ÖSTERREICHISCHES ÖKOLOGIE INSTITUT

NPP Output Flexibility

Expectations in the Light of Reality

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1. INTRODUCTION

Greenpeace International commissioned Ms Antonia Wenisch, Austrian Institute of Ecology and Ms Oda Becker, Scientific Consultant in Hannover, to prepare this study on NPP output flexibility.

An electrical grid needs to maintain constant power (voltage and frequency) for its consumers. The balance of generation and load in the electricity grid continuously fluctuates, often significantly and on varying timescales as industrial and household demand ebb and flow throughout a day, a week, or a season. Since there are not many options for storing electricity at a larger scale, power generation must take place where and when required. This flexibility is called load following.

Flexibility is a key issue in the current discussion about the future role of nuclear energy in the European electricity system, concerning operating plants as well as planned NPP.

In past years, German nuclear industry executives warned against a growing share of wind turbines and other renewable sources for CO_2 reduction, because this would destabilize the electricity grid.

However, in fall 2009 when Chancellor Merkel's newly elected, pro-nuclear coalition confirmed the government's commitment to renewable energies development, the big utilities changed tactics and tried to figure out how their NPP could contribute to Merkel's long-term energy strategy. E.On Energie AG commissioned the IER (Institute for Energy Economy at the University of Stuttgart) to examine the potential share for operating reactors in load-following mode as a support for a significant expansion of renewables until 2030.

Mostly NPP are operated as baseload plants at 100% power for economic and technical reasons. Operators and power utilities in general have not much interest in load following operation.

Therefore only a few scientific papers about nuclear power and load following were published. Two of them we refer to in our study:

- Compatibility of renewable energy and nuclear power, University of Stuttgart, commissioned by E.ON (IER 2009)
- Electricity Policy Working Group (EPRG); Can nuclear power be flexible? (POURET 2007)

Further information on the integration of nuclear power into the grid and potential load following problems are mentioned in several publications, which were not specifically focused on load following operation of NPP. On top of studying existing literature, we conducted some interviews with experts of other institutions. In particular, we need to thank Mr. M. Baumann from the Austrian Energy Agency and Mr. T. Kapetanovic from the Austrian energy regulator authority "e.control" for their valuable information.

- Our study provides information on fundamental physical phenomena which are crucial for the understanding of reactor power control, flexibility (Chapter 2),
- on the grid requirements for reserves and flexibility of generators. This chapter discusses the IER study and makes a comparison of the statement on load following capabilities and the actual contribution of German NPP to grid stability (Chapter 3),
- and adverse effects of extensive load following in operating and new plants, which

could influence the safety of NPP (Chapter 4),

- at the end we present our conclusions (Chapter 5).

2. BASIC INFORMATION ON REACTOR POWER REGULATION

A nuclear power plant is a thermal power plant. The difference to fossil fuelled power plants being that steam is produced by nuclear fission. Nuclear fission takes place inside the reactor vessel in the reactor core. Thermal energy (thermal power) generated by nuclear fuel is transferred to the coolant – e.g. water. The coolant can be used to produce steam directly (boiling water reactor) or via the steam generator -a heat exchanger- (pressurized water reactor). As in other thermal power plants the steam drives the turbine-generator. The conversion of thermal energy to electricity has an efficiency of about 33%. Thus the thermal power from the nuclear fuel must be 3 times higher than the electrical power output.

Load following operation concerns the electrical part of the plant. There are two main options for the plant to respond to load following:

- regulation of the reactor core (reactivity control)
- regulation of the turbine-generator

REACTOR REACTIVITY CONTROL

Reactivity is the parameter used to measure and control reactor power changes. As a simple analogy, reactivity to a core is like heat to a kettle full of water. Assuming the core is already critical, adding reactivity increases power (neutron flux) just as adding heat to a kettle increases the water's temperature inside.

At each output level a certain quantity of nuclear fissions per time unit needs to take place in the reactor core. Stable operation requires the amount of neutrons produced by fission to equal out the number of neutrons lost through absorption and leakage. This is exactly the case, when the multiplication factor k, which gives the ratio of neutrons of succeeding generations, is 1.

For a self-sustaining chain reaction of fissions, the neutron population is neither increasing nor decreasing. This status is called critical.

> The average lifetime of neutrons □and the time between neutron generations lasts in the range of seconds. This time is the principle reason, which makes the reactor power control possible.
>
> If k is less than 1, the number of neutron exponentially decreases. If k is greater than 1, the number of neutrons and thus also the reactor power exponentially increases. Instead of k often the reactivity □ = (k-1)/1 is used. The following formula applies for reactor power: $P(t) = P_0 e^{\frac{\frac{k-1}{k}}{\Lambda}t} = P_0 e^{\frac{\rho}{\Lambda}t}$
>
> In principle the multiplication factor k is defined by the number of fissile atoms (enrichment grade and burn-up rate of nuclear fuel) and the *moderator* to *fuel volume ratio*. When the control rods are inserted always k < 1, resp. □ < 0 applies. A freshly refuelled PWR with control rods pulled out, has a multiplication factor of about 1,3. With increasing burn-up factor k develops towards 1.

Start-up of a reactor takes place by pulling out the control rods, respectively by reducing the absorber concentration in the reactor cooling system. The number of neutrons as well as the size of the neutron generation continuously increases. This leads to an increased number of nuclear fissions and a higher coolant temperature.

The most widely used tool, for controlling the reactivity are control rods. Their effects are indeed much faster than injected diluted neutron poisons, such as soluble boric acid. Roughly speaking, the more control rods a reactor has, the better is its flexibility. It is important to note that while most reactor types have control rods for reactor shut-down, these rods are not optimised for adjusting reactor output to changing levels.

The shut-down rods are known as **'black rods'** indicating their complete absorptive capacity for stopping the passage of fission neutrons.

REACTOR REGULATION FOR LOAD FOLLOWING

- Flexible reactor operations are facilitated through the use of special reactor control rods known as **'grey rods'**. These rods do not completely absorb the fission neutrons that try to pass through them. For load-following manoeuvres, a clever management of both control rods and soluble boron is found to be optimal.
- Another output regulation mode is applicable in PWR: This regulation is initiated by the turbine-generator. An increase or reduction of the electrical output influences the steam production and this initiates a feedback reaction: temperature change in the secondary circuit is transferred to the primary coolant, thus reactivity changes into the desired direction.
- BWR have no self regulation mechanism. For output regulation besides use of control rods, it is possible to change the rotation speed of the main circulating pumps. The pressure regulation changes the turbine valves and thus the desired electrical output is achieved.

PRESSURIZED WATER REACTORS (PWR)

Pressurized Water Reactors control the thermal power of the core with the control rods and the boron water ratio in the coolant coupled with an inherent feedback mechanism. PWR are able to follow changes in electric power output on their own by changing the average coolant temperature. When a certain generator output is required, the turbine inlet valves are adjusted. This causes a higher steam extraction and then a decrease in the average coolant temperature. This comes with a higher density of the moderator, leading to a higher number of thermal neutrons and therefore a higher number of fission processes. In this way the reactor adjusts itself to the required steam output (at a slightly different temperature level inside the reactor).

If, however, the temperature excursion reaches a certain set point, the temperature regulation adjusts the control rods in such a way, that the medium coolant temperature returns to its set point.

In the power range of 50 to 100% small disturbances are rebalanced by inherent self-regulation.

Due to the proportional response of the feedback mechanism a limited temperature excursion continues, which however, after having reached a certain limit value, can be reduced by inserting the control rods. Steam production by nuclear reactors is generally faster than by most other thermal plants. This is an advantage for grid operators.

Nuclear power plants, however, are mostly used as base load for economic (lower fuel costs) and technical reasons (avoiding mechanical wear of the fuel cladding due to differences in the thermal expansion of fuel claddings and fuel – the “pellet cladding interaction“)

BOILING WATER REACTORS (BWR)

Controlling power in boiling water reactors is based on changing the moderator density via the amount of steam bubbles ("voids") in the boiling coolant. Higher steam extraction causes a decrease in moderator density, because the decreased steam pressure leads to an increased volume of steam bubbles; output then decreases. Boiling water reactors do not have a self regulating behaviour, therefore boiling needs to be kept on a constant level. At a constant pressure level the steam bubble effect can be used for power control.

Power control between 60 to 100% is regulated with the bubbles ratio, which is dependent on the coolant flow. The set point is set with the control rods. For load-operations, first the reactor output needs to be changed by inserting the control rods or by changing the pump rotational speed into the needed direction. The pressure constant regulation changes the turbine control valves; the intended load change takes place.

