capacity utilization in order to determine the risk or the necessity for nuclear generation to be flexible, and then to perform economic dispatching, system planning and reliability evaluations. An LDC is a graph that displays the demand (load) values on the vertical axis against the number of hours in the year, on the horizontal axis, by which the demand values are exceeded.[11] It is usually superimposed onto the generation curve to compare the contribution of generation at those demand levels. The area under the LDC represents the energy consumed by the system and the area under the generation curve shows the energy generated. The key LDC characteristics can be summarized as follows:

- The general shape of the curve gives important information about the needs for generation, specifically the magnitude of impact on the nuclear generation load factor (i.e. for what fraction of the year demand is above 50% of the maximum demand).
- The gradient of the LDC provides valuable information to determine the plant load factor and the frequency of load manoeuvres. A small change in the load will have a significant impact on operating generator hours and on plant load factors. A flatter LDC curve, which is the case for developed Member States, demonstrates a higher risk of power change with a slight change in demand.

A sample LDC, the 2012 French case[12], shown in Fig. 19 (superimposed onto nuclear generation capacity shown as the red dotted rectangle) illustrates these key characteristics.

The sample LDC in Fig. 19 has three distinctive regions:

- Region A, the peak period, illustrates that most of the generating units are needed to run, and nuclear generation is listed in the merit order during these hours.
- Region B, the intermediate demand period, illustrates the main gradient to determine the plant load factor and frequency of load manoeuvres in this large period between the peak and low demands. A small slope in this region characterizes the nature of the main demand, which will be stable if the region is large and flat.
- Region C, the low demand period, illustrates the times when ‘must run’ generating units are operated. There is a strong need for grid system operators to instruct other generators to ramp power down, because the power gradient is still very high between hours and demand is low.

Some general conclusions from the LDC superimposed onto the nuclear energy generated can be drawn as follows:

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[11] When plotting an LDC for a system that has a substantial proportion of renewable or other non-dispatchable energy generation, then the LDC plots the ‘residual demand’ (as defined in the glossary) instead of the ‘demand’.

[12] In 2012, nuclear installed capacity in France was about 63 GW, with an average load factor of 73.6%. Nuclear generation was greater than national demand for about 750 hours, but when considering energy exported and stored in pumped storage hydro stations, nuclear energy was marginal on the market for only 12 days in that year. During this year, about 48 nuclear power plants (of the 58) performed daily load following and frequency control.

— For a Member State considering nuclear energy in a defined time horizon, analysis of the forecast of electricity demand and of generation from nuclear energy could reveal possible baseload operation if the volume of energy generated by the nuclear power plant is always significantly below the LDC minimum (low demand period, region C in Fig. 19).
— Nuclear power plants might need to be flexible for a significant number of hours if the nuclear generation will be of the same order of magnitude as the LDC minimum. Precisely assessing the number of balancing hours is challenging because of the large uncertainty of the demand in the case of a flatter LDC gradient (i.e. the slope of region B in Fig. 19) and due to the uncertainties caused by the intermittency of renewable energy generation and export capacity.

4.2.1.2. Minimum nuclear generation

When a Member State has a large proportion of nuclear generation, an important parameter is the level of 'minimum nuclear generation' (see Glossary). When the residual demand approaches the minimum nuclear generation for a few hours, it may be optimal to temporarily curtail some renewable energy generation rather than shut down some nuclear power plants for such a short time. This is because nuclear generating units generally have a long startup time and may not be able to be on-line in time for the next ramp-up period.

It should be noted that this situation can conflict with the provisions set by the market, as the market could cause a reduction of higher cost generation technologies first by merit order, or by a policy priority promoting specific technology. In those situations, where the minimum nuclear generation is greater than the residual demand for a short period of time (e.g. a few hours), exceptions to the market rules may be needed to avoid shutting down a nuclear power plant that may not be available when the demand increases shortly thereafter. Thus, in some Member States, regulatory rules are established to provide such special case exemptions to the market requirements. These may include curtailing renewable energy generation to keep a plant on-line, even though the market requirements may normally give priority to renewable energy.

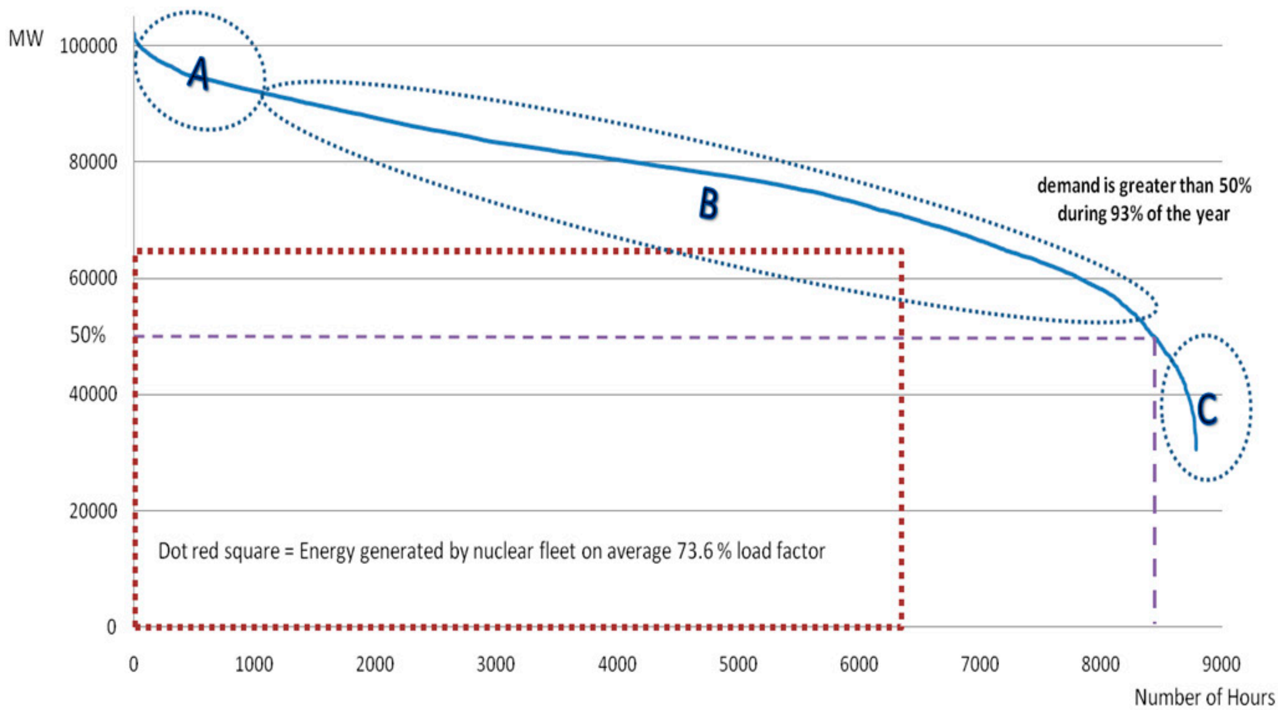

FIG. 19. Load duration curve of demand and generation for nuclear energy in France in 2012 (courtesy of P. Lebreton, reproduced from Ref. [23]).

Figure 20 illustrates this key aspect of the electricity demand and minimum nuclear generation within the context of various generation sources in France during Easter week of 2013. This illustrates the sensitivity of nuclear generation to the variation of demand when the demand is at its minimum.

The following points in Fig. 20 highlight three key events:

— On 31 March 2013, at 17:00 (point 1), there was very low demand due to a non-working day, and demand was reduced by 10 700 MW. Residual demand was too low versus nuclear capacity. The nuclear fleet had to reduce its output by about 4400 MW.
— On 1 April 2013, the peak demand occurred at 10:00. The nuclear generation was at maximum output, except for the units requested for frequency response. The nuclear fleet had ramped up slower than the demand.
— On 30 March 2013 (point 3), the decrease in demand was not large enough to request nuclear generating units to reduce output. Compared with point 2, a difference of minimum demand of 4200 MW (between points 3 and 2) caused a reduction of generation by the nuclear fleet of 4400 MW.

An important conclusion that can be drawn from this figure is that small variations in demand may trigger a significant variation in nuclear generation output when they occur at the time of minimum demand. In some cases, this need for change in output may be so large that it almost creates a cliff effect (i.e. a very small change in demand can make a very large change to the need for flexible operation of nuclear generating units).

4.2.2. Assessing the type of flexibility for nuclear generation in the energy mix

The need for nuclear generating units to have the capability for flexible operation in combination with other generation sources can be determined by analysing the results of power studies and energy plans, which combine and collectively consider share and flexibility capability/capacity of every generation source in the energy portfolio.

At this stage, the concern is the compatibility between the grid system requirements identified in the previous studies and the flexibility specifications of the existing or the candidate nuclear power plant(s). If the requirements/

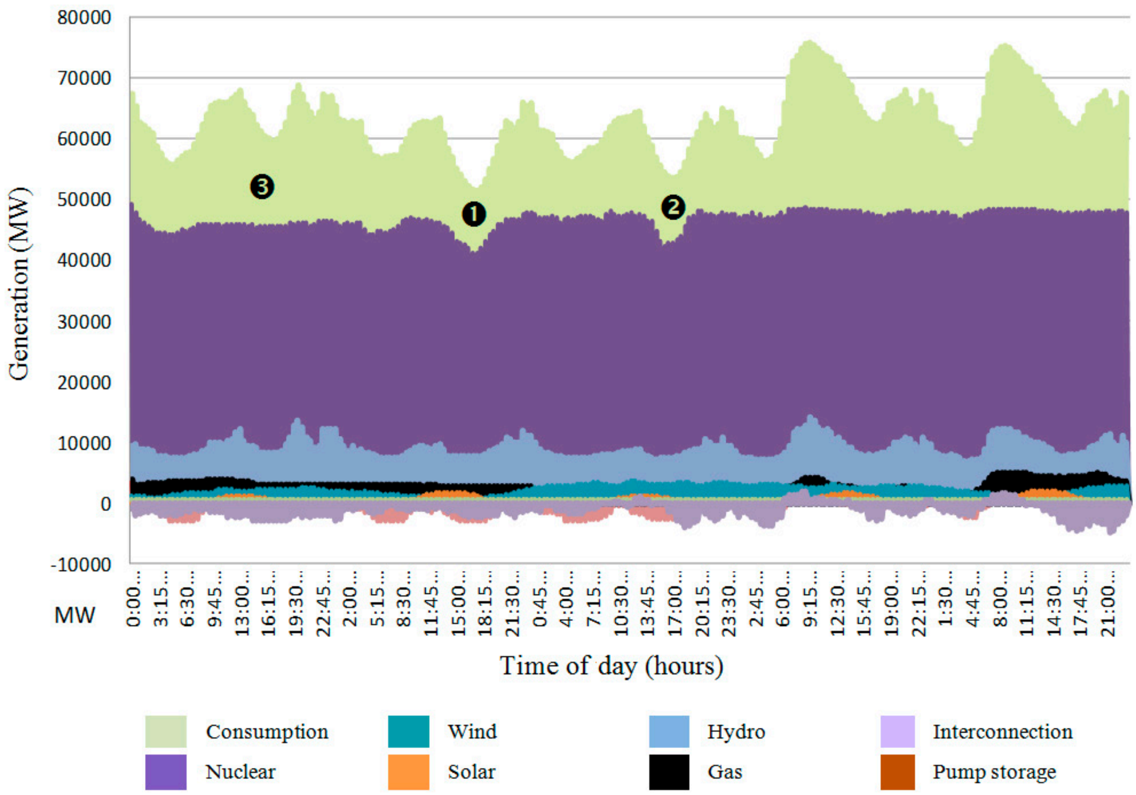

FIG. 20. Generation mix and demand in France during the Easter holiday, from 30 March to 3 April 2013 (reproduced from Ref. [23]).

needs are outside the design and operational specifications of the plant, this comparison will provide additional requirements for a plant to change its current (or proposed) design and safety analysis. Alternatively, plans and policies for the development of the electricity network could be revised so that the requirements on nuclear power plants are relaxed, such that they can be met by the existing capability and safety analysis for the plant. Hence, it is essential at this stage to include grid and nuclear regulator perspectives and preliminary reviews of proposed changes in order to proceed with the decision making process of the plant owner/operating organization along with the plant designer/vendor.

Figure 21 illustrates a sample analysis for determining the extent of flexibility in a mix of nuclear and renewable energy generation sources for a case in Romania. This figure shows the integration of nuclear power

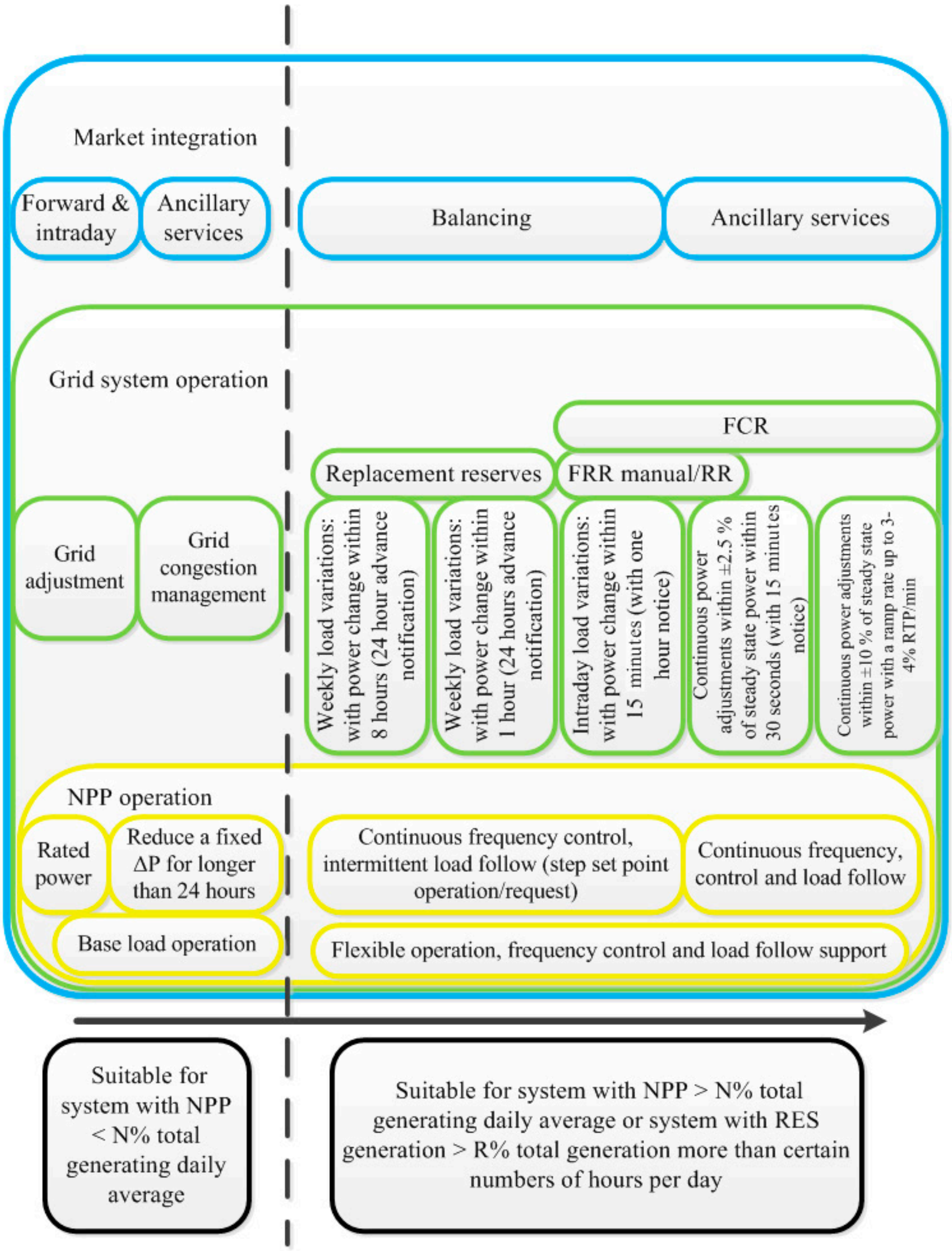

FIG. 21. Operation modes and nuclear/renewable energy generation capacity (courtesy of D. Ilisiu as an addendum to Ref. [24]). FCR — frequency containment reserve; FRR — frequency restoration reserve; N% — maximum percentage of nuclear generation; NPP — nuclear power plant; R% — maximum percentage of renewable energy generation; RES — renewable energy system; RR — replacement reserve; RTP — rated thermal power.

plant operation modes (baseload and flexible) into power market and power system operation and the influence of nuclear and renewable energy generation capacities on flexible operation of plants.

Starting from a general objective of a target capacity of nuclear and intermittent renewable energy generation and its timing (e.g. '*X*' GW(e) in year '*YYYY*'), power planning studies can be used to assess the:

- Generation master plan and grid reinforcements needed to balance electricity generation and demand;
- Maximum percentage of nuclear generation (N% in Fig. 21);
- Maximum percentage of renewable energy generation (R% in Fig. 21).

The horizontal arrow in Fig. 21 represents the ratio of renewable energy intermittent generation, *R*%, and the vertical dotted line represents the threshold above which there will be a need for the nuclear generation capacity of *N*% to operate flexibly.

The consideration of the dynamic effects due to large and rapid variations of renewable energy generation such as solar or wind power requires a reduction in the *R* factor and an increase in the capacity of backup thermal generation or a diversification of renewable energy generation capacity.

4.2.3. Assessing the technical requirements for flexible operation of nuclear power plants

The technical requirements that are requested by the grid system operators are input into the assessment to determine the nuclear power plant evaluation of whether the existing design/facility is capable of meeting those, or what changes to the design/facility need to be implemented. At this stage, an overall feasibility study on the plant capabilities is performed by the plant owners/operators, and several iterations may take place between the grid system operator and the plant owner/operator and designer, as well as the grid and nuclear regulators, to agree on what is requested and what can be provided. Table 2 gives a set of considerations to start the iterations.

TABLE 2. BASIC CONSIDERATIONS OF FLEXIBILITY IN RESPONSE TO GRID OCCURRENCES

Event	Response	Associated methods or parameters
Predicted daily demand variation	Load following	Low power period Power change rate Number of occurrences per given time (seasonal, monthly, weekly) Duration at low power for longer period planned demand (extended low power operation) Minimum power for secondary system efficiency
Real time small demand variation	Frequency control	Power change equivalent of frequency disturbance (amplitude, ramp rate, required control type, e.g. local/remote, manual/automatic)
Grid disturbances, large and infrequent power variations	Spinning reserves	Ramp (amplitude, rate, initial power level) Step (amplitude, initial power level) Minimum stable power level, house load capability Instantaneous (a few per cent rated thermal power change, return to full power notice)

The key technical parameters of interest to the grid system operators for stabilizing the grid are: frequency response capability, power ramping and power output. Current practices from experiences in Member States among the stakeholders demonstrate the following:

- Frequency response capability is an important performance requirement for the grid system operator because its fast response helps to cope with the stochastic fast fluctuations of generation and demand. Grid system operators in some Member States are increasingly requesting such a capability, mainly due to the increasing share of renewable energy generating units that have intermittent and fluctuating output and that do not participate in frequency control. Those renewable energy generating units are also connected via power inverters, which do not contribute inertia to the grid, as discussed in Section 3.2.2. On the other hand, in some Member States, frequency response is considered an ancillary service carried out by a specific market. In those cases, the grid system operator may request the frequency response capability and the nuclear power plant owner/operator can control utilization by means of the price of providing support for frequency control.

- Power ramping is also an important performance requirement for the grid system operator when it is necessary to reduce (or increase) the generated output in balancing the electrical system and controlling the frequency if the system frequency gets too high (or too low). For compliance with this requirement, the grid system operator needs to achieve adequate power ramping, with the necessary timing, magnitude and speed. Specifically, the grid system operator’s main criteria include the amount of power change per minute, the minimum and maximum power levels of stable operation and the allowable time of operation at minimum or intermediate power levels. However, the grid system operator trying to achieve this performance ought to also take into account the implications and impacts of power manoeuvring of a plant, especially in terms of how often it needs to be achieved (i.e. whether a few times per year, or on a weekly or daily basis), the possible ramp rate (i.e. whether it is a few or tens of per cent of RTP per hour) and the limiting duration of long term reduced power operations.
- The stabilization of the power output (steady state or after ramping) at the right level and at the right time is considered important by the grid system operator because the quality of the frequency depends also on correctly operating at the power levels scheduled. Requirements of better than ±1% accuracy and within ±3 minutes are commonly observed in Member States, as agreed by the grid and plant operators.
- The minimum electrical output at which a generating unit can operate (i.e. design minimum operating level or design minimum load point) is also an important parameter. Below that power output, in response to a grid event, the generating unit would not be able to make a rapid (typically within seconds) reduction in active power to a level that needs to be sustained for an undefined time. Lowering this minimum operation point may become necessary in the context of flexible operation of plants[13], and for some plant designs, there could be technical challenges.

Additionally, nuclear power plants may have physical and operational limitations on the minimum operating power, particularly for:

- Extended low power operation (i.e. length of periods at low power level);
- Minimum reactor power level (i.e. minimum core power), below which a plant cannot maintain stable, long term operations without some risks to its SSCs, or during which some control and protection systems are outside their operating range.

These low power operation limitations are based on several factors, including turbine and secondary system efficiency, control and protection system ranges, and mechanical and hydraulic limits, such as vibrations in components or perturbations in the reactor parameters.

Only a few Member States have explicit nuclear power plant designs and configurations to operate in a wide range of flexibility with load following and frequency response. Specifically, France and Germany have accumulated many reactor-years of experience designing and operating their nuclear power plants in load following and frequency response modes, including AGC or AFC. Some of those plants were initially designed to have such capabilities [25], while others required modification to transition from their original baseload design in order to achieve higher capability load following and frequency response [26].

Figure 22 shows a German pressurized water reactor (PWR) flexibility scheme considered in the design phase of Konvoi technology, as an example [27]. The blue lines show the grid requirements at the time (1992) that were considered in the safety analysis and in establishing the design limits (red lines) for flexible operation. The reviewed and approved operational limits (green lines) by the regulatory body, together with the grid requirements, were confirmed and qualified during commissioning. The blue shaded area represents the typical practised range of load following and frequency control operations by German PWRs initially, providing large margins to the operational limits. The grid requirements that were based on the 1992 grid configuration and plans, meanwhile,

[13] This issue is also very important for other types of generating units, particularly for coal fired units, gas turbines or combined cycle gas turbines.

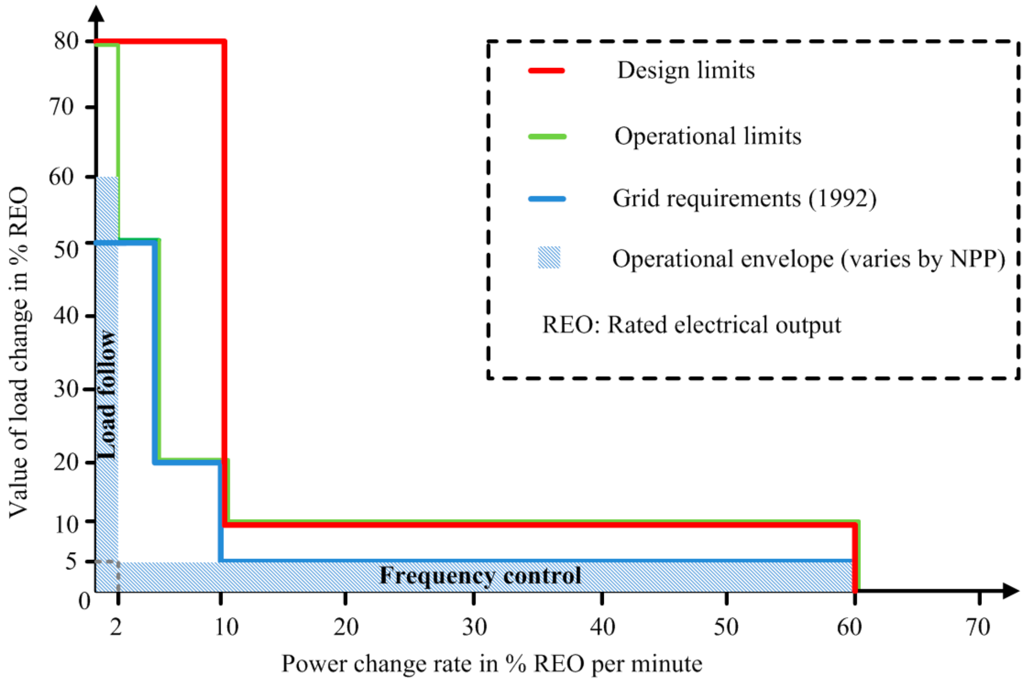

FIG. 22. German pressurized water reactor flexibility requirements and designed capabilities (courtesy of H. Ludwig, AREVA GmbH, reproduced from Ref. [27]). NPP — nuclear power plant.

have evolved, requiring expansion of the operational envelope and, in some cases, review and approval of the operational limits by the regulatory body. Currently, in some nuclear power plants in Germany, the operational envelopes have been expanded to load changes up to 8% REO with gradients up to 60% REO/min for frequency control and to load changes up to 70–80% REO with gradients up to 2% REO/min for load following, to meet the latest grid requirements (see Annex I for further details on the flexibility capabilities and requirements in Germany).

As discussed in detail in Section 5.2.5, following a refuelling outage of a PWR or a boiling water reactor (BWR), the nuclear fuel needs to be ‘conditioned’ based on the fuel design. In addition, the plant equipment must be calibrated following the extensive periodic maintenance that is typically performed together with the refuelling outage. Plants typically request about 7–14 days of no flexible operation to allow for fuel conditioning and equipment calibration. In addition, late in the operating cycle of a PWR reactor, the plant operator may limit flexible operation because boric acid, the neutron absorber used to control some reactors, becomes highly diluted. Reactor power changes late in core life result in large quantities of liquid (primary water) waste generation, which must be processed and discharged. This curtails flexible operation in the period towards the end of the fuel cycle and, depending on the core design, it may be up to a month before flexible operation can be performed again. Figure 23 illustrates an example of a French nuclear power plant where non-flexible operation periods are determined and communicated to the grid system operator.

Additionally, a few nuclear power plants in the United States of America and Europe [29, 30] have conducted studies and have experience of carrying out some load following manoeuvres in a planned manner, as described earlier in Section 2.2.1. Figure 24 shows a limited load following scheme currently practised in Belgium. Some plants in the UK have agreements with the grid system operator to carry out rapid load reductions that may be required under certain infrequent grid conditions, as described in Section 2.2.3. Annex III provides further studies and experiences of several Member States.

From operating experience, the common capabilities that are currently included in design and utilized in some nuclear power plant operations include [31]:

- A power (load) cycle between 100% and 20% RTP, sometimes on a daily basis;
- A power (load) cycle over a smaller range more frequently, or over a larger range less frequently;
- When power cycling, a ramp rate of 2% RTP per minute;
- Power adjustments of up to ±5% RTP, in the AGC mode;

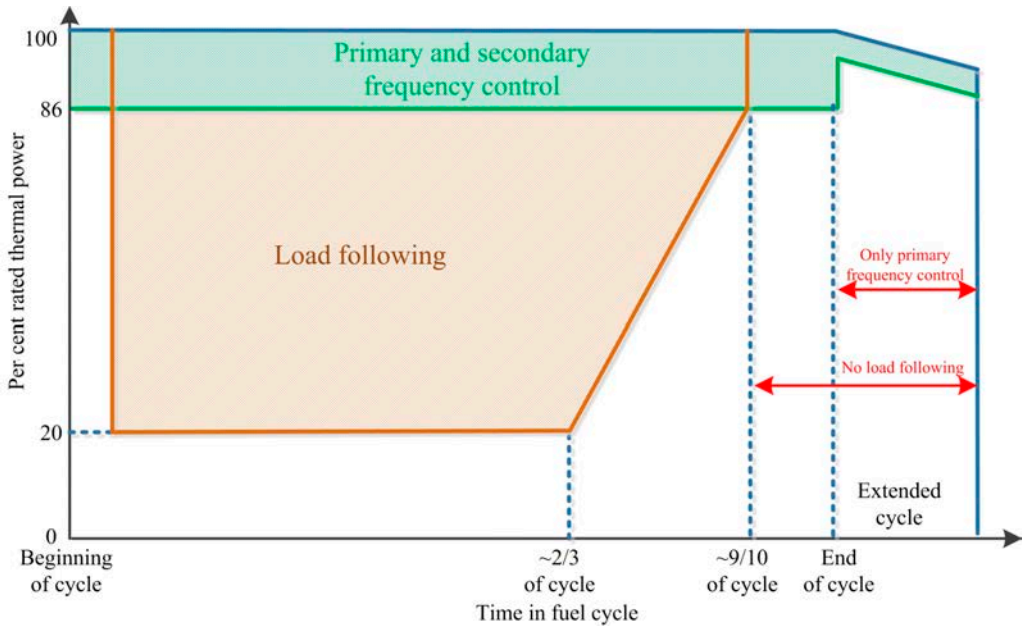

FIG. 23. Flexible operation limits during a fuel cycle in a French pressurized water reactor (courtesy of S. Feutry, Électricité de France, reproduced from Ref. [28]).

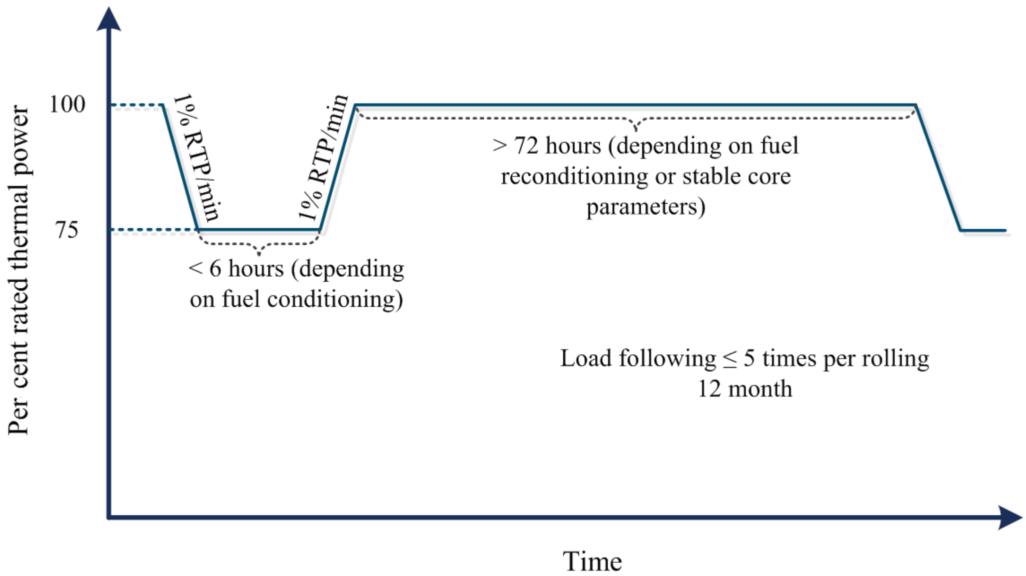

FIG. 24. Limited load following practised by Belgian nuclear power plants (courtesy of F. Flachet, Electrabel, reproduced from Ref. [30]). RTP — rated thermal power.

— Power adjustments of up to ±2% RTP within 30 seconds in the AFC mode;
— No flexibility at certain times, such as during fuel conditioning or at the end of a cycle (in PWRs);
— A minimum power for extended low power operations of 20–40% RTP.

4.2.4. Assessing the capabilities of a nuclear power plant to meet the flexibility requirements

Once the extent and the type of necessary flexibility are determined, in-depth impacts on the nuclear power plant design and operation (i.e. requirements of the safety analysis), on operational parameters and limits, on design and on operation need to be assessed. This assessment will provide inputs for additional specifications to be implemented and qualified. A comprehensive list of technical and operational impacts on the plant is provided in

Section 5. Examples, based on experience of technical realization, are given in Annexes I and II, for different types of plant design and conversion, respectively.

Results of investigations in Member States also show that some designs of nuclear power plants cannot achieve a significant level of flexibility, although they may have capabilities to perform a limited amount of load following and/or frequency control. Furthermore, even if a plant has the capability and design to operate flexibly, there are certain operational and technical conditions that could restrain the utilization of that capability. For example, following a planned periodic refuelling outage in a PWR or BWR, it is necessary to increase the power slowly in a planned manner for fuel conditioning and for recalibration of instruments. Hence, it is not possible to operate the unit flexibly for several days, or even weeks following a refuelling outage. In addition, towards the end of the fuel cycle, the capability for flexible operation may be diminished, up to several weeks prior to the end of the cycle, because of the reduced reactivity margin in the core, the reduced boron concentration in the coolant or the conditioning of the fuel. These issues are discussed further in Section 5, and illustrated in the case studies provided in the annexes.

The feasibility of flexible operation and the resultant decision as to whether the nuclear power plant should be operated in a flexible or baseload mode of operation can be influenced by several factors. These include whether the plant in question is new or is an existing plant that currently operates in baseload mode and is being considered for load following and frequency control mode of operation. There are different assessments for the extent of additional modification of plants that were already designed for flexible operation and those that have to be converted from a baseload design to flexible operation.

Regardless of whether a nuclear power plant is new or currently operating, the process of identifying the impacts of flexible operation on the plant design and operation mainly focuses on:

- The impact on the design and safety analysis, which would require demonstration of the facility meeting the applicable design and safety requirements under flexible operation conditions.
- The impact on the plant SSC design and operation (identified by the design and safety analysis), which would require changes to the design and operation of the SSCs (and of the entire facility) to meet the applicable design and safety requirements under flexible operation conditions. This impact evaluation covers:
  - The design limits of SSCs (component based evaluation);
  - The design durability of SSCs (phenomenon based evaluation).
- The impact on the efficient and economic operation of the plant (performance and economic based evaluation).

The results of this impact determination process provide preliminary information on the extent and feasibility of flexible operation — which can be implemented and performed — during the decision making process. Although the focus of impact determination is similar for new and currently operating nuclear power plants, decision making may considerably differ from new to existing plants, as explained below.

4.2.4.1. New nuclear power plants

New nuclear power plants that are now being built or planned are expected to operate for up to 60 years, or even longer. During this long operating lifetime, the structure of the electricity supply systems and the electricity market arrangements are likely to change significantly. This may alter the needs for flexible operation by plants in the future. Consequently, it may be beneficial if new plants are designed to have the potential for future flexible operation, even if they are not required to operate flexibly in the early part of their operating lives.

New nuclear power plants may have an advantage because the nuclear steam supply systems (NSSSs) and the balance of plant (BOP) systems, including the control systems, are generically designed with the anticipation and consideration of some degree of flexible operation. These systems need to be confirmed by the purchaser of the technology as meeting or exceeding the flexibility requirements of nuclear and grid regulations of the Member States, as well as the requested degree of operational flexibility by the owner/operating organization. Any short-fall of requirements and expectations needs to be considered and incorporated to meet the detailed design.

Furthermore, every nuclear power plant has to be licensed in the country where it is to be built and operated. This may require consideration of national regulatory requirements for flexible operation in addition to the requirements in the country where the design was originally licensed or generically approved. It has to be demonstrated that the selected technology is aligned with the international and generic nuclear safety requirements (e.g. IAEA safety requirements, which are described in the design and operation safety standards [32, 33]) and also meets the national — and in some cases, regional — requirements (national nuclear regulations, national or regional grid codes, environmental regulations or intergovernmental agreements with neighbouring countries, etc.). These additional requirements need to be satisfied at this stage.

Some comprehensive plant specifications and procedures have been developed by organizations comprising designers, developers, vendors, and electrical and nuclear industry associations that include the performance requirements for load following and frequency control [34, 35]. These will be useful for Member States building a new nuclear power plant where the energy planning models predict a need for various magnitudes and forms of flexible operation. For example, these specifications can be used in the bid invitation specification by plant purchasers to make their request for a bid as clear and complete as possible to the technology provider. The bid invitation specification related to flexible operation includes the maximum and minimum load conditions, the frequency control range and dynamics, and the rate of ramping when load following, etc. However, it must be understood that it is the responsibility of the plant owner/operating organization to ensure that the specifications related to flexible operation comply with the national laws and regulations, such as nuclear, electrical, commercial and financial codes and regulations.

Furthermore, those requirements for flexible operation need to be validated during initial startup testing, and any limitations in capabilities confirmed at the beginning of operations. Additionally, the safety case for licensing needs to be developed to support flexible operation.

Any decision on the type and extent of flexibility would also allow nuclear power plants to establish the necessary engineering and operation and maintenance (O&M) philosophies to support flexible operation in advance. This should include how and when maintenance activities are scheduled, as well as the operating procedures and training needed to support flexible operation.

4.2.4.2. Existing nuclear power plants

Conversely, a nuclear power plant that previously operated in a baseload mode of operation only and is now considering flexible operation faces a more complicated situation, as it will revise not only some technical aspects, but also operational philosophies. For some current plant designs, existing SSCs may permit the transition from baseload to flexible operation conditions, such as limited frequency control or planned and infrequent periodic power ramping. These may be within the existing main design and licensing conditions, and may be accomplished with some minor modifications, depending on the extent of flexibility. Depending on the plant design, major modifications, particularly of the control systems, may be required to support frequency control or load following with the specifications that were determined (see Section 4.2.3). Licensing changes will also be required, and existing engineering and O&M philosophies, including the plant life management, will require review and adjustment to support extensive frequency control and load following. As various existing maintenance and surveillance activities would require performance at steady state conditions, they have to be carefully incorporated into flexible operation activities. There will also be a need for changes to the monitoring and maintenance schedules and retraining for the maintenance resources, including ageing assessments and other supporting engineering analysis. More importantly, retraining will be required for the operators to switch from a traditional baseload operation mindset to one that supports flexible operation.

A number of existing nuclear power plants are considering life extensions of 20 years or further. The plant owners/operating organizations that are considering significant life extensions should also include in their plans whether the need for flexible operation is likely to arise before the end of plant life, as recommended in Ref. [36].

4.2.5. Establishing pre-agreements among stakeholders

At this stage, it is beneficial to establish an initial agreement between the nuclear power plant owner/operating organization and the grid system owner/operator(s). This agreement, commonly called the ‘operational constraints and guidelines agreement’, ought to stipulate the restrictions and capabilities from both the plant and grid perspectives.

The basis of such agreements has to comply with the framework of nuclear and energy regulations. For example, the grid code requirements define the minimum restrictions and capabilities for the interface agreements between the nuclear power plant owner/operating organization and the grid system owner(s)/operator(s). As mentioned in Section 4.2.3 above, discussions with the regulatory bodies are beneficial in order to agree on what is requested and what can be provided within the nuclear regulatory requirements.

Regardless of the agreement envelope, both parties must understand that nuclear safety is the overriding requirement for any flexible operation. From the nuclear power plant owner/operator side, any time that the flexible operation will place the facility outside its operational limits and conditions (OLCs) and operating licence requirements, they have to be able to reject the request.

Similarly, the grid system operator may need to have the nuclear power plant perform flexible operation in case there is an urgent need for it to stabilize the grid and/or prevent it from significant degradation and collapse. Noting that this may require additional evaluation and judgement with respect to plant operation and licence requirements, specific conditions[14] for grid emergency flexibility may be a subset of the agreement.

For newly planned nuclear power plants, some of these are typically communicated to the technology vendor for verification or consideration in the design and operation. If there are multiple (domestic or international) plant and grid owners, or interregional/international power flow agreement parties, inclusion of those in this agreement would be beneficial.

The specific parameters for meeting the grid system operator needs and the nuclear power plant capacities, as a minimum, may include one or a combination of restrictions and capabilities:

- Load reduction range in power terms (e.g. '*X*'% to '*Y*'% of RTP or '±*X*' MW(e) power) for each flexible operation type (e.g. primary/secondary frequency control or load following).
- Power ramp rates (e.g. '*X*'% RTP/min, ascending and descending).
- Maximum/minimum time at reduced power (e.g. maximum '*X*' hours at low power or minimum '*Y*' hours at a plateau after power increase).
- Number of load cycles (e.g. '*X*' numbers per day, month or fuel cycle).
- Periods of no flexibility (e.g. '*X*' weeks after refuelling outage or '*Y*' months towards the end of the cycle).
- Condition based plant restrictions and impossibility for flexibility (e.g. no flexibility if there is a known and monitored fuel leak, equipment out of service, or conduction of a test requiring steady power or equipment conditions). These can also indicate physical limits, such as the available capacity of tanks and condensers and the environmental limits, such as effluent discharge allowance, or operational limits, such as vibration boundaries for condensers or heater drains.
- Specific load balancing conditions for flexibility (e.g. no concurrent frequency control and load following).
- Identification and prioritization of flexible operation unit(s) in a multiunit site and multisites under the same ownership.
- Advance notification time (e.g. the request is to be submitted '*X*' hours/days/weeks before the load change).
- Communication methods (e.g. manual, telephone, email, fax or automatic).
- A common language for communications.
- Requesting and responding entities (e.g. grid control room operator, plant control room operator or plant owner dispatch/planning centre[15]).
- Decision making and overruling authorization.

Reference [37] discusses a specific example of such an agreement.

4.2.6. Assessing optimal implementation of flexible operation of a nuclear power plant

A utility (public or private) that includes nuclear energy sources in its generation portfolio may consider adjusting the output of the nuclear units when optimizing the generation plan because:

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[14] These may be similar to the emergency load reductions described in a typical agreement between the grid system operator and a baseload operating nuclear power plant.

[15] The protocols in some Member States are defined in regulatory documents. For example, the national/regional grid code may require all operational communications go only to the control room of the plant. Nuclear power plant owners/operators that have a 24/7 power trading organization may elect to have the requests for flexible operation communicated through them, although this would not be acceptable in some Member States where communications go directly to the generating plant operators. On the other hand, plant owners/operators without a power trading organization would need to establish a line of communication between the grid control centre and the control room staff.

— Nuclear generation will be balancing during certain periods of time.
— It will be necessary to keep enough non-nuclear generating units on-line to provide the needs for operational reserves and frequency control.
— The actual amounts of power being generated by the non-renewable and renewable energy sources may be higher than expected, thus affecting the initial generation planning.

The planning and scheduling of a generation portfolio, including a nuclear generation share, depend on the requirements by all regulations (nuclear, electrical, financial, commercial, etc.) and the requirements, expectations and specifications of other stakeholders of the electrical system (generation/storage technology utilization, demand response incentives, energy saving plans, development of smart grids, etc.). These requirements may be determined by the various stakeholders in different electrical regimes, and optimization of national and corporate portfolios differs in each case. In addition, in Member States where the electrical grid system is deregulated and privatized, there are incentives — within market rules and regulations — for the generating units, including nuclear units, to provide frequency control and for management of power flows across interconnections. These may include, for example, payments for providing ancillary services and balancing mechanisms.

At the operation level, grid system operators monitor the performance of the generating units (electrical output and frequency, typically in seconds or minutes), taking action to balance overall demand and generation by requesting plants to adjust output, as necessary.

4.2.6.1. Vertically integrated electrical regimes

In vertically integrated electrical regimes, the grid system operator manages the optimization of the generation plan by utilization, in order of merit, of non-renewable energy sources (including run of the river hydroelectric generating units) and renewable energy sources (solar, wind, etc.) as codified in the policy and regulations, and then by identifying and ranking dispatchable generating units from the least to the most expensive according to generation costs provided by plant owners/operators. This optimization of the cost of balancing demand and generation is performed by integrating the costs and constraints for all grid users (unit performances, contracts such as power purchase agreements, redispatch costs due to plant or grid outages or insufficient transmission capacity, loss coverage, etc.).

Again, the obligation to operate a nuclear power plant flexibly will be determined by:

— The probability that the plant will participate in balancing;
— The number of hours in the plant lifetime when it will participate in balancing.

If the probability and the number of hours are not significant, the constraints brought by intermittency of renewable energy sources or by needs for power reserves can be solved using specific regulations imposing curtailment for renewable energy sources and specific capacity payment for reserve capacity, respectively. These regulations can be based on cost–benefit analysis assessing the overall benefit of these measures.

4.2.6.2. Unbundled electrical regimes

In unbundled electrical regimes, the owners/operators of generation, transmission and distribution are generally separate organizations, each with different roles in determining the cost and constraints for their entities. The dispatch of generation may be the responsibility of the transmission system owner, or of a separate organization (e.g. an independent grid system operator). There may also be separate supply companies that trade between generating companies and end consumers. In this arrangement, the different users of the grid system have to be treated in a fair and equable manner, to avoid competition distortion in determining the generation plan. Optimization of flexibility (i.e. optimization of generation dispatch for grid flexibility) in the unbundled electrical regimes shows wide variety in Member States. Some examples of these practices are:

— In some Member States, optimization of the whole electrical system is performed by the grid system operator(s) by integrating costs and constraints (technical, contracts, outages, etc.) for all users. Each generating company notifies the grid system operator of the availability, prices and technical parameters

such as ramp rates, for each of its generating units, typically for the day ahead. The grid system operator then produces an optimized schedule giving the planned load profile for each generating unit. The individual generating units are then expected to follow the load profile they have been given. The grid system operator will request changes from the planned load profiles in real time where necessary to achieve system balancing.
— In some markets in Member States, individual generating companies attempt to optimize the operation of their generating units to meet their contracts, and submit their planned load profiles to the grid system operator. The individual generating units are expected to follow the load profiles that they have submitted. In these regimes, however, the grid system operators also try to optimize only their obligations and areas of profit. Therefore, the grid system operator will order changes to the load profiles submitted by the generating units where necessary to achieve system balancing.
— In some Member States, companies hold both generation and demand assets and are responsible for achieving an approximate balance between their own generation and demand, which can include energy transferred across interconnections. Such companies, which are referred to as balancing responsible parties, also provide their demand–generation profiles to the grid (transmission) system operator to ensure that their share in the total portfolio is balanced. The grid system operator collects and integrates all balancing responsible party positions, then adds its specific needs as loss coverage.

4.2.6.3. Fleet consideration at owner/operator optimization

The capability of a fleet of nuclear power plants to be operated flexibly offers more degrees of freedom when optimizing the operating costs of nuclear plants, as follows:

— In developing a schedule for 1–5 years ahead, plant outages for refuelling and for scheduled major maintenance are planned for by considering the best period for electricity prices (when prices are low) and for smoothing the use of industrial resources for repair and maintenance activities (Fig. 25).
— In planning the ‘months to 1 year ahead schedules’, shorter term options, e.g. delaying outages by reducing the thermal power (sequential down power plateaus or coastdowns) within the limitations of effective fuel cycle length and regulatory requirements for shutdowns for maintenance and inspections, are considered. The concept of ‘usage value’ of generation is practised in French plants to optimize the use of each nuclear generating unit (Box 1).
— In planning the ‘weekly and daily schedules’, the generating units are optimally selected to balance electricity demand and to provide flexibility.

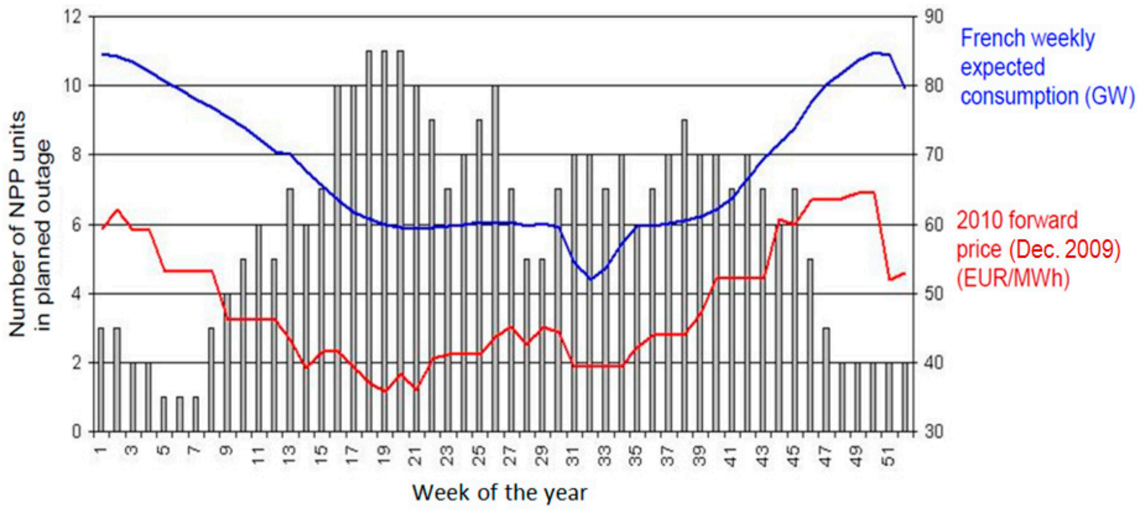
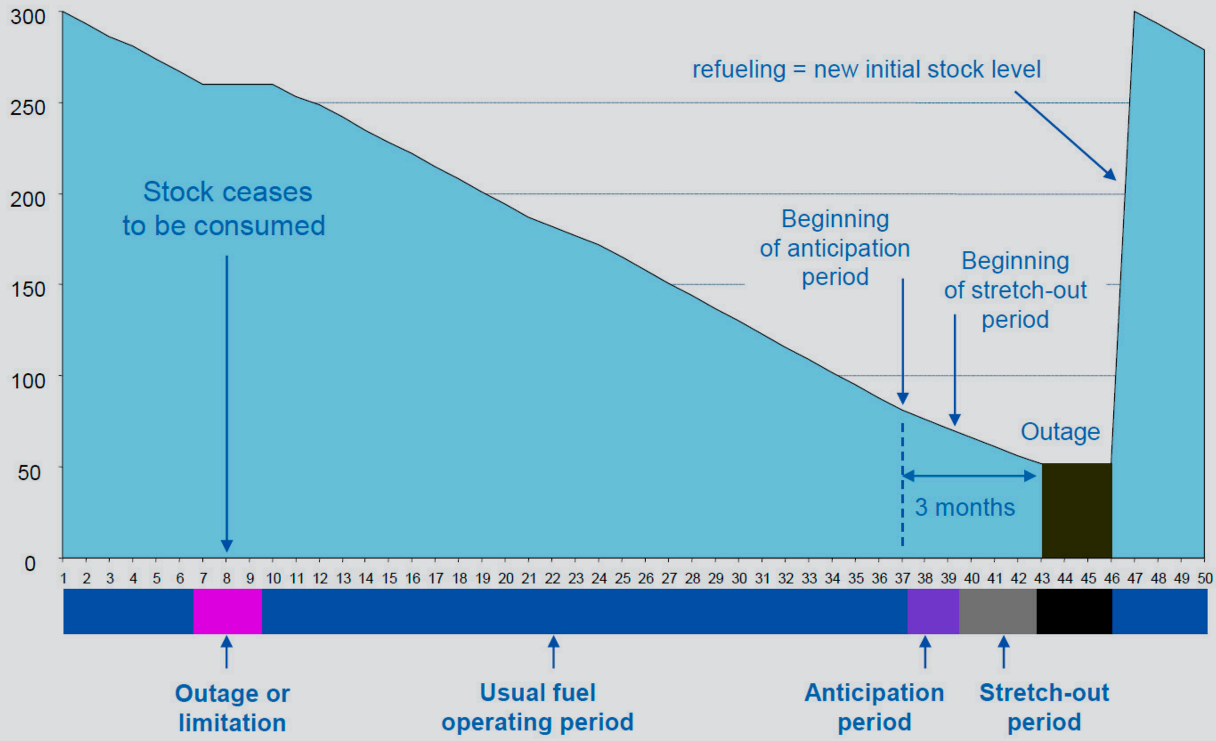


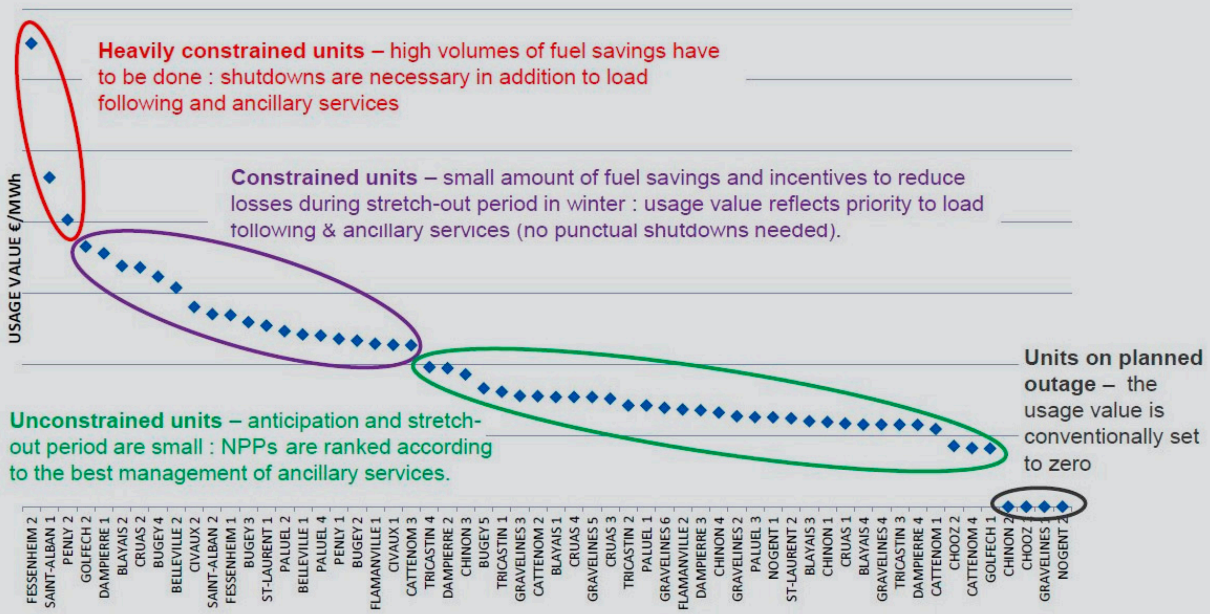
FIG. 25. Weekly break-down of the French nuclear power fleet outages in a ‘1 year ahead’ schedule in 2010 (courtesy of F. Farruggia, Électricité de France, reproduced from Ref. [9]). NPP — nuclear power plant.

Box 1. Usage value for nuclear generation optimization in France.

Usage value management is a way of allocating nuclear fuel savings to a plant in order to keep and/or optimize its outage or its generation schedule [9]. Usage value is an economic criterion used to decide whether the generation is to be used at present or in the future. Treating a nuclear generating unit as a stock of energy, the energy available and rationed throughout the year can be planned.



The usage value can then be used for ranking and classifying the generating units in merit order for supplying electricity. The graph below shows an example of this ranking and classification for every nuclear power plant unit in a fleet.



Courtesy of F. Farruggia, Électricité de France, reproduced from Ref. [9]. NPP — nuclear power plant.

4.2.7. Establishing agreements between nuclear power plants and grid system owners/operators

After establishing the envelope for flexible operation, the initial agreement that was recognized between the stakeholders (see Section 4.2.5) is modified and finalized to settle the commercial and technical terms. This agreement is documented and signed by senior officials of the owners/operating organizations for the nuclear power plant and the grid system.

As the grid infrastructure, the facility and/or generation fleet and location will change during the nuclear power plant lifetime, periodic reviews and revisions of the agreement will be necessary to incorporate new structures of the grid and configurations of the plant.

4.3. STAKEHOLDER INVOLVEMENT IN FLEXIBLE OPERATION DECISION MAKING

4.3.1. Nuclear power plant owner/operating organization

The owner/operating organization has the ultimate responsibility for safe operation of the nuclear power plant, ensuring compliance with the plant's licensing basis, and for deciding the modes of flexible operation that can be offered to the grid system operator. It is the main stakeholder of investment, purchase, construction and O&M of the facility. It is also the authority responsible for preparing preliminary safety, feasibility and business cases for the stakeholders, as applicable at the decision making stage. In order to achieve flexible operation of its plant, the owner/operating organization will lead efforts to acquire and implement flexible operation capabilities while working closely and collectively with a number of stakeholders. This involvement includes the following:

- Communicating and agreeing on the technical requirements and limitations with the responsible designers for the plant (reactor, fuel and power conversion technology providers) and associated technical support organizations, in order to carry out studies to demonstrate that the plant is designed and operated in a safe and acceptable manner, and all applicable regulations are complied with, during flexible operation.
- Gathering all regulatory requirements and guidance that would set the boundaries of the operation and safety case, and holding discussions with regulatory bodies to gain preliminary acknowledgement of operational and design conditions.
- Collecting detailed operating experiences from plants of similar design and vintage that have experience with flexible operation. For new plants, this includes consistency and compliance with national, regional and international codes and requirements, changes to generic design features and parameters, operation, surveillance, and monitoring and maintenance programmes and procedures. For plants that are transitioning from baseload to flexible operation, understanding and knowledge have to be obtained regarding plant system design modifications; changes to plant O&M programmes, procedures and practices; and training scope changes, etc., that have been implemented and utilized for converting the facility and personnel from baseload to flexible operation.
- Communicating and agreeing with the grid system operator(s) on the extent of flexible operation that is to be performed, including the acceptable and feasible technical and operational limits, such as the magnitude and speed of load changes, and how often and for how long operation at less than 100% RTP will be proposed.

It is recommended that the plant owner/operator establish a formal procedure or protocol document, as described in Section 4.2.5, as early as possible in the nuclear power plant project.

