SURVEY ON OPERATIONAL EXPERIENCES OF NPPS IN A TRANSITIONING ENERGY SYSTEM GOING FROM BASE-LOAD TO FLEXIBLE OPERATION – GERMANY CASE STUDY

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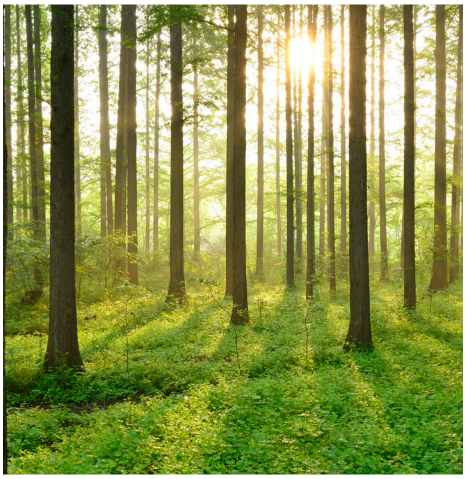

NUCLEAR

GRID INTERFERENCE ON NUCLEAR POWER PLANT OPERATIONS

Energiforsk

Survey on operational experiences of NPPs in a transitioning energy system going from baseload to flexible operation

– Germany case study

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Foreword

The research and development program GINO aim at gaining better understanding and ability to pro-actively minimize interference on nuclear power plant (NPP) operation due to factors relating to the external grid. Traditionally the role of nuclear power plants has been to supply base load to the power system. However, as the power system is changing with more unplannable power in the mix, there is a growing need and demand for flexible load.

In Germany this transition of the power system has been ongoing on a large scale for several years. With a decreasing amount of base load, it has been necessary to operate the remaining NPPs more flexibly than historically. This project has performed in-depth interviews with German utilities to gather the experiences of this transition. It covers impacts on the design as well as operational and organisational aspects.

The study was carried out by Tatiana Salnikova at Framatome. The GINO programme is a part of the Energiforsk nuclear portfolio, financed by Vattenfall, Uniper, Fortum, TVO, Skellefteå Kraft and Karlstads Energi. GINO has additional funding from SSM and SVK.

Sammanfattning

Denna rapport ger en kartläggning av drifterfarenheter för kärnkraftverk i ett energisystem som är i en övergångsperiod, där efterfrågan går från baslast till flexibel drift (FlexOp). Den är baserad på drifterfarenheter vid tyska tryckvattenreaktorer (PWR) och kokvattenreaktorer (BWR), insamlade av Framatome via fyra intervjuer med chefer på högre nivå, kunniga om FlexOp-strategin. Påverkan på kraftverkens design, drift och organisation samt motsvarande åtgärder för att förbättra flexibiliteten eller för att mildra påverkan sammanfattas. Nivån på den uppnådda flexibiliteten och vissa specifika egenskaper noterades också, mestadels fokuserade på att ändra den aktiva effekten. Nordiska kärnkraftverk skulle kunna dra nytta av denna information, och minimera möjliga risker när en sådan övergång krävs.

"Inbyggd" flexibel kapacitet hos KWU-designade kärnkraftverk angavs vara en nyckelfaktor för FlexOp-kapaciteten hos de tyska kärnkraftverken. De analyserade erfarenheterna och genomförda intervjuerna visar att utvärderingar av anläggning för anläggning, tillsammans med kunskap från andra kärnkraftverk, gjorde det möjligt för kärnkraftverk att utveckla ett driftsomfång med minimal påverkan på anläggningen. PWRer utförde FlexOp-tjänster mestadels inom effektområdet för den konstanta genomsnittliga kyltemperaturen mellan 100 och 50 - 60 % av den elektriska effekten (Rated Electrical Output, REO). För BWR:er tillhandahölls flexibel drift för det mesta utan stavrörelser av de varvtalsstyrda interna recirkulationspumparna med en typisk minimal belastning på 70 % REO. Utbudet av de utförda tjänsterna har ökat avsevärt under det senaste decenniet. Med avseende på utförda moderniseringar var införandet av den digitala kontrollutrustningen (I&C) tillsammans med utförda optimeringar av reaktorkontroll m.h.a Advanced Load Following Control (ALFC) & prediktionsteknik det mest fördelaktiga i olika PWR. Riktlinjer för effektkontroll, bränslehanteringsstrategier och driftsprocedurer nämndes också under varje intervju för att vara viktiga med hänsyn till bränsleaspekter för alla kärnkraftverk. Tillsammans med lämpliga övervaknings- och underhållskoncept för de mest påverkade komponenterna och systemen anpassade till flexibilitetsnivån, stödde de en säker och pålitlig FlexOp. När det gäller kommunikationsregler noterades att kontinuerlig återkoppling mellan skiftpersonal och reaktorfysikavdelningen vara viktig för att mildra bränsleproblematik. För sådana ändamål användes härdövervaknings-, simulerings- och prediktionsverktyg för att stödja FlexOp. Dessutom ansågs en tydligt organiserad kommunikation mellan säljare (load dispacher) och anläggning vara viktig. Fjärrstyrning sägs vara fördelaktig, vilket ger säljare uppdaterad information för rimligt beslutsfattande (fjärrstyrning av aFRR tillhandahölls mestadels av alla kärnkraftverk). Utbildning i simulator och att kunna utesluta anläggningen från tillhandahållandet av nättjänster vid speciella tillfällen är också relevant med avseende på säkerhet och tillförlitlighet. För införandet av FlexOp rekommenderades det att börja med pilotdrift i ett givet FlexOp-läge och tillämpa den stegvisa metoden med avseende på effektområde

och hastighet. Även om baslastdrift angavs som bästa driftläge för anläggningen, kan drift i detta läge under en lång period leda till kärvning/nedsatt reglerbarhet i komponenter t.ex. reglerventiler i BWR. Bred kunskap om anläggningen under varierande driftförhållanden är mycket fördelaktigt med hänsyn till säkerheten. Anläggningens lönsamhet var alltid en huvudmotivation för den utökade flexibiliteten som skulle läggas till och tillhandahållas av kärnkraftverken. Dessutom kan nettovärdet av en flexibel anläggning vara högre, vilket bör beaktas under beslutsprocessen.

Summary

This report provides a survey on operational experiences of NPPs in a transitioning energy system going from baseload to flexible operation (FlexOp). It is based on the existing operational experience in German Pressurized Water Reactors (PWR) and Boiling Water Reactors (BWR), collected by Framatome via four interviews with high level management, knowledgeable on the FlexOp strategy. Impacts on the plant from a design, operational and organization point of view, as well as the corresponding measures to improve the flexibility or to mitigate impacts were summarized. The level of the performed flexibility and some specific features were noted as well, mostly focused on altering the active power. Nordic NPPs could benefit from this information, minimizing possible risks when such a transition is required.

"Built-in" flexible capability of KWU-designed NPPs was stated to be a key factor for FlexOp capabilities of the German NPPs. The analyzed experience and performed interviews show that plant by plant evaluations, together with knowledge from other NPPs, allowed NPPs to develop an operational envelope with minimal impact on the plant. PWRs performed FlexOp services mostly in the power range of the constant average cooling temperature between 100 and 50 - 60 % Rated Electrical Output (REO). For BWRs, flexible operation was mostly provided without rod movements by the speed controlled internal recirculation pumps with a typical minimal load of 70 % REO. Range of the overall performed services has significantly grown in the last decade. With respect to performed modernizations, introduction of digital I&C, together with performed optimizations of core control by Advanced Load Following Control (ALFC) & predictor technology, was the most beneficial in several PWRs. Power maneuvering guidelines, fuel management strategies and plant operational procedures were also mentioned during each interview. Together with appropriate monitoring and maintenance strategies for the most impacted components and systems adapted to the level of flexibility, they supported safe and reliable FlexOp. With respect to communication rules, continuous information feedback between shift personnel and the reactor physics department was noted to be important to mitigate fuel failures. For such purposes, core monitoring, simulation and prediction tools supported FlexOp. Furthermore, clearly organized communication between the load dispatcher and plant was recognized as important. Remote control is mentioned to be favorable, giving the load dispatcher up to date information for reasonable decision making (remote aFRR was provided mostly by all NPPs). Training on simulator and exclusion of the plant from the provision of grid services at each moment are also relevant with respect to safety and reliability. Pilot operation in single FlexOp mode was advised as a best start, followed by a step-wise approach with respect to power range and rate. Even though baseload operation was stated as the preferred operational mode for the plant, operation in this mode over a long period can lead to sticking effects in components e.g. control valves in BWR. Broad knowledge of the plant at variable

conditions is furthermore considered beneficial with respect to safety. The profitability of the plant was always a main motivation for the advanced flexibility to be added and performed by the NPPs. Additionally, the net value of a flexible plant could be higher, which should be taken into account during the decision making process.

Keywords

Flexible operation of NPPs, transfer from baseload to flexible operation, mitigation measures for negative impact, operational experience of German NPPs

Abbreviations

Term	Description
aFFR	Frequency Restoration Reserves with Automatic Activation
ALFC	Advanced Load Following Control
approx.	approximately
BWR	Boiling Water Reactor
COMSY	Condition Monitoring System
CRDM	Control Rod Drive Mechanism
CRDS	Control Rod Drive System
CT	Coolant Temperature
CVCS	Chemical and Volume Control System
ELPO	Extended Low Power Operation
ENBW	ENBW AG (power station operator)
FCR	Frequency Containment Reserve
FlexOp	Flexible Operation
FC	Frequency Control
FRR	Frequency Restoration Reserve
H2	Hydrogen
IAEA	International Atomic Energy Agency
KWU	Kraftwerk-Union (predecessor of Areva, Framatome GmbH)
LFO	Load Follow Operation
LF	Load Following
mFRR	Frequency Restoration Reserves with Manual Activation
MR	Minute Reserve
MPa	Mega-Pascal
MWel	Mega-Watt (electric)
NPP	Nuclear Power Plant
OEM	Original Equipment Manufacturer
PEL	Preussen Elektra
PFC	Primary Frequency Control
PCI	Pellet Cladding Interaction
PN	Nominal Power
PWR	Pressurized Water Reactor
RCC	Recirculation Control Curve
REO	Rated Electrical Output
RPV	Reactor Pressure Vessel
RTP	Rated Thermal Power
RWE	RWE AG (power station operator)
SFC	Secondary Frequency Control
VGB	German Association of Plant Operators

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1 Introduction

This report provides a survey of experiences of Nuclear Power Plants (NPPs) in a transitioning energy system going from baseload to flexible operation. It is based on the existing plant experience in Pressurized Water Reactors (PWR) and Boiling Water Reactor (BWR) collected via four interviews with high level management from German NPPs that have been or are still in operation and have about two decades experience of advanced flexibility each.

During the interviews, the main focus was to address possible impact for NPPs connected in a grid with a new mix of energy generation and to be able to identify suitable measures in nuclear operations to ensure safety and operability as well as enhancing capability in a more dynamic environment based on the realized optimization projects and their short-, mid- and long-term results.

This report is **mostly focused on altering the active power**, but some information on the performed level of voltage regulation by German NPPs and some constraints has been summarized in Appendix G as well. Nordic countries are also currently evaluating different types of flexible operation including load following and enhanced low power operation. The Swedish and Finnish nuclear fleet has operated in base load for more than 25 years. Today the integration of the intermittent renewable energy sources increases the need for flexibility. The COVID pandemic time demonstrated a strong need for some such mode. Indeed, such increased levels of flexibility may be required in the near future.

The Energiforsk GINO (Grid Interference on Nuclear Power Plant Operation) program supported the project through:

- Reference group with experts from the participating NPPs and representatives from transmission system operators and safety authorities. They supported by preparation of the detailed questionnaire, actively participated in the interviews and provided additional clarification of questions, providing also the required information from the Nordic plants. Furthermore, they reviewed the draft report.
- Steering group with experts from the participating NPPs and representatives from transmission system operators and safety authorities. They took strategic decisions and reviewed and approved the final version of the report.
- Energiforsk project leader who assisted in the administration of the project.

This project was performed by Framatome GmbH. Framatome’s team collected the operational experiences of KWU-built NPPs before the interview, moderated the interview and also added the aspects dealing with design of the plant and some particular Framatome solutions applied to the NPPs to optimize flexible operation with respect to profitability, reliability and safety of the interviewed NPPs. Employees of various departments have participated in this project as consultants to assist in illustrating possible countermeasures and their effectiveness e.g. project management, safety, I&C and fuel departments.

The interviewed persons from German NPPs represent mostly a high level management of the NPPs. The project was strongly supported by German Utilities like Preussen Elektra, represented by vice president Thomas Fuchs, providing information about German PWRs in the North and Carsten Müller, plant manager in the South of Germany. Also RWE, represented by the operational plant manager Gerhard Hackel and his team, kindly agreed to discuss BWR experiences. Vattenfall contributed to the project with Heiko Rades giving feedback from the north of Germany, which performed flexible operation in the past having e.g. remote secondary control performed in BWRs already for 20 years. Thomas Franke, former plant manager of PWR and deputy plant manager of BWR and today plant manager of Swiss GE-built BWR, gave support in e.g. comparing capabilities of PWRs and BWRs.

2 Background

2.1 INTRODUCTION

NPPs have traditionally been constructed for base load operation, meaning that NPPs are generating electricity at stable (nominal) load and other, more easily adjustable generating units, are regulating the Grid. However, the significant increase of electricity production of highly intermittent nature, like wind and solar, can cause a situation where non-baseload operation of NPPs becomes necessary.

To minimize the risk for deterioration and premature failures due to flexible operation, it is vital to have an understanding of what type of problems may occur and how it might affect the plant. Apart from understanding the potential problems, it is important to know how to avoid problems or mitigate them and what operational experience already exists. In this way, a safe and reliable Long Term Operation of the NPP can be assured.

The scope of the current report is focused on "Lessons learned" from plant design, operation and organizational aspects. In the next step the applicability to Nordic plants can be studied in detail.

The operational experience in different flexible modes of operation has already been increasing over the decades. The most extensive experience exists in France and Germany. As the BWR experience can be found only in Germany, it will be the first country to look at for the overall evaluation feedback. It also has to be mentioned that the level of the proactive monitoring in German plants is very high, so that some effects can already be noticed in the early stage.

To illustrate the flexible operation performance of German PWRs and BWRs, the annual production curves from year 2009, with strong impact of negative prices, is shown in Figure 1.

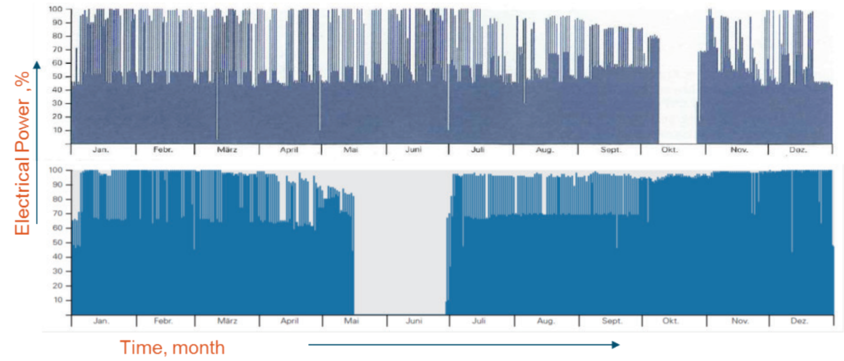

Figure 1: Electric output in % in 2009 of two German NPPs , PWR (top)/ BWR (bottom) (ATW, 2010), (Ludwig, H., Salnikova, T., & Waas, U., 2010).

Such curves include various types of grid services provided by NPPs. Thereby, the corresponding operational modes of the plant providing flexibility can be illustrated in a simple way, corresponding to the type of the grid requirement it is dealing with (see Figure 2). Voltage control is not included.

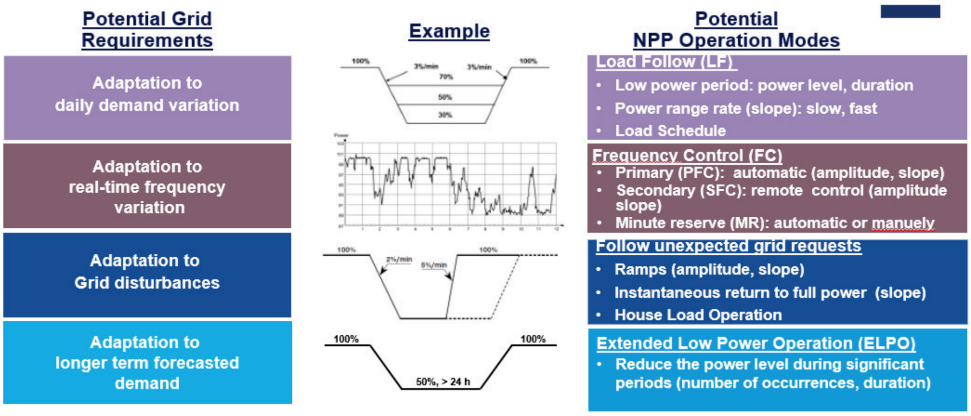

Figure 2: Flexible Operation modes from NPP point of view.

