



Load cycling capabilities of German Nuclear Power Plants (NPP)

Holger Ludwig, Tatiana Salnikova, Andrew Stockman and Ulrich Waas, Erlangen

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In the debate on whether lifetime extension of existing nuclear power plants facilitates or impedes the increased use of renewable energy sources in power generation, one claim being made is that nuclear power plants can only be operated to meet base-load demand at more or less constant power output.

In fact, as early as the seventies nuclear power plants in Germany were designed to compensate load changes over a large range. The corresponding design included the following specific features: a part-load diagram with constant coolant temperature (PWR: Pressurized Water Reactor) or recirculation control (BWR: Boiling Water Reactor) in the upper load range, a special control rod maneuvering concept (PWR), complex measuring equipment, special instrumentation and control systems for regulating and limiting power and power density, and consideration of a large number of load cycles for the fatigue design of components.

Operating experience gained to date clearly confirms that the nuclear power plants designed for this cycling duty are well suited to compensating load changes such as are to be expected to result from wind fluctuations in the event of a further significant increase in wind power plant generating capacity. Furthermore, a review of operating experience and current know-how also shows that there are no safety-related concerns that preclude routine load cycling operation of existing NPPs. Consequently, this implies that the continued operation of NPPs can secure the increased use of renewable energy sources in power generation.

Load cycling capabilities of German Nuclear Power Plants (NPP)

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1. Requirements for the load cycling operation of German NPPs

The debate on whether lifetime extension of existing nuclear power plants facilitates or impedes the increased use of renewable energy sources (especially wind power and photovoltaics) in power generation has been going on for some time. It is often claimed that nuclear power plants can only be operated to meet base-load demand at more or less constant power output and cannot readily react to changes in load demand (see for instance the policy question raised by the SPD opposition faction in the *German Bundestag* on 25 February 2010 [1]).

This impression may have been propagated in the general public because German nuclear power plants ran mainly in base-load operation in the past. In actual fact, however, detailed information on load cycling capability was published as early as the seventies and eighties (e.g. fundamental principles published in [2] in 1985). The reason behind this design was primarily the forecast of larger proportions of nuclear power plants in the installed capacity of small-sized grids, and not the present substantial increase in the share of renewable energy in total power generation. Nevertheless, the question of whether an unexpected spell of calm weather devoid of wind or the half-time break of the World Cup final is the cause of the change in demand for power from the nuclear power plant fleet is irrelevant; only the power gradient (rate of change in power) and the power increment (the amount of the power change) are important.

A recent study by the *Institute of Energy Economics and Rational Use of Energy (IER)* [3] for the years 2020 and 2030 has examined, on the basis of an estimated 30 - 40 % of electricity being generated from renewable energies, to what extent the power plant fleet probably existing at that time would be suitable for timely compensation of the fluctuating power supply from renewable energies. The study concluded that the fleet would meet this task in the

scenario with lifetime extension of existing nuclear power plants better than in the phase-out scenario. The "lifetime extension" scenario proved to be more cost-effective and resulted in greater CO₂ emission cuts. The IER used a power gradient of up to 65 MW/min for each nuclear power plant and a power increment of 50 % (for pressurized-water reactors: PWR) and 40 % (for boiling-water reactors: BWR) of rated power. With these parameters, the German nuclear power plants provide a total regulating power of up to 9,600 MW. (In fact, the design allows a little more, namely up to about 10,000 MW regulating power from the NPPs.)

Nuclear power plant operators (VGB) have requested the manufacturer (now AREVA) to review these assumptions under consideration of present experience and knowledge from a technical perspective, so as to make a technically sound statement on the interplay of nuclear power with other CO₂-free energy production systems. These are outlined below:

- load cycling for PWRs and BWRs,
- the most important existing design characteristics,
- the operating experience with load cycling gained to date, and
- the effects of more frequent load cycling on the systems and components.