LONG TERM REACTOR CONTROL

Long term control is about keeping the reactor power stable until refuelling. During burn-up of fuel, reactivity of the core decreases. To prevent the neutron flux and in consequence the thermal reactor power from decreasing, the neutron absorber has to be reduced toward the end of the refuelling cycle. Boric acid is usually added to the coolant of a PWR. To keep the neutron generation stable cooling water cleaning system needs to remove the boron simultaneously as the reactivity decreases.

The past years saw the introduction of burnable absorbers (gadolinium) being integrated into the fuel assemblies as a solution to this problem: because the absorption capability of gadolinium decreases in time in the reactor, less and less neutrons are captured. This keeps the reactor power stable until the end of the refuelling cycle, i.e. until fresh fuel is loaded.

Control rods should be used as little as possible for long term control, to avoid wear-out and have them ready for fine tuning of reactor power and reactor scrams.

REACTOR POWER LIMITATION

During power operation of a PWR the coolant temperature control system makes the reactor output follow the generator output. The generator control system, however, does not recognise, when the power demanded is too high. In this case the reactor power limitation is activated;

XENON POISONING

A key factor concerning power control is xenon poisoning after a reactor shut down or also a power reduction. Xenon is one of the most significant neutron poisons. Under normal operation, i.e. steady power, after approximately 40 hours the production and decay of ^{135}Xe reaches an equilibrium. However, after a power reduction the ^{135}Xe concentration increases; this can lead to a situation, where the reactor depending on the existing reactivity reserves, cannot start-up as quickly as might be desired (see also chapter 4)

FUEL RODS BEHAVIOR

Between the fuel pellets and the cladding of a fuel rod, is a gap (from fabrication). The gap is kept as small as possible, to achieve a support effect of the rod early on. The rods diameter shrinks continuously during operation, while the fuel pellet diameter starts to grow after a short shrinking phase; this closes the gap. The pellet then puts pressure on the cladding. After some time this pressure would cause a failure of the cladding. This point in time can be calculated fairly precisely in advance, however, only if the fuel assemblies were not exposed to quick temperature changes, i.e. load changes. For this reason the acceptable load change rate is clearly defined.

CONTROL RODS

The control rods are grouped in assemblies:

For smaller or slower changes in output of a PWR the D-bank is used. It is called “Doppler bank”, because its purpose is to compensate the Doppler effect. For large or fast changes in output, the “L bank” is inserted, which consists of the majority of control rods.

3. Requirements on power plants in the liberalized electricity market & nuclear power

The delicate balance of generation and load on an electricity grid continuously fluctuates, often significantly and on varying timescales as industrial and household demands ebb and flow throughout a day, a week, or a season. Generation must adapt where and when required. Morning and evening demand swings generally occur over a few hours; but there are also significant plant trips to deal with (well over 1000 MWe in a single instance). It is evident that utilities have developed plans to account for a number of potential scenarios.

Utility operators can vary the electrical output from some power plants quickly to adjust total generation to total demand. Hydro power is an example. In generation mode the water falls through a turbine generating electricity. In nearly all cases, power can be quickly changed by reducing or increasing the amount of water passing through the turbine. Some hydro stations can work in reverse; taking power from the grid to pump the water back up into a reservoir (pump storage). Demand can be added by increasing the pump speed or total number of pumps in operation. Such facilities give operators the flexibility to manipulate either side of the load / generation balance. This mode of operation is referred to as load following. (Nuttal 2007)

The deregulation of the electricity sector in Europe towards the very end of the 1990s led to the development of short-term markets, where traders can compare available generation in various locations, right down to the shortest time-frames (week or day, or even hours of the current day). The transactions carried out on these markets, where the operating conditions are relatively well known, offer the most efficient means of ensuring the least-cost generating units across the interconnected systems are used in priority.

The only limitation to this optimal use comes from network congestion: If the lines serving a zone are saturated, all additional demand in that zone must be met by local generation, even if there are less expensive generating units available elsewhere. (RTE 2009)

Electric energy can not be stored to a great amount in the European grid and can not be made easily and fast available if needed. Every discrepancy between power input and output causes a frequency deviation.

However, power frequency deviation needs to be kept in certain limits: as frequency increases immediately in case of an overflow of active power and decreases in case of a deficiency of active power. In the grid generation and consumption of electricity must be balanced, in order to avoid damage on equipment and guarantee the stability of the supply.

Power supply in the Europe-wide integrated grid with lots of big and small power generators and millions of consumers has to provide the following services (Erlacher 2005):

- steady availability even in case of large and fast fluctuations of electricity generation
- steady availability even in case of large and fast fluctuations of electricity demand
- steady frequency of AC in the grid even in case of fast fluctuations of load and supply.

Electrical measures for the stabilization of the power grid are provided by control power reserves. Control power is provided by power plants, with high flexibility and standby capacity which can be activated fast.

Table 1: Overview on important overall fixed values an annual operational data applied for the European grid (UCTE Policy 1)

Subjekt	**Value**	**Dated**
Nominal Frequency	50 Hz	Fixed
Activation of PRIMARY CONTROL	±20 mHz	Fixed
Full Activation of PRIMARY CONTROL RESERVES	±200 mHz	Fixed
Reference Incident	300 MW	Fixed
SELF-REULATION of Load	1% Hz	Fixed
Highest load in the system (from 03.12.2008)	412000 MW	2009
Contribution by SELF-REGULATION of Load	4120 MW/Hz	2009
Minimum NETWORK POWER FREQUENCY CHARACTERISTIC of PRIMARY CONTROL	15000 MW/Hz	Fixed
Average NETWORK POWER FREQUENCY CHARACTERISTIC of PRIMARY CONTROL	19500 MW/Hz	2009
Mean generation power (in the system)	306000 MW	2009
SURPLUS-CONTROL OF GENERATION (50% of mean generation power in the sytem / 50 Hz)	3060 MW/Hz	2009
Overall NETWORK POWER FREQUENCY CARACTERISTIC	26680 MW	2009
Overall PRIMARY CONTROL RESERVE	3000 MW	Fixed

In German speaking areas we speak of reserves available in seconds, minutes and hours, according to the requirements to be fulfilled. Since the power supply can sometimes be too large compared to the demand, positive and negative control power is needed.

For very fast regulation (i.e. primary control) normally gas-turbines, working at partial power are provided, which can very fast achieve full power (e.g. to replace a big power plant, which failed suddenly). In case a big power consumer turns off unplanned, the overflow of power has to be used. Usually this can be done by pumped storage power plants, which can deliver the stored energy back to the grid, if needed later. Pump storage plants are reserves available within a minute and play an important role for balance control as a positive and negative reserve. (Information: Austrian e-Control)

Fluctuations lasting longer than a few minutes are known from statistics or announced by power trading and regulated with power plants which need more time for start-up like nuclear and coal power plants (tertiary control).

The steadily increase of power trade in the existing grid leads to usage of reserves in normal operation, and this results in loss of supply security. Transmission system operators (TSO) have to find ways to meet this new requirement.

The answer to this new need for flexibility in electricity generation cannot be large thermal plants, like nuclear and coal fired plants; because their economic and technical characteristics restrict them mainly to serve as base-load.

PRIMARY CONTROL RESERVE

Must be activated within 30 seconds and has to be provided for 15 minutes (this power is mainly provided by gas turbines) – supply is independent of the site of generation. A capacity of 3000 MW has to be provided for primary control for the European grid. The generating units are distributed over all 32 European grid control areas. (Austria for example has to provide 74 MW). Activation of primary reserve has to be carried out automatically by the dispatcher. Within 15 minutes secondary reserves are activated and have to take over the required electricity generation. Fast replacement of the primary control reserve is required, because this generation capacities are provided for events where a big plant or part of a grid fails.

The provision of primary reserves is contracted out. Companies offer generation capacity.

SECONDARY CONTROL RESERVE

Secondary reserves have to be activated within 5 minutes (activation is automatic) and have to run at least one hour. Secondary reserve must not be as fast as primary. But within 15 minutes the primary reserve’s capacity has to be replaced.

Large thermal power plants (coal, nuclear older gas power plants), usually are not used for primary and secondary control because they are not reasonable qualified for this operation: they are not fast enough, could be affected by an increase of mechanical fatigue of material and for this power plants partial power operation is not efficient economically and energetically.

TERTIARY CONTROL

This is needed for the scheduled exchange of power. The aim of power trade is to offer the consumers a secure and cost efficient electricity supply. For this exchange energy to guarantee the balance of supply and demand has to be provided.

The challenge for the control areas is to guarantee the physical balance due to the stochastic deviations between power demand and generation.