4.3.2. Nuclear regulatory body

While specific regulations governing the safe operation of nuclear power plants vary among Member States, the general regulatory philosophy is consistent: plants must be designed, built and operated within the bounds set by safety criteria. Regardless of small variations in different regulatory frameworks as manners of oversight and involvement vary among Member States, the nuclear regulatory body's roles and responsibilities are consistent: establish and maintain regulatory requirements governing safe operation, oversee the owner/operating organization maintenance of the plant's design and licensing bases, and approve changes to them. Therefore, the nuclear regulatory body is a main stakeholder because it reviews, assesses and authorizes the safe construction and O&M of the facility, including the flexible operation aspect, that are demonstrated within the plant's design and licensing bases[16], to ensure public health and safety. These design and licensing basis documents demonstrate the integrated plant system's response and the ability of its safety related SSCs to mitigate the consequences of anticipated operational occurrences (AOOs) and postulated design basis accidents (DBAs). Basis documents also capture plant staffing requirements, operating and training requirements, and normal and abnormal operating procedures.

Nuclear safety prevails over any other aspects; therefore, the nuclear regulatory body has a critical and primary role in the flexible operation decision, and it is essential to obtain its involvement in this decision making process as early as possible.

For new nuclear power plant licensing, the nuclear regulatory body ensures that the plant construction and operating licence application captures the extent of flexible operation and its impact on the plant's design and licensing basis documents (see Section 5 for further information on potential impacts of flexible operation that are associated with safety evaluation.) The regulatory body ensures that all applicable regulatory requirements have been satisfied over the entire range of operating conditions. Relevant operating experience of similar plant designs and flexible operating modes need to be reviewed and included in the regulatory assessment. Based upon its review of the plant design and licensing basis documents, the demonstrated ability to safely and reliably support flexible operation, and relevant operating experience, the regulatory body ought to clearly define any limitations and conditions on the extent of flexible operation.

For new nuclear power plant licensing, the increase in scope, schedule and cost associated with flexible operation is relatively small compared with the overall plant design, construction and licensing. Completing the activities necessary to support flexible operation during the initial phase (prior to construction) is the most economical approach compared to a future revision to the plant's design and licence bases. Even for cases where flexible operation is not anticipated and only baseload operation is planned, owners/operating organizations need to consider ensuring design capabilities and requesting approval for flexible operation. Similarly, the nuclear regulatory body would inquire about possible future flexible operation and the plant's capabilities to support this operating mode.

For nuclear power plants that are transitioning from baseload operation to flexible operation, the regulatory body ensures that the licence amendment application captures the extent of flexible operation and its impact on the plant's design and licensing basis documents. The regulatory review needs to ensure that all necessary upgrades to support flexible operation have been implemented, including instrumentation and control (I&C) systems, operating procedures and operator training (see Section 5 for further information on the potential impacts of flexible operation). The regulatory body ensures that all applicable regulatory requirements have been satisfied over the entire range of operating conditions. Relevant operating experiences of similar plant designs and flexible operating modes are reviewed and included in the regulatory assessment. Based upon its review of the revised plant design and licensing basis documents, the regulatory body may define new, or modify existing, limitations and conditions on plant operations.

The regulatory body may also require there to be continued monitoring or periodic inspections of the nuclear power plant's technical and administrative programmes and procedures during periods of flexible operation, to validate conformance with the acceptable range of licensing conditions at all times.

It is a good practice to have the regulatory body establish requirements and any specific limitations, such as acceptance criteria or method of ensuring safe operation, and to communicate these to the owner/operating organization early in the project, certainly much earlier than the construction phase in the case of a new nuclear power plant.

It is beneficial if the nuclear regulatory body can also communicate the restrictions and limitations for any extent of flexible operation — from the perspective of nuclear safety considerations — with the electricity system regulator in order to establish a consistent and common understanding of the rules for nuclear and electrical system regulation.

[16] Design and licensing basis documents, such as the nuclear power plant's operating licence, technical specifications and safety analysis report, capture the OLCs, as well as reactor protection systems and engineered safety feature functions, set points and protection/prevention capabilities credited in the safety analysis. In addition, instrumentation and control system uncertainties, response times, calibration and surveillance requirements are captured to ensure adequate and appropriate safe plant response to events.

4.3.3. Electrical system regulatory body

The nuclear regulatory body governs the safe operation of nuclear power plants, and in most Member States an electrical system regulatory body oversees the safe, stable and reliable operation of the grid system in order to secure electrical energy supplies and manage Member State energy policies. Where that is the case, this entity may establish requirements and limits (e.g. minimums/maximums) for the extent of flexible operation, and their method of application through electrical network (grid) codes and plans. These regulations will affect not only the grid system operators but also the owners/operating organizations of generating units, including the nuclear units.

It is a good practice to have the regulatory body for the electricity system establish or endorse a grid code that includes the requirements and any specific limitations, such as technical characteristics, grid operational modes and compliance criteria, and to communicate those to the grid and nuclear power plant owners/operating organizations.

The electrical system regulatory body also needs to communicate requirements for flexible operation to the nuclear regulator in order to establish consistency in the regulations on both nuclear and grid aspects.

4.3.4. Grid system operator

Typically, the grid system operator governs the access to and usage of the grid system according to a grid code similar to that of Ref. [7]. Such codes set the technical and commercial requirements with which the grid users must comply. The grid code may require generating units to have a specified capability for frequency control, for power ramping and for operation for prolonged periods at reduced load. The owner/operator of a nuclear power plant needs to enter into discussions with the grid system operator at an early stage to ensure a common understanding of the requirements, how they are to be interpreted and how compliance with the requirements will be assessed. These requirements may be enforced by law and governed by specific regulations. In some cases, alternative methods for achieving compliance may be guided, and collectively agreed by the grid users and other generating unit operators, as the regulations allow. For example, the regulations may allow the quantity of frequency response supposed to be delivered by a nuclear generating unit to be provided by modifying hydroelectric generating unit operations to assume and contribute to the overall frequency response magnitude and capability.

Specifically, the key design and operation parameters for flexibility and their overall governance ought to be discussed and agreed with generating unit owners/operators, and protocols established on methods of meeting the requirements and complying with the regulations on those parameters. It is strongly recommended that the grid system operator communicate and discuss such design requirements with the nuclear power plant owner/operator very early in the design stage so that they can be considered in the design requirements and safety assessments. This communication and agreement on the requirements may also be an important factor in technology selection.

5. ASPECTS OF FLEXIBLE OPERATION IMPLEMENTATION IN NUCLEAR POWER PLANTS

Comprehensive understanding and evaluation of a nuclear power plant’s design and licensing bases are necessary to:

— Reach an informed decision on the need for and extent of flexible operation;
— Confirm the capacity and capability of the design and configuration for flexible operation;
— Plan and implement design features or modifications to achieve the capabilities needed;
— Perform flexible operation in a plant, safely, reliably and efficiently.

These include comprehensive evaluation of the design and O&M specification of the plant SSCs, design and safety analysis, OLCs, regulations, codes and standards, operating procedures and training, and needs for instrumentation and human resources for special controls and monitoring. The scope and extent of this evaluation depend on many variables, including operating experience, plant and system design, regulatory environment and magnitude, and the rate and periodicity of power manoeuvring required.

This section investigates the potential impacts of flexible operation on key aspects of a nuclear power plant's design and licensing bases and O&M, including the human performance aspect. The identified impacts need to be addressed by a series of technical and administrative controls and solutions for implementation and performance of flexible operation, which is also elaborated on in this section. In addition to what needs to be considered, as investigated in various studies [25, 30, 31, 38], the section discusses how flexible operation could be implemented in plants.

The topics discussed below are not a complete list of all potential impacts, as they will differ depending on the plant location, design, configuration, size, age (including the vintage of technology), fuel type, O&M practices, effectiveness and extent of existing programmes, etc. Rather, they are the common impacts/issues/solutions that have been observed and collected from operational experience, as well as those that can be anticipated on the basis of the latest knowledge and technical fundamentals.

The technical and programmatic requirements can then be used in economic considerations, which are discussed in Section 6, because the ultimate decision for the extent of flexible operation to be implemented at a specific nuclear power plant will involve its costs and returns on investment.

The discussion of the impacts and counter-measures is organized into four areas in this section:

— Analysis based aspects;
— Phenomenon based aspects;
— Component based aspects;
— Human performance based aspects.

Table 3 illustrates the interface of the phenomenon and component based aspects and contains cross-references to the subsections below in which they are discussed. It should be noted that some discussions are repeated as part of different perspectives for cross-reference. For example, nozzles are discussed under both component based aspects and phenomenon based aspects for fatigue.

Annexes I and II further supplement the information discussed, by providing specific methods that are utilized with examples of original design considerations (German case study) and baseload to flexible operation conversion (French case study), respectively. They also discuss lessons learned in addressing some of these impacts and issues and illustrate some possible solutions.

It should be recognized that the majority of impacts discussed in this section primarily apply to the load following type of flexible operation. Based on the existing technologies and operating experience, frequency control, particularly primary frequency control, has a very limited impact on plant SSCs. This is because small frequency deviations typically do not cause significant cycling in pressure, temperature or flow, and do not require activation of many components. An exception would be the control systems, such as the turbine controller module that helps the turbine change power on a frequency deviation.

5.1. ANALYTICAL ASPECTS OF FLEXIBLE OPERATION

Flexible operation may challenge the underlying assumptions within the licensing basis of an existing nuclear power plant or of generic design and licensing of a new plant, as well as the plant technical specifications (TSs) and the safety analysis report. As such, a comprehensive assessment of the plant licensing basis is required prior to undertaking flexible operation. This includes the initial safety assessments [39] and periodic safety reviews [40].

In some cases, depending on the Member State regulatory requirements, prior review and approval by the regulatory body are required before implementing flexible operation. The subsections below briefly discuss the potential impacts of flexible operation on key analysis supporting the licensing basis as well as SSC performance. The analysis associated with particular phenomena and components is further discussed in the sections describing the phenomenon and component aspects.

TABLE 3. AGGRAVATED PHENOMENA BY FLEXIBLE OPERATION AND AFFECTED PLANT SYSTEMS, STRUCTURES AND COMPONENTS

Component (section of this publication) / Phenomenon (section of this publication)	Fuel rods (5.3.1)	Fuel assemblies (and fuel channels for boiling water reactors) (5.3.2)	Control rods (5.3.2)	Control rod drive systems (5.3.4)	Core detectors (5.3.5)	Core shrouds (5.3.6)	Boiling water reactor jet pumps (5.3.7)	Reactor coolant pumps (5.3.7)	Steam dryers (5.3.8)	Pressurizers (5.3.9)	Steam generators (5.3.10)	Chemical and volume control systems (5.3.11)	Valves and pipes (5.3.12)	Turbine components (5.3.13)	Other conventional island mechanical components (5.3.14)	Conventional island electrical components (5.3.15)	Instrumentation and process control components (5.3.16)
Fatigue (5.2.1)	X	X	X	X		X	X		X	X	X	X	X	X	X		
Erosion/corrosion (5.2.2)	X										X		X		X		
Wear and tear (5.2.3)			X	X									X	X	X	X	X
Core power redistribution (5.2.4)	X				X												
Pellet–cladding interaction (5.2.5)	X																
Creep induced channel distortion (5.2.6)	X	X															
Extended operating cycle (5.2.7)	X	X	X	X													X
Chemical impurities (5.2.8)	X	X						X			X		X		X		
Ageing (5.2.9)			X	X									X		X		X

Note: 'X' denotes the aggravated phenomena.

5.1.1. Safety analysis

5.1.1.1. Accident analysis

As described above, a nuclear power plant licensing basis captures the boundary of plant operation and response of SSCs designed to mitigate the consequences of AOOs and DBAs to ensure safe operation. However, a presumption of baseload operation may exist in the plant licensing basis, and this would affect the scope of the safety analysis report. For example, the licensing basis of a plant may limit the safety analysis of AOOs and DBAs only to reactor startup conditions (subcritical up to hot zero power) and full power conditions. This limitation is based on the assumption that a plant does not operate for a significant duration at intermediate power conditions. If that is the case, flexible operation will challenge this underlying assumption in safety analysis, as plant manoeuvring will likely result in being off those specified nominal conditions for reactor power redistribution, xenon oscillation, steam generator (SG) and pressurizer liquid levels, core flows, control rod insertion, etc.

Therefore, the plant's response to AOOs and DBAs initiated from previously off-nominal conditions (i.e.initiated at intermediate power conditions) may become necessary due to a higher probability of occurrence or a more severe consequence, resulting from longer and more frequent operation at those conditions. With those power levels where operational transients may occur, other associated initial plant conditions (e.g. the possible deformation of the shape of the axial power distribution by control rod manoeuvring) have to be taken into account. The amplitude of such perturbations has to be limited in order to avoid a violation of the OLCs after power changes. Consequently, if the results of the analysis show more severe consequences, other plant protection and control requirements, as well as additional OLCs, might be needed.

For example, the occurrence of design basis seismic and loss of coolant accident (LOCA) transients initiating during operation at reduced power plateaus may not have been fully addressed in the design bases for components. In such cases, the impacts of new plant initial conditions resulting from flexible operation that were previously not part of normal operation on existing safety analysis space need to be reconsidered. During initial design of plants, on the analysis space, the design basis may not have included analysis from intermediate power levels in all cases, considering the scenario is a limited time plant state, where the plant would be operated at full RTP for the vast majority of the time. As a result, as higher temperatures and higher power would be more limiting in terms of consequences, the design basis analysis for seismic, LOCA forces and LOCA short term mass/energy releases could be performed only at full power conditions. If that is the case, the seismic, LOCA forces and LOCA short term mass/energy release analysis at full power conditions have to be revised to specifically address operation at reduced power for an extended period of time with a reduced hot leg temperature, as it becomes a part of normal operations. Consequently, these evaluations may require the component and hot leg piping support gap conditions to be addressed, as the physical gap between a component and its support may deviate from the 'zero gap' assumption based on operation at full power for the majority of the time.

Additionally, for a plant design or configuration that has protection and control systems optimized for baseload operation, there might be the possibility of new plant transients being created or the probability of consequences of previous transients being increased. Those transients that were not previously evaluated would require analysis, either to determine readjustment of protection and control system parameters (e.g. process set points or the specific range) for which they have been tuned, or to demonstrate the acceptability of consequences. This may be an issue particularly for those plants that are being converted from baseload to flexible operation.

To minimize reload design costs, many plant owners/operators have opted for cycle independent reload safety analysis, which establishes an enveloping analysis space based on bounding input and assumptions, instead of reperforming safety analysis for each core reload design. Instead, the validity of this envelope is confirmed for each reload design by targeted parameter checks, also referred to as the reload checklist process, by comparing cycle specific core physics and reload parameters to bounding parameters that form the bases of the safety analysis (the 'analysis of record'). This approach reduces core reload design efforts; however, it also reduces operating margin and fuel management flexibility. Flexible operation requires larger operating margins (e.g. a wide band on the allowable axial power distribution and control rod insertion limits) than baseload operation. Thus, in order to support flexible operation margins, the plant owners/operators who utilize cycle independent bounding analysis may need to migrate to cycle specific core reload safety analysis based on as-built core loading and as-burned reload depletions. This approach improves the operating margins and fuel management flexibility; however, it increases the reload design cost. Planned power manoeuvring (daily load following, end of cycle coastdown to manage timing of refuelling outages, etc.) could be built into core reload depletion and safety analysis. However, unplanned power manoeuvring may alter power and burnup profiles, change core physics parameters and necessitate additional reanalysis.

5.1.1.2. Component design analysis

Component design analysis demonstrates that all plant SSCs which are important to safety conform to the design requirements under all operational modes throughout their intended lifetime. They provide a demonstration that all relevant functional and regulatory requirements have been considered adequately. For systems important to safety, this demonstration is supported by the assessments of design function performance under potential operational conditions. The assessments for overall reliability complement these assessments by considering the applicable failure modes and effects.

Any increase in thermal and mechanical cycling as a result of flexible operation will adversely affect evaluation for components with respect to fatigue, wear, erosion/corrosion, ageing, etc. For systems important to safety, the deviations from the existing component design assumptions, failure modes and effects that demonstrated insufficient system and design capacity to perform the safety functions throughout the intended lifetime in all operational modes must be reviewed and addressed. These include the expected response to static and dynamic mechanical loads and their behaviour, and a description of the effects of flexible operation on the ability of the SSCs to perform their safety functions adequately over the lifetime of the plant, including any changes for human and machine reliability.

Similarly, for systems not important to safety, evaluations have to ensure that the system changes due to flexible operation preclude the possibility of affecting safety system performance, as well as efficiency and availability. In particular, the operating conditions of secondary system components will change, thus affecting their design assumptions, such as turbine efficiency. These include changes in the efficiency of each component, as well as the overall heat balance of the secondary system, which may require reanalysis of heat balance calculations for various power levels, considering that the percentage change in REO will be neither equal nor proportional to the percentage change in RTP in the proposed operational spectrum.

Although in most cases, the extent of cycling is bounded by conservative lifetime assumptions, they have to be confirmed, and measures have to be taken to monitor that they will remain bounded. The effects of service on the performance of design functions, including surveillance, inspection and maintenance programmes, need to be described.

In addition, as noted above in the accident analysis, the component design analysis can be affected by the creation of new conditions if the plant's design or configuration basis assumptions are based on the response and performance of protection and control systems that are optimized for baseload operation. These assumption and design conditions would require evaluations either to determine the readjustment of protection and control system parameters (e.g. process set points of the specific range) for which they have been tuned, or to demonstrate the acceptability of component performance under these new design conditions.

5.1.1.3. Risk informed analysis

In addition to the traditional deterministic safety analysis, nuclear power plants may utilize probabilistic risk analysis to 'risk inform' plant O&M. Such risk analysis models usually calculate core damage frequency and large early release frequency.

Flexible operation has the potential to increase the probability of equipment failure (e.g. transformers or feedwater control systems), plant transients (e.g. loss of feedwater or power) and reactor trips, which may affect the predicted core damage frequency and large early release frequency. A systematic review of inputs to the probabilistic risk assessment and to the assumptions and supporting sensitivity analysis to address the potential impacts on equipment and operations may be necessary to support flexible operation.

5.1.1.4. Prediction of core physics parameters

Core reload depletions and core physics calculations provide input to downstream safety analysis, plant monitoring and protection systems, and operator guidance. Physics inputs include reactor startup predictions for core parameters (e.g. critical boron concentration and rod position), reactor kinetics, fuel temperature coefficients, moderator temperature coefficients, control rod and bank worth, and power peaking factors. Predicted core physics parameters are based on predetermined plant operation schemes and plans. Unplanned power manoeuvring during flexible operation may alter the power and burnup profile across the core (relative to the predictions). As such, core reload depletions and physics calculations may need to be continuously checked and evaluated following power manoeuvring, depending on the instrumentation utilized for monitoring.

5.1.1.5. Prediction of instrumentation and control system settings

Flexible operation will increase the use of I&C systems to accommodate power changes. Operation at lower powers will utilize the I&C systems for long periods of time beyond the specific range for which they have been tuned. This may require design evaluations to determine the effects on instrument uncertainties and set points. Furthermore, for existing plants being converted to flexible operation, there may be changes to plant control systems (e.g. reactivity, temperature and pressure control systems) that are associated with the changes to plant operation. These are further discussed in the sections on phenomenological and component aspects, below.

In addition, continuous operation at less than full power may extend the operating cycle beyond the existing calibration period for the various plant instruments considered in the design calculations that determine the overall instrument uncertainty and define field set points. An increase in the calibration period may negatively affect these calculations and alter the analytical set point credited in the accident analysis.

Therefore, design I&C calculations (and any necessary changes to safety analysis) to bound anticipated cycle length, operation range and operating schemes with flexible operation need to be reviewed and revised, if needed, with respect to uncertainties, set points and calibration.

5.1.2. Analytical models

Validated analytical models are used to demonstrate the performance of SSCs designed to mitigate the consequences of AOOs and postulated DBAs. The ability of these models to accurately simulate the SSC response to plant events may be affected by flexible operation.

Plant system models are based on the first principles of thermohydraulics. However, variables within the model algorithms are used to calibrate the model predictions to known operating conditions. For example, primary to secondary heat transfer is adjusted to achieve operating SG pressure in a PWR. Many of these operating parameters are power dependent and will need to be adjusted to support flexible operation. Another example is calculation of the SG liquid inventory, which is an important parameter for the postulated main steam line break DBA, and which increases at lower power levels in U-tube SG designs.

Fuel rod thermal and mechanical models are used to demonstrate compliance with regulatory performance requirements. These models are usually calibrated against a large empirical database of separate effects testing (e.g. irradiated mechanical property measurements) and in-reactor data (e.g. in-pile fuel temperature measurements or rod puncture fission gas release measurements). Flexible operation involving frequent power manoeuvring, especially when driven by control rod movement, may challenge the accuracy of these fuel performance models. Data from power ramp testing, prototypical of the power oscillations experienced during flexible operation, are used to confirm the accuracy of these models.

5.2. PHENOMENOLOGICAL ASPECTS OF FLEXIBLE OPERATION

5.2.1. Thermal load and fatigue

Components made from metallic materials have the property of losing mechanical strength under cyclic loadings that exceed certain limits — this is known as fatigue. The loadings associated with the respective load cycles have to be determined for components susceptible to fatigue and included in their sizing. The design of nuclear power plants considers a certain number of oscillations based on the anticipated load cycling during the entire lifetime, and the number of load cycles is included in the component design by assuming a relatively high number of cycles to bound the anticipated value.

Potential impacts of flexible operation: Cyclic loadings will be aggravated by flexible operation, especially when large temperature transients occur in the material, adversely affecting the proposed/established design assumptions and margins. Specifically:

— Load cycling within a limited scope is predominantly associated with only minor changes in global plant parameters such as pressure and temperature in the systems. The resulting low thermal stresses are normally not relevant to the fatigue of the affected components. Large temperature gradients with correspondingly higher loads can occur when different hot fluids meet in individual components. Therefore, small operational changes may cause abrupt and/or large impacts, referred to as cliff edge effects, concerning fatigue: for example, vibration at throttling devices (high cycle fatigue), thermal stratifications (surge line or chemical and volume control system (CVCS)) or actuations of the spray line in the pressurizer.
— High cycle fatigue may occur due to vibrations of pipes or components that are operated in an unfavourable operating range, such as surge/spray lines or pressurizer welds. High cycle fatigue may also become relevant due to fluctuating, intermittent thermal loads aggravated by flexible operation.
— Typical primary circuit components and systems that would be subjected to increased load cycling due to flexible operation include steam dryers and jet pumps (applicable to BWRs), core shrouds, nozzles, surge lines, spray lines, SG tubes and CVCS components. Particular attention has to be paid to weld seams, especially if they are not worked over in an appropriate manner.
— Specific consideration is to be given to existing plant piping design, especially regarding the weld joints and piping support gap conditions.
— On the secondary circuit, feedwater inlet temperatures will vary, possibly resulting in increased feedwater nozzle fatigue. Operating plants under sliding pressure operation or frequent thermal cycling mode will affect weld joints in piping and heater drain lines. Dryers and heaters are subject to higher load cycling due to flexible operation, resulting in an increased probability of thermal fatigue cracking. Other potential areas that might be susceptible to fatigue include turbine blade attachments and disc bores and blades.

Safety analysis: Common regulations require demonstration that the SSCs of the NSSS are designed to fulfil their design and safety functions during a plant's lifetime. Any systematic failure of components, especially the loss of integrity of the fission barrier, has to be prevented. A monitoring system has to be established to validate that actual load cycles remain bounded by the load cycles anticipated by the design. If components have to be replaced during the plant lifetime, the safe date (service life) has to be determined and demonstrated.

Possible solutions: The following solutions have been employed to address such thermal loads and fatigue phenomena:

— In addition to a low stress mode of operation, such loadings can be well controlled by a suitable design, namely the choice of suitable materials and appropriate dimensioning or mechanical design to reduce temperature changes (e.g. in the area of injection nozzles). This design is normally based on defined numbers of service conditions (in this case, load cycles) predicated on the anticipated cycles during the lifetime of the plant (or component), including the increased cycling due to flexible operation.
— Continuous fatigue monitoring (measuring, recording and analysis of wall temperatures), which facilitates graduated quick evaluation and detailed fatigue analysis, can be performed by utilizing state of the art methodology for components susceptible to fatigue. By accounting for the history of operating conditions, such as load cycles or operational transients, and comparing the actual (observed) values with the design assumptions documented in the thermal load specifications, it can be ensured that the component design imposes no restrictions on the flexible operation of plants.
— Operational control modifications can be tuned to reduce the number of cycles (e.g. set point modifications of the pressurizer level control).
— Additional periodic, non-destructive testing at specified intervals can be performed, especially for safety related components.

— Preventive measures to further mitigate the impact of flexible operation on material fatigue, including optimization of the operational controls, may be necessary. Enhanced fatigue analysis towards more realistic methods will also be helpful in fatigue assessment during flexible operation.[17]
— High cycle fatigue due to vibrations can be avoided by appropriate analysis of the components (e.g. piping) in the expected operation range. If possible, antivibration measures, such as changing thermohydraulic conditions (speed controlled pumps instead of throttling), stiffer mounting devices or other measures, can be realized. Otherwise, the related component has to be rigid enough to withstand the expected high cycle fatigue.
— Despite all of these, if a single component, or length of piping, reaches its design limits, replacement of the affected component, or pipe, would also be possible in principle.

5.2.2. Erosion/corrosion

Potential impacts of flexible operation: In the fluid systems of a nuclear power plant, throttling of flow rates may be required in flexible operation, which could result in increased erosion/corrosion due to local flow rate increases. Even though some components could be subject to reduced flow rates due to flexible operation — which would reduce flow accelerated corrosion (FAC) — the reduced temperatures resulting from flexible operation might increase the FAC in other lines.

Erosion/corrosion applies mainly to operational systems (e.g. at valves of the main feedwater system (PWRs) and extraction steam lines), rather than safety systems, which are usually on standby during normal operation of the plant. Furthermore, operational experience shows that the fluctuations of the physical parameters (pressure, temperature and flow rate) of the reactor coolant system (RCS) caused by flexible operation tend to be of secondary importance for corrosion mechanisms in the RCS, with no or only minor effects on the primary systems. However:

— Chemical impurities (e.g. aluminium, calcium, magnesium or silica) increased by flexible operation may have an impact on primary components, such as the reactor coolant pump (RCP) seals, which have been observed in some French nuclear power plants, or the SG tubes (in PWRs).
— Load following operation will typically result in a higher corrosion product transport into the SGs compared to baseload operation. This can result in the formation of corrosive environments, particularly around the top of the tube sheet area, which could accelerate common degradation processes on the SG materials.

Safety analysis: Common regulations require demonstration that the SSCs of the NSSS are designed to fulfil their design and safety functions during a plant's lifetime. Any systematic failure of components, especially the loss of integrity of the fission barrier due to erosion/corrosion, has to be prevented.

Possible solutions: The following solutions could be considered to address erosion/corrosion phenomena:

— Where components or systems are at risk of erosion/corrosion as a result of flow throttling during flexible operation, this has to be minimized either by appropriate design measures or by more vigilant and frequent monitoring and more rigorous assessments by plant specific erosion/corrosion tools and methods.
— Water chemistry procedures or guidelines may need to be revised to support flexible operation for stricter monitoring and control of increased impurities. Elements with increased concentrations need to be the subject of targeted continuous monitoring of the RCS. As necessary, corrections can be initiated in accordance with the plant's chemistry programme:
  • For the primary side of PWR plants, the pH is controlled by lithium. Control of lithium (pH) levels is important for protection of the fuel, and the control band is specified in the plant's fuel reliability procedures

[17] The influence of a water environment on fatigue (i.e. the environmental assisted fatigue effect) may be higher than predicted under the design rules and standards used in the design process of most plants. New methods for consideration of the environmental assisted fatigue effect are among the current issues to be addressed by international rules and standards. Recent investigations on fatigue have shown that the design for fatigue process described previously in standards (e.g. American Society of Mechanical Engineers codes) may not be conservative for some plants, and these findings should be taken into consideration for fatigue evaluations of new designs or conversions from baseload to flexible operation.

or guidelines based on input from the fuel vendor. During flexible operation, the control band needs to be closely monitored, and changes in lithium levels made, as required.

  - For the primary side of BWR plants, adjustment to zinc injection, hydrogen or noble metal chemistry control, based on the water chemistry, might be needed. For BWR plants with pure water operation, there are no special chemistry requirements for flexible operation. Water chemistry should be monitored more rigorously, and measures taken in the case of deviations.
  - For the secondary side of the plant, water chemistry control is important to limit corrosion to the BOP components. Flexible operation could result in the need for increased monitoring and control of the secondary side water chemistry.

— For PWRs, the effects of increased chemical impurities on RCP seals and SG tubes need to be monitored.

— For PWRs, corrosion product transport into the SGs may result in a higher frequency of required mechanical cleaning of the affected SGs.

— For BWRs with zinc and hydrogen operation, injection occurs with the feedwater. The injection is monitored and regulated based on power output, and the hydrogen discharge with the main steam depends on the cycle criterion in the reactor. For end of cycle/stretch out operation, an appropriate counter-measure, for example, could be to increase the hydrogen concentration in the feedwater. It should be noted that platinum injection, which may be performed once or twice per reactor cycle for about 10 days, requires operation at constant power to stabilize the conditions for better monitoring and controlling.

— Maintenance practices may need to be adjusted for increased maintenance on condensate polishing systems and resin bed replacements.

5.2.3. Wear and tear

Potential impacts of flexible operation: Active components (e.g. control valves or pumps) can be exposed to increased wear and tear from use, or fretting, due to flexible operation. In general, these are non-safety-related components, as the safety systems are usually on standby during normal operation of the plant, although some specific safety systems that are used often for flexible operation, such as control rod drive mechanisms (CRDMs), are particularly affected.

Increased wear will also occur in specific components that use variable controls. For example, in a conventional island, increased use of condensate and feedwater pump turbine speed controls may result in additional wear.

If flexible operation is performed by redirecting steam into the condenser, then the condenser shell and tubes and steam bypass lines will all be subject to significant additional wear and tear due to extra heat load and steam flow. Furthermore, the turbine bypass, stop and throttle valves will be subject to notably increased wear due to increased operation, which will also affect the steam spargers within the condenser.

Safety analysis: Common regulations require demonstration that the SSCs of the NSSS are designed to fulfil their design and safety functions during the plant lifetime. Any systematic failure of components, especially the loss of integrity of the fission barrier, has to be prevented.

Possible solutions: The following solutions have been employed to address wear and tear phenomena:

— Where components of safety systems (e.g. CRDMs) are used often as a result of flexible operation, this has to be considered as a specified number of duty cycles in the design (see also Section 5.3.4 for CRDM solutions).

— As anticipated, the effects of flexible operation have to be detected at an early stage of wear and tear through increased periodic inspections of SSCs of concern.

— The effects of flexible operation can be considered in maintenance and repair plans.

5.2.4. Core power redistribution

Potential impacts of flexible operation: Compared to steady operation at full RTP, power density redistributions in the core — that are caused promptly by control rod movement[18] as well as the feedback effects linked with reactor coolant conditions and the xenon distribution — will occur during load following operation:

— More frequently;
— For longer durations in the fuel cycle;
— Throughout the fuel cycle;
— More at intermediate power levels.

This core power redistribution, which will likely be promoted by flexible operation, will generate power density deformations characterized by higher peak power densities (e.g. higher linear heat generation rates (LHGRs)) and/or lower departure from nucleate boiling ratios (DNBRs) compared to the unperturbed conditions. These increases in linear heat generation and a departure from nucleate boiling crisis could affect the fuel safety limits in the OLCs.

Safety analysis: Safety analysis of accidents (e.g. LOCAs) is based on a number of parameters, including the peak cladding temperature that occurs in the course of the accident. This temperature must not exceed a specific maximum limit determined from high temperature steam oxidation testing under LOCA conditions to ensure acceptable fuel performance. This is primarily confirmed by emergency core cooling analysis. The set of the relevant input parameters includes the maximum LHGR under initial conditions. The safety criterion, for example, "fuel cladding temperature after LOCA below maximum limit", therefore defines an upper limit for maximum LHGR during normal operation, which has to be maintained as an OLC.

The safety requirements governing design and operation of PWRs also demand the avoidance of film boiling during normal operation and during AOOs with an adequate degree of confidence. The margin for the local thermohydraulic conditions associated with film boiling is generally expressed as the DNBR — the ratio between the critical heat flux (predicted by correlation) and the actual local heat flux. The occurrence of departure from nucleate boiling at the rod surface is associated with the formation of a vapour film between the cladding and coolant, which may significantly degrade the heat transfer to the coolant, causing the cladding temperature to reach such high values that the cladding integrity of the rod would be lost (burnout). The safety requirement is fulfilled as long as the transient DNBR remains above a permitted minimum safety limit.

Possible solutions: For flexible operation, the different power levels, where operational transients may occur, have to be taken into account as well as the possible deformation of the shape of the axial power distribution by control rod manoeuvring. Therefore, the amplitude of such perturbations ought to be limited, preferably already at part load, in order to avoid a violation of the OLCs after power escalation.

The following solutions have been employed to avoid violation of the LHGR:

— Fixed in-core detectors (e.g. self-powered neutron detectors (SPNDs) in German PWRs), calibrated in absolute units (watts per centimetre), are processed to generate representative signals for the key safety parameters 'peak power density' and 'minimum steady state DNBR' and the margins to OLCs. These margins are inputs to the power density limitation system, which keeps core conditions automatically within the OLC limits defined on the basis of safety analysis, as shown in Fig. 26 [41, 42].
— Plant OLCs define an allowable space based on the accident analysis initial conditions. An example of such allowable space for axial shapes versus power is given in Fig. 27 [26, 28].

In order to prevent a departure from nucleate boiling crisis, film boiling can be avoided by selecting and applying a penalty for off-normal conditions on the setting of an OLC, and dynamically adjusting this penalty based

[18] Typically, a frequency control within ±5% RTP would not have a large impact on core power redistribution, as small frequency deviations do not require significant movement of control rods due to the self-regulating characteristics of core feedback. However, in a PWR, frequency change affects the reactor coolant pump speed, which affects the core flow and temperature variation along the core.

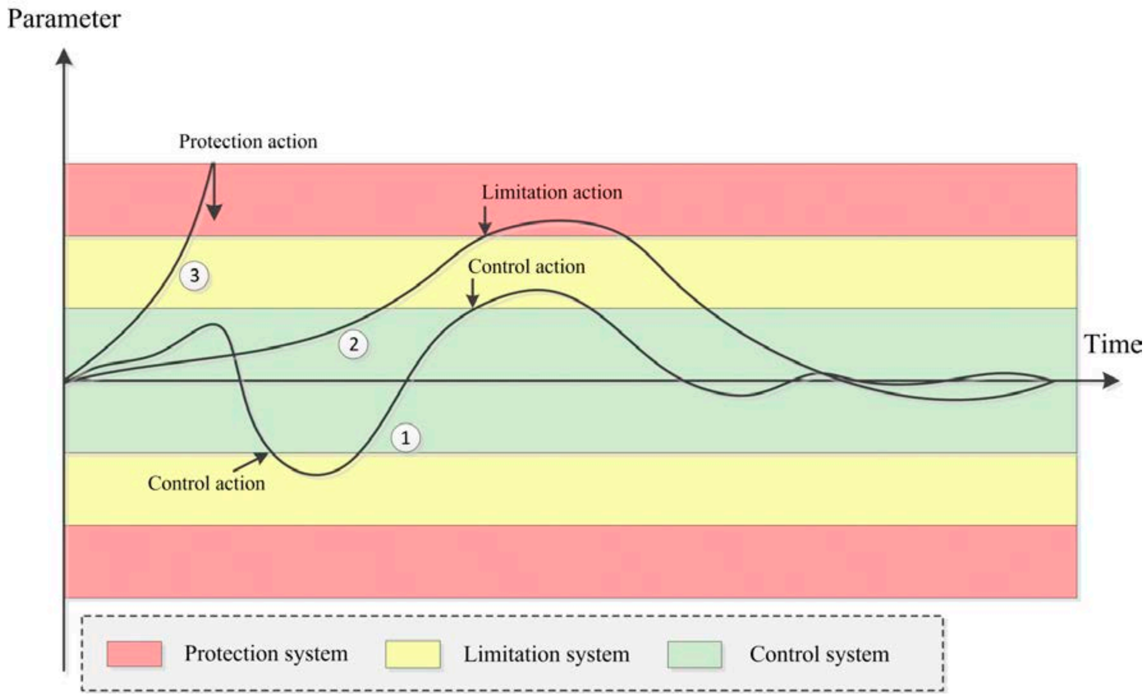


FIG. 26. Schematic diagram of control system adjustments to maintain the linear heat generation rate and departure from nucleate boiling ratio during 1 — fast; 2 — slow; and 3 — swinging changes in the controlled operating parameter (courtesy of G. Geer, EnBW, reproduced from Ref. [42]).

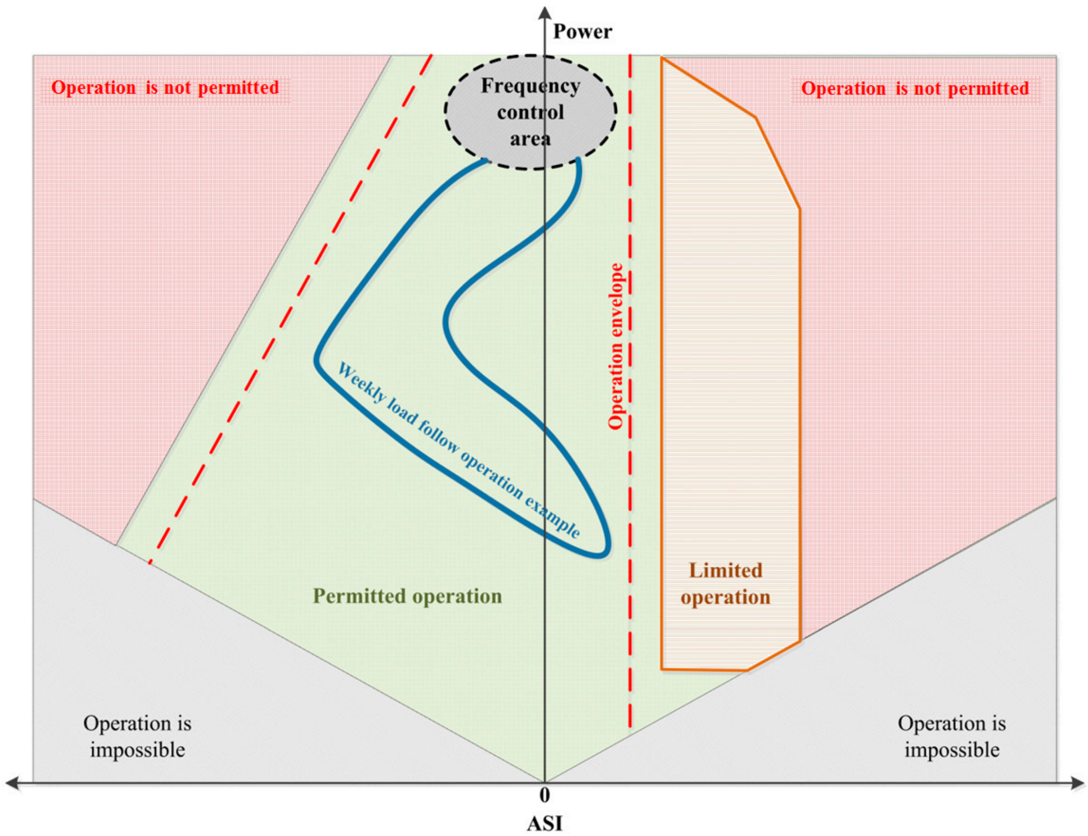


FIG. 27. Sample plant operation, axial shape index versus power (courtesy of H. Hupond and S. Feutry, Électricité de France, reproduced from Refs [26, 28]).

on in-core detectors and transient conditions during flexible operation. This is accomplished in German PWRs, for example, by applying the penalty on the worst anticipated transient with respect to the DNBR, which is the coupled coastdown of all RCPs (loss of flow event). To cope with such events, in addition to reactor trips, the maintenance of a minimum permitted steady state DNBR, called $DNBR_0$, is required as the initial condition defined by safety analysis. This $DNBR_0$ includes an allowance that precludes the violation of the minimum permitted transient DNBR during this event, taking into account uncertainties in the assessment of DNBR relevant parameters related to coolant conditions and power density distribution. This allowance incorporated in the definition of $DNBR_0$ is bounding for all AOO DNBR transients, and an OLC function for DNBR is imposed. This function — based on input from fixed in-core detectors (SPNDs) — generates permissible power density limits linked to $DNBR_0$ for each of the upper three SPND planes, taking into account the current coolant conditions and power density distribution. At the actuation of these OLC limits, automatic actions with counter-measures are initiated to restore the permitted initial conditions.

5.2.5. Pellet–cladding interaction

Potential impacts of flexible operation: Fuel rods are generally manufactured with a prescribed gap between the fuel pellet and the inside diameter of the cladding. During reactor operation, fuel pellet thermal expansion and irradiation induced fuel swelling — or in some cases, irradiation assisted cladding creep down[19] — bring about a reduction in the size of this gap and may eventually lead to hard contact between the fuel pellet and the cladding. This is referred to as pellet–cladding mechanical interaction (PCMI).

As mentioned above, the load following operation will likely promote changes in local power density. Depending on the fuel and operating conditions, PCMI may produce an increase in cladding stress (e.g. due to fuel pellet thermal expansion), proportional to any increase in local power density, which can lead to mechanical fracture of the cladding during transients. The magnitude of this stress mainly depends on the conditioned status of the fuel, considering the prior operating history (e.g. power levels or fuel burnup) and initial fuel to cladding gap size, as well as the corresponding present fuel to cladding gap size condition and the present operating conditions (power level, change of power level and rate of power increase).

High induced cladding stress combined with the aggressive chemical agents present in fission products (e.g. iodine) may lead to cladding failure via stress corrosion cracking (SCC), which is referred to as pellet–cladding interaction (PCI).

Another potential stress driven cladding failure mechanism during power manoeuvring is delayed hydride cracking. In addition to an increase in local power density, delayed hydride cracking requires the presence of zirconium hydride platelets within the cladding metal (due to waterside corrosion). Delayed hydride cracking and PCI/SCC require cladding stress to be maintained for a relatively long time period (to allow for crack propagation), and may occur well below established PCMI regulatory limits on uniform cladding strain (e.g. 1% elastic plus plastic).[20]

Past BWR operating experience has shown that PCI induced cladding failures may occur as a result of local power changes during control blade manoeuvring following a longer period of operation with inserted control blades, indicating that flexible operation achieved via control blade insertion/withdrawal has the potential to promote local power increases, leading to conditions amenable to PCI.

Recent PWR operating experience has shown that PCI induced cladding failures may occur when flaws exist on the surface of fuel pellets. Localized stress concentration at the location of a missing pellet surface resulted in non-classical PCI induced cladding failure, caused by a stress concentration in the vicinity of the missing pellet surface. To avoid this phenomenon, the size and depth of flaws introduced in the manufacturing process are controlled via manufacturing quality control procedures; these include high quality requirements as allowable tolerances and quality levels documented in the pellet specifications. Prompted by these in-reactor failures, fuel vendors have already adapted the related fuel specifications as well as tightened manufacturing tolerances and/or inspection procedures.

[19] Cladding creep down is permissible provided it is demonstrated that no creep collapse occurs (for PWRs/BWRs). Some designs (e.g. CANFLEX) are designed for rapid creep down of cladding onto pellets.

[20] In addition, 'outside in failure' of high burnup cladding due to delayed hydride cracking has been observed in some power ramps. According to the results obtained from ramp tests, this type of failure is correlated with the local power level and hold time at the terminal power level.

Safety analysis: Common regulatory requirements impose limits intended to prevent fuel cladding failures during normal operation, normal plant transients and AOOs.

Possible solutions: As described in Annexes I and II, recent operating experiences achieved for operating conditions that are based on a combination of fuel management strategies and power manoeuvring guidelines have proven effective at significantly reducing the risk of PCI induced cladding failure during flexible operation.[21] The following specific solutions have been employed to avoid PCI induced cladding failure during plant manoeuvring:

— Restricting flexible operation early in the fuel cycle until the fuel has been properly conditioned in accordance with fuel vendor guidance.
— Following periods of extended low power operations, ensuring proper fuel reconditioning during power ascension (e.g. accommodated power increase or power level holding periods). Fuel reconditioning promotes cladding stress relaxation and has been shown to improve PCI resistance.
— Plant manoeuvring guidelines, including power levels and ramp rate restrictions, have proven to be effective (see Annexes I and II for examples of manoeuvring limits).
— In some cases, analytical models, based on stress modelling and validated against in-pile ramp tests, have been utilized to predict cladding stress (or strain energy) prior to the planned power manoeuvring. The predicted stress/strain energy is then compared to an empirically based PCI failure threshold to assess the plant evolution in terms of PCI induced cladding failure risk, demonstrating that the planned plant evolution will not result in cladding failure.
— Plant TSs may need to be updated to reflect the established fuel conditioning guidelines or safety limits to prevent PCI induced cladding failure (e.g. power ramp limitations or analytical limits on cladding stress) and to include power manoeuvring during flexible operation, which becomes a normal plant transient. In particular, during periods of extended low power operations, it is possible to decondition fuel that has previously been conditioned, thus leading to restrictions for flexible operating and manoeuvring conditions.
— Cyclic LHGR variations below the conditioned LHGR profile must not lead to cladding strain or PCI failures. A transient overshoot beyond the conditioned LHGR can potentially lead to transient fission gas release and additional cladding stress due to PCI. It is therefore sufficient to restrict the transient overshoot to a permissible limit.

In addition, the utilization of advanced fuel designs can reduce or eliminate PCI risk as follows:

— Advanced cladding materials and/or advanced fuels that are designed to either reduce cladding stress or limit chemical interaction have proven effective at reducing PCI susceptibility (e.g. Canada deuterium–uranium (CANDU), reactor fuel that includes a thin lubricating film of graphite between the fuel pellet and Zircaloy cladding, or a thin barrier of natural zirconium or low alloy Zircaloy inside the Zircaloy-2 in most BWR reactor fuel cladding).
— Advanced and optimized fuel pellets.
— Modern BWR fuel assembly designs contain larger numbers of smaller diameter fuel rods (10 × 10 versus 8 × 8 arrays). These designs reduce the core average LHGR, which improves PCI resistance (unless the achieved margins are consumed by advanced fuel operating conditions).

As operational experience in German PWRs has demonstrated, where continuous core monitoring and surveillance are based on fixed in-core detectors (SPNDs), PCI failure risks are ruled out by a dedicated I&C function incorporated in the power density limitation system. In this function, a ‘gliding PCI limit’ is generated that follows the measured peak power density together with the power gradient associated with the fuel conditioning and deconditioning rate. This provides a transient margin at steady state for transient overshoots, referred to as

[21] Owing to the complex thermal–mechanical–chemical interactions associated with PCI, in-pile ramp testing is necessary to understand the phenomenon and its sensitivity to burnup, cladding stress, conditioned power level, ramp rate, ramp step, maximum LHGR (and level of maximum LHGR after ramp) and hold time. This information is used to establish ‘power manoeuvring guidelines’. It may also be used to validate fuel rod thermomechanical models and to assess power changes during normal operation and AOOs. These can be translated into tools to assist plant operators during power manoeuvring to prevent PCI induced cladding failure or can be engineered in the reactor power regulation and safety systems.

the overshoot allowance (OA). If the peak power exceeds the gliding PCI limit, staggered automatic actions are initiated. The principle of this gliding PCI limit is illustrated in Fig. 28.

The gliding PCI limit is adapted depending on its margin to the measured peak power density. If this margin lowers the OA, the gliding PCI limit is upwardly corrected with the conditioning rate until the margin, OA, is re-established. If the margin exceeds the OA, the gliding PCI limit is downwardly corrected with the deconditioning rate until the margin, OA, is re-established or the minimum PCI limit is reached. Below this minimum threshold, no restrictions on ramps and steps are imposed by the fuel. This function limits power escalation during startup after refuelling, after prolonged part load or if the power has to be increased above the conditioned level plus the OA, but it does not restrict load following operation starting from the conditioned full power state because the deconditioning rate is considerably smaller than that of the conditioning.

5.2.6. Creep induced channel distortion

BWR channel distortion is caused by creep, often referred to as 'bulge', resulting in channel deformation outwards by irradiation assisted creep due to differential pressure across the wall, often referred to as 'bow'. The channel may deform as a result of differential growth. Differential growth results from: (a) a fluence gradient across the channel (e.g. higher neutron flux towards the core centre) and (b) hydrogen uptake on the channel face adjacent to the control blade. Hydrogen uptake is caused by corrosion due to dissimilar metals in close proximity (e.g. a stainless steel blade or Zircaloy channel), and is often referred to as shadow corrosion.

Potential impacts of flexible operation: Flexible operation may necessitate more frequent control rod insertion, which would promote more channel distortion due to shadow corrosion. BWR operating experience

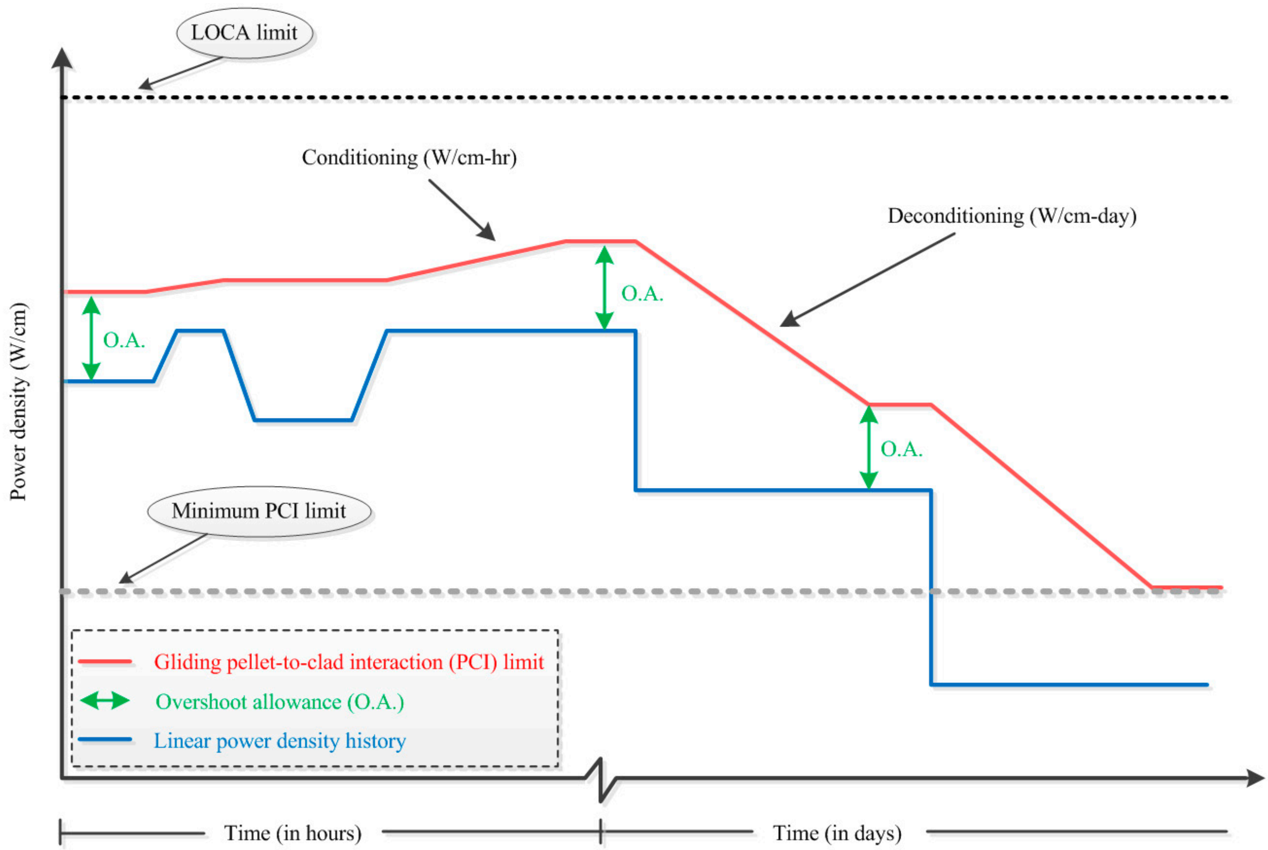


FIG. 28. Establishing a gliding pellet–cladding interaction limit in operation in some German nuclear power plants (courtesy of T. Salnikova, AREVA GmbH, as an addendum to Ref. [41]). LOCA — loss of coolant accident.

has shown that without proper attention, control blade interference due to channel distortion may result in slow to settle/inoperable control blades and forced outages.

While no operating experience exists (due to normal all rods out operation), PWR Zircaloy guide tubes may be susceptible to shadow corrosion and enhanced growth (due to their close proximity to stainless steel control rods).

Excessive guide tube growth would result in hard contact with core support plates (e.g. bottoming out of the top nozzle spring) and promote guide tube and assembly bow, which could eventually affect control rod insertion. Hence, PWR flexible operation achieved with control rod insertion may introduce this phenomenon, and its contribution towards guide tube growth would need to be evaluated.

Safety analysis: Control rods must remain operable to perform their design function. In addition, scram insertion times must not exceed those assumed in safety analysis.

Possible solutions: BWR control blade interference due to channel distortion, which results in significantly increased friction, must be avoided. The following solutions have been employed to control BWR channel distortion:

- Fuel management guidelines that limit fluence gradients and track control blade exposure;
- Migration to zirconium alloys that are less susceptible to shadow corrosion;
- Migration to channel materials with less irradiation induced growth;
- Rechannelling assemblies exhibiting excessive channel bow for early in life control for subsequent reloads;
- More frequent channel bow measurements of highly exposed assemblies.

For PWRs, any enhanced guide tube growth resulting from rodded operation must be accounted for in fuel assembly design.

5.2.7. Extended operating cycle

Potential impacts of flexible operation: Continuous operation at less than full power may extend the operating cycle, and this prolonged residence time may have a detrimental impact on fuel performance.[22] In particular:

- Flow induced PWR grid to rod fretting and BWR debris fretting are two cladding damage mechanisms that may be negatively affected by extended operating cycles.
- Fuel assembly component and fuel rod corrosion may also be affected by longer residence times. Constraints on corrosion (e.g. maximum oxide thickness or hydrogen uptake) have been established to ensure acceptable fuel performance during both normal operation and postulated accidents. The specific constraints on oxide thickness and on hydrogen levels, typically established by the fuel vendor, have to be confirmed to not be adversely affected under the flexible operation conditions and prolonged residence time.
- Fuel assembly mechanical design calculations are based on an established residence time that will change due to a longer residence time induced by flexible operation.
- Additionally, the prolonged operating cycle beyond the existing calibration period for various plant instruments may result in an increased period between calibrations. As the design calculations for the I&C consider the calibration period when determining overall instrument uncertainty and defining field set points, an increase in the calibration period may negatively affect these calculations.

Safety analysis: Common regulations require demonstration that the fuel assembly will perform its safety function over its lifetime.

With respect to prolonged periods between the instrument calibrations, common regulations require the consideration and determination of instrument set points and uncertainties for crediting protective actions in the accident analysis.

[22] It should be noted that the fuel will likely be used in a non-optimal manner. Therefore, discharge burnup is likely to decrease with flexible operation with respect to the burnup impact discussed in Section 5.2.5.

Possible solutions: In order to address the impacts of extended operating cycles on fuel:

- — Nuclear power plant operators need to confirm that the fuel vendor's fuel mechanical design calculation accounts for any extended residence time.
- — Operating experience or flow induced vibration testing should be used to justify a longer residence time with respect to grid to rod fretting susceptibility.
- — Corrosion levels for extended residence time need to be monitored.
- — Advanced cladding materials exhibiting more favourable corrosion properties should be used.
- — Advanced PWR grid designs exhibiting more favourable grid to rod fretting experience should be used.
- — Improved foreign material management procedures should be developed to effectively reduce the debris.

To address extended reload cycle impacts on instrumentation, the calibration period in design I&C calculations needs to be adjusted, and any necessary changes to set points or safety analysis are to be implemented to bound anticipated cycle length to flexible operation. Design calculations for I&C consider the calibration period when determining the overall instrument uncertainty and defining field set points. An increase in the calibration period may negatively affect these calculations and alter the analytical set point credited in the accident analysis.

5.2.8. Chemical impurities

Potential impacts of flexible operation: Fluctuations of the physical parameters (pressure, temperature and flow rate) of the RCS caused by flexible operation may aggravate corrosion. In addition, the corrosion particles, which may be activated in the reactor core and then transported into other parts of the plant, may increase the personal dose rate. However, operational experience shows no to minor impacts on corrosion (and dose rates as a result of corrosion product particles in the coolant) of flexible operation, because this tends to be of secondary importance for corrosion mechanisms in the RCS.

However, the increase in chemical impurities (e.g. aluminium, calcium, magnesium or silica) caused by flexible operation may have an impact on some components, such as the RCP seals; this was observed in some French nuclear power plants and PWR SG tubes.

Additionally, changes in boron concentration in the coolant needed for flexible operation cause changes in the pH value and lithium concentration, which could potentially influence the corrosion and delamination of the activated corrosion products.

Safety analysis: Common regulations require demonstration that the SSCs of the NSSS are designed to fulfil their design and safety functions during a plant's lifetime. Any systematic failure of components, especially the loss of integrity of the fission barrier or the loss of functionality due to corrosion, has to be prevented.