2. Description of load cycling

PWR

The schematic part-load diagram of a PWR (Figure 1) 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 % = RTP – rated thermal power). The range of the constant coolant temperature between (in 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

Author's address:
Dipl.-Ing. Holger Ludwig
Dr.-Ing. Tatiana Salnikova
Andrew Stockman
Dipl.-Phys. Ulrich Waas
Areva NP GmbH
Paul-Gossen-Str. 100
91052 Erlangen
Germany

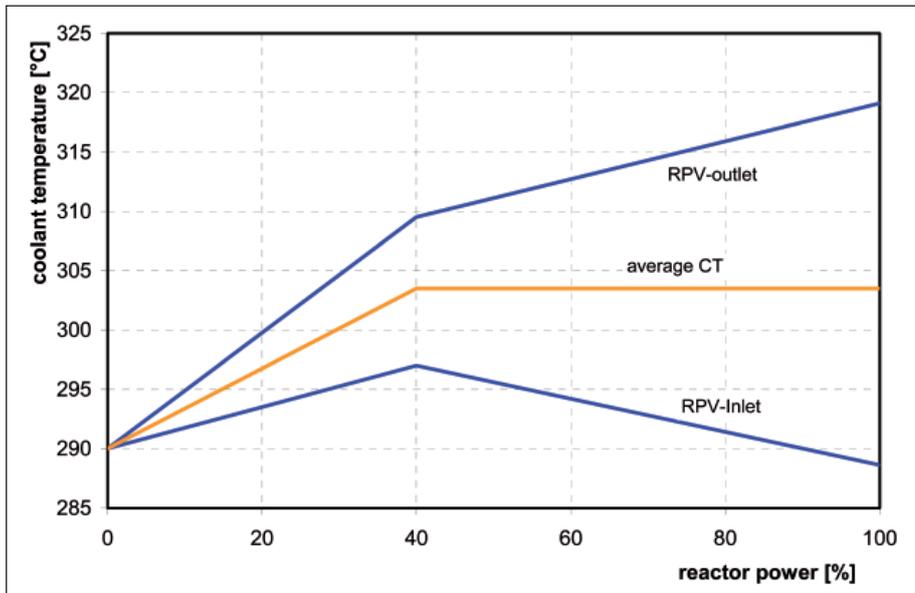


Fig. 1. Schematic part-load diagram of a PWR.

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 preserves the shutdown margin, which is a variable that is important to safety. Slower changes of 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. On a power increase, the D bank is 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 overview of the above components, see Figure 2).

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.

BWR

The output of boilingwater reactors can be regulated either by maneuvering 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 rated electrical output – REO). 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 3 shows the characteristic curve for recirculation control; this plots the reactor power as a function of the core flow for a constant control rod position. A major advantage of recirculation-only control is that the relative power distribution in the core is not significantly affected upon load changes, because no maneuvering of con-

trol 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 % REO/min 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 totalling between 20 and 100 % can be achieved at sufficiently high power gradients (for overview of the above components, see Figure 4).

Startup and shutdown

The 9,600 MW regulating power assumed in the IER study [3] can be provided by the German nuclear power plants particularly well in the upper power range in which they are readily maneuverable. In addition, it would be possible to disconnect units temporarily from the grid, and then restart later. In this case, an NPP does not require the often mentioned 1 to 2 days to reach full load, but only 1 to 2 hours. The difference lies in the different plant states at shutdown conditions. While 1-2 days are required for starting up a nuclear power plant after a refuelling, starting from the hot standby state takes just about 2 hours to reach nearly full load. It is even faster if the unit is kept running at house load, namely the power demand of the power plant is provided by its own generator. The generator remains synchronized with the grid. Run-up to full load is then possible in less than an hour. This mode of operation is designed for special situations and meets the requirements for nuclear power plants formulated by the grid operators (required maximum startup time is 3 h) [4].

3. Design characteristics

Stringent requirements with regard to controllability were placed on the German NPPs even during the design phase. Therefore, they have special design features that stand out from the international standard (see e.g. [2, 5, 6]).

Control rod maneuvering program (PWR)

The maneuvering of control rods for the purpose of power control always has an effect on the axial power distribution in the core which ideally is cosinusoidal in shape. A power increase will generally result in increased local power density. In this case, the installed power and power