The control areas came up together with the grids. Since the grids have been national, the control areas are determined by policy. In Austria three control areas evolved: Illwerke/

Vorarlberg where the first transnational cooperation was introduced – with EnBW, Tirol and the rest of Austria. These three areas will be united to one Austrian control area. Germany has 4 control areas, which are allocated to the 4 large power utilities: EON, RWE, EnBW and Vattenfall. The optimal size of a control area from a physical point of view should have a radius of about 400 km. (That's the reason why Austria will unite its three control areas to one).

Technical requirements on primary control

Generation units > 100 MWe
Positive and negative reserve
Activation within 30 seconds
minimal provision 15 minutes;
Bandwidth for regulation ±2% of nominal power and minimal ±2 MWe
Frequency control ±10 mHz (VERSTEGE 2003, UCTE 2008)

Technical requirements on secondary control

Activation within 5 min
Minimal provision: 1 hour
Velocity of power change: thermal plants 2% of nominal power per minute (VERSTEGE 2003)

Power delivered on schedule in 15 minutes exchange timing, also manually available (UCTE P1)

Table 2: Dynamic characteristics of thermal power plants (IER 2009)

Plant type	**Start-up time [h]**	**Minimum power [% of nominal power]**	**Velocity of power change [%/min]**
Natural gas turbine	0	20	20
Natural gas co-generation plant	1	33	6
Natural gas steam turbine	1	38	6
black coal steam turbine	2	38	4
Lignite steam turbine	2	40	3
NPP (Light water reactor)	0,25 0,50	80 50-60	<.10 4-6

QUALIFICATION OF LIGHT WATER REACTORS FOR LOAD FOLLOWING OPERATION

Germany

Germany's biggest reactor-owning company E.On Energie AG, contracted IER to examine the potential for operating reactors in load-following mode to support a significant expansion of renewables through 2030. The study came to the conclusions that the design basis of all German reactors, permits load-following (as illustrated in the figures above). About 9.6 GW of German reactors' capacity could be dedicated to load following without any technical restrictions during periods when the load changes at a rate of up to 5.2% per minute. According to IER, this means that, within 15 minutes, about half the country's total nuclear capacity could be called upon to meet intermediate and peak demand. (NW 2009)

Pressurized water reactors

In PWR fast regulation is possible in the high power range by inherent self regulation. Therefore, PWR are adequate for grid frequency stabilization in the power range (>80%).

The IER study states that within 15 minutes a 50% power change can be reached in a German PWR, however, the power level is not allowed to drop under a minimum of 50% nominal power. The power increase gradient is 3,8 – 5,2% per minute[1]. This is understood to be a conservative approach, since the operator's handbook would permit a 10% power increase per minute. The figures for PWR also include a power change gradient for an EPR with an output flexibility of 20 – 100% nominal power (1600 MWe) within 20 minutes. (IER 2009)

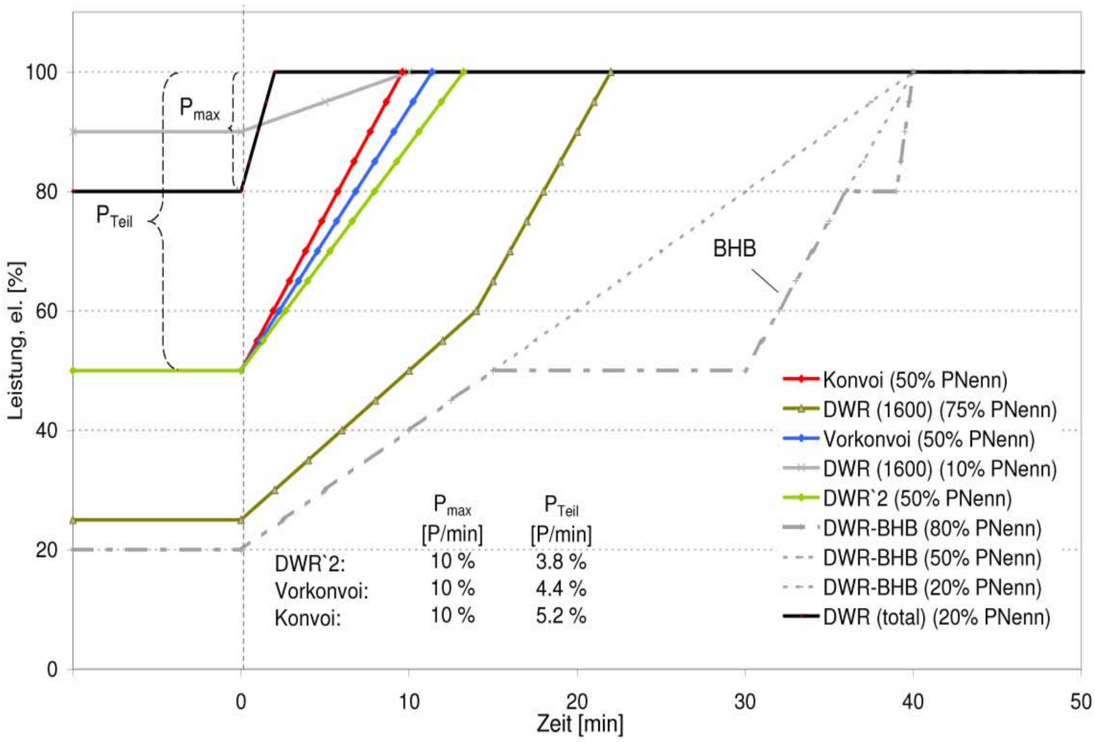
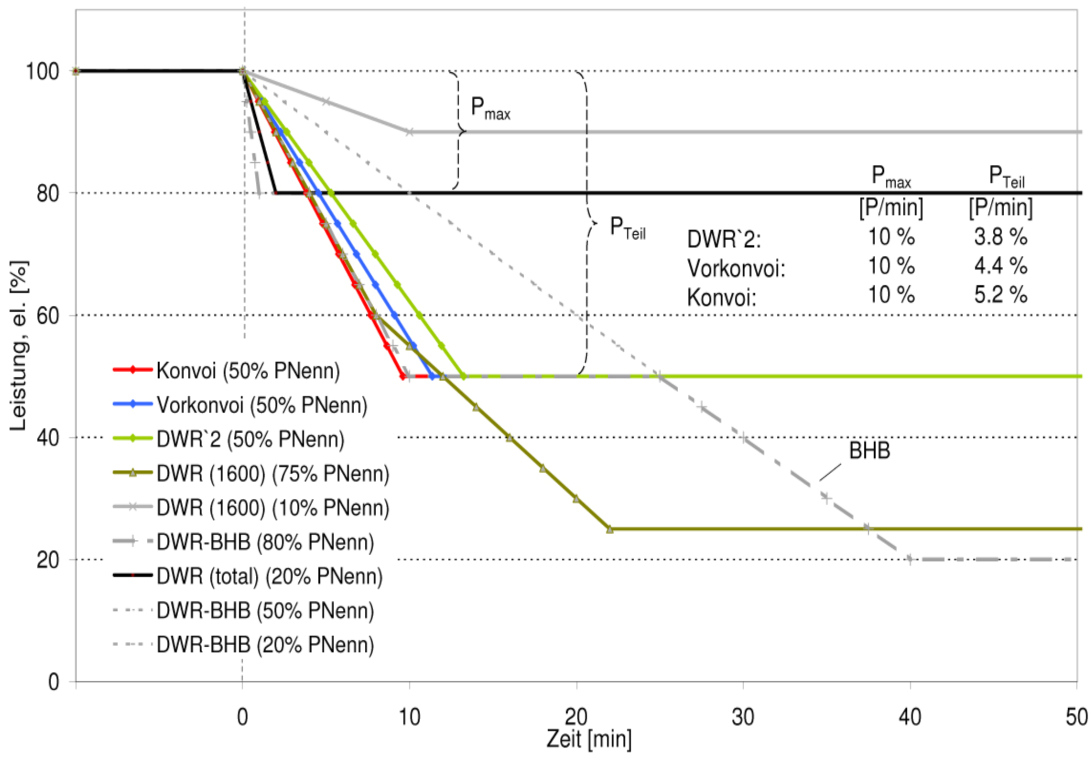


Figure 1 (IER 2009): Power increase in pressurized water reactors (PWR)

1 According to the design series (Vorkonvoi, Konvoi)



Legend: DWR = PWR; Leistung = power, Zeit = time; Vorkonvoi / Konvoi - German type series, P_{nenn} = nominal power, BHB= operators handbook. DWR 1600 = EPR

Figure 2 (IER 2009): Power decrease in pressurized water reactors (PWR)

In the real world of power generation and exchange nuclear power plants are used mainly in base load operation. With the exception of three units, German power reactors have not been operated for load following. Only Philippsburg-1, Neckarwestheim-1, and Unterweser — have been operated for any considerable time in load-following mode.