Possible solutions: The following solutions have been employed to address chemical impurities by means of controlling water chemistry in a manner similar to that for addressing the erosion/corrosion impacts discussed above:

- — For the primary side of PWR plants, the pH is controlled by lithium. Control of lithium (pH) levels is important to protect the fuel; the control band is specified in the plant's fuel reliability procedures or guidelines based on input from the fuel vendor. During flexible operation, the control band needs to be closely monitored and changes in lithium levels made, as required.
- — For PWRs, the effects of increased chemical impurities on RCP seals and SG tubes need to be monitored.
- — For BWRs, adjustment to zinc injection, and hydrogen or noble metal chemistry control based on the water chemistry might be needed.[23]
- — For the secondary side of the plant, water chemistry control is important to limit corrosion to the BOP components. Flexible operation could result in the need for increased monitoring and control of the secondary

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[23] Operational experience shows that for BWRs with pure water operation, there may not be any special requirements for flexible operation on chemistry; however, monitoring of water chemistry needs to, of course, continue, and measures need to be taken in case of deviations.

side water chemistry and increased maintenance and replacement, particularly on the condensate polishing systems and resins.

5.2.9. Ageing

Potential impacts of flexible operation: The increased variation of the physical parameters (pressure, temperature and flow rate) of the SSCs caused by flexible operation may aggravate existing ageing mechanisms such as fatigue, erosion/corrosion, wear and tear, chemical impurities, as discussed specifically above.

Thus far, there has been no evidence of new ageing mechanisms being created by flexible operation; however, the effects of aggravated known ageing mechanisms have been identified or anticipated for SSCs (e.g. CRDMs, pumps and valves, nozzles and pipes) due to flexible operation.

Possible solutions: Specific solutions for controlling and managing the aforementioned ageing mechanisms were discussed earlier in this section. Additional considerations that are applicable for ageing management include:

— Revision of ageing assessment and component lifetime determination to include the increased effects of ageing mechanisms;
— Increased monitoring and assessment of suspicious SSCs;
— Increased preventive and predictive maintenance of affected SSCs.

5.3. COMPONENT ASPECTS OF FLEXIBLE OPERATION

The majority of impacts discussed below for the component aspects primarily apply for the load following type of flexible operation. Based on the existing technologies and operating experiences, frequency control, especially primary frequency control, has a very limited impact on nuclear power plant components. For example, for a small frequency range, control rod movement may not even be necessary. This is because small frequency deviations typically do not cause significant cycling in pressure, temperature or flow, and do not require actuation of many components. An exception would be control systems such as the turbine controller module that helps the turbine change power on a frequency deviation. However, this is a general rule and the impacts from the frequency response may differ from one design, technology or operation strategy to another. Thus, stakeholders, providing frequency control above and beyond the currently allowed and practised range of frequency control operation, ensure that all potential impacts are considered and addressed.

5.3.1. Fuel rods

Potential impacts of flexible operation: The potential impacts on fuel design functions[24] depend upon many factors, including the fuel design, operating history (e.g. power levels or fuel burnup), operating conditions (power level, periodicity, rate and magnitude of the power change, insertion of control rods, etc.) and coolant chemistry. Mainly, the impacts are the result of power density redistributions in the core during load following operation, which are caused by control rod movement as well as the feedback effects linked with reactor coolant conditions and xenon distribution. In flexible operation mode, this redistribution will occur frequently and throughout most of the fuel cycle, and is likely to occur at intermediate power levels and in non-steady-state conditions. Generally, the impacts of load following on the fuel could be one or more of the following:

— The load following operation will likely promote changes in local power density. This, in turn, affects the fuel safety limits for the LHGR and DNBR in the OLCs, and may necessitate investigation of these safety parameters for normal operations and in AOO and DBA analysis, as well as review of the operating procedures.
— As a result of fuel pellet thermal expansion, depending on the fuel and operating conditions, PCMI may produce an increase in cladding stress proportional to any increase in local power density.

[24] Such functions include transferring heat generated within the fuel pellet to the reactor coolant and retaining fission products.

- High induced cladding stress combined with the aggressive chemical agents present in fission products (e.g. iodine) may lead to cladding failure via SCC.
- Increased impurities may aggravate corrosion, necessitating stricter monitoring and control of increased impurities.
- Depending on the rate, depth and periodicity of the load changes, there is potential for increased thermal and mechanical cycles on the fuel rods, which may reduce their predicted lifetimes. In addition, fatigue calculations may be further affected by any increase in core residence time.
- Continuous operation at less than full power may extend the operating cycle, and this prolonged residence time may have a detrimental impact on fuel performance.
- Flow induced PWR grid to rod fretting and BWR debris fretting may be negatively affected by extended operating cycles resulting from flexible operation.
- As a result of local power changes during control blade movement (if load following is achieved via control blade insertion/withdrawal), following a longer period of operation with inserted control blades has the potential to promote local power increases leading to conditions amenable to PCI.

Possible solutions: Advanced fuel designs as well as fuel management strategies, power manoeuvring guidelines and operator assistance tools have proven effective at significantly reducing the risk of impact on fuel during flexible operation. However, if any impact is identified, this would require:

- Restrictions on flexible operation, such as no load following early in the fuel cycle until the fuel has been properly conditioned;
- Following periods of extended low power operations, proper fuel reconditioning during power ascension (e.g. accommodated power increase or power level holding periods);
- Fuel mechanical design calculation reviewed to account for any increase in thermal and mechanical cycling.

5.3.2. Fuel assemblies (including fuel channels for boiling water reactors)

Potential impacts of flexible operation: The following aspects of flexible operation are considered impacts on the design function:[25]

- Flexible operation may necessitate more frequent control rod insertion, which would promote more channel distortion due to shadow corrosion. BWR operating experience has shown that without proper attention, control blade interference due to channel distortion may result in slow to settle/inoperable control blades and forced outages.
- While no operating experiences exist for PWRs (due to normal all rods out operation), Zircaloy guide tubes may be susceptible to shadow corrosion and enhanced growth (due to close proximity with stainless steel control rods). Excessive guide tube growth would result in hard contact with core support plates (e.g. bottoming out of the top nozzle spring) and promote guide tube and assembly bow, which may eventually affect control rod insertion. Hence, flexible operation achieved with control rod insertion in PWRs may introduce this phenomenon, and its contribution towards guide tube growth would need to be evaluated.
- Fuel assembly component and fuel rod corrosion, as well as fuel assembly fatigue calculations, may be further affected by any increase in core residence time.
- Fuel assembly mechanical design calculations are based on an established residence time, which will change due to the longer residence time induced by flexible operation.
- Increased thermal and mechanical cycles on fuel assembly components may reduce each component's predicted lifetime.

[25] Maintaining the fuel rod array positions the fuel within the reactor core and provides a path for the coolant and control rods into the core.

— Fuel assembly components, such as spacer springs, hold down springs and guide thimbles, will be adversely affected by the alternating stresses and may need additional verification that they are safely below the fatigue limits.[26]

Possible solutions: Use of advanced zirconium alloys that are less susceptible to shadow corrosion, channel materials with less irradiation induced growth, fuel management guidelines that limit fluence gradients and track control blade exposure, and core design strategies that rechannel the assemblies exhibiting excessive channel bow for early in life control for the subsequent reloads are all effective methods to control channel bow and its impacts, and are examples of practised solutions.

In addition, nuclear power plant operators need to ensure that the fuel vendor's fuel mechanical design calculations account for any impacts from load following operations and improve foreign material management procedures to effectively reduce debris.

5.3.3. Control rods/blades

Potential impacts of flexible operation: The following aspects of flexible operation are considered impacts on the design function:[27]

— Flexible operation achieved via control rod motion will likely reduce control rod lifetime. Control rods/blades are designed to a specified mechanical and nuclear lifetime. Their mechanical lifetime is limited by swelling of the absorber material (e.g. silver–indium–cadmium or boron carbide), while the nuclear lifetime is related to the reactivity worth (e.g. loss of absorber strength). The control rod lifetime is usually expressed in terms of neutron fluence or absorber material depletion. BWR operating experience shows that, depending on design attributes (e.g. clearance between boron carbide capsule and absorber tube), control blades may be either mechanical or nuclear lifetime limited. BWRs and PWRs have experienced mechanical failures of control rods/blades due to excessive swelling of absorber material.
— Flexible operation may necessitate more frequent control rod insertion, which would promote more channel distortion due to shadow corrosion. BWR operating experience has shown that without proper attention, control blade interference due to channel distortion may result in slow to settle/inoperable control blades and forced outages. While no operating experience exists (due to normal all rods out operation), PWR Zircaloy guide tubes may be susceptible to shadow corrosion and enhanced growth (due to close proximity to stainless steel control rods). Hence, PWR flexible operation achieved with control rod insertion may introduce this phenomenon, and its contribution towards guide tube growth would need to be evaluated.
— Control rod/blade lifetime (e.g. fluence) must be carefully monitored during flexible operation. A through wall crack in the control blade absorber tube or control rod cladding may expose absorber material to the RCS coolant, resulting in leaching of the absorber material and eventual loss of negative reactivity (worth). Safety analysis requires a prescribed amount of shutdown margin, which is usually dictated in plant TSs. Leaching of absorber material (leading to loss of control rod/blade worth) is difficult to detect during operation.
— BWR control blade interference due to channel distortion that results in significantly increased friction must be avoided. For PWRs, any enhanced guide tube growth resulting from rod insertion must be accounted for in the fuel assembly design. Excessive guide tube growth would result in hard contact with core support plates (e.g. bottoming out of the top nozzle spring) and promote guide tube and assembly bow, which may eventually affect control rod insertion.

Possible solutions: The following solutions have been employed to increase control rod/blade lifetime:

— In high neutron flux regions of the control rod/blade (e.g. tip of the rod or end of the blade wing), replacing the absorber material with a material less susceptible to swelling.

[26] Fuel vendor investigations and evaluations support the conclusion that alternating stresses in fuel assembly components are generally below the fatigue limits; however, this conclusion needs to be validated for any cases that are not considered in the fuel vendor evaluations.

[27] The design function is to provide a means of global and local reactivity control and reactor shutdown. Control blades must remain operable to perform their design function.

— Increasing the tolerance between the absorber material and the outer tube wall to accommodate swelling.
— Increasing the end phase of the absorber to provide additional space for swelling.
— Improving the design methodology based on a correlation between the absorber swelling and the fast neutron flux (which is measured up to very high fluence values).
— Reducing conservatism in individual rod control cluster assembly design limits, which can be achieved by considering the rod control cluster assembly specific conditions, derived from one time measurements of hoop strain (equivalent to determining the as-built gap size). By using this methodology and applying the same strain criterion, the design lifetime can be increased.

5.3.4. Control rod drive systems

Potential impacts of flexible operation: Flexible operation achieved via control rod motion will likely reduce the lifetime of control rod drive system (CRDS)/CRDM components, as they are active components. More frequent control rod/blade motion will increase fatigue and wear on CRDS components. Failure of the CRDS/CRDM to perform its intended function may result in inoperable control rods, forced outages and loss of shutdown margin. In the worst case, the rods/blades do not insert when called upon during a reactor trip or the scram insertion times exceed those assumed in the safety analysis. The additional fatigue and wear may result in a higher probability of plant transients (e.g. inadvertent control blade withdrawal or control rod drop).

Possible solutions: In order to ensure that the control blades/rods remain operable to provide a means of global and local reactivity control and reactor shutdown during flexible operation, control rod usage and remaining life have to be monitored and managed. Therefore, a monitoring system that counts and records control rod motion (i.e. number of steps) for comparison to design CRDS/CRDM lifetime and increased frequency of maintenance of CRDS/CRDM components is necessary during flexible operation. The following specific solutions have been employed in the plants that are performing (or designed to perform) flexible operation to avoid causing CRDSs/CRDMs to exceed their lifetime:

— Reassignment of control rods in the control banks to rotate mission time among the CRDSs/CRDMs (German approach);
— Replacement of CRDSs/CRDMs prior to reaching end of life (French approach).

5.3.5. Core detectors

Ex-core detectors provide a measurement of total neutron flux and flux distribution. Signals from ex-core detectors are used to monitor reactor power and axial power distribution (e.g. power tilts) and to initiate alarms and trips. In-core detectors provide a measurement of three dimensional (3-D) neutron flux distribution in the core. Plant operators may need to consider the potential impacts of flexible operation on predicted core power distribution and safety margins.

5.3.5.1. Ex-core detectors

Potential impacts of flexible operation: Flexible operation, especially when achieved via control rod insertion/withdrawal, may alter the relationship between peripheral core power (as measured by ex-core detectors) and interior core power. Many plants rely on fast responding, safety grade ex-core detectors to measure the total core power level and to initiate a timely reactor trip signal if the power exceeds a prescribed set point.

In addition, ex-core detectors monitor axial power distribution to ensure that the limits assumed in safety analysis are preserved. These ex-core instruments are periodically calibrated to other measurements of reactor power. A change in the relationship between interior to peripheral core power would effectively change the calibration of the ex-core detectors. This issue may necessitate a change to the periodicity of the ex-core calibration during and following flexible operation.

Possible solutions: In order to address the change in calibration of ex-core detectors, a thermal reactor power signal is generated as a combination of the average loop temperature rise and the ex-core neutron flux signals. In

German PWRs, for example, the neutron flux signals are the inlet temperatures corrected and primarily used to speed up the rather slow temperature rise signal in case of transient perturbations. Therefore, the consequences of possible changes in calibration of ex-core signals are minimized. The axial power shape is continuously assessed and monitored by fixed in-core detectors (SPNDs), calibrated in absolute units (watts per centimetre) used to control axial power shape and limit peak power density in the upper and lower core halves.

5.3.5.2. In-core detectors

Potential impacts of flexible operation: Coupling coefficients are generated on the basis of the predicted power distribution and used to generate 3-D power/flux profiles of the core based on in-core instrument signals. Power manoeuvring, especially unplanned manoeuvring relative to core depletions, may alter the power and burnup profile across the core (relative to these coupling coefficients). As such, core reload depletions and coupling coefficients may need to be continuously evaluated following power manoeuvring.

Detailed 3-D power/flux profiles are generated periodically to measure or confirm power peaking factors used in the monitoring of important safety margins, including maximum LHGR and DNBR/critical heat flux limits. Plant monitoring and protection systems often include control room alarms and reactor trips used to preserve these safety margins. Flexible operation creates two concerns related to this issue: (a) the accuracy of coupling coefficients and the resulting power profile and peaking factors and (b) the periodicity for generating the 3-D power/flux profile during and following flexible operation. The second item becomes even more important for reactor designs without fixed in-core detectors (e.g. transverse in-core probes).

Possible solutions: The following solutions have been employed to address changes in calibration of in-core detectors in German light water reactors where the in-core instrumentation concept is an important part of the I&C structure. It combines two complementary systems that are linked by the calibration process (Annex I provides more details of these systems):

- In PWRs, a fast flux mapping system called the Aeroball Measuring System is used to assess the 3-D flux and power density distribution, verify core conformity, determine key safety parameters (e.g. local peak power density), determine the steady state DNBR and the margins to the OLCs under normal operating conditions, and calibrate the SPNDs. In addition, a monitoring system employing the SPNDs is used for continuous monitoring of the power density distribution. Their signals are provided for core surveillance, axial power shape control, monitoring signal generation to represent core conditions (e.g. peak power density and DNBR) and ensuring compliance with the OLCs by means of the limitation system, local core protection and termination of fast transient perturbations.
- BWRs use traversing in-core probe systems instead of the Aeroball Measuring System, with which the in-core power distribution detectors are regularly calibrated during operation.

5.3.6. Core shrouds

Potential impacts of flexible operation: Under cyclic loadings, fatigue of core shrouds can be aggravated by flexible operation, especially when large temperature transients occur in the material. However, the design of core shrouds anticipates a certain number of oscillations based on load cycling spanning the entire lifetime. Accordingly, the number of load cycles has to be included in the design by setting relatively high cycle counts to bound the anticipated value. The loadings associated with the respective load cycles have to be determined.

Possible solutions: The solutions that have been employed to address thermal loads and fatigue phenomena are discussed in Section 5.2.1. Accordingly, for the core shrouds:

- Fatigue loadings ought to be well controlled by a suitable design (i.e. material selection and dimensions) and by proper operation to minimize temperature changes of the core shrouds.
- By comparing the history of service conditions, such as load cycles or operational transients, with the design assumptions documented in the thermal load specifications, it can be ensured that the core shroud design imposes no restrictions on the flexible operation of the plants.

— If deemed necessary, additional periodic, non-destructive testing at specified intervals may be performed.
— Specific attention has to be paid to weld seams, especially if they are not worked over in an appropriate manner.

5.3.7. Boiling water reactor jet pumps/pressurized water reactor coolant pumps

Potential impacts of flexible operation: BWR jet pumps will be subject to higher load cycling due to flexible operation and can be exposed to increased wear and tear. In addition, increased chemical impurities (e.g. aluminium, calcium, magnesium or silica) due to the use of flexible operation may have an impact on PWR RCP seals.

Possible solutions: Increased periodic monitoring, visual inspection and non-destructive testing of jet pump assemblies (in BWRs) and pump seals (in PWRs) would be a good practice to follow the effects from fatigue or water chemistry. For example, in French PWRs, pump seals are inspected during periodic maintenance outages (i.e. every other refuelling outage).[28]

Measures to control chemical impurities may be necessary if there is evidence of coolant chemistry effects.

5.3.8. Steam dryers

Potential impacts of flexible operation: BWR steam dryers are subject to higher load cycling during flexible operation, which may result in an increased probability of thermal fatigue cracking. High cycle fatigue may also become relevant due to fluctuating, intermittent thermal loads aggravated by flexible operation.

Possible solution: On-line inspection and monitoring for damage and wall thickness deterioration should be performed.

5.3.9. Pressurizers

Potential impacts of flexible operation: Pressurizers and associated components are subject to higher thermal cycling due to load following and frequency control. As high cycle fatigue may occur owing to fluctuating and intermittent thermal loads aggravated by flexible operation, this becomes particularly relevant for the components that are being operated in an unfavourable operating range. The specifically affected components are surge/spray lines and nozzles, as well as pressurizer welds.[29]

Possible solutions: The solutions for increased thermal cycling as a result of flexible operation can be implemented in the pressurizer component design or by controlling the number of cycles in the following ways:

— Pressurizer level and pressure control system modification, which can reduce the number of cycles with set point modifications;
— Use of materials and thermal sleeves that are more durable for thermal cycling during the mechanical design of the components;
— Optimization and improvement of mechanical design of the components for extended flexible operation;
— Optimization and improvement of procedures to minimize the transients.

5.3.10. Steam generators

Potential impacts of flexible operation: There are several effects of flexible operation that may affect the primary and the secondary sides in SGs:

[28] In France, there are three types of periodic outages: a refuelling outage at the end of each cycle, a refuelling and maintenance outage at the end of every other cycle and a 10 year outage that consists of refuelling, maintenance and major plant modification activities.

[29] Particular attention has to be paid to weld seams, especially if they are not worked over in an appropriate manner.

- Typical primary circuit components and systems that would be subjected to increased load cycling due to flexible operation include SG tubes. High cycle fatigue may occur due to vibrations, and may also become relevant due to fluctuating, intermittent thermal loads aggravated by flexible operation.
- On the primary side, although flow rates will remain constant, the SG inlet and outlet temperatures will be cycled during the power manoeuvres. In general, the frequency of thermal fatigue on components in the SGs, including the tubes and SG nozzles, will increase compared to baseload operation, as they will be subject to higher cycling due to flexible operation.
- Flexible operation may also affect the contaminants in the secondary water and increase impurities in the primary water. Chemical contaminants and impurities increased by flexible operation may have an impact on the SG tubes.
- On the secondary side of the SGs, the secondary flow rates will be reduced when the power is reduced, which will reduce the amount of contaminants flowing through the SGs, but will also reduce velocities in the tube sheet area. For example, the effective water level will change with the load, possibly changing the deposition of suspended solids.
- Changes in local flow conditions may affect erosion/corrosion due to increases in the local flow rate.

Possible solutions: Solutions practised to address the impacts of flexible operation on SGs include:

- Increased and proactive inspection schedules need to be implemented to monitor thermal fatigue SCC, and other damage mechanisms.
- Additional on-line monitoring tools to minimize ramp rates of thermal cycles on components need to be considered, evaluated and implemented.
- The chemistry controls in the primary and secondary sides of a nuclear power plant being converted from baseload to flexible operation need to be re-evaluated as the impact type and area may differ from baseload operation experience.
- One method to perform flexible operation is to bypass the turbine and direct extra steam into the condenser, when possible, to meet the extent and duration of cycling requested. In this case, the primary side flow rates and temperatures do not change notably, and the plant will be generating the same amount of steam on the secondary side in the SGs, from an energy/mass balance viewpoint. This type of flexible operation would minimize any temperature impact it might cause.

5.3.11. Chemical and volume control systems

Potential impact of flexible operation: CVCS components are subject to higher thermal cycling due to load following and frequency control. The component particularly affected is the charging line.

Possible solutions: The increased number of thermal cycles as a result of flexible operation can be accommodated by component design or by controlling the number of cycles as follows:

- Optimization of boration and dilution cycles in power manoeuvres;
- Pressurizer level control system modification to reduce the number of cycles with set point modifications;
- Use of materials and thermal sleeves that are more durable for thermal cycling during the mechanical design of the components;
- Choice of suitable materials and appropriate dimensioning or mechanical design to reduce temperature changes (e.g. in the area of nozzles);
- Optimization and improvement of procedures to minimize the transients.

5.3.12. Valves and pipes

Potential impacts of flexible operation: Valves and piping systems, both in nuclear and in conventional islands, are subject to higher load cycling when flexible operation is used. High cycle fatigue may occur due to vibrations of pipes or valves that are operated in an unfavourable operating range. High cycle fatigue may also become relevant due to fluctuating, intermittent thermal loads aggravated by flexible operation.

If operating under sliding pressure operation, frequent thermal cycling and potentially higher vibration will affect valves and pipes. Operation in a frequent thermal cycling mode will particularly affect weld joints in piping.

In conventional islands, the components that would be affected by increased wear from redirecting steam are the steam bypass lines, the steam turbine stop valves and throttle valves, and the steam spargers within the condenser (see Section 5.3.14).

Other impacts of flexible operation on valve and piping components may include:

- Operation at reduced loads places the valves in increased throttled positions. It is therefore likely that operation at reduced loads will significantly increase the required frequency of valve rebuilds. The turbine regulating valves typically require expensive rebuilds.
- Throttling of flow rates may be required in flexible operation, which could result in increased erosion/corrosion due to local flow rate increases. This applies mainly to operational systems such as the valves of the main feedwater system in PWRs and extraction steam lines, as erosion/corrosion may be aggravated.
- Active components (e.g. control valves) can be exposed to increased wear and tear, or fretting, from extra use.
- Main steam and reheat steam flow rates and the temperatures of the condensate, feedwater, extraction steam and heater drain piping will vary approximately in proportion to the power level, although the effects on the main steam and reheat piping are expected to be minimal.
- The extraction steam lines will operate at varying flow rates, pressures and temperatures, and might have higher moisture content at reduced power levels. Increased chances of FAC and water hammer are possible in heater drain lines, if heater level controls do not operate properly due to increased load following operation.
- The effects of reduced flow rates, pressures and temperatures on FAC will require evaluation at the plants. (Note that feedwater, condensate and feedwater heater drain flow rates and temperatures will reduce with load. The reduced flow rates will reduce FAC, and the reduced temperatures will reduce FAC in some lines and increase FAC in other lines. Specific evaluation of the effects of FAC in these lines is required.)

Possible solutions: The following solutions can be implemented to prevent or minimize the impact of flexible operation on the valves and pipes:

- Inspecting high risk areas in the piping system along with monitoring for possible thermal shock of any piping system needs to be performed.
- Applicable piping system damage mechanisms need to be determined based on plant flexible operating conditions. Modifications may be needed for inspection and repair schedules based on changing plant operating conditions.
- Specific consideration needs to be given to existing plant piping design, especially regarding the weld joints and piping support gap conditions.
- High cycle fatigue due to vibrations can be avoided by appropriate analysis of the piping in the expected operating range. If possible, antivibration measures such as changing thermohydraulic conditions (speed controlled pumps instead of throttling), stiffer mounting devices or other measures should be realized. Otherwise, the related component has to be rigid enough to withstand the expected high cycle fatigue.
- The effects of varying flow rates, pressures and temperatures on FAC will require additional inspections. Extraction steam lines as well as feedwater, condensate and feedwater heater drain lines are some of the components that will require additional monitoring and inspection for FAC damage.
- Review of the impact of varying flow rate on check valve wear will be needed for the feedwater, condensate and main steam systems.

5.3.13. Turbine components

Potential impacts of flexible operation: Operation at reduced loads will likely increase the moisture content in the lower pressure stages of the low pressure turbine. The increased moisture content could have two adverse effects: increased wear of the last few stages of the low pressure turbine and increased seal clearances.

Turbine control valves will also observe increased demand during load following operation compared to steady state baseload operation, potentially increasing the required frequency of valve rebuilding.

Other likely effects on the turbine components are:

— Seals/packing wear/damage;
— Blade attachment fatigue;
— Disc bore and blade fatigue/cracking;
— Silica and copper deposits;
— Wilson line movement (changes in the location where condensation actually occurs);
— Bearing damage.

Possible solutions: The main solution for controlling the impact of flexible operation on the turbine components is to maintain the ramp rate and depth of load manoeuvres below the turbine vendor's design and warranty limits, which are typically well beyond the operation ranges demanded by flexible operation:

— The rate of change (ramp rate) and depth of load change will determine the thermal ramp rates on the steam turbines. In most cases, if the ramp rate is controlled below the design limits, damage from thermal cycling will be minimal on the turbine.
— For extensive rates and depths of load changes, some conventional plants that have been modified for extensive cyclic operation have found merit in installing turbine stress monitors.

Additionally:

— Turbine overhauls and inspections need to be modified to specifically look for typical fatigue damage trends.
— Continuous vibration monitoring and operator training need to be considered, especially if extensive low power operations are expected.

5.3.14. Other conventional island mechanical components

Potential impacts of flexible operation: In addition to the valves and pipes, most mechanical systems in conventional islands are also subject to higher load cycling due to flexible operation. These impacts are similar to those observed in nuclear power plants that are load following, and more so in fossil fuel generating units, and may include:

— Components that would be affected by redirecting steam into the condenser; these include the condenser shell and tubes due to extra heat load and steam flow, the steam bypass lines, the steam turbine stop/throttle valves and the steam spargers within the condenser due to possible wear from increased operation. This would be more significant if flexible operation is performed only by redirecting steam to the condenser by turbine bypass.
— Variations in feedwater inlet temperatures, possibly resulting in increased feedwater nozzle fatigue.
— Changes in temperatures of the heat exchangers almost proportional with load. However, shell side/tube side differential temperatures in the heat exchangers will be small.
— Cycling transients that will result in increased use of the feedwater pump turbine and condensate pump motor controls. The effect of reduced flow operation on the condensate pumps will also require evaluation. Feedwater heater level controls are typically tuned for optimal performance at full load (100% RTP). There is a possibility that existing controls may not control the feedwater heater level properly at reduced loads. Failure to control the level correctly can result in greatly increased wear of the feedwater heaters, the heater drain lines, the heater relief lines and the level control valves. It can also cause water hammer, and, in extreme cases, turbine trips.
— Dryers and heaters that are subject to higher load cycling due to flexible operation, which may result in increased probability of thermal fatigue cracking.
— Throttling of flow rates, which may be required in flexible operation, resulting in increased erosion/corrosion due to local flow rate increases in various components.

Possible solutions: In addition to the aforementioned solutions for valves and pipes, the following are practised to minimize or eliminate the impacts of flexible operation on conventional island SSCs:

— On-line inspection and monitoring for tube damage as well as shell (wall thickness) deterioration in the heaters and dryers.
— For the secondary side of the plant, water chemistry control is important to limit corrosion to the BOP components. Flexible operation could result in a need for increased monitoring and control of the secondary side water chemistry.
— Maintenance practices may need to be adjusted for increased maintenance on condensate polishing systems and resin bed replacements.

5.3.15. Conventional island electrical components

Potential impacts of flexible operation: Electrical components are minimally affected by load following operation, based on the flexible operation experiences from French and German nuclear power plants. While starting or stopping may have some effect, load following operation will certainly not cause significant changes in breaker operation or component temperatures. However, depending on the specifications of the components, some additional costs for maintenance and replacement of components in the electrical[30] or control systems have been observed in fossil fuel generating units.

Possible solutions: Increased monitoring and proactive inspections to detect any impacts from thermal cycling are employed. These may require some additional monitoring methods. For example, some fossil fuel generating plants have installed glass portholes as inspection viewing devices in the back of breaker cabinets to allow for infrared viewing (thermography) to detect hot spots. Electrical systems are updated, wherever and whenever any impact is observed or predicted.

5.3.16. Instrumentation and process control components

Potential impacts of flexible operation: Flexible operation of nuclear power plants will increase use of I&C systems to accommodate power changes. Operation at lower powers will utilize the I&C systems for long periods of time in an operating range in which there may be limited operating experience. Some control systems tend to operate less reliably when they are outside the specific range for which they have been tuned.

Additionally, some additional costs for maintenance and replacement of components in the I&C systems may be incurred.

In specific components that use variable controls, increased wear and fatigue will occur. For example, increased use of condensate and feedwater pump turbine speed controls may result in wear and fatigue.

Furthermore, the prolonged operating cycle beyond the existing calibration period for various plant instruments may result in increased periods between calibrations. As the design calculations for I&C consider the calibration period when determining the overall instrument uncertainty and defining field set points, an increase in the calibration period may negatively affect these calculations.

Possible solutions: To minimize the impacts of fatigue and wear, increased monitoring and proactive inspections for cycling issues are performed. Control systems could be updated whenever and wherever the impacts are observed and expected.

To address the impacts of the extended reload cycle on the instrumentation, the calibration period in design I&C calculations may need to be adjusted and any necessary changes to set points or safety analysis implemented to bound anticipated cycle length with flexible operation.

[30] As discussed in Section 2.2.3.3, if active power is reduced in order to provide a greater range of reactive power as a specific additional form of flexible operation due to local grid conditions, this may affect conventional island electrical components. Operation at maximum lagging reactive power, which corresponds to maximum excitation current on the rotor and maximum stator current, could lead to increased vibration of the generator rotor and of the stator endwindings. Hence, a generating unit that has previously only provided small amounts of reactive power may experience new operational problems.

5.4. PROGRAMMATIC AND HUMAN–MACHINE INTERFACE ASPECTS OF FLEXIBLE OPERATION

5.4.1. Reactivity control

Potential impacts of flexible operation: Reactivity management is an important issue for baseload and flexible operation. Frequent manoeuvring of the reactor will require a stricter adherence to reactivity management standards, as baseload operation provides a simpler and easier approach than flexible operation in managing the reactivity state of the reactor. Flexible operation, especially when achieved via control rod insertion/withdrawal, will alter the power and xenon distribution within the core, will affect key core physics parameters (e.g. critical boron concentration) and will involve rod pilot, bank position control, insertion limits and associated design analysis. A deformation of the neutron flux distribution can cause inadvertent xenon oscillations. In the case of a power increase, such a deformation will cause a nearly instantaneous decrease of core safety margins for parameters such as maximum LHGR and DNBR/critical heat flux limits or PCI restrictions, which were discussed earlier.

The reactivity management standards can also be influenced by the regulatory environment. For example, in the USA, direct reactivity changes may only be made by a licensed reactor operator, as discussed in Section 2.2.2. This would require the grid system operator or corporate energy planners to contact the plant's main control room and communicate the desired power change and ramp rate to the plant operators. The operators would then perform the activity. In France, on the other hand, reactivity (power) changes can be the direct result of grid system operator actions. The role of the licensed reactor operator in overseeing plant reactivity changes cannot be overemphasized.

Safety analysis: The OLCs that preserve safety margins by means of the prescribed initial conditions assumed in the safety analysis include limits on various core power distributions (e.g. axial, radial or azimuthal). Reactivity management during power manoeuvring is essential for maintaining the reactor within these boundaries. In most cases, control room alarms will warn operators if these power distribution limits are approached. In some cases, a reactor trip signal is generated if the prescribed power distributions are exceeded.

Possible solutions: In PWRs, using reactor coolant soluble boron concentration to control the reactor power is advantageous due its global effect on reactivity. However, large quantities of CVCS wastewater would be generated during dilution operation, especially later in the core life. Alternatively, using existing, standard control rods (e.g. full length/full strength) to control reactor power has the advantage of minimizing plant modifications. However, this approach requires careful monitoring of bank worth (shutdown margin) and prompt and accurate in-core instruments to measure core power distribution. Using grey control rods (e.g. full length/part strength) to control reactor power has the advantage of minimizing core power redistribution (relative to full strength), which is not generally included in shutdown margin requirements.[31]

The following solutions have been employed to control reactivity during flexible operation, and details of implementation of these solutions are provided in Annexes I and II.

For PWRs:

— Utilization of an optimized control rod manoeuvring programme to minimize transient overshoot of the peak power density in combination with modified part load diagrams. For example, the control rod manoeuvring programme in German PWRs utilizes standard control rod assemblies [25]. These control assemblies can be used for both regulation and shutdown of the reactor, which are, as per their function, grouped into two banks: the D-Bank (Doppler Bank, i.e. the power reactivity relevant control rod bank) and the L-Bank (control bank). Both banks are manoeuvred in a mutually compensating sequence in order to control the power distribution while maintaining a constant reactor power. The D-Bank, which is used for regulating the integral reactor power, comprises four sequentially moving groups. Each group consists of only four control rod assemblies, and therefore the distortion of axial power distribution is minimized. The L-Bank, which is the remaining majority of the control rod assemblies, can be used to back up reactor power control. The L-Bank is primarily designed to fine control the axial power distribution (only a few centimetres of movement

[31] It should be noted that many nuclear power plants do not have grey rods or do not reserve excess shutdown margins to allow swapping of full strength control rods for part strength ones.

can provide an adequate effect). This control rod manoeuvring scheme, together with the correspondingly selected part load diagram (see Section 5.4.1.1) characterized by a constant plateau in the 'upper power range', minimizes the transient overshoot of the peak power density after a quick return to full power. As a result, the required operational margin, which has to be considered in the optimization of the core design, does not significantly depend on the plant operating mode (e.g. baseload or flexible). Consequently, advanced loading strategies for fuel economy can be implemented. It should be noted, however, that while this control rod manoeuvring concept enables rapid power changes, it may require prompt and accurate measurement of core power distribution. Therefore, German light water reactors use special in-core instrumentation made of in-core power distribution detectors, which are precisely calibrated, and the Aeroball Measuring System (see Section 5.3.5.2), which continuously monitors and assesses the 3-D flux and power density distribution.
— Utilization of part strength, or grey, control rods to adjust the reactor power with less of an impact on the power and xenon distribution. For example, in French PWRs, the reactor control is accomplished by different modes of rod operation. In 'A mode' (or 'black mode'), four banks of rods are utilized to adjust power and temperature. In 'grey mode', one bank (black or heavy rods) is dedicated to temperature control while four banks (two grey rods plus two black rods, with turbine power dependent positions) are dedicated to power compensation. This mode requires a calibration of the position versus electric power at the beginning of a cycle, and every 2–3 months thereafter, to take into account variations in efficiency (i.e. control rod worth) during the cycle. In both modes of operation, additional shutdown safety rods, which are black, provide shutdown margins.
— Power dependent modification of the part load control system (the part load diagram) for provision of operation with a constant primary coolant temperature or a constant SG pressure (see Section 5.4.1.1).

For BWRs:

— Control of reactor power via an optimized recirculation control (i.e. adjust the reactor coolant flow rate). This approach equivalently combines, for BWR conditions, the benefits of the optimized control rod manoeuvring programme and the part load diagram of a PWR, as it has a global impact on core reactivity and less of an impact on power peaking (see Section 5.4.1.2).

5.4.1.1. Pressurized water reactor part load diagram

The part load diagram of a PWR displays the relationship between the set point of the average primary coolant temperature and the reactor power output. The part load diagram is a specification for how to control the parameters of the NSSS that depends on the power output. In principle, two schemes (and combinations of both) are possible for PWRs, as shown in Fig. 29. Mode (a) in Fig. 29 (solid lines) represents keeping the coolant temperature constant with increasing reactor power. This mode of operation requires a dethrottling and therefore a pressure decrease on the secondary side due to the given and unchanged conditions for heat transfer in the SG. Mode (b) in Fig. 29 (dashed lines) allows the coolant temperature to increase with increasing reactor power.

Potential impacts of flexible operation: Operating a PWR in flexible operation means that the parameters of the primary coolant and main steam will vary. The fluctuations in average coolant temperature will have various relevant impacts on other parameters, such as:

— Thermal stress, which would induce fatigue (see Section 5.2.1).
— Reactivity changes in the reactor core, which will cause more and deeper movement of control rods and therefore more deformation of the power density distribution in the core.
— Changes to the stored heat (energy) of the RCS. (For increasing power, the components of the primary circuit will adopt the increased coolant temperature and the additional energy produced in the reactor). This may cause inadvertent overswing of the reactor power control.
— Changes to the coolant volume, which requires more effort for the CVCS, and waste management.
— Changes to the lithium (pH) level, which requires more effort for water chemistry control and regulation.
— Changes to the secondary system overpressure protection components and controls due to main steam pressure changes.

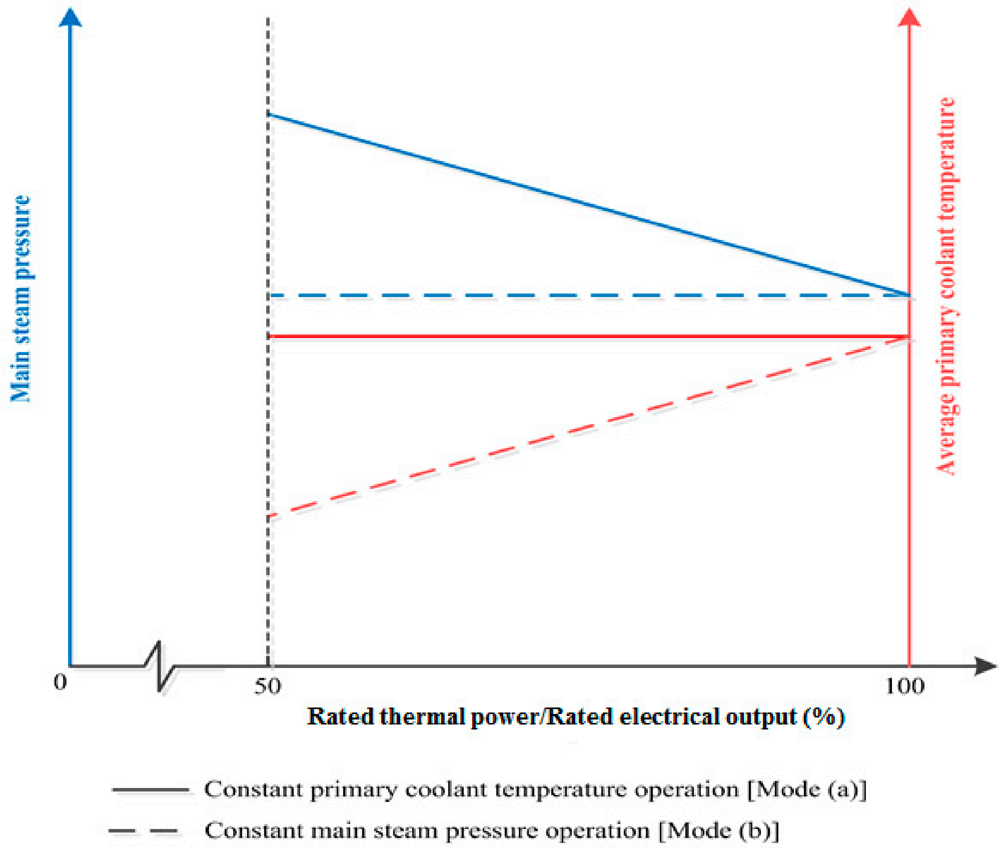

FIG. 29. Schematic (steady state) part load diagram for a pressurized water reactor.

Safety analysis: The operation mode will not have a direct impact on accident analysis. However, it will affect the variation of safety relevant properties such as fatigue, core criticality and other core physics parameters (LHGR and DNBR).

More importantly, the fluctuations in the main steam pressure will have an impact on the system design of the secondary system (e.g. protection against overpressure).

Possible solutions: By combining and optimizing for the applicable power ranges, PWRs combine the benefits of modes (a) and (b) and minimize the drawbacks in the relevant power range for flexible operation.

The characteristics of the simplified scheme for the combined part load diagram that are adopted by German PWRs (see Annex I) can be summarized as follows:

— In the upper power range (e.g. 40–100% RTP), where the majority of load following is performed, the average coolant temperature is kept constant (i.e. mode (a) in Fig. 29 is applied). In addition, flexible operation is less constraining in this range as less restrictive requirements to core, fatigue, criticality and coolant volume management are applicable with fewer challenges to safety and operational margins. The benefit of this mode of operation is reduced control rod movements, because temperature feedback of reactivity during power manoeuvres is minimized. Additionally, the RCS volume remains essentially constant, resulting in less ingress/egress through the pressurizer surge line, which reduces the temperature variations on the components, as well as reducing the CVCS manoeuvres.

— In the lower power range (e.g. 0–40% RTP), mode (b), as shown in Fig. 29, is applied. In this power range, flexible operation is difficult, and the main steam pressure is kept constant. The benefit of this scheme is a reduced challenge to margins for the secondary side design pressure (e.g. overpressurization is minimized).

5.4.1.2. *Boiling water reactor recirculation flow curve*

The reactor power in BWRs is controlled either by control rods (blades) or by the reactor coolant flow rate. The latter, called recirculation control, is typically used as the speed of the forced circulation pumps is adjusted. A reduction of coolant flow rate increases the amount of steam in the reactor core, reducing the moderator density and the reactivity; an increase in the coolant flow rate results in increasing moderator density and reactivity and thus an increase in power (Fig. 30). This approach has a global impact on core reactivity and less of an impact on power peaking.

Potential impacts by flexible operation: The operation mode will not have a direct impact on accident analysis. However, flexible operation will have impacts on the corresponding changes of the core physics parameters as well as on the thermohydraulic parameters of the NSSS, as it will affect the variation of safety relevant properties such as fatigue, core reactivity and other core physics parameters (LHGR and DNBR). Thus, an optimized power control scheme is necessary to minimize the impacts, such as minimized movements of control blades.

Possible solutions: An optimized recirculation control can be used to achieve minimized impacts from flexible operation in BWRs. For example, optimization is utilized in German BWRs as it is suitable for flexible operation in the upper power range (approximately 60–100% RTP), because BWRs, in principle, are able to change power in this upper range with faster and fewer power distribution changes in the core. The optimized recirculation curve provides the reactor power as a function of the core flow for a constant control rod position. Recirculation only control is advantageous for flexible operation as load changes can be performed without manoeuvring the control rods, and, therefore, the relative power distribution in the core is not significantly affected [25]. This also minimizes stressing of the fuel rods and changes in fuel rod temperature caused by flexible operation. Power changes beyond the recirculation control range are made by manoeuvring the control blades.

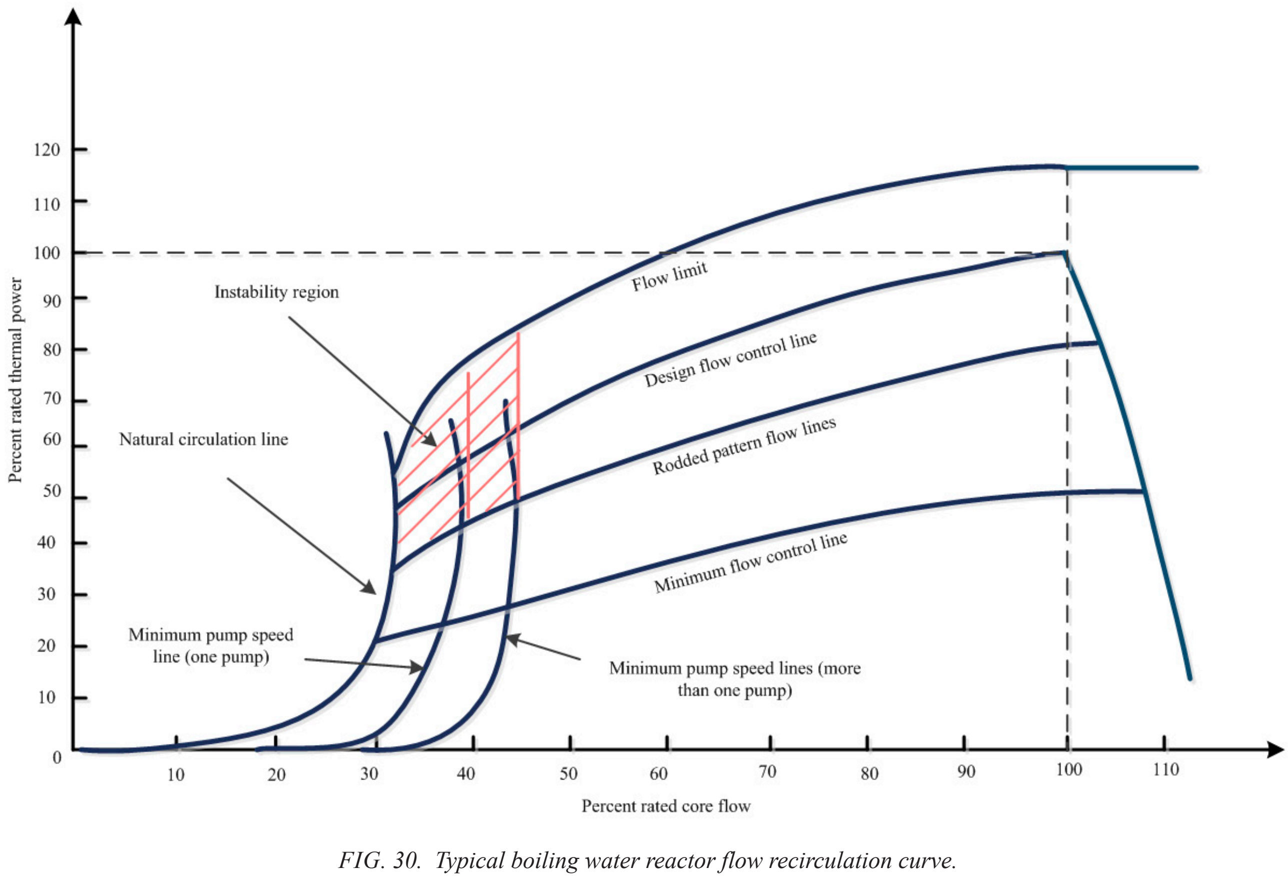

FIG. 30. Typical boiling water reactor flow recirculation curve.

5.4.1.3. Reactor power monitoring

Nuclear power plant operators are required to monitor and comply with the plant's licensed power limit.

Potential impacts of flexible operation: Several indications of reactor power are available for plant operators to monitor reactor power. For example, many PWRs have neutron flux, primary calorimetric and secondary calorimetric power measurement indications. Flexible operation creates two concerns with power monitoring: (a) application of power dependent uncertainties within the monitoring and protection system set points in safety analysis and (b) calibration periodicity for these various power indications during and following flexible operation. These issues may also affect RCS flow measurements.

Safety analysis: Each of the reactor power indications has unique, power dependent uncertainties, which must be accounted for within monitoring and protection system set points and safety analysis. For example, the uncertainty of the PWR secondary calorimetric power may be less than 1% RTP at full RTP; however, it increases to a few per cent as the power level decreases. This increase in uncertainty must be accounted for during power manoeuvring.

Furthermore, the periodicity of power calibration and surveillance requirements may be based on an assumption of baseload operation. For example, PWR TSs require reactor power and RCS flow measurements and calibrations at key power plateaus during initial power ascension and then periodical surveillance and recalibration at full power operation. Subsequent power manoeuvring may invalidate the TS bases for these surveillances and must be addressed.

Possible solutions: In order to address reactor power monitoring impacts, the power signal needs to be calibrated at regular intervals (monthly or more frequently) at steady state, and full power conditions to the thermal reactor power provided by the secondary heat balance. In German PWRs, for example, this balance is calculated every minute by the process computer and displayed to the operator. This enables the operator, even after a load variation and a subsequent stabilization period of approximately 15 minutes, to compare the power signal with its reference and to verify compliance with the acceptance criteria. A calibration at a reduced power level is only performed for prolonged part load operation, but in this case, holding points for calibration purposes are imposed during power ascension in analogy to the first startup after refuelling.

5.4.2. Operating procedures

The staff of the operation department is responsible for conducting safe operation of the plant in accordance with the plant OLCs and the design and licensing bases. Plant operating procedures, covering all plant operational modes and providing instructions for safe and reliable operation, are developed, reviewed and approved by the plant operations and management staff for use by plant operators. Operators are initially and continually trained on procedure usage and adherence to ensure safe operations.

Potential impacts of flexible operation: For plants that are operating (or optimized in design) as baseload and transitioning to flexible operation, the plant operating procedures generally do not have explicit and extensive guidance on the actions necessary during extended periods of low power operations, as well as on manoeuvring the reactor with large power level adjustments on a regular and frequent basis. The baseload plant procedures typically cover routine startup and shutdown manoeuvres based on the steps and actions needed to reach and perform full power operations. Therefore, flexible operation may require detailed review and revision of procedures — or creation of new procedures.

Possible solutions: The operating procedures of a nuclear power plant, of which design and operation are optimized as a baseload plant, might need to be revised to address flexible operation aspects. These aspects and particular procedures, as per experience and practices, may include:

— Core monitoring requirements and guidance (e.g. ex-core monitoring calibrations, set point changes, and burnup and control rod worth calculations);

- Assurance of proper plant response to changes in the reactor power level on the primary loop (e.g. pressurizer levels, SG levels and heater control system responses);
- Assurance of proper response of the secondary side of the plant to changes in the power level (e.g. feedwater heater system control responses, turbine control valve responses and heater drain level control systems);
- Primary system chemistry controls and adjustments as required in accordance with primary water chemistry guidelines;
- Secondary side chemistry controls and monitoring to ensure protection of secondary side components;
- Fatigue monitoring plans — cycle counting and monitoring of critical components (e.g. pressurizer surge lines);
- Controls to limit the time at a power level when manoeuvring the plant through a known region of harmonics or high vibration for some components (e.g. condenser, exchangers and drains), including additional support staff to monitor vibration levels;
- Cross-guidance and synchronized instructions for use by plant operators and grid system operators.

Flexible operation may not be possible or have reduced capability if some components have degraded performance. These limitations and restrictions have to be clearly included in the prerequisites in the operational procedures. These may include:

- High vibrations at the turbogenerator;
- Hydrogen leaks at the generator;
- Liquid waste tanks being unavailable;
- Controlled leakage of primary fluid from the RCS;
- Degraded performance of SGs.

As explained in Section 2.2.3, the extent of flexible operation may not be that severe or frequent so that some power manoeuvring can be possible with an expansion of scope in existing procedures (e.g. small load rejection or excess steam bypass to the condenser or atmosphere). Although in such cases there may be no need to change the fundamental steps in the operating procedures, surveillance, calibration and testing procedures still have to be reviewed to confirm that the number of power manoeuvres does not affect their frequency. Any changes in procedures or any impacts on the operation strategy require evaluation to determine whether classroom or simulator based training is needed to familiarize staff with changes in operator actions.

It is also a good practice to have the nuclear power plant operators and grid system operators cooperate in either the preparation or review of those procedures.[32]

5.4.2.1. Plant surveillance

Potential impact of flexible operation: Various plant surveillances require performance at a steady state power level or are required to be carried out at full RTP. Flexible operation may affect the time and window of opportunity for these. The surveillance requirements, therefore, might need to be reviewed to determine the possibility of performing these at intermediate power levels, which would be normal operation, in flexible mode.

Possible solution: As necessary, the procedures and programmes might need to be modified to ensure compliance with the required surveillance intervals, together with determining the ‘no flexibility’ periods during operations.

5.4.2.2. Calibration of plant instrumentation

Potential impact of flexible operation: Continuous operation at less than full power may extend the operating cycle beyond the existing calibration period for some plant instruments.

[32] It may also be beneficial for the operators of nuclear power plants and grid systems to use common procedures from the beginning. For example, procedure pages with instructions for plant operators on one side and for grid operators on the other were used in the early days of flexible operation in France.

Safety analysis: Design calculations for the I&C systems consider the calibration period when determining overall instrument uncertainty and defining field set points. An increase in the calibration period may negatively affect these calculations and alter the analytical set point credited in the accident analysis.

Possible solution: In order to address the impacts of extended reload cycles on instrumentation, it is general practice to increase the calibration period in design I&C calculations, and to make any necessary changes to safety analysis in order to bound the anticipated cycle length with flexible operation.

5.4.3. Maintenance

Potential impacts of flexible operation: Additional maintenance and replacement of components may be needed as a result of flexible operation causing an increase in maintenance activities and resources. Wear on components (e.g. CRDMs), due to excessive use, vibrations and changes in temperature, can occur.

Load following can induce more frequent maintenance, while reducing the availability of power plants in terms of increased outage frequency, duration or risk of equipment degradation or failures, as well as additional monitoring and surveillance requirements.

The operating lifetime of a plant may be affected — in some cases where frequent load changes may translate into higher wear and tear of equipment. The magnitude of that effect will depend upon the extent of operation in the flexible mode and the properties and programmes that exist for the design and operation.

Possible solutions: In order to take into account the consequences of flexible operation, maintenance actions in periodical maintenance programmes might need to be reviewed, as their periodicity may be revised or augmented. The effects of flexible operation need to be considered and included in maintenance and repair plans, and the maintenance classification changes due to flexible operation need to be reflected in plant maintenance programmes and procedures. Some operational experiences include:

- In French PWRs, load variations have shown nearly no impact on primary system component maintenance classification, and hence, there were no specific maintenance programmes or actions defined to take into account the consequences of flexible operation on the primary SSCs (with a few exceptions). For example, there is more likely to be a discrepancy in control rod positions when they are moved instead of staying in one position during the fuel cycle.
- Corrective maintenance (replacement) would be needed for CRDMs in French PWRs after a defined number of manoeuvres. The CRDM replacements affect the outage schedule and cost, as well as the radiation dose to personnel. In order to minimize the cost and personnel dose, a CRDM maintenance policy may necessitate keeping a nuclear unit at full power for one or two fuel cycles without load following to optimize the outage strategy. The increased number of design transients in cycling temperature (mainly at the pressurizer surge line) is evaluated and found to be compatible with design assumptions.
- Temperature transients are more significant for secondary systems. Specifically, leakage at welded joints, erosion of pipes and/or ageing of heat exchangers may increase the risk of unplanned shutdown and more corrective maintenance during an outage, unless the load following conditions are taken into account in preventive maintenance programmes.
- For chemistry control, maintenance practices may need to be adjusted for increased replacements of resin beds.
- With respect to the I&C systems and components, it should be recognized that failures may appear only when the I&C systems or components are activated, and they may have otherwise gone undetected.

5.4.4. Chemistry control

Potential impacts of flexible operation: Chemical impurities (e.g. aluminium, calcium, magnesium or silica) increased by the use of flexible operation may have an impact on components, such as RCP seals, which has been observed in some French nuclear power plants.

As discussed in Section 5.2.2, load following operation generally results in a higher corrosion product transport into the SGs than that observed in baseload operation. This can accelerate the formation of corrosive environments, especially at the top of the tube sheet area, which accelerates typical degradation processes in the SG materials.

Furthermore, corrosion particles may be activated in the reactor core and then transported into other parts of the plant, where they may increase the personal dose rate. As mentioned earlier, operational experience shows no or only minor effects of flexible operation on corrosion and dose rates as a result of corrosion product particles in the coolant systems.

Possible solutions: The following solutions have been employed to address the water chemistry:

— Procedures or guidelines may need to be revised to support flexible operation for stricter monitoring and control of increased impurities. Elements with increased concentrations ought to be the subject of targeted continuous monitoring of the RCS. As necessary, corrections are initiated in accordance with the plant's chemistry programme.
— For the primary side of PWRs, the control band of lithium (pH) levels needs to be closely monitored, and changes in lithium levels made as required in the plant's fuel reliability procedures or guidelines based on input from the fuel vendor for protection of the fuel during flexible operation.
— Flexible operation could result in the need for increased monitoring and control of the PWR secondary side water chemistry and for increased maintenance of condensate polishing systems and resin replacements.
— For BWRs with zinc and hydrogen operation, injection with feedwater, which is monitored and regulated in accordance with the power level, may need to be adjusted during flexible operation.[33]
— Although there may not be any special requirements for flexible operation in BWR plants with pure water operation, commonly called normal water chemistry, close monitoring of water chemistry may need to be performed and measures taken in case of deviations.

5.4.5. Waste management

Common regulations require demonstration that nuclear waste can be handled safely, and that any inadvertent release of radioactive material to the environment can be avoided and remain within allowable limits.

5.4.5.1. Liquid waste management

Potential impacts of flexible operation: The impacts of load following[34] on liquid waste management are primarily a concern for PWRs. In a PWR, fuel depletion over the fuel cycle is offset by the dilution of soluble boron in the RCS to maintain the reactivity balance. As the end of a cycle approaches, the RCS boron concentration is reduced such that increasing amounts of dilution are required to maintain the reactor core reactivity balance. If the plant were to employ flexible operation during this timeframe, even though the direct power changes might be made with control rods, changes in boron concentration might also be required to offset effects such as xenon concentration changes. Therefore, flexible operation, when performed near the end of the fuel cycle, requires large amounts of dilution, generating large volumes of borated wastewater. Storage capacity and reprocessing ability (additional waste cleanup, additional water, evaporator/demineralizer, resin beds, etc.) may therefore limit flexible operation at the end of a cycle.