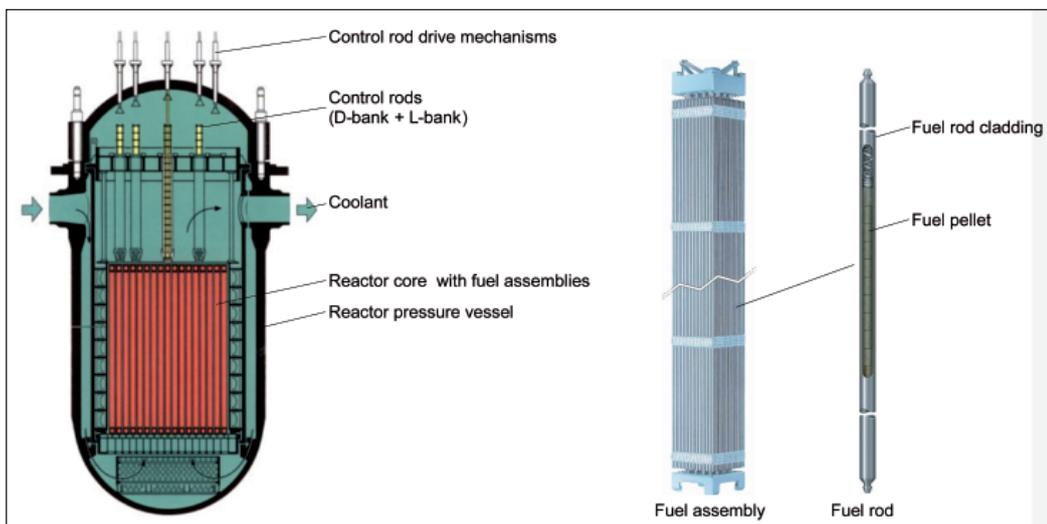


Fig. 2. Illustration of typical RPV internals of a PWR.

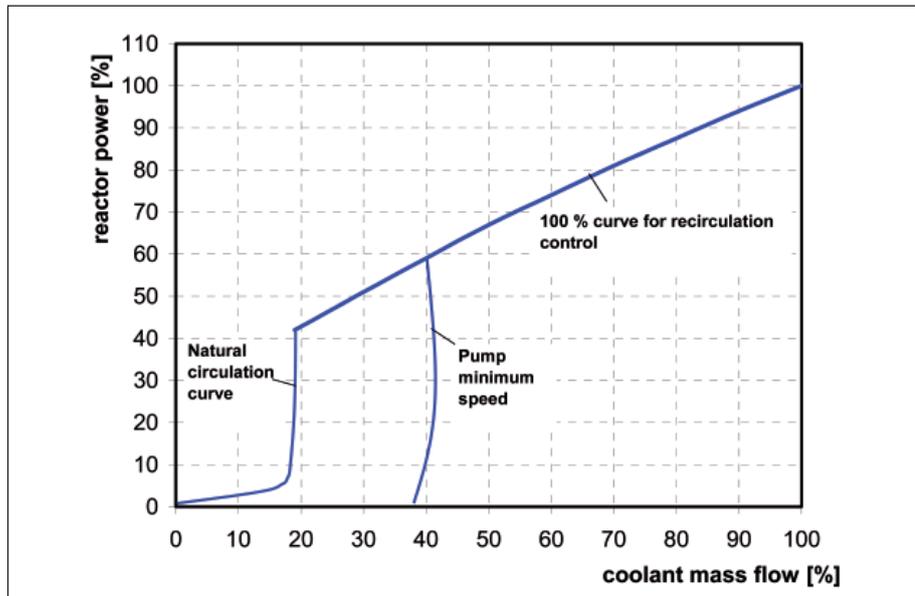


Fig. 3. Schematic characteristic curve for recirculation control (BWR).