The power ramps – said to be conservative- in the EIR study differ from reactor operator information:

According to E.ON operation handbooks for Konvoi PWRs power change gradients are given as follows:

- 10% per minute for changes of max. 20% of nominal power,
- 5% per minute for changes of max. 50% of nominal power and
- 2% per minute for changes of max. 80% of nominal power.

(MÜLLER 2003)

Furthermore only the three newer German PWR can achieve power changes of 50% nominal power in 15 minutes. The 9 older German PWR need 20 minutes for 50% change of power.

Boiling water reactors

In BWR fast regulation is possible in the range above 90% nominal power: ± max. 10 % is possible. According to IER study BWR are as adequate for grid frequency stabilization as PWR in the power range of > 90%. If the minimum of 60% nominal power is kept in BWR a power change is possible with a gradient for partial load in the range of 1,1 – 4,6% of nominal power per minute[2] . (IER 2009)

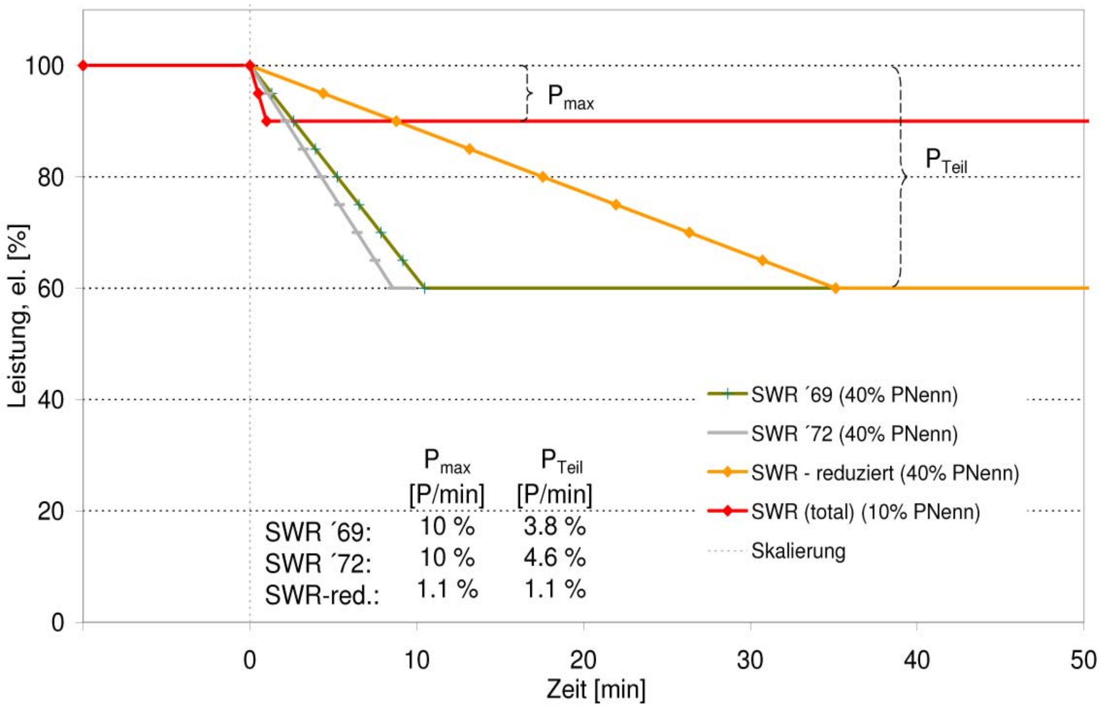


Figure 3 (IER 2009): Power increase in boiling water reactors (BWR)

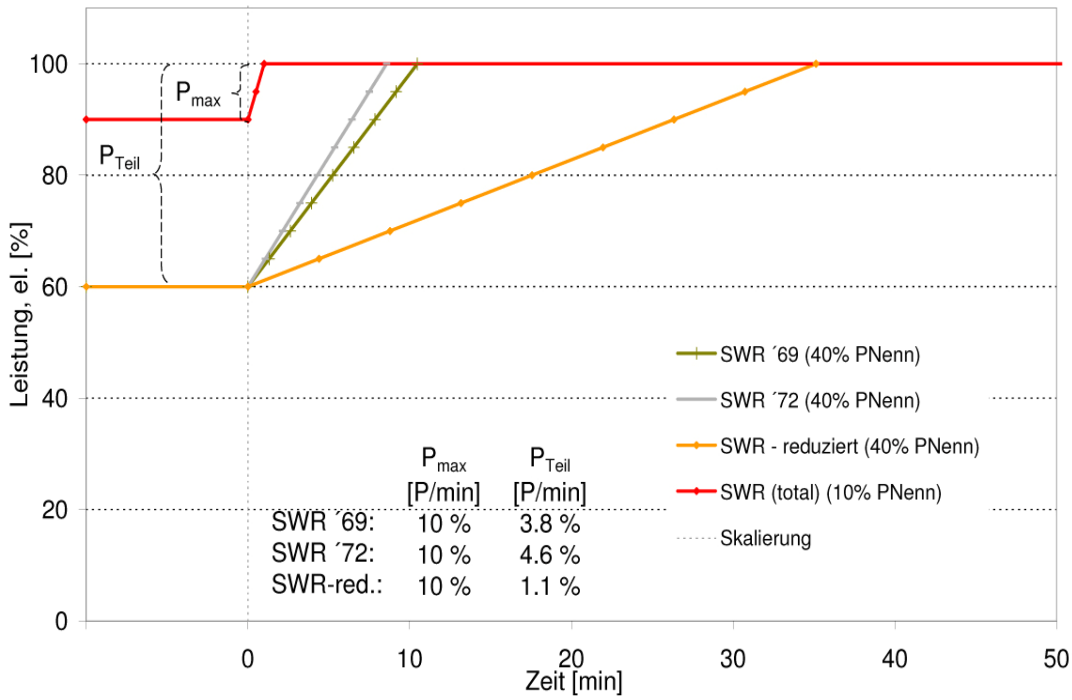


Figure 4 (IER 2009): Power decrease in boiling water reactors (BWR)

Legend: SWR = BWR; Leistung = power, Zeit = time; P_{nenn} = nominal power, SWR 69 SWR 72 - German type BWR series; SWR-red. BWR reduction due to fuel damages

2 According to the design series (SWR 69, SWR 72)

For BWR the IER study reports power gradients of 3.8 and 4.4% per minute in the range of 60 to 100% nominal power. Even in the IER study it is mentioned, that potential fuel damages could cause a reduction to 1% per minute. But this problem is not considered in the “conservative” assessment. According to the EIR study in the power range of 90-100% it is even possible to use a power gradient of 10% per minute. In contrast to the IER study, the operator of the BWR Isar 1 states that the range for power cycles of 40% nominal power has to be reduced to protect the fuel from high loads (FRANK 2003).

In reality Isar 1 provides the dispatcher a primary control reserve of ± 2.5% in the power range of 60 to 97.5%.

German government sources familiar with the discussion of possible future nuclear load following said that, should the government and industry move forward on this issue, the Federal Ministry of Environment & Nuclear Safety, BMU, Germany’s regulator, and its technical support organization, Gesellschaft fuer Anlagen und Reaktorsicherheit bmH, would likely formally study the safety implications of shifting most or all of German power reactors to load-following operation. One safety expert said that some investigation on critical component stress would be obligatory (NW 2009b).

The IER study is misleading, because the maximal technical capability for load following manoeuvres neglects safety relevant restrictions, which are enforced on the operating German NPP. The energy scenario of the IER study suggests an expansion of nuclear power and lifetime extensions of existing NPP. The assumptions regarding load following operation do not consider safety aspects. Therefore it is not likely, that load following operations will be implemented to a larger extent in the near future.

France

Even in France the flexibility of PWR is used mainly for frequency control, in order to ensure this function NPP have to be operated with a reduced capacity. Over 40 units are operated on load following mode, which allows for the power output to be modified on the short term within a ca. 5% margin

Normally base-load generating plants, with high capital cost and low operating cost, are run continuously, since this is the most economic mode. It also it is technically the simplest way, since nuclear and coal-fired plants cannot readily alter power output, compared with gas or hydro plants. The high reliance on nuclear power in France (75% of the electricity) thus poses some technical challenges, since the reactors collectively need to be used in load-following mode.[3] (NUTTAL 2007)

RTE, a subsidiary of EdF, is responsible for operating, maintaining and developing the French electricity transmission network. France has the biggest grid network in Europe, made up of some 100,000 km of high and extra high voltage lines, and 44 cross-border lines, including a direct current (DC) link to UK. Electricity is transmitted regionally at 400 and 225 kilovolts. Frequency and voltage are controlled from the national control center, but dispatching of capacity is done regionally. Due to its central geographical position, RTE is a crucial entity in the European electricity market and a critical operator in maintaining its reliability.