Detailed definitions for such modes and corresponding procured grid services, the way it is activated and the typical range for the plants providing flexibility in Germany can be found in Table 13 of the survey on power system ancillary services provided by NPPs (Hänninen, S., et al., 2020).

Various modes are often superposed and the plant operator, e.g. in case of remote controlled operation, can hardly differentiate between different ramping products, such as operating in secondary frequency control (SFC) and providing aFRR (automatic Frequency Restauration Reserve), minute reserve (MR) and providing mFRR (manual Frequency Restauration Reserve), load following (LF) mode used for economical dispatch or redispatch measures. In this case, remote secondary control is activated within a predefined power range and with defined allowable power ramp rates upwards and downwards, respectively.

In Table 1 the overall results from (Salnikova, T, et al., 2021) were simplified, giving an overview of the provided FlexOp modes and the corresponding provided ancillary services by interviewed NPPs in Germany.

Table 1: Classification of the flexible operation by NPPs incl. ancillary service products (Salnikova et al, 2021).

Plant mode/ Service	Aim	Time Frame for activation	Range	Typical values	Minimum power level
Primary frequency control/ FCR	Contain the frequency	up to 30 sec	from 2 % to 10 % REO	± 50 MWel	50% - 60% REO
Secondary frequency control/ aFRR and Minute reserve/ mFRR	Return frequency to nominal	up to 5 mins / up to 15 mins	Ramp rate 10 - 30 MWel/min	± 50 MWel / ± 150 MWel	50% - 60% REO
Load Following/ Redispatch measures	Economical dispatch or overload management	Corresponding to the ramp rate	Ramp rate 10 - 30 MWel/min	till 50 % - 60 % REO	50% - 60% REO
Extended Low Power Operation	Long time (> 12 h) demand variation	Corresponding to the ramp rate	can be slow	till 50 % - 60 % REO	Single example: till min. load 30-40 %

From this it can be noted that NPPs are trying to avoid FlexOp at low power levels, where the minimum power level for all services is defined at typically 50-60 % REO. For some BWRs it can even be stated that the minimum power level for frequently performed services is around 70 %. But operational history of the interviewed NPPs also shows depending on the grid situation operation for few hours/days or even for months at minimal load.

The term "FlexOp" will henceforth be used as a simplification for all ramping modes providing different services to the grid, except some cases where differentiation is required in the context.

3 Scope

The objective of this project has been to provide the stakeholders of the GINO program with a survey of relevant challenges in NPPs during a transition from base load to flexible operation through performed interviews with a number of plant operators and other individuals possessing such operational experience.

The long-term **focus** of this project is

- to address possible impact for NPPs connected in a grid with a new mix of energy generation
- to be able to identify suitable measures in nuclear operations to ensure safety and operability as well as enhancing capability in a more dynamic environment

The project team has performed four interviews overall, with high level plant management collecting practical information from ten German NPPs (PWRs and BWRs) in total, all of which have experienced a transfer from mostly base load to flexible operation in the past. Between interviewed NPPs, there are plants that have been performed flexibly in the past and are already shut down due to political phase-out from nuclear or were still operating in various flexible modes providing ancillary and balancing services at the time of the interview. Thereby, the corresponding FlexOp modes of the interviewed plants have been analyzed previously and were presented as an introduction to each particular interview. This gave the project team an introductory background to better understand the answers from the German utilities. The questions themselves were prepared beforehand by the GINO steering group and have been adapted as required during the interviews.

The main goal of the following report is to summarize the results of the performed interviews and to show qualitatively the key insights.

Overall, the achieved results are indicative and not directly applicable to business applications for Nordic plants due to the requirement of detailed case-by-case studies. Nevertheless, this generic work will be helpful to use the existing lessons learned and allow avoidance or to minimize the risk for the Nordic NPPs in a potential future where a higher level of flexibility is required.

4 Results

4.1 TRANSITION FROM BASELOAD TO FLEXIBLE MODE - GERMAN CASE

Appendices C-F present the results from each of the four performed interviews. The plant specific information for the first and the last section of the Appendices has been collected during a previous project (Salnikova, T., et al., 2021*)* and was partly discussed during the performed interviews, giving additional insights. This was important for better understanding of the answers to the prepared questions from the middle section. Some relevant information has been also added from (Hänninen, S., et al., 2020).

In the following subchapters, the answers to the main questions have been summarized.

4.1.1 Overall strategies

One of the important questions to be answered in the following subchapter is if operating in FlexOp modes *was a foreseen and planned evolution* or rather *a gradual adaptation due to necessity* for the German NPPs. The past two decades have showed NPPs applying both strategies.

On the one hand, the NPPs have been designed for flexible operation. Annex I of the IAEA document related to Non-baseload operation of NPPs (IAEA, 2018) related to German cases explains the introduction of the high level flexibility into the original design of both PWRs and BWRs by the planned high nuclear share in the overall German power mix. The accelerating factor of the nuclear program of that time was the oil price shock in 1973 and the nuclear share was planned to reach 69 % in the country's energy mix by 1985, comparable to today's France. So, as a result, NPPs of the predecessor company of today's Framatome GmbH, German KWU, had already been designed for enhanced flexible capability for load following, primary and secondary frequency control, minute reserve and with partial load capability in the 1980s. The design of the NPP even included more flexibility than was required by the German Grid Code at that time to make the plant design more attractive. Built-in flexible capability included ramp rates of up to 10 % REO and could be performed in the power range from 100% to minimum load. Such ramp rates have been verified during the commissioning phase of the plants, but for a long time these capabilities were only occasionally used to cope with grid-related events.

The strong need for frequent FlexOp has appeared in the last two decades in order to compensate for the rapidly increasing, yet fluctuating, power generated by renewable energy sources. Such developments have led to, among other things, the first modernization projects related to the improvement of the turbine instrumentation and control systems. It also has to be mentioned that, compared to the original design, in the subsequent operating time the plants were modified to some extent (e.g., enrichment increases, power uprates) and fuel management strategies were optimized for base-load operation. This generally resulted in the margins available for load cycling (intervals until power and power density limits are reached) becoming rather tighter. The margins have been partly increased again through improvements in fuel technology (e.g. transition to larger number of fuel rods per fuel assembly in BWRs), but improvements of the reactor control have also played an important role, especially in PWRs.

Since 2008, the German electricity market has allowed negative electricity prices. Overall energy and balancing market development has also led to new business cases for NPPs and the ranges for the various grid services to be performed by the plants were gradually increased. The highest levels within the given limits in all phases of the burn-up cycle were achieved by the PWRs that introduced Advanced Load Following Control (ALFC) as an upgrade of the TELEPERM-XS reactor control.

Furthermore, monitoring and maintenance concepts optimized beforehand for base-load operation were adapted to the performed flexible mode. The main goal was to thereby reach advanced flexibility without compromising safety and operability of the plant.

The real necessity for flexibility can be seen in the overall increase in the required flexibility from NPPs on hand of a single NPP in the south of Germany. As it was stated during the interview the overall amount of the provided Grid services increased by the factor of mostly seven during first decade following 2002.

The impact of fuel failures on available flexible operation ranges is also a necessary part to consider in the overall strategy. It is known that in such cases NPPs limit flexible operation to only urgent cases.

The level of the performed flexible operation can also be limited by the plant if the detection limit for fuel failures is reached. Such limit is influenced by the existing level of radiation in the systems and is dependent on the previous operational experience of the plant. Flexible operation level will be limited to avoid being unable to detect the new small failures.

During the interviews, one new interesting aspect was also mentioned with respect to flexible operation. Various flexible operation modes are on one hand more encouraging for the plant shift, whilst on the other hand providing the plant operator with overall additional knowledge about plant performance under various conditions and contributing in such way to the overall safety awareness.

By analyzing various kinds of performed grid services of the NPPs, a common optimized operational envelope for the German plants can be estimated as following:

- During flexible operation, various ramping modes are typically activated with a power ramp rate from 10 to 30 MWel per minute and in the range from full power to approximately 50 % of Rated Electrical Output (REO) in PWRs and 60 -70 % REO in BWRs in order to
- Keep dynamic effects within the plant reasonably small to reduce potential stress effects with long-term negative impact and potential control issues

- From an I&C point of view higher ramp rates, as well as a range from 100 % to minimum load, could be achieved if required. As an example, the commissioning test of ALFC was performed with 40 MWel per minute.

4.1.2 Key experience derived from transition phase

Most of the NPPs have stated the importance of collecting individual stepwise operational experience. The right optimization program can be best estimated based on pilot tests for various modes of flexible operation. As a starting point, evaluation of "pure" part load operation should be carried out at various power levels and then followed by load ramps and frequency control. They have also been sequentially added into German plants and the power ranges and ramp rates increased with time. Decision making has to be taken by evaluating the market opportunities and the additional flexibility costs on a plant by plant basis to find the optimum conditions.

Following this, advice was given on aspects that should warrant attention, mostly with respect to I&C, fuel and aging:

- I&C considerations
  - × Change to **digital I&C** should be considered. Among other advantages e.g. with respect to life-time, it allows for the application of advanced algorithms e.g. PWRs may apply Advanced Load Following Control (ALFC) to better deal with possible reactivity issues. BWRs have mentioned advantages of **digital I&C** as well, but has not modernized the I&C due to the phase out decision.
  - × **Control parameter settings** need to be adapted to get the formal qualification from the grid operator to provide services e.g. for FCR (mentioned by BWRs),
  - × **Xenon imbalances** have to be considered and **minimization of movements of control rods** is preferred to reduce load on fuel rods (mentioned by BWR)
  - × **Control and power electronics** evaluation has to be performed in advance within the new control requirements; robustness for the increased switching frequency has to be checked e.g. flexible operation experience showed that power contactors in defined control circuits had to be substituted in a shorter interval then before (mentioned by PWR)
- Fuel & Control rods
  - × **Fuel management** has to take into account the planned flexibility for the next cycle
    - – cycle adjustment of the reactivity inventory of the core to the expected loss of produced energy is required
  - × Proper strategy for **conditioning of the fuel** needs to be defined in advance.
    - – **Computer-based fuel conditioning program**, which is able to simulate all load situations in forecast, concerning xenon transients and fuel deconditioning is an important tool to be applied to ensure safe and reliable operation of NPP performing flexible operation. This program also needs to calculate holding times at different power levels to fulfill

fuel conditioning rate (FA) especially with respect to power increase (coming back to full power after the part load).
  - It has to be ensured that the required flexibility is included in the design of the applied fuel assemblies and the **conditioning rules.** The fuel elements of different suppliers have shown their capabilities on existing operational experience.
  - Based on the operational experience, it is recommended to develop a procedure which contains major boundary conditions and limitations, e.g. power ranges, ramp rates, area in power flow map, incl. corresponding simulator test program (BWRs, similar for PWRs)
  - Furthermore, various PWRs performing aFRR within a high power range have gone a step further by applying a fully **automated mode with fuel guidelines** and **flexible operation rules** implemented automatically in the control. NPPs stated that such further development will be helpful for both PWRs and BWRs in the future if the level of participation on the Grid services should become comparable to that of German PWRs.
- × The **control rods** have a limitation regarding hoop-strain due to swelling of absorber. Checking in advance is required, since the control rods are exposed to higher flux during power transients.
- × The **control rod drives** require fine motion control and robustness for a high number of movements. Coil measurements of the control rods have to be performed.

- Aging considerations & maintenance
  - × **Vibration phenomena** of the whole plant is an important parameter that has to be taken into account from the very beginning. It is valuable to have both vibration and corresponding plant operational data available to analyze the impact.
  - × Monitoring of the **fatigue usage factor** for the most impacted components is an important issue, having a strong impact on the flexible capability e.g. reducing of the ramp rate for the grid services, was decided to increase the life of the impacted components
  - × **Erosion monitoring** for both PWRs and BWRs plays an important role with respect to flexible operation
  - × Influence on **water chemistry** from part load and frequent load changes should be monitored e.g. for primary side chemistry: impact on Zinc-dosage (mentioned by BWR)[1] or Hydrogen injections by PWRs.
  - × Overall **maintenance strategy** was optimized for the whole plant for base-load conditions and has to be adapted to the planned flexible operation in advance. For the most impacted components, inspection and maintenance intervals had been reduced e.g. for full power feed water control valves or main steam control valves in the PWR with the highest level of flexibility. Also, a positive impact was noticed by some components performing low

[1]Zn is added in general in LWR either for dose-rate reduction purposes or mitigation of primary water stress corrosion cracking. Additionally, the existing material concept including Zinc-dosage was used for an optimized water chemistry, having a positive impact with respect to optimized crud formation on the fuel assembly surface and indirectly had an impact for further plant flexibility (feedback from two BWRs).

level of flexibility as they were kept in motion e.g. for control valves in BWR.

4.2 KEY PLANT DESIGN ASPECTS & REQUIRED MODERNIZATIONS INCL. STUDIES

4.2.1 Key plant design aspects

Flexibility of the German power plants has been reached to a very high level thanks to important design characteristics presented e.g. in (Ludwig, H, et al., 2010). These are:

- a part-load diagram with the constant average temperature of the coolant in the upper load region, which is frequently used for flexible operation
- control rod maneuvering program
- axial power distribution control with the goal to inhibit any axial power distribution oscillations (e.g. axial xenon oscillations), caused by power changes or by control rod movements.
- accurate, mostly real-time, in-core measurement of power distribution, achieving greater operating margins for load following and preventing Pellet Cladding Interaction (PCI)
- optimized Primary Coolant Management and Treatment

Regarding BWR, recirculation control and in-core measurements have to be mentioned in general.

In Appendix 1, power change description is given in a simplified way.

The number of the load cycles considered for the original design of the plant components was quite high. Table 2 shows an Example from PWR of Konvoi type. The design value of the ramp rate was up to 10 % REO / min between 100 % and 20 % REO and of the step change - 1 % REO/s.

Table 2: Number of load cycles considered for design

Load cycle [% REO]	Number
10 (step change)	100,000
100-80-100	100,000
100-60-100	15,000
100-40-100	12,000

At the time of successive transition to more flexible operation, as the overall need for the Grid services has started to increase, the number of the transients already performed by all German NPPs was rather small for all types of transients, so enough margins relating to the number of the load cycles considered in the design were still available.

The previous chapter mentioned various design-related aspects of high importance that were discussed during the interviews. Some additional ones are:

- Capability of the **reactivity control**:
  - × Dealing with imbalance of xenon content after power changes is one of the main control issues.
  - × Water treatment capabilities (Boric acid management and recovery as well as Deionat production) is one of the limitation and cost factors (for PWRs)
  - × Frequent power control was performed by the speed controlled recirculation pumps in the range between 60 and 100 % without disturbing local core power distribution by movement of control rods (for BWRs)
- The **design of piping** with respect to thermal stratification, **nozzles** and **heat exchangers** should be robust enough for temperature transients.
- Critical components for thermal **fatigue** need to be identified and require thermal **monitoring.**

  Some components have experienced increased wear and tear e.g. in the case of movement of valves or during flexible operating conditions of the electrical generator. Impacts on the main generator are depending on local grid conditions and special characteristics of the generation. Impact from voltage regulation can be found in Appendix G. This should be reflected in the design and/or monitoring and/or maintenance concept.

- Other important features with respect to plant flexibility are:
  - × **Balance of water chemistry** (specific parameters) and appropriate monitoring program especially for PWRs e.g. B-Li coordination or pH adjustment and ensuring reducing conditions (e.g. by Ammonia, Hydrazine, Ethanolamine, etc.) in primary or secondary side, respectively (Bolz et.al, 2013); German BWRs were operated with Normal Water Chemistry (NWC).
  - × Introduction of the **spray control valves** (continuously) in PWRs was mentioned as an advantage with respect to flexible operation

4.2.2 Performed modernizations incl. studies

Before the German NPP began with the advanced flexible operation, various feasibility studies had been carried out to evaluate the impact of flexible operation on I&C, NSSS and Fuel performance.

In 2010, a general study for all German PWR and BWR was performed by Framatome, taking into account the changes carried out within the life time of the plants that can be sensitive to the flexible operation mode compared to the designed conditions e.g. such as modern core optimization with respect to burn up and economy or power uprates.

As the next step, operational experience was collected including corresponding measured data leading to various plant specific detailed analyses. Items like power plant chemistry and lifetime of components were stated to be of particular importance. As a result, some operation mode optimizations and maintenance program improvements were proposed e.g. pressurizer set points.