Most of the liquid waste is treated (e.g. by a gas stripper or evaporator to separate boron from water) and recycled in boron and demineralized water tanks for the primary system. In that manner, final liquid waste volumes can be minimized; however, the capacity of the tanks and of the evaporator may be challenged by the increased volume of liquid waste due to load following operation, particularly late in the cycle. Interim storage, pumping capacity and reprocessing capability, if not engineered adequately, may be limiting factors at the end of a cycle.

[33] Hydrogen discharge with the main steam depends on the cycle criterion in the reactor. For end of cycle/stretch out operation, an appropriate counter-measure could be, for example, to increase the hydrogen concentration in the feedwater. Platinum injection, once or twice per fuel cycle, necessitates operation at constant power for up to 10 days to maintain stable conditions for monitoring and control of the injection.

[34] Frequency control operations do not generate notable additional liquid waste.

During load variations performed for load following operation, the liquid waste generated is comparable to that generated during a typical refuelling outage. For example, a 900 MW(e) French PWR generates about 20 m^3 of additional liquid waste if the power manoeuvre range is less than 50% RTP during the first two thirds of the cycle length (roughly 70% of full cycle effective full power day). The amount of liquid waste doubles (to about 40 m^3) if the power manoeuvre range exceeds 50% RTP. After two thirds of the cycle, the liquid waste generation increases significantly.

French PWR operational experience also shows that the total additional activity, excluding tritium, released due to load following is less than 0.3% of the allowable limit.

Possible solutions: The following solutions have been employed to address liquid waste management in PWRs:

— Minimization of the need for boron exchange by appropriate reactivity management concepts:
  - Core power levels for flexible operation can be controlled by either dissolved boric acid (e.g. chemical shim in the coolant water) or part strength neutron absorbers, commonly termed ‘grey control rods’. The advantage of the grey control rods is that they allow a faster response time to change reactor power levels, minimize the impacts of xenon oscillations and require fewer changes in the primary water chemistry. For an existing plant being modified for flexible operation, the disadvantages are that installation will be a significant capital expenditure, they will require accident and transient analysis to be reperformed, require changes to operating procedures and require review and approval by the regulatory body.
  - An alternative to grey control rods may be an appropriate control rod manoeuvring programme. For example, the control rod manoeuvring programme of German PWRs relies on standard control assemblies, all of which can be used for both regulation and shutdown of the reactor (see Annex I).
  - If the PWR operator elects to use boration/dilution for flexible operation, then there will be a significant increase in water usage, especially later in the core life. The plant owner will need to evaluate the abilities of the boron recovery system, including evaporators, demineralizers and resin beds and the system capacity to handle the additional liquid waste. By using boration/dilution, there will be an increase in the amount of waste discharge, and the potential impacts of these discharges on the environment need to be understood and addressed.

— Minimization of the need for coolant exchange by appropriate operation mode of the plant. For example, using a constant coolant temperature that will minimize the effort for the CVCS (see Section 5.4.1.1) is one method that could be used.

— Larger volumes of primary liquid waste are generated during flexible operation (dilution, boration) at the end of a cycle, and the capacity and capability of systems and equipment, such as interim storage, pumping capacity and reprocessing capability, might have to be reviewed and reengineered, if necessary, to adequately handle this increased volume.

5.4.5.2. Gaseous waste management

Operating under load following implies changing the level of the primary CVCS and gas stripping of liquid waste. A daily load variation has nearly no impact on gas release. French experience shows a two day shutdown can produce 1% of the unit total gas capacity storage volume (mainly hydrogen and nitrogen).

It should be noted that if flexible operation is performed by dumping steam (i.e. directing excess steam to the condenser (and/or atmosphere in PWRs) by bypassing the turbine), environmental release limits have to be considered, depending on the plant conditions and external temperatures.

5.4.5.3. Solid waste management

There is a negligible impact on the solid waste volume generated due to flexible operation. For example, from French PWR operational experience, it is comparable to the solid waste volume produced during a typical refuelling and maintenance outage.

5.4.6. Special tests

To demonstrate that the NSSS equipment adequately satisfies operational flexibility requirements, an equipment qualification and performance test might need to be performed for the equipment that is subject to deviation from previous operational conditions due to flexible operation. These tests may include, but are not limited to:

— Wear and fatigue resistances of components subjected to the highest loading under remote frequency control (e.g. CRDMs, control rods and guide tubes);
— Lead test assemblies, to observe trends for power changes, especially when the power level is mainly adjusted by control rod motion;
— Performance and reliability tests of instrumentation.

Some of these tests may be required by the regulatory body in order to approve flexible operation. For example, in France and Canada, extensive irradiation and fuel depletion under a load following programme has been carried out using research and lead test reactors.

5.4.7. Long term operations and plant life management

Potential impacts of flexible operation: The real impact of flexible operation is primarily on the economics of long term operation for the plants whose life extensions have been decided assuming baseload operation. With appropriate ageing management programmes, inclusive design considerations and modifications and preventive maintenance, the technical impacts of flexible operation on plant life extension and long term operation may not be a factor. It is possible, but not expected, that the regulatory bodies may impose some additional requirements on the O&M of SSCs during long term operation [36].

Furthermore, the effects of fatigue, erosion/corrosion or wear/tear by frequent flexible operation, discussed earlier, may be factors in the determination of the long term operation period. This would be the case for fatigue, for example, where an increased number of cycles because of the use of flexible operation consume the available margin provided by the number of cycles postulated in the original design, which was based on baseload operation during the entire licensed lifetime.

Possible solutions: The safety case for long term operation can be expanded to include technical analysis for determining the impacts of flexible operation. For example, the increased number of cycles by flexible operation may be bounded by the maximum number of cycles postulated in the original design of the components for fatigue during the licensed lifetime, but it may result in exceeding them during a proposed long term operation with load following. In this case, it could be a limiting factor for the years of operation beyond the original design lifetime or necessitate replacement of components to regain the margins.

Nuclear power plants that have been operating as baseload units with their safety case for approved long term operation based on continuing baseload operation could follow the processes described in Sections 3 and 4 for determining the need and extent for flexible operation and resultant modifications. Such an assessment is necessary from the technical aspect. Additionally, an economic assessment, similar to that described in Section 6, could be performed if the cost–benefit analysis for longer term operation is based on continuing baseload operation. This will determine the optimum length of the prolonged lifetime with updated cost–benefit analysis to include the effects of flexible operation on the plant SSCs, and may affect the original approval of a longer licensed life as a baseload unit.

5.4.8. Training

Potential impacts of flexible operation: Flexible operation will change the plant operation strategy and actions, maintenance, surveillance, monitoring and inspection conditions and practices, and will affect the environmental conditions and hazards around the plant SSCs.

Possible solutions: Continued and special training is important to support safe plant operations and reduce human performance events during flexible operation. For plants that are transitioning from baseload to flexible operation, it is essential that the training reaches all of the stakeholders and plant staff. Topics to be covered include:

- Why the plant is transitioning to flexible operation;
- The type of flexible operation and its relationship with the grid system operator, including the procedures or protocol agreements on limitations of flexible operation;
- Operating experience with flexible operation with an emphasis on information from plants of a similar design and vintage, as well as flexible operation performed by other generating units (different generation technology);
- Plant capabilities for load following and frequency control, including existing design features and implemented/planned design changes to enhance plant operation, surveillance, monitoring and modifications to accommodate manoeuvrability;
- Revised design and licensing bases, including changes in limiting conditions for operation and impacts on safety limits;
- Changes in plant operation programmes, practices and procedures, including reactivity management, reactor control and plant manoeuvres (e.g. startup, shutdown, normal transient response or AOO response);
- Changes in operator response for xenon, control rod and boron effects, caused by flexible operation as part of normal operations;
- Monitoring programme implementation;
- Changes in chemistry and waste management programmes, practices and procedures;
- Changes in plant maintenance programmes, practices and procedures;
- Changes to core design and fuel management.

It is also essential to review the industrial safety training curriculum, as flexible operation may affect environmental conditions and existing hazards. For example, heater drain system components that are under steady conditions during baseload operation will have dynamic conditions under flexible operation, which may require new hazard identification, awareness and protection for industrial safety.

Even where staff have been thoroughly trained for flexible operation, it is important to organize retraining for them if the plant spends a prolonged time operating at baseload before returning to flexible operation. This has been a common practice in plants that are currently operating flexibly.

Cross or mixed training of nuclear power plant operators and grid system operators, as applicable, might be beneficial to understand the effects and impacts of their own actions on each other's facility and operational schemes.

5.4.9. Plant simulators

Potential impacts of flexible operation: Plant simulators are important tools for understanding plant responses, for demonstrations and for training control room staff. Any modifications or changes made to the plant and operating procedures need to be added to, modelled on and validated on the plant simulator. For existing plants that have previously only operated at baseload, the simulator may require modifications and updates to correctly model the proposed flexible modes of operation. These modifications also need to include the controls for conventional island components and consider the dynamic responses of the components to changes associated with flexible operation (see Annex I for examples of German experience in simulator utilization).

Possible solutions: For baseload plants transitioning to flexible operation, simulators can play an important role in demonstrating the procedures prior to implementation and in training operators prior to implementation of flexible operation, including managing interfaces with grid system operators and reinforcing human performance aspects of operation.

Simulator scenarios for training based on 'as-burned' core data need to be practised. In France, for example, recent core depletion history is recorded in dedicated simulators that are developed to help control room operators forecast xenon distribution and prepare a dilution/boration strategy.

5.4.10. Cybersecurity barriers

5.4.10.1. Barriers for plant control

Because nuclear generating units are generally turbine driven, it is necessary to guarantee the control of core reactivity by design and operation features, including no common failure mode between turbine and reactor control systems and full independence between turbine limitations and reactor limitations. This guarantee is a prerequisite for operators to maintain a stable core and generator balance during power variations.

Any change in core reactivity (and therefore thermal power) due to automated requests to change the electrical output (planned variation of power as described in Section 2.2.1 and frequency control within a power range as described in Section 2.2.2) must be limited[35] in terms of amplitude (typically less than 10% RTP for steps or less than 5% RTP for continuous) and rate (typically 2−5% RTP/min) by a specific safety classified limitation system to the maximum admissible capability of the reactor.

5.4.10.2. Barriers for the nuclear power plant–grid interface

Grid system operators need to have a continuous overview of the system's state, which includes information on the operating conditions of nuclear power plants as well as the requirement to communicate with them in order to provide operational instructions (Fig. 31).

All automated requests to change the electrical output from the grid–plant interface system must be certified and authenticated. This mission is performed by secure information technology systems, including adequate physical and logical independence, redundancy and diversity.

Before varying the electrical output, plant operators have to set reactor power limitation ranges (typically, the electrical output set point ±5% RTP) in classified safety systems independently of the power variation programme of the turbine controller.

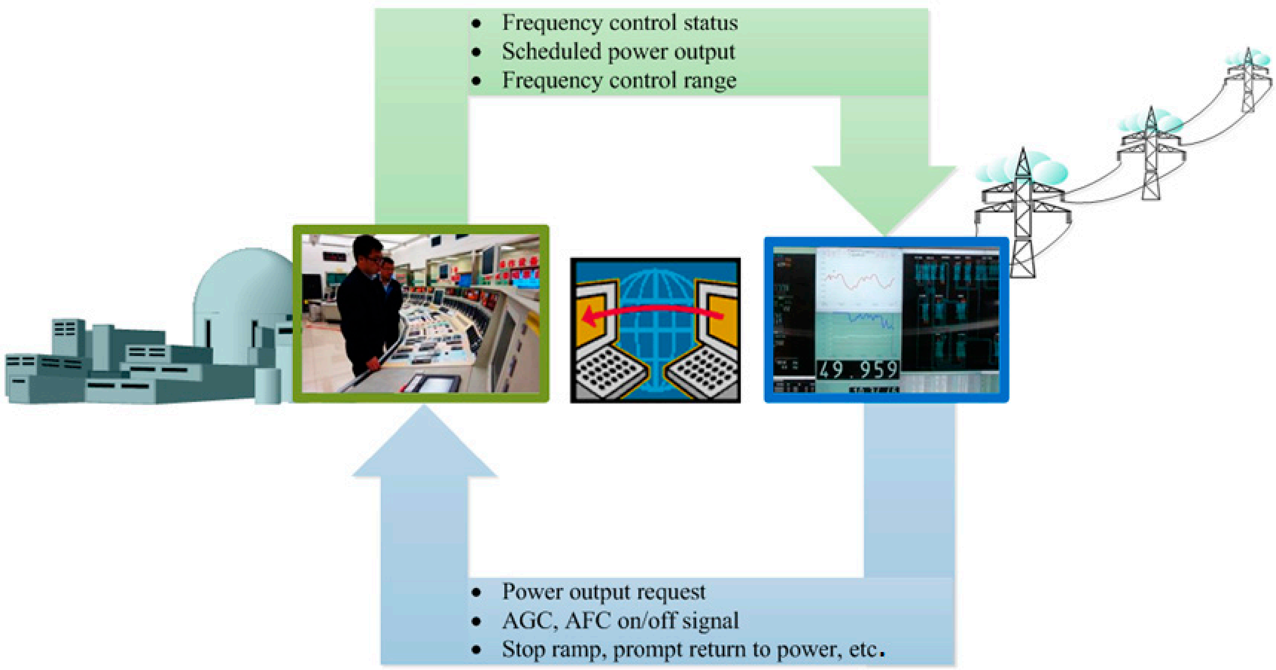

FIG. 31. Typical signal exchange between the grid and nuclear power plant control centres. AFC — automatic frequency control; AGC — automatic generation control.

[35] This generally applies to normal nuclear power plant and grid operations. In France, automated fast electrical power reductions, up to 200 MW(e)/min, are allowed by automatic control systems in some plants in response to grid emergencies, such as potential imminent loss of synchronization.

For an existing nuclear power plant that is converting from baseload to flexible operation, it is necessary to review existing communications with the grid system operator, and the signals or data that are transferred. In addition to the interface required for baseload operated plants, new requirements necessitated by a switch to flexible operation would include, at a minimum, the signals depicted in Fig. 31:

— From plant operator to grid operator (or plant planner):
  - Status signal of frequency control: whether it is set ON or OFF and changes;
  - Active power output: in megawatts (electrical) or percentage REO and as scheduled (and as forced by plant conditions);
  - Frequency control range: provision of maximum and minimum set points (e.g. upper/lower limits) and changes.
— From grid operator (or plant planner) to plant operator:
  - Power output request: as scheduled, in megawatts (electrical) or percentage REO;
  - Other signals/requests: informing the plant operator of the grid situation (e.g. stop ramping or return to full power promptly);
  - Switch frequency control (AFC) ON or OFF, if applicable/exercised;
  - AGC signal, if applicable/exercised.

6. ECONOMIC CONSIDERATIONS OF FLEXIBLE OPERATION

Operating nuclear power plants at baseload is generally considered to be the most economically advantageous method. Nuclear units have high upfront capital costs and relatively low fuel and operational costs compared with fossil fuel generating units. In competitive markets with individual nuclear plants acting as price takers, revenues from electricity generation are maximized at full load operation.

However, for the reasons given in Section 3.2, it may become necessary to operate nuclear power plants in load following mode. Consequently, establishing the ability of plants to physically ramp up and down for load following — to varying degrees at different timescales — will certainly affect the economics of plant operation. The plant owner/operator will identify the origins of the costs and the possibility of benefitting from flexible operation as a value to the grid system operator and the nation's energy policy. Therefore, in economic terms, the questions of why and how non-baseload operation may add value to the power system need to be evaluated together with the associated costs. In this evaluation, the factors that necessitate deviation from baseload operation of plants, and the cost and value of doing so — with associated uncertainties — need to be identified.

This section discusses the associated costs and values of flexible operation for nuclear generation. The factors behind an economic analysis of flexible operation are described first in Section 6.1, followed by a discussion of two means by which the profitability of a nuclear generating unit can be adversely affected: increased costs and decreased revenues (see Sections 6.2 and 6.3). By referring to this section, a plant owner/operator can identify the origins of the costs and the possibility of benefitting from flexible operation. It should be noted, however, that the specific costs and benefits may differ for each case, depending on the commercial, legal and financial frameworks.

6.1. FACTORS BEHIND A COMPREHENSIVE ECONOMIC ANALYSIS

6.1.1. Needs for and added values of flexible operation

If nuclear power plants constitute, or will constitute, a significant share in a country's energy mix, or if this technology is used as a backup of intermittent energy sources, "the load following operating mode can be either an option or a necessity" [43]. The issue of economic impacts will likely become a central challenge in a future electricity system in which the nuclear units might coexist with high, and even increasing, amounts of renewable energy. Although the integration of renewable energy generation may represent the central case for flexible operation of plants in many grid systems, it is not the only driver of flexible operation of nuclear generating units. From the economic perspective, citing the reasons discussed in Section 3.2, non-baseload operation may add value to the power system for the following:

— *Integration of renewable energy generation.* The integration of large and growing shares of variable renewable energy sources, as envisaged in several Member States, can become a central challenge in current and future electricity systems [44]. A large penetration of intermittent renewable energy sources introduces additional requirements for balancing output, and, by nature, this intermittent generation is less predictable than conventional generation, with large forecast errors. To cope with potential problems related to grid stability, additional amounts of flexible energy sources become necessary. Therefore, the temporal variation of renewable energy generation — in particular the short term intermittency of wind and solar power plants — puts demands on the dispatchable generation technologies to vary substantial shares of their loads. To provide variability at short timescales (beyond primary and secondary frequency control operations), higher ramping rates or deeper, i.e. larger magnitude of thermal power changes, and more frequent cycling patterns by dispatchable generating units, including nuclear units, are needed, as production schedules can vary more frequently with increased deviation from advance plans.

— *Power oversupply (overgeneration).* Oversupply occurs when inflexible power generation (i.e. must run generators such as non-dispatchable renewable energy sources, combined heat and power, baseload nuclear energy, run of river hydro and thermal) meets low demand. On the supply side, overgeneration has recently been primarily associated with the integration of steadily increasing 'must buy' capacity (e.g. renewable energy sources) into rigid grid systems. When priority grid access laws/regulations for renewable energy apply, wholesale markets can repeatedly reflect electricity oversupply through negative prices, for example, on sunny and breezy days. On the demand side, low (or substantially decreasing) electricity consumption, particularly by large consumers, may result in excess generation. For example, a decline in energy intensive industries, particularly in aluminium production, has contributed to power market imbalances in Australia [45], and low demand growth rates have contributed to a risk of overgeneration in the mid-term in Norway [46]. Box 2 provides additional details about negative prices, showing the operational experience of power overgeneration and generation cuts at nuclear power plants in Germany in 2013.

— *Low degree of transborder electricity grid interconnections.* International power grid interconnections allow two or more adjoining/linked electricity grid systems to share power generating resources. Where the electricity network in a region has suitable electrical interconnections to neighbouring grid systems, it may be possible to develop commercial arrangements for the import/export of surplus generation during low demand periods (e.g. on weekends or at night). The differences in the price of electricity among neighbouring regions may provide commercial incentives for building or increasing the capacity of such interconnections. Additionally, interconnections among neighbouring countries can help to contribute towards the process of sustainable development through the increased reliability of electricity for use in a number of development related activities including, but not limited to, education, health care and employment generation [49]. However, arrangements for power sharing are extremely complex undertakings, because a variety of technical, economic, legal, political, social and environmental issues have to be taken into account, especially when on an international scale.

6.1.2. Scale and structure

Profound economic analysis calls for a comparison of impacts resulting from flexible operation with those from a baseload operation mode. The costs and benefits associated with flexible operation have to be considered in a comprehensive and integrated manner because they may be mutually exclusive at different scales, as well as mutually dependent in specific interfaces.

Stakeholders at each scale will be affected differently in different situations. On the one hand, a nuclear power plant operator will experience impacts in terms of higher initial installation costs or O&M costs for flexible

Box 2. Negative prices and production cuts in German nuclear power plants in 2013.

In comparison to all other markets in the economy, the electricity market has a distinguishing feature. Typically, goods can be stored for future use, whereas there are very limited storage solutions for electricity on a large scale, at least at the moment. Therefore, the supply and demand of electricity have to be in a state of equality or balance (equilibrium) at any given time. The markets are then said to be ‘cleared’. In economic theory and practice, freely adjustable prices play a role as ‘natural regulators’ by bringing together the supply of, and the demand for, electricity. Negative prices fulfil the same function as they clear the markets, but they do this in a rather paradoxical way. In cases of overproduction — as signalled by negative prices — producers have to pay consumers for electricity usage.

The integration of technologies with low short run marginal costs (i.e. variable renewable energy sources, such as wind or solar) into the German electricity market, in the past, resulted in a number of moments with low (below €10/MW(th)), or even negative, prices. According to a study published by the Fraunhofer Institut für Solare Energiesysteme [47], the frequency of low price periods in the German market in the first half of 2013 reached roughly 200 hours, quadrupling from 2012. The number of hours with negative prices also increased — although at a lower pace (approximately 50%) — and approached 40 hours over the same period.

Bloomberg [48] reported a snapshot of production cuts at German nuclear power plants on 16 June 2013, during the phases of low and negative prices when wind and solar generating units provided more than 60% of the electricity demand in Germany, which was a record. According to the data analysed by Bloomberg, German plant owners/operating organizations RWE, E.ON and EnBW reduced nuclear output: the RWE Gundremmingen nuclear power plant units B and C, both BWRs, reduced output for about 2 hours to approximately 46% REO (a reduction of more than 700 MW(e)) and to about 42% REO (a reduction of nearly 800 MW(e)), respectively; E.ON operated the 1360 MW(e) Grohnde nuclear power plant and 1400 MW(e) Isar nuclear power plant unit 2, both PWRs, at around 88% REO (approximately 1200 MW(e)) for 15 hours and for 3 hours, respectively; Brokdorf nuclear power plant, also a PWR, was operating at approximately 85% of its 1410 MW(e) REO, for 4 hours; and EnBW’s Neckarwestheim nuclear power plant unit 2 (1395 MW(e) PWR) reduced its output below 1200 MW(e) (at around 86% REO) for 18 hours.

The overall installed nuclear capacity in Germany was utilized at a rate of 96% during the periods of negative prices between the first half of 2012 and 2013, with the minimal load reaching 49% [47]. Other market participants experienced more substantial increases (lignite and coal fuelled electricity generating units) and decreases (gas fired generating units) in their production levels while facing negative prices. International power grid interconnections in Germany allowed for the sharing of power generating resources, thus minimizing losses. The electricity exports in Germany quadrupled in the first half of 2013 in comparison to the same period in 2012 when low prices prevailed.

The appearance of low and negative prices in electricity markets demonstrates, in general terms, the need for enhanced flexibility of the energy system, which is likely to increase with the amount of integrable renewable energy sources. From the economic point of view, the costs to provide additional flexibility services have to be internalized.

operation. On the other hand, a grid system operator may find that the added flexibility allows for more renewable energy resources to be added, and for grid reliability and stability to be provided or improved. However, the same plant owner/operator might benefit from market structures that pay the plant for the added flexibility. Additionally, governments and relevant ministries would be primarily interested in the impacts on the overall economy, which would include impacts on various sectors in addition to the nuclear and energy sectors.

Therefore, four distinct levels are considered in this publication for which a systematic impact assessment (cost–benefit analysis) can take place, as illustrated schematically in Fig. 32. The following subsections will also discuss mutual interdependencies among individual cost–benefit levels, as indicated by the arrows in Fig. 32.

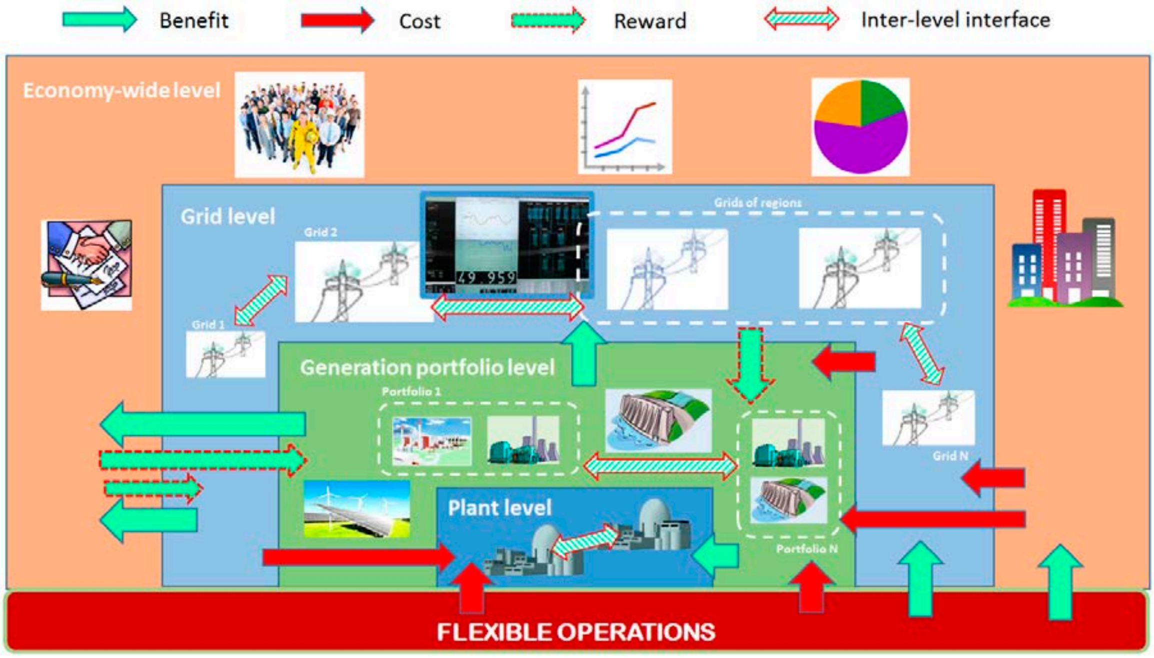

FIG. 32. Subsets of cost and benefit levels in a comprehensive analysis of a flexible operation.

6.1.2.1. Plant level

The first level of analysis includes assessments of costs and potential benefits associated with provision of flexible operation services at the plant level. One of the most crucial aspects here is cost related issues: in particular, what additional costs are likely to be incurred when adapting conventional baseload systems or changing the standard design to meet new operating requirements. A recent study presented and quantified the impacts of flexible operation on fossil fuel plant operating costs [50]. It showed the 'lower bound' cost of starting, as well as load following, a fossil fuel power plant that, in most aspects such as conventional island impacts, could be extrapolated and which counts as operating experience for nuclear power plants.

6.1.2.2. Generation portfolio level

Evaluation at the generation portfolio level implies impact assessment associated with flexible operation beyond the level of individual plants. In general, the energy manager will optimize, as best as possible, the dispatch planning of the nuclear units across the fleet to minimize costs and to maximize revenue from real time to long term schedules, while preserving grid reliability and security. In economic theory and practice, flexible operation of nuclear power can, under certain conditions, be used strategically to maximize revenues if a portfolio consists of different types of technologies.

6.1.2.3. Grid level

Individual generating plants (or portfolios) interact with each other and with a broad variety of other economic agents through the electricity grid and through the market. In interactions with those market participants at the grid level, revenue streams of nuclear power plants are determined. For example, the level of deployment of renewable sources in the energy system would determine the revenues of flexibly operated nuclear plants through price and output impacts.

6.1.2.4. Economy level

Finally, the economy wide level evaluation encompasses a cost–benefit analysis of adapting flexible nuclear operation beyond the level of a country's energy system. This evaluation could cover potential technology spillovers to non-energy sectors, movement of labour within the nuclear and energy sectors and among them and other sectors in the economy, environmental impacts (benefits or losses), etc. Substantial impacts, however, are more likely to be felt in Member States with a significant initial share of nuclear baseload generation in the energy mix.

6.1.3. Uncertainties

As a basic evaluation at the plant or the fleet level, the impacts (benefits or losses) of flexible operation may be assessed by determining changes in supplemental costs and revenues as a result of adopting flexible operation. At the grid level, where a number of actors — owners of different generating technologies, operators, regulators, consumers, etc. — are involved in interactions within the energy system, estimating the effects that the introduction of flexible nuclear generation may bring to the electricity system becomes a more complex undertaking. Once the costs and revenues are identified, allocated and weighted, the economic effects (benefits or losses) of flexible operation may be assessed by estimating the difference between the supplemental revenue and the supplemental costs resulting from flexible operation. In any assessment, of course, the time aspect and the uncertainties associated with time matter when accounting for various impacts and changes. For example:

— Even if the design and O&M costs are well determined and controlled by the nuclear power plant owner/operator, the evolvement of electricity prices (and thereby revenues) is much more difficult to forecast, in particular, in a constantly changing electrical system — as has been evidenced for a few decades by the introduction of renewable energy sources or shale gas.
— A possible future with energy management solutions driven by smart grids is a major factor of uncertainty affecting all flexible generation and storage solutions.
— The commercial arrangements within current market rules and regulations that may provide payment for service for balancing and frequency control may depend on future market conditions.

6.1.4. Importance of impacts on particular stakeholders

The relative importance of the four cost–benefit levels could differ depending on the market arrangements and on the stakeholder(s) for a particular area of consideration. Stakeholders will be affected differently in the different situations and uncertainties described above. For example, a utility planning on installing a new nuclear power plant in a foreign deregulated market would place more emphasis on the plant and portfolio levels, but would have almost no interest in the grid or economy wide levels. By contrast, a grid system operator in a country where a plant would be located, would only be interested in grid level issues. And in a country with centralized ownership of much of the electricity system, although governments and relevant ministries would be interested in all levels, the economy wide level would be their top priority or emphasis.

6.1.5. Operational experience and research

Until recently, the majority of the available research on economic impacts from flexible operation has mainly focused on the grid level perspective, especially the impacts of renewable energy systems. Most of the current literature on this topic discusses general aspects of integration of renewable energy sources [51, 52]; more academically oriented research applies different types of numerical models to quantify the impacts on the energy system from integrating renewable energy sources, such as wind generation systems as discussed in Refs [53–56].

Given that load following mode is, to a lesser degree, a preferable operational option for nuclear power generating units than for most fossil fuel generating units, the impact of load following on the economics of nuclear generating units has attracted little attention. Studies focusing explicitly on potential economic benefits and challenges faced by the nuclear power sector due to the integration of renewable energy sources have been much less common than those on fossil fuel generating units. However, recent studies that present and quantify the impacts of flexible operation on fossil fuel plant operating costs, for integration with renewable energy generation, have provided insight for grid level effects that would also be extended to nuclear generating units. Some studies to be noted here are the following:

— Reference [43] was the first systematic study to assess the grid level system costs of integrating different technologies in member countries of the Organisation for Economic Co-operation and Development. It was also the first to quantify the incidence of load following at nuclear power plants on O&M costs. A primary objective of the study was to assess to what extent the economic profitability of flexibly operating plants could be impaired by potentially higher O&M costs. These are true costs accruing inside the power sector (the grid system) to producers, consumers and taxpayers. The integration of significant amounts of variable renewable energy generating units might cause substantial additional costs to be incurred by a plant because of the requirement for increased flexibility. Given the lack of data, the study draws on personal communication and on publicly available aggregated data from an IAEA database containing yearly average losses of production of plants worldwide [57][36].
— The data from the study in Ref. [50], which presented the lower bound cost of starting as well as load following a fossil fuel power plant, were utilized in a broader grid level renewable integration study, while determining the additional cost of cycling the fossil fuel fleet.
— Reference [58] evaluated the ability of nuclear reactors to follow the load in the French power system in 2030 with at least 28 GW of wind power (11% of the total energy generation). Based on a dynamic optimization dispatching model, namely Dispa-SET [59], the study showed that operating the French power system with a high infeed of wind power seems to be technically feasible. However, this relies heavily on the capacity of nuclear reactors to follow variations, energy storage to ensure flexibility and market capacity to allow generators to adapt continuously to the demand. The study showed that balancing wind power variation was less a matter of installing more flexible capacities, and more an issue of ramp rates and unit schedules, power market regulation and real time market interactions with the day ahead and intraday markets.
— It is argued in Ref. [60] that in the future, more flexible nuclear systems could enable wind energy to achieve a 50% share of the renewable energy contribution to the energy mix. Accordingly, SMRs could provide power generation to back up the supply from renewable energy resources and load following. The study concluded that the reduction of 1000 MW(e) offshore wind farm variability was best achieved with 700 MW(e) SMRs using 100 MW(e) modules. However, for a 100% reduction of the wind variation, additional balancing measures (e.g. smart grids, storage and hybrid nuclear systems) would still be needed.

6.2. COST RELATED IMPLICATIONS OF FLEXIBLE OPERATION

As no recent overview of the state of knowledge on the costs of flexible operation of nuclear power plants was available, the current analysis was undertaken to gain a more in-depth understanding of the economic consequences of non-baseload operation. The analysis presented in this section aims to assist policy makers responsible for making strategic choices about flexible operation. The section does not analyse the details of the costing approach, but summarizes insights from the available sources and underlines the pressing needs in filling the missing knowledge gaps.

6.2.1. Impacts at plant level

In the absence of economically viable large scale energy storage — other than in pumped storage hydroelectric plants, where it is available — the ability of nuclear power plants to operate flexibly is limited by physical constraints and economic profitability. While there may be net benefits of increased plant flexibility at the grid and portfolio levels, the deterioration of a plant's profitability is considered to be one of the major economic risks associated with flexible operation at the plant level. The first channel through which the profitability of a plant can be affected is related to the potentially higher plant costs associated with flexible operation. The literature distinguishes between four different cost categories that are likely to be affected when flexible operation, especially load following, mode is introduced. These cost categories are described schematically in Fig. 33.

[36] The latest edition in this series publication of Ref. [57] is the 2016 edition.

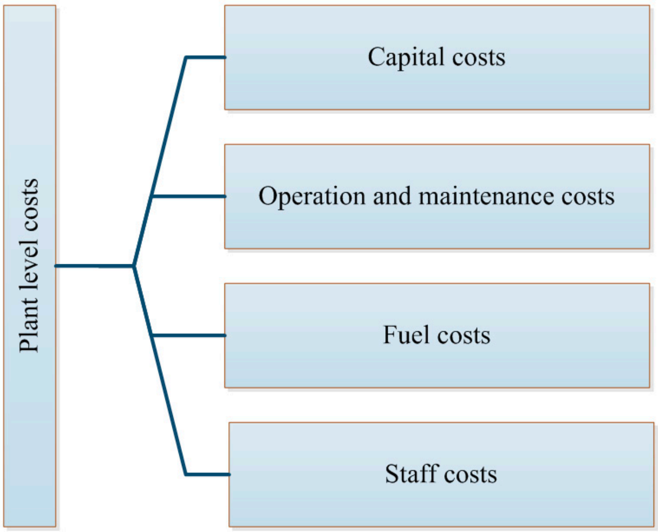

FIG. 33. Plant cost categories affected by using the load following mode.

6.2.1.1. Capital costs

Flexible operation will require capital costs associated with a design that is compatible with flexibility needs, or conversion of existing units to acquire those needs, owing to the technical and programmatic changes discussed in Section 5, if these have not already been considered in the design or installed in the facility. Capital costs associated with a design compatible with flexible requirements — or conversion of an existing facility — would accrue from additional studies and replacement equipment for the modified design/facility, as well as requalification, retesting and amended licensing processes.

If existing generating units were not configured for the proposed capability of flexible operation that was discussed in Section 4, retrofitting of equipment (operating procedures, as well as capital improvements) will be a major factor in capital costs. Additionally, grid system owners/operators and nuclear power plant owners/operators will make their decisions on which units to operate flexibly based on economic factors, including unit size, plant age, plant configuration and fuel costs. For economic reasons, plant owners are more likely to be inclined to continue operating existing units with marginal upgrades, instead of undergoing major equipment retrofits to improve plant flexibility.

Similarly, the purchasers of a new plant would prefer less change to the standard design to minimize their investment and financing. For the same level of flexibility, however, the associated capital costs may be different for a new design than for converting an existing facility. For example, additional investment could be needed in I&C to become eligible for operation in flexible mode, especially for earlier vintage nuclear power plants. An upgrade of existing plants — through retrofits and the installation of advanced control systems — would also be needed to provide better monitoring of physical wear, while these advanced control systems are readily available in the newer vintage of plant design. The capital costs will vary for each specific unit and cycling conditions. Figure 34 illustrates one example of capital costs for initial design and later design upgrades for a sample generating unit and their impacts on plant life and forced outage, in terms of the equivalent forced outage rate (EFOR).

In the case of a nuclear unit, there are additional issues that must be addressed and that do not come into play for fossil fuel plants: regulatory requirements and licensing commitments. These additional requirements and commitments may lead to major plant modifications, activities and programmes that might not be required for a fossil fuel generating unit and that will also add to the cost of flexible operation in nuclear power plants.

6.2.1.2. Operation and maintenance costs

A major cost that has been overlooked, while the initial capital costs are investigated, is the life cycle cost of operational changes. Life cycle costs include equipment and maintenance expenditures for component upgrades, equipment life reduction and potential derating due to equipment degradation associated with flexible operation

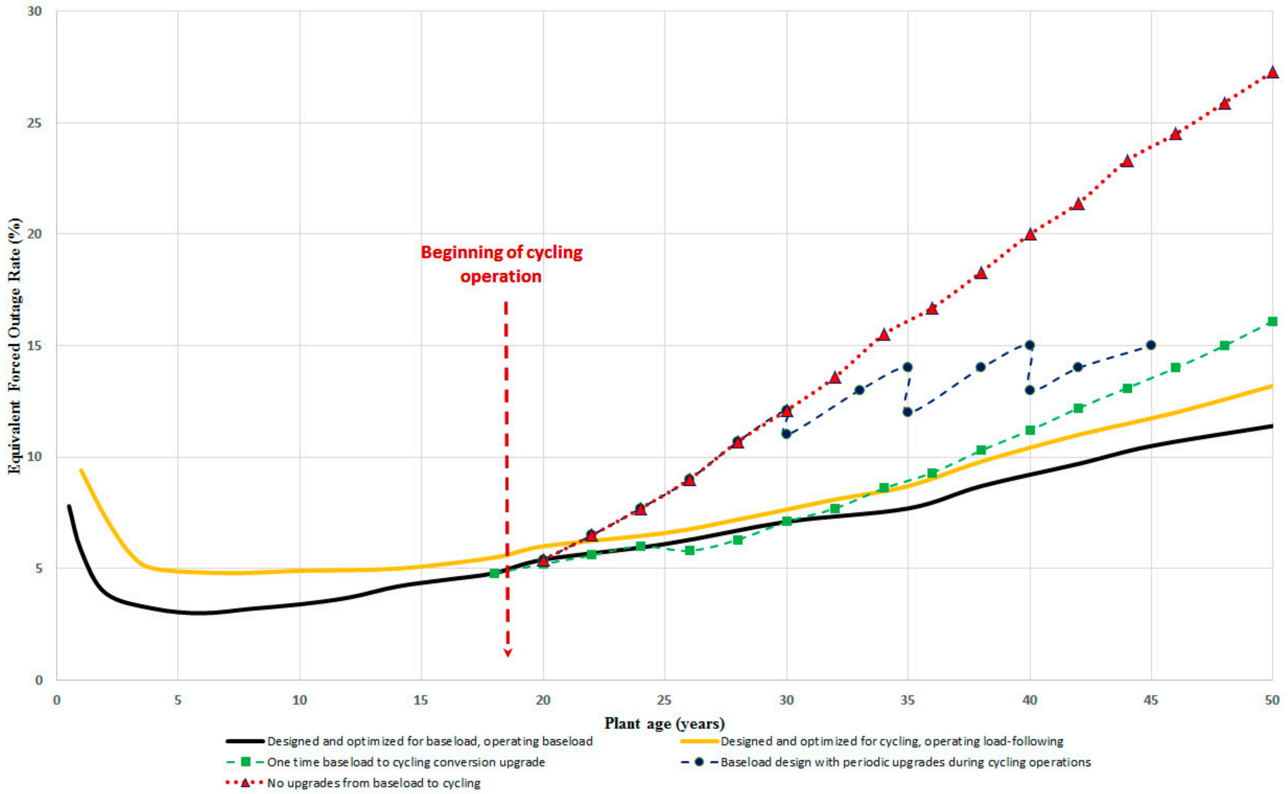

FIG. 34. Example of relationships among capital improvements and forced outages for a 600 MW(e) thermal plant (courtesy of N. Kumar, Intertek, reproduced from Ref. [50]).

over the remaining lifetime of a nuclear power plant. These costs become higher as the depth and periodicity of load cycling increase. The plant owner/operator needs to know the effect of flexible operation on the plant equipment in the long term, in terms of overall reliability, in order to decide how to allocate and recover costs.

In addition, the nuclear power plant owner/operator needs to establish a formal way of predicting future costs so that system changes can be designed to minimize the total cost. Flexible operation will cause an increase in O&M costs, and the magnitude of those costs will depend on the extent of flexibility needs and also on the properties and programmes that exist for design and operation. As discussed in Section 5, some of these equipment and programme related effects include:

— Wear on components due to repeated use (e.g. CRDMs) and to vibrations and changes in temperature. Operating lifetimes of SSCs may be affected in some cases, as frequent load changes translate into higher wear and tear of equipment.
— Load following can induce more frequent maintenance, while reducing the availability of power plants in terms of increased outage frequency/duration or increased risk of equipment degradation or failures, as well as additional monitoring and surveillance.
— Waste management changes may be considered in the O&M costs associated with flexible operation, such as control of liquid waste in PWRs, as they potentially result in additional operation costs.

It is important to note that plant level costs are unique to every unit. Several factors affect the cost of flexible operation at a plant, and differ from one site to another, including the following:

— Unit design and vintage of technology;
— Equipment design and manufacturer;
— Size (output capacity in megawatts);
— Economies of scale;
— Plant configuration;

— I&C technology;
— Retrofit of equipment (operating procedures as well as capital improvements), for increased flexibility;
— Operation strategy and methods used to perform flexible operation (e.g. grey rods, pump speed or turbine bypasses);
— Past maintenance related activities;
— Age and condition of SSCs, including the effectiveness of ageing management programmes;
— Time between planned outages;
— Timing of major overhauls such as turbogenerator overhauls;
— O&M and capital expenditures with respect to forced outage rates;
— Past cycles and the characteristics of past cycles (e.g. number of planned or unplanned shutdowns (hot or cold), startups[37], power changes and extended low power operation);
— Strength of operator training and operating procedures.

Using plant specific and operational experiences, together with industry data for similar plants, the O&M costs can be estimated for each specific unit. This estimation utilizes unit composite damage accumulation models and actual and historical data on the component and system level, as well as experience collected by plant staff. There are several tools developed for analysis via statistical regression and benchmarking of these inputs, converting them to cost estimations applicable to each case or an industry average. Figure 35 presents one of the methods that is sampled from Ref. [50] and provides the methodology and elements of plant cycling costs accounting for changes to:

— System production costs (including fuel, radioactive waste and auxiliary power);
— Forced outage recovery costs;
— Maintenance and overhaul costs;
— Long term and short term efficiency costs;
— General engineering and management costs;
— Capital costs of cycling improvements;
— Regulatory/licensing (nuclear and environmental) costs.

The change in each category represents the increase/decrease in costs associated with load following. Costs associated with changes in production and system upgrades/analysis are relatively straightforward to estimate. Costs that are very often difficult to quantify are associated with increased failure rates (owing to lower availability, increased EFOR and increased time of scheduled outages) and decreased component life (resulting in higher capital and O&M expenses).

While failure rate increases may not manifest themselves immediately on cycling, eventually, increases in component failure rates occur, resulting from components reaching end of life sooner, which causes higher plant forced outage rates. How soon these detrimental effects will occur will depend on the amount of cumulative damage present and the nature and frequency of load following. Figure 36 illustrates cumulative damage predictions — in terms of EFOR — based on the scenarios considered in Ref. [50]. As can be seen, early in the plant lifetime, the impacts manifest themselves later compared to faster manifestation as the plant ages.

6.2.1.3. Fuel costs

Operation at less than full load will have an impact on fuel costs. This is because fuel will likely be used in a non-optimal manner, and in some cases, fuel management may not be optimized in anticipation of the next several fuel cycles. Fuel costs may also be affected by decreases in the thermal efficiency of the power conversion (secondary) system, particularly by low turbine efficiency rates at low power operations.

In practice, it is difficult to quantify fuel cost impacts due only to load following, as they are difficult to distinguish from those that are attributable to other fuel cost drivers.

[37] Typically, load following or transient reductions in power are much less damaging and operationally easier to achieve, so they are much less costly than shutdown and startup cycling.

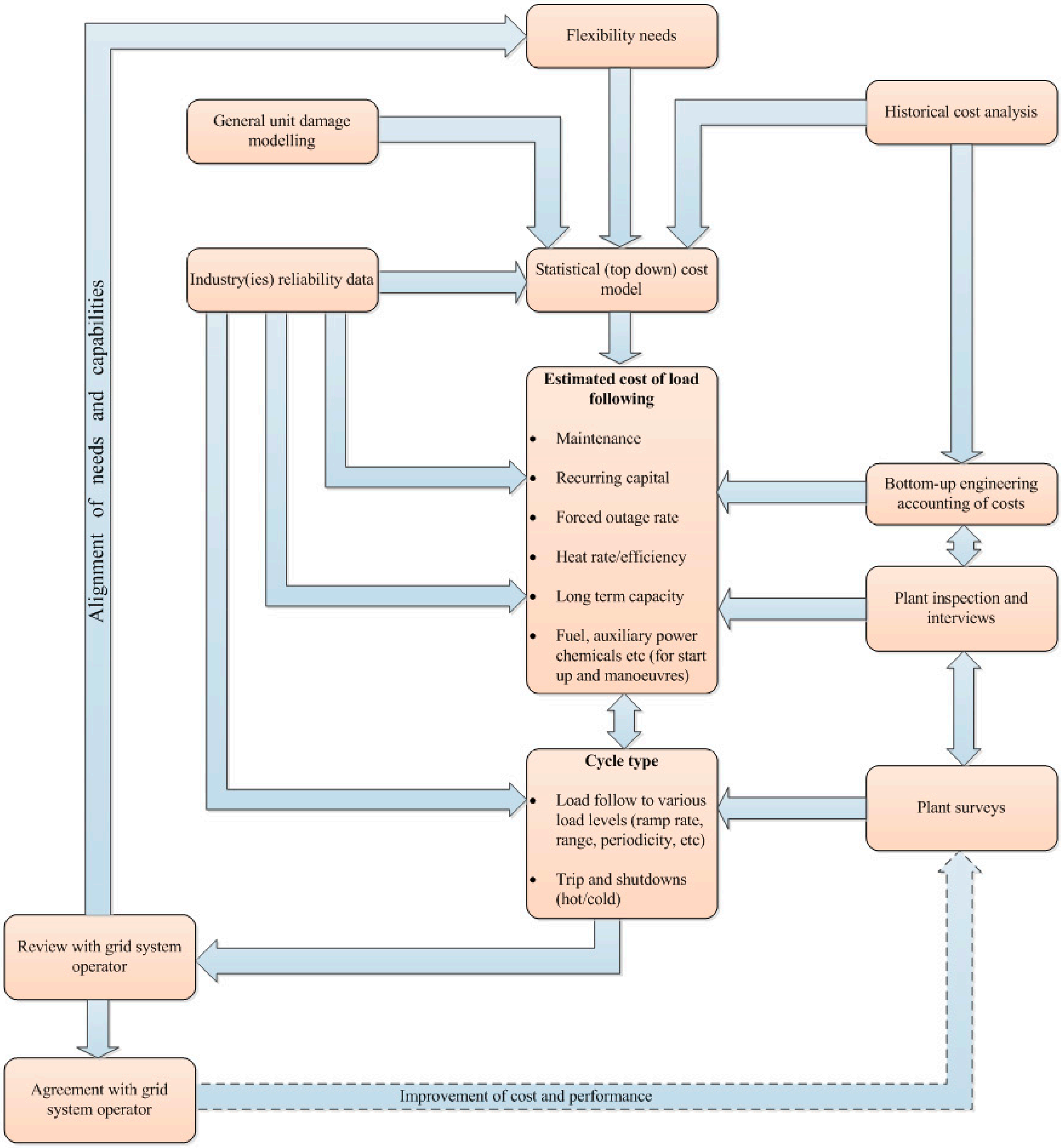

FIG. 35. Typical elements of methods to predict load following costs (courtesy of N. Kumar, Intertek).

6.2.1.4. Staff costs

Staff needs to be permanently available to adjust the load frequently, and, in some cases, unexpectedly, because ramping operations for nuclear plants are not always automated. Additionally, initial and continuing training (technical knowledge, and industrial, nuclear and radiological safety) of current and additional personnel, who will be needed for additional/revised monitoring, surveillance and maintenance and for more frequent or brisk plant system interventions, will be an additional cost to consider.

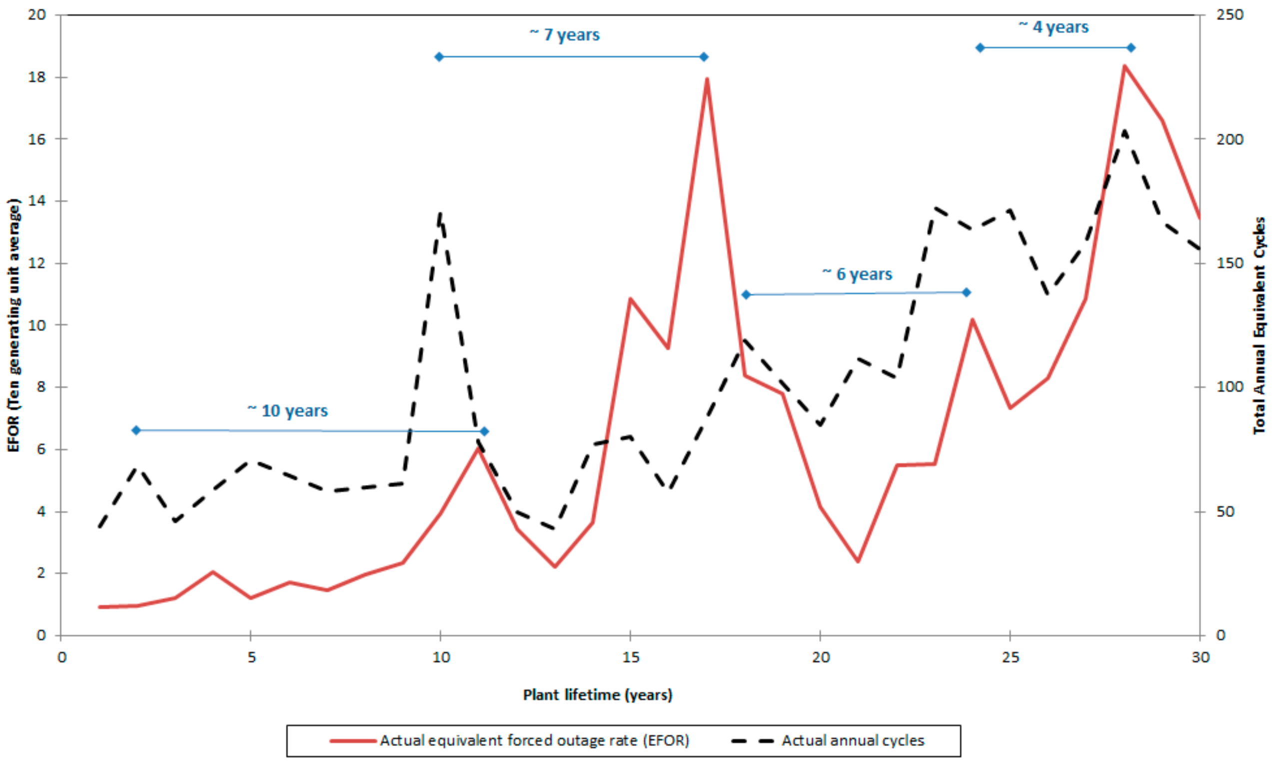

FIG. 36. Lagging impact of cycling as interpreted from the collected data in Ref. [50]. Note that the actual plant data reflect the creep fatigue interaction design curve (courtesy of N. Kumar, Intertek).

6.2.2. Impacts at generation portfolio level

At the portfolio level, system dispatch and outage planning are optimized (in real time and forward looking) in order to minimize costs while meeting grid reliability requirements. This is typically accomplished by several means, including:

— Expanding options for the generation master plan if the variable costs due to flexible operation are identified;
— Weighting and selecting units that can/cannot operate flexibly to optimize fuel usage;
— Closely coupling generation planning and outage planning.

In deregulated markets, traders offer supply bids for each of the assets in their portfolio based on market demand. It is important for portfolio managers to be aware of the flexible operation costs of nuclear power plants in their portfolio to adequately recover the additional costs of providing flexibility. At the same time, without violating grid stability constraints, portfolio managers can make economic decisions on including increased amounts of renewable energy generation, which often has lower operating costs, thus minimizing the overall portfolio cost.

Portfolio owners/managers may find that there is an upfront cost of capital retrofits, or maintenance costs associated with increased nuclear power plant flexibility, but they may be able to offset this cost by choosing lower fuel cost units to dispatch. This may not be an option for all portfolio managers, in which case, they would require market mechanisms or cost recovery opportunities. In addition, net revenue at the plant level may play an important role in deregulated markets, where the decision to operate flexibly is driven by an opportunity to profit (see Ref. [61]).

It is also possible for energy/portfolio managers to reduce the costs (including plant level costs) of flexible operation for the whole portfolio by balancing the delivered flexibility among the multiple nuclear generating (and other generating) units in the portfolio, instead of operating the nuclear units individually to meet all required flexibility needs. This can be performed more easily in a fleet of nuclear generating units by:

— *Planning balancing services.* Optimizing the revenue generated using a technique to select which units are to operate flexibly each day (this technique manages the usage value of the unburned nuclear fuel in each reactor);
— *Generation planning.* Allowing more flexible planning when deciding the generation master plan to manage nuclear fuel savings and maximize the value of load following;
— *Outage planning.* Better coordinating outage planning by making use of the capability for flexible operation when planning the outage.

6.2.3. Impacts at grid level

At the grid level, several units in multiple different portfolios will be dispatched. As at the portfolio level, some units on the grid, including nuclear power plants, may be affected significantly more than other units. Flexible operation of power plants at the grid level is typically required for system reliability and stability, or preferred for economic reasons, although system reliability and stability are always bigger concerns than economic issues. In some cases, a plant at a particular node on the grid may also be required to load follow significantly because of other factors, such as increased renewable energy generation. However, the decision or ability to load follow a plant may lie with the plant operator, who may have to incur additional costs to improve plant flexibility; the portfolio manager, who may not find it economically feasible to do so; and the grid operator, who may require flexibility to maintain grid reliability.

System reliability is usually at risk due to short term imbalances in the supply and demand of electricity. Therefore, grid operators employ ancillary services to respond to these imbalances, by dispatching resources within seconds or minutes of an imbalance. The costs of ancillary services to a grid are usually quite high, due to their relatively random nature. To minimize costs at the grid level, therefore, the costs for ancillary services could be reduced if nuclear power plants contribute to balancing and frequency control. It would be also be cheaper during low demand periods to continue to operate the on-line nuclear generating units at reduced power rather than shutting them down and replacing them with fossil fuel generating units.

The local or regional public organizations participating in energy planning may also run their cost–benefit analysis to integrate all direct and indirect costs/benefits caused by flexible nuclear generation at local and regional levels. Exploration of cost reductions and determination of benefits at the local and regional levels may support optimizing the costs and benefits for the generating units.

6.2.4. Impacts at economy wide level

At the portfolio level, portfolio managers maximize revenue for their portfolios, while grid operators have to ensure system reliability, and nuclear power plant operators will incur increased costs of flexible operation. System level net benefits will depend on production cost savings and the capital and operating costs associated with plant flexibility. In other words, while it may be possible to observe benefits at the system level, there will be negative cost impacts at the plant level. These additional plant flexibility related costs would eventually be passed on to the economy, for example, in terms of cost recovery or unplanned plant outages.

There are additional impacts on the economy that will go beyond the plant and system level costs. As discussed in Section 3, nuclear power plant flexibility may be required in some situations for grid reliability, where nuclear generation dominates the overall capacity of the grid, but in other cases, the added flexibility can also help to reduce transmission constraints, allow for growth in non-dispatchable resources of renewable energy or provide opportunities for increased profitability in new energy markets. Furthermore, increasing plant flexibility may allow grid operators to shut down older fossil fuel based power plants, which may transfer labour from fossil fuel plants to renewable energy sources or other parts of the economy.

Moreover, several studies that have evaluated the addition of renewable energy sources to the grid have highlighted the need for increased flexibility of the grid. With the addition of these renewable energy resources, the economy and society will see benefits in terms of reduced emissions. In addition to replacing fossil fuel based capacity with non-emitting renewable energy, even when the fossil fuel fleet is operated at lower loads leading to increased emissions (the emissions rate is higher, but the net quantity may be lower), emissions can be further reduced with plant flexibility.

One way of answering the question of how the economy will be affected by integrating renewable energy sources is offered by the public finance notion dealing with economic cost distribution. In practice, estimation of the effects requires application of large scale economic models that take into account all interactions among economic agents in all sectors of the economy. In the basic concept of incidence analysis, the degree to which integration of renewable energy sources imposes costs — or generates benefits — to the economy is related to the following: whether and to what extent the costs and benefits of integrating renewable energy sources may be partly or fully shifted (passed through) by electricity producers to another type of economic agent (i.e. to private and industrial consumers as higher (or lower) electricity prices ('pass through') or to workers and plant (or fleet) owners ('pass backward')). The latter could occur if dispatchable technologies provide costly services of load following for which they are not remunerated, with a resulting deterioration of profitability. The former case depends on the ultimate effect that the integration of renewable energy sources would have on electricity prices in the short and long terms, when all the related effects are taken into consideration: remuneration for the provision of flexibility services, internalization of system costs (see below), etc. Depending on the direction of the effect (price increases or decreases), virtually all economic agents will be affected, as electricity represents a major consumption and production factor.