All France's nuclear capacity is from PWR units, which are equipped with some less absorptive "grey" control rods thus allow sustained variation in power output. This means that RTE can depend on flexible load following from the nuclear fleet to contribute to regulation in three respects:

3 The time periods, frequency of adjustment and response time required by loads following are in direct conflict with the nature of xenon transients at NPP. For this reason, most NPP operators choose not to subject their facilities to load following operating modes. (Nuttal 2009)

- Primary power regulation for system stability (when frequency varies, power must be automatically adjusted by the turbine),
- Secondary power regulation related to trading contracts,
- Adjusting power in response to demand (decrease from 100% during the day, down to 50% or less during the night, etc.) (WNA)

RTE has continuous oversight of all French plants and determines which plants adjust output in relation to the three considerations above, and by how much. (WNA 2010)

While the availability NPP in France had increased since 2000 from 80.4% to 83.6% in 2006, in 2007 the load factor dropped by 3.4% to 80.2%. This drop is clearly of technical nature: mainly to generic steam generator clogging and electric generator maintenance (SCHNEIDER 2009).

The steam generator plugging is only one of the latest of a list of serious generic problems that hit the French reactor fleet. While there is no doubt that the high level of reactor standardization has multiple technical and economic advantages, it has also brought along the problem of systematic multiplication of problems into large parts of the reactor fleet. However, also the overall number of safety relevant events has increased steadily from 7.1 per reactor per year in 2000 to 10.8 in 2007 (SCHNEIDER 2009).

In 2009 EDF expected its 58-unit PWR fleet to average 78% availability, compared to 79.2% in 2008 and a goal of 81%.

The financial community (including investors in Great Britain) has criticized EDF for not achieving the high levels of availability. EDF use load-following operation to justify the low capacity factor. But actually the reduction caused by load-following operation is low. According to EDF itself 2008 only 1.5%-plus difference was due to load-following with nuclear plants in France, versus the baseload operation in the US. Other reasons are: EDF's use of 12-month operating cycles, instead of the 18- or 24-month cycles used in the US, accounted for more than 1.5%. 1.5% or more are due to the requirement for the decennial outages. 1% is due to restrictions on thermal effluents during summer months that require reduction in some riverine plants' output (NW 2008a).

Technical problems have affected the availability more, only the steam generator clogging problem, shaved 2.2% off EDF's average availability in 2007 and 1.9% in 2008 (NW 2009a).

EDF said in 2009 only 1.8% of 6.2%t total gap in availability between French and US reactors are caused by load following operation (NW 2009a).

Every decrease of capacity factors is criticized by investors. High load factors are of high relevance in particular for investors interested in new NPP.

4. OUTPUT FLEXIBILITY OF NPP - TECHNICAL LIMITATIONS AND SAFETY ISSUES

REACTIVITY CONTROL

The most widely used tool, for controlling the reactivity are control rods. Their effects are indeed much faster than injected diluted neutron poisons, such as soluble boric acid. Roughly speaking, the more control rods a reactor has, the better is its flexibility (in particular its frequency control capabilities). It is important to note that while most reactor types have control rods for reactor shut-down, these rods are not optimized for adjusting reactor output to changing levels.

The shut-down rods are known as 'black rods' indicating their complete absorptive capacity for stopping the passage of fission neutrons.

Flexible reactor operations are facilitated through the use of special reactor control rods known as 'grey rods'. These rods do not completely absorb the fission neutrons that try to pass through them.

For load-following maneuvers, a clever management of both control rods and soluble boron is found to be optimal. The exclusive use of control rods for regulating the output power would have negative consequences, such as:

- flux distribution disturbances,
- component materials fatigue,
- mechanical wear,
- adverse impacts on burn up balance in the core

These unwanted effects are the consequence of grid frequency control which consists of many low-amplitude rod movements (up to several hundreds a day); this may limit the lifetime of control rod mechanisms, as was observed in France.

In his paper published 1990, the author describes specific core monitoring and control system which allows for economic core fuel management, and economic load following operation (GRUEN 1990) The main features of this system are:

- Minimal use of control rods: Control rod insertion in the core causes perturbations in local power distribution, reducing margins to core thermal limits and also – if control rods remain inserted for longer periods – leads to burnup delays in this part of the core. Hence, the ideal case of "control rod free operation" should be approached as closely as possible.
- A steam pressure/coolant temperature vs. load program which is most appropriate for load following: This program keeps the average cooling temperature constant in the upper power range, while decreasing main steam pressure as power increases. Thus, reactivity change associated with power change is minimal, requiring only a minimum of control rods movement. It is an important optimization goal to have high load change capability while keeping exceedance of reactor core operational limits at a minimum.

The example given for power regulation covers the range of 60% - 100% power level. This paper (GRUEN 1990) demonstrates that considerable effort is required to make load following economically viable in terms of fuel use, and to avoid undue reductions of margins to core thermal limits (GRUEN 1990). However, it is not clear in which nuclear power plants this system was actually used.

TEMPERATURE FLUCTUATIONS IN THE REACTOR CORE

Temperature (as well as pressure) fluctuations are crucial to assess the thermal constraints and fatigue for the core vessel and other components. These difficulties are exacerbated by load following operations. Assessments of fluctuations of pressure and temperature and their inhomogeneity along the height of the reactor vessel are especially important in this regard.

The load following capabilities of a reactor stem largely result from pre-construction design choices, including such issues as design for thermal and mechanical stress. The lifetime of a reactor used for load following is also affected by the care taken by reactor operators concerning their use of control rods and/or soluble boron (POURET 2009).

ON-LINE MONITORING SYSTEMS TO CALCULATE THERMAL STRESS

Pressurized components of an NPP suffer from stresses during startup, shutdown and load following. A recently published paper (PANG 2008) presents a method to calculate the thermal stress these parts are exposed to. The method can be applied in practical on-line monitoring systems permitting operators to observe actual stress during operation. Also, the on-line monitoring systems provide inputs to the lifetime monitoring and management systems (PANG 2008). The development of an on-line monitoring system for thermal stress calculation proofs that load-following is an important factor to be taken into account. It also shows that load following is a topic in China where a rapid increase of NPP capacity is planned in the next decade.

FUEL DEFECTS

Although NPP are typically operated as base load, the author (STEINAR 1975) states that load following may become necessary when there is a high share of nuclear power in the grid. A typical power cycle for an NPP in load following mode could be 18 hrs at full power and 6 hrs (during the night) at 40%. Change rates of 10% of full power per minute should be achieved. The objective of the paper was to define the conditions under which changes in fuel rod temperature lead to defects of fuel cladding.

The thermal expansion coefficient of fuel is higher than that of the cladding. Thus, with increasing heat load, the gap between fuel and cladding will be closed and the cladding will be forced to follow the thermal expansion of the fuel; some plastic deformation will occur. Once a fuel pin has been through one power cycle, in general, no additional deformation of the cladding will occur later on any more (unless the previous maximum power level is exceeded).

If the power increase is too large, plastic deformation cannot compensate for the strain and the cladding will crack.

When a fuel rod is permitted to adjust at an intermediate power level (i.e. when the power increase is interrupted for a “resting period”), defects will occur at higher power levels.

In concluding, the author emphasizes that a multitude of factors influence the performance of a fuel rod, which mostly cannot be described quantitatively. (STEINAR 1975).

This paper shows that load following was an issue already in the early phase of commercial nuclear power use. It also examines basic problems and phenomena. The conclusions, of course, cannot be fully supported since knowledge has certainly progressed considerably since the time this paper was written.

In 1988, some experts expected an increasing importance of load following for nuclear power plants in Germany. They were referring to a day/night cycle or power reductions during the weekends. A reference reporting on load following operations at Unterweser NPP is quoted in (FISCHER 1988).

Power cycling experiments were performed at Obrigheim NPP and at the High Flux Reactor (HFR) Petten. The aim was to investigate whether an increased incidence of fuel rod damage would occur.

In all cases two PWR fuel rods were used for the tests. They were cycled up to 50 times with a sequence 100%-70%-110%-100% linear heat generation rate. The power overshoots (110%) almost reached defect thresholds determined by other experiments.

Burnup reached 25 and 35 GWd/t at Obrigheim, up to 40 GWd/t at Petten.

The test rods remained intact; they did not release any activity during the experiments. Swelling of fuel pellets (increase of diameter and ridge formation) practically occurred only during initial power increase and first load cycle; there were hardly any further dimensional changes during the subsequent cycles. Also, the fission gas release corresponded to that of comparable PWR fuel rods which had been ramped only once.

The test report concluded that *"… the experiments confirm the good behavior of KWU PWR fuel rods in load following operation up to high burn-ups"*.