Various operation modes have been analyzed e.g. part load operation with respect to:

- Flow Accelerated Corrosion analyses with COMSY-tool (Zander, A., 2005) for different part load levels to optimize the maintenance of the most impacted components (mentioned by PWRs)
- Vibration impact, analyzing available measured data and site walk downs performing various part levels
- Fatigue analyses of the most impacted components
- Corrosion products and impurities transport into steam generator

Over the last 30 years, Framatome has developed tools related to fatigue, flow-accelerated corrosion (FAC) and vibration phenomena. For example, fatigue-related new evaluation methods based on local temperature measurements and corresponding realistic loads are being implemented. In this way, fatigue margins can recover with respect to flexible operation as well as other new requirements such as Environmentally Assisted Fatigue (EAF)[2]. For some components, even the need for replacement could be waived. Proactive action is of great importance for safe and economic long term operation of any NPP taking into account flexible operation.

Main performed optimizations:

- The introductions of digital turbine I&C and later on reactor control had a strong positive impact on the advanced flexibility of the NPPs. This allowed the application of advanced algorithms. Power distribution control was improved with Advanced Load Following Control and automatic reactivity management was introduced in four KWU-build PWRs. This digital solution covers Xe-calculation, automated reactivity management and optimized axial power distribution control, which inhibits any axial oscillation of the axial power distribution in the beginning. It also allows, when required, the performing of flexible operation without manual intervention of the operator, corresponding to stochastic load changes (Kuhn, A. & Klaus, P., 2016). Such developments were originally started by Framatome to improve plant flexibility with respect to fuel loadings (low leakage configuration) and during the project the need for flexibility became present. One of the key success factors of this project was continuous involvement of the NPP incl. I&C and plant operator's feedback.
- Furthermore, another PWR was a realized pilot for ALFC with added predictor technology within I&C, including, among others features, visualization of the reactivity management (Kuhn, A. & Schirrmeister, K., 2018). Overall, thanks to ALFC, smoother operation also became possible with respect to FlexOp impact on systems and components. Later on, based on collected operating experience and the needs of ELPO, additional optimization strategies were included for part load operation. Today, Framatome is further developing

[2] The influence of a water environment on fatigue due to high temperature water exposure (i.e. the environmental assisted fatigue effect) may be higher than predicted under the rules and standards used in the design process of most nuclear plants. During the transition to flexible operation it could be an additional requirement similar to the applications for the new NPPs).

predictor technology for FlexOp as a separate expert system for each type of plant (e.g. Morokhovskyi, V., 2020).

- Adaptation of the pressurizer controls has been performed after the start of advanced flexible operation (PWRs)
- Based on operational experience, plants have developed overall rules/regulations for flexible operations, an operational handbook and organized the corresponding trainings e.g. documents such as "Guidelines for flexible operation and fuel reliability program" were mentioned that includes both planned and unplanned maneuvers.

4.3 KEY PLANT OPERATIONAL ASPECTS E.G. REQUIRED TESTS

From an operations point of view

- The plant shift has to be **well-trained at the simulator** at special requirements and faults, even if automatic mode is installed.
- **Exclusion** of the plant **from provision** of grid services has to be possible and performed without any difficulties if any doubt of any kind arises.

Performed Tests

- Flexible capability of German NPPs tested during the **commissioning phase** e.g. ramp rate of 10 % REO/min and also during part load operation
- **Commissioning tests** for the **new digital reactor control** incl. introduction of the **advanced load following control** and **predictor** were performed; Started by a test program **at a plant simulator** to be able to compare the simulated plant performance with the real one and to train the shift team (PWRs)
- All NPPs providing ancillary services have performed **prequalification tests** e.g. for PFC, aFRR, mFRR. Beforehand **on-site hardware-in-the-loop-tests** of the existing plant equipment, especially turbine controller has often been performed, using a real time digital plant and grid simulator.

4.4 KEY ORGANIZATIONAL ASPECTS INCL. COMMUNICATION ISSUES E.G. WITH GRID /LOAD DISPATCHER

Appendix B provides a summary of the existing flexible operation modes in German NPPs, with examples including communication aspects.

Following feedback was given during the performed interviews:

- **Continuous information feedback** between **shift personnel and reactor physics** is of a large importance to mitigate fuel failure
- There is a high importance placed upon the **proper communication** between **load dispatcher and NPP**. There should be a **clear** method of communication and should be **tested often** to avoid misunderstandings.
- In principle, the following **methods of communication** and control are possible:
    - × Shift operator activates primary control on request for the planned range → power controller adapts power automatically

  - Shift operator activates the possibility for plant control in a certain power range and with the pre-defined ramp rate (secondary control) → load dispatcher can set plant power level within the allowed range remotely
  - Informing the shift operator by phone / mail → operator manually sets power level and ramp rate
- **Significant role of automatic methods of** communication was described, giving additional overall flexibility
  - In this case it is a key factor that activation of the primary/secondary control is still the responsibility of the plant operator
- **Up to date information** about capabilities and limitations of the plant with respect to flexible operation has to be provided by the plant to the **load dispatcher** to allow the planning of the utilization of plant flexibility properly.
- One of the challenges mentioned during the interviews with respect to flexible operation was a situation in which strong **transients are required in both directions** (likely due to market driven activities) and mostly at the same time. Such grid requirements led to a misunderstanding by the plant team asking if such operation is reasonable with respect e.g. to cycling costs. Unfortunately, no improvements were possible to negotiate with the grid operator on this point. Some other plants introduced a waiting time between new requests.
- With respect to the realization of the flexible operation projects, it is important to include the stakeholders from different departments from the very beginning, due to the fact that flexible operation impacts the whole NPP from grid connection to the fuel. A feasibility study analyzing the impacts could be an important first step.

5 Conclusions and future work following this project

Conclusions:

The following conclusions can be made by analyzing the performed interviews with participants from four different utilities:

- Most of the NPPs were used primarily in baseload until approx. 2010
  - × Since that time, overall Grid services provided by the German NPPs increased significantly with respect to the range, ramp rate and the types of the services driven by the new grid needs and the market value.
- **"Built-in" flexible capability of KWU-designed NPP both PWR and BWR** is a key factor for the performed flexible services by the German NPPs.
  - × The additional modernizations, optimizations and justifications that had to be performed only with the goal to fulfill increased flexibility were overall very limited. Mostly, such work had also a positive impact on base load operation as well improving plant performance and safety.
  - × Power uprate at a high scale was not performed by interviewed German NPPs, but further development of the fuel (e.g. MOX fuel) adding further constraints was a challenge with respect to plant flexibly. For PWRs, especially after improving control functions, more precise control was possible within existing margins.
- **Main optimisation work** was performed in the following fields:
  - × Introduction of **digital I&C** was very beneficial for further optimisations like e.g. ALFC & predictor technology in PWRs. Initially applied at single plant, other NPPs and utilities soon followed.
  - × **Power manoeuvring guidelines** (PCI) / Fuel management strategies/ Plant operational procedures
  - × **Monitoring and Maintenance concepts** were adapted to the level of flexibility to allow safe and reliable flexible operation
- **Plant-by-plant evaluation** and **lessons learned** from other NPPs allowed German NPPs to develop operation envelope with minimal overall impact on the plant.
  - × PWR: performing flexible operation services mostly between 100 and 50 % REO constant average cooling temperature
  - × BWRs: performing flexible operation between approximately 100 and 70 % REO mostly without rod movements by the speed controlled internal recirculation pumps
- **Continuous information feedback between shift personnel and reactor physics** is of a large importance to mitigate fuel failure
  - × Core monitoring, simulation and prediction tools provide the required support to operator
- **Clear and transparent communication between load dispatcher and plant** is of a large importance
  - × **Remote control is favorable**, giving load dispatcher up to date information for reasonable decision.

- × **Simulator training** is of a large importance for flexible operation in both fully automated and semi-manual control.
- × **Exclusion of the plant** from provision of grid services must always be possible.

Overall, flexible operation has been performed by German NPPs in a safe, reliable and profitable way. To illustrate such reliability, the German NPP with the highest level of flexibility (see Appendix D) was analyzed looking at number of internal events. No negative impact has been noticed (Müller, C., 2022). Sufficient level of instrumentation and an optimized maintenance program, which was previously updated with respect to flexible conditions contributed strongly to that result.

In general, when considering a potential 60-year operation lifetime extension, more in-depth analyses are considered to be obligatory e.g. with respect to fatigue. Any performed extended power uprates carried out may be a challenge for advanced plant flexibility and need to be evaluated. Any additional HW/SW and optimizations, as well as required verifications and analyses, have their costs, so provision of such services has to be monetized to ascertain whether or not such investments are feasible for each particular plant and market conditions.

In general, there is an opinion that baseload operation is the most favorable operation mode for the plant with respect to e.g. the operator burden or aging considerations. But, it was also mentioned that long-time operation in base-load can lead to sticking effects on some components e.g. control valves in BWR. Hence, a small level of performed flexibility can be regarded as favorable for the plant performance.

Operating more dynamically also leads to enhancing the knowledge of plant operational staff of plant behavior, which can be seen as favorable in light of safety.

With respect to safe and reliable operation of NPPs in flexible operation modes enhanced automation and additional monitoring play an important role.

Future work:

- Similar interviews with some German TSOs (TenneT, Amprion, 50Hertz, ...) to get more insights in Grid/NPP interactions that have not been addressed in detail yet, including reactive power and voltage management and possibly the impact on the auxiliary power system
- Similar interviews with EDF and RTE, having feedback from 58 NPPs over 30 years
- Feasibly study to adapt main outcomes from this project to any pilot plant in Nordic grid (PWR and/or BWR)

5.1 OVERALL CONCLUSIONS

The analyzed experience and performed interviews show that plant by plant evaluations together with lessons learned from other NPPs allowed German NPPs to develop an operation envelope with minimal impact on the plant. I&C, fuel management & operational procedures as well as monitoring and maintenance concepts were adapted to such flexibility and allow safe and reliable flexible operation in various available modes. Overall, transition to advanced flexible operation and performing it was stated as a task that was successfully solved by all interviewed NPPs.

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Appendix A: Description of the power change

PWR

The schematic part-load diagram of a KWU PWR (Figure 3) shows the temperature of the coolant (CT) at the reactor pressure vessel (RPV) inlet, the RPV outlet and the average CT across the steam generator as a function of the reactor power (100% = rated power).

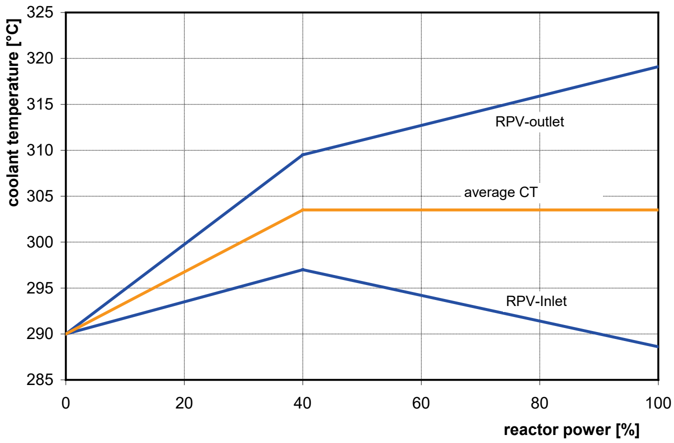

Figure 3: Schematic part-load diagram of a KWU PWR.

The range of the constant average coolant temperature between (in the example) 40 and 100 % can be clearly seen. In the event of a power reduction, the so-called D-bank (4 groups, each comprising 4 control assemblies distributed across the reactor core) is inserted into the reactor core until the desired power change is achieved. The remaining control assemblies (typically 45) are assigned to the so-called L-bank, which always remains at a high position during power operation and thus guarantees the shutdown margin, which is a variable that is important to safety. Slower changes in power distribution in the core, occurring after reaching the desired output, and the concentration of xenon isotopes in the nuclear fuel are compensated by minor movements of the L-bank and changes in boron concentration in the coolant. During an increase in power, the D-bank is the first to be withdrawn from the core. If necessary, the power increase can be boosted by withdrawing the L-bank simultaneously; however, this depends on the position of the L-bank (for an overview of the above components, see Figure 4).

The power gradient for a power increase is limited, for example by the permissible power density. Power reduction is possible at virtually any desired rate.

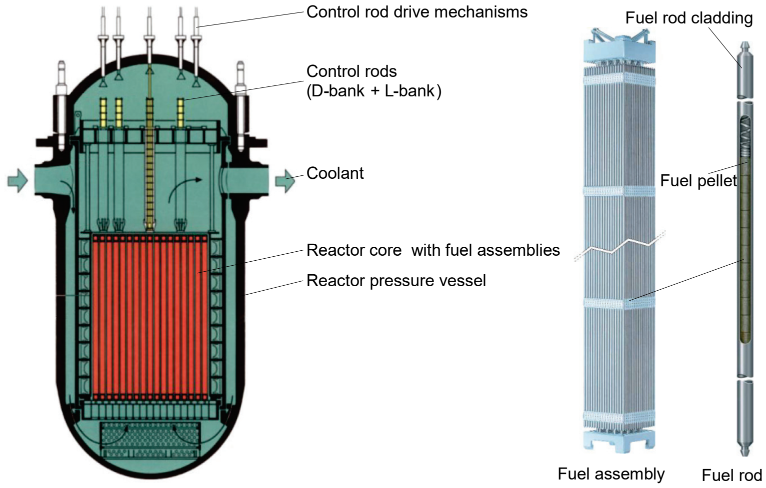

Figure 4: Illustration of typical RPV internals of a PWR.

BWR

The output of boiling water reactors can be regulated either by the maneuvering of control rods or by changing the speed of the forced circulation pumps and, thus, the coolant flow rate (recirculation control). Recirculation control is perfectly suitable for load cycling in the upper power range (about 60 to 100 % of the rated power). The amount of steam in the reactor core increases with a reduction of coolant flow rate, thus reducing both moderator density and 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. Figure 5 shows the characteristic curve for recirculation control (RCC); this plots the reactor power as a function of the core flow for a constant control rod position.

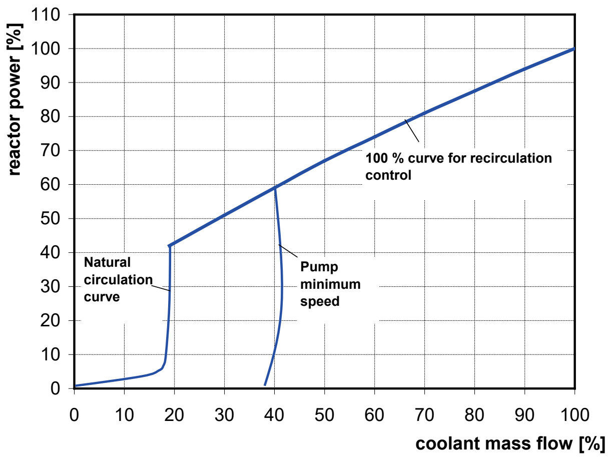

Figure 5: Schematic characteristic curve for recirculation control (BWR).

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 maneuvering of control rods is required for this purpose. This minimizes stressing of the fuel rods caused by load cycling and consequent changes in temperature in the fuel rod. The maximum feasible load change rates are about 10 % nominal power per minute in the recirculation control power range. Power changes beyond the recirculation control range are done by maneuvering control rods. With optimized control rod maneuvering sequences, power increments totaling between 20 and 100% can be achieved at sufficiently high power gradients (for an overview of the above components, see Figure 6).

All German BWR have frequency controlled recirculation pumps which simplifies the flow control and minimizes throttling losses. But in principle load following is also possible with BWR Plants using external recirculation loops with flow control valves.

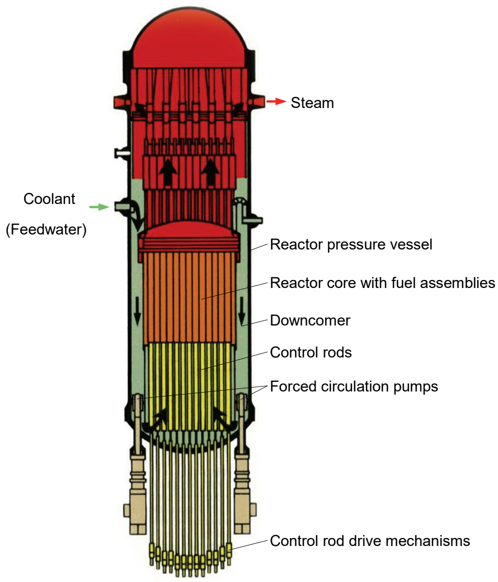

Figure 6: Illustration of typical RPV internals of a BWR.

Appendix B: Definition of the existing flexible operation modes

Table 3: Definition of the existing flexible operation modes including German examples.