6.2.5. Internalization of additional costs

Reference [52] is the first systematic study to assess the grid level system costs of integrating different technologies in member countries of the Organisation for Economic Co-operation and Development. The integration of significant amounts of variable renewable energy generating units might cause substantial additional costs to be incurred by a nuclear power plant because of the requirement for increased flexibility.

There is little disagreement in the literature that the criterion of economic optimality requires that grid level costs be internalized into plant level levelized costs. Hence, increased flexibility of baseload generation will require new regulatory practices to allocate the recovery of the additional capital cost among intermittent generating units and to compensate for sufficient capacity to balance supply and demand in the face of uncertainty in both aspects [51]. Various policy options, such as capacity markets, capacity payments or reliability options, are potential initiatives to support the availability of flexible capacity.

6.2.6. Case studies for cost quantification

A European Commission Joint Research Centre study [43] provided quantification based on the incidence of load following at nuclear power plants with respect to the O&M costs and tried to assess the extent to which economic profitability of flexibly operating plants could be impaired by potentially higher O&M costs. Although the aggregated data from the IAEA Power Reactor Information System database [62] containing yearly average loss of production of plants worldwide were utilized, the compiled data did not make a distinction between plants that are normally load following and those that are baseload, as defined in Section 2, above. The study noted that the additional O&M costs due to load following are likely to be rather low (well bounded by 2% of the theoretical available capacity of a plant). However, it argued that the conclusions may need to be reconsidered for large scale deployment of intermittent electricity generation technologies.

A study conducted in four Member States (Finland, France, Germany and Sweden) — commonly known as the Elforsk report [63] — quantified the impacts on different cost categories at the plant level due to load following operation. Component level impact assessment was carried out on wear, maintenance, staffing, fuel costs and operation. According to the report, the experiences of Finland, France, Germany and Sweden showed that the current degree of flexibility is likely to cause very few additional costs at the plant level:

— One of the most relevant cost impacts was determined to be due to fuel cost increases, although load following is not likely to cause any fuel damage. Additional fuel cycle costs of load following for BWRs are estimated to be 17–23% higher than the baseload plants. Accordingly, the fraction of fuel cost in the total production cost is likely to increase by approximately 20–24%, if load following is performed in an unplanned manner. For PWRs, additional fuel cycle costs of load following are considered to be higher, at around 25–34% compared with those of the baseload plants. According to the study, however, the worst case scenario is when

all load following is unplanned. If the fuel cycle is planned for load following, there should be no, or low, additional fuel costs.
- One of the conclusions from the study was that from a strict fuel cycle cost perspective, load following is preferably to be performed by BWRs. For both reactor types, the cost difference due to load following mode can also arise from impacts on equipment wear and tear. Additional costs in PWRs, such as power consumption and water treatment costs associated with boron treatment, are likely to be minimal. The overall conclusion is that additional costs for PWRs might be higher than for BWRs, but the cost differential is not likely to be significant.
- The report argued that there is no significant cost associated with training personnel when training for reactor operators already implements load variations, which is the case for nuclear power plants worldwide. It is possible, however, that additional staff (e.g. chemical or system engineers) and associated training may be required for increased flexible operation at nuclear power plants.

Additionally, there might be differences in load following costs associated with SG design in PWRs — recirculating versus once through — as well as with PWR specific components such as pressurizers and RCPs.

6.3. REVENUE RELATED IMPLICATIONS OF FLEXIBLE OPERATION

Individual generating plants interact with each other and with a broad variety of other economic agents through the electricity grid and the market. This is why nuclear power plants cannot be considered in isolation. Rather, the focus is on the impacts of adapting conventional baseload systems to meet new operating requirements.

As discussed in Section 6.2.1, the potential deterioration of plant profitability is considered one of the major economic risks associated with load following, if there are no additional incurred costs for flexibility. As stated earlier, the first means by which a plant's profitability can be adversely affected is the higher costs associated with flexible operation.

The second means by which the profitability of nuclear power plants can be unfavourably affected is potentially decreased revenues from flexible operation as a combination of quantity and price effects. Revenues are likely to decrease because of the so-called compression effect, which is directly related to reduction in the load factors and reduced payment for energy delivered when a plant operates at reduced power. These direct effects on plant revenues might be reinforced by declining prices at the electricity markets (see Section 6.3.2). However, commercial arrangements within the market rules and regulations may provide payment for balancing services. If there is a payment — the amount of which depends on the market rules, regulations and arrangements — for providing grid flexibility, some revenue losses could be compensated.

6.3.1. Load factors

As mentioned above, the most profitable mode for nuclear power plants under perfect competition conditions is operating at high load factors. In general, capacity uprates are important in spreading fixed O&M costs over a higher output, resulting in lower generation costs per kilowatt-hour. Hence, reducing a load factor would result in increased generation costs, as fixed costs have to be spread over the lower output level. High load factors are also essential to pay back the investment cost inherent in nuclear generation [52].

The studies reviewed show that load following operation has resulted in very limited, if any, impacts on load factors. According to Ref. [43], the impact of load following on the load factor was estimated to be around 1.2%. The Elforsk report [63] came to a similar conclusion, noting that the capacity factor was reduced by less than 1.8% for the entire fleet in France.[38]

Although the impact of load following on the load factor is low, in the longer term, the introduction of significant amounts of variable renewable energy sources into the energy system can imply massive additions of generation capacity, and is likely to cause substantial shrinking of load factors of dispatchable technologies. Reference [52] further assessed the impacts on load factors for different penetration levels of wind and solar

[38] This small reduction was mainly due to unexpected or increased maintenance of CRDMs.

technologies in the energy systems. Table 4 shows that for high penetration levels of wind and solar energy, the adjustments in load factors for nuclear energy might be rather substantial. For high penetration rates of variable renewable energy sources such as wind and solar, the impacts on load factors and profitability are estimated to be in the tens of a per cent.

TABLE 4. IMPACTS ON LOAD FACTORS FOR DISPATCHABLE TECHNOLOGIES AT DIFFERENT PENETRATION LEVELS OF WIND AND SOLAR ENERGY IN THE ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

Technology	Change in load factor (%)			
	Wind	Solar	Wind	Solar
	with 10% penetration		with 20% penetration	
Nuclear	−4	−5	−20	−23
Coal	−27	−28	−62	−4
Combined cycle gas turbine	−34	−26	−71	−43
Open cycle gas turbine	−54	−40	−87	−51

Note: 2011 scenario from Ref. [52].

In some Member States, regulations may also require wind and solar energy generation to be a ‘must take’ resource, unless grid stability is in jeopardy. In those regions, when wind and solar energy generation are high and demand is low, baseload generation, such as from nuclear or coal, will be displaced in the merit order and will affect the capacity factor of other generation sources. Figure 37 shows the results of a study [64] investigating the increased penetration impact of renewable energy on a North American region, specifically the PJM Interconnection in the USA.

The top graph in Fig. 37 shows the progression of the PJM portfolio to 20% penetration of wind and solar energy, while the lower graph extends to 30% penetration. In both cases, nuclear generation is assumed as must run baseload. While this study did not evaluate the potential of nuclear generation to be operated at lower or cycling loads, it clearly illustrates the variation of impacts on the production rate (in this case, by the fossil fuel generating units, i.e. gas and coal) such that generation shifts from gas and coal to renewable sources as renewable energy penetration increases.

6.3.2. Price impacts

The direct effect on plant revenues might be reinforced or partly offset by price impacts from electricity markets. The latter encompass level and volatility effects. The substitution of baseload nuclear energy, with low or zero short run marginal costs, by variable renewable energy sources, such as wind or solar, will result in declining electricity prices, as long as the system costs are not internalized.

A related issue is periods with negative prices and higher volatility of prices, which decrease profits and make them less predictable (Table 5).

In economic theory, supplying electricity by technologies with low or zero short run marginal costs is not optimal as long as system costs are not internalized. This may pose risks to electricity supply in the medium and long terms, as fixed costs of installations cannot be covered by the decreasing price. The disruption and added uncertainty within the grid system are also potential implications.

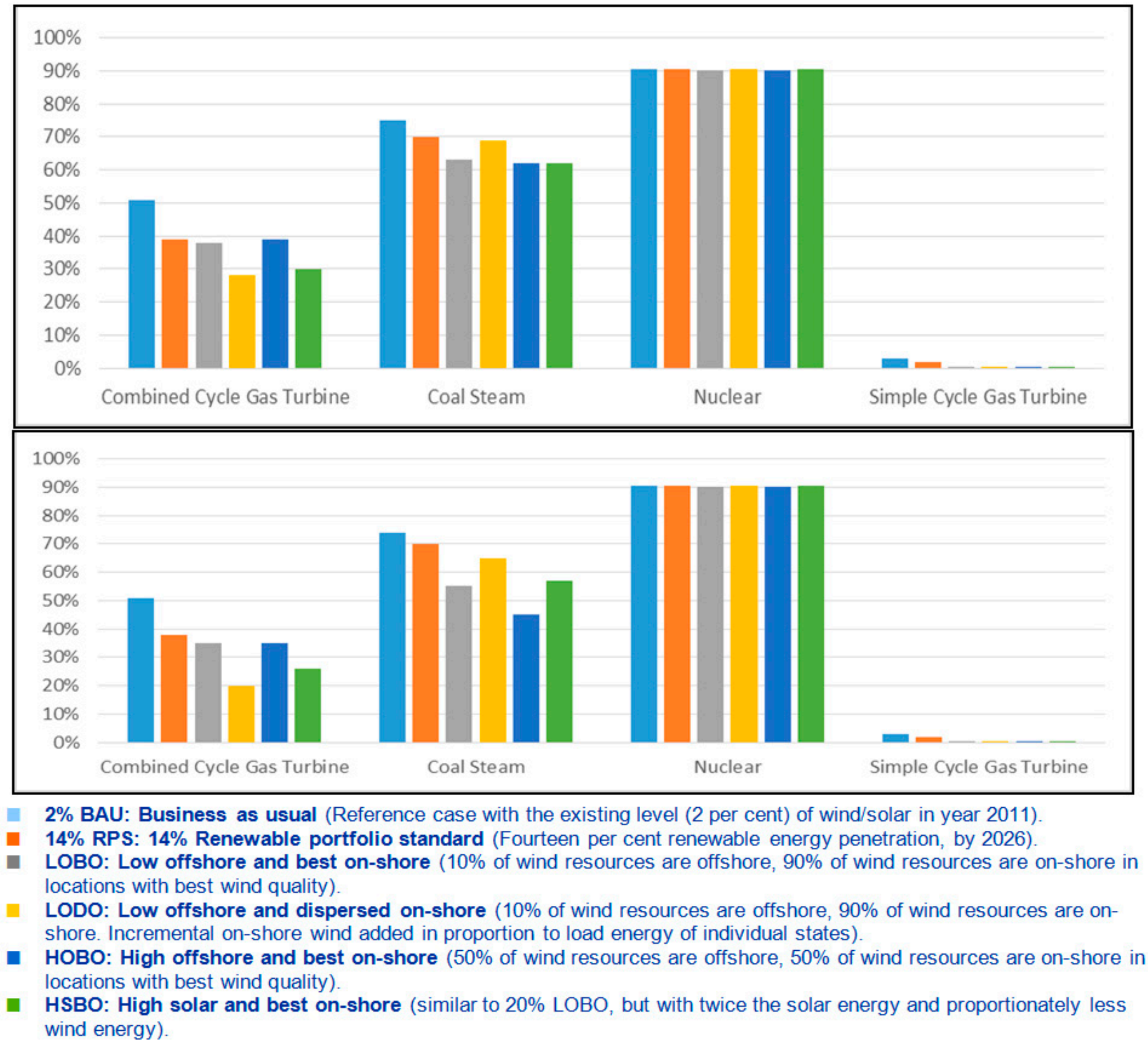

FIG. 37. Potential impact on the weighted capacity factor of various technologies with 20% (top) and 30% (bottom) renewable energy generation penetration, where nuclear generation is assumed as a baseload resource (courtesy of N. Kumar, Intertek, reproduced from Ref. [64]).

6.3.3. Profitability

The introduction of significant amounts of variable renewable energy sources into future energy systems can cause the profitability of dispatchable technologies to shrink substantially (see Ref. [52]). Profitability losses for the nuclear sector can range between 39% and 55% in a scenario with a high penetration of renewable energy sources (Table 6).

When profitability decreases, the incentives for investors to invest in additional capacities (capacity uprates) for dispatchable technologies, including nuclear, decrease. Studies have shown that with more volatile prices, recovering the investment costs will also become more difficult [66]. Obviously, less profitability at a lower load factor reduces investor interest in flexible capacity additions. The result is underinvestment in dispatchable technologies, including nuclear.

TABLE 5. ANNUAL MINIMUMS OF ELECTRICITY WHOLESALE PRICES ON THE DAY AHEAD MARKET AT EPEX SPOT AND NUMBER OF HOURS WITH NEGATIVE ELECTRICITY PRICES IN RECENT YEARS [65]

Year	Minimum price (€)	Number of hours with negative prices
2008	−101.52	15
2009	−500.02	71
2010	−20.45	12
2011	−36.82	15
2012	−221.99	56
2013	−100.03	64
2014	−65.03	64

TABLE 6. IMPACTS ON PROFITABILITY FOR DISPATCHABLE TECHNOLOGIES FOR DIFFERENT PENETRATION LEVELS OF WIND AND SOLAR ENERGY

Technology	Profitability (%)			
	Wind	Solar	Wind	Solar
	with 10% penetration		with 20% penetration	
Nuclear	−24	−23	−55	−39
Coal	−35	−30	−69	−46
Combined cycle gas turbine	−42	−31	−79	−46
Open cycle gas turbine	−54	−40	−87	−51

Note: 2011 scenario from Ref. [52].

6.4. IAEA ECONOMIC CASE STUDY

In parallel with this publication, the IAEA has prepared an economic study to quantify the cost–revenue aspects for nuclear power plant operations in mixed energy systems, including flexible operation. The purpose of this study was to explore economic opportunities for using nuclear energy in future power markets with increasing deployment of renewable energy. Based on a large scale country level power plant dispatching model, the IAEA study assessed the requirements for nuclear flexibility in the European Union up to 2050. As European Union Member States differ in terms of current and future renewable energy penetration rates, overall energy mix portfolios, grid interconnectivity levels, load profiles and size of the power market, liberalized electricity markets in the European Union represent an important case for analysis of flexible operation. Therefore, the European Union was selected for the case study.

A brief summary of this IAEA study is provided in Annex IV. Some findings of the study were used as the bases for some points discussed in this section. The following are the main findings of the simulations performed in the pilot IAEA study:

- Integration of renewable energy sources is not the only factor driving the provision of flexible operation. A lower interconnection degree and an inflexible generation mix are also drivers. For example, in a particular region, lower interconnection degrees may put additional pressure on domestic generation fleets, including nuclear generating units, to provide flexibility services. In some others, additional pressure for provision of flexibility services comes from an inflexible energy generation mix.
- Even with flexible operation, flexibility needs may not be resolved in some regions.
- Shortened lifetimes of flexible reactors are possible, if no constraints are put in place on the extent of load following (i.e. periodicity or length and depth of power cycles). The extent of load following will vary significantly among regions, resulting in different impacts on nuclear power plant lifetimes. For example, in a particular region or Member State, requested load following schemes particularly affect fatigue of plant SSCs, resulting in more life limiting cases.
- In most cases, flexible operation is likely to decrease the load factor if the share of renewable energy is high and to generate less payment for energy delivered when operating at reduced power.
- Revenue impacts from flexible operation need to be understood in detail, as revenue is dependent upon specific market arrangements or volatile electricity prices. In the absence of specific market arrangements for flexibility services, it is likely that revenues of plant owners/operators will decrease in comparison to the baseload mode, driven mainly by the decrease of load factors of flexibly operated plants.

6.5. SUMMARY

In the future, flexible nuclear power could potentially enable the growing penetration of renewable energy. The limited economic research conducted so far indicates that technologies with high capital costs and low fuel costs, in particular nuclear generating units, could experience significant adverse economic impacts if the costs of providing flexible services are not internalized within the energy system. However, the exact economic impacts have yet to be understood in detail. From operating experiences and case studies, some conclusions emerge:

- Adding nuclear power plant flexibility to the grid will most likely increase operational and maintenance costs at plants and occurrences of unplanned outages to maintain or restore reliability and availability. It is important to consider market arrangements that would allow plants to recover these costs.
- The change in cycling costs at the plant level is not proportional to the needs of flexibility. Several factors such as age, vintage, design, maintenance activities and past cycling affect the plant level cycling costs. Moreover, the frequency and intensity (rate of change and magnitude of change) of future flexibility requirements will have a direct impact on plant cycling costs.
- Depending on the design of the electricity market, the revenue for flexible operation may vary significantly over a large range. The remuneration for flexible operation is addressed in some Member States by a payment mechanism (e.g. by a capacity payment mechanism paying back the fixed costs):
  - In a deregulated market region, plant owners/operators will make their decision to retrofit based on the potential for increased profitability. This decision is primarily based on the net benefits of increased plant flexibility at the system level, as there may not be a benefit at the plant level.
  - Contrarily, in some Member States, there could be a large financial penalty for not being able to operate flexibly. Policy makers could develop mechanisms to incentivize plant owners/operators to install retrofits to provide flexibility in support of system benefits.
- Owing to differences in technology, the cost of expanding the capability for flexible operation might be higher for PWRs than for BWRs, mainly due to fuel cycle cost differences.

7. CONCLUSIONS

Baseload operation of nuclear power plants is the preferred mode of operation, because it is the most efficient use of capital invested in plants as well as being simpler than other modes. For these reasons, the majority of plants are currently operated as baseload generating units. However, there is a recent and increasing need in some Member States for plants to be capable of operating flexibly for a variety of reasons. As grid flexibility becomes necessary and inevitable, with an emphasis on reducing global greenhouse gas emissions and increasing the use of renewable energy and the share of nuclear generation, electricity grids would benefit from increased flexibility. The conclusions drawn from this publication when considering operating plants flexibly are the following:

- It is feasible to design a new plant, or convert an existing plant, for flexible operation safely, reliably and efficiently.
- The primary consideration for flexible operation is matching the flexibility needs of the grid system and the capabilities of plants for flexible operation. Therefore, the owners/operators of the plant and the grid have to understand and agree to a feasible solution that would satisfy their needs and capabilities. Similarly, the nuclear and grid regulatory bodies have to confirm and agree that flexible operation does not compromise the safety and reliability of the plant and the grid within acceptable regulatory limits and margins.
- In general, flexible operation of plants will add incremental capital and O&M costs at the plant level, but will likely provide benefits at the portfolio and grid levels and to the economy at large.
- The incremental costs associated with flexible generation at the plant level are not proportional to the needs of grid flexibility. Several factors such as age, vintage, design, maintenance activities and past cycling affect the plant level costs. Moreover, the frequency and intensity (rate of change and magnitude of change) of future flexibility requirements will have a direct impact on future plant operating costs.
- The additional costs at plant level for flexible operation may or may not be recoverable, depending on the electricity market arrangements, and there may or may not be benefits realized at the plant level by operating plants in a flexible mode. Policy makers might look at mechanisms to incentivize plant owners to operate flexibly when there are benefits at the grid and economy wide levels.
- Modifications to existing plants, operational and procedural changes, along with proactive inspection scheduling and training and education of all stakeholders, can minimize the impacts of flexible operation.
- The cost and operational complexity associated with flexible operation depend on the nature of the flexible operation and the characteristics of unit design, technology and O&M strategies.

When a new nuclear power plant is being designed, or an existing plant is being converted to accommodate flexible operation, there are some key considerations to determine the level of flexibility and its management. These considerations are independent of the reasons for flexible operation and are as follows:

- Some existing plant designs have an implicit capability and capacity for a limited range of non-baseload operation that may or may not be currently exercised. In cases where the flexibility needed is beyond that included in the current design and operation of the plant, adapting a design or a facility to achieve and manage the capability for flexible operation necessitates technical, organizational and economic considerations.
- In order to avoid financial, technical and operational burdens later, the extent of flexibility expected from a plant requires an early and combined decision by the plant owner/operator and the grid owner/operator, as well as by energy planners and plant designers. Therefore, it is necessary to establish a full understanding of the needs of the electricity system and of the capability of the plant to match that need. This requires good communication and close cooperation among these stakeholders as early in the process as possible.
- It is also necessary to communicate with both the grid and nuclear regulatory bodies during the process to inform and obtain guidance for an effective regulatory and operational decision making framework. A comprehensive understanding of the regulatory body's view on intended safety assessments and the owner/operator's demonstration of safety in the intended design and operation of the plant need to be clarified early, during the decision making stage, and must be based on industry experience and sound technical knowledge.
- New plants that are being built or planned are expected to operate for up to 60 years or longer, and a significant number of existing plants are considering lifetime extensions of 20 years or more. During this long operating lifetime, the structure of the electricity supply systems and the electricity market arrangements are likely to

change significantly. This may increase the need for flexible operation of plants in the future. Consequently, it is beneficial if new plants are designed to have the potential for future flexible operation, even if they are not required to operate flexibly in the early part of their operating lives. Similarly, owners/operating organizations of existing plants that are considering significant lifetime extensions need to consider whether the need for flexible operation would arise before the end of plant life.
— If, in the foreseen or planned operating life of a new or existing plant, flexible operation is likely to be necessary, enabling the capability early reduces the risk of major financial and technical issues later.

In several Member States, flexible operation has been a daily operational reality for many years, with full compliance and conformance with safety, quality and reliability requirements while managing the efficiency and financial impacts of such operation. This operational experience provides a knowledge base for technical and economic management of flexible operation in nuclear generating units. Additionally, in many Member States that have not operated their nuclear power plants flexibly, the electricity system and associated energy plans and strategies have been assessed and evaluated and decisions made for the current or future plants to operate flexibly. This decision making also provides valuable experience in identifying the common needs and requirements that have already been encountered. The experience and knowledge of both plant design and operation, and the energy and electricity system policies and strategies that have been implemented, are beneficial resources for the nuclear industry and electricity system stakeholders. This experience will help organizations understand the requirements, needs, challenges, solutions and lessons learned in order to make informed decisions to build, convert or optimize their plants for flexible operation. The key observations and lessons learned from those experiences include:

— Owing to changes in the traditional energy generation mix and electricity market arrangements, grid system operators are required to operate their systems with increasing variability of generation sources, and are asking several existing plants to modify their operating regime to perform frequent power manoeuvres.
— The technical impacts of flexibility on the design and operation of nuclear power plants are largely known, and technical solutions have been available for modifying the design or operation of a plant that is optimized for baseload operation.
— Alternatives to minimizing or eliminating the need for operating plants in flexible modes exist. These alternatives have to be explored in advance to determine whether the plants could continue to operate in baseload mode or with minimal need for flexibility.
— Good communication among the energy planners, grid system operators and plant owners/operators (including communication among their internal organizations) is necessary to establish and agree on the type and extent of flexibility needed from the plant. This is essential for:
  • Design and operational requirements of the plant;
  • Safety assessments of the plant;
  • Selection of technology for new plants;
  • Availability, efficiency and profitability of nuclear generation;
  • Grid stability and reliability.
— The financial impacts of flexible operation will depend on the type of flexible operation required and the magnitude of the changes to the design and operation of the plant. It will also depend strongly on the structure of the electricity market. It may be possible to minimize the financial impacts by commercial arrangements among market participants in accordance with financial rules and regulations.
— Changing the design or operation of a plant that is optimized for baseload operation will have an impact on organizational and human performance issues. This impact can be managed by appropriate training, programmes, processes and procedures, some of which can be common between the plant owner/operator and grid operator. Human capacity and performance are very important for successful implementation of flexible operation.

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Annex I

DESIGNING A NUCLEAR POWER PLANT FOR FLEXIBLE OPERATION: GERMAN OPERATING EXPERIENCE

I–1. INTRODUCTION

This annex provides details of German efforts towards designing a nuclear power plant for flexible operation. This case study[1] illustrates the experiences gained in the initial design stage and subsequent operation, specifically the considerations in decision making for design of plants for flexibility and establishing specific capabilities and design features. It further discusses certain design features that are fundamental for flexible plant operation.

I–2. DECISION MAKING FOR FLEXIBILITY

The oil price shock in 1973 accelerated the German nuclear programme under the Government at the time (1972–1974), with a goal to achieving 18 GW(e) of nuclear power by 1980 and 40 GW(e) by 1985. The planned share of nuclear power required load following capability and became a 'built in' feature for new nuclear power plants in Germany. These plants were designed to compensate load changes over a large range of outputs. Thus, as early as the 1970s, German plant designs (pressurized water reactors (PWRs) and boiling water reactors (BWRs)) considered and incorporated features to compensate for load changes over a large power range and a fast gradient (up to 5% rated electrical output (REO)/min, or, for some designs,10% REO/min).

The corresponding design to those specifications required specific features, including: a 'part load diagram', with a constant coolant temperature (PWR design) or recirculation control (BWR design) in the upper load range; a unique control rod manoeuvring concept for the PWR technology; comprehensive measuring (in-core) equipment; special instrumentation and control (I&C) systems for regulating and limiting power and power density; and postulation of a large number of load cycles for the fatigue design of components. Applicable to both BWR and PWR technologies, special I&C systems for reactor power and power distribution control, extensive fatigue, erosion/corrosion and wear/tear monitoring were also engineered for and implemented in German nuclear power plants as design and operational solutions to the effects associated with flexible operation.

The capability and capacity for load changes over a large power range and with a fast gradient were demonstrated and validated in the plant commissioning phase. But, in the operation phase, German nuclear power plants were initially operating mainly in baseload mode, as only a 31% nuclear share in the energy mix materialized compared to the planned 60% nuclear share in the country's energy mix by 1985.

However, the situation changed as large scale renewable energy sources had to be integrated into the German electricity generation mix (Fig. I–1). In 2013, more than 37 GW(e) from installed wind power and 35 GW(e) from solar power had to be integrated with priority input. This is why nuclear power plant flexibility became significant and necessary; it is now used continuously for nearly all nuclear power plants in Germany.

[1] The IAEA expresses its appreciation for the generous contributions of all the experts from Germany in preparation or review of this study, particularly J. Fandrich, A. Kuhn, H. Ludwig, O. Panzer and T. Salnikova of AREVA, F. Schulze of Isar nuclear power plant, W. Wischert of KSG Kraftwerks-Simulator-Gesellschaft mbH, C. Ahrens and S. Oltmanns of E.ON and G. Geer of EnBW. Their participation, and the courtesy and permission of their organizations to include the information provided, including the figures and tables, in this publication are acknowledged.

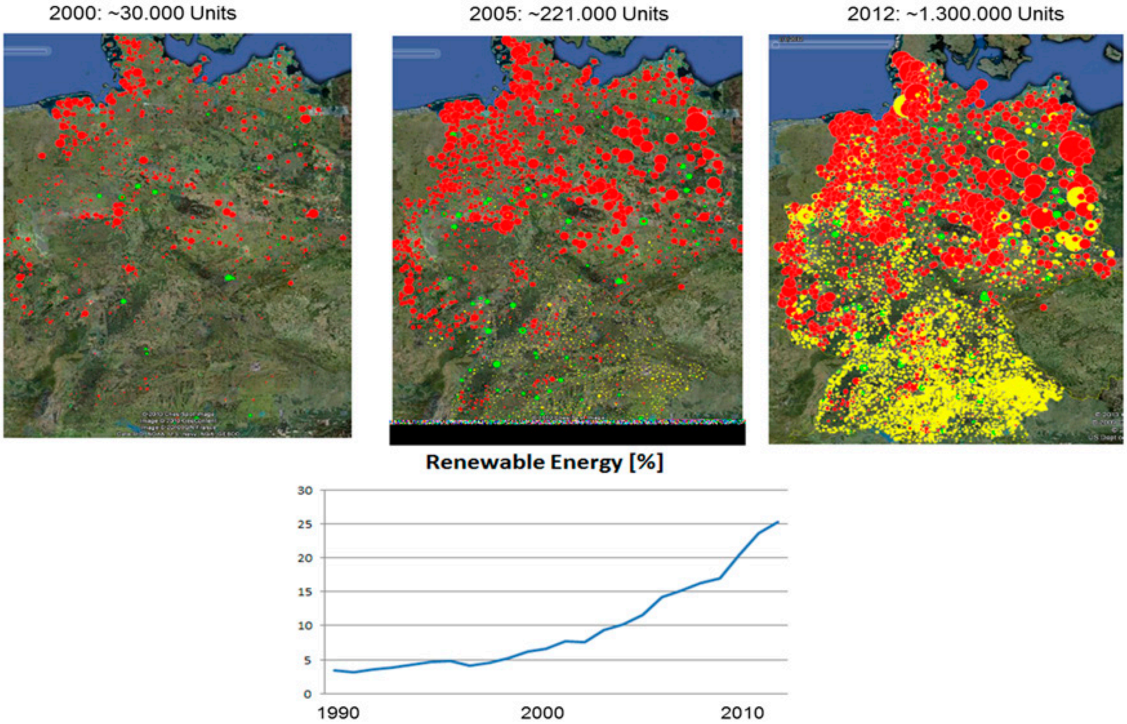

FIG. I–1. Development of renewable energy in Germany [I–1].

I–3. ESTABLISHING SPECIFIC CAPABILITIES AND DESIGN FEATURES FOR FLEXIBILITY

Table I–1 provides some of the key features in German nuclear power plant design for flexible operation. These design features were included in the original design, even though the plants were not expected to need to operate flexibly in the early years of operation.

TABLE I–1. DESIGN PHILOSOPHY FOR FLEXIBLE OPERATION IN A GERMAN LIGHT WATER REACTOR [I–2]

Response basis	Response mode	Parameter and properties
Predicted daily demand variations	Load following	Low power period (power level and duration) Power change rate (slow, fast) Time in cycle (beginning, end)
Spontaneous limited demand variations	Frequency control	Local frequency control: frequency deviation (ΔF) converted into power change (ΔP) (ΔP amplitude, slope of change) Remote frequency control: signal from the dispatcher (ΔP amplitude, slope of change) Superimposition of local and remote frequency control
Grid disturbances	Spinning reserve	Ramp (amplitude, slope, from which minimum power level) Steps (amplitude, from which minimum power level) House load capability (loss of off-site power without reactor trip) Fast (e.g. 5% rated thermal power/minute) return to full power without advance notice
Longer term forecasted demand	Extended low power operation	Reduced power level during extended period (number of occurrences, duration)

Based on this design approach and the grid requirements that were defined by the grid system operators, the capability of nuclear power plants regarding flexible operation was incorporated into the design basis. The 'load case catalogue' (the transient load specification for design and safety analysis) took into account phenomenological aspects, such as stress and fatigue analysis, taking into consideration the following:

— Improved materials;
— Appropriate dimensioning;
— Optimized mechanical design;
— Low stress mode operation;
— Sophisticated process control and monitoring technologies.

Figure I–2 shows a German PWR flexibility scheme considered in the design phase of Konvoi technology [I–2]. The blue lines show the grid requirements at the time (1992) that were considered in the safety analysis and in establishing the design limits (red lines) for flexible operation. The operational limits (green lines), which were reviewed and approved by the regulatory body, and the grid requirements (blue lines) were confirmed and qualified during commissioning. The commissioning tests demonstrated that the design was proven to allow for load change performance up to the design criteria (red lines) (i.e. 10% rated thermal power (RTP)/min in a power range of 100–20% RTP, with a 5 minute pause between power down and power up manoeuvres). The test also demonstrated that the flexibility capability according to the licensed operational manual limits (i.e. operational limits and conditions) was met, and at the same time, the existing grid requirements were fulfilled. Finally, the blue shaded area represents the planned range of load following and frequency operation by German PWRs to meet the grid needs at the time.

As can be seen in Fig. I–2, the design also provided a substantial margin at each power level over the operational limits approved by the regulatory body.

The plant commissioning test also confirmed the following load changes, from the licensed operational manual (black curves in Fig. I–3), including the time allowed between manoeuvres (5 minutes versus 10 minutes) [I−3]:

— Power change rates up to 10% REO/min in a power range of 100–80% REO;
— Power change rates up to 5% REO/min in a power range of 100–50% REO;
— Power change rates up to 2% REO/min in a power range of 100–20/30% REO.

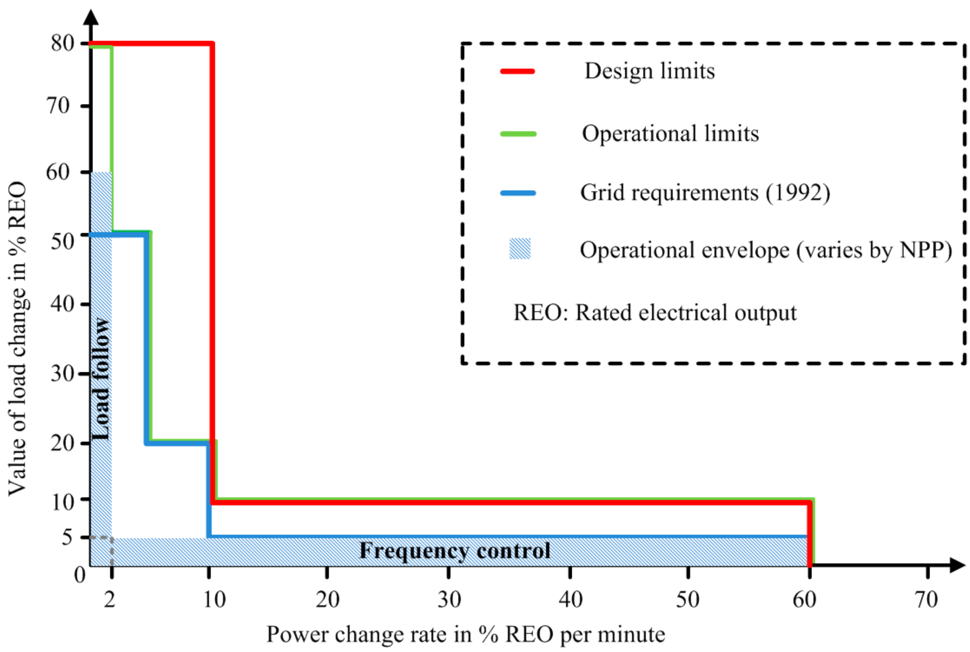

FIG. I–2. German pressurized water reactor flexibility requirements and design capabilities (reproduced from Ref. [I–2]). NPP — nuclear power plant; REO — rated electrical output.

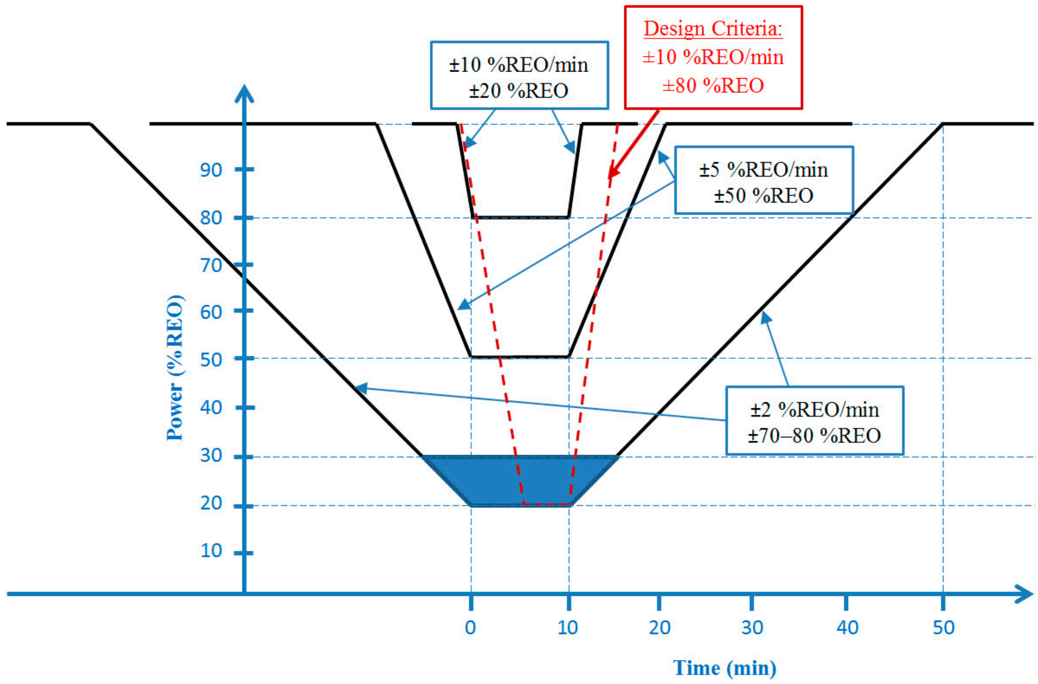

FIG. I–3. Power manoeuvre operational limits versus design limits in Konvoi design nuclear power plants (reproduced from Ref. [I–3]). REO — rated electrical output.

The power range in the last item above is the part load power level, which varies depending on the adjustment of the specific minimum load point (e.g. 20% REO or 30% REO) of the nuclear power plant, which is shown as the blue shaded zone in Fig. I–3.

In reality, the nuclear power plant capability for flexibility that the grid system operator requested was beyond the need of the grid for a long time, so that the full capability provided by the plant design was not used during many years of plant operation. Most German plants ended up operating in baseload mode after commissioning, because there was no, or very minimal, need for flexible operation in Germany.

However, the grid requirements that were based on the 1992 grid configuration and plans have evolved. Today, the grid needs much more flexibility, primarily because the variable and intermittent energy generation from renewable energy sources has increased and the economics for baseload operation have changed. Thus, the need for flexible operation of nuclear power plants in primary frequency control and secondary control has increased, prompting load following operation with increasing load change ranges and gradients to meet the latest grid requirements. This has required expansion of the operational envelope and changes to the operational limits while still remaining within the design limits.

The operational and hardware changes utilizing optimization and upgrade of nuclear power plants, such as optimized core loading strategies, advanced control system and advanced fuel designs, have enabled wider load change performances by plants with sufficient design margins, such as the following:

— Up to 2% REO/min in a power range of 100–40% REO [I–4];
— Ramp down to the minimum load point, which varies between 20% REO and 30% REO depending on the plant, prompted by negative electricity prices;
— Power changes up to 8% REO with ramp rates up to 60% REO/min for frequency control;
— Power changes up to 70–80% REO (depending on the minimum load point of the plant) with ramp rates up to 2% REO/min for load following.

Some of these cases have required review and approval of operational limits by the regulatory body; however, so far, they have not necessitated major design changes owing to the capability provided by the original design features.

I–4. DESIGN FEATURES

I–4.1. Part load diagram of a pressurized water reactor

A part load diagram of a German PWR displays the relationship between the set point of the average primary coolant temperature and the reactor power output. The part load diagram is an operational specification for controlling the parameters of the nuclear steam supply system (NSSS) based on the power output. In principle, two modes (and combinations of both) are possible for PWRs, as shown in Fig. I–4.

Mode (a), depicted in Fig. I–4, keeps the coolant temperature constant with increasing reactor power. Owing to the given and unchanged conditions for heat transfer in the steam generator (SG), this requires a dethrottling and therefore a pressure decrease on the secondary side. Mode (b), on the other hand, allows the coolant temperature to increase with increasing reactor power.

Operation of a PWR in flexible mode means that the parameters of the primary coolant and main steam will vary as prescribed in the part load diagram. These fluctuations will have various relevant impacts on other parameters, such as: the thermal stress, which would induce fatigue; the reactivity of the reactor core, which will cause more and deeper movements of the control rods and therefore more deformation of the power density distribution in the core; and the stored heat (energy) of the reactor coolant system (RCS). For increasing power, the components of the primary circuit will adopt the increased coolant temperature; the additional energy has to be produced in the reactor as well. This may cause [I–5] the following:

— Inadvertent overswing of the reactor power control;
— Coolant volume changes requiring more effort for the chemical and volume control system (CVCS) and waste management;
— Lithium (pH) level changes, requiring more effort for water chemistry control and regulation;
— Main steam pressure changes, which will affect the design of the secondary system (e.g. protection against overpressure).

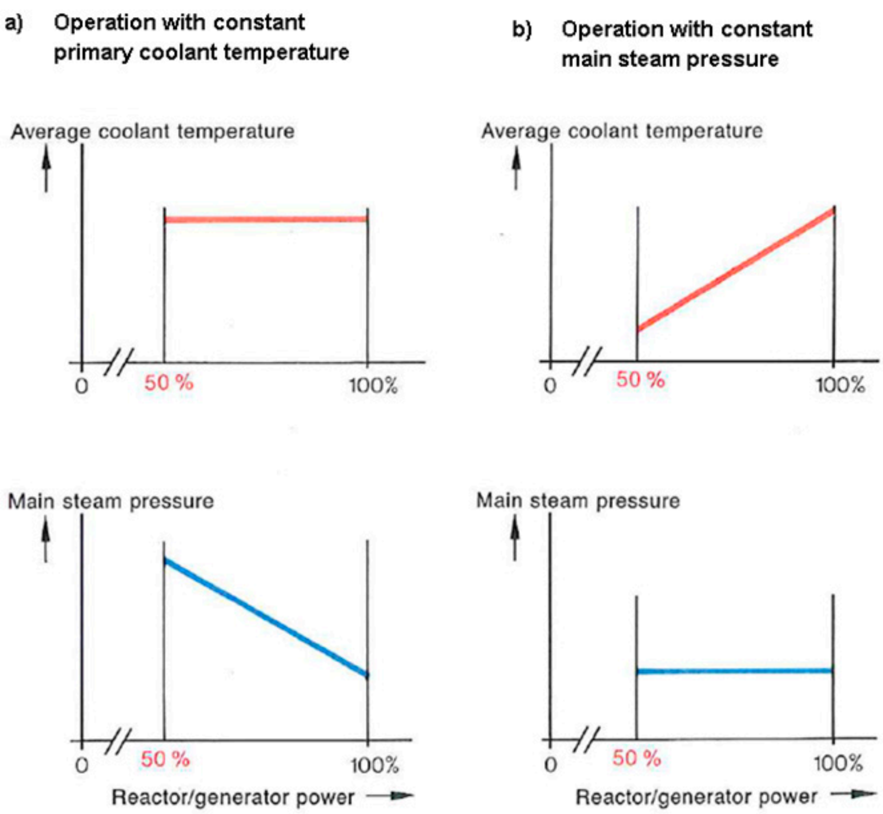

FIG. I–4. Schematic (steady state) part load diagrams for a German pressurized water reactor.

By combining and optimizing for the applicable power ranges, German PWRs combine the benefits of modes (a) and (b) and minimize the drawbacks in the relevant power range for flexible operation. A simplified part load diagram in German PWRs can be seen in Fig. I–5.

The characteristics and benefits of this part load diagram can be summarized as follows:

— In the upper power range (e.g. 40–100% RTP), where the majority of load following is performed, the average coolant temperature is kept constant (i.e. mode (a) is applied). In addition, flexible operation is less constraining in this range as less restrictive requirements apply to core, fatigue, criticality and coolant volume management, with fewer challenges to safety and operational margins. The benefit of this mode of operation is reduced control rod movements as temperature feedback of the reactivity during power manoeuvres is minimized. Additionally, the RCS volume remains essentially constant, resulting in less ingress/egress

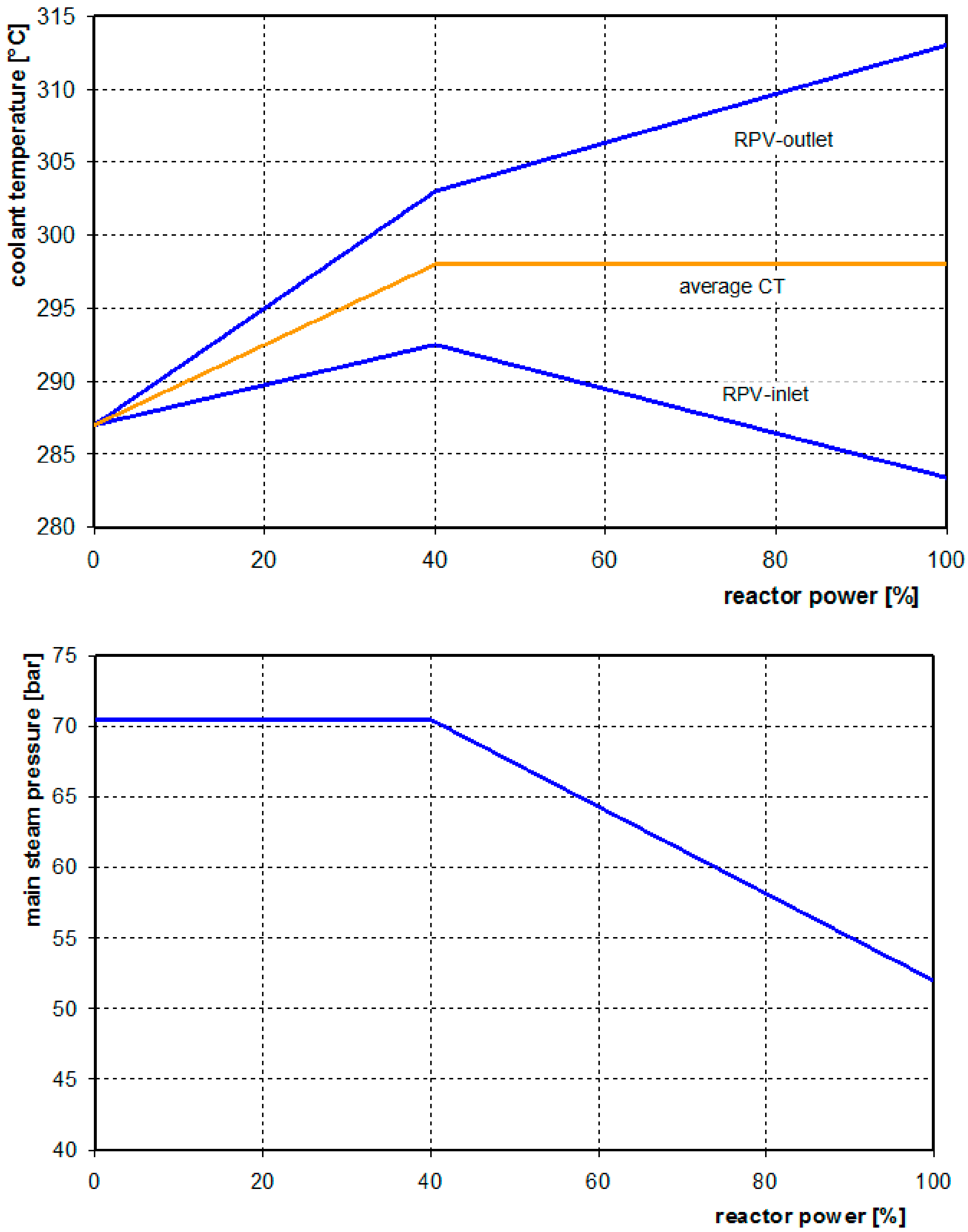

FIG. I–5. Combined and optimized part load diagrams for German pressurized water reactors [I–6]. CT — coolant time; RPV — reactor pressure vessel.

through the pressurizer surge line, which reduces the temperature variation on the components, as well as reducing the CVCS manoeuvres.

— In the lower power range (e.g. 0–40% RTP), mode (b) is applied. In that power range, flexible operation is more difficult, and the main steam pressure is kept constant. The benefit of this scheme is reduced challenges to the margins for the secondary side design pressure (e.g. overpressurization is minimized).

I−4.2. Recirculation control in boiling water reactors

The reactor power in BWRs can be regulated either by manoeuvring the control rods or by changing the speed of the forced circulation pumps and thus the coolant flow rate (recirculation control). The amount of steam in the reactor core increases with a reduction of coolant flow rate, which reduces the moderator density and the reactivity. By contrast, increasing the coolant flow rate leads to an increase in the moderator density and reactivity and thus to an increase in power. This approach has a global impact on core reactivity and less of an impact on power peaking.

As for PWRs, the operation mode of flexible operation will have an impact on the corresponding changes of core physics parameters as well as on the thermohydraulic parameters of the NSSS, because it will affect the variation of safety relevant parameters, such as fatigue and core reactivity, and other core physics parameters, such as linear heat generation rate and departure from nucleate boiling ratio (DNBR).

An optimized recirculation control is utilized in German BWRs because it is perfectly suitable for flexible operation in the upper power range (approximately 60–100% RTP), as BWRs, in principle, are able to change power in this upper range with faster and fewer power distribution changes in the core. A typical optimized recirculation control curve is shown in Fig. I–6.

The optimized recirculation curve provides the reactor power as a function of the coolant mass flow (i.e. core flow) for a constant control rod position. A major advantage of recirculation only control is that the relative power distribution in the core is not significantly affected by load changes, because no manoeuvring of control rods is required for this purpose. This minimizes stressing of the fuel rods caused by flexible operation and consequent changes in temperature in the fuel rods. Power changes beyond the recirculation control range are made by manoeuvring the control rods. Additionally, temperature and pressure remain constant in the main steam system, resulting in reduced loads on the RCS and other components.

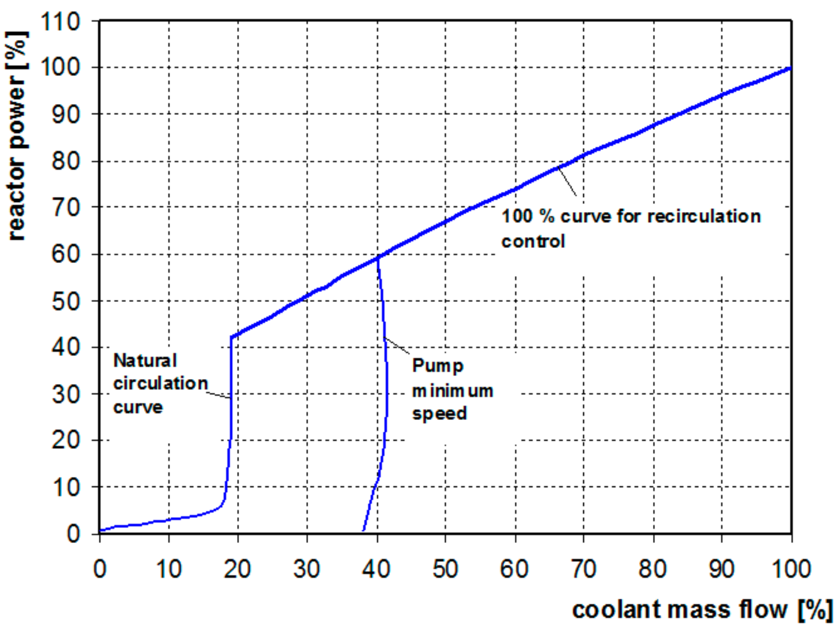

FIG. I–6. Optimized recirculation curve for a German boiling water reactor [I–7].

I–4.3. Reactivity control

In German PWRs, the control rod manoeuvring programme utilizes standard control rod assemblies [I–4]. These control assemblies can be used for both the regulation and shutdown of the reactor. From a functional perspective, the control assemblies are grouped into two banks: the D-Bank (Doppler Bank, i.e. the power reactivity relevant control rod bank), made up of four sequentially moving groups, each consisting of only four control assemblies; and the L-Bank (control bank), with the majority of the control assemblies. The D-Bank is used for regulating the integral reactor power. As a result, the axial power distribution is only slightly distorted by the four moving control assemblies. The L-Bank can be used to back up reactor power control. Its main task is to control the axial power distribution, for which a change in position of only a few centimetres can yield a sufficient effect. (The L- and D-Banks have to be manoeuvred in a mutually compensating sequence to change the power distribution at a constant reactor power.)

This control rod manoeuvring scheme, together with the correspondingly selected part load diagram (see Section I–4.1) characterized by a constant plateau in the upper power range, minimizes the transient overshoot of the peak power density after a quick return to full power. As a result, the required operational margin that has to be considered in the optimization of the core design does not significantly depend on the plant operating mode (i.e. whether it is baseload or flexible). Consequently, advanced loading strategies for fuel economy can be retained.

It should be noted, however, that while this control rod manoeuvring concept enables rapid power changes, it may require prompt and accurate measurement of power distribution. Therefore, German light water reactors use special in-core instrumentation made of precisely calibrated in-core power distribution detectors and a fast flux mapping system, the Aeroball Measuring System in PWRs and the 'traversing in-core probe system' in BWRs, which continuously monitor and assess three dimensional flux and power density distribution [I–4].

Long term reactivity effects (e.g. xenon concentration or burnup) are compensated by the boron concentration of the coolant, without affecting the axial power distribution (as long as xenon oscillations are avoided).

I–4.4. Protection and control systems

The I&C structure of German PWRs comprises three hierarchically organized levels of defence: controls, limitations and protections with specific importance for operation and safety. These functions actuate gradually staggered automatic counter-measures, with clearly defined priorities if corresponding set points are reached. The intensity of these measures increases with increasing deviation of the monitoring variable from its operational target.

I–4.4.1. Basic protection and control design

The following concepts have been employed in German PWRs to maximize operational flexibility, ensuring appropriate safety margins for relevant variables:

— Limitations assume guidance over the process as soon as relevant variables abandon their normal operation range and lead the plant back to a safe equilibrium state by automatic actions so that controls can govern again. Limitations maintain the limiting conditions for operations. At a higher intervention level, they are also enabled to actuate a fast power cutback to avoid a further reduction of margins to safety limits and to prevent a reactor trip.

— The continuous monitoring of the key safety parameters — such as local peak power density and DNBR — and the maintenance of the limiting conditions for operations by automatic actions allow controls to be designed and optimized entirely for the requirements associated with normal operation, thus allowing almost completely automatic load following operation. The monitoring signals are directly compared with the corresponding limits, the margins are displayed to the operator, and on violation of the limits, alarms are actuated and automatic counter-measures initiated to restore normal operating conditions.

These concepts enable nuclear power plant operators to utilize available margins to the full extent to maximize operational flexibility because power density is continuously assessed, with the use of self-powered neutron detectors (the fixed in-core detectors that are described in Sections 5.2 and 5.3.5 of this publication), and is kept within permissible limits by the limitation system. This design also helps to:

— Minimize the scope of cycle specific analysis;
— Minimize the potential for human errors by relieving operators from having to pay attention to additional tasks, particularly during load following operation;
— Increase the reliability and accuracy of maintaining operational limits and of preserving margins to operational limits.

I−4.4.2.Limitation systems (pressurized water reactors and boiling water reactors)

There are safety related limits for key operating parameters in nuclear power plants that may not be exceeded. To ensure this, sequential I&C systems (Fig. I–7) provide the following step raised automatic actuations of counteractions:

— Deviations from the normal state are first detected and restored to normal (i.e. control range of the operational controls) by the control systems.
— If the control systems are unable to do this, prioritized limitation systems intervene and return the plant to the control range of the operating controls.
— If this is insufficient in the case of serious malfunctions, a safe state is established by the reactor protection system, in particular by initiating a reactor trip.

The intervention of the reactor protection system (e.g. the reactor trip) is averted for most malfunctions by the limitation systems, which thus minimize life limiting loadings on plant systems. As a result, the limitation systems not only fulfil a safety function but also increase the availability of the plant. German nuclear power plants are

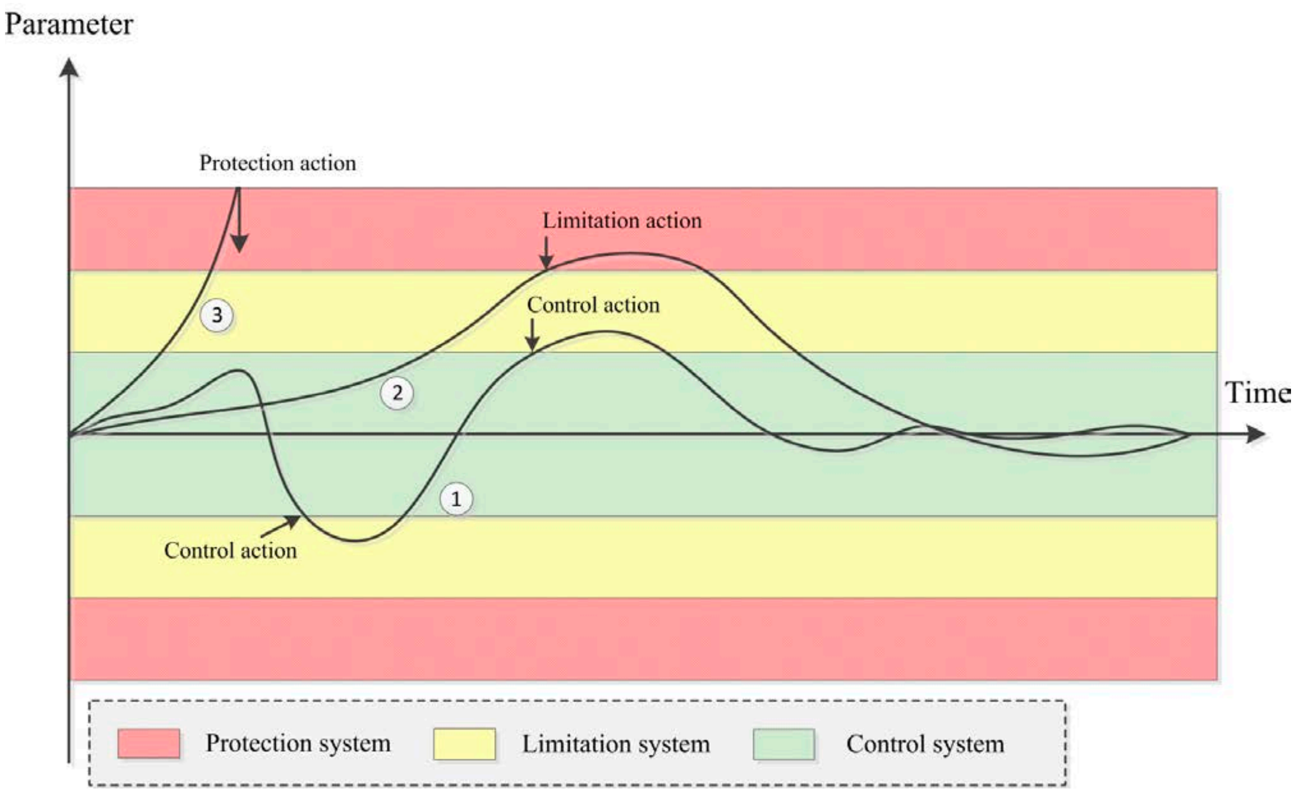

FIG. I–7. Schematic diagram of conceptual control system adjustments to maintain the linear heat generation rate and departure from nucleate boiling ratio during 1 — fast; 2 — slow; and 3 — swinging changes in the controlled operating parameter (reproduced from Refs [I–3, I–4]).

international leaders in the automation of such limitation functions. A great deal of thought and experience has gone into the limitation system concept of German PWRs and BWRs with respect to load cycling. In particular, the power and power density limitation systems, with their various constituent functions, and the control rod manoeuvring limitation systems contribute significantly to maintaining sufficient margins to safety limits, particularly taking load cycling into account.