For the current situation, the results are of limited value for three reasons:

- Burn-up at German and other PWR has increased to 50 – 60 GWd/t.
- The load change cycles covered a limited power range (70% -100%)
- The tests were limited to 50 load-change cycles.

Power decreases were tested only on weekends. Therefore these tests did not sufficiently prove that existing or new built NPP can operate in load-following mode without fuel damage.

Studies currently under way take much more different load following cycles into consideration. In 2006 the Institute for Nuclear Research (Romania) presented its investigations on fuel behaviour. One of the current research objectives is to investigate the reliability of nuclear fuel during power cycling operation conditions. The power history comprised **367 power cycles**, mostly between 50% and 100% of power level. The first results showed that during a series of power reductions followed by depressurization the fuel pellet relocation has played a very important role in cladding deformation. (HORHOIANU 2006).

FUEL ENRICHMENT

While it is a relatively minor factor, it is worthwhile to note that a higher level of fuel enrichment increases the reactivity of the core. Therefore fuel enrichment is an important design-specific aspect of the reactor. Reactors with higher levels of fuel enrichment are typically more difficult to control and have core neutron flux distributions that are less well suited to flexible operation.

XENON TRANSIENTS

A detailed description of load following operation in NPP and xenon transients is presented in

(NUTTAL 2009):

A load following generator's principal attribute is responsiveness. With respect to nuclear power plants, responsiveness of currently available light water reactors (LWR) is challenged by neutron poisons – in particular the isotope xenon-135 (xenon). Xenon is a powerful thermal neutron absorber (poison) and will capture neutrons otherwise available for fission of the reactor fuel. It is produced directly and indirectly from fission in all reactors.

Withdrawing control rods increases core reactivity. As a poison, xenon absorbs neutrons and therefore reduces core reactivity with increasing concentration. Xenon transients challenge reactor operation due to continuously changing reactivity addition or withdrawal depending on the nature of the power history and attempted maneuver. For example, consider a reactor start-up about one day after a reactor trip from full power where xenon concentration had been at equilibrium. At the time of start-up, xenon concentration would have already peaked from the decay of iodine in the fuel at the time of the trip. The concentration would be decreasing steadily (adding positive reactivity to the core). This is not a safety concern since the control and safety rods add more than enough negative reactivity to maintain the reactor in a safe shutdown condition.

> Xenon production and removal in thermal reactors has been well understood for decades. However, nonlinearities related to the xenon equilibrium equation challenge the control of power swings required to support a load following mode of operation. Xenon transients have the negative impact of significant reactivity addition or removal over the time periods required by many load following scenarios (i.e. periods of several hours). The operational challenge of an in-progress xenon transient is further exacerbated by increasing or decreasing reactor power as the terms of the xenon equilibrium equation are each impacted by neutron flux (reactor power level) to varying degree.
>
> The neutron flux or power level of a reactor determines the production rate of xenon, iodine and tellurium (xenon precursors) as well as the xenon burn up. Xenon decay and tellurium / iodine decay into xenon are purely time dependent but are constrained by different half lives. Xenon concentration will reach equilibrium after a period of steady state operation or shutdown; in the later case following an initial spike in concentration due to the decay of the remaining iodine and zeroing of the xenon burnup term following the shutdown. Xenon equilibrium is not directly proportional to reactor power level. For example, the equilibrium concentration at 25% power is more than half the equilibrium concentration at 100%.

In some cases high post-trip xenon concentrations add enough negative reactivity to prevent operators from commencing reactor start-up until adequate xenon decay time has passed.

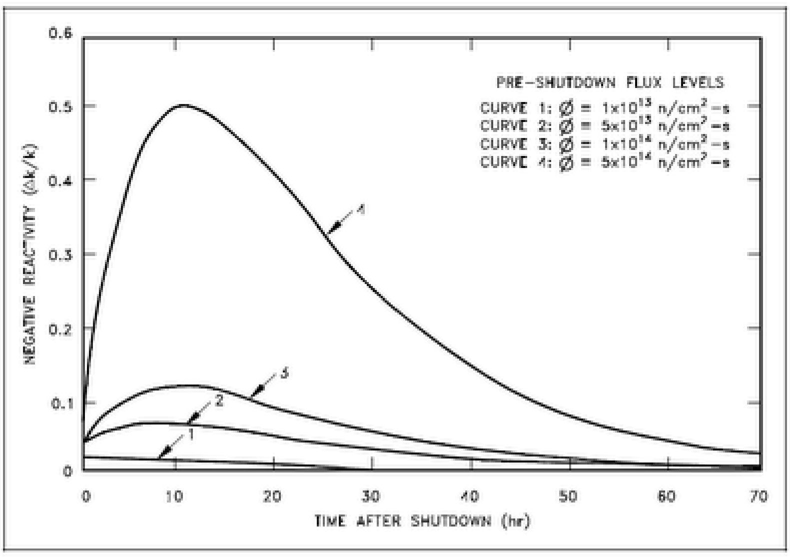


Figure 5 Xenon-135 Reactivity After Reactor Shutdown

Figure 5: Post trip Xenon-135 transient (NUTTAL 2007)

As the reactor start-up progresses, the remaining xenon continues to decay but the concentration reduction is accelerated by the increasing reactor power's impact on the xenon burn-up term of the equilibrium equation. As xenon concentration is reduced, positive reactivity is added to the core (equally accelerated). Operators must closely monitor core reactivity and take any required mitigating action to ensure the reactor is not shutdown automatically by reactor protection systems designed to limit the rate of power increase. Adding to this challenge, many reactor designs and license commitments require discrete hold points during power maneuvers to calibrate instruments, perform reactor physics checks, synchronize the generator to the grid and perform other tests or surveillances

Alternatively, if power is quickly reduced from 100 to 50% the resulting xenon spike, due to reduced burn up but continued iodine decay, will add negative reactivity for several hours and then reverse, adding positive reactivity as a new equilibrium is approached. As with the start-up example above, close operator monitoring and adjustment are required to ensure plant control remains within acceptable parameters.

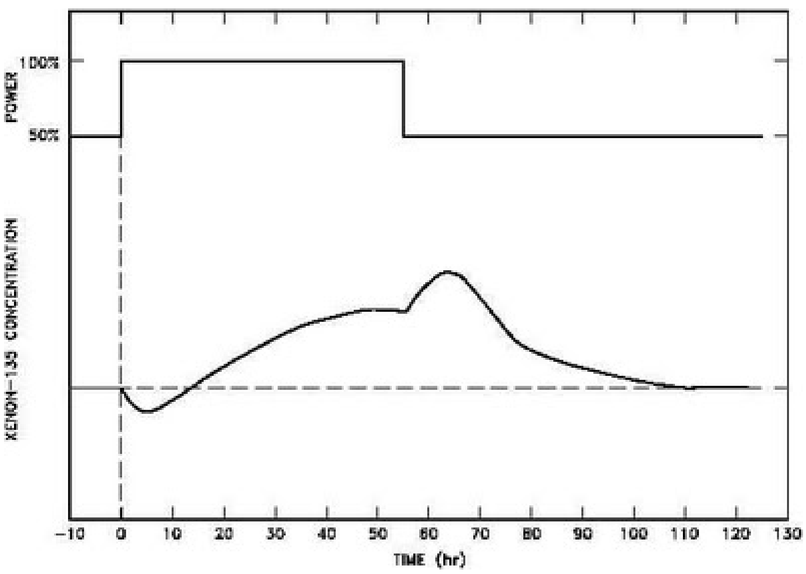


Figure 6: Xenon-135 transients from power changes between 50 - 100% (Nuttal 2009)

The time periods, frequency of adjustment and response time required in load following are in direct conflict with the nature of xenon transients at NPP. For this reason, most NPP operators choose not to subject their facilities to load following operating modes**.** (Nuttal 2007)

Flexibility constraints with respect to the reactor type

In principle, all nuclear reactors might reasonably be regarded as having some flexibility to follow load. In practice, however, the ability to meet grid needs efficiently and safely is restricted to a certain set of design types. Some reactor types that might conceptually be regarded as being suitable for load following are excluded (for technical engineering reasons) because they have not been subjected to necessary safety related testing and licensing.

Pressurized Water Reactors

PWR are the most widespread design in the world and are inherently able to load-follow.

Further reactivity control devices have also been implemented to improve transient performance, especially to deal with flux oscillations and to tackle power instability (arising from the higher core power density and the use of enriched fuel). Depending on the choice of these devices, the reactors are more or less able to follow load quickly. PWR usually use soluble boric acid to offset xenon poisoning and fuel burn-up, and to change reactivity.

In France, where nuclear load-following is required to ensure supply-demand balance in a 75% nuclear electricity system, some additional control rods have also been added to the usual design. As a result, reactivity control mainly consists of a smart management of three parameters: the reactor coolant temperature and boron concentration, and the control rods.