NPP Mode/Grid Service in Germany	Description and Examples
primary frequency control (PFC) providing **PCR / FCR**	Depends on the current grid demand, performed as a step change of the grid supply or in the load • German transmission code requires ± 2 % REO linear provided in 30 s, in accordance with European grid code (German transmission code, 2007), can be positive and negative. • Grid frequency is linked directly to the turbine power controller in order to compensate the energy misbalance in the grid directly. • The prequalified range for PFC varies considerably plant by plant, from 2 % to 10 % REO (maximum for German NPPs was realized during the test for a load drop of 14 %). Typical range would be ±50 MWel. • Depending on the optimum dispatch, the typical response is often lower than the prequalified level. • PFC is initiated by the plant shift on demand of grid dispatcher, resulting from market auction & TSO requirements. • PFC can be performed within a specified power level range, thereby the minimum power level is typically defined at 50% - 60% REO
secondary frequency control (SFC) providing **SCR/aFRR**	Depends on current grid demand (stochastic load changes, supplier outages) and is performed as an automatic remote controlled ramp in a specified power range (by the grid dispatcher) • SFC is an automatic response in 5 minutes, can be positive and negative. • The activation of the SFC is carried out by the plant shift on request of the grid dispatcher, resulting from market auction & TSO requirements. • Ramp rate (rate of change in power) is also set by the reactor operator and is typically in the range between 10 and 30 MW/min in Germany. • The dispatcher directly governs the target setpoint of the turbine load within the mentioned range (limited in the turbine control). • Some NPPs take part mostly or only on the negative SFC. • SFC can be performed within a specified power level range, thereby the minimum power level is typically defined at 50% - 60% REO
Minute Reserve (MR) providing	Depends on current grid demand and can be performed as an automatically or manually actuated ramp • The activation time of this reserve is between 7.5 and 15 min and the duration is from 15 minutes to a few hours. It can be

NPP Mode/Grid Service in Germany	Description and Examples
MR / mFRR	requested, at the latest, 7.5 min in advance, can be positive and negative. • The activation of the MR is carried out by a plant shift on request of the grid dispatcher, resulting from market auction & TSO requirements. • The ramp rate is also set by the reactor operator and is typically, in Germany, in the range between 10 and 30 MW/min (depending on the ramp duration at the low level). • Often NPPs take part only on the negative MR. • PFC, SFC and MR can be superimposed. • MR can be performed within a specified power level range, thereby the minimum power level is specified and typically defined at 50% - 60% REO
Load Following (LF) as a result of portfolio optimization **(Economic dispatch)**	Depends on demand/supply balance • LF works on the predefined variable load programs, i.e., reductions or increases in power output agreed in advance. • The load program is defined by the load dispatcher (day ahead) according to availability and cost optimization for all generators of this electric utility (portfolio optimization). Results from the Intraday-market can change the load plan several times during the day. • It is typically requested more than one hour in advance. • It can be performed manually or automatically with the help of corresponding software. The ramp rate is set by the reactor operator on request of the load dispatcher and is typically in the range of 10 to 30 MWel/min – and could be lower, e.g., depending on the time in the fuel cycle. • Minimum power level is specified in advance. • LF could be performed by a German NPP from full power till minimum load, approximately 30%- 40%, but typically the minimum level for LF is defined at about 50%-60% REO for PWRs and approximately 60% REO for BWRs to reduce the possible impact on the plant.
Redispatch (Overload management)	Defined as a shift in the planned power production to avoid network bottleneck, leading to an agreed short-term change in the predefined load program - single power reduction • Start of ramp down by the plant shift on demand of grid dispatcher, resulting from TSO requirements • Ramp rate and minimum power level is specified • Typically, the same ramps and power levels as for economical dispatch are defined

NPP Mode/Grid Service in Germany	Description and Examples
Extended Low Power Operation (ELPO) as a result of portfolio optimization **(Economic dispatch)**	Performed with single power reduction, and is applied to adapt to a longer-term demand forecast • Power level and duration are forecast. After performing the ramp, the NPP returns back to full power on request of the load dispatcher • Definition is country-dependent with typical duration of > 24 h • Fuel conditioning / deconditioning is an important limitation factor for the return to full load • The ramp rate and minimal power level is set by the reactor operator on request of the load dispatcher • The ramp rate depends on the Boron concentration and strongly differs between up- and downwards. • Existing operation experience for daily, weekly, monthly ELPO, e.g., several months, at less than 40% RTP (100% = RTP - rated thermal power) in addition to extensive load following for about 2,5 years • Overall, ELPO at minimum power level is used only in some German NPPs and in very specific cases (e.g. very high negative prices)
Emergency access	Applied in the case of grid emergency situation (imminent danger, danger of grid safety) • Expanded control rights are given to the grid dispatcher/authority to issue an instruction to reduce power (via telephone) • A minimum load level is specified. • The grid dispatcher typically gives info about the level, the required ramp rate, the reason and the planned duration Maximal ramp rates are at maximal design values e.g. 10% /min for PWRs and 30% /min for BWRs, lower rates can be agreed, e.g., 60 WM/min for BWR (1344 MWel)

Voltage regulation
 	
providing
 	
reactive power
	Secures voltage stability of the grid
	• Activated by Short Term grid dispatcher request via telephone
	• The grid dispatcher can have access to the tap changer of the NPP
	• Currently, various NPPs are operating in the underexcited mode most of the time, e.g. annual participation in voltage regulation of a single NPP is including
	    • typical inductive activation of approximately 150 Mvar (up to approx. 450 Mvar)
	    • mostly in under-excited mode, typical activation of about approx. 200 Mvar (up to approx. 350 Mvar)

Appendix C: Transition from Base load to Flexible Operation – Interview N°1 (BWR)

Introduction

This Interview was performed online on 23trd of February, 2021. Thereby, operational feedback from following BWR has been collected.

BWR A of approx. 1350 MWel

Performed plant flexibility:

PFC was qualified for +/-40 MWel, but not often requested by the grid. SFC was not introduced in the NPP. The typical ramps were performed between full power and 70-80 %, activated via telephone, and the minimal power level was set at about 60 % to avoid control rod movements (recirculation control), with a typical duration of about 3 days.

The typical flexible operation for BWR A can be illustrated with the following figure. The ramp rate upwards was typically of 10-15 MWel / min and about 1 % REO / min upwards (depending on the ramp duration at the reduced power level).

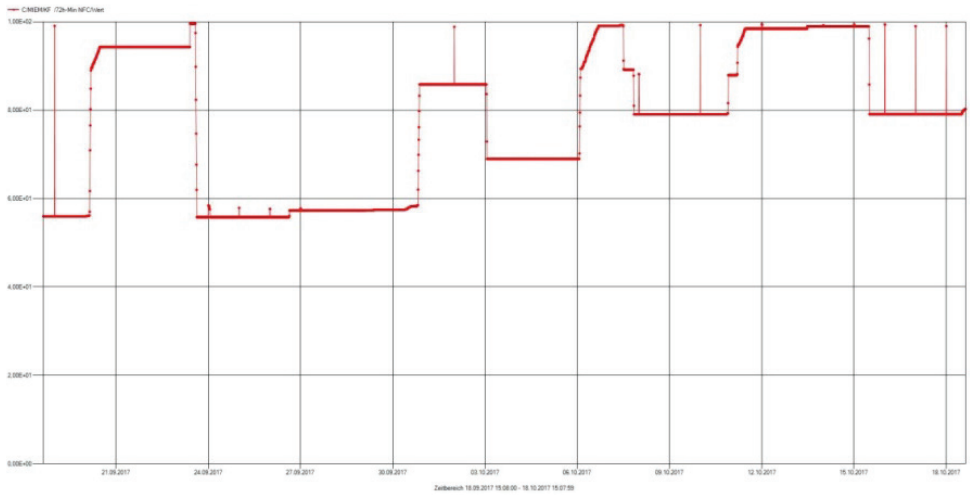

Figure 7: Electrical output in % provided by BWR A over a month period in 2017.

Special conditions and features related to flexible performance:

- The detection limit for Fuel failures is influenced by the existing level of radiation in the systems depending on the previous operational experience (not related to flexible operation). To avoid small fuel failures which are below the existing detection limit, it was decided to operate based on an ambitious fuel reliability program. In order to realize this program, it was decided to minimize the number of performed load changes from 2017 onwards.

- The existing material concept including Zinc-dosage was used for an optimized water chemistry, having a positive impact with respect to optimized crud formation on the fuel assembly surface (indirectly for further plant flexibility).
- With the introduction of the spectral shift operation with an increased rod line in the power flow map, multi group rod insertion was introduced as an adequate safety measure to avoid / master core power oscillations. Due to this new limitation, the minimum possible power at the highest rod line was increased. This is taken into account performing FlexOp.

Questions & Answers

What are experiences of the German NPPs from this transition?

- Was it apparent from the start that this evolution would take place, or has it been a gradual development? E.g. were there early discussions and strategies to "go flexible" or has it been more gradual adaptations due to necessity?

  From the start of commercial operation, it was intended to operate on load following service for the grid. The design of the NPP even included more flexibility that was required by the German Grid code in that time to make the plant design more attractive. From the design point of view, both recirculation control and advanced flexibility using control rods was foreseen. Design power rates and number of cycles were quite high. It was planned to practice cycling operation mainly by varying the core flow by the circulation pumps. It was assumed that this load follow should be possible between 100 % load down to 60 % load corresponding to the design documentation. Over its life time, it can be noticed that such cycling was mostly performed between 100 % and 70-80%. Frequency control (primary PFC and secondary SFC) was also already included in the design of the NPP due to the generic requirements from the grid. But in this particular BWR, SFC were not commissioned as this service was successfully provided by other sources (e.g. gas plants). PFC was required by the Grid in 2016 and after some adaptation of the control parameter settings, NPP was qualified for +/-37 MWel so that this capability could be traded (without such adaptation, first tests showed a problem with achieving the currently required profile of the step). Request for flexible operation comes from RWE load dispatcher. For providing PFC, fuel has to be conditioned to the max value and the power reduced to 95 % to be able to perform upwards and downwards PFC and is only to be allowed until a specified minimum power level of 2800 MW. In praxis, for PFC real activations are very rare. The most frequently performed Load following was in the 90s, with typically two ramps a day. Part load experience over a long period of time is not available. In stretched out operations, load following can be also performed.

- Are there any key experiences to share from the transition? E.g. could anything be done to better prepare for such a transition?

Evaluate aspects of "pure" part load operation (steady state) as a first step and then the aspect of load changes with the desired gradient and frequency as a second (pilot). A BWR that practices load follow needs a computer-based fuel condition program, which is able to simulate all load situations in a forecast, concerning xenon transients and fuel deconditioning. This program also has to calculate holding times at different power levels to fulfill fuel conditioning rate. The main focus is on power increase (after the part load). In this particular NPP, it is realized by means of an online Core simulator (KSIM) which was installed in 2000. This allowed visualization and simulation of the ramps and includes conditioning rules. If the lifetime of the NPP were to be extended and flexibility often required, introducing further levels of automation could be a next development step e.g. it can be proven that digital technology allows the realizing of fuel guidelines and load following rules automatically implemented in the control.

A few other ideas as to special topics:

a. Improvement idea for impact evaluation e.g. vibration - saving vibration data and operational data together for better understanding of the impact
b. Part load impact on H2- accumulation should be analyzed (temperature measurement of the radiolysis monitoring is power dependent) -> power dependent limits were implemented
c. Influence on water chemistry from part load and frequent load changes should be monitored e.g. impact on Zinc-dosage: The existing material concept including Zinc-dosage was used for an optimized water chemistry, having a positive impact with respect to optimized crud production on the fuel assembly surface and indirectly had an impact for further plant flexibility.

What is your view on the safe operations of the plant in the short and long term during and after the transition to flexible operations?

- Experiences of unexpected behavior of balance of plant instrumentation and control or balance of plant equipment in general?

  A plant should test with different rates of power change, mainly by ramping down. The condensate level control valves, the feedwater control valves, the levels of the turbine condenser, the feedwater tank (It has advantages for the flexible operation damping the temperature changes) and the preheaters must come along with the rate of decreasing power.

  These components always must work safely and reliably. e.g. tests with ramp rate downwards till maximum value of 60 MWel/min were performed (End of the last century) with corresponding measures identified and realized e.g. corresponding to the achieved results, changing of the overrule sequence of three existing condensate release stations was performed.

- Experiences of reactor operations including core management, e.g. fuel utilization, neutron flux distributions or reactivity inventory?

Several years ago, optimizations concerning the operating diagram were established. To enhance the thermal output of the fuel by increasing the breeding rate, the rod line was set on a higher level. The intention was to save fuel by operating in spectral shift mode. Additionally, the core was refueled in a low leakage configuration.

However, these measures produced an area of instability by neutron flux oscillation within the operating diagram. Therefore, we installed a forbidden area from 15% to 65 % thermal power. In this area, a large distance from the full power rod line must be maintained, meaning that first we have to ramp up the core flow to increase power, and only at the power level of 65 % can we withdraw the rods up to the full power rod line. Automatic multi-group rod insertion was introduced as a counter measure to avoid operations in the forbidden area. These regulations also had restrictions for ramping down thermal power beneath 70 % on a high rod line. Flexible load following is only possible nowadays between 100 % and 70 % by varying the core flow by circulation pumps when using a high rod line.

This means that if deeper ramps are required, it can be reached by setting rod line on a lower level. That will allow the minimum level of 60 % to be reached without using control rods, but by taking into account some disadvantages regarding fuel economy. It is also worth mentioning that the last 5 % during the ramp up (from 95% to 100 %) is typically performed with a reduced gradient due to fuel restrictions. So the best range to perform flexibility is defined as up until 95%. Typically performed ramp rates are defined between 10 and 15 MW / min, but e.g. downwards NPP can be performed up until 60 MW/min in extreme Grid situations if required without difficulties. Otherwise, the plant needs periods without load following to optimize the control rod pattern and to condition fuel and compensate the burn up at 100 %.

There is no differentiation in core design if a high rate of load following is expected or planned. However, the expected average capacity factor of the plant over of the year should be calculated. The refueling strategy should be aligned to the yearly fuel consumption. The company and/or the grid operator has to provide the expected scope of part load following to optimize fuel utilization.

- Experiences of transients or incidents?
  The shift personal must always be aware of the regulations concerning the fuel conditioning program. They have to know the maximum power ramps, the appropriate rate of power changes, the holding times, and the fuel constrains in the area of near maximum power level, to avoid fuel element fail. The shift personal need a high-level education and good information to operate according to the fuel regulations. Therefore, very detailed instruction for load following e.g. so-called load following Instruction/procedure/handbook has to

be provided. An advanced core simulator would be beneficial (see above) in introducing further level of automation to consider the fuel guidelines.

- Experience from maintenance of plant?
  i. Has there been any effect on the aging management of the plant, for example an increase in maintenance intervals?

     We don´t have such experiences. During load follow, many components remain in motion, which provides better operation and prevents damage via immobility. There might be an upcoming higher washout inside drain systems during phases of decreased power. Wet steam might produce higher erosion. But we don´t have concrete experiences about that.

     The NPP implemented an automatic fatigue monitoring system and the results of its measurements allowed the optimization of operation modes. Impact of load following was not evaluated and had no reasons for such evaluation.

     Overall, the secondary side is very robust. Generator and transformer didn't show any problems due to water cooling with load following from 30 % to 100 %. E-technic was overall very robust with respect to flexible operation

  ii. Has there been any issues with frequency variations in the grid during load-testing of emergency diesel generators? Any consequences thereof and management?

     We never observed frequency variations in the grid during diesel operations.

What do you consider the key enabling capabilities, already existing or from modifications, that enable effective operation in a flexible environment?

- From a plant design point of view?

  All plant components should be able to work in a big operational range without problems. Pumps, control valves, preheaters, drains, turbines and generators must work safely at all power levels. The interactive operation of all systems must be safe at all power levels. Oscillation of electric controllers, bearings, pipe hangers, tank levels, should not occur.

- From an operations point of view?

  Besides a good training and education, adequate regulations, and substitution by a computer-based fuel conditioning program, the operations need a global preview of the planed load follow. There should be good communication between the grid operator and the plant operators. Two-way communication is necessary. The plant has to know about the planning of the net operator and the net operator should be informed about the load follow capacity of the plant.

- From an organization point of view?

  During load following programs, the xenon concentration is steadily changing. The xenon distribution must not come to instability. Therefore, the general rod line should stay 5% below the full power curve to avoid fuel constrains. Maximum power has to be achieved by enhanced core flow to provide a better core power distribution.

During load following, the core should be free of fuel failure. A continuous examination program to detect fuel failures has to be set up. When fuel failures occur, the load follow program has to be stopped.

What is your view on and experiences of inter-organizational (grid-interface/s and communications) issues?

- What is your view on the management of roles and responsibilities of each party? Has it been efficient to solve challenges together or has it been more of 'pushing requirements over the fence'? What is your opinion of how it should be managed and are there any recommendations that can improve the inter-organizational dialogue?

  Challenges must be solved together. The grid operator must be informed about the regulations of core management, about the ranges of ramping up and down and about waiting times. The grid operator has to know the capabilities of flexible operation. Therefore, informational meetings have to be organized. The grid operator should visit the plant (control room). Otherwise, the plant operators need the opportunity to view the grid control center. If possible, the grid operator should give forecasts of load following.
- Do you have any particular example that could be shared as either good practice or not-so-good practice?