The advantages of the automated limitation functions with regard to the load cycling capabilities of German nuclear power plants are:

— The controls can be primarily designed from the point of view of optimum function without regard for safety issues, which are covered by the limitation systems.
— The operating staff is relieved of monitoring responsibilities and can therefore devote special attention to load cycling operation.
— Plant availability and thus grid reliability can be improved.
— The high accuracy and reliability of the limitation systems (in conjunction with the in-core instrumentation) allow greater scope for load cycling.

I–4.5. Advanced reactor control system for automatic load following

Whereas the above described features have already been realized in the original designs of German PWRs, the increasing use of modern digital I&C systems has allowed further improvements to be made. One recent development is the adaptive reactor power control system, which provides operator aid to perform load following automatically instead of manually.

I–4.5.1. Basics of the adaptive reactor control concept

A stable reactor power control system that manages new challenges without manual support is becoming increasingly important. Therefore, an ‘adaptive reactor power control system’ (in German: *adaptive leistungsverteilungsregelung*, also known as advanced load follow control (ALFC)) was designed and installed first in PWR Philippsburg nuclear power plant unit 2 in 2008 [I–7]. This was followed by installation and use in other plants. The reactor power control system eliminates the need for manual actions — even the power distribution set point was eliminated by the supplemental adaptive ‘power distribution control mode’ module (see Section I–4.5.2) — with the exception of the set points for the D-Bank operation mode and the cycle dependent manual L-Bank set point, which has to be adjusted by the operator based on the operational strategy and core physics calculations.

Compared to the operational requirements and conditions during Kraftwerk Union pre-Konvoi and Konvoi PWR commissioning and early operations, automatic power distribution control has become so complicated that, in many nuclear power plants, stable operation without manual intervention is no longer possible. The primary reasons that automatic power distribution control has become more challenging are:

— Migration to low leakage core loadings (to minimize fuel costs);
— Increase of the nominal integral reactor power;
— Increase of the plutonium production rate due to mixed oxide fuel assemblies and/or enrichment increases;
— Flexible (non-baseload) operation for load following and frequency control.

These increasing challenges have led several projects in German PWRs to implement the ALFC adaptive reactor control system in all nuclear power plants following Philippsburg nuclear power plant unit 2 in 2008. The ALFC system was subsequently installed in Isar nuclear power plant unit 2 in 2014, and in Brokdorf and Grohnde nuclear power plants in 2015; a project to install the system in Gösgen nuclear power plant in Switzerland was started in 2015.

The possibilities of a digital I&C reactor protection system, namely TELEPERM XS (TXS) technology [I–8], have been fully exhausted with these ALFC projects, which is why the possibility of physical parameterization — adaptation to the reactor core — is being used. The reactor power control receives a new set of reactivity coefficients from the TXS service unit for every new core reload. These coefficients and their changes are determined for each fuel cycle as a function of the reference boron concentration, which decreases during the fuel cycle. The boron concentration set point of the primary side leakage make-up system is used as an input for the reference boron concentration c_R (boron concentration at full load with xenon balance). The relevant reactivity coefficients to be considered are:

— Boron worth (Γ_c);
— D-Bank worth (Γ_D) for power distribution fine control near the full load point;
— Average D-Bank worth for reactivity balances in conjunction with load cycles (Γ_{DM});
— L-Bank worth (Γ_L);
— Coolant temperature coefficient (Γ_T);
— Power reactivity coefficient (Γ_P) (basically, Doppler reactivity).

Knowing these coefficients, in conjunction with more precise calculation methods in the form of physical balances, allows reactivity to be controlled with much greater accuracy by automatically controlling reactivity coefficients in an integrated manner. This system:

— Supports several I&C functions by balancing reactivity and adapting to the efficiency change during the fuel cycle;
— Provides precise control with reduced dead bands;
— Eliminates the need for manual intervention by operators.

Therefore, the system enables the power distribution fine control mode at steady state full power and optimal automated reactivity management at intermediate power levels (transient and steady state) during load cycling, thus providing great assistance to operators during load following.

With this system, a high control quality is achieved at full power because the driving margins regarding peak limitation (with limiting values for DNBR, pellet–cladding interaction and fuel condition limits for accident analysis) are very low. Therefore, near full power, the control rod (L- and D-Banks) position dead bands could be reduced. This helps to return the unit to conditioned full power following a part load condition. Balancing reactivity, including the calculation of the xenon reactivity behaviour, the system helps:

— To ensure the necessary control rod bank movement at part load is capable of reaching full load again;
— To ensure a sufficient margin to the bank movement limitation functions, which assure shutdown reactivity and the insertion limits established for protection from a reactivity insertion accident (e.g. a control rod ejection accident).

Figure I–8 depicts an overview of reactivity coefficients that a service unit integrates into an automated control scheme.

I−4.5.2.Automatic power distribution control

Supplementing the adaptive reactor control system, an adaptive automatic power distribution controller — driven by a two point xenon calculation for the upper and lower core halves — helps to keep the axial power distribution shape nearly constant, which inhibits the beginning of any axial xenon oscillation. This is also a basic necessity for flexible operation.

In principle, the power distribution control should only dampen axial power distribution oscillations (i.e. axial xenon oscillations). These are caused by power density distribution changes, which are the result of changes in the average coolant temperature or the temperature rise along the core caused by power changes or by control rod movements. When the average coolant temperature or the temperature rise decreases, the power density distribution redistributes more into the upper half of the core. This redistribution would be temporarily reinforced by a xenon reactivity change, and, in an uncontrolled condition, would subsequently move in the opposite direction after approximately 6 hours. It is possible that axial xenon oscillations will continue to increase if the core power distribution is not controlled. These oscillations should be dampened by the power distribution control in order to avoid approaching the peak power limits.

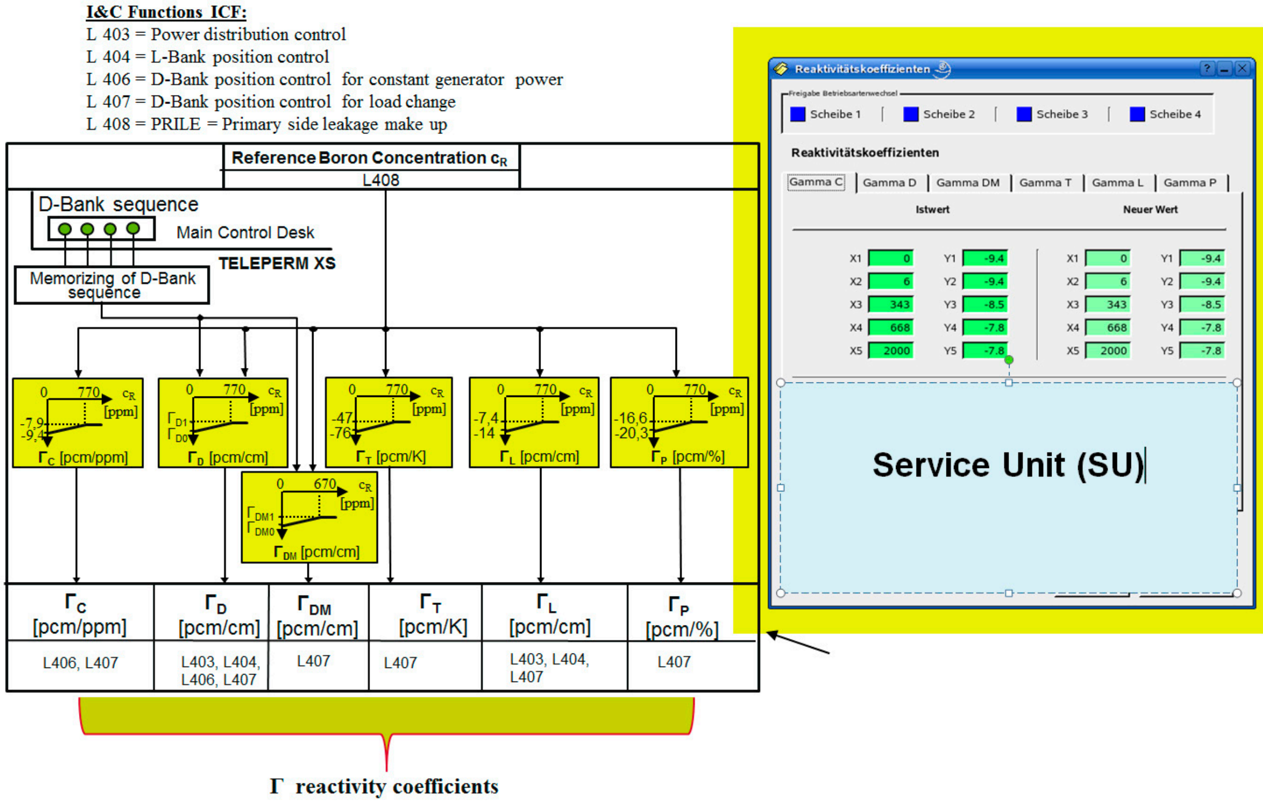

FIG. I–8. Adaptation to reactivity coefficients via a service unit (reproduced from Ref. [I–7]). I&C — instrumentation and control; ICF — instrumentation and control functions.

By use of the automatic power distribution controller functions, shown in Fig. I–9, development of xenon oscillations is detected early on by a two point xenon calculation and is used as the control variable in a suitable power distribution master controller. The xenon development in each core half is derived from the corresponding power density distribution signals (by the in-core instrumentation) in each core half. Defining the self-adapting power distributor controller manual set point is therefore no longer necessary.

As deboration (dilution) of the RCS in order to compensate for fuel burnup causes a redistribution of the power density into the lower core half, plant engineers have to take the following into account as part of the operation strategy:

— This redistribution can, in principle, be compensated by withdrawing the entire L-Bank in the first fuel cycle phase so that the axial power distribution signal of the in-core instrumentation remains constant. If the L-Bank has reached a strategic upper position (either top of the core or a strategic upper position in which it is still capable of moving in both directions), further power density redistributions downwards can no longer be compensated. The power distribution controller does not detect this redistribution as a xenon oscillation. The equilibrium power distribution, which is important for the part load transients, is automatically stored.
— The controller's self-adaptation towards the equilibrium power distribution (Fig. I–10) eliminates the need for any manual actions to adjust the power distribution controller. Therefore, only the corresponding L-Bank manual set point adjustment is needed to define the long term operation strategy.

I–4.5.3. Benefits of automatic control systems

Combining the automatic and self-adapting power control measures allows for:

— Control of the power density distribution without any manual intervention of the reactor operator because the adaptive power distribution controller keeps the axial power distribution shape nearly constant and therefore inhibits any xenon oscillation;

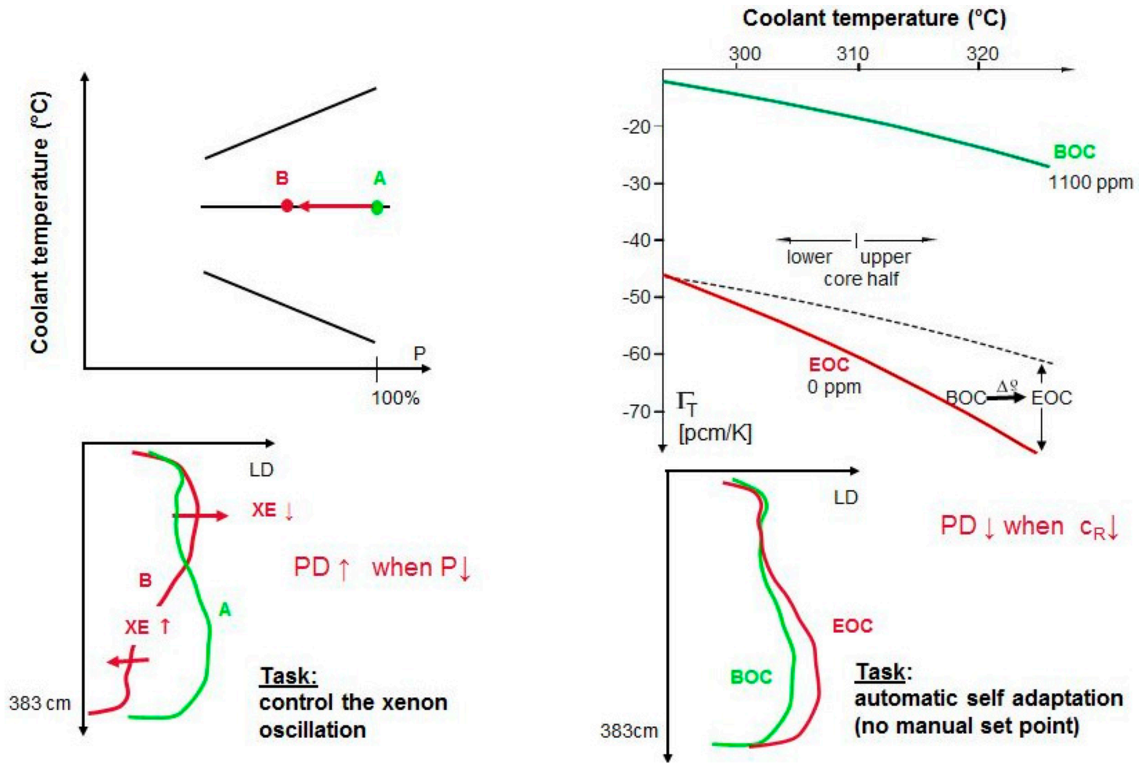

FIG. I–9. Functions of a power distribution controller (reproduced from Ref. [I−7]). BOC — beginning of cycle; EOC — end of cycle; LD — power distribution; PD — power distribution; XE — xenon.

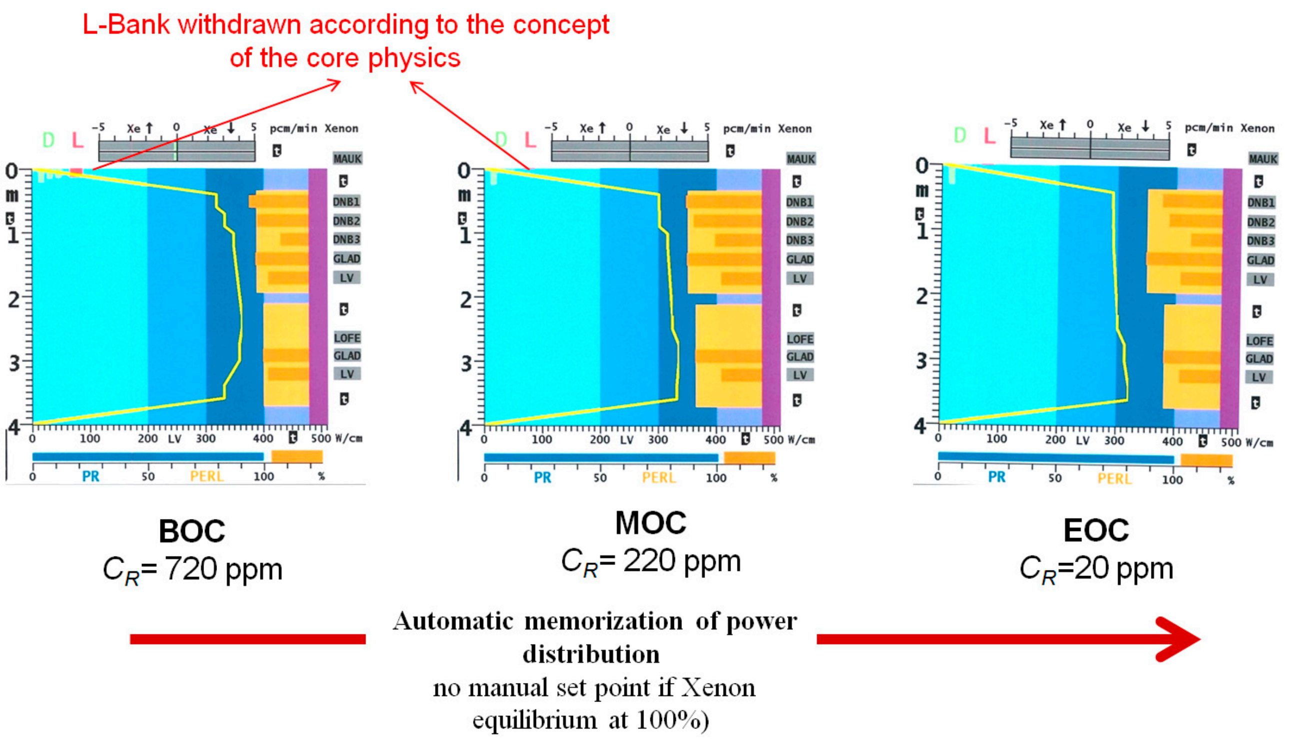

FIG. I–10. Self-adaptation to fuel burnup dependent power distribution change (reproduced from Ref. [I−7]). BOC — beginning of cycle; EOC — end of cycle; MOC — middle of cycle.

— Control of the reactor power with small margins to the limit values of the limitation system.

Figure I–11 illustrates this stability in control, depicting the results of commissioning tests performed to qualify and implement the self-adapting control system project in Isar nuclear power plant unit 2, which took place in August 2014. The commissioning load cycles with ramp rates up to 40 MW/min (2.7% REO/min) are:

— A 100–30–100(% REO) manoeuvre with 6 hours at part load, shown in Fig. I–11;
— A 100–60–100(% REO) manoeuvre with 2 and 6 hours at part loads.

These tests demonstrate the capability to operate large load ramps without any manual intervention and without actuation of the limitation system.

I–4.6. Thermal load specifications

Load cycling within the scope outlined above is predominantly associated with only minor changes in global plant parameters such as pressure and temperature in the RCS. The resulting low thermal stresses are not relevant to the fatigue of the affected components.

Large temperature gradients with correspondingly higher loads can, however, occur when different hot fluids meet in individual components. In addition to a low stress mode of operation (see the part load diagram described in Section I–4.1 above), such loadings are well controlled by a suitable design, namely the choice of suitable materials and appropriate dimensioning or mechanical design to reduce temperature changes, for example in the area of injection nozzles.

German light water reactor designs consider the thermal load specifications during the design stage with consideration of type, magnitude and associated transients, as shown in Fig. I–12.

The thermal load specifications are the basis for the fatigue and stress analysis. Typical fatigue sensitive components particularly addressed include [I–5], but are not limited to:

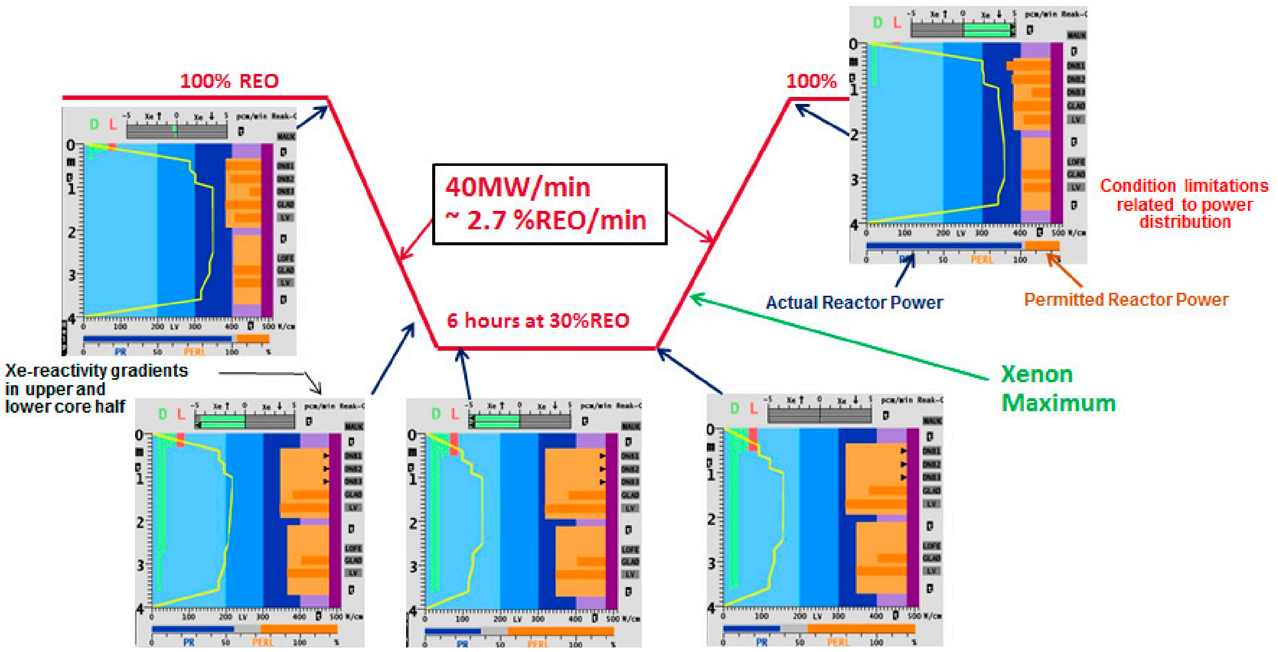

FIG. I–11. Rod positions and power distribution during the Isar nuclear power plant commissioning test for the 100–30–100% rated thermal power manoeuvre (reproduced from Ref. [I–9]). REO — rated electrical output; Xe — xenon.

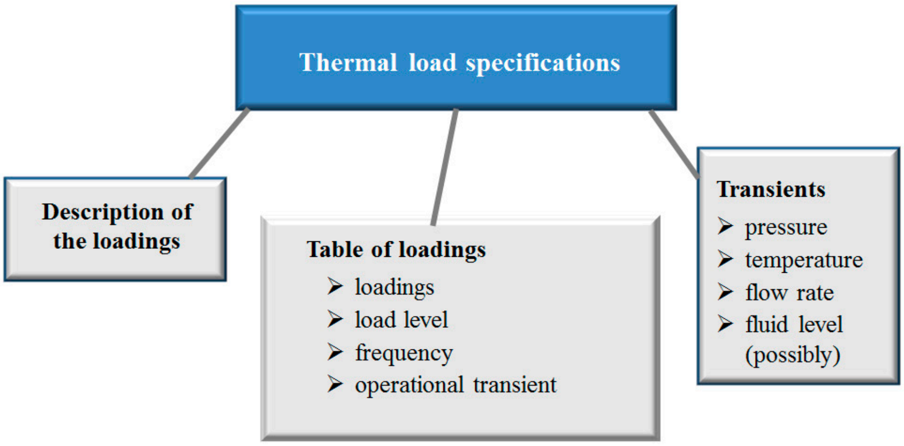

FIG. I–12. Considerations in determining thermal load specifications [I–6].

For PWR designs:

— Spray lines;
— Surge lines;
— CVCSs;
— Feedwater systems, feedwater injection nozzles at SGs;
— SG blowdowns (dependent on the operation mode).

For BWR designs:

— Main steam and feedwater system components (only for startup and shutdown);
— Moisture separators and reheaters.

Frequent flexible operation can be considered inherently in the mechanical design of components. German nuclear power plants are designed for the stresses associated with load cycling. This design is based on defined numbers of service conditions (in this case, load cycles), which bound the frequencies expected during the lifetime of the plant. As the German plants have mainly been operated at constant power in their operating lifetimes to date, there are still significant reserves with respect to material fatigue. The number of cycles postulated in the design of components is shown in Table I–2.

TABLE I–2. NUMBER OF LOAD CYCLES CONSIDERED FOR DESIGN OF THE KONVOI PRESSURIZED WATER REACTOR [I–6]

Load cycle (% rated thermal power)	Number of load cycles
10 (step change)	100 000
100–80–100	100 000
100–60–100	15 000
100–40–100	12 000
100–20–100	1 000
100–0*–100	400

* Hot zero power.

As an approximate and simple example to illustrate the potential impact on the variation and the intermittency impact of wind power generation: typically, a nuclear power plant accumulates 2000 load cycles between 60% RTP and 100% RTP during its licensed life and would still be capable of running 13 000 more of such load cycles before using up the remainder of the budgeted amount of cycles in the design. Assuming — even unrealistically — that such load cycles would be needed to compensate for daily changes in wind power generation, the number of design load cycles would be reached only after 35 years. It should be kept in mind that the design still includes a significant safety margin until a failure (e.g. a leak) might occur.

Moreover, continuous fatigue monitoring and assessment ensure timely and effective response action to any new findings (e.g. observed signs of degradation) and new requirements (e.g. mechanical strength properties).

I−4.7. Fatigue monitoring and evaluation

Continuous fatigue monitoring (measuring, recording and analysis of wall temperatures), which facilitates graduated quick evaluation and detailed fatigue analysis, is available for components susceptible to fatigue. Moreover, by comparing the history of service conditions, such as load cycles or operational transients, with the design assumptions documented in thermal load specifications, it can be ensured that the component design imposes no restrictions on the operation of the plants. In addition, periodic, non-destructive testing at specified intervals is performed especially for safety related components. Therefore, if unexpected effects should occur, these would be detected in time.

Early experiences of German nuclear power plants showed that there were differences between design loads and actual loads due to other mechanisms (e.g. stratification). As a result, German utilities, together with the original equipment manufacturers (responsible designers and equipment vendors), created a system to control the loads and their fatigue relevance (Fig. I–13) with continuous measurement, and established an annual reporting requirement for the fatigue status.

This annual fatigue status report compares the design and actual load situations and provides a raw annual and accumulated cumulative usage factor. If there are differences between design and real operation, utilities can react and can perform assessments based on the real transients. A special network of load cycle measurements at fatigue prone locations and positions continuously delivers input and provides a basis for this assessment. Owing to such

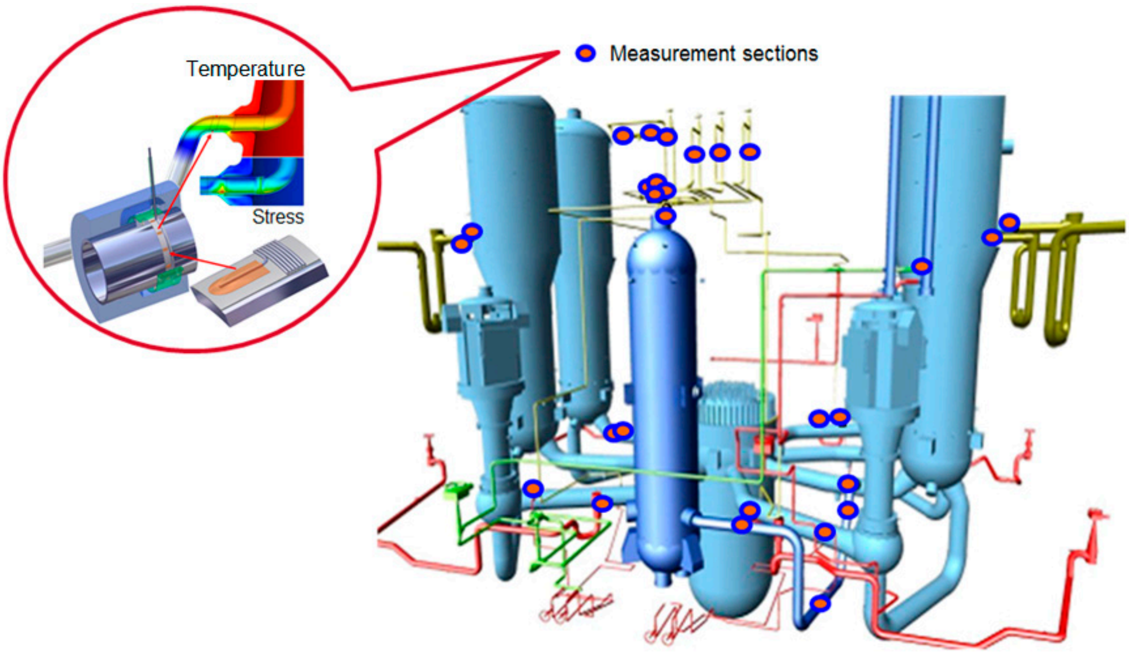

FIG. I–13. Typical arrangement of a monitoring system in reactor coolant systems in German pressurized water reactors (courtesy of T. Salnikova, AREVA GmbH).

monitoring and assessment methods, all types of loads are considered in cumulative usage factor. Consequently, for load following operation — which could slightly increase fatigue loads — fatigue prone systems, structures and components are always under control, including consideration of potential fatigue damage mechanisms. The AREVA fatigue concept and the special measurement equipment, namely FAMOSi, are well established fatigue monitoring methods [I−10]. Using the AREVA fatigue concept methods, additional influences on cumulative usage factor determination (e.g. environmental assisted fatigue effects) can be evaluated on a real time loading basis.

I−4.8. Chemistry

All Siemens designed PWRs operate according to the adjusted boron/lithium chemistry control. This chemistry control scheme is characterized by achieving the following target values:

— Boron concentration according to reactor physics demands;
— Maximum lithium concentration of 2 parts per million (ppm);
— Target pH of 7.4 (at 300°C);
— Hydrogen concentration of 1.5–4 ppm to ensure sufficient reducing conditions within the primary coolant.

Fluctuations of pH, which are caused by boric acid concentration variations induced by load change are compensated for by operation of the coolant purification system filters, which serve as a buffer.

Comparing dose rate levels observed in baseload and load following nuclear power plants in Germany, load following operation could result in a slight increase of cobalt (^{58}Co) activity as one of the main contributors to long term dose rate accumulation. The reason for this behaviour is the more frequent fuel rod movements, which cause a release of cobalt deposits. As a consequence and counter-measure, zinc chemistry has been implemented in the affected plants to prevent the incorporation of the mobilized cobalt into the existing oxide layers in the primary coolant system components.

With respect to corrosion, no specific impacts and changes from flexible operation have been observed, as indicated by the same level of corrosion product activities measured before and during load following operation.

With respect to secondary side chemistry, all Siemens designed PWRs operate with high all volatile treatment systems. This treatment is characterized by the addition of hydrazine, which is thermally decomposed to ammonia, maintaining a high pH within the feedwater.

A factor of major importance for long term reliable operation of the SGs is the corrosion product transport. This is aggravated by transient conditions, which occur more often during load following operation. This factor can result in a larger amount of deposits in the SGs. Abnormal operational events (e.g. condenser leakages, ingress of regeneration chemicals or poor make-up water quality) will adversely affect chemistry operation of the water–steam cycle. In such cases, the formation of corrosive environments, particularly in the top of the tube sheet area, can result in a negative impact on the mid and long term integrity of the affected SGs, thus requiring more effort in maintenance and cleaning operations.

Reference [I–11] provides details of the systems, processes and methods, including an evaluation of associated costs, of chemistry control in some German PWRs.

I−4.9. Human factors

I−4.9.1. Simulator verification and training

Training simulators can be used for pretesting nuclear power plant modifications such as I&C capabilities; verifying the capability and capacity for flexible operation; and establishing and validating plant operating procedures and process models prior to commissioning or design change implementation in real plants, in addition to training plant operators for flexible operation. For example, the adaptive reactor control described above for automatic power distribution control, which is especially helpful during load manoeuvres, was an I&C implementation project utilizing a training simulator. For several weeks prior to the commissioning of the system in the reference plant [I−12], closed loop tests and pretests of the plant commissioning procedures were conducted at the Isar nuclear power plant unit 2 full scope simulator. More details on the upgrading/modernization of plant training simulators are provided in the IAEA guidelines [I−13].

Using training simulators as part of the engineering process requires integrating a simulator project into the schedule of the nuclear power plant project. When setting up a verification and validation (V&V) project in a plant, the training simulator should generally be involved from the very beginning in order to minimize project risks for the plant. A common project schedule, including test and data delivery plans for the simulator, should be contractually agreed upon between the plant and vendor. For example, the schedule of the commissioning of a digital control system (DCS) in a plant should take into account completion dates for the V&V on the simulator and, if requested, operator training on the simulator prior to the operation of the DCS in the plant. Figure I–14 depicts the principal dependencies among the plant and simulator projects.

V&V of plant modifications, including changes to the process and procedures utilizing a training simulator, also requires an appropriate test strategy. Figure I–15 depicts an example, DCS commissioning of the Kraftwerks-Simulator-Gesellschaft mbH test strategy.

In the first step (phase 1), an emulator solution is provided for the simulator for the DCS. The DCS engineering database is transferred to the simulator and interface signals among the DCS and plant models are checked in phase 2. In phase 3, I&C functions are tested followed by the integral tests in phase 4. Once the integral tests have been completed, power plant commissioning procedures are performed in phase 5. On the simulator side, support from the commissioning engineers of the DCS designer, as well as the nuclear power plant operation shift personnel, is typically needed and requested in phase 3 and thereafter.

When it comes to V&V of I&C modifications, the test facilities of I&C vendors are best suited for open loop tests of control systems. Full scope training simulators are most appropriate for closed loop tests of a control system in an integrated environment, as simulators are validated by training and test programmes over the entire range of nuclear power plant operation: normal operation, operational disturbances, as well as all incidents and severe accidents.

I–4.9.2. Operational experience

The introduction of new I&C technology in nuclear power plants has begun in the field of training simulators over the last decade at the German simulator centre Kraftwerks-Simulator-Gesellschaft|Gesellschaft für Simulatorschulung. In past decades, conventional I&C systems were implemented in simulators relying on the data package provided by the plant (i.e. after its implementation). For major I&C changes, the DCS being a typical example, nuclear authorities (i.e. the regulatory bodies) generally request V&V and training for the DCS on simulators prior to implementation in an actual plant. Furthermore, they may request the plant, together with

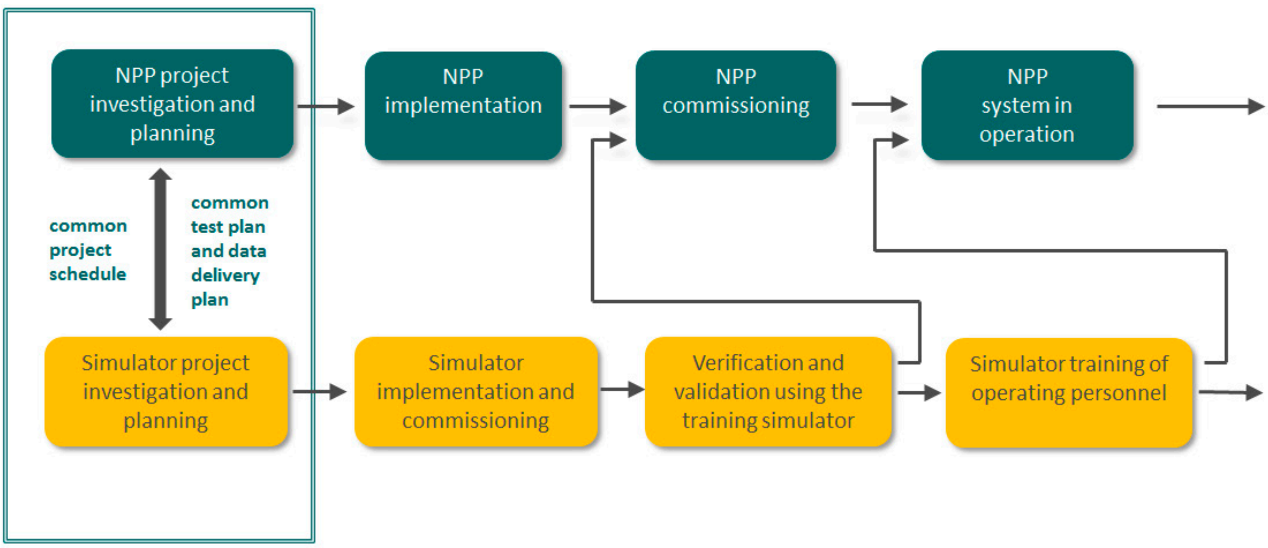

FIG. I–14. Dependencies among plant and simulator projects when using simulators as an extended test bed for plant modifications prior to commissioning (courtesy of W. Wischert and F. Schulze, reproduced from Ref. [I–12]). NPP — nuclear power plant.

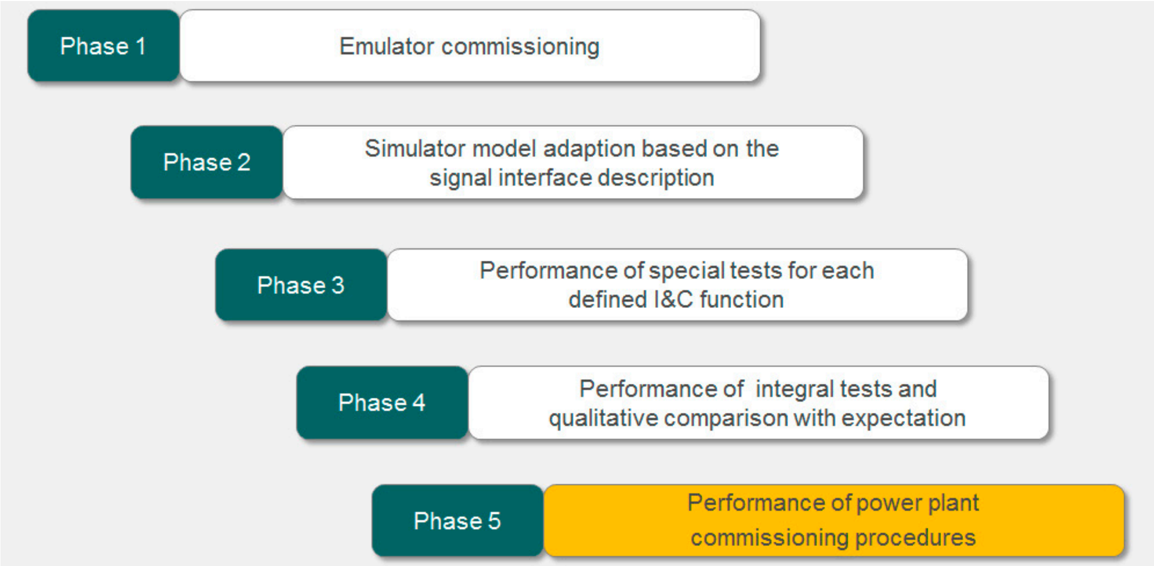

FIG. I–15. Test strategy for a digital control system (courtesy of W. Wischert and F. Schulze, reproduced from Ref. [I–12]). I&C — instrumentation and control; LEFU — control and protection functions (LEittechnik FUnktion).

the I&C vendor involved, to conduct closed loop tests to validate and verify optimization strategies. This leads to a situation where functional design and parameter adjustment are based on raw data and undergo various iteration cycles prior to final implementation. The simulator is used, in this case, as a test bed for plant I&C upgrades and optimizations.

Digital reactor control and/or limitation systems have been implemented by Kraftwerks-Simulator-Gesellschaft in German training simulators since the end of the 1990s. A milestone for digital I&C implementation and pretesting was the Philippsburg nuclear power plant unit 2 I&C upgrade, from analogue reactor control and limitation systems to the DCS TXS [I–8], with an adaptive reactor control system, known as the ReaDig Project. Discussions in the project initiation phase led to the perception that the use of full scope simulators as an extended test bed for DCS modernization projects requires an emulation or simulation implementation method. In 2002, an emulator concept for the digital I&C system TXS was developed by Kraftwerks-Simulator-Gesellschaft|Gesellschaft für Simulatorschulung in cooperation with Framatome Advanced Nuclear Power (AREVA), allowing V&V of the digital I&C system in the simulator environment. This very successful utilization of the Philippsburg nuclear power plant unit 2 full scope simulator led to wider use thereafter. In the following years, Kraftwerks-Simulator-Gesellschaft implemented TXS based reactor control systems in the full scope simulators of Brokdorf nuclear power plant, Isar nuclear power plant unit 2, Emsland nuclear power plant and Grohnde nuclear power plant, as well as the in-core and ex-core instrumentation in the Grohnde nuclear power plant simulator.

I–4.10. Safety evaluation

I–4.10.1. Transients/accidents

Safety analysis is performed for abnormal operating transients and accidents. As required by German nuclear safety regulations, the worst conditions for normal operation are assumed as initial conditions for transients and accidents. As part load conditions are unfavourable, they have been generally taken into account in the analysis in that the potential reactor states due to load cycling were approved in the original licensing procedure.

Load changes have an impact on various parameters that describe the initial state of possible transients, such as reactor power, coolant temperature, core flow, xenon concentration and distribution, critical boron concentration, power distribution and control rod positions. The above parameters are controlled or limited within a narrow range by various controls, the control rod insertion limits and various power limitations (with margins, e.g. for loss of coolant accidents or loss of off-site power). Even if load changes alter various parameters, the parameters are maintained within the control ranges and the set points of the limitation functions, regardless of the power history.

I–4.10.2. Operational experience

Extensive experience with load cycling exists in Germany. In particular, so-called primary control, in which power control is linked to the grid frequency directly and without the intervention of the operator, is an established practice. The power increments are typically limited to a maximum of 5% REO, so that any power change within this range can take place quickly. This mode of operation stresses the system only minimally due to the limited power increments, and experience with it has been positive during initial tests. Subsequently, it has been used regularly by most German nuclear power plants. More recently, in August 2015, the system was successfully qualified in Philippsburg nuclear power plant unit 2 upon request by the load dispatching centre for a load drop of 14% REO (i.e. 200 MW(e) in a 1460 MW(e) plant) within 30 seconds and back to full REO within 15 minutes, as shown in Fig. I–16.

Larger load ramps (i.e. load following for secondary control) have usually been initiated and performed manually by the operator prior to implementation of ALFC. All plants have run corresponding load ramps in the course of their operating lifetimes, some of which are now performing it utilizing the ALFC. The load gradients were up to 2% REO/min, the power increments were generally in the range of constant average coolant temperature in PWRs and in the recirculation control in BWRs. Existing operational experience with this mode of load cycling is also positive, as 2% REO/min — which, for larger nuclear power plants, corresponds to approximately 400 MW(e) change in 15 minutes — was more than adequate to meet the requirements for compensation for wind power generation fluctuations.

Installation of the ALFC system enabled a fully automatic load following that was remotely controlled by the load dispatcher. Figure I–17 provides an example of fully automated load following: Isar nuclear power plant unit 2, which operated almost entirely in fully automatic load following mode in the 2014–2015 fuel cycle. In this unit, the ALFC was installed during the outage and was commissioned with additional testing at the beginning of the cycle. After testing, the set point for the ramp rate was set to 30 MW/min (2% REO) for most of this fuel cycle. After three quarters of the cycle, the set point was reduced to 22.5 MW/min (1.5% REO) in response to a request from the grid operator, and it varied in the range of 2–5 MW/min (0.1–0.3% REO) after 90% of the cycle until the end of the cycle and into the stretched cycle, due to boron concentration and axial power distribution limits.

Figure I–18 illustrates the movement of L- and D-Bank control rods over 1 day of load following operation. The sequence of load changes at the nuclear power plant was able to automatically meet random demands by the grid system needs.

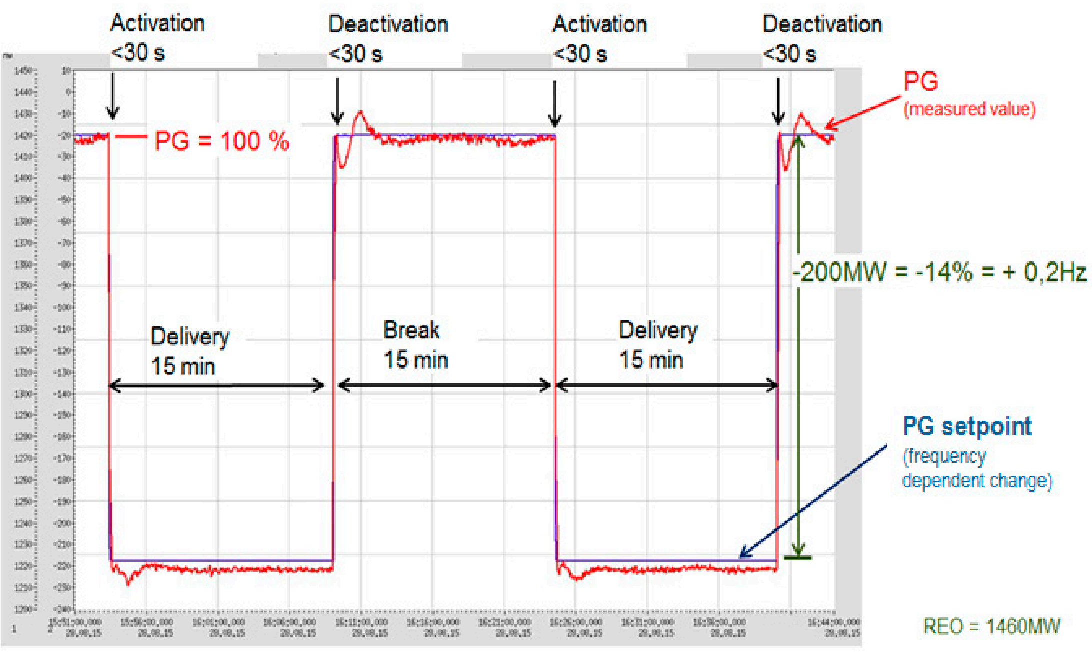

FIG. I–16. Results of the Philippsburg nuclear power plant unit 2 qualification test scheme with fully automatic secondary frequency control: 14% rated electrical output (REO) power jumps required by the grid operator [I–9]. PG — generator power.

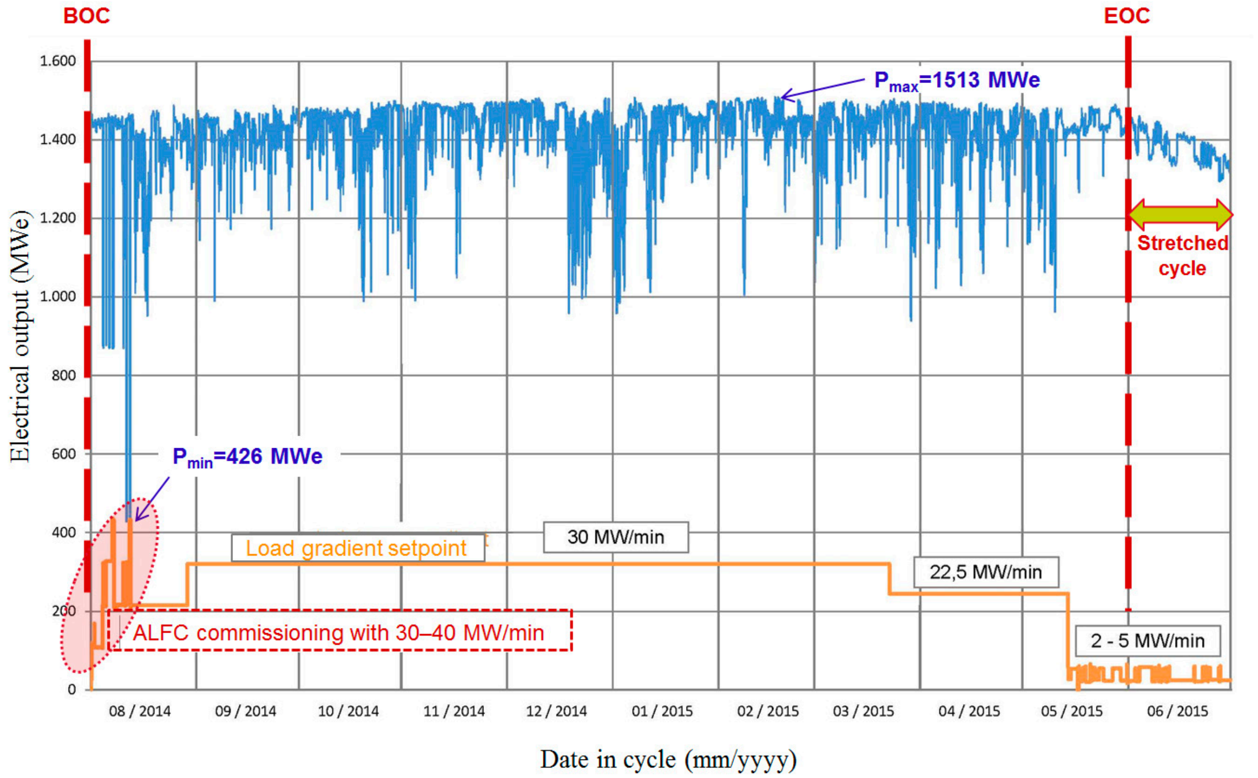

FIG. I–17. Fully automatic continuous load following operation of Isar nuclear power plant unit 2 during the 2014–2015 fuel cycle with the adaptive reactor control system, for advanced load follow control (ALFC) [I–9]. BOC — beginning of cycle; EOC — end of cycle.

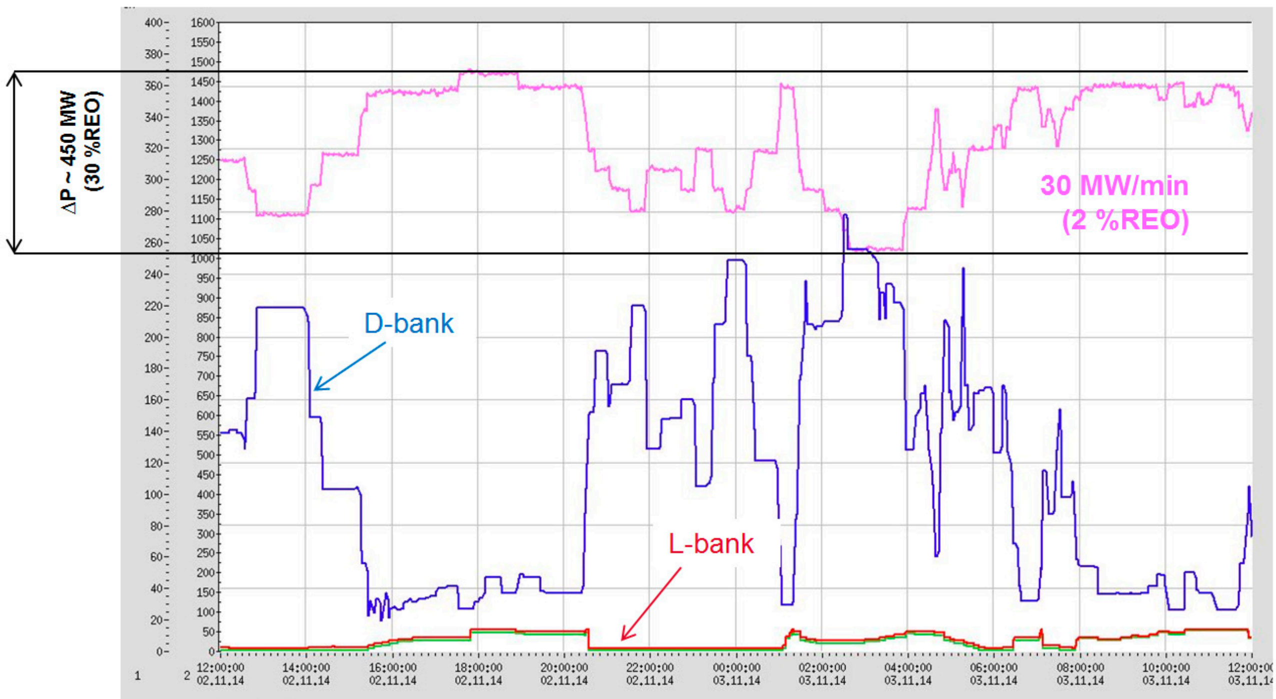

FIG. I–18. Control rod positions in response of Isar nuclear power plant unit 2 to stochastic load changes requested by the grid dispatcher over 1 day at end of cycle [I–9]. REO — rated electrical output.

Details of near end of cycle load following are shown in Fig. I–19. This load following operation took place with a reference boron concentration, c_R, of 115 ppm at nearly the end of the cycle in Philippsburg nuclear power plant unit 2.

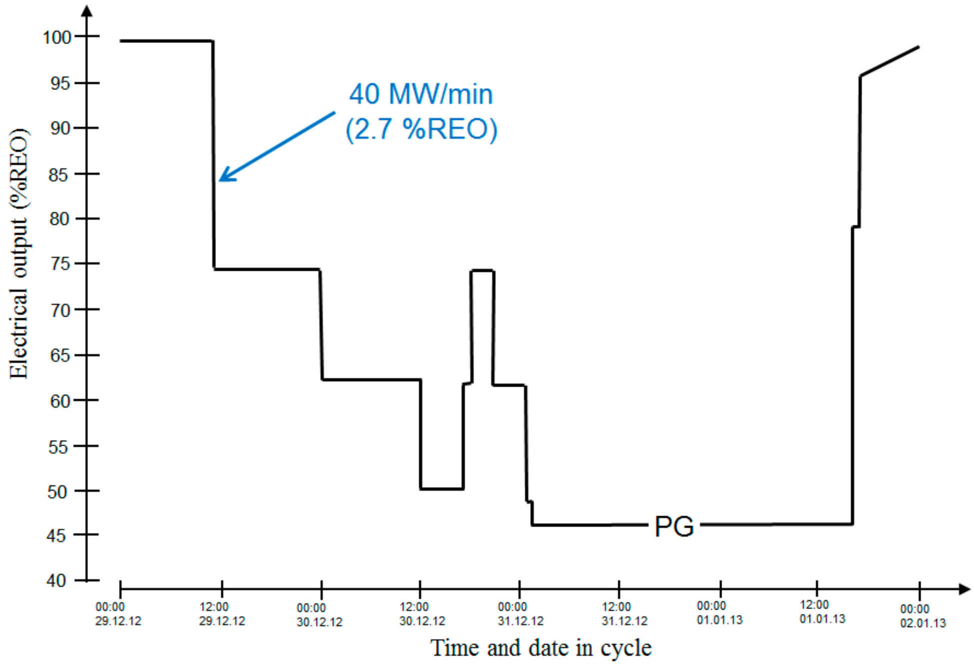

FIG. I–19. The 4 day load following operation of Philippsburg nuclear power plant unit 2 at nearly the end of the cycle, with c_R=115 ppm [I–7]. PG — generator power.

The typical load following as currently practised in German nuclear power plants involves load changes up to 60% REO; however, there are now examples of reactors in Germany that have performed load following with load changes up to 70% REO, or even 80% REO, depending on the minimum load point in the part load diagram. The minimum load point is typically 20% REO (for Brokdorf/Grohnde nuclear power plants) or 30% REO (Konvoi and Philippsburg nuclear power plant unit 2), depending on the plant. The part load at the minimum load point was actually only used in very specific cases. For example, load following operation to the minimum load point was utilized during negative electricity prices in the market.

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Annex II

CONVERTING A BASELOAD DESIGNED NUCLEAR POWER PLANT FOR FLEXIBLE OPERATION: FRENCH OPERATING EXPERIENCE

II–1. INTRODUCTION

This annex provides details of French efforts towards converting a nuclear power plant that is optimized for baseload operation to perform flexible operation. This case study[1] illustrates the experience gained in the design changes and for operation, including the considerations in decision making for flexible operation of nuclear generating units and establishing specific capabilities for flexibility in baseload optimized plants by design and operational modifications.

II–2. DECISION MAKING FOR FLEXIBILITY

After the first world oil crisis, uncertainties in primary energy sources and costs led the French Government to launch an ambitious nuclear programme based almost exclusively on pressurized water reactor (PWR) technology. After an initial order of six units in the early 1970s, programme agreements were signed in 1974 and 1976, planning and scheduling construction of 34 units of 900 MW(e) power and 20 units of 1300 MW(e) power. For the first time, nuclear energy captured the largest share in the energy mix of a country. By 1985, 60% of French electricity generation was from nuclear units, and this has recently reached 75%.

In the early 1970s, France correctly anticipated that in 10 years' time, nuclear power plants would have to broadly participate in the balancing of electricity generation and demand. The variation in electricity demand was characterized by two aspects at that time:

— *On a macro scale, seasonal variation.* The daily electricity demand was doubling between summer and winter (500 GW·h in the summer of 1984 versus 1000 GW·h in the winter of 1983–1984). The variation was more visible in terms of peak power (15.5 GW on 14 August 1984 versus 57.7 GW on 8 January 1985).
— *On a micro scale, weekly or daily variation.* The electricity demand was nearly doubling, characterized by high gradients, twice a day (2.8 GW·h for 4 hours in the morning and 2.0 GW·h for 2 hours in the evening of 14 December 1983).