Special care is also needed to manage changes in xenon concentrations and hence both to ensure a uniform power distribution across the core and to monitor overall temperature effects. The relatively low coolant temperature margins in PWR limits the plant's thermodynamic efficiency. Thermal stress, and the fatigue of components are stronger limitations for flexibility compared to other reactors. According to the GRS ageing of passive components and mechanical and thermal fatigue due to changing thermal loads are fundamental causes for damage. (GRS 1997).

For many years, load-following requirements have been specified in standard terms of reference. For example, most PWR plants are capable to follow loads in a power range of 30-100% at rates from 1 to 3% per minute. Exceptional rates of 5% per minute or even 10% per minute are possible over limited ranges (Germany has particularly interesting load-following requirements). (IAEA 1999)

Reactor power control has to guarantee the required output and is responsible for keeping the permitted physical and thermohydraulic limits. Most important in this context is the spatial distribution of power density in the reactor core. The relevance of xenon oscillations decreases considerable during operation compared to the first reactor core. This allows a larger range for economic efficiency by the use of safety relevant margins (MÜLLER 2003). In other words, this results in the reduction of safety margins.

BWR

In principle reactor power levels in BWR can be changed with control rods as well as with changes to the reactor coolant flow. The latter mode is used for load following.

Controlling power in boiling water reactors is based on changing the moderator density via the amount of steam bubbles ("voids") in the boiling coolant. Higher steam extraction causes a decrease in moderator density, because the decreased steam pressure leads to an increased volume of steam bubbles; the power level then decreases. Boiling water reactors do not have a self regulating behavior, therefore saturation steam pressure needs to be kept on a constant level. At a constant pressure level the steam bubble effect can be used for power control.

If a BWR is operated on partial load over a long time, control rods need to be inserted because of changes in xenon concentration. To avoid heavy loads on the fuel the power increase has to be limited. According to the IAEA, BWR have some fuel restrictions concerning e.g. departure from nucleate boiling (DNB).

Neutron flux oscillations are to be considered if a main coolant pump fails. Pump failures are an increasing problem in German BWR:

At the NPP Isar 1 the main circulating pump failed several times in 2008. Pump failures also occurred in the years 2000, 2003 and 2004.

At NPP Philippsburg 1 a power reduction took place because of the failure of one main circulating pump because of high oscillations, thus resulted in a prolonged revision of the pump (2003).

Secondary effects of load following

Pouret 2007 discussed secondary effects of load-following operation; for instance, load-following operation may imply an increased use of soluble poison to control the reactor power. In such modes of operation much more water must then be treated and discharged, which might imply extra operating costs at the margin.

In France, NPP have relatively low availability coefficient (about 80%). A recent study by EDF (Electricité de France) shows that operating NPP at their maximum load improves their overall performance. It especially reduces the unscheduled outage coefficient from 3% to 1.8% in four years. The cost of such a difference of the unscheduled outage coefficient has been estimated at several millions euros.

More generally, some costs also arise from the maintenance and the lifetime issues. Load-following and frequency control indeed imply numerous and demanding manoeuvres, which increases the constraints on core equipment. Some careful monitoring and maintenance are therefore needed to ensure reactor safety. Control rod mechanisms, temperature and pressure fluctuations especially need to be monitored. Even if this induces higher maintenance costs, it is difficult to estimate the costs implied by R&D developments, extra monitoring systems, more frequent maintenance and potentially increased outages. No study has yet been undertaken by the French authorities to estimate these costs.

Moreover, one can indeed assume that because of frequent load-following cycles, thermal stresses, fatigue and mechanical constraints, flexible NPP are likely to age quicker than those operating at base-load. However, according to Framatome ANP, EDF and the French regulatory authority, there is today no clear evidence that load-following will accelerate the ageing of NPP. Even if they concede that a very small number of pieces of equipment (control rods drives for instance) may be adversely affected, they still argue that proper designs and load-following procedures ensure the core components are not excessively degraded.

Load following with new reactors

Nuclear industry maintains the claim that load-following is a feasible option for nuclear reactors. Plants being built today, e.g. according to European Utilities' Requirements (EUR), supposedly have load- following capacity as a design feature.

Even if a high flexibility is promised for the new reactors, some more research will be necessary until load following with the necessary capability can be implemented. However, until now no Generation III reactor is operating in Europe and only two are under construction.

Controlling the reactor core during load following is challenging and difficult also for advanced reactors. The reactor has to perform the load changes, while keeping the core limitations for local power peaking and safety margins.

Local power peaking is a complex three-dimensional phenomenon, influenced by different parameters (fuel loading, power level, temperature distribution, position of control rod groups, Xe oscillations etc.). Local power peaking can be divided into a radial and an axial component. Radial power peaking is flattened by the fuel loading pattern; axial power peaking, however, changes continuously due to the perturbations from control rod maneuvers. BROUSHAKI et al. referred in Nuclear Engineering and Design to a study on new control mechanisms:

Axial offset (AO) is the parameter usually used to determine core power peaking. Control rod groups are the main control agent for AO (boric acid concentration can also be used). The variation and control of AO during transients has a fuzzy nature.

An intelligent core controller based on fuzzy logic and using a recurrent neural network (RNN) was developed and tested in a simulation (for a simulated VVER-1000/320 core). This simulation showed that, axial offset remained within the specified band. But this study has two limitations:

- So far, load following has not been implemented in real VVER plants. Hence, only simulated transients could be used for the test.
- The authors had no access to western benchmarked case studies and relevant computer codes.

The authors are convinced that their method can improve load following capabilities of modern PWR. However, they point out the following drawbacks:

A vast amount of data is needed for the training of the recurrent neural network, as well as a long training time. Before practical application, further steps need to be undertaken: Uncertainty analysis and stability analysis (BOROUSHAKI 2004)

<u>This shows that load following constitutes a considerable challenge for reactor control, which require the development of very sophisticated methods – which are not technically mature yet</u>

Looking to the future, further improvements of the Westinghouse Advanced Passive series designs (AP600 & AP1000) and of the EPR in respect of “grey” rods (“Mode G”), electro-mechanical equipment such as Reactor Advanced Maneuverability Package (RAMP) and in the case of the EPR a constant primary average temperature for power levels between 60 and 100%, ensure that flexibility will become a growing capability of nuclear power. The table below shows the improvements of the EPR’s load-following performance from mode A (mainly soluble boron use) to mode G (control rod use. Furthermore, Framatome’s intermediate operation “mode X” facilitates the mixed management of boron concentration and control rods and thus enables more operational flexibility.

Table 3: European pressurized water reactor operating flexibility (source framatome)

GRID DEMAND		MODE A	MODE G
LOAD FOLLOW	Power range (% of rated power)	Between 30 and 100%	Same
	Variation rate (% of rated power/mn)	0.3%/mn	Up to 2%/mn daily
SPINNING RESERVE	Amplitude and rate of power increase	+15 to 20% at 5%/mn Rate of further power increase limited by dilution	Return to full power at 5%/mn
FREQUENCY CONTROL	Automatic (local) frequency control; Power range (%)	± 3%	Same
	Load regulation (remote frequency control): Power range	± 3%	± 5%
	Variation rate	1%/mn	Same

However, opinions concerning the variability of reactor output differ significantly: In a statement, EDF, as part of their input in consultation on the UK renewable energy strategy early 2009, stated:

"For example, we agree with SKM's analysis that the new EPR nuclear plant design can provide levels of flexibility that are comparable to other large thermal plant. However, there are constraints on this flexibility (as there are for other thermal plants). For example, the EPR can ramp up at 5% of its maximum output per minute, but this is from 25% to 100% capacity and is limited to a maximum of 2 cycles per day and 100 cycles a year. Higher levels of cycling are possible but this is limited to 60% to 100% of capacity. Our detailed analysis shows that, as the intermittent renewable capacity approaches the Government's 32% proposed target, if wind is not to be constrained (in order to meet the renewable target), it would be necessary to attempt to constrain nuclear power more than is practicable - even when assuming that all other non wind plant has already been constrained first. This leaves only one option available - once constrained, nuclear will need to remain constrained off for longer periods of time."