  During a cycle, the plant needs periods without load following to optimize the control rod pattern and to condition fuel and compensate the burn up. These phases should be coordinated between plant and grid operator in advance. The plant can then arrange the core management to be prepared for the phases with required load following.

  In phases in which load following is possible in principle, the plant informs the grid dispatcher about possible load changes (power level and gradients), then the grid dispatcher can ask for plant operation depending on grid requirements.

  In the particular, communication planned with the load dispatcher of RWE (or Grid dispatcher by redispatch measures in emergency cases) has the following scheme:

  The request goes via telephone to the shift supervisor, who defines the set point for the control (inside of the allowed range by fuel guideline, which is known to the dispatcher long time in advance). The control is then realized automatically. After a long period of time at baseload operation, automatic control is disabled and the recirculation control is carried out manually. In practice, the requests come 15 min in advance (the shortest time for the request can be for the ramp downwards 1 min).

- Do you have any particular example or recommendation regarding regulatory interaction to highlight?

Regulatory interaction only took place when fuel failures appeared. In this case, flexible operation was interdicted or reduced to extreme cases.

What kind of plant specific necessary studies and analyses of this transition have been done?

- What kind of preparatory detailed studies and analyses of this transition **should/could** have been done to validate the design and operation?
  The Instruction/Handbook concerning all regulations about flexible operation has to be developed. It should detail the allowed power ranges incl. minimum and maximum power levels, holding times (to compensate Xenon poisoning during upwards ramp), ramp rates, the operational area within the Operation diagram (rod line), fuel constrains, etc..

What kind of plant specific tests have been performed, prior to or following, this transition?

- What kind of plant specific tests **should/could** have been done prior to or following, this transition to validate the design and operation?
  Load ramps up and down, with different rates and gradients, should be executed. Therefore, the fuel conditioning, the xenon poisoning and further fuel constrains have to be monitored. The maximum load change gradient has to be determined.
  In particular, NPPs, the maximum design values have been tested during a commissioning test already.

What has been your role in nuclear operations during the transition from baseload to flexible operations?

Design capability to flexible operation has been the main role, but internal plant main optimization was carried out as a responsibility of the physics department

Overall feedback

From the start of operation our plant was run flexibly. Prior to this (until 2017), load following was our daily business. We continuously worked on the specific conditions of load following in order to fulfill the requirements of fuel constrains which became more and more rigid over time. The reactor physics department developed rules/regulations for flexible operations. The operations department developed the handbook for the shift and organized the training. The operation department (shift), works strictly together with the department of reactor physics. Nowadays, we have detailed handbooks for load following programs. It is included in the common document "Guidelines for flexible operation and fuel reliability program" and includes both planned and unplanned maneuvers. There is continuous information feedback from both sides. In unclear situations, the shift personnel may contact the reactor physics department at any time. The operations department lead the informal discussions with the grid operator when necessary.
The detection limit for Fuel failures is influenced by the existing level of radiation in the systems depending on the previous operational experience (not related to flexible operation). To avoid small fuel failures which are below the existing detection limit, it was decided to operate based on an ambitious fuel reliability

program. In order to realize this program, it was decided to minimize the number of performed load changes from 2017 onwards.

Flexible operation impact on specific components:

- Recirculation pumps:

  Auxiliary pipes of the pumps were observed to vibrate at certain speeds. This was solved by the adaptation of additional supports, or implementation of vibration dampers.

- Steam dryers:

  Due to low leakage fuel, during part load operation, an impact on the efficiency of the steam drying within the cyclones of the outer circular RPV area was observed. To avoid subsequent erosion effects, an adapted FA-configuration in the outer area was implemented, which solved the problem.

- Condensate discharge control:

  Additional vibration and poor control was observed in partial load operation. An exchange of internal flow restrictors could solve the problem.

- Feedwater pumps:

  Due to vibrations in part load operation, the minimum flow switch point was changed to avoid unfavorable resonant speed regions.

- Mechanical vibration dampers:

  The operator implemented a significant number of mechanical vibration dampers on relevant piping/components that he considers a sufficient measure to avoid vibration on small components at base and part load conditions.

- Additional observations:

  A change from magnetic to mechanic filter cartridges in the condensate cleaning device led to a reduction of loose particles in the complete system. Previously it had a negative impact in the form of abrupt power change, thus impacting on flexible mode.

  Erosion corrosion in the low pressure preheaters on the tapping and steam piping have been observed, which would have led to exchange activities if longer operation were to be foreseen. Flexible operation could have an impact on this phenomenon.

  Corrosion at small-bore piping was observed.

Appendix D: Transition from Base load to Flexible Operation – Interview N°2 (PWRs)

Introduction

This Interview was performed online on 29th of February, 2021. It was mostly dealing in general with PWRs operated by this utility, but most of the information was related to a single one in the South of Germany that has performed with the highest level of flexibility. Information about other PWRs can be found in (*Salnikova, T., et al., 2021,* PWR D and PWR E*).*

PWR A of approx. 1500 MWel

Performed plant flexibility:

This plant has been performing various grid services over the last two decades, and since 2014 in the advanced fully automatic way (IAEA, 2018). Implementing Advance load following control (Kuhn, A. and Klaus, P., 2016) and further on the predictor technology (Kuhn, A. and Schirrmeister K., 2017), allowed the plant to adapt to the new challenges increasing the reliability and the range of the performed services. The flexible operation modes were optimized among other additional advantages also with respect to smooth plant performance, e.g. with minimization of the boron/demineralized water injections (reducing activation of chemical and volume control system (CVCS)). The target ramp rate was up to 40 MWel/min and the modernizations should allow flexible operation without manual intervention in the whole range between minimum load and 100 %.

With the performed I&C improvements, the NPP achieved one of the most advanced flexibility levels worldwide with primary frequency control mode providing FCR up to ± 100 MWel, secondary frequency control mode providing aFRR up to ± 150 MWel, and minute reserve with mFRR typically in the range of ± 300MWel (Hänninen et al., 2020).

The next two pictures show the prequalification tests for PFC and SFC.

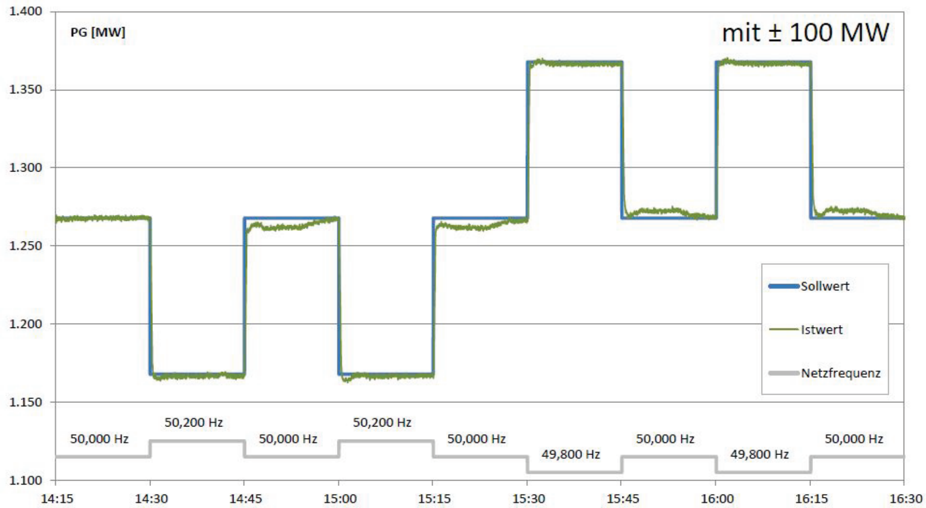

Figure 8 Prequalification test for PFC (symmetric, approx. 100 MWel) (Müller, C., 2022).

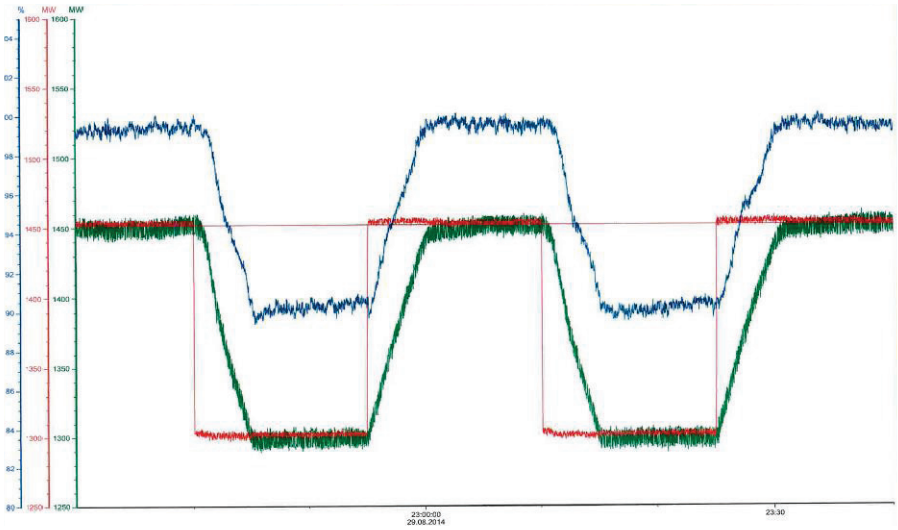

Figure 9 Prequalification test for SFC with ramp rate of 30 MWel/min and 5 min activation, X-axis = Time, Y-axis = Power (MW) (Müller, C., 2022).

Such modes are overlapped by the load following with a ramp rate of up to 40 MWel/min. Currently the ramp rate is stated to be defined up to 20 MWel/min. The minimum level for the performed services is given for the whole fuel cycle and is typically defined at about 60 % REO.

Figure 11 illustrates the plant operation in the fully automated remote secondary control mode during a period of almost one month, with a ramp rate of approximately 30 MWel/min. The graph depicts the changes in the generator power within a band of approximately 560 MWel and the fully automatic compensation of the long-term reactivity effects of the Xenon reactivity with boric acid and demineralized water (BODE), according to the basic design of any PWR. Additionally, the correlation of Xenon in the upper and lower core half is to be noted, as the result of the installed ALFC power distribution (PD) controller which inhibits any axial oscillation of the axial power distribution in the beginning (Kuhn, A. and Klaus, P., 2016).

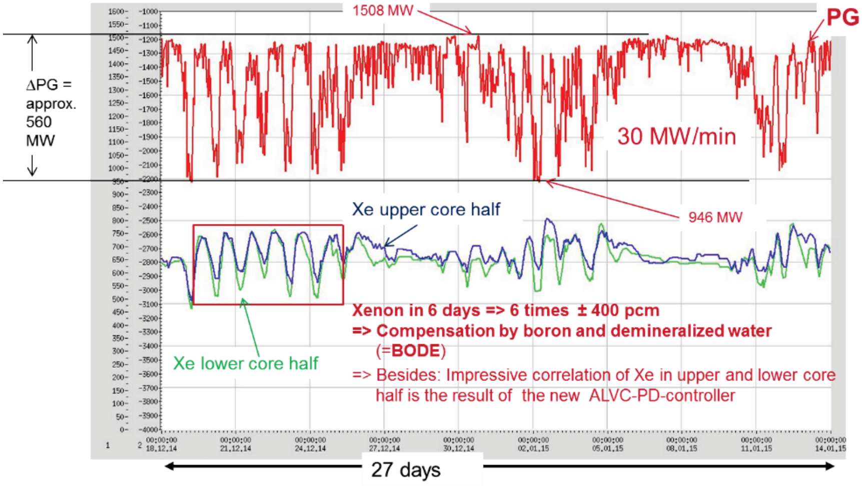

Figure 10 Electrical output (gross) in MWel generated by Konvoi NPP over a 27-day period, providing fully automated remote secondary control, X-axis = Time, Y-axis = Power (MW) (Kuhn, A. and Klaus, P., 2016).

The enhanced low power operations at a constant low level for a long time in general and especially at low levels much lower than the 60 % level is stated to be a very rare event and is performed only due to very special grid conditions.

Special conditions and features related to flexible performance and vibration impact:

- ALFC, including predictor technology
- spray control valves (continuously)

Questions & Answers

What are experiences of the German NPPs from this transition?

- Was it apparent from the start that this evolution would take place, or has it been a gradual development? E.g. were there early discussions and strategies to "go flexible" or has it been more of gradual adaptations due to necessity?

  KKI 2 was originally designed for the flexible operation. In the first years of operation and approx. till 2010 it was typically used in base load. The request from the grid operator came slowly and more often with each year, showing a strong increase since 2012, showing especially a need for reactor control optimizations.

  The extensive operation experience for various types of flexible operation has existed for the last 10 years. Such OPEX were over time integrated in the plant and maintenance optimization. It was a slow lessons learned process, which is why it is hard to define one exact point of the introduction of the new operation strategy. It is important to mention that thanks to the right level of instrumentation and an optimized maintenance program, updated for flexible operation, PWR A, NPP with the highest level of performed flexibility worldwide, has shown no impact on the "number of internal events" in the plant. Of course, additional HW/SW and optimizations, as well as required verifications and analyses have their costs, so provision of such services has to be monetized to ascertain whether or not such investments are feasible.

Are there any key experiences to share from the transition? E.g. could anything be done to better prepare for such a transition?

Some level of optimizations will be always required. Operation experience will increase this such level. There are some aspects that can be foreseen in advance e.g. control process in accordance with the maintenance strategy should be analyzed. Some components will be heavily burdened and wear and tear will increase. Also, as already mentioned, the plant operation department should analyze if the existing control and power electronics meet the control requirements and are robust enough for the increased switching frequency. It could be required to change to the modern technology (PWR A changed to digital I&C and introduced advanced load following control including first of a kind in that time predictor technology provided by Framatome). It should be analyzed whether the introduction of the variable speed drives for the pumps to reduce the throttle losses could be favorable. It is also important to take a look at vibration phenomena of the whole plant and e.g. look for already existing plant experience in part load operation.
Additionally, the usage factor of the most impacted components was monitored by PWR A from the very beginning. This allowed the NPP to be operated until 2022 without an exchange of the components caused by reaching the fatigue end of life numbers.

What is your view on the safe operations of the plant in the short and long term during and after the transition to flexible operations?

- Experiences of unexpected behavior of balance of plant instrumentation and control or balance of plant equipment in general?

  None.

- Experiences of reactor operations including core management, e.g. fuel utilization, neutron flux distributions or reactivity inventory?

  The reactivity inventory of the core needs to be adjusted to the expected loss of produced energy during the cycle.
  The fuel elements of different suppliers have shown their capability for load follow. No negative issues have been observed.
  The fuel conditioning gains more importance to prevent negative

effects of temperature transients on the fuel pellets (this could lead to pellet cladding interaction, PCI)
The control rods have a limitation regarding hoop-strain due to swelling of the absorber. This needs to be checked in advance since the control rods are exposed to higher flux during power transients.
The control rod drives require fine motion control and robustness for a high number of movements.
Nothing special regarding fuel utilization or neutron flux distribution have been observed.

- Experiences of transients or incidents?

  None, that can be caused directly by increased flexible operation.

- Experience from maintenance of plant?
  - Has there been any effect on the aging management of the plant, for example an increase in maintenance intervals?

    Yes, for the most impacted components inspection and maintenance intervals have been reduced e.g. full power feed water control valves, main steam control valves, control module and control valves, coil measurements of the control rods, Erosion monitoring.

  - Has there been any issues with frequency variations in the grid during load-testing of emergency diesel generators? Any consequences thereof and management?

    None, up until now.

What do you consider are the key enabling capability, already existing or from modifications, to enable effective operation in a flexible environment?

- From a plant design point of view?

  The reactivity control has to be capable: control rod drives requires fine motion control and robustness for many movements, PWR: boron acid management and recovery as well as demineralized water production has to be capable enough, BWR: Power control by the recirculation pumps should be capable for frequent actions.
  The design of piping (preventing thermal stratification), nozzles (thermal siphons) and heat exchangers should be robust enough for temperature transients. Identified critical components for thermal fatigue require thermal monitoring.
  Some components experience increased wear and tear (e.g. movement of valves, flexible operating conditions of the electrical generator). This should be reflected in the design and/or monitoring and/or maintenance concept.

- From an operations point of view?

  The plant shift has to be well-trained. Special requirements due to often performed small or deep ramps have to be known and trained. Some special faults e.g. fault condition of full power feed water control valve (unnoticed staying in the current positon) should be trained by simulator as the requirement to the shift are strongly increased during load transient. It should be clear, possible and practiced without any difficulties for the Operation department to exclude the plant from the provision of grid services during a particular day or for any time slot if any doubt of any kind arises.

- From an organization point of view?

  No organization optimizations in the PWR A have been required.

What is your view on and experiences of inter-organizational (grid-interface/s and communications) issues?