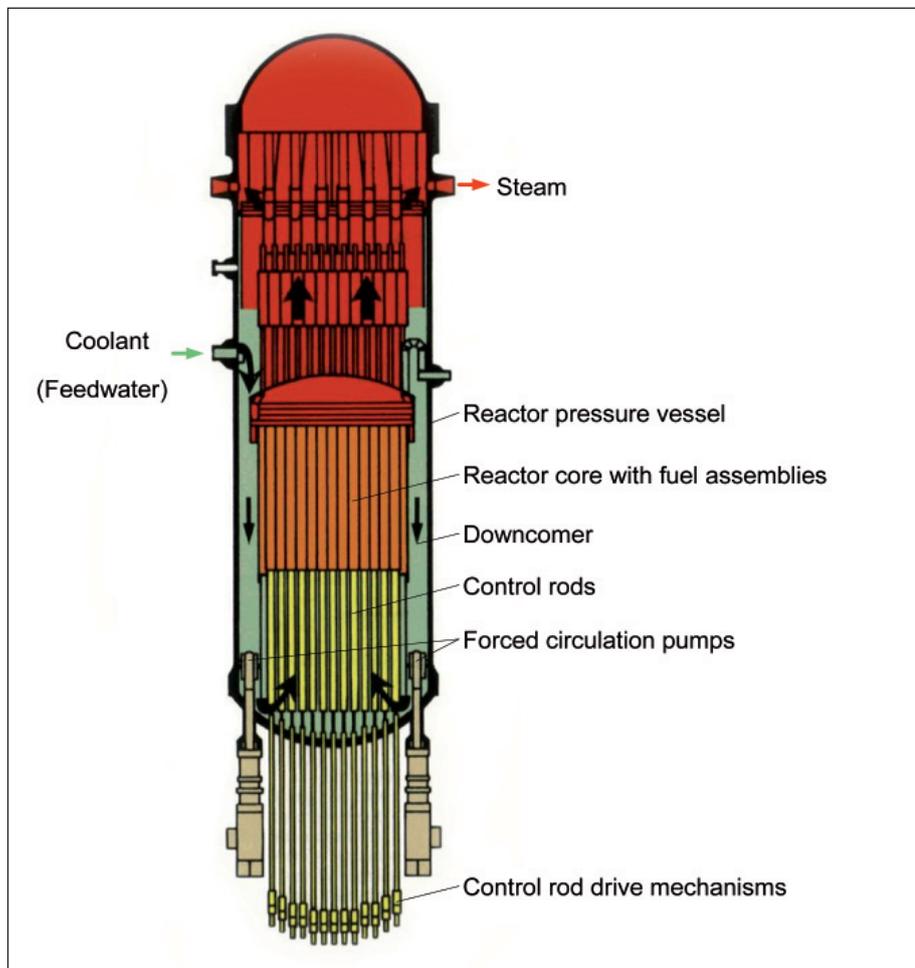


Fig. 4. Illustration of typical RPV internals of a BWR.

density limitation functions ensure that permitted maximum values of power density are not exceeded despite such changes. However, as activation of the limitation system slows down the power increase, it is important for effective and especially fast reactor control that power and power distribution can be controlled independently. The control rod maneuvering program of

the German PWRs relies on standard control assemblies, all of which can be used for both regulation and shutdown of the reactor. From a functional perspective, the control assemblies are grouped in two banks: the D bank made up of 4 sequentially moving groups each consisting of only 4 control assemblies; and the L bank with the majority of the control assem-

blies. The D bank is used for regulating the integral reactor power. As a result, the axial power distribution is only slightly distorted by the four moving control assemblies. The L bank can be used to back up reactor power control. Its main task is to control the axial power distribution, for which a change in position of only a few centimetres can yield a sufficient effect. (The L and D banks have to be maneuvered in a mutually compensating sequence for changing the power distribution at a constant reactor power). This control rod maneuvering concept enables rapid power changes but requires prompt and accurate measurement of power distribution by appropriate in-core instrumentation.

In-core Instrumentation (PWR and BWR)

The power density, together with burnup, is significant for fuel management. Therefore, there are limits for the power density that may not be exceeded. In case of load cycling (by control rod maneuvering), the pattern of the power distribution changes and, with it, the maximum local power density. The difference between the relevant maximum local value of power density and its limit defines the margin available for such redistributions. The more reliably and more precisely the local power density is measured and controlled during operation, the greater the operating margins for load cycling. The core monitoring system used in German nuclear power plants, especially in international comparison, is fast and accurate, and thus provides larger margins for load cycling. This is made possible by an in-core instrumentation system with both in-core power distribution detectors (PDD) which continuously measure the power distribution directly in the core (therefore fast), and an Aeroball flux measuring system (PWR) or traversing in-core probe system (BWR), with which the PDDs are regularly calibrated during operation (therefore precise).

Part-load diagram (PWR)

There are basically two types of part-load diagrams for PWRs, one with constant average CT and the other with varying CT but constant main steam pressure. In German PWRs, a mixture of both types is applied (see Figure 1). Load cycling is done with constant average CT in the power range from 60 to 100 %, in which most load cycling operations are run. This has the advantage that the coolant volume remains relatively constant and the change in reactivity with varying CT is low in case of power changes. Thus, the requirements for the volume control system and reactor power control (control rod maneuvering) are reduced. Moreover, the mass exchange between the pressurizer and the rest of the reactor coolant system is reduced, leading

to lower temperature fluctuations in the surge line.