New nuclear designs have higher installed capacity to take advantage of economies of scale. However, even if these units would have a high flexibility, such large units are a threat for grid stability. Therefore the IAEA formulated a list of recommendations for expansion of the nuclear capacity into the grid (IAEA 2009b):

- The electric grid should provide reliable off-site power to NPP with a stable frequency and voltage.
- Any potential lack of reliability in off-site power from the grid must be compensated for by increased reliability of on-site power sources.
- Enough reserve generating capacity should be available to ensure grid stability to replace NPP generation during planned NPP outages.
- The grid should also have a sufficient 'spinning reserve' and standby generation capacity that can be quickly brought online in case the NPP were to be disconnected unexpectedly from the grid.
- The off-peak electricity demand should preferably be large enough for the NPP to be operated n a baseload mode at constant full power.
- If there is any possibility of the NPP being operated in a load following mode, any additional design requirements to ensure safe load following operation should be discussed in advance with the NPP designer or vendor company.
- If baseload operation will not be possible, the NPP should have additional design margins to compensate for the increased exposure to thermal stress cycles, and more sophisticated instrumentation and control systems.
- The national grid should have enough interconnections with neighboring grids to enable the transfer of large amounts of electricity in case it is needed to offset unexpected imbalances of generation and demand.
- In preparation for the introduction of an NPP, if grid reliability and the frequency and voltage stability of the existing grid are insufficient, they should be made sufficient before the NPP is brought online. Any improvements will not only allow the grid to incorporate the new NPP but will have additional benefits for all customers and other generators.
- Communication is critical, in this case between the NPP operators and grid dispatchers. . Effective communication protocols will need to be developed.

5. CONCLUSIONS

A nuclear power plant is a thermal power plant. The difference to fossil fuelled power plants consists of the fact, that steam is produced by nuclear fission. Nuclear fission takes place inside the reactor vessel in the reactor core. The thermal energy (thermal power) generated by the nuclear fuel is transferred to the coolant. The coolant can be used to produce steam directly (BWR) or via the steam generator - a heat exchanger - (PWR). Like in other thermal power plants the steam drives the turbine - generator.

Load following operation means that electrical power is regulated. But there are different ways for the plant to respond to load following, which are not fully independent:

- regulation of the reactor core (reactivity control)
- regulation of the turbine-generator

Mostly NPP are operated as base-load plants at a steady power level of 100%. Startup, shutdown and load changes are very infrequent. Pressurized water reactors (PWR) can rebalance small disturbances by inherent self-regulation. Thus nuclear plants can contribute to the stabilization of the grid frequency.

Operating NPP in load following mode causes technical disadvantages, because plant components are exposed to numerous thermal stress cycles; this leads to faster aging and requires more sophisticated systems for reactor monitoring and control. An economic disadvantage of load following operation of NPP in a larger power range occurs if the plants are operated on reduced power.

Flexible reactor operations are facilitated through the use of special reactor control rods known as ‘grey rods’. These rods do not completely absorb the fission neutrons that try to pass through them. For load-following maneuvers, a clever management of both control rods and soluble boron is found to be optimal.

Germany’s biggest reactor-owning company E.On Energie AG, contracted IER to examine the potential for operating reactors in load-following mode to support a significant expansion of renewables through 2030. The study came to the conclusions that the design basis of all German reactors allows for load-following. About 9.6 GW of German reactor capacity could be dedicated to load following without any technical restrictions during periods when the loadchanges at a rate of up to 5.2% per minute. According to IER, this means that, within 15 minutes, about half the country’s total nuclear capacity could be called upon to meet intermediate and peak demand.

However, the IER study is misleading, because the maximal technical capability for load following manoeuvres neglects safety relevant restrictions, which are currently valid in the operating German NPP. The energy scenario of the IER study suggests an expansion of nuclear power and lifetime extensions of existing NPP.

Only three units of the German NPP fleet operated in load-following mode for a considerable time. The IER‘s assumptions regarding load following do not consider safety aspects and therefore it is not likely, that load following operations will not be introduced to a larger extent in the near future.

The power ramps in the EIR study described as conservative differ substantially from reactor operator information:

For BWR the IER study reports power gradients of 3.8 and 4.4 % per minute. Even the IER -study mentions that potential fuel damages could cause a reduction of up to 1% per minute.

Contrary to the claims in this study, the operator of the BWR Isar 1 states that the range for flexibility needs to be reduced to protect the fuel from high loads. In reality Isar 1 provides a primary control reserve of ± 2.5% to the dispatcher in a limited power range.

Furthermore only the three newer German PWRs could achieve changes of 50 % nominal power in 15 minutes. The 9 older's response is slower.

Operating NPP in Europe are mainly working in base load. Their flexibility is limited a few two percent of nominal power.

For new plants (under construction and planned) load following suggested to be fully implemented. But there is not much experience from operation practice. Investigations into the possible impacts of load following operation are limited and do not allow conclusions on the impacts in future.

Due to economic aspects the new nuclear plants currently under construction or planned in Europe have a high capacity of 1200 to 1700 MW. Output flexibility may be a requirement, if this much generating capacity shall be integrated into the grid. The integration of large plants into the grid poses considerable risks:

A trip of such a large NPP unit causes a grid disturbance, which could result in a total collapse of the grid. Therefore a large reserve capacity must be provided.

A loss of offsite power caused by external events (e.g. transmission line fault) is considered in the NPP safety systems design. In this case the plant can be powered by emergency diesel generators and batteries

For safe operation the NPP itself relies on the grid's frequency stability, because the speed of coolant pumps is directly proportional to the frequency of the power supply. If the frequency drops, the pumps will slow down which leads to inadequate cooling and causes a reactor trip. Also AC motors and pumps of other systems like the steam generator feed-water or decay heat removal depend on the electric grid to function properly.

When a NPP looses its load suddenly (e.g. due to failure of breaker) the plant should be able to be operated (as an "island") on a reduced power level to supply the electricity the plant needs itself, which is about 5%
(which sometimes failed).

The IAEA emphasizes that NPP not only contribute to the supply security, but can also be a hazard: when large NPP are connected to the grid, abnormalities occurring in either can lead to the shutdown or collapse of the other.

The time periods, frequency of adjustment and response time required in load following are in direct conflict with the nature of xenon transients at NPP. For this reason, most NPP operators choose not to subject their facilities to load following operating modes.

Nuclear industry maintains the claim that load-following is a feasible option for nuclear reactors. Plants being built today, e.g. according to European Utilities' Requirements (EUR), supposedly have load- following capacity as a design feature.

Even if a high flexibility is promised for the new reactors, some more research will be necessary until load following with the necessary capability can be implemented. However, until now no Generation III reactor is operating in Europe and only two are under construction.

Controlling the reactor core during load following is challenging and difficult also for advanced reactors, in particular for reactors with large cores. The reactor has to perform the load changes, while maintaining the core limitations for local power peaking and safety margins.

Load following constitutes a considerable challenge for reactor control requiring the development of very sophisticated methods – which are not technically mature yet.

6. Annex: Information on other reactor types flexibility

Advanced Gas-cooled Reactor (AGR)

Drawing on prior experience with the Magnox reactors[4], in the 1960s the UK continued with gas-cooled and graphite moderated designs for the second generation of British nuclear power plants – the AGR. However, unlike Magnox, the rapid transit time of feed water into steam makes the generic AGR concept far more responsive, in principle, to demand changes. Nevertheless, the AGR reactors would still face technical obstacles to load-following arising from Xenon poisoning, thermal stress and reactor instability (due to the use of enriched uranium fuel).

These factors coupled with design specification (e.g. control systems), licensing formalities and only limited relevant operational experience explain the fact that AGR systems have not been used to follow load. Given that future strategies for the AGR now look towards decommissioning, the possibility of life-extensions notwithstanding, there appears to be no reason to seek greater flexibility from these ageing plants.

Heavy Water Reactors: The ACR

ACR have two features that can facilitate load-following. First, as with PWR, the operating temperature range is only weakly coupled to output power, which helps limit the thermal stresses arising from power changes. Furthermore, CANDU reactors (of which the ACR is the most modern version) have five control devices to ensure both flexibility and stability, especially through flux distribution control.

As a result, **Heavy Water Reactors** are inherently very flexible and are able to load-follow between 60 and 100% of their full power. For instance, according to the International Atomic Energy Agency, the older “CANDU 6 plant can load-cycle on a daily basis.”

Pebble Bed Modular Reactor:

The “Generation III+” PBMR design is also expected to have excellent load-following capabilities, despite the high level of enrichment of the fuel. PBMR have some other promising features, for instance, the reactor temperature at each point within the core remains at a constant high level (between approximately 500°C and 900°C, the inlet and outlet coolant temperatures) regardless of the load. Moreover, the flux distribution is relatively homogeneous. Generally in nuclear reactors problems of uneven flux distribution often greatly limit load-following possibilities. The PBMR power density is very low. Furthermore, continuous reactivity control is achieved via “boosters” able to boost helium coolant pressure. This capability allows for quick load variations without excessive disturbance to the core flux distribution.
Control rods (located in the reflector rather than the core itself) and absorber spheres are therefore only expected to be used for reactor shutdown.

4 Only two of the Magnox reactor units are still in operation

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