- What is your view on the management of roles and responsibilities of each party? Has it been efficient to solve challenges together or has it been more of 'pushing requirements over the fence'? What is your opinion of how it should be managed and are there any recommendations that can improve the inter-organizational dialogue?
  Balancing and control services are traded in Germany on the market. This is the main incentive to participate. In case the NPP is not participating, the load dispatcher (in our case, Partner company) would ask the NPP to operate at a defined steady state (base load) position at low level. Such continuous low level operation is easier to control from an operator point of view but not from an economic point of view.
  Proper communication between load dispatcher and NPP is very important. The means of communication should be clear and often tested to avoid misunderstandings. For such purpose, the automatic means of communication is also very significant e.g. remote controlled primary and secondary regulation (FCR, aFRR, mFRR) as well as providing the range for the power ramp (upper and lower limits) as well as the possible maximum ramp rate defined by the operator and proper transmission of this information to the load dispatcher). Activation of the primary/secondary control (on/off) should still be in the hands of the operator.

- Do you have any particular example that could be shared as either good practice or not-so-good practice?

  Example for good practice: remote controlled fully automatic operation helps to fulfil advanced requirements from the grid side and decrease operator burden and decrease probability of the human failure.
  Example for not-so-good practice: Transients in both directions are required quite often at the same time e.g. deep power reduction and in a short time frame again a strong power increase. Such a requirement is coming from the load dispatcher and cannot be controlled by the NPP. The NPP is following the

request, but the NPP team cannot understand a need for such strong transients. Unfortunately, no improvements were able to be negotiated with the load dispatcher on this point.

- Do you have any particular example or recommendation regarding regulatory interaction to highlight?

  No.

What kind of plant specific necessary studies and analyses of this transition have been done?

- What kind of preparatory detailed studies and analyses of this transition **should/could** have been done to validate the design and operation?

  As already mentioned, PWR A was designed for flexible operation and it was tested during the commissioning phase. Thus, additional studies were not required to start with flexible operation. But, in 2010 Framatome (OEM) was requested by all German utilities (VGB) to prove if the performed changes over the years (e.g. Fuel developments carried out over the years increased enrichment, higher burn up, MOX fuel, power uprate ..) could have any impact on the whole plant incl. fuel, which optimizations can be required and what level of flexibility can be reached without any modifications. This was a first very generic study and various topics were further analyzed by collecting the operational experience in parallel e.g. erosion corrosion analyses with the COMSY tool for different part load levels to optimize the maintenance or pressurizer controls were adapted for the flexible operation mode. As already mentioned, I&C was digitalized and extra development carried out for increased flexibility and reduced operator burden. WANO recommended reactivity management be introduced in PWR A and two other PWRs and additional predictor technology was introduced in PWR A, developed with the strongest support and advise from the NPP staff. This allowed the adaptation to the new challenges, increasing the reliability and the range of the overall performed services.
  PWR A also has another positive feature with respect to flexible operation: spray control valves (continuously).
  For the base-load plants, it should be a large and very costly effort to perform all required tests and analyses that should be discussed with OEM.

What kind of plant specific tests have been performed, prior to or following, this transition?

- What kind of plant specific tests **should/could** have been done prior to or following, this transition to validate the design and operation?

  PWR A performed prequalification tests (for primary and secondary regulation, PFC, aFRR, mFRR). Further on, the commissioning tests for the new digital reactor control incl. advance load following control (with power distribution controller and reactivity management with predictor) were performed firstly by simulator. Such simulator tests were very important to train the shift team and also to be able to compare the simulated plant performance with the real one.

What has been your personal role in nuclear operations during the transition from baseload to flexible operations?

Both participants have had a high level management role in the plant and central office for decades: from 2003, a management role during the time that digital reactor control with ALFC was designed, including responsibly for the project and testing and now plant manager of PWR A or technical vice president of the utility

Overall feedback
See above.

Flexible operation impact on specific components:

Control rod drives:

The plant is facing an increasing number of control rod adjustments caused by FlexOp. The number of control rod movements partly exceeded the design number of 1 million. The drives were checked, assessed and are regularly monitored for their drive voltage and current shapes. Together with the manufacturer and authority bodies, the drives were found to be able to run for more than the envisioned steps, but are kept under observation.

Pressurizer:

The high number of fast load reductions lead to more and longer periods of spraying into the pressurizer. The spray nozzles in particular are seen to be exposed to a higher thermal load by this prolonging of operation. E.g. in the year when the increased flexibility began, the overall number of actuations reached about 1.600, 10 times more compared to previous years. It caused a 50 K temperature difference in the spray line, and the fatigue contribution caused by this had to be taken into account for the life time management. Further on, I&C measures have been integrated, in order to decrease the transient thermal influences of the spraying on the nozzles (the lead spraying is distributed to more nozzles). The target is to keep the specific usage factor below 0.4 until the envisioned end of operation in 2022. Longer usage would strongly increase the additional, cost intensive effort which needed to be carried out. Beyond this time, even an exchange of those nozzles could become necessary. Steam generators (PWR):

FlexOp leads to more acoustic noise events in the vicinity of the feedwater intake nozzles. The events appear quite similar, and seem to be related to thermal effects due to changes of the primary and feedwater temperatures. Alarm values are not exceeded, though alarms can be avoided by similar noise pattern analysis of the LPMS.

Volume control system (PWR):

FlexOp brings more thermal transients to the recuperative heat-exchangers of the volume control system. Calculative mitigation measures have been performed. One outcome is to keep on running 2 system pumps during the secondary load control to decrease thermal transients on the coolers. The target is to keep the usage factor < 0.4 until the end of operation in 2022.

Feedwater pumps (PWR):

The operator has observed changing vibration behavior due to load follow, especially on axial vibrations. Nevertheless, all vibrations remain within specified limits, and return to previous values. The vibrations are monitored regularly.

Valve Drives:

The operator observed a significantly increasing number of valve drive operation steps on all drives in steam- and water circuits. On some systems, he went back from a 6-year regular maintenance to a 4-year period. Regular and systematic monitoring of the drives is performed.

Electrical components:

The electrical components of the Unit Auxiliary Power Supply System are generally minimally affected by the flexible active operation of the plant. Experience has shown that especially power contactors in defined control circuits have to be substituted in a shorter interval than before (e.g. 2 years) and a higher maintenance effort could be necessary.

Main generator:

Vibrations may be introduced by the turbine to the main generator. Experience in Germany has shown that this depends on the special characteristics of the Turbo-Generator and the conditions of the connecting point to the grid.

Appendix E: Transition from Base load to Flexible Operation – Interview N°3 (BWR)

Introduction

This Interview was performed online on 28th of June, 2021. From this, operational feedback from the following BWR has been collected.

BWR B of approx. 800 MWel

Performed plant flexibility:

The flexible operation of BWR B was already strongly required by the grid in the 90s due to a special grid connection situation, the night demand reduction of the large city in the north was typically compensated by the NPP. Automated remote secondary control (corresponding to aFRR) was activated in the range of 100 MW (whereby the defined ramp rate was at about 20 MWel/min upwards and downwards, much higher values can also be achieved due to the design) with the defined minimal power level at about 60 % REO (recirculation control). The limitation system did not allow the load dispatcher to increase the power more than allowed (20 MW always remained between the maximal power level and the maximal set point for the load dispatcher). The load following could be additionally activated via telephone, but also typically in the range of recirculation control.

PFC was qualified at +/- 22 MWel, but PCR was not often performed by the NPP in that time as the introduction of the renewables was as much of an important factor as it now is. After the owners and grid connection situation changed and the market conditions in the deregulated market became different, primary as well as secondary control were not required anymore for the NPP and only the activation via telephone for the load following operation became feasible. It required about 10 minutes between the request and start of the ramp. Here the planned reductions during the weekends and holidays became the main type of flexible operation of the NPP. The downward ramps stayed at the same rate of 20 MWel/min and the upwards ramp rates were dependent on the fuel deconditioning. The operation guidelines were provided by the fuel department of the plant based on the individual FA results from the core monitoring computer. The typical ramps were performed between full power and 70 - 80 % REO and the minimum power level was at about 60 % REO in order to avoid control rod movements. In this case, a positive minute reserve of about 256 MWel was provided by the gas turbine plant, which was originally built to support the black start of the NPP during the loss of offsite power.

The enclosed diagrams of neutron flux signals and recirculation pump speeds show the load changes during night time at the end of year, providing automatic secondary control (see Figure 11).

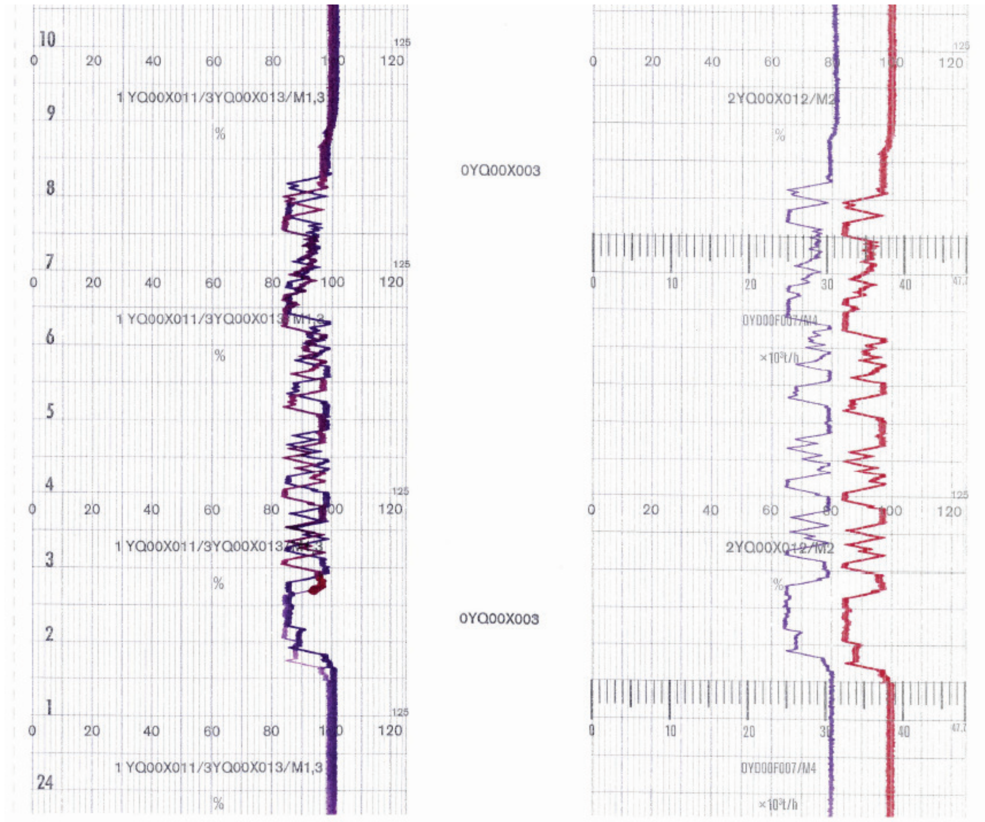

Figure 11: Correlation between Neutron Flux signal (left) and Recirculation pump speeds (right) during FlexOp in night time, end of year 1999.

As an illustration of longer time flexibility provided by BWR B, a one-month figure can be chosen. In regards to the below figure, all power ramps, except three deep ones at about 50 % of reactor power (blue color) due to maintenance and inspection needs, were required by the load dispatcher. The change of the generator output in MWel is shown by the red curve. To get more general feedback it should be mentioned that in that particular year there were also months without any requests from the dispatcher.

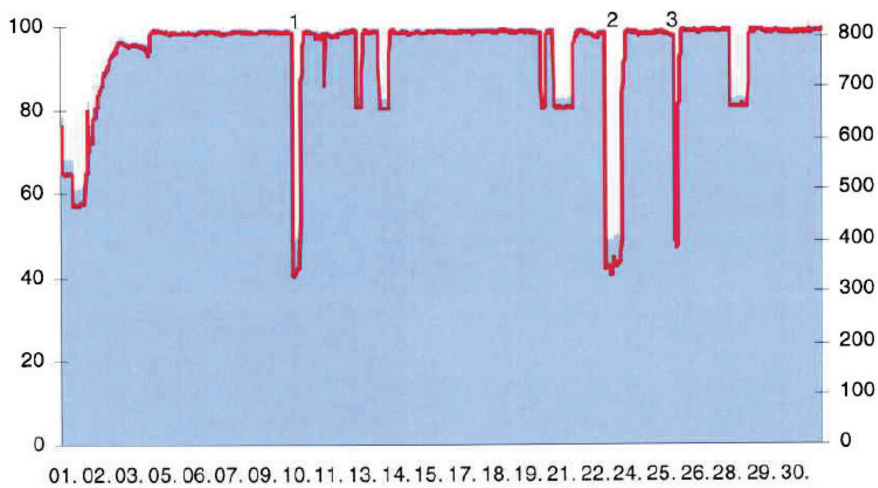

Figure 25: Flexible operation of the BWR B during one-month period of time, end of year 2007.

Special conditions and features related to flexible performance:

- Speed controlled internal recirculation pumps
- Horizontal preheaters (design feature with influence on fatigue, special attention on loads had to be taken)
- Main steam piping was changed (because of unfavorable pipe material)
- Steam separator was replaced after 2 years (reason was design / material optimization but not the consequences of load following operation).

Questions & Answers

What are experiences of the German NPPs from this transition?

- Was it apparent from the start that this evolution would take place, or has it been a gradual development? E.g. were there early discussions and strategies to "go flexible" or has it been more of gradual adaptations due to necessity?

  BWR B was already designed for flexible operation (internal speed controlled recirculation pumps, fine motion control rod drives, reactor power controller, high level of automation in the steam-feedwater cycle, high number of load changes considered in the load specification). The background to this was the grid situation in Germany. The owner of BWR B was also responsible for the grid of the large city in the North of the country. Together with one other NPP, the power supply for this city was secured and for such a small grid, flexible operation of NPPs was necessary. Later on the owner changed and power was sold to the larger Grid leading to decreased flexibility requirements for this NPP.

Are there any key experiences to share from the transition? E.g. could anything be done to better prepare for such a transition?

One of the key issues to be considered is fuel conditioning, taking into account load-dependent xenon content. Operating procedures has to be optimized for flexible operation. Existing procedures showed positive operation experience for the performed level of flexibility by the NPP.

What is your view on the safe operations of the plant in the short and long term during and after the transition to flexible operations?

- Experiences of unexpected behavior of balance of plant instrumentation and control or balance of plant equipment in general?

  Good experiences with flexible operation based on the suitable design of the plant, i.e. power control circuit and good knowledge and procedures have been shown over the years.

- Experiences of reactor operations including core management, e.g. fuel utilization, neutron flux distributions or reactivity inventory?

Flexible operation could be taken into account during the core design phase. It has to be defined in advance in which range flexible operation will be performed.
Operating guidelines optimize loads on fuel (Brennstoff-schonprogramm) and are used to mitigate fuel cladding failures defining the ramp rates with respect to fuel conditioning. The improvements of the FA-design have also allowed more flexibility within the lifetime of the plant e.g. FA design has been changed from 8x8 to 10x10 configuration. The corresponding original plant procedures have been adjusted and operational experience showed them to be very well applicable for such type of operation.

- Experiences of transients or incidents?

  Even though automation control was available for the plant BWR B used manual operation mode during phases with load following operation to avoid unexpected events driven by the correlation between pump speed and void content in the core. If the internal pumps were not in automatic mode, in some rare cases the steam bypass station has been opened guiding steam directly into the condenser due to handling failures.
  Improved information for the conditions of system for the shift supervise by automatic control could improve the acceptance of the such mode.

- Experience from maintenance of plant?
  - Has there been any effect on the aging management of the plant, for example an increase in maintenance intervals?
    No.

  - Has there been any issues with frequency variations in the grid during load-testing of emergency diesel generators? Any consequences thereof and management?
    No.

What do you consider are the key enabling capability, already existing or from modifications, to enable effective operation in a flexible environment?

- From a plant design point of view?

  From the original design, the plant had a quite advanced degree of flexibility due to speed controlled internal recirculation pumps, fine motion control rods drive, a high level of automation of the steam water cycle and the condensate regulation system. In the original design loads specifications, the high number of loads has been specified and not used during the plant operation time, so enough margins were still available. The core design was adapted to the flexible operation needs. The overall design of the control circuit, the design of feed water pumps and the preheater was also suitable for the flexible operation.

- From an operations point of view?

  Overall knowledge of plant behavior, well defined procedures, testing and training at the simulator (will be recommended to be performed before implementation in the plant) are the key factors with respect to operational issues.
  The operation was supported by the core monitoring system providing a calculated status of the core e.g. with respect to the limits for the shift supervisor. Later on, the core department was supported by simulator (PESTO 2) predicting the required data for the planed power increase.

- From an organization point of view?

  The plant has defined acceptable ramp rates and ranges of power load and the dispatcher could request to perform flexible operation within these ranges.

What is your view on and experiences of inter-organizational (grid-interface/s and communications) issues?