Recirculation control (BWR)

Expressed simply, the above-explained recirculation control for BWRs (see *Figure 3*) combines the benefits of the optimized control rod maneuvering program and the part-load diagram of the PWR for BWR conditions. Consequently, it is intrinsic to the BWR that it can change power in the upper load range faster and with less power distribution deformation than the PWR, because no maneuvering of control rods is needed. Temperature and pressure remain constant in the main steam system, so that also the loads on the components of the reactor coolant system and adjoining systems remain low.

Limitation systems (PWR and BWR)

There are safety-related limits for key operating parameters in nuclear power plants that may not be exceeded. To ensure this, sequential instrumentation and control systems provide step-raised automatic actuation of counteractions:

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

The intervention of the reactor protection system (e.g. RT) is averted for most malfunctions by the limitation systems, which thus minimize life-limiting loadings on plant systems. As a result, the limitation systems not only fulfil a safety function but also increase the availability of the plant. The German nuclear power plants are international leaders in the automation of such limitation functions. A wealth of thought and experience has gone into the limitation systems concept of German PWRs and BWRs with respect to load cycling. In particular, the power and power density limitation systems with their various constituent functions, and the control rod maneuvering limitation systems contribute significantly to maintaining sufficient margins to safety limits, taking load cycling especially into account.

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

- The controls can be primarily designed from the point of view of optimum function without regard for safety issues which are covered by the limitation systems.

- The operating staffs are relieved of monitoring responsibilities and can therefore devote special attention to load cycling operations.
- Plant availability and thus, grid reliability can be improved.
- The high accuracy and reliability of the limitation systems (in conjunction with the in-core instrumentation) allow greater scope for load cycling.

Design measures to mitigate and control cyclic loadings (PWR and BWR)

Load cycling within the scope outlined above is predominantly associated with only minor changes in global plant parameters such as pressure and temperature in the reactor coolant system. The resulting low thermal stresses are not relevant to the fatigue of the affected components. Large temperature gradients with correspondingly higher loads can occur when different hot fluids meet in individual components. In addition to a low-stress mode of operation (see part-load diagram), such loadings are well-controlled by a suitable design, namely the choice of suitable materials and appropriate dimensioning or mechanical design to reduce temperature changes, for example in the area of injection nozzles. German nuclear power plants are designed for the stresses associated with load cycling. This design is based on defined numbers of service conditions (in this case load cycles), which bound the frequencies expected during the lifetime of the plant.

Fatigue monitoring (PWR and BWR)

Continuous fatigue monitoring (measuring, recording and analysis of wall temperatures), which facilitates both graduated quick evaluation and detailed fatigue analysis is available for components susceptible to fatigue. Moreover, by the comparing of the history of service conditions, such as load cycles or operational transients, with the design assumptions documented in thermal load specifications, it can be ensured that the component design imposes no restrictions on the operation of the plants. In addition, periodic, non-destructive testing at specified intervals is performed especially for safety-related com-

ponents. Despite all of this, if unexpected effects should occur, these would be detected in time.

4. Operating experience

Extensive experience with load cycling exists both in Germany and internationally. In particular, so-called primary control, in which reactor power control is linked to the grid frequency directly and without intervention of the operator, is established practice. The power increments are limited to a maximum of 5 % REO (equivalent to 65 MW per unit) in which the power change can take place quickly. This mode of operation stresses the system only minimally due to the limited power increments, and experience with it is positive (*Isar 2 (KKI 2)* [5] and *Isar 1 (KKI 1)* [6]).

Larger load ramps are usually actuated manually by the operator. Preparations for the use of an automated secondary control, in which the plant output is controlled by an outside signal, are already complete or are currently being performed for various plants. All plants have run corresponding load ramps in the course of their operating lifetimes. In 2009, some units such as *Phillipsburg 1 (KKP 1)* and *Neckarwestheim I (GKN I)* operated almost entirely in the load follow mode (see *Figure 5* [7]).

In this case the load gradients were up to 2 %/min, the power increments were generally in the range of constant CT (PWR) and the recirculation control (BWR). Existing operational experience with this mode of load cycling is also positive. The mentioned 2 % REO/min still means approximately 400 MW of power change in a quarter of an hour for only one of the larger nuclear power plants, so that the requirements for compensating wind fluctuations are practically met.