Therefore, due to the French energy mix specifics, the Électricité de France nuclear fleet was designed to provide load following and full ancillary services (primary and secondary reserves), mainly due to a large demand consumption pattern with high seasonal variations (Fig. II–1).

From an economic point of view, the use of generating units with low variable costs was started before the use of other types of generating units with higher variable costs. However, when the share of nuclear generation in the energy mix became larger, it was necessary to adjust the generation of nuclear energy. In addition, other constraints from grid operation (fine frequency control, ramping rate, etc.) required starting generating units (e.g. hydroelectric and fossil fuel units) that had more flexibility than nuclear generating units.

Consequently, as the French nuclear programme matured and the share of nuclear energy in electricity generation increased, the need arose for improved methods and tools to simplify and optimize nuclear power plant operation. The improved methods and tools aimed, in particular, at avoiding or minimizing unexpected

[1] The IAEA expresses its appreciation for the generous contributions of all the experts from France in preparation or review of this study, particularly F. Farruggia, S. Feutry, H. Hupond, P. Lebreton and D. Souque of Électricité de France. Their participation, and the courtesy and permission of their organizations to include the information provided, including the figures and tables, in this publication are acknowledged.

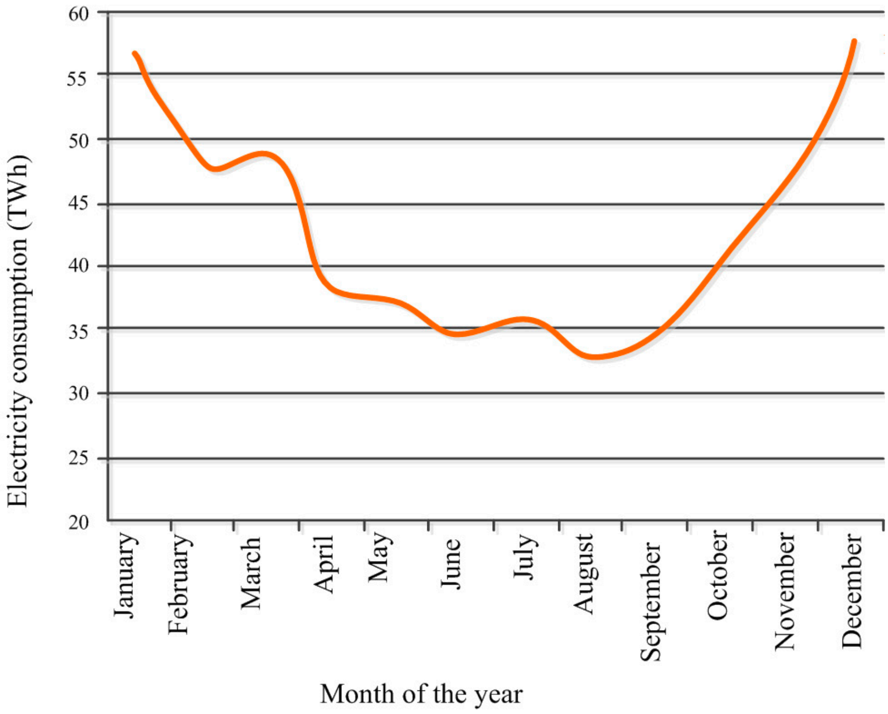

FIG. II–1. Typical monthly variation in French electricity demand (reproduced from Ref. [II–1]).

or unplanned reactor shutdowns and extensive power changes. For example, the utilization of plants to balance electricity generation and demand created a specific issue on the refuelling outage management of plants: the timing of refuelling outages became contingent on the flexible operation of the plant for frequency control and load following. Additionally, a specific consideration was that the ability to perform flexible operation was dependent on the time in cycle, so the allowed period and extent for flexible operation had to be determined based on the time in operating cycles.

More importantly, the goals of these improved programmes were to accomplish rapid load following (from 100% rated thermal power (RTP) to 30% RTP), frequency control (±7% RTP) and rapid (up to 5% RTP/min) return to full power. While meeting these goals, important considerations were to minimize the number of inadvertent reactor trips and to maintain stable power at various power levels.

Therefore, new plant configuration and operating conditions were generated. Upgrades to nuclear power plants were implemented with additional plant modifications, including optimized fuel loading patterns, which were determined and assessed by conducting theoretical studies, and validated by rigorous experiments, test programmes and in-reactor monitoring. The key strategies used for this upgrade of the French nuclear fleet can be summarized as follows:

— Accurately anticipating grid requirements;
— Evaluating the current plant design and increasing capabilities to the greatest extent possible;
— Developing a new core monitoring and control strategy and corresponding hardware;
— Adapting all equipment to new operating conditions;
— Performing long term V&V and confirmation tests on actual plants;
— Implementing the necessary modifications at all plants;
— Obtaining authorization from the regulatory body.

II–3. MAJOR AREAS OF STUDIES

Studies of the impacts of load following and frequency control on plant design and operation can be divided into different categories:

— The first category consists of performance improvements to the core reactivity and power distribution controls, to enable following the grid requirements using control rod banks and the boration/dilution system.
— The second category results from the impacts of these new performances on components and materials. Owing to numerous load changes, these components are subjected to additional loads that may increase their wear, possibly even beyond acceptable levels, unless the appropriate modifications are made.
— The third category deals with the adaptation of the plant operating conditions and the use of actual operating experience to perform some retrofit improvements.

Prior to performing this work, obtaining a thorough knowledge of the various grid transients that affect the nuclear power plant is essential.

II–3.1. Grid characteristics

There are a number of factors affecting power distribution control strategies when nuclear power plants are on-line. These include:

— Fraction of electricity produced by the power plants;
— Capacity distribution of the plants;
— Geographical distribution of the plants;
— Capacity of non-nuclear plants, especially hydroelectric facilities;
— Economic constraints.

These factors vary widely from one utility or country to another; manoeuvrability requirements that exist or will ultimately exist in other countries will be highly specific to each grid.

II–3.2. Analysis scope

The goals of the prospective studies were to allow analysis of the following:

— What kind of power manoeuvres would have to be performed by the PWRs during their operating life?
— How many power manoeuvres of each kind would have to be accounted for in component design?

II–3.3. Core and reactor control

The power generated in the reactor core must be constantly matched to the power extracted from the steam generators (SGs), or vice versa. Two main physical phenomena affect core reactivity: the power effect (nearly instantaneous) and the xenon effect (varying over hours). The core adjustment is performed by varying three parameters: reactor coolant temperature, control rod position and boron concentration of the primary coolant. An operational mode is defined by the manner in which these three parameters are altered [II–2]:

— It is possible to absorb slight power variations required by the grid that are neither filtered out by the turbogenerator control system nor absorbed by the thermal inertia of the SGs simply by allowing free variation of the reactor coolant temperature.
— Additional means of acting on core reactivity are nevertheless necessary in order to avoid temperature variations originating from larger power transients, which would produce excessively high thermomechanical loads on equipment or actuation of the reactor protection system.
— Control rod movement generates rapid variations in core reactivity, but obviously results in mechanical loads on control equipment and causes axial and radial disturbances in power distribution.
— Variations in boron concentration have little effect on power distribution, but their action is time delayed (due to the time required for the borated fluid to spread uniformly through the reactor coolant). In addition, the effects of dilution decrease and eventually disappear as the fuel cycle advances. This action is therefore relatively ineffective if immediate results are required and also produces waste, especially at the end of a cycle.

After having studied the inherent limit of the original operating mode (mode A), it was decided that a new control mode (mode G) should be developed to meet specific French utility requirements, instead of simply trying to improve mode A for operational flexibility.

II–3.4. Loads on fuel components

For a PWR, changing from baseload to load following and frequency control operations puts the components under new kinds of stress.

The power variations thus authorized have effects on plant equipment that should be taken into account. This mainly concerns the control rod drive mechanism (CRDM) and control rods, as well as the mechanical structures of the reactor coolant pressure boundary. The authorized operating conditions induce cyclic loads on the fuel, which also have to be considered.

Once the loads put on the components (including fuel) have been identified and quantified, it is necessary to verify if the components are able to withstand such loads and to justify the behaviour of these components, either by theoretical and calculational analysis, or by the use of test results.

In some cases, when a specific potential problem was highlighted, it was necessary to develop and implement some improvements.

II–3.5. Operating conditions

Overall nuclear power plant response to any grid demand results from intrinsic plant capabilities and from operator skills. New equipment may lead to improved manoeuvrability, simply because it substantially increases plant capabilities. On the other hand, some modifications do not affect the physical plant manoeuvrability, but, by simplifying the required operator actions, they produce a significant improvement in overall plant response.

Therefore, it is advantageous to improve:

— The procedures used by the plant operators during load change operation or periodic testing;
— The training of the plant operators, who improve their skills when they gain a better understanding of the basic phenomena;
— Some devices, either to provide information on an easy to understand display or to perform some new functions, such as automatic boration/dilution and computer aided power control.

These improvements and changes continue to be made in French nuclear power plants. Continuous improvement benefits from operational experience feedback, which is accumulating quickly in France, as load following and frequency control capabilities have become increasingly practised. Observation of operator actions and monitoring of system and component behaviours are instrumental in applying these feedback actions in procedures and training.

II–4. VERIFICATION TESTS

Two major tests were conducted during the work dedicated to increase operational flexibility in French PWRs: one to verify the plant response during load changes and another to qualify the equipment.

II–4.1. Functional tests

A good overall view of plant operation in mode A was obtained after testing both slow and load following and frequency control mainly at Fessenheim nuclear power plant, a 900 MW unit.

Improved flexibility core control with mode G was extensively tested at Tricastin nuclear power plant unit 3 (900 MW(e)), during actual on-line operation, from 1981 to 1983.

Later, load following and frequency control operations with larger cores, those of the 1300 MW design, were tested at the Flamanville nuclear power plant (1985) and Saint-Alban nuclear power plant (1986) units.

Analysis of the mechanical behaviour of reactor coolant system (RCS) components and structures must include consideration of the transients induced by power variations. This can lead to complementary analysis and some improvements in the regulations, as well as a better knowledge of the pressure and temperature variations caused by reactor load changes at different locations around the RCS.

II–4.2. Equipment qualification tests

To demonstrate that nuclear steam supply system equipment adequately satisfies operational flexibility requirements, an equipment qualification and improvement programme was undertaken. This programme included:

- Test of the wear and fatigue resistance of components subjected to the highest loading under remote frequency control (i.e. automatic generation control), such as the CRDM, control rods and rod control cluster guide tubes.
- Simulation of fuel assembly response to power changes, as the local power level was affected by control rod motion. Extensive irradiation and fuel depletion under a load following programme was carried out using a small experimental PWR.

Électricité de France and its manufacturers have conducted fatigue tests or fatigue computations on other RCS components, to demonstrate the equipment integrity under load following and frequency control conditions and transients.

II–4.3. Limiting conditions for flexible operation

Typical French specific technical specifications for load following and frequency control operations are as follows:

- The frequency control operation mode should be stopped:
  - During periodic tests for core instrumentation calibration;
  - When a safety system or a safety component is unavailable.
- The power frequency control range should never exceed the authorized fixed power value (i.e. megawatt) range.
- During the frequency control operation mode, the maximum core power should be limited to 99.6% RTP compared to the baseload operation, to maintain safety margins against dynamic frequency power overshoots.
- During load following and frequency control operations, the axial offset should be kept within ±0.05 of the reference axial offset.
- The load following programme should not exceed two deep variations per day.
- All power stabilizations should last a minimum of 2 hours.

II–4.4. Continuous monitoring

Continuous monitoring procedures that count and keep track of the number of transients throughout the lifespan ensure that the remaining margin is adequate by comparing the accumulated cycles to the allowable limit. This continuous determination assists in maintaining the capability and capacity of nuclear power plants to perform flexible operation, as well as in planning for component replacement. For example, load following transients are taken into account in the design for the maximum number of cycles (e.g. the number of steps), in the case of CRDMs, which establish the design provision for the components. CRDMs must be changed when the end of life number of steps is reached.

Figure II–2 shows sample counting and monitoring of one type of transient on components.

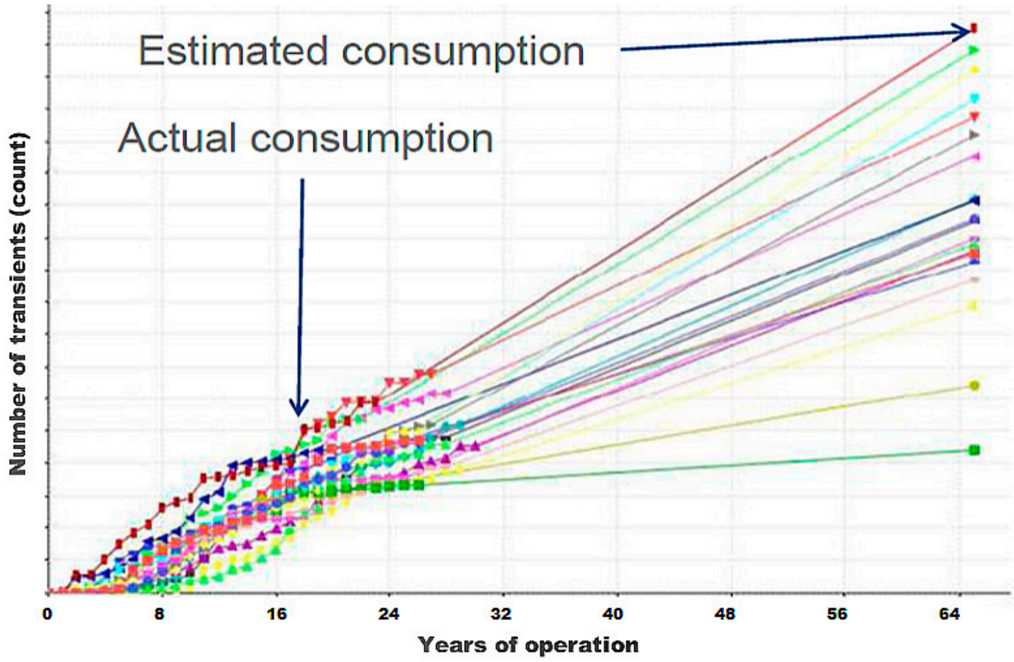

FIG. II–2. Typical tracking of cycles on components (indicated by different colours) during operational lifetime (courtesy of H. Hupond, Électricité de France, reproduced from Ref. [II–3]).

II−5. CHALLENGES WHEN UTILIZING THE CAPABILITIES OF EXISTING DESIGNS

II−5.1. Frequency control

Generally, PWRs have a basic minimum capability of self-control: variations of temperature act on the moderation capability of the reactor coolant water in a self-controlled way. This property may lead to a perception that PWRs have some inherent capability to perform frequency control without a need for additional features. However, this self-control has limitations:

- The amount of inherent frequency control by feedback largely depends on the time in cycle. In the best case scenario, a frequency deviation of 3% RTP can be controlled by this temperature feedback self-control, while this is almost 0% RTP for new fuel.
- This self-control capacity depends on the boron concentration in the reactor coolant water.
- This capacity has to be managed and controlled:
  - Transfer functions of the plant systems, dynamics and amplitude of frequency control are important when controlling the frequency, requiring explicit and dedicated frequency control systems;
  - Reactors equipped with black rods (i.e. only full strength control rods) may have a very low frequency control capability by using only high frequency sensitivity control.
- The amount of inherent frequency control by feedback may not be sufficient for grid needs.

Therefore, in French PWRs, the control capability of the inherent frequency, f, had to be improved and expanded (e.g. to ±5–7% RTP). To accomplish this goal, a frequency deviation parameter, $k \times \Delta f$, and a frequency response parameter, $N \times Pr$, were created to provide primary and secondary frequency control, respectively.[2] In order to control the reactor power automatically, these parameters were incorporated into plant control systems. Figure II–3 illustrates a frequency control scheme that is implemented in the control of a turbine governor.

[2] The multipliers k and N are predetermined or dialled in by operators and applied to the frequency change, Δf, and power change, Pr.

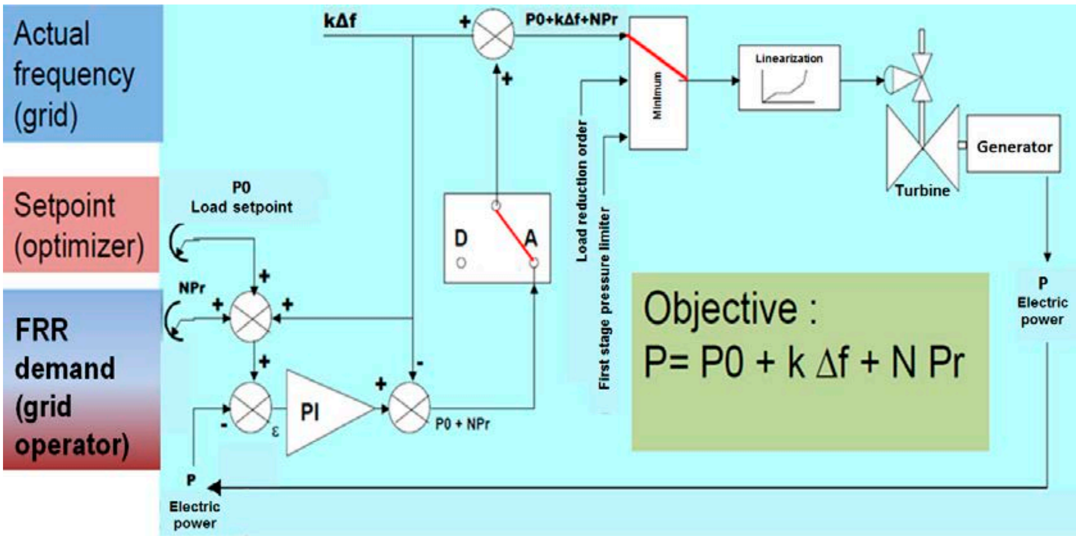

FIG. II–3. Automatic primary and secondary frequency control scheme in a typical French pressurized water reactor turbine governor (courtesy of D. Souque, Électricité de France, reproduced from Ref. [II–4]).

Two main parameters complete the design of the control scheme: the level of the electric power contribution to the frequency response, ΔP, and the droop, s, related by $1/s = (\Delta P \,/\, P) \,/\, (\Delta f \,/\, f)$. The power variation ΔP is generated within a few seconds (typically 0−30 after the appearance of the frequency deviation Δf. Frequency control is then performed primarily by automatically adjusting the turbine valves and moving the black rods accordingly. The action of grey rods is exceptional. Control is typically provided by the following (values are indicative):

— The variation of the power admitted to the turbine, which causes a variation of the reactor coolant temperature, which then affects the reactivity. Without any other mechanism and with adequate boron concentration, the system will be stabilized at the initial temperature, θ, according to the self-control effect.
— The control loop between the black rod positions and the reactor temperature, θ, which moves the black rods if $|\Delta\theta| > 1.6$°C (where $\Delta\theta = \theta_{\text{set point}} - \theta_{\text{reactor}}$).
— Moving the grey rods, if the frequency deviation is greater than 60 mHz.

The French electrical system (typical of those synchronously interconnected to other networks) also requires a frequency restoration control capability, which is typically 5–10% RTP, complementary to the action of the frequency control. For this case, automatic frequency control is used to operate in a stable condition for frequency restoration, to safely support balancing the load and for generation in the grid. The total variation of the power set point leads to:

— Moving the grey rods sufficiently according to the power difference;
— Modifying the set point of the reactor temperature because of the relationship between power and temperature;
— Moving the turbine valve to adjust the electrical power.

II−5.2. Load following

The limitations for ramp rates and for operations at intermediate power are due to the necessity of limiting stresses on fuel. Calculations and test programmes are used to qualify ramp rates, power levels and times of operation at reduced power. A ramp gradient of 2% RTP/min can be expected, but many factors, such as counteracting the xenon effect, managing liquid waste, fuel reconditioning and pellet–cladding interaction limits, may affect this ramp rate, as the conditions apply.

The French experience shows that adaptation of existing equipment in baseload unit designs for use in load following operation should particularly ensure:

- Adequacy and quality of the man–machine interface to facilitate the roles of the operators during ramping periods;
- Management and monitoring of ageing of specific equipment, such as CRDMs;
- Efficiency of the systems recycling the liquid waste.

II–6. FUTURE CHALLENGES

The continuous development of renewable energy sources has caused renewed focus on the established technical abilities summarized above. In this context, Électricité de France has developed advanced tools and knowledge to manage nuclear fuel savings and maximize the value of nuclear modulation. Increasing the share of intermittent renewable energy electricity in the generation mix has a major effect on the dispatch of nuclear power plants. As long as the legal priority for renewable energy generation remains, this will lead to increased modulation volumes, which will become harder to manage. Électricité de France considers that this situation may not be sustainable in the longer term, as increasing occurrence of negative spot prices is a precursor of economic dysfunction.

REFERENCES TO ANNEX II

[II–1] FARRUGGIA, F., “Flexibility and nuclear energy management in France with increasing shares of intermittent renewable electricity in the generation mix”, paper presented at IAEA Technical Meeting on Flexible (Non-baseload) Operation Approaches for Nuclear Power Plants, Paris, 2013.

[II–2] FEUTRY, S., “Load following EDF experience feedback”, paper presented at IAEA Technical Meeting on Flexible (Non-baseload) Operation Approaches for Nuclear Power Plants, Paris, 2013.

[II–3] HUPOND, H., “Load following and frequency control transients vs. loading and design: EDF experience and practice”, paper presented at IAEA Technical Meeting on Flexible (Non-baseload) Operation Approaches for Nuclear Power Plants, Paris, 2013.

[II–4] SOUQUE, D., “Frequency control experience in French NPPs”, paper presented at IAEA Technical Meeting on Flexible (Non-baseload) Operation Approaches for Nuclear Power Plants, Paris, 2013.

Annex III

DECISION PROCESS OPERATING EXPERIENCES OF FLEXIBLE OPERATION IN SOME MEMBER STATES

III–1. INTRODUCTION

As France and Germany have already designed or converted nuclear power plants for flexible operation capabilities, some other Member States have also considered the need for their plants to be able to operate flexibly in accordance with the need from grid systems where those plants are, or will be, operating. This need has arisen owing to the various factors discussed in the main text of this publication, and, in each case, addressing the need has ranged from undertaking significant design and plant modifications to justifying the exclusion of plants from flexible operation. In several Member States, extensive studies have been conducted in order to decide whether a plant should be operated flexibly within the energy policy and technical, economic and legal constraints/incentives, as presented in Refs [III–1 to III–7]. There have also been documented case studies for various countries and regions based on industry surveys and national policies [III–8, III–9].

The following experiences of Member States[1] have been provided for this publication, to disseminate the decision making processes on whether or how to operate nuclear units flexibly. The evolution of the decision making processes is provided in order to illustrate methods of validation, verification and adaptation, to achieve or to manage flexible operation of nuclear power plants.

III–2. BELGIUM

Belgium started its nuclear programme following the Second World War, and began construction of its first nuclear power plant in the 1950s. Establishment of a consortium in 1954 led to the construction and start of operation of seven commercial nuclear power plants between 1974 and 1985 (see Table III–1). Since then, nuclear energy has achieved a large share of Belgian energy sources. During 2014, Belgian nuclear power plants supplied the grid network (in the coupled central and western European market), with over 33.7 TW·h or nearly 47% of the total net electricity generated (72.7 TW·h) in Belgium [III–10].

In 2003, the Belgian Government passed legislation stopping the construction of new nuclear generating units. It also decided to phase out existing reactors after a 40 year lifetime. Under this legislation, the seven Belgian nuclear power plants were to be phased out between 2015 and 2025. In July 2012, the Government specifically decided that Doel nuclear power plant units 1 and 2 would be shut down after 40 years of operation according to the original law, and Tihange nuclear power plant unit 1 would have long term operation permission for 10 years. For the other units, the lifetime was limited to 40 years with a possibility of extension, in case of insufficient energy supply. Additionally, the energy policy of Belgium focused on reducing greenhouse gas emissions, in accordance with the Kyoto Protocol and European Union commitments to reducing CO_2 emissions. This policy included significant increases in renewable energy generation sources. Furthermore, renewable energy generation has been given a higher ranking of available sources of energy, due to the lower marginal cost to first meet electricity demand. The increase in renewable energy sources and their priority in the merit order prompted Belgian nuclear power plants, which have a large share in energy generation, to expect more frequent and extended power reductions as they are expected to increasingly become balancing generating units [III–2].

Currently, the nuclear power plants in Belgium participate in automatic primary frequency control within 2.5% rated thermal power (RTP), except at the end of a fuel cycle and in cases of fuel leakage. They have also

[1] The IAEA extends its appreciation to the experts, organizations and Member States who provided their experiences, and also expresses its appreciation for the generous contributions of many Member States. The IAEA is grateful to all the contributors to this annex: S. Balassone and F. Flachet (Belgium); R. Kothe and D. Serghiuta (Canada); A. Laciok (Czech Republic); X. Wang (China); J. Sohn (Republic of Korea); D. Ilisiu (Romania); K. Kornienko (Russian Federation); P. Hanney and D. Ward (UK); and S. Bernhoft, S. Bragg-Sitton, P. Clifford, D. Coxon, R. McFetridge and L. Sandell (USA). Their participation and the courtesy and permission of their organizations to include the information provided, including the figures and tables, in this publication are acknowledged.

TABLE III–1. OPERATING NUCLEAR POWER PLANTS IN BELGIUM [III−10, III−11]

Nuclear power plant	Type	Nuclear steam supply system design	$MW(e)_{(net)}$	MW(th)	Date connected to grid
Doel-1	PWR	Two loop Westinghouse	433	1311	28 Aug. 1974
Doel-2	PWR	Two loop Westinghouse	433	1311	21 Aug. 1975
Doel-3	PWR	Three loop Westinghouse	1006	3054	23 Jun. 1982
Doel-4	PWR	Three loop Westinghouse	1039	2988	8 Apr. 1985
Tihange-1	PWR	Three loop Framatom	962	2873	7 Mar. 1975
Tihange-2	PWR	Three loop Westinghouse	1008	3064	13 Oct. 1982
Tihange-3	PWR	Three loop Westinghouse	1046	3000	15 Jun. 1985

Note: PWR – pressurized water reactor.

performed ‘limited load reductions’ on request from the grid system operator subject to the boundaries of the operating envelope, which is determined by conservative assumptions to prevent and/or minimize impacts on the mechanical and fluid systems and the reactor fuel during those power manoeuvres. These assumptions are illustrated in Fig. III–1, and include:

— *Maximum allowable power decrease:* 25% RTP (based on xenon behaviour).
— *Maximum allowable power ramp:* 1%/min (based on safety analysis, as well as on minimization of boration/dilution evolution and control rod movement limits).
— *Maximum duration of a manoeuvre:* 6 hours (based on no fuel deconditioning).
— *Minimum duration between two manoeuvres*: 72 hours (based on reconditioning of fuel and stabilization of core physics parameters).
— *Number of manoeuvres allowed per unit:* three (or five) times per 12 rolling months (based on fuel rod internal pressure in rods).

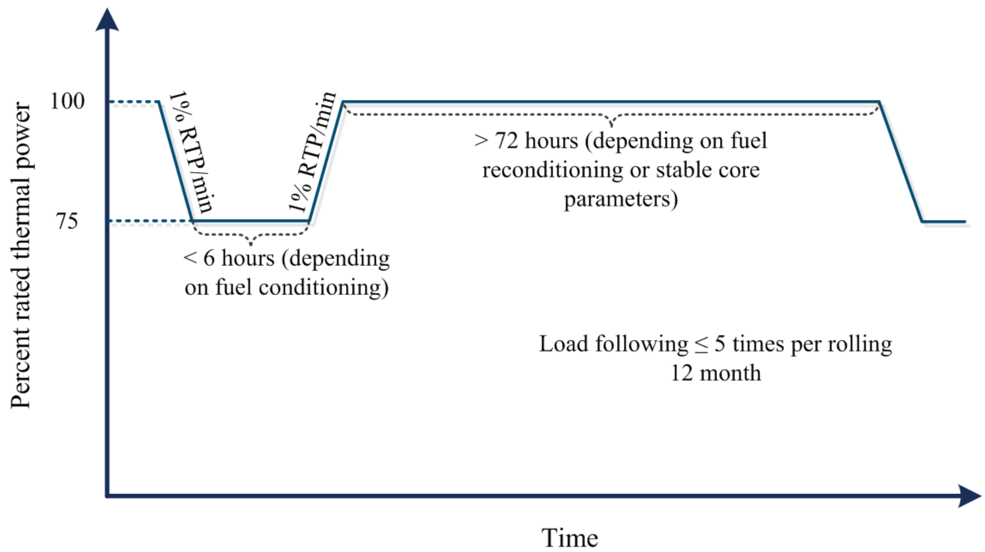

FIG. III–1. Limited load following practised by Belgian nuclear power plants (courtesy of F. Flachet, Electrabel, reproduced from [III−2]). RTP — rated thermal power.

These restrictions are also limited by the criteria of applicability, as follows:

- No load following during primary frequency control;
- No load following at the end of a cycle when the boron concentration is less than 200 parts per million;
- No power manoeuvre if there is a fuel leak;
- Liquid and gaseous waste storage is available and adequate;
- Power manoeuvre is approved by the nuclear power plant operator.

Expecting more frequent and extended power reductions beyond these limited load reductions, the Belgian nuclear power plants are conducting a feasibility study for extensive load reductions: to increase the maximum allowable power decrease from the current limit of 25% to 50% RTP; to expand the minimum duration between two power manoeuvres to 2–72 hours; and to perform 30 power manoeuvres, instead of the current limit of 5 in 12 rolling months. The feasibility studies for this extensive load following include:

- Safety analysis and core design analysis, such as core physics parameters, penalties and shutdown margins;
- System/component operation and controls, such as reactivity control, chemical and volume control system capability, and pressurizer and steam generator (SG) level controls;
- Thermal, mechanical and hydraulic evaluation for components such as control rod drive mechanisms, pressurizer spray nozzles, surge lines, charging nozzles and reactor internals;
- Generation of liquid and gaseous waste, including capacity of waste tanks, resins and filters;
- Economic impacts.

III–3. CANADA

In Canada, 18 of the 19 operating nuclear generating units are located in the province of Ontario, with flexible plant operation (FPO) of nuclear units applicable to Ontario alone. All nuclear power plants in Canada are pressurized heavy water reactors, of Canada deuterium–uranium (CANDU) design. In 2013, the 18 Ontario nuclear units contributed approximately 56% of the baseload generation to meet primary demand in the province. During periods of low demand, the contribution from nuclear generation can be higher. Over the past several years, Ontario governmental policies have required the retirement of all coal burning generating units. At the same time that this phase-out was occurring, laid up nuclear units were being brought back on-line following refurbishment, renewable energy construction and generation increased, and the economy moved into a prolonged recessionary period. This combination of events contributed to a decreased demand and a surplus of baseload generation in Ontario starting in 2009.

This situation resulted in the independent electricity system operator for Ontario introducing a requirement for nuclear power plant operators to decrease their output during periods of high generation and low demand [III−12]. To meet these requirements, selected nuclear generating units maintain reactor (thermal) power at 100% RTP, while plant operators reduce generator (electrical) output by up to 300 MW(e) for short periods. Excess steam is directed (dumped) to the condenser steam bypass system (SBS) to provide flexible operation in response to the independent electricity system operator requests during periods of surplus baseload generation. This methodology to address FPO allows for faster manoeuvring and does not affect fuel burnup rates or reactivity control. The SBS was originally designed to keep the reactor from poisoning out after very infrequent loss of load events (e.g. grid collapses). It was not originally designed for frequent use [III−13], and so its design capabilities to allow such flexible operation had to be evaluated and confirmed.

When longer reductions in power are required, the plant owner/operating organization has the option to shut down a unit or multiple units. In addition, as the plants in Ontario are multiunit, the plant operating staff has the flexibility to determine which unit will be operated at reduced power or shut down. This flexibility, which differs from that of most other plants worldwide, allows the plant owner/operator to avoid reducing the power of units that are in an increased risk condition due to equipment abnormalities, or conversely, to shut down a unit where an outage may be desired to repair an equipment abnormality.

At the Ontario based Bruce Power nuclear plant, over 1500 event free FPOs have been completed on the eight units since the inception of the requirement in 2009. Plant staff involved in FPO have been trained for this, and have well defined procedures in place to guide their activities.

The use of FPO in Ontario is expected to continue into the foreseeable future. The contribution, construction and integration of renewable energy sources into the Ontario generation mix is also expected to continue.

III–4. CZECH REPUBLIC

The decision in the Czech Republic to develop nuclear power as an alternative to fossil fuel power goes back to the 1950s, because of a lack of oil and the anticipated future depletion of coal reserves. It was based on well established research and the experienced machinery industry in the former Czechoslovakia. Construction of a heavy water gas cooled reactor began in the early 1960s in Jaslovské Bohunice (now Slovakia), and it was commissioned in 1972. However, following two accidents, it was permanently shut down in 1976, and the design project for a bigger reactor of the same type was also cancelled. The technology was replaced with a Russian pressurized water reactor (PWR) design and four WWER-440/213 units were chosen for the Dukovany site. This design was adopted, and production of the plant equipment, with the exception of the fuel and the main circulation pumps, was localized. Czech industries also became the suppliers of nuclear power plant parts for WWER designs in other Eastern European countries (e.g. 20 reactor vessels were made by Škoda). In the mid-1980s, construction of four units, larger WWER-1000 V-320 units, was started at the Temelín site; however, the Temelín project was later reduced to two units. Two Temelín nuclear power plant units were completed and put into commercial operation in early 2001 and 2003 (Table III–2).

TABLE III–2. RECENT HISTORY OF NUCLEAR ENERGY ELECTRICITY PRODUCTION AND CAPACITY IN THE CZECH REPUBLIC [III–10]

Plant name	Type	Status	Operator	Reactor supplier	Reference unit power (MW(e))	Gross electrical capacity (MW(e))	First grid connection
Dukovany-1	PWR	Operational	ČEZ	Škoda	468	500	Feb. 1985
Dukovany-2	PWR	Operational	ČEZ	Škoda	471	500	Jan. 1986
Dukovany-3	PWR	Operational	ČEZ	Škoda	468	500	Nov. 1986
Dukovany-4	PWR	Operational	ČEZ	Škoda	471	500	Jun. 1987
Temelín-1	PWR	Operational	ČEZ	Škoda	1026	1080	Dec. 2000
Temelín-2	PWR	Operational	ČEZ	Škoda	1026	1080	Dec. 2002

Note: PWR — pressurized water reactor.

Czech electricity generation is still primarily based on coal. For baseload generation, it currently provides nearly 60% of the electrical energy and a large proportion of the heat energy through district heating. Brown coal is the main source of energy, and continues to cover approximately 57% of the primary energy sources, although its use has decreased by about 30% from its share in the 1990s. Importation of crude oil (mainly for transport) and natural gas has increased, largely as a result of road transport expansion and replacement of coal by gas for heating. During restructuring of the economy and due to the lack of demand for nuclear equipment, most of the industrial capacity was lost in the 1990s. In the past few years, the industrial capacity has been partially re-established for subdeliveries, mainly for foreign reactors. The most significant change in the last decade has been the construction of the Temelín nuclear power plant. As a result, primary heat and electricity (mainly nuclear) was increased between 2000 and 2005 [III–10] (Table III–3).

TABLE III–3. RECENT HISTORY OF ELECTRICITY PRODUCTION AND CAPACITY IN THE CZECH REPUBLIC [III–10]

	1991	2000	2005	2010	2012
Electricity production (TW·h)					
Total	60.527	73.466	82.579	85.910	87.573
Steam power plants, including combined cycle gas turbines	47.138	57.550	52.269	53.905	51.643
Renewable energy (hydro and wind)	1.257	2.313	3.027	3.381	3.381
Nuclear power plants	12.132	13.590	24.728	27.998	30.324
Internal combustion engines and gas turbines	—	0.013	0.013	0.030	0.053
Nuclear share (%)	20.0	18.5	29.9	33.9	34.6
Installed capacity (GW(e))					
Total	14.957	15.324	17.412	20.073	20.520
Steam power plants, including combined cycle gas turbines	11.626	11.431	10.698	11.726	11.758
Renewable energy (hydro and wind)	1.360	2.097	2.167	2.203	2.216
Nuclear power plants	1.760	1.760	3.760	3.900	4.040
Internal combustion engines and gas turbines	0.211	0.036	0.010	0.067	0.157
Nuclear share (%)	11.8	11.5	21.6	19.42	19.7

Note: —: no data available.

In August 2009, ČEZ, a. s. relaunched a tender for the construction of two previously planned units at the Temelín nuclear power plant site (Temelín units 3 and 4). Final selection should have been made in September 2013, but the decision has been delayed.

The current version of the State Energy Policy of the Czech Republic [III–14], with a 30 year time horizon, was approved by the Czech Government in March 2004.[2] The energy policy specifies a comprehensive set of priorities and long term goals, taking into account energy issues together with environmental, economic and social aspects, particularly considerations for nuclear and renewable energy generation:

— *Nuclear generation.* After coal, the second most important source of energy, currently used primarily for the generation of electricity, is nuclear. Nuclear generating units now supply over 35% of all electricity generation [III–11] in the Czech Republic. The State Energy Policy identified nuclear energy as an important option for energy independence and noted the following as a strategy for balancing electricity generation and demand in the planned time horizon utilizing nuclear sources:
  - Constructing additional nuclear units to produce approximately 20 TW·h/year by 2035;
  - Extending the lifetime of four Dukovany nuclear power plant units (up to 60 years);
  - Planning for construction of another unit to replace nuclear generation after decommissioning of the Dukovany nuclear power plant.

[2] An updated version of the policy, with an extended time horizon up to 2040, was drafted in December 2014 and was approved on 18 May 2015.

In the long term, nuclear energy could provide in excess of 50% of the total amount of electricity generated, thus replacing a large proportion of the coal sources.

— *Renewable energy sources.* The Czech Republic committed to ensuring that, by 2020, 13% of its gross final energy demand is to be from renewable energy sources, including from hydropower. Achieving this target is challenging and requires support by flexible generation and gradually downsized fossil fuel sources. The Czech Republic used hydroelectric energy sources for decades in the past. However, these have now been considerably exhausted and their share in the energy mix, which is currently around 3.5%, will not increase significantly in the future. Hydroelectric generation is important in the Czech Republic's energy mix as it provides flexible generation and covers fluctuations in intermittent sources. In addition, several pumped storage power stations — which are the only form of storage — are used at times of peak demand, provided that the water levels are adequate. There are a few possibilities in the form of small sources and some potential for several larger reservoirs to gradually participate in hydroelectric generation. For wind and solar renewable energy sources, there are limited generation options due to geographic and climatic conditions. There are a few areas with regular, adequately strong and stable winds, mostly in the mountainous region of the country; however, these are located in natural conservation areas. Owing to strong incentives, there has been a sharp increase in the capacity of solar energy. This strong trend has pushed the electricity network to its limits and has challenged the protection of farmland, so the incentives have been reduced. Moreover, the integration of renewable energy sources, particularly intermittent sources, will certainly require significant upgrade and modification of the grid infrastructure, which is particularly important due to the country's role as a transit nation (i.e. one that allows power to flow through the country from one neighbouring country to another). It is now considered appropriate to use solar energy as a small power source (e.g. in buildings).

— *Cogeneration.* The Czech Republic has successfully introduced combined heat and power use of fuel sources. Cogeneration produces 12–13% of gross electricity generation, and the share of large and medium sources in cogeneration is nearly 70% of the total gross heat generation. However, the ratio of heat cogeneration to overall heat generation — including decentralized sources but excluding households — is less than 50%. Therefore, effective use of heat and electricity is identified as a priority for future development.

— *Interconnections.* The Czech Republic's electrical grid system is connected to all neighbouring countries. The total available transmission capacity for export is more than 35% of the national peak load and 30% for imports. There is also increasing north–south transmission of up to 30% of the peak load.

It should also be noted that the energy policy advises the use of nuclear generating units for cogeneration to heat larger urban areas.

In the Czech Republic, nuclear generating units are located outside densely populated areas. They have always been used as baseload generating units, although the provision of some ancillary services by nuclear generating units has been explored and implemented in the past. For example, Dukovany nuclear power plant was modified to provide primary frequency control in the mid-1990s. The modifications included changes to reactor and turbine control systems, as well as to operating procedures and plant information systems, including the development of computerized operator assistance. In 1996–1997, modifications to the Dukovany nuclear power plant were also implemented to enable plant operation during extreme frequency deviations. Furthermore, in 1997, a project for load following was developed in order to allow secondary frequency control operation and to enable the plant to contribute to tertiary control with the capability of limited[3] load following in the range of 100–50% rated electrical output (REO) [III–15]. Although these evaluations determined that the proposed load following by Dukovany nuclear power plant was technically feasible with significant plant modifications, regular flexible operation was found to be economically unfeasible due to low fuel costs in addition to foreseen limitations by the plant's operational parameters.

The current electricity grid is controlled by the central dispatching of ČEPS; for the execution of secondary frequency regulation and minute reserve management (tertiary output regulation), the control of individual Dukovany nuclear power plant units in the remote control regime is utilized. The start of this unit operation regime is driven by the central dispatching requirements, considering the technological conditions of individual units. The remote control regime enables (is certified for) 5 MW/min output power changes (allowed trend of 1% RTP/min).

[3] Only on weekends and with a limited annual number of load cycles.

However, based on an agreement between ČEPS and ČEZ, only 2 MW/min output power change requirements are inserted into the 'DAMAS' application, which serves the remote output regulation requirements for units. The remote control of the unit power is enabled in the range from 80% REO (turbogenerator power greater than 170 MW(e)) to full load. The remote controlled unit has to be operated in the stabilized, nominal operational mode, and a set of further technological and organizational measures has to be fulfilled and observed.

Similar conditions must be ensured for other instruments of the grid control support, where, based on telephone instruction, the output unit power may be decreased (within approximately 30 minutes) by:

- A maximum of 90 MW(e) (~20% REO) at a rate of 5 MW/min (1% REO/min);
- A maximum of 250 MW(e) (~50% REO) at a slower rate (less than 0.5% RTP/min);
- A stabilization period (less than 24 hours) after a decrease to nearly 50% REO is needed.

There are similar grid support conditions for non-baseload operation of units at the Temelín nuclear power plant. The ČEPS dispatcher can telephone a request (in order to resolve or prevent the emergency grid status) to reduce the power of one or two turbogenerators by bypassing the steam production into the main condenser, accompanied by an output decrease of up to 850 MW(e) (while maintaining reactor power at 100% RTP); in this manner, each unit can still supply approximately 240 MW(e) to the grid.

Remote control from central dispatching is also available at Temelín nuclear power plant, but this regime is not currently certified as a grid support service.

III–5. CHINA

China is the world's most populous country, with a population of over 1.3 billion, and the second largest energy consumer (after the USA). Its land area is about 9 597 000 km^2. China is rich in coal and water resources, which are unevenly distributed throughout the country. Coal deposits are predominant in the north and northwestern regions, while water resources are mainly in the southwestern region. In contrast, southeast China is densely populated and has extensively developed industry and agriculture, but is deficient in coal and hydroelectric resources.

By June 2014, the total installed capacity of China amounted to nearly 1298 GW(e), of which the installed capacity of thermal, hydroelectric and nuclear power accounted for approximately 73%, 19.4% and 1.4%, respectively, of the total energy mix. Gross electric output in the first half of 2014 reached 2780 TW·h, mostly generated by thermal power (95.7%), while the electricity generated by nuclear power amounted only to 2%.

China's national economic and social development plans called for the ratio of non-fossil-fuel energy to primary energy consumption to increase to 11.4% by 2015; the energy consumption and the CO_2 emissions per unit of gross domestic product to decrease by 16% and 17%, respectively, compared with those of 2010. The Chinese Government has been committed to increasing the ratio of non-fossil-fuel energy to primary energy consumption to approximately 15% by 2020 and reducing the CO_2 emissions per unit of gross domestic product by 40–45% from 2005 emissions.

China intends to expand the nuclear power installed capacity to 58 GW, with another 30 GW under construction by 2020, in accordance with its current nuclear power development plans. In June 2017, there were 20 nuclear units under construction and preparations for an additional 6 nuclear power plants had begun [III–10, III–11].

Even with this expansion, the share of nuclear generation will still be less than 4% of the overall installed capacity. This small percentage of the share does not necessitate any deviation from the current mode of operation of nuclear power plants as baseload generating units.

However, at the regional scale on the grid network, the share of nuclear generation may be much higher in provinces with massive development plans, such as in Guangdong Province, where it could approach 15%. In such cases, pumped storage units will be built that provide an alternative to load following. Thus, load following operation of nuclear power plants is not a consideration in the near future [III–16]. On the other hand, if the plant generation capacity becomes the main part of the grid network, some primary frequency control function by the plants might become necessary.

III–6. REPUBLIC OF KOREA

The Republic of Korea has carried out a very ambitious nuclear power programme since the 1970s in parallel with the nation's industrialization policy. It has maintained a strong commitment to nuclear power development as an integral part of its national energy policy, aimed at reducing external vulnerabilities and insuring against global fossil fuel shortages.

During the early years of nuclear power development, power plants were constructed mostly through turnkey contracts, providing little opportunity for domestic industries to participate in the construction. Since then, however, domestic participation in overall construction management, design, equipment supply and civil construction has continuously increased through the adoption of non-turnkey approaches. As part of this trend, a high degree of technological self-reliance in various fields of the nuclear industry has been achieved through the construction of Yonggwang nuclear power plant units 3 and 4. The first domestic reactors were Ulchin nuclear power plant units 3 and 4, both 1000 MW(e) PWRs, originally named the Korean Standard nuclear power plant, but now referred to as OPR-1000, which entered commercial operation in 1998. Ulchin nuclear power plant units 3 and 4 became the reference plant for OPR1000 plants thereafter. Eight more OPR-1000 plants were built (Yonggwang nuclear power plant units 5 and 6, Ulchin nuclear power plant units 5 and 6, Shin Kori nuclear power plant units 1 and 2 and Shin Wolsong nuclear power plant units 1 and 2). In 2012, nuclear energy capacity exceeded 20.7 GW(e), which was nearly a quarter of the total installed capacity of 81.8 GW(e) (Table III–4). Nuclear generation contributed slightly more than 150 TW·h of electricity generation — an almost 30% share in the 509.58 TW·h of total energy generation.

The new Advanced Power Reactor (APR)1400 models, 1400 MW(e) PWRs, are being operated and built. Of those, Shin Kori nuclear power plant unit 3 started operation in January 2016, while Shin Kori units 4

TABLE III–4. ENERGY GENERATION AND SOURCES IN THE REPUBLIC OF KOREA IN 2012 [III−17]

Generation type			Status as of end of 2012		
			Capacity (GW)	Share (%)	Number of units
Nuclear energy			20.71	25.32	23
Fossil fuel energy	Steam power plant	Coal (import)	23.41	28.62	45
		Coal (domestic)	1.12	1.38	6
		Oil	3.95	4.83	16
		Natural gas	0.89	1.08	4
		Total	29.37	35.90	71
	Combined cycle		19.80	24.20	148
	Internal combustion		0.38	0.45	208
	Total		49.54	60.55	427
Group energy			2.77	3.38	44
Pumped energy			4.70	5.75	16
Renewable energy		Hydro	1.75	2.13	239
		Other renewables	2.86	2.33	3 674
Total			81.81 (gross: 74.21)	100	4423

and 5 and Shin Hanul nuclear power plant units 1 and 2 are under construction. Four more APR-1400 plants, Shin Kori nuclear power plant unit 6 and Shin Hanul nuclear power plant units 3 and 4 are under consideration. Furthermore, according to the 6th Basic Plan of Long Term Electricity Supply and Demand, which was finalized in February 2013, six new nuclear power units will be constructed by 2024, as shown in Table III–5. Four more APR+ design (1500 MW(e)) plants, which are newly developed, will be built in the near future, if appropriate sites can be selected.

TABLE III–5. PLANNED NUCLEAR POWER PLANT CONSTRUCTION IN THE REPUBLIC OF KOREA [III−10, III−11]

Station/project name	Type	Capacity (MW(e))	Construction start year	Expected commercial year
Shin Hanul-1	PWR	1400	2012	2018
Shin Hanul-2	PWR	1400	2013	2018
Shin Kori-4	PWR	1400	2016	2021
Shin Kori-5	PWR	1400	2016	2022
Shin Hanul-3	PWR	1400	2016	2022
Shin Hanul-4	PWR	1400	2016	2023
Unit 1	PWR	1500	TBD	TBD
Unit 2	PWR	1500	TBD	TBD
Unit 3	PWR	1500	TBD	TBD
Unit 4	PWR	1500	TBD	TBD

Note: PWR — pressurized water reactor; TBD — to be determined.

In the Republic of Korea, flexible operation of nuclear power plants such as load following, frequency control and low power have not been of concern for operating plants. All existing plants have been operated in baseload mode at steady full power, as long as possible, to meet the electricity demand. The generators of nuclear power plants are not assigned to balance generation with demand of electricity (i.e. load following), and also are not designated as generators for frequency control (i.e. automatic frequency control). Hydroelectric, fossil fuel and pumped storage power generating units operate flexibly to balance the generation and demand of electricity. This is mainly because of the perceived negative aspects of flexible operation of nuclear power plants, such as technical difficulties, complexities of operation and lower plant safety margins. Furthermore, the existing rules and regulations do not allow for extended flexible operation of plants, though this may be needed in the future for grid stability considering renewable energy integration, if the Government policies require it.

Nuclear power plants in the Republic of Korea are capable of performing uninterrupted operations in case of load rejection at any power level, loss of one feedwater pump, turbogenerator runback to house load, etc. They also can perform ‘limited’ power cycling [III−17]. For example, the OPR-1000 design can perform a daily load cycle with typical 100–50−100% RTP in 14−2−6−2 hour patterns for up to 90% of the cycle length. Similarly, CANDU plants can be operated in frequency control mode without major design changes, as their normal operation mode is ‘reactor follows turbine’. Daily extended load following operation in APR+ designs are constrained by the potential operator burden to control rodded[4] operation duration and control rod lifetime. Those constraints can be resolved

[4] As baseload operation is usually performed with all control rods withdrawn from the core (i.e. an ‘all rods out’ configuration), operation at intermediate power would have the control rods inserted into the core (i.e. a ‘rodded’ configuration), as allowed by the plant’s technical specification, which would result in core power redistribution requiring additional operator monitoring and actions.

by: using a constant average temperature programme, applying a model predictor controller, using operator aid systems for soluble boron control, having a longer rodded operation duration and extending control rod life by means of a new control element drive mechanism design that would increase the lifetime twofold or more (i.e. from a current lifetime of 3 million cm to 6–9 million cm (100 000 feet to 200 000−300 000 feet)).

A few design changes in most of the nuclear power plants in the Republic of Korea would enable a capability for frequency control, even if this has not been a design basis criterion. Evaluation of frequency control capabilities in OPR-1000 plants shows that:

— A primary regulation (local frequency control) capability within ±2.5% RTP can be achieved:
  • Without control rod movement;
  • Within the current limiting condition of the operation band for cold leg temperature;
  • With modifications to the reactor regulating system.
— A secondary regulation (remote frequency control) capability of ±5% RTP can be achieved by removing the limitations in the power dependent insertion and power distribution control.

Local frequency control (by the nuclear power plant operator) was included in a proposal for a 2014 government research and development project. This proposal required preunderstanding between the dispatcher, Korea Hydro and Nuclear Power, and the licensing body, as it is not currently allowed by the rules and regulations. Expected licensing steps for implementation of local frequency control include:

— A 2−3% RTP local frequency control for one unit;
— Completion of plant modification;
— Droop setting for smaller local frequency control;
— Conduction of plant tests (for 1–2 months);
— Evaluation of and obtaining approval for higher capabilities.

III−7. ROMANIA

The electricity generated annually by Cernavodă nuclear power plant units 1 and 2 represents approximately 19% of Romania's overall electricity production (Figs III–2, III–3). In August 2004, the Government advertised for companies that would be interested in completing Cernavodă unit 3, a 700 MW(e) CANDU6 unit, through a public–private partnership arrangement. This proved impractical, and a feasibility study in March 2006 analysed further options for units 3 and 4 (Table III–6). Under the long term energy policy, priority is given to boosting renewable energy in an effort to reduce CO_2 emissions. Wind energy generation contributed, in an accelerated manner, to more than 4% in 2012, and more than 12% in 2014, of the total generation, with most of the wind farms being located in the same regions as the plants.

In Romania, the special rules for dispatch that are in place for nuclear power plants are as follows [III−18]:

— *Technical rules:* no frequency containment reserve (FCR) and primary reserve activation for $\Delta f > 500$ mHz, with a step of 180 MW.
— *Operational rules:* decreasing power for grid congestion and special system load conditions.
— *Market rules:* special price for reducing power (the same as wind, photovoltaics and cogeneration) and special contracts to settle imbalances.

However, as more incentives were provided under environment installation certificates, renewable energy source integration exceeded national targets, while consumption decreased from the initial period of the nuclear power plant and grid system rigidity increased. For example, in 2013, at the time of highest annual electricity demand, which occurred in January, nuclear generation was 15% of the total generation, with full rated power baseload operation (Fig. III–2); however, in May, at the time of lowest electricity demand, the share of nuclear generation at baseload operation reached 37% of the total generation, reducing the FCR and frequency restoration reserve (FRR) and increasing the rigidity of the system (Fig. III–3). The construction of an additional two units, as

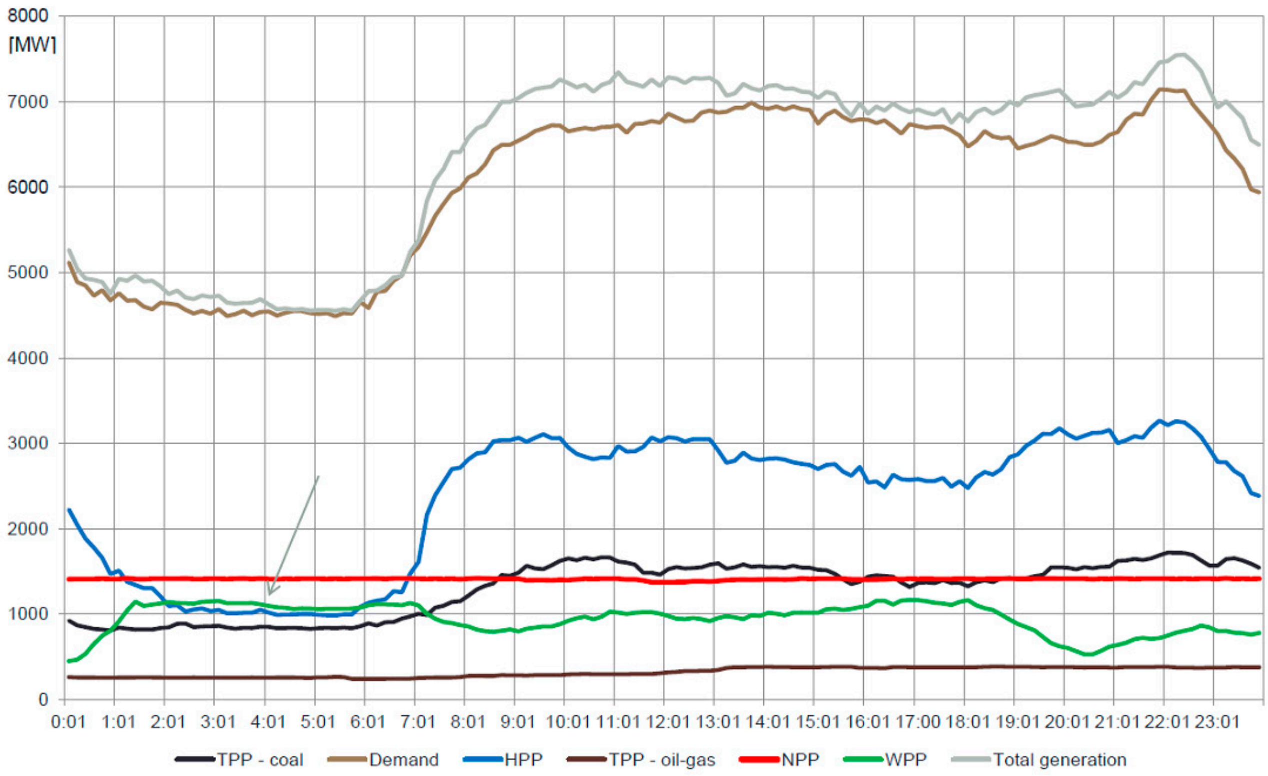

FIG. III–2. Electricity generation and demand in Romania in January 2013 [III−18]. HPP — hydroelectric power plant; NPP — nuclear power plant; TPP — thermal power plant; WPP — wind power plant.