- What is your view on the management of roles and responsibilities of each party? Has it been efficient to solve challenges together or has it been more of 'pushing requirements over the fence'? What is your opinion of how it should be managed and are there any recommendations that can improve the inter-organizational dialogue?

- Do you have any particular example that could be shared as either good practice or not-so-good practice?

- Do you have any particular example or recommendation regarding regulatory interaction to highlight?

  The dispatcher called the plant to set "NKR-Mode" (automatic grid oriented control mode), then the dispatcher could set the plant power within the predefined range (during time NPP was connected to a small Grid).

  Later with the restructuring of the German grid, NKR operation was stopped. Load following was then organized by telephone contact between dispatcher and shift.

  Primary frequency control (PC) was activated most of the time but the service was provided only occasionally.

  The key commutation factor is that the power range and ramp rate is defined by NPP in advance and clearly communicated to the load dispatcher and such operational borders are firmly fixed, independent from the current market situation.

What kind of plant specific necessary studies and analyses of this transition have been done?

- What kind of preparatory detailed studies and analyses of this transition **should/could** have been done to validate the design and operation?
  The flexible operation was already a built-in function and was used as a standard mode.
  A generic BWR/PWR study has been carried out by Framatome to take into account changes performed in the meantime, like, for example, new fuel developments in 2010, as greater flexibility has been required.
  Flexible operation procedure was adjusted to the current flexibility needs.

What kind of plant specific tests have been performed, prior to or following, this transition?

- What kind of plant specific tests **should/could** have been done prior to or following, this transition to validate the design and operation?

  Unfortunately, when the NPP started flexible operation the type of the existing plant simulator didn't allow to test flexible operation. Today, due to the further development of the plant simulators with a detailed plant model it will certainly be possible and important to start with such tests on the simulator even if it is using a simplified core model. As mentioned before, the core design, the main control circuit of the plant and the plant response in case of malfunction of the external control have to be investigated.

  After that, it is reasonable to start with small steps with respect to the ramp rate and ranges of the performed services.

What has been your personal role in nuclear operations during the transition from baseload to flexible operations?

Operational manager in the BWR B

Overall feedback

Depending on the plant design, flexible operation is not a problem. But today, in times of cyber-attacks, the connection between the plant and the grid controller must be very safe (SEWD-IT).
If the NPP has performed thermal power uprate, it has to be taken into account planning flexible operation. The flow window will be narrower at the higher power, but flexible operation will be still possible.
The main driver for the plant flexibility was an increased profitability of the plant's providing capability (capacity price), as some grid services were already very profitable.

Flexible operation impact on specific components:

The main steam piping was changed in 1998 due to the effect of erosion/corrosion/cracks, reducing the diameter and improving the steam flow performance (improved material was used). One result of this was a new design and a quite strong structural support of those pipes, leading to low frequency vibration (independent from FlexOp). As countermeasures, a number of anti-vibration dampers (type Gerb) have been installed on the pipes, reducing the vibrations satisfactorily.

It was remarked that an operation with load changes during the cycle was favorable for the control valves because their regular movement avoided increased local friction marks over the time.

Limitation of the ramp rate (typical value of 20 MW/min) after taking into account the fuel limitations was caused by a plant specific issue connected to horizontal preheaters. Preheater trains reacted sensitively to fast load transients. It took a longer period of time before stable operation could be observed again. Unstable operations can cause fatigue issues in the long term.

Appendix F: Transition from Base load to Flexible Operation – Interview N°4 (BWR/PWR)

Introduction

This Interview was performed online on 16th of March, 2022, from which operational feedback from the two following NPPs, both BWR and PWR, has been collected.

BWR C of approx. 900 MWel

Performed BWR plant flexibility:

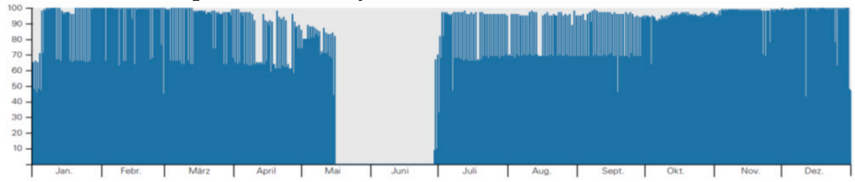

Figure 12: Electrical output in % provided by BWR C over the annular period in 2009 (ATW, 2010).

BWR C had two control bands for PFC that could be activated successively (-11 MWel and -22 MWel), which was used quite often. Both bands could be activated at the same time, achieving -33 MWel. Initially, this BWR provided only downwards service and performed it primarily between 74 % and 100 % REO.

As the service has to be carried out symmetrically, the upwards product was provided by another power plant block (PWR). Secondary frequency control was qualified downwards with -30 MWel and MR was qualified for -90 MWel with a typical ramp rate of 10-15 MWel/min, although the NPP was not often activated for such services.

Load following was performed down until a low level of approximately 60 % downwards with a ramp rate of 30 MWel/min, but higher ramp rates downwards could have also been possible. Upwards, the ramp rate was about 10 MWel/min, but this was reduced tenfold for the last 5 % before reaching the full load, depending on the duration at the low level. The power was reduced for a few hours, but weekends at low level were also quite common. An example of ELPO with a long duration was performed at about 48 % REO for more than 12 days in December 2008 and additionally 5 more days in January 2009, as can be seen in the previous figure.

During the last years of operation, provision of the services was required by the plant in both directions.

Some power reductions at the beginning of the year were carried out due to cooling tower operation conditions. Deep reductions were carried out a few times per year due to periodic testing.

<u>Special conditions/features related to flexible performance:</u>

- Frequency controlled internal recirculation pumps are extremely favorable for flexible operation.
- The usage of the demineralized water without additives (Normal Water Chemistry (NWC)) makes the flexible operation less complicated with respect to chemistry management.
- This NPP had 100 % cleaning of the condensate, which had a positive impact on the chemistry and as a result also had a positive effect with respect to fuel rod damage. This is an important aspect related to flexible operation, as NPPs with fuel rod leaks are not available anymore for the performance of the Grid services. Core Monitoring System, CMS, allows the detection of core power oscillations * and initiates countermeasures; such as control rod bulk insertion.

  *) BWR stability issue – high power/low flow areas, where oscillations in thermal-hydraulic quantities may induce oscillations in neutron-related quantities (mostly, neutron flux), this region will be avoided

PWR B of approx. 1500 MWel

<u>Performed PWR plant flexibility:</u>

It was the first PWR plant to begin with the ALFC modernization of reactor controls in 2008, achieving a world record in August 2015 with a PFC downwards regulation of -200 MWel, approximately 14 % REO within 30 seconds, and then back to full power in 15 minutes. This prequalification is illustrated in Figure 2 by the corresponding change of the generator power in MWel over the primarily 1-hour test period.

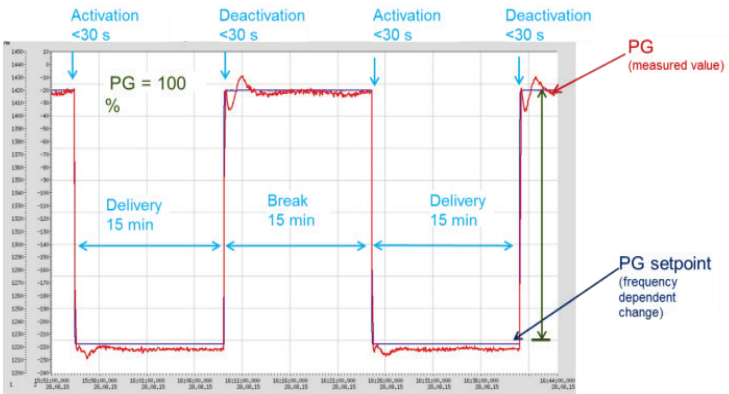

Figure 13 Prequalification test of asymmetric downwards PFC of 200 MWel, German pre-Konvoi NPP, X-axis = Time, Y-axis = Power (MW) (Kuhn, A. and Klaus, P., 2016).

Energiforsk

The licensed range of the PFC reached a maximal value of 130 MWel. Typically, the NPP has delivered up to 70 MWel of PFC. Moreover, SFC and MR can be superposed (in this case e.g. with -50 MWel for SFC and -150 MWel for MR).

The ramp rates for the ramps downwards and upwards vary strongly over time in the current cycle (boron concentration), e.g. they can vary from 80 MW/min downwards at the beginning of cycle to 8 MWel /min at the end of cycle, and upwards from 40 MW/min at the beginning of cycle to 1,5 MW/min at the end of cycle. The average value was about 30 MW/min. During down and upward ramps themselves, PFC and SFC were deactivated.

The typical minimum load for MR/load following is stated to be at about 50 % REO. The minimum load for all three types of ancillary services (PFC, SFC and MR) together was defined at about 38 % REO, but the typical minimal value was at about 60 % REO.

Figure 13 is an illustration of 1 month's continuous primary and secondary control and a four times deeper load follow operation with the lowest power level for the reduction at about 50 % REO. Such a deep reduction is typical for Christmas and new year holidays. In this case it was about 7 hours long. Additionally, power reductions due to the limitations corresponding to the low water level of the river were performed during the first three days of the month. For example, in 2017, the load follow to the lowest power level of 38 % was requested and lasted for about 22 hours, though this can be seen as an extreme case for this NPP.

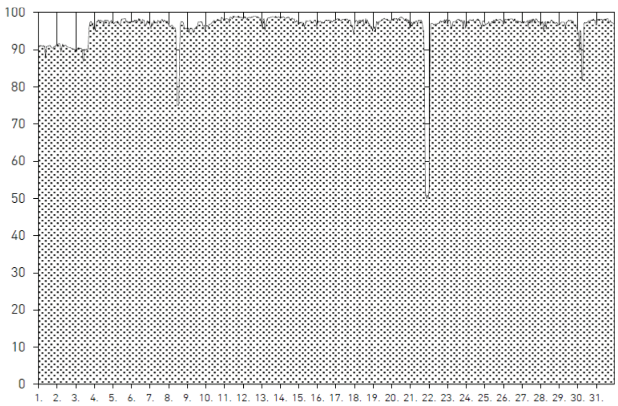

Figure 14 Electrical output in % provided by PWR A over a 31-days period in 2018.

An example of the advanced load following capabilities can be found in IAEA document (IAEA, 2018), showing load following between 100 % and 45 % REO, performed by the plant with a ramp rate of 40 MW/min (2,7 %/ REO), even in the end of the cycle.

<u>Special conditions and features related to flexible performance:</u>

- Advance Load Following Control (ALFC) with improved BODE (Boron/Demineralized water injection control)

Questions & Answers

What are experiences of the German NPPs from this transition?

- Was it apparent from the start that this evolution would take place, or has it been a gradual development? E.g. were there early discussions and strategies to "go flexible" or has it been more of gradual adaptations due to necessity?

  In the BWRs, only small steps had been required for increased flexibility at first. But since 2008, Grid requirements have massively increased as well as the price level for various Grid services. The NPP has been forced to raise the technical and economic level of the provided Grid services. The introduction of the digital turbine control was very favorable.

  In the PWR, the optimization of the NPP core control played one of the most important roles. It was started by Framatome originally within the modernization project, introducing digital reactor I&C. The main original goal was to improve plant flexibility with respect to fuel loading strategies e.g. MOX and low leakage configuration. During the project, the increased need for flexible operation became an additional optimization goal with respect to operational margins. One of the key success factors of this project was continuous involvement of the NPP incl. I&C and plant operator's feedback. Additionally, the use of the engineering simulator at the early stage of the project was very beneficial. What is perhaps interesting to mention is that the main Framatome developer of this system was very familiar with process and safety, I&C and operator training for this particular plant. All these advantageous conditions led to the first ALFC project realized in German PWRs, significantly increasing the range of the performed Grid services.

- Are there any key experiences to share from the transition? E.g. could anything be done to better prepare for such a transition?

  On the one hand, theoretical considerations have to be taken into account, however, on the other hand, flexible operation should be tested in small stages as well as the inspection intervals for the most impacted components being redefined.

  Plant specific evaluations have to be carried out with respect to loadings on systems and components. As an example, main loadings for the primary side of PWR are to be expected on following components /phenomena:

  - the pressurizer spray valve
  - CVCS
  - higher number of control rod movements
  - increased reactor inlet cooling temperature and as a result higher loadings on reactor coolant pump

- changing of the chemical operational mode due to the changed temperature and solubility as well as Boron concentration

Amongst other things, the following secondary side components/phenomena have to be looked at:

- pressure increase
- changes of the steam humidity, water preheater loadings, turbine loadings and feed water pumps loadings
- vibrations of the main steam trip and regulation valves due to throttling
- vibrations of piping's of the turbine condenser
- fluttering of the valves due to throttling of feed water mass flow

Moreover, the control has to be adjusted to the particular operation mode. The Core monitoring program is required to prove the fuel rod loadings.

Xe-prediction is very important as Xe-oscillations have to be avoided.

BWRs: Attention should be paid to the increased loadings due to the changed mass flow in the core and increased throttling for the BWRs with external recirculation pumps. Flow stability and fuel conditioning issues have to be taken into account in advance. A performed thermal power uprate could be a strong limitation factor for a plant.

What is your view on the safe operations of the plant in the short and long term during and after the transition to flexible operations?

- Experiences of unexpected behavior of balance of plant instrumentation and control or balance of plant equipment in general?

  KWU design showed no negative experiences. It should be mentioned that operation envelope has been defined based on the main limits.

  - For BWRs, left corner point in operation diagram, at about 60 % thermal power
  - For PWRs, constant average cooling temperature (higher than about 60% REO)

- Experiences of reactor operations including core management, e.g. fuel utilization, neutron flux distributions or reactivity inventory?

  Flexible operations have a negative impact on the fuel utilization.

- Experiences of transients or incidents?

  No

- Experience from maintenance of plant?

  - Has there been any effect on the aging management of the plant, for example an increase in maintenance intervals?
    One additional topic to be mentioned for BWR is the damage of heating condensate slider.

For PWR, collected feedback is summarized in the last section of this Appendix F.

- Has there been any issues with frequency variations in the grid during load-testing of emergency diesel generators? Any consequences thereof and management?
  Frequency variations have not been ever observed in the grid during load-testing of emergency diesel generators.

What do you consider are the key enabling capability, already existing or from modifications, to enable effective operation in a flexible environment?

- From a plant design point of view?

  The components are obligated to completely cover the required range of mass flows and temperatures. Appropriate control is also essential for the operation. For BWRs, what is most important is the frequency controlled internal recirculation pumps. Reliable core stability monitoring and fuel conditioning programs are key preconditions for successful flexible operation. For PWRs, the part load diagram with constant average cooling temperature from 100 % till about 50 % REO and performed optimizations for reactor control, realized within digital platform (including optimizations for power distribution controller and reactivity management), is the key factor. A precise core monitoring system, reliable fuel conditioning program or advanced water treatment capabilities are also important with respect to achieved flexible capability of the plant. For frequency control, the capability of the turbine controller is the first step to be proved and optimized.

- From an operations point of view?

  Training and stepwise introduction of the control modes are the main key factors. Overall introduction of the digital control was very beneficial with respect to turbine control and for PWR reactor control as well.
  For all NPPs, an online Core monitoring tool provides the main information alongside an appropriate fuel management program. For BWR, this task was carried out by applying Minuteman Advanced Core Monitoring System with new results each 5 minutes and with a power ramp performed by the plant operator and for PWR by Core Monitoring System POWERTRAX/S providing inputs for ALFC including reactivity management (with online Xe-calculation) using a fully automatic approach.
  Of course, depending on the level of plant automation, a flexible operation mode could require more work for the plant operator. The overall advance of automation level of both PWR and BWR have allowed a significant reduction in possible operator burden.

- From an organization point of view?

  None.

What is your view on and experiences of inter-organizational (grid-interface/s and communications) issues?

- What is your view on the management of roles and responsibilities of each party? Has it been efficient to solve challenges together or has it been more of 'pushing requirements over the fence'? What is your opinion of how it should be managed and are there any recommendations that can improve the inter-organizational dialogue?

- Do you have any particular example that could be shared as either good practice or not-so-good practice?

- Do you have any particular example or recommendation regarding regulatory interaction to highlight?

Introduction of the remote control was required to perform the Grid qualification for the corresponding services. Initially, it was not a comfortable situation for the plant operator noticing the plant being controlled by someone situated hundred kilometers away from the plant, however this was only the starting phase. The activation of the remote control, ramp rate and the power range is always set by the operator.
The open communication between plant and the load dispatcher is a key factor. If required, the plant has to be capable of stopping remote control and flexible operation due to any constrains e.g. any valve issues. In such cases, the first remote control will be switched off, then there is a communication via. telephone with a load dispatcher with a brief explanation of the current situation and later on, a formal document has to be issued, including the course and time forecast for the interruption.
It has to be mentioned that in this particular case, the owner of the plants and of the Grid was the same company, making the communication much more efficient. It must always be proven that flexible operation is not compromising safety and, following this, market driven flexible operation may be used as an important tool to be used for plant profitability.