With regard to experience with load cycling, it is also worthwhile to take a glance across the Rhine, to France where, in 2008, approximately 58 % of power generation capacity was nuclear, and its share in electricity production was as high as 76 %. Naturally, the French nuclear power plants contribute to both frequency stabilization and balancing out medium-term load

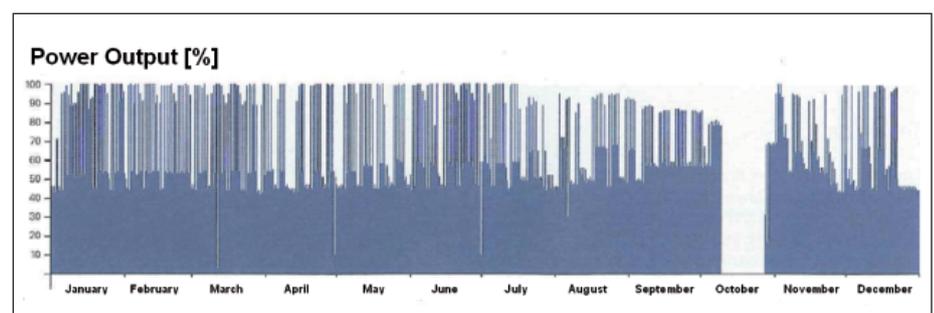


Fig. 5. Load follow operation of GKN I NPP in 2009.

fluctuations. Load gradients of up to 5 %/min in a load range from 30 to 100 % are specified.

5. Effect of load cycling on the plant

The effect of load cycling on the plant was taken into account by the manufacturer in design and is now being reviewed from a modern perspective. In the following, the effects on the reactor core are described and then the effects of load cycling on other components and systems and on transient processes are assessed from mechanical, chemical, radiological, process control and electrical standpoints.

Reactor core

The feasibility of the specified load ramps of up to 10 % REO/min was proven for both BWRs and PWRs in the course of commissioning. In the subsequent operating time, the plants were modified to some extent (e.g., enrichment increases, power up-rates) 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 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). The power gradient of 2 % REO/min (corresponds to about 25 MW/min in most plants) desired for an decrease of wind energy can be achieved in any case. Larger power gradients of up to 100 MW/min can be achieved for BWRs in the range between 60 and 100 % REO without violating design limits relatively easily by changing the speed of the forced circulation pumps. In PWRs, it is now possible in certain circumstances for power increases with large gradients and increments to cause limits on maximum power density to be reached at which the limitation functions would automatically reduce the rate of power increase. (Fast power reductions are always possible.) The actuation of the limitation systems is permissible for safety reasons but undesirable from the operational point of view. Therefore – where desirable for grid stabilization – operational improvements can also be undertaken to allow greater power gradients for large power increments. These include:

- Optimized fuel management strategy (PWR/BWR)
- Optimized control rod maneuvering controls (PWR/BWR)
- Optimized measurement selection for the PDD signals (I&C (instrumentation & control) consideration of masking effects of the D Bank) (PWR)

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

Tab. 1. Number of load cycles considered for design (example KONVOI PWR)

Fuel rods and fuel assemblies are generally designed for the loadings of load cycling. The Pellet Clad Interaction (PCI) damage mechanism is especially relevant with regard to such loadings. PCI is the combination of Pellet Clad Mechanical Interaction (PCMI) and mechanisms of stress-corrosion cracking in the interior of the fuel rod. PCMI is caused by contact between fuel pellet and cladding due to differential thermal expansion. Fuel expansion occurs as a function of power, and accordingly, the “expansion differences” between pellet and cladding depend on the power increment. The PCI threshold defines the power level below which no PCI damage can be expected. Stress relief through relaxation of the cladding at higher power levels can raise the PCI threshold. This process is known as conditioning.

A specific limitation function takes into account the power history of the reactor and thus the conditioning of the fuel in the limits for avoiding PCI. Both analyses and the operational experience demonstrate the effectiveness of this measure. However, as a precaution, further operational experience, including with higher power gradients, should be collected and evaluated.

On the whole, implementation of the above measures ensures that fuel rod failures are not to be expected even in load cycling operation. If isolated fuel rod failures do occur (leaks in individual fuel rods of the more than 40,000 present in the reactor core – although rare – have occurred for other reasons), the coolant purification system is designed to remove radioactive materials from the coolant and thus limit impact on personnel and the environment to acceptable levels. Furthermore, general practice is not to carry out load cycling on a large scale if fuel rod failures have occurred.