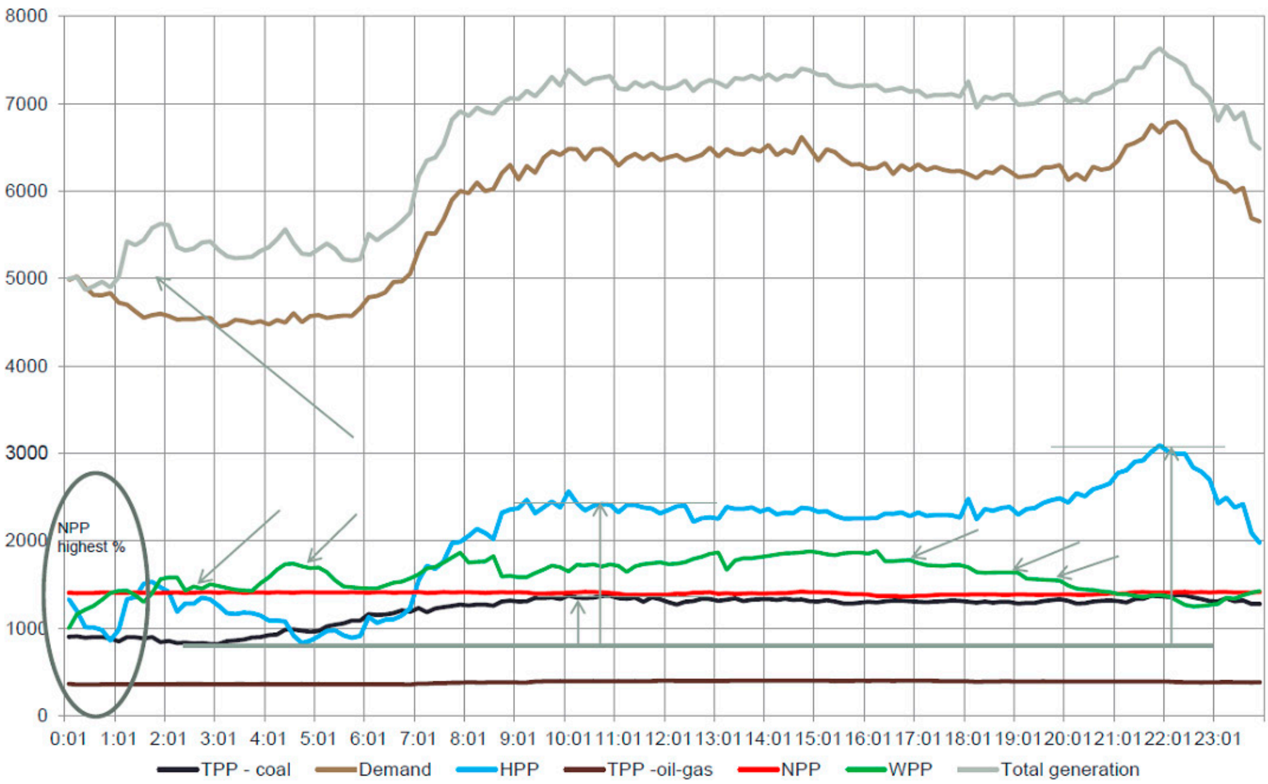

FIG. III–3. Electricity generation and demand in Romania in May 2013 [III−18]. HPP — hydroelectric power plant; NPP — nuclear power plant; TPP — thermal power plant; WPP — wind power plant.

TABLE III–6. STATUS AND PERFORMANCE OF ROMANIAN NUCLEAR POWER PLANTS [III−10, III−11]

Reactor unit	Type	Net capacity (MW(e))	Status	Reactor supplier	Construction date	Commercial date	UCF for 2015
Cernavodă-1	PHWR	650	Operational	AECL	Jul. 1982	Dec. 1996	92.7
Cernavodă-2	PHWR	650	Operational	AECL	Jul. 1983	Oct. 2007	89.4
Cernavodă-3	PHWR	655	Suspended construction	AECL	Feb. 1984	Proposed 720 MW(e)	
Cernavodă-4	PHWR	655	Suspended construction	AECL	Aug. 1985	Proposed 720 MW(e)	

Note: AECL — Atomic Energy of Canada Limited; PHWR — pressurized heavy water reactor; UCF — unit capability factor.

well as cohabitation in a region with the highest wind potential may require a higher degree of flexibility for plants, including load following in the range 40−100% RTP, hourly ramps and balancing for FRRs and FCRs.

III−8. RUSSIAN FEDERATION

III−8.1. Russian nuclear power plants and the grid system

Nuclear power has been a large part of electricity generation in the Russian Federation (and the former Soviet Union). The nuclear share in generation, which was less than 1% in 1970, passed the 10% share in 1990 and reached nearly 17% (almost equal to that of hydroelectric generation) in 2013, with an average annual 2.56% growth rate between 2000 and 2013 (Table III–7).

The Russian power grid is the world's largest automated complex to generate, transmit and distribute electric power. The power grid is a complex network of power plants that have the same operating mode and centralized dispatching control. Working in parallel with the Russian power grid are the power systems of Kazakhstan, Ukraine, Moldova, Belarus, Estonia, Latvia, Lithuania, Azerbaijan and Georgia, which are synchronously connected to the Russian grid system. Additionally, through a high voltage direct current line to the power system of Finland, the Russian grid system is interconnected to the Nordic grid system, and there are plans to connect the unified power system (UPS) network with the European Network of Transmission System Operators for Electricity. Six of the seven integrated power systems are part of the UPS of the Russian Federation: the Centre, Middle Volga, Urals, Northwest, North Caucasus and Siberia. The Far East region is the only one not connected to an integrated power system; the Far East integrated power system operates separately from the Siberia integrated power system [III−10].

The Russian Federation's nuclear power plants, with 35 operating reactors and a total generation of approximately 25 GW(e), comprise four first generation and two second generation WWER-440 reactors, 12 third generation WWER-1000 (mostly V-320) type PWRs, 11 channel type light water graphite high power channel type reactors, four small graphite moderated (EGP-6 model) boiling water reactors (BWRs) and two fast breeder reactors (one BN-600 type and one BN-800 type, see Fig. III–4). Additionally, there are seven units under construction, with approximately 7.8 GW(e) of output.

Four small graphite moderated BWRs (EGP-6 model) at the Bilibino nuclear power plant in eastern Siberia, which were constructed in the 1970s for cogeneration, are connected to the Far East 'island' grid, while all other operating plants are connected to the UPS electricity system.

TABLE III–7. ELECTRICITY CAPACITY AND GENERATION IN THE RUSSIAN FEDERATION [III–10]

Year	1970	1980	1990	2000	2005	2006	2013	Average annual growth rate (%) 2000–2013
Installed capacity (GW(e))								
Thermal	81.3	121.1	149.7	138.9	149.2	149.2	155.4	0.83
Hydro	23.0	35.1	43.4	44.4	46.1	46.1	45.9	0.26
Nuclear	0.8	9.2	20.2	21.2	23.2	23.2	25.2	1.45
Total	105.1	165.4	213.3	204.5	218.5	218.5	226.5	0.83
Generation (TW·h)								
Thermal	373	622	797	568.5	629.2	664.1	676.8	1.46
Hydro	94	129	167	165.4	174.4	175	174.7	0.43
Nuclear	4	54	118	129	149.5	154.7	172.0	2.56
Total[a]	471	805	1082	862.9	953.1	993.8	1024	1.28

[a] Electricity transmission losses are not deducted.

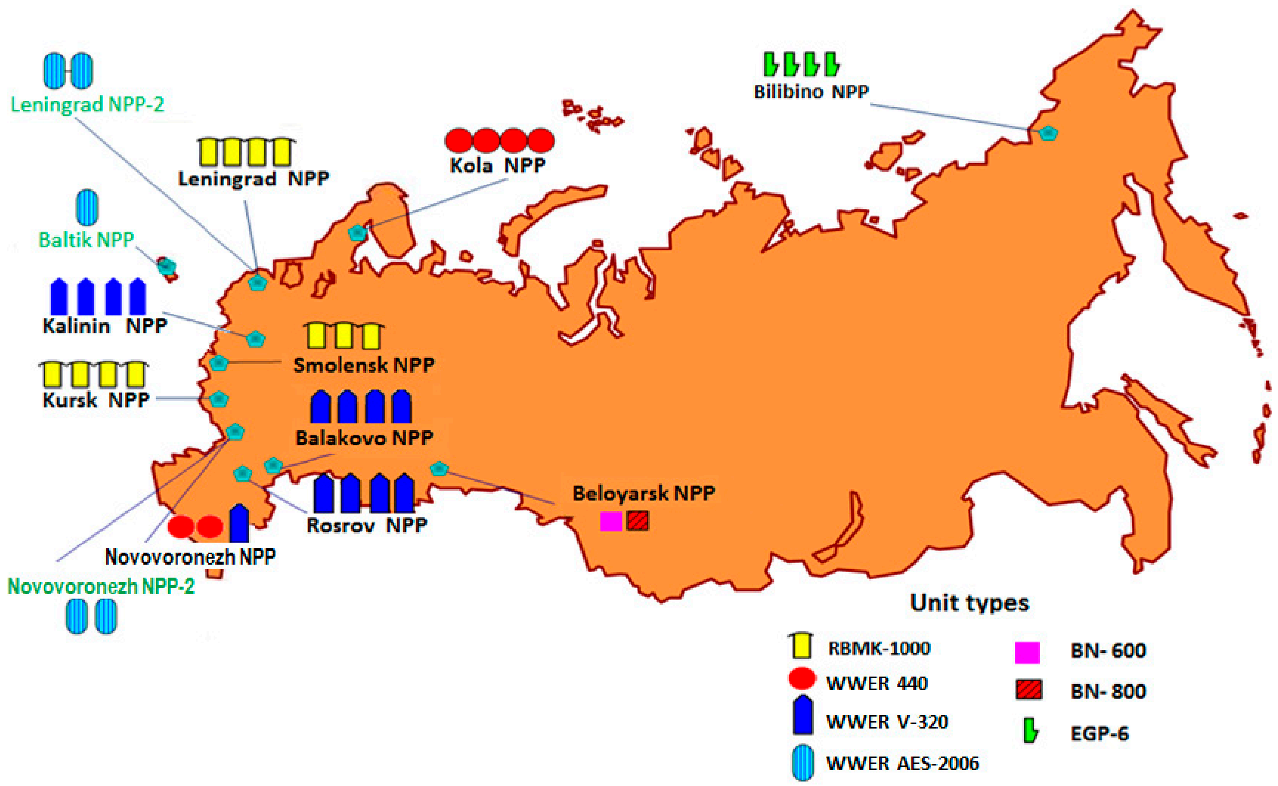

FIG. III–4. Operational nuclear power plants and those under construction in the Russian Federation as of 2014. NPP — nuclear power plant.

III−8.2. Flexible nuclear capabilities

Nuclear generating units in the Russian Federation (and in the former Soviet Union) have operated in baseload mode since the beginning, as the share of nuclear power in the UPS of the Russian Federation grid system did not exceed 18% in its Russian portion. In such a mode, the power units (reactors) mainly operate at constant levels of full capacity. Limited load changes are permitted, such as transition to the other steady level or unloading for some time (hours) with subsequent restoration of the full RTP [III−19]. It should be also noted that in 1998, a series of tests was carried out at the Zaporozhskaya nuclear power plant, a WWER-1000, to explore daily load following operation of plants with WWER reactors.

As per design, all the WWER type nuclear power plants that are either operational (WWER-440 and WWER-1000) or under construction (WWER-1200 and WWER-TOI) have the capacity to provide various degrees of flexible operation. However, the designs have operational algorithms that are optimized for baseload operation. Furthermore, the equipment and systems are designed for operations with capacity flexible regulation modes 100−50−100% RTP in WWER-TOI and 100−80−100% RTP in NPP-2006 designs. System requirements for rated primary and automatic secondary regulation typically are:

- Automatic change of the generating unit power when the frequency changes (providing the primary control capacity required) for the actual period of time with:
  - Requirements on the dynamics of load changing at a spasmodic frequency deviation;
  - Continuous changes of the given primary capacity when the frequency goes outside a dead band of primary frequency regulation (the load following mode of primary frequency regulation).
- Regulation of the turbine rotation frequency (the proportional channel) and load regulation with frequency correction on the speed of rotation of the turbine rotor (the central channel) without restriction.

Table III–8 provides details of flexible operation capabilities of WWER-TOI and NPP-2006 designs. Additionally, the nuclear power plants are designed for the following commands from the systems and components of the emergency control system:

- Impulse turbine unloading with the speed of capacity dumping not to exceed 2000 MW/s and any depth of unloading up to 100% of the rated capacity;
- Long turbine unloading on a ‘fast loop’ (used together with impulse unloading) with the subsequent restriction of the plant load at any load level in the range 30−100% REO;
- Long turbine unloading on a ‘slow loop’ with a speed of 25 MW/s from any initial load less than 50% REO (not to exceed the minimum power limit provided by safety analysis);
- Generator shutdown (dumping of loading down to the house load).

III−8.3. Need for flexible operation

In the mid-2000s, the grid system operator of the Russian Federation started asking nuclear power plants to ensure modes of frequency regulation and load following in the grid system as the share of nuclear generation increased [III−19]. Although the nuclear generation was only 16.5% of the total generation in the entire Russian Federation, the electricity from nuclear generation was supplying nearly one third (31.5%) of the UPS European region grid and approached 40% (37.1) in the UPS European region’s Centre subregion (Fig. III–5).

Participation in balancing by nuclear generating units was also agreed because:

- All new nuclear power plants to be placed in operation and all upgraded plants have to participate in the primary regulation of frequency in the grid.
- Plants with channel type reactors and with fast breeder reactors will not participate in operation with flexible modes.

The requirements contained in the European utility requirements for light water reactor nuclear power plants, as well as the Russian grid code, SO UPS, were considered for implementation in WWER type nuclear power plants for frequency regulation and load following (Table III–9).

TABLE III–8. EXISTING FLEXIBILITY CAPABILITIES IN RUSSIAN NUCLEAR POWER PLANT WWER-TOI AND NPP-2006 DESIGNS [III−19]

Balancing mode		Parameter	Technology	
			WWER-TOI	NPP-2006
Primary frequency control	Rated primary frequency regulation	Range of regulation of turbogenerator electrical capacity	±2% rated thermal power (RTP) with possibility of increase up to ±5% RTP	±2% RTP
		Number of cycles[a]	Maximum 7 × 10^6 in plant lifetime	
	Total primary frequency regulation	Range of regulation of turbogenerator electrical capacity	+2% RTP to −8% RTP with possibility of increase up to range of +5% RTP to −8% RTP	+2% RTP to −8% RTP
		Number of cycles[a]	Not more than once in a 6 hour period and not more than 20 per year	
Secondary frequency control		Range of regulation of turbogenerator electrical capacity	±5% RTP with possibility of increase up to ±5% RTP[b]	—
		Maximum speed of change of the turbogenerator electrical capacity	Loading: 1% RTP/min Unloading: 3% RTP/min[c]	—
		Number of cycles[a]	Maximum 5 × 10^6 in plant lifetime	—
Daily load following		Range of change of turbogenerator electrical capacity	100–50–100% RTP	100–80–100% RTP
		Speed of change of the turbogenerator electrical capacity	Loading: 1% RTP/min Unloading: 3% RTP/min[c]	Loading: 0.2% RTP/min Unloading: 3% RTP/min[c]
		Number of cycles[a]	Total 200 per year Total 15 000 in plant life Not more than 2 per day	The nuclear power plant is intended for operation in baseload mode, with limited electrical demand changes

[a] ‘Cycle’ means the change of electric output of a turbogenerator with dynamics of the corresponding mode and return to the initial level.
[b] Decrease of electric capacity of a turbogenerator for not more than 10% rated electrical output, increase of electric power of a turbogenerator at the rate depending on current state of the reactor and control resources, but not more than 10% rated electrical output.
[c] Technical safety limit and the technical specifications for the fuel.
—: no data available.

To expand the flexibility capacity to meet or exceed the latest requirements, the designer, Rosenergoatom Concern JSC, started research and development on optimizing operations with extended flexibility at nuclear power plants with WWER technology. The target parameters in defining the limits of range of plant flexibility

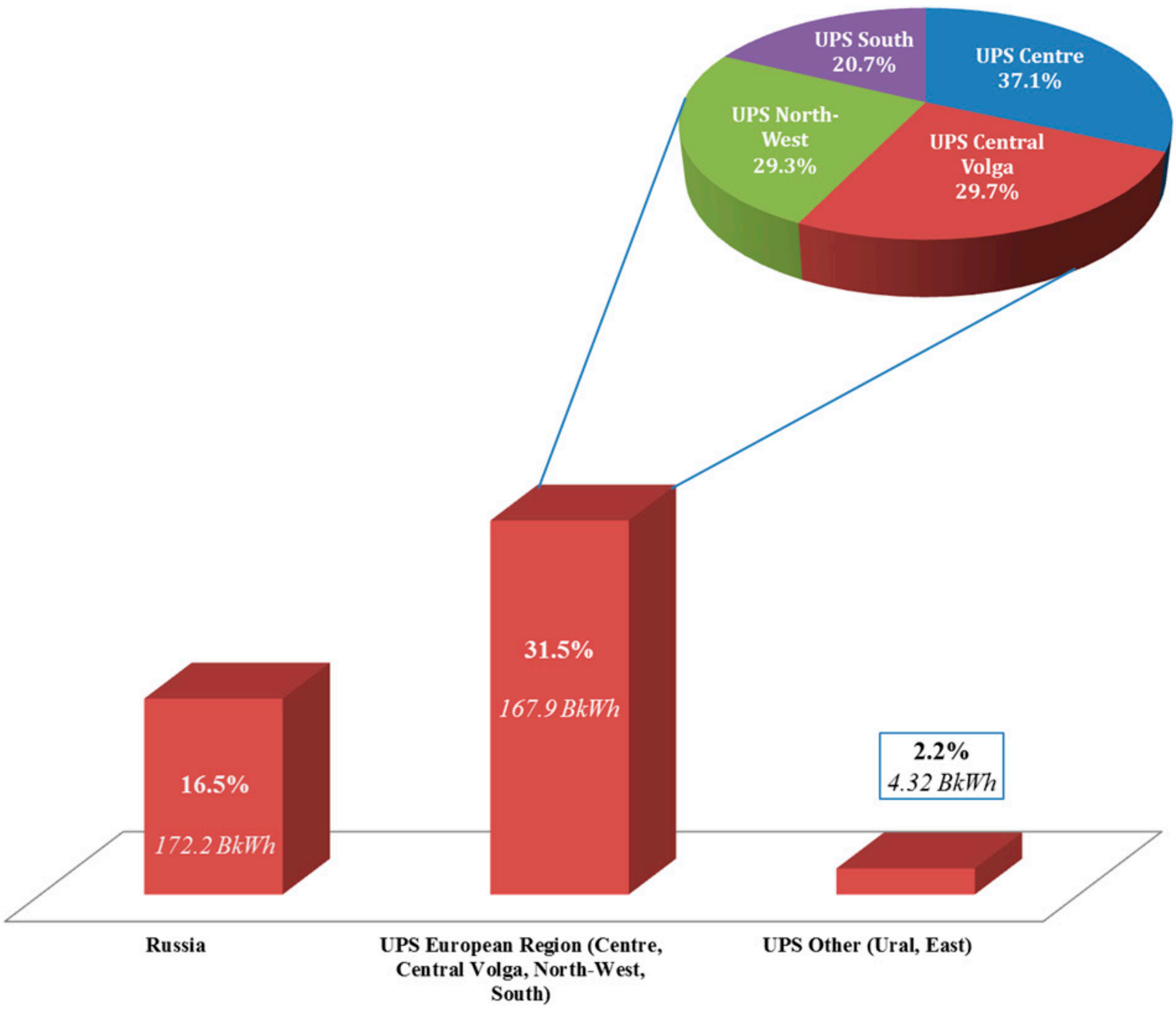

FIG. III–5. Share of nuclear generation by the unified power system (UPS) grid regions in 2013.

TABLE III–9. FLEXIBLE OPERATION REQUIREMENTS [III−19]

Balancing mode	Russian requirements (SO UPS)	European utility requirements Revision D requirements
Primary regulation of frequency	Rated primary frequency regulation: ±5% rated electrical output (REO), time of reaching required power within 30 s while providing half of required power within 10 s Total primary frequency regulation: ±10% REO, time of reaching required power within 120 s while providing half of required power within 10 s	±3% REO (with possibility of increase up to ±5% REO), time of reaching required power within 30 s
Secondary regulation of frequency	±10% REO with a rate of 2% REO/min	±10% REO with a rate of 1–5% REO/min
Daily load follow	Rate is not defined Participation as needed	3% REO/min Participation as needed

characteristics were selected in accordance with the requirements of the Russian grid system code and the European utility requirements.

III–9. UNITED KINGDOM

All of the nuclear power plants in the UK have been built within Great Britain (England, Scotland and Wales), with none in Northern Ireland. Apart from the one newest reactor, all these plants in Great Britain have gas cooled reactors and were built at a time when the power stations and grid system were owned and operated by state owned utilities. At that time, the percentage of nuclear generation in the system was not large, and the long term strategic plan was not to increase the capacity of nuclear generation to a level that would require limiting or reducing nuclear electricity output during the low demand summer period or providing frequency control. Consequently, the reactors were designed and built with the expectation of only baseload operation.

The percentage of nuclear generation has not increased in the past two decades. However, there has recently been rapid growth in generation from renewable energy sources, mainly from wind turbines and solar photovoltaic systems. There has also been growth from other forms of renewable energy or embedded generation, such as generation from landfill gas, domestic combined heat and power, tidal current turbines, etc., which can have variable output and cannot readily be controlled by the grid system operator. The growth in the capacity of such forms of generation is set to continue, thereby increasing pressure on conventional large generating units, including nuclear units, to be able to perform load following, and to provide frequency control and reserve.

Furthermore, modern large wind turbines and solar photovoltaic systems do not provide any inertia to the grid system. High voltage direct current connections also do not contribute any inertia, and several have been built between Great Britain and other networks. An increase in generation from such sources displaces generation from conventional turbogenerators that normally provide significant inertia. Consequently, the total system inertia in Great Britain has been reducing and is expected to reduce further. A consequence is that the rate of change of frequency following the trip of a large generating unit is increasing. It may be possible in future for wind turbines, high voltage direct current systems or battery systems to provide synthetic inertia, but to control the system frequency adequately, it may be necessary for more generating units, including nuclear units, to operate in automatic frequency control (AFC) mode or for generating units to respond quickly to changes in frequency.

In the UK, the electricity industry was deregulated and largely privatized in 1990. The technical rules in the deregulated market (codified in the grid code in Ref. [III–20]) were developed by the grid system operator, with the following points on flexible operation:

- A requirement was included for all generating units to have some capability for frequency control, although the amount of response was not specified initially.
- The capability for load following was assumed but not stated as a requirement.
- The existing gas cooled nuclear power plants were granted an exemption from the requirement to operate in AFC mode so there was no immediate change in their operating regime. However, the one plant with PWR technology, which was commissioned after the industry was deregulated, was required to demonstrate the ability to operate in AFC mode. As the magnitude of response required was not specified, it was possible to meet this requirement without great difficulty by demonstrating the capability to provide a small amount of response. In practice, this plant operator has not been asked to perform power reductions or provide frequency response.

As the amount of frequency response required was not specified at the time, many of the new power stations that were built soon after 1990 (mainly gas fired combined cycle gas turbines) were capable of much less response than most of the existing coal and oil fired power plants that they were gradually replacing. Consequently, the grid system operator needed to change the rules to specify a minimum capability requirement that was similar to what most of the existing coal and oil fired power plants could achieve. The requirement for all new large generators connecting now is to be able to change output by at least 10% of the rated output within 10 seconds in response to a large frequency deviation. To comply with this and all the other technical requirements in the grid code will be very challenging for a nuclear unit. No nuclear power plant has been built since the current rules have been in place, although several are planned or under construction. The future evolution of the rules is uncertain, as they may need to be modified to be compliant with the planned common set of rules within Europe (European Network of Transmission System Operators for Electricity).

The earliest reactors in Great Britain (Magnox design), which all ceased operation by the end of 2015, used natural uranium and had a small reactivity margin. Owing to this small reactivity margin, frequent power cycling (e.g. with a large drop in load at night-time) would not have been possible, because of the effect of xenon poisoning.

The second generation of reactors were advanced gas cooled reactors (AGRs), which are of several different designs unique to Great Britain. They used enriched uranium oxide fuel pellets in thin walled stainless steel cans, with a graphite moderator and CO_2 coolant. AGRs differ from water cooled reactors in that when changing the load, both the reactor coolant flow and the reactor outlet temperature are changed. To change the load, the operator would manually adjust the load change parameter, for example, the feed flow. The automatic control systems would then act to adjust the reactor gas flow and reactor gas outlet temperature to the new demanded values [III–21]. Some of the AGRs had control systems that, in principle, would allow load following or frequency control, but these control systems were never commissioned because they were not needed.

From the experience gained during operation, the AGR oxide pellets indicated cracks during normal operation, and it was found that frequent load changes led to increased fuel failures from pellet–cladding interaction (PCI). Additionally, in some designs, fast deloads can cause problems with the hot box dome at the top of the reactor. As a consequence, AGRs do not perform AFC operation or frequent load following.

Although the AGRs do not offer AFC operation or frequent load following, some of them are able to offer occasional load reductions or automatic tripping as an ancillary service for the grid system operator. Load reductions may be used if required by local transmission constraints, and automatic tripping might be used following a grid system fault during certain grid outage conditions. The number of load reductions or trips is limited for each reactor by the nuclear safety case for the reactor fuel. In practice, the grid system operator has rarely utilized these services.

III–10. UNITED STATES OF AMERICA

Nuclear power plants in the USA are operated as baseload units, with only a few exceptions. The reason for this is due to the high fixed capital costs and low fuel costs that make it the economically favourable choice for utilities to dispatch. Based on this long history of baseload operation, plant owners/operators have traditionally designed and implemented the fuel loadings and plant modifications based on a full cycle of 100% RTP operation. Load cycling (reduced load and extended time at reduced power operation) has typically been used, though infrequently and irregularly, in plants, either in response to plant issues or to extend the cycle owing to other generating units on the grid being unavailable for a certain period of time.

The US grid (and part of the Canadian grid) consists of three synchronous grids (interconnections) with eight North American Electric Reliability Corporation regions and multiple balancing authorities, referred to as independent system operators [III–22 to III–24].

Distribution of nuclear and other energy sources and the energy market structures differ among the regions, sometimes within each region and grid system balancing territory. Therefore, the flexibility reasons, needs and grid balancing may vary from region to region [III–25].

With the increasing capacity in wind, solar and hydroelectric power generation, production tax credits and a growing number of states requiring must take renewable energy, nuclear power plants are starting to encounter periods of zero or negative power prices if they are not able to reduce power when requested by the grid system operator(s). The situation with increasing wind generation, or large capacity of hydroelectric generation, exists on a seasonal basis in the Northwest region and areas of the Upper Midwest region of the USA. In several states, plant operators are in discussion with their grid system operators on the need for flexible operation due to must take renewable energy policies.

From the regulatory perspective, the nuclear regulatory body stipulates that only a licensed reactor operator can make changes in reactivity limiting load following operation to power changes being made by the nuclear power plant control room operator. Hence, the current experience within the USA is limited to seasonal preplanned power level changes at a few plants based on periods of high renewable or hydroelectric generation and low power demand. The plant with the most experience — although rather limited — with such power operation periods is the Columbia nuclear power plant, a BWR, in Washington State, where river flow management necessitates seasonal load following. There, the plant operators communicate frequently with the independent system operator and plan the power output schemes based on weather, flow of the Columbia River and forecasted load demands.

Looking towards the future, there will be further increased pressure for nuclear power plants to consider flexible operation, especially as older fossil fuel generating units are retired and further increases in renewable energy generation are planned and projected [III–25]. Investigative work has been initiated to support transitioning the US plants to FPO, as needed to support their regional grid needs and requirements. This investigation has included the collection of operating experiences from countries with flexible operation. A gap analysis [III−3] was developed by subject matter experts from the industry under the efforts initiated and carried out by the Electric Power Research Institute and the Institute of Nuclear Power Operations. Research and development have started to close the higher priority gaps in support of transitioning the US plants to flexible operation.

Specific to design and operation, capability and capacity for load cycling were included in the design of the majority of the US light water reactors, as a repeating power cycle on a daily basis, which consists of the following series of steps:

- A load increase from 50% RTP (or 15% RTP) to 100% RTP, with a maximum 5% RTP/min ramp rate;
- Steady state operation at 100% RTP for a period of time;
- A load decrease from 100% RTP to 50% RTP (or 15% RTP), with a maximum 5% RTP/min ramp rate;
- Steady state operation at 50% RTP (or 15% RTP), for a period of time.

As an example, in the Westinghouse and Combustion Engineering PWR fleet plants that replaced SGs or implemented power uprates, system and component design transients were developed and analysed. These efforts demonstrated that the load following capabilities in the original design were maintained and that the hardware continued to comply with applicable regulatory requirements and industry codes and standards, demonstrating that the load following manoeuvre has been, and continues to be, an integral part of the Westinghouse and Combustion Engineering nuclear steam supply system (NSSS) design bases.

During the initial design of the plants, it was believed that higher temperatures and higher power were limiting and, as a result, the design basis analyses for seismic, loss of coolant accident (LOCA) forces and LOCA short term mass/energy releases were performed at full power conditions. Performing the seismic, LOCA forces and LOCA short term mass–energy release analyses at full power conditions has been Westinghouse/Combustion Engineering practice, and the US Nuclear Regulatory Commission accepted this approach for the fleet dating back to the 1970s. As a result, the occurrence of design basis seismic and LOCA transients initiated during operation at reduced power plateaus does not appear to have been totally addressed in the design basis for components. In 2006, a notification, WEC Infogram 06-03, was issued to the Combustion Engineering and Westinghouse PWR fleet plants to specifically address operation at reduced power and the associated potential impacts of reduced hot leg temperature on LOCA forces, LOCA short term mass–energy releases and seismic analysis. The overall conclusion from that notification was as follows:

> "If Westinghouse and Combustion Engineering designed NSSS plants choose to operate for an extended period while at reduced power or zero power levels, the impact of reduced hot leg fluid temperature on LOCA blowdown forces and LOCA short term mass/energy releases will need to be re-evaluated. Additionally, for the Westinghouse NSSS plants, the component and hot leg piping support gap conditions will need to be addressed. A change in the physical gap between a component and its support, where it is currently assumed that the gap is essentially zero while at full power, could require that impact loadings be considered when analysing LOCA and seismic conditions. This would be a departure from the existing Westinghouse approach and could produce higher support loads than those currently calculated for the full power case. Westinghouse has informed utilities of the need to address the potentially higher LOCA blowdown forces and component and hot leg piping support gap conditions if they choose to operate for an extended period while at reduced power or zero power levels."

In addition, the designers of nuclear power plants have provided plant owners/operators with additional guidance and procedures to address the restrictions associated with extended low power operation, as well as guidelines concerning fuel conditioning and deconditioning. The fuel vendors have issued guidance regarding additional monitoring and limitations associated with power cycling operation and operation of the fuel at less than full power for periods that exceed two weeks, addressing fuel integrity, including the PCI, in addition to implementing advanced fuel designs. For example, Westinghouse issued an extended reduced power operation guideline providing information regarding additional monitoring and limitations associated with operation of the fuel at less than full power for periods that exceed two weeks for Westinghouse and Combustion Engineering designs utilizing Westinghouse designed fuel.

In summary, specific load following manoeuvres have been, and continue to be, an integral part of the US nuclear power plant design bases that could satisfy some grid needs for flexibility. The ability to satisfy US grid flexibility needs must address: (a) future energy generation and demand plans; (b) balancing and market structure within each North American Electric Reliability Corporation region; and (c) balancing authority responsibility areas among the grid interconnections. Based on the above being defined, flexibility needs can be compared against the existing plant flexibility capabilities that are needed for specific areas, and informed decisions can be made relative to the extent of plant modifications required, if any, to implement the ability of a plant to support flexible operation manoeuvres.

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Annex IV

ECONOMIC ASPECTS OF LOAD FOLLOWING IN FLEXIBLE OPERATION

IV–1. INTRODUCTION

To supplement this publication, the IAEA has prepared an economic study[1] to quantify the cost–revenue aspects for nuclear power plant operations in mixed energy systems, including flexible operation. The purpose of this study was to explore economic opportunities for using nuclear energy in future power markets with increasing deployment of renewable energy, specifically investigating the following:

— How much power ramping could future reactors support and at what penalty?
— What type of flexibility is required on the grid — larger down power and faster ramp rate for load following or increased start/stop capability? What is the optimal level of flexible capacity in a system?
— How can nuclear energy be used in different grid environments (e.g. different sizes or complexities) to cope with variable power demand and fluctuating supply from renewable energy sources?
— What are the economic implications (including different revenue streams) for using large reactors?
— How do market regulation and real market interaction affect the economic viability of using nuclear power under the various system modes?

To answer these questions, an analytical case study approach, which directly assesses the difference between energy specific production costs for a baseload nuclear system and a load following nuclear system, was selected. Such a study, based on a large scale country level power plant dispatching model, could assess the difference between the total short term costs of producing a given amount of electricity by both types of operation in a particular system. This approach may answer the questions of whether adding flexible nuclear operation to the power system is capable of generating overall system benefits by minimizing total system costs at different levels.

This annex briefly summarizes the IAEA study, together with insights from the available sources, and underlines the pressing needs in filling the missing knowledge gaps in the economic aspects of flexible operation. It does not provide specific details of the costs and benefits approach, which are to be published later.

IV–2. SELECTION OF CASE STUDY

Liberalized electricity markets remain a source of uncertainty and thus represent an important case for analysis of flexible operation. Based on a large scale country level power plant dispatching model, the IAEA study assessed the requirements for nuclear flexibility in the European Union up to 2050. The Member States of the European Union differ in terms of current and future renewable energy penetration rates, overall energy mix portfolios, grid interconnectivity levels, load profiles and sizes of the power markets. Therefore, liberalized electricity markets in the European Union represent an important case for analysis of flexible operation.

IV–3. METHODOLOGY AND KEY ASSUMPTIONS

The present analysis uses a complementary modelling approach: a dispatching model, which optimizes the operation of individual power generators in a given power system (in this case, the 28 European Union Member States), and an economic model, which builds upon the results retained from the dispatching model and assesses the profitability of nuclear power investments for a given set of key parameters associated with this power system.

[1] The IAEA expresses its appreciation for the generous contributions from R. Loisel, of the University of Nantes, and V. Alexeeva and D. Shropshire, of the IAEA.

As such, it relies on computer based model cases to simulate potential ‘value added’ effects from flexible nuclear operation up to 2050 in the European power system(s).

The main features of the dispatching and economic models can be summarized in a non-technical way as follows:

— The dispatching model minimizes total annual variable costs — defined as a sum of fuel costs, operation and maintenance (O&M) costs, costs of importing electricity and carbon prices for all operating power generators in the given energy system — whereas major generator types are mapped together into 12 representative technologies.
— For a given amount of installed generation capacity, the dispatching model determines the most cost efficient combination of existing technologies that meets the demand under the system constraints. The selection of technologies is based on a merit order principle applied to variable costs.
— The energy system is described at the country level on an hourly basis over 1 year. The load factors and total energy system costs from the dispatching model are fed into the economic module. The latter calculates the revenue streams, the profitability (expressed as the net present value indicator) and the levelized cost of electricity for a number of scenarios.
— Two sets of assumptions are used to calibrate the model to the target year, 2050:
  • First, major assumptions on energy scenarios at the country level rely on projected trends of energy, transport and greenhouse gas emissions up to the year 2050 [IV–1] — including, but not restricted to, the installed capacities per technology (nuclear, coal, gas, wind, solar, etc.), fuel costs, CO_2 constraints and prices. Assumptions on the degree of interconnection between neighbouring countries (defined as the grid capacity over the installed electricity production capacity) are derived from Refs [IV–2, IV–3] (see Box IV–1).

Box IV–1. The European Union’s energy infrastructure policy and interconnection challenge.

The lack of investment in energy infrastructure, including missing interconnections among Member States, is an obstacle to ensuring affordable, secure and sustainable energy across the European Union. The European Commission therefore adopted a framework strategy, the European Union Package, to ensure full integration of the internal electricity market through adequate levels of interconnection. By 2020, all Member States should have an interconnection capacity of at least 10% of the installed electricity production capacity in place. As proposed by the European Commission, this target has to be extended to 15% by 2030 [IV–2].

The European Climate Foundation estimates additional grid expansion requirements in the European Union to be around 87 GW by 2050, an increase of 160% in comparison to 2010 levels [IV–3]. Hence, the completion of the internal electricity markets with more cross-border exchanges might require a stepping up of current European Union efforts in the longer term, while at least partially isolated national electricity systems might coexist even beyond the 2050 horizon.

  • Second, assumptions on the economic characteristics of different technologies, such as overnight investment costs, O&M costs, etc., are taken from a variety of sources.
— Key technology related constraints are made as follows:
  • Following Ref. [IV–4], the ramping rates selected are ±14% rated thermal power (RTP)/h for coal fired plants and ±50% RTP/h for combined heat and power, biomass and combined cycle gas turbines.
  • Half of the nuclear fleet is assumed to be fully flexible by 2050. All other technologies are considered to be flexible.
  • The maximum transient budget puts an upper limit on the number of cycles with amplitudes of 10%, 20%, 40% and 60% of RTP that can be performed by a flexible nuclear plant within a given licensing period. In the study, typical values used in the design of a typical nuclear technology [IV–5] are assumed (Table IV–1). Each cycle type induces an associated fatigue category and thus affects the reactor lifetime.

This transient budget is reflected in the number of annual cycles. The maximum transient budget, together with the simulated number and deepness of cycles, based on the European Union average for 2050, is used in the model. The same transient budget of upward and downward power generation variation has been applied to all flexible nuclear reactors.

TABLE IV–1. ASSUMED MAXIMUM TRANSIENT BUDGETS FOR THE LIFETIMES OF NUCLEAR REACTORS [IV–5]

Load cycle (% power range)	Number of cycles
100–90–100	100 000
100–80–100	100 000
100–60–100	15 000
100–40–100	12 000

- Minimum operational loads for nuclear power are set at 40% of the nominal capacity to avoid low secondary system efficiency rates and potential ancillary disturbances, which can occur during operation or maintenance phases. For combined heat and power plants, the minimum operation constraint is set at 10%. All other technologies are not bound by minimum operational loads.
- Maximum load factors represent the maximum use of a technology. The assumptions are largely derived from Ref. [IV–6].

IV–4. KEY FINDINGS

The following are the main findings of the simulations performed in this pilot IAEA study:

— Integration of renewable energy sources is not the only thing driving the provision of flexible nuclear operation. The effects of a lower degree of interconnection and an inflexible generation mix are also drivers. For example, in a particular region, lower degrees of interconnection may put additional pressure on the domestic generation fleet, including nuclear generating units, to provide flexibility services. In others, additional pressure for provision of flexibility services comes from an inflexible energy generation mix.
— Even with flexible nuclear operation, flexibility needs may not be resolved in some regions.
— A shortened lifetime of flexible reactors is possible, if no constraints are put in place on the extent of load following (periodicity, length and depth of power cycles). The extent of load following will vary significantly among regions, resulting in different impacts on nuclear power plant lifetime. For example, in a particular region or Member State, requested load following schemes particularly affect fatigue of plant systems, structures and components, resulting in more life limiting cases.
— In most cases, flexible operation is likely to decrease the load factor if the share of renewable energy is high and generate less payment for energy delivered when operating at reduced power.
— Revenue impacts from flexible operation need to be understood in detail, as revenue is dependent upon specific market arrangements or volatile electricity prices. In the absence of specific market arrangements for flexibility services, it is likely that the revenues of plant owners/operators will decrease in comparison to the baseload mode, driven mainly by the decrease in load factors of flexibly operated plants.

IV–4.1. Renewable energy sources

In the model simulation, increasing penetration of intermittent renewable energy sources introduces additional requirements for balancing outputs. The more intermittency that is put in place, the larger the demand for flexibility.

However, integration of renewable energy sources is not the only reason driving the provision of flexible nuclear operation in the European Union by 2050:

- In some parts of the European Union, lower degrees of interconnection put additional pressure on national generation fleets, including nuclear generating units, to provide flexibility. In energy systems with low and medium degrees of interconnection, the need for flexibility can be rather high. The latter implies that flexible operation is used as a substitute for establishing or upgrading interconnecting links among neighbouring countries.
- In some other European Union Member States, additional pressure for provision of flexibility comes from an inflexible generation mix.

IV–4.2. Regions

The question of how much flexibility is needed in an energy system is central in the economic evaluation of load following. The model results report a rather heterogeneous picture from low to very high additional flexibility requirements at the country level by 2050. In some regions, the model shows that flexible nuclear generation cannot provide all the flexibility needed — under the assumptions made above.

IV–4.3. Plant life

At the energy system level, the interplay of driving forces behind flexible operation needs determines how often (i.e. number of cycles) and with what intensity (i.e. depth of cycles) nuclear power plants will be called upon to provide flexible services by 2050. In the model, the highest requirements for flexible nuclear generation are in regions with high shares of nuclear and renewable energy capacities, as well as with low and medium degrees of interconnection. It should be noted that the applied model does not determine the optimal level of provision of flexibility services for plants. It optimizes the operation of plant interaction with other technologies depending on the energy system needs. Therefore, moments of excessive cycling of flexible nuclear power can be observed in the model for 2050, if no constraints are put in place, as given in Table IV–2. This is reflected in a number of cycles higher than allowed by the licence on a yearly basis, additional plant fatigue and shorter lifetimes of reactors as a consequence.

TABLE IV–2. MAXIMUM TRANSIENT BUDGETS AND REQUESTED FLEXIBILITY (EUROPEAN UNION AVERAGE) FOR 2050 IN THE IAEA STUDY

Load cycle depth (% rated thermal power/rated electrical output)	10	20	40	60
Annual budget of load cycles	1667	1667	250	200
Simulated number of load cycles	57	63	86	259

The same transient budget of upward and downward power generation variation has been applied to all flexible nuclear reactors. But, depending on the system flexibility needs, the cycling type — and hence the potential reduction in a component lifetime — varies significantly across regions. The nuclear fleet in some parts of the European Union is requested to provide deep short cycles, while others might deplete the yearly transient budget with light frequent cycles to match the residual load. In still other countries, the budget is well balanced across all cycle types: the simulated number of cycles does not exceed the licensed design.

It can be concluded that both investors and plant operators need to anticipate the load following pattern and its potential effect on life cycle costs (i.e. increased capital equipment and maintenance expenditures for component upgrades, equipment life reductions and potential deratings due to equipment degradation) and the levelized cost of electricity. A formal method can be used to determine the optimal level in flexibility provision for nuclear generation, if the market is likely to request a significant amount of flexibility services.

IV–4.4. Load factors

It is well known that high load factors are important for nuclear generating units in spreading fixed O&M costs over a higher output, resulting in lower generation costs per kilowatt-hour. High load factors are also essential to pay back the investment cost inherent in nuclear generation. Potential reduction of a load factor would result in increased generation costs, as fixed costs have to be spread over the lower output level.

In the model simulation, the load factors of the nuclear fleet across the European Union Member States decrease in 2050 by up to 10% in comparison to baseload operation. This represents a significant impact, putting the profitability at risk, though at a lower rate than that given in Ref. [IV–7]. In one region, load factors increase in load following mode in comparison to baseload operation in 2050. Against the background of increasing renewable energy penetration rate, the load factor in 2050 might be significantly lower than it is currently, at least in some regions. Flexible operation could then potentially offer the possibility to increase the load factors against the 2050 levels. The latter, however, is a possible outcome only under very specific conditions.[2] In most cases, flexible operation is likely to decrease the load factor and generate less payment for energy delivered when operating at reduced power.

IV–4.5. Prices and revenues

In the absence of specific market arrangements for flexibility services, it is likely that revenues of nuclear power plant owners/operators will decrease in comparison to the baseload mode, driven mainly by the decrease of load factors of flexibly operated plants, as discussed earlier.

As the model results suggest, however, this is not the only possible outcome, even if there is no payment for flexibility. It should be noted, once again, that individual generating plants interact with each other and with a broad variety of other economic agents through the electricity grid and the market. If, due to provision of flexibility services, the position of certain energy technologies in the merit order curve is modified, spot market price changes are possible. Indeed, in some regions, the model determines the new spot price, which can at least partly offset adverse impacts on revenues from decreased load factors. This obviously depends substantially on the market power of nuclear operators.

With the flexible mode of operation, high volatility in revenue streams is also likely, in particular, if load factors and spot prices vary significantly over time. In contrast, baseload operation assures rather stable revenue streams. With volatile prices, recovering the investment costs will also become more difficult. Obviously, less profitability at a lower load factor reduces investor interest in flexible capacity additions by reducing incentives. The result is underinvestment in dispatchable technologies, including those of nuclear energy.

IV–5. ADDITIONAL CONSIDERATIONS

Increased flexibility of baseload generation will require new regulatory practices to allocate recovery of the additional capital cost among intermittent generating units and to compensate for sufficient capacity for balancing supply and demand in the face of uncertainty. Various policy options, such as capacity markets, capacity payments or reliability options to support the availability of flexible capacity need further discussion, as applicable to specific regions and markets.

The model calculations presented above raise the question of how to adequately reward baseload units for provision of flexibility services. This payment depends on the market arrangements and should provide enough incentives to allocate additional short and long term costs associated with flexible operation.

It should be acknowledged that the insights presented and discussed in this section need to be seen in the context of the tools and methods used to derive them. This is particularly true for quantitative estimation of potential effects resulting from flexible operation at the grid level, which is subject to a number of assumptions.

The development of energy markets in general and the role that nuclear power can potentially play in the future energy mix — particularly in the selected case study of the European Union energy mix up to the year 2050 — are subject to multiple uncertainties. Obviously, individual assumptions and methodological conventions can

[2] For regions that have both a high share of nuclear generation and large contributions from renewable energy sources.

be challenged by exploring alternative expectations about the future. As such, they should not be mistaken for an official IAEA position. Instead, key assumptions, modelling tools, sensitivity evaluations and study limitations serve the sole purpose of developing a reasonable base case study analysis and encouraging further discussion and work on the subject.

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GLOSSARY

ancillary service. A service that may be provided by generating units to assist control of a grid system. Ancillary services can include: provision of reactive power and control of system voltage; automatic frequency and generation control; load following; provision of spinning reserve, standing reserve and black start capabilities; grid loss compensation; and emergency control actions. In electricity systems that have been deregulated, there would normally be a payment to generators for providing ancillary services.

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

automatic frequency control/automatic frequency responsive operation. A method of operating a generating unit at less than full output, under automatic control, so that its output increases automatically if the system frequency falls, and decreases automatically if the system frequency rises.

automatic generation control. A method of operating a generating unit so that its output can be changed automatically in response to a signal from the grid system operator's control centre, without requiring actions by the operators at the power plant.

balancing mechanisms. The totality of means and processes to ensure continuous balancing of electricity generation and demand in real time. The means may differ from one Member State, or region, to another based on electricity market type, rules or techniques. In deregulated markets, for example, the balancing mechanism is based mainly on market rules, i.e. by bids and offers to increase/decrease generation or demand or to provide automatic frequency control.

balancing service. All actions and processes, on all timescales, through which grid system operators continuously ensure and maintain the system frequency within a predefined range.

baseload operation. Operation of a power station or generating unit at steady full load as far as possible, and not load following or providing automatic frequency control.

design basis accident. Accident conditions against which a nuclear power plant 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 minimum operating level/design minimum load point. The electrical output below which a generating unit has no high frequency response capability; below this level, the generating unit is not able to make a rapid reduction in output when in automatic frequency control mode, in response to a grid event of high system frequency.

dispatch. The issuing of instructions or signals by the grid control centre to generating units to increase or decrease electrical output.

dispatchable generating unit. A generating unit that is able to receive and act on instructions or signals from the grid control centre to adjust its output. (Grid control centres do not generally have a means of communicating with small generating units that are connected to low voltage distribution networks; hence such units are non-dispatchable.)

frequency containment reserve (primary reserve). Reserve for continuously stabilizing the system frequency in case of an imbalance. Such a reserve is normally provided by generating units operating in automatic frequency control mode, which are able to increase or decrease output automatically within a few seconds in response to changes in frequency. The magnitude of the frequency containment reserve is equal to the sum of the frequency response of all the generating units on the system.

frequency response. The magnitude of the change in generator electrical output power that can be achieved within a certain time in response to a change in system frequency.

frequency restoration reserve (secondary reserve). Operational reserve activated to restore the system frequency to the nominal frequency and, where applicable, the power balance to the scheduled value. Such a reserve is normally provided by generating units operating at part load that are able to respond within a few minutes to an instruction or signal from the grid control centre to increase or decrease output.

grid control centre. The control centre that provides high level control of the grid system. It issues instructions to generating units to increase or decrease output, or to shut down or start up in order to balance generation with load. It also issues instructions to operate in automatic frequency control mode. The control centre may also control the transmission system, switching circuits into or out of service as necessary. A large grid system may have several control centres.

grid system/electrical system. May refer to just the transmission system in a country, or in interconnected countries, or include the transmission and distribution systems.

grid system operator. In this publication, this term is used to refer to the company or organization that operates the grid control centre, and is responsible for issuing instructions to power plants to increase and decrease generation to match generation with demand and to control frequency. In some Member States, the grid system operator is the same company that owns and maintains the high voltage transmission system (transmission system operator), while in some other Member States, the grid system operator is a separate organization, termed an independent system operator.

house load operation. The ability of a nuclear reactor to remain at power (reactor critical) if there is an unplanned event that disconnects the nuclear power plant from the electrical grid. The reactor continues to provide electrical power to the house load (all the auxiliary electrical load of the plant), and the reactor control system reduces reactor power to allow stable operation in this low power condition.

load following. Varying the output of a generating unit in a planned way, or in response to an instruction or control signal from the grid control centre, reducing the output when the load (electrical demand) on the system is reduced (e.g. at night, at weekends and on public holidays) and increasing the output to maximum when the electrical demand is high.

load shedding. A rapid reduction in the electrical output of a generating unit, which could be triggered by tripping the unit, or by steam bypassing the turbine.

marginal cost. The additional cost per megawatt-hour of increasing the electrical output of a generating unit. For nuclear power plants or fossil fuel power plants, the cost is mainly that of the additional fuel consumed to generate the additional output.

minimum nuclear energy generation. The minimum level of generation that can be achieved without shutting down any of the nuclear units, i.e. reducing every nuclear unit to its minimum operating level.

normal operation. Operation of nuclear power plants within specified operational limits and conditions.

nuclear power plant owner/operating organization. The company or organization that is the operator of a nuclear power plant. This organization has the primary responsibility for the safe operation of the plant and will have to satisfy the requirements of the nuclear regulatory body in the country.

nuclear unit/nuclear generating unit. Comprises a nuclear reactor and all the auxiliary equipment (generator, transformers, motors, pumps, electrical supplies, protection systems, etc.) that is required for operation. A nuclear power plant may have one or more nuclear units.

operational limits and conditions. Rules setting parameters, the functional capability and the performance levels of equipment and personnel approved by the regulatory body for safe operation of an authorized facility. Also referred to as limiting conditions of operation.

reactive power. Product of the magnitude of the voltage and current and the sine of the phase angle between them, normally expressed in units of megavar, which can be positive or negative. The inductance of overhead lines and of the motor load within consumer demand is said to absorb reactive power, while the capacitance of underground cables is said to produce reactive power. Generating units and reactive compensation devices need to produce or absorb varying amounts of reactive power as necessary to balance this, which is important for controlling the voltage on the transmission system.

replacement reserve (tertiary reserve). Power reserve that is used to restore the required level of frequency restoration reserve to be prepared for a further system imbalance. This includes operating reserves with activation times up to hours, including generating units that can start up from a shutdown condition.

reserve. A reserve or operating reserve comprises the additional generating capacity that is available to the grid system operator within a defined interval of time. It includes the frequency containment reserve and the frequency restoration reserve, which are available within seconds or minutes, and replacement reserves, which are available on longer timescales. In some systems, controllable demand also contributes to operating reserves.

residual demand. The total electricity demand on an electricity system minus the generation from variable generation sources, such as wind turbines or solar photoelectric sources, which may have priority status, and from other generation sources that are not dispatchable. Residual demand is the demand met by large generating units, including nuclear power plants, which are subject to control by the grid system operator (i.e. dispatchable generating units).

safety case. A collection of arguments and evidence in support of the safety of a facility or activity. Normally includes the findings of a safety assessment and a statement of confidence in these findings.

spinning reserve. The unused but available generating capacity that can be activated on request from the grid system operator by the generating units that are already synchronized to the grid.

system frequency. The frequency of the alternating voltage on the system. In an interconnected system, the frequency is the same throughout the system at any instant in time. The nominal frequency in almost all countries is either 50 Hz or 60 Hz.

ABBREVIATIONS

3-D	three dimensional
AFC	automatic frequency control
AGC	automatic generation control
AGR	advanced gas cooled reactor
ALFC	advanced load follow control
AOO	anticipated operational occurrence
BOP	balance of plant
BWR	boiling water reactor
CANDU	Canadian deuterium–uranium
CRDM	control rod drive mechanism
CRDS	control rod drive system
CVCS	chemical and volume control system
DBA	design basis accident
DCS	digital control system
DNBR	departure from nucleate boiling ratio
EFOR	equivalent forced outage rate
FAC	flow accelerated corrosion
FCR	frequency containment reserve
FPO	flexible plant operation
FRR	frequency restoration reserve
I&C	instrumentation and control
LDC	load duration curve
LHGR	linear heat generation rate
LOCA	loss of coolant accident
NSSS	nuclear steam supply system

O&M	operation and maintenance
OA	overshoot allowance
OLC	operational limit and condition
PCI	pellet–cladding interaction
PCMI	pellet–cladding mechanical interaction
PWR	pressurized water reactor
RCP	reactor coolant pump
RCS	reactor coolant system
REO	rated electrical output
RTP	rated thermal power
SCC	stress corrosion cracking
SG	steam generator
SMR	small modular reactor
SPND	self-powered neutron detector
SSC	system, structure and component
TS	technical specification
TXS	TELEPERM XS
UPS	unified power system
V&V	verification and validation
WWER	water cooled water moderated energy reactor

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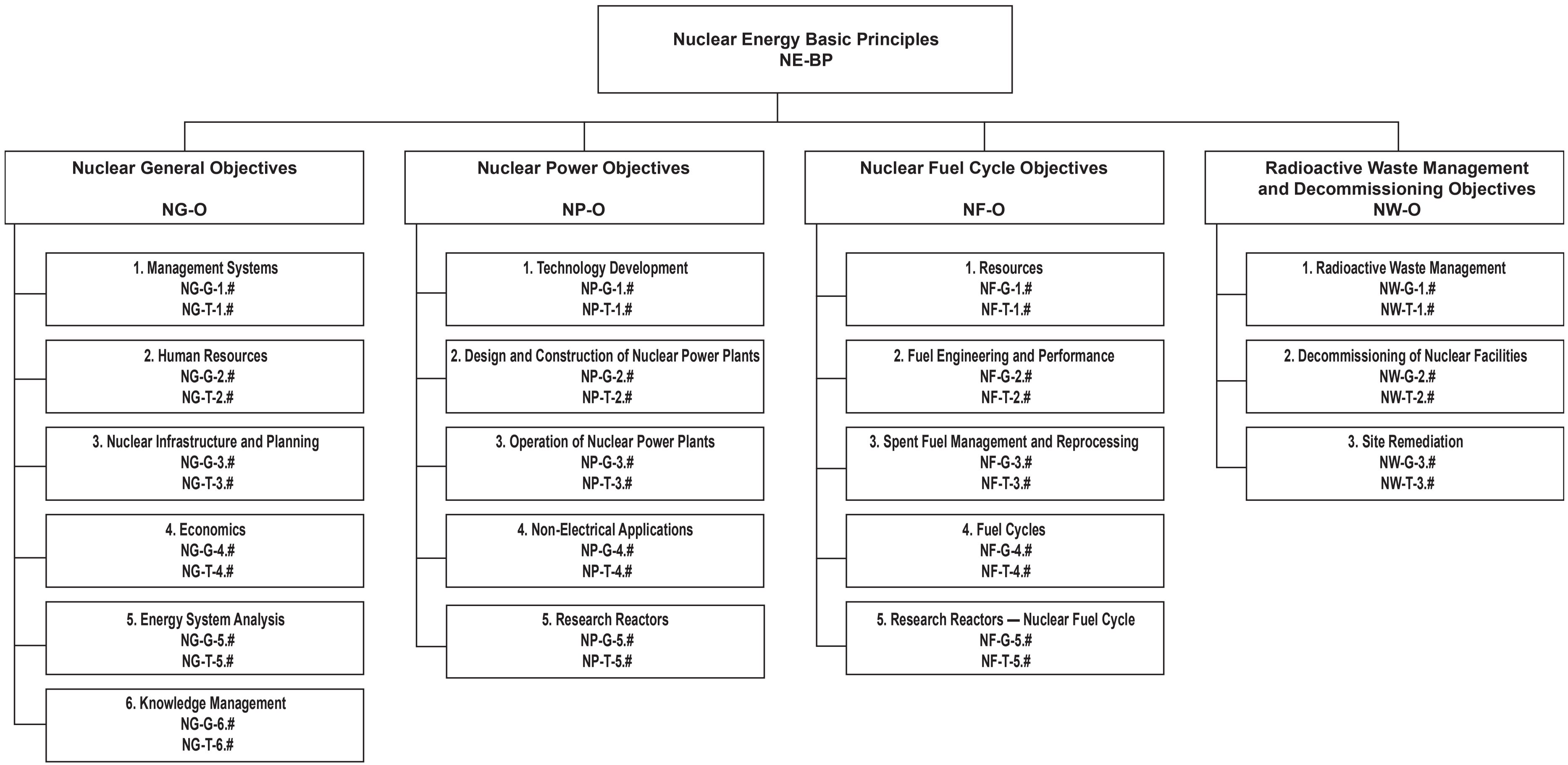

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