What kind of plant specific necessary studies and analyses of this transition have been done?

- What kind of preparatory detailed studies and analyses of this transition should/could have been done to validate the design and operation?

  Before the increased ranges of the Grid services has been procured by PWRs, various detailed analyses had been performed e.g. plant staff have performed detailed analyses to define the optimized operation envelope with respect to profitability, reliability and safety. Overall limitation from primary and secondary sides had been summarized, with the overall result of the range of the performed flexibility linked to the vibration issue of the main steam regulation valves. Special attention was given to the plant chemistry under flexible conditions (Bolz et.al, 2013). This study also defined the ramp rates depending on the Boron concentration. As per the results, some operation mode optimizations and changing of the maintenance intervals e.g. for the feed water pumps or preheaters, had been performed. Following this, Framatome

analyzed the available measurement data in detail, looking at overall impact on systems and components including fuel issues e.g. real impact on the power plant chemistry like compliance with the water chemistry specification ensuring plant integrity (primary and secondary side) or impact on the lifetime of the components e.g. analyzing findings with respect to flexible operation with overall positive feedback.
It should also be mentioned that the operation department has developed an instruction/handbook for the plant shift, including required input from the reactor physics department for all types of flexible operation (PFC, SFC, MR, reactivity control, emergency access) for both blocks. The all information required for the plant operator has therefore been included e.g. ramp rates, power ranges, power levels. This document is continuously updated on new levels of flexibility.

In respect to the cost of the flexibility, PWR was analyzed within an economic study looking at the additional costs, most of which were due to increased inspection intervals and maintenance actions e.g. economical dispatch to low power levels during holidays and additional primary control were the most valuable in that time and led to the most positive business cases.

What kind of plant specific tests have been performed, prior to or following, this transition?

- What kind of plant specific tests should/could have been done prior to or following, this transition to validate the design and operation?

For BWR, tests for ancillary services have been carried out, increasing power ranges and adding provision of the services in both directions (not the case in the beginning). Intensive testing was required for PWR, as much higher power ranges had been qualified for the Grid services. As a result, various modernizations and optimizations have been carried out e.g. introduction of the ALFC, including changes in Boron/Demineralized water injection control and adjustments of the pressurizer control, have been carried out.

What has been your role in nuclear operations during the transition from baseload to flexible operations?

Shift supervisor, outage planner and deputy plant manager of BWR C. Shift supervisor and later on, plant manager of PWR between other tasks, developing the strategy for flexible operation considering utility needs as well as taking into account safety aspects.

Overall feedback

Generally, it can be stated that baseload operation is most favorable operation mode for the plant. But, it was also mentioned that operation in base-load over a long period of time can lead to staking effects of some components e.g. control valves in BWR. Specifically, in regards to this issue, a small level of performed flexibility is even favorable for the plant performance. The profitability of the plant it is a main motivation for the advanced flexibility to be added and performed. Net value of the plant with flexible capability is also higher, and this also must be taken into account during the decision making process.

BWR:

Overall, the NPP was performing very reliably in flexible operation mode; the level of flexibility was not very high but e.g. remote secondary control was realized and performed. Overall, main difficulties were connected to reaching 100 % of power again.

PWR:

It was the first plant that performed adaptation of the reactor control that increased the available flexibility. For the PFC, the highest range in the world was achieved. Various internal and external studies have been performed to optimize the flexible operation, taking into account the whole plant.

General comparison:

PWRs has been described to be more suitable overall for Primary control then BWRs due to the higher coolant inventory available. For the secondary control, BWRs are considered to be more suitable due to easier control. For PWRs, Boron/Demineralized water management is an additional topic to be addressed. This means coolant treatment is continuously required via. filter cleaning, degassing and evaporation of Boron. As the result, CVCS will be more stressed and more filter resins required.

However, still looking at the German operational experience, it can be shown that PWRs have performed the required adaptations and optimizations with respect to control and have shown the highest level of qualified and performed Grid services in Germany and worldwide. Among other topics, optimization of required Boron/Demineralized injections during flexible operation has been carried out due to a more detailed evaluation of the dead time behavior of the CVCS.

Flexible operation impact on specific components:

BWR C of approx. 900 MWel

The generator operated louder in flexible mode, although it should be mentioned that particular generators (the former and the substitute) were noticed to be noisier in normal operation compared to other German BWRs.

PWR B of approx. 1500 MWel

Control Rod Drive System (CRDS)

The plant was facing an increasing number of control rod adjustments, caused by FlexOp. The number of overall control rod movements exceeded 1 million steps. This was not the design limit for such types of plants, but increased probability of spring fracture of the latch unit was shown previously from the operation experience to occur nearing this value. For checking the performance of the drives, regular assessment of the moving operation by evaluation of the voltage and current shapes was performed. Reassignment of control rods in the control banks to rotate mission time among the CRDSs/CRDM was carried out, and proactive replacement of CRDSs/CRDMs with an increased step number was also performed.

Pressurizer spray nozzles

The leading spray train was assigned to all available ones as a means to optimize controls, to reduce specific usage factors on the nozzles. Furthermore, a calculative consideration of measured thermal transients, compared to theoretical ones, led to a dramatic decrease of anticipated fatigue usage factors (e.g. 0.9 to 0.1). The main observation was that thermal transients (approx. 20 to 30 K) occurred only in lower range.

Pressurizer Surge Line

More frequent in- and out-surges were observed during FlexOp. However, the thermal transients were situated within 20 to 30 K, so did not affect fatigue issues significantly.

Branch to volume control system

This pipe component is seen to be confronted with significant thermal transients during FlexOp, and was instrumented with thermal sensors. An influence on fatigue is anticipated.

Main coolant pumps

A rising level of vibration could be observed in the past. Though a causal relationship with FlexOp could not be seen, the levels were kept under observation in relation to FlexOp.

Main steam regulation valves:

On loads < 50 %, vibration on these valves was anticipated, based on experience from another PWR of approx. 850 MWel.

As countermeasures, the regular inspection periods on those valves were reduced, and loads < 50 % are avoided.

Preheater between HP- and LP-turbine

An insufficient separation of droplets was anticipated (residual humidity >> 0.5 %). Additional perforated sheets had already been implemented. Inspection will be further focused on inner conditions.

Condenser pipes:

More vibration due to FlexOp was anticipated. Several mechanical mitigation means had already been implemented. Normal inspection intervals were kept.

HP- and LP-turbine

More erosion effects on turbine blades were anticipated. Prior to this, a more durable blade material (more chrome-ratio) had already been implemented.

On stator vanes, erosion effects occurred. The respective countermeasures were overlay welding and frequent inspections.

Feedwater pumps:

In part load conditions (under 60 % REO), only one feedwater pump should perform the operation, because cavitation effects during part load conditions are known to occur on that pump type. As countermeasures, smaller inspection intervals and additional spare part rotors have been implemented.

Feedwater check valves

Long operation periods in part load conditions may lead to an incomplete opening of those valves, which might cause instabilities in the feedwater flow and wear on the internals. More inspections were anticipated.

Preheaters

The heat exchangers are run with lower mass flows and a higher steam humidity rate. A higher effect on erosion, vibration or fretting could not be excluded. A more frequent inspection was envisioned.

General fatigue assessment

A heavy fatigue impact on the primary side, even from strong flexible operation, was not confirmed. In most circumstances, the temperature differences were much less than 60 K and were approximately 20 K, as the plant was performing the flexible operation in the region of the constant average temperature in the primary circuit. Overall, in regards to the consideration of the real transients, applying online monitoring and more detailed fatigue analyses facilitated the decrease of the cumulative usage factor on the most impacted components.

In general, when considering a potential 60 year operation lifetime extension, more intense fatigue analyses are considered to be obligatory.

Appendix G: Voltage regulation provided by NPPs

The overall impact on electrical components, including main generator from overall changed operation requirements and grid conditions was collected in (Salnikova et.al., 2021).

Over the years, a change of the power factor (from overexcited to underexcited operation) can be seen in various German NPPs.

During the design and construction phase of NPPs, the foreseen operation of the main generator was in an overexcited (inductive) mode, as shown in the next Figure 15 with a power factor of 0.9 inductive.

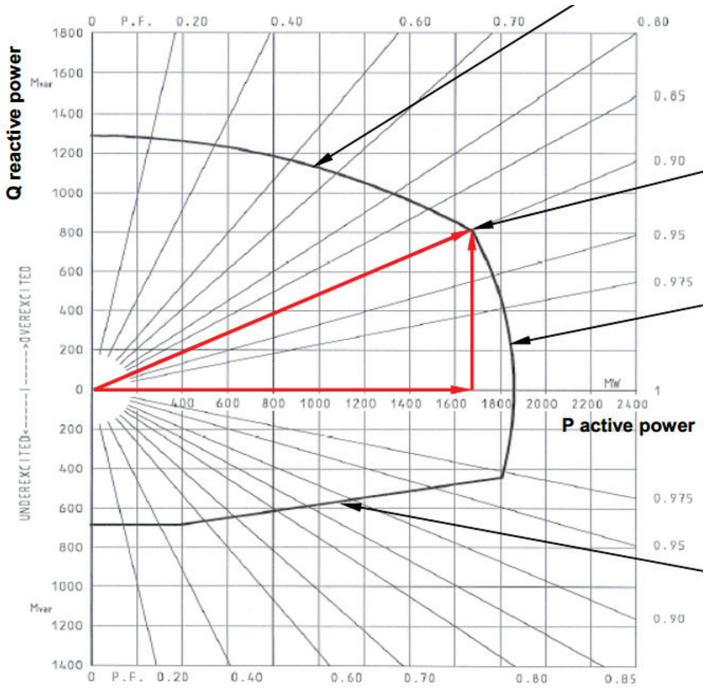

Figure 15: Generator diagram with "standard operational point".

Depending on the local grid conditions of an NPP, in many cases the operation of the generator is carried out mainly in an underexcited (capacitive) mode, as shown in the following Figure 16. This operation mode is necessary because renewables, especially photovoltaic sources, may create a high voltage in the grid, which has to be reduced by the conventional plants with underexcited (capacitive) operation mode. If the electric utility has no other conventional alternatives, this has to be done by NPPs. Otherwise, with fossil fuel fired plants available in the operating park, NPPs are used only in rare cases in the underexcited (capacitive) operation mode.

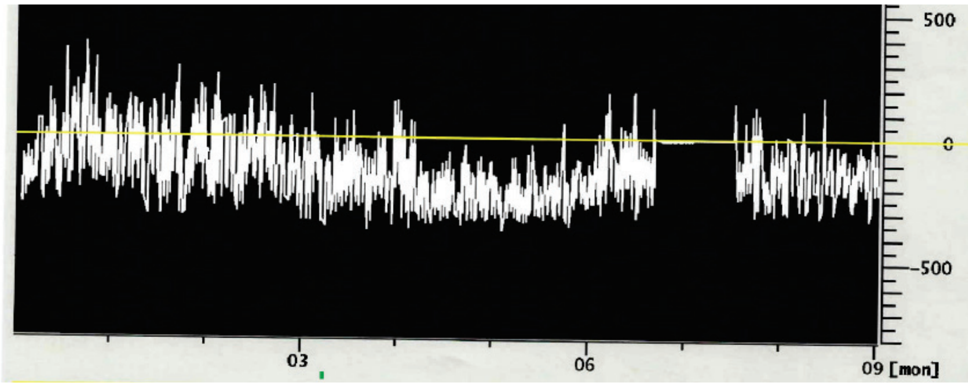

Figure 16: Reactive power (inductive/capacitive) of PWR A over 9 months.

The underexcited (capacitive) operation mode is afflicted with some technical constraints, as described in the following:

a). Active power production may be affected.

The generator curve presented in Figure 15 shows that with a power factor (capacitive) lower than 0.975, the active power production has to be reduced. This is also shown in Figure 17 for a specific plant. The maximum capacitive reactive power which can be produced without reduction of the active power for PWR A is approx. 400 MVAr.

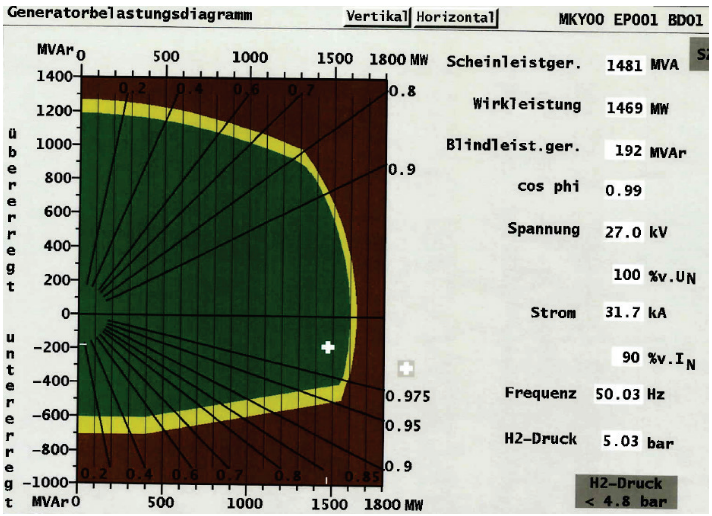

Figure 17: Generator diagram of PWR A.

b). Instability of the generator in case of a short circuit in the grid (fault ride through (FRT)).

In case of a short circuit in the grid, the unit has to remain connected to the grid with stable generator until the fault clearance time (150 ms in Central Europe, 250 ms in the NORDEL area). With the same fault clearance time, the generator of a capacitive operated plant gets faster instable than a plant operated at the nominal point of Power factor 0.9 inductive.

c). Initiation of switch-over to standby grid in case of short circuit in the grid, depending on power factor

The initiation of the switch-over of the unit auxiliary power supply to the standby grid is initiated in many plants from the unit protection, due to underfrequency and undervoltage.

In case of a short circuit in the grid, the plant has to remain operable and connected to the grid under conditions defined by the Grid Code. Additionally, to the risk that the generator gets instable, the initiation of the switch-over to standby grid by the undervoltage protection is high. As shown in Figure 18, the voltage sag after fault clearance (150 ms in this case) depends on the power factor. During underexcited operation (capacitive power factor), the time until voltage recovery increases significantly. The risk that a power plant will be disconnected in case of a fault in the grid increases while the generator is performing in underexcited mode.

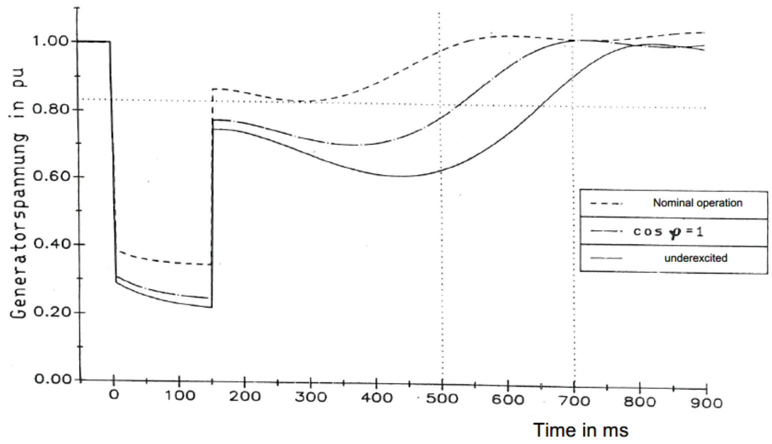

Figure 18: Typical generator voltage in case of a short circuit in the grid, depending on the power factor.

Remark: At load conditions with very high capacitive reactive power, the stator core and especially the end zones could be subjected to higher thermal and vibrational stresses, which should be avoided to assure a reliable operation of the generator. Other influences from the Grid

Due to the influence of the renewable energy sources, the stability in the grid has lowered. The windmill parks supply their energy to the grid via fast reacting static inverters, which produce a “non-perfect” sinus with influence on the generator. The harmonics may produce vibrations in the stator lamination.

Compared to the past, the Power System Stabilizer acts more often (approximately 10x). This creates also stress for the generator.

SURVEY ON OPERATIONAL EXPERIENCES OF NPPS IN A TRANSITIONING ENERGY SYSTEM GOING FROM BASELOAD TO FLEXIBLE OPERATION – GERMANY CASE STUDY

This report provides a survey on operational experiences of NPPs in a transitioning energy system going from baseload to flexible operation (FlexOp). It is based on the existing operational experience in German Pressurized Water Reactors (PWR) and Boiling Water Reactors (BWR), collected by Framatome via four interviews with high level management, knowledgeable on the FlexOp strategy. Impacts on the plant from a design, operational and organization point of view, as well as the corresponding measures to improve the flexibility or to mitigate impacts were summarized. The level of the performed flexibility and some specific features were noted as well, mostly focused on altering the active power. Nordic NPPs could benefit from this information, minimizing possible risks when such a transition is required.