NPPs can carry out load changes more easily (faster, larger increment), if the operator is informed of the impending load change a couple of hours earlier. With better prediction of the power yield from renewable energies, the potential for optimized load sequence of NPP also grows. For example, if the required load change is known an hour in advance, the reactor operator can prepare the plant (setting of optimum parameters with regard to available control rod reactivity, power distribu-

tion, PCI margin) so that the transient processes involved in the power increase are simplified.

Mechanical phenomena

Material fatigue

Components made from metallic materials have the property of losing mechanical strength under cyclic loadings which exceed certain limits; this is known as fatigue. Such cyclic loadings can also be generated by load cycling, especially when large temperature transients occur in the material. However, the design of German nuclear power plants, as already mentioned, was based on load cycling spanning the entire lifetime. Accordingly, the number of load cycles has been set relatively high (see Table 1 for load changes relevant in this context). The loadings associated with the respective load cycles were determined for components susceptible to fatigue and included in their sizing. Furthermore, ongoing fatigue evaluations are conducted based on the data obtained by fatigue monitoring.

Since the German NPPs have mainly been operated at constant power in their operating lifetimes to date, there are still significant reserves with respect to material fatigue. A simple example for illustration: a power plant which has run a typical number of 2,000 load cycles run between 60 and 100 % would be capable of a further 13,000 such load cycles before using up the remainder. Under the (unrealistic) assumption that such load cycles would be needed daily to compensate for changing wind power generation, the design number of load cycles would be reached only after 35 years. It is to be borne in mind that the design in any case still includes a significant safety margin until damage (e.g. leakage) might occur.

Moreover, continuous fatigue monitoring and assessment ensure that any new findings and requirements (e.g. mechanical strength properties) can be responded to quickly and effectively.

The plants can also take preventive measures to further mitigate the impact of load cycling on material fatigue. Optimization of the operational controls is to be mentioned here first. Further developments in fatigue analysis towards more realistic methods will also be helpful in the assessment of load cycling. Despite all of

this, if a single component or length of piping should reach its design limits, replacement of the affected component or pipe would also be possible in principle.

Erosion corrosion

In the fluid systems of a nuclear power plant, throttling of flow rates may be required in load cycling operation, e.g. at valves of the main feedwater system (PWR), which could result in increased erosion corrosion due to local flow rate increases. This applies in principle to operational systems only, but not to safety systems as these are usually on standby during the normal operation of the plant. For operational reasons, plant-specific assessment and monitoring of these effects may be useful.

Wear and tear

Active components (e.g. control valves, pumps) can be exposed to increased wear and tear due to load cycling. In general, these are operational systems with no importance to safety. The effects of load cycling can be considered in maintenance and repair plans.

Where components of safety systems (e.g. control rod drive mechanisms) are activated often as a result of load cycling, this has been considered as a specified number of load cycles (see above) in the design. If necessary, the effects of load cycling would be detected at an early stage through periodic inspections.

Chemistry/Radiology

The fluctuations of the physical parameters (pressure, temperature, flow rate) of the reactor coolant system caused by load cycling tend to be of secondary importance for corrosion mechanisms in the reactor coolant system. Variations of chemical parameters are detected by continuous monitoring of the coolant. If necessary, corrections are initiated by the staff. Operational experience shows no or only a minor effect of load cycling on corrosion and dose rates as a result of corrosion product particles in the coolant [8].

Process Engineering

The process engineering sequences which take place during load ramps were already roughly described in Section 2. A nuclear power plant consists of numerous interacting controls and systems. There are power states in which the system can be operated more smoothly than in others (minimal challenging of operational controls). From an operational perspective, such "smooth-running" power states are to be preferred, and it is desirable to extend this power

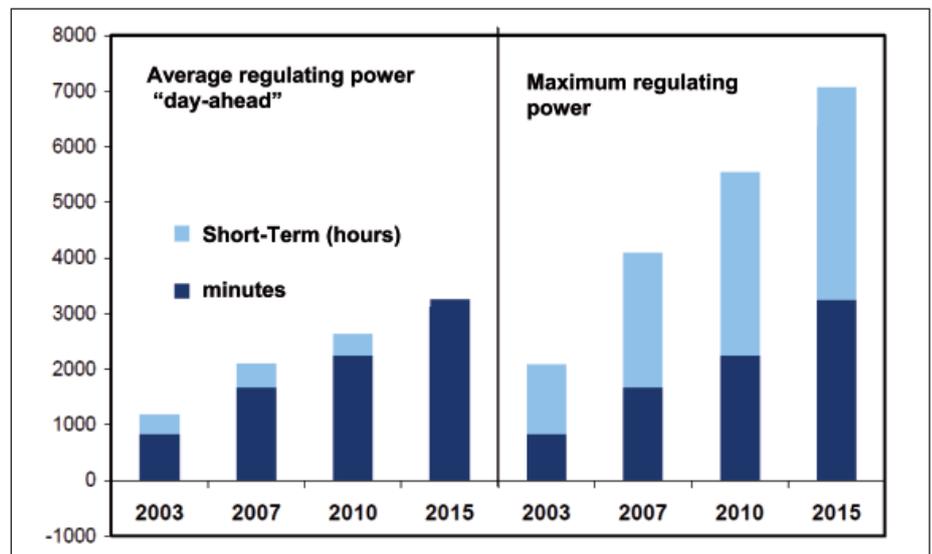


Fig. 6. Regulating power necessary for compensation of fluctuating energy production of wind power plants [9]

range as much as possible. An example of such an improvement of operational processes would be the use of variable speed pumps instead of throttling valves. This would also reduce the electrical house load demand of the plant.

Electrical equipment

No significant effect of load cycling on the generator is to be expected, as the generator has to provide less active power in the part-load range, and therefore the reserves are higher. The effect is marginal also for the transformers, as the generator transformer is less loaded in the part-load range. The auxiliary transformers are virtually unaffected by load cycling because the house load hardly varies with the load condition of the plant.

Transients/accidents

Safety analyses are performed for abnormal operating transients and accidents. As required by German regulations, the worst conditions for normal operation are assumed as initial conditions for the transients and accidents. Insofar as part-load conditions are unfavourable, they have been generally taken into account in the analysis in that the potential reactor states due to load cycling were approved in the original licensing procedure.

Load changes have an impact on various parameters that describe the initial state of possible transients, such as reactor power, coolant temperature, core flow, xenon concentration and distribution, critical boron concentrations, power distribution and control rod positions. The above parameters are controlled or limited within a narrow range by various controls, the control rod insertion limits and various

power limitations (with margins, e.g. for loss-of-coolant accidents or loss of offsite power). Even if load changes alter various parameters, the parameters are maintained within the control ranges and the setpoints of the limitation functions regardless of the power history.

6. Conclusions

Extensive operational experience exists for load cycles with power gradients of up to 2 %/min and power increments in the range from about 50 to 100 %, partly also for higher gradients. Such load cycles in the existing nuclear power plants, with a total of up to 10,000 MW, are certainly sufficient to compensate for fluctuations in the wind-generated electricity supply required according to the present analyses [9] (see Figure 6).

Larger power gradients and increments required by the grid can also be achieved. Depending on the plant, the current maximum achievable gradients/increments can be limited, for example, by the margins to the setpoints of the limitation functions. But there are plenty of possibilities for optimizing systems and achieving higher power gradients. Approaches include:

- fuel management strategy optimized for load cycling
- optimized control rod maneuvering controls and
- look-ahead operating strategies.

Likewise, there are options for optimizing low-stress operation, preferably in the range of operational controls to reduce the additional loadings caused by load cycling. Basically, the stresses due to load cycling are already covered by the design of the NPP.

The safety of NPPs is not affected by load cycling, since:

- all relevant plant states (even different load conditions) were considered in the applicable safety cases,
- reliable limitation systems are available,
- continuous monitoring of fatigue of exposed parts is provided and
- periodic inspections of critical safety-related components are carried out.

Therefore, from a safety perspective, there is no objection to load cycling as would be needed in combination with a further expansion of renewable energies.

From the perspective of efficient energy use, further expansion of renewable energy increases the demand for power plants that are suitable for large, rapid load changes. Compensation for feed-in fluctuations through correspondingly large storage capabilities is not foreseeable in the near future. Hence, nuclear power plants are particularly suitable for combination with renewable energies.

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Redaktion:

Christopher Weißelmann
Im Tal 121, 45529 Hattingen
Telefon +49 2324-4397723, Fax +49 2324-4397724
E-Mail: redaktion@atomwirtschaft.de

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Satz:

Waltraud Zimmer, Bonn
Telefon: +49 228 2428867, Fax: +49 228 2428967
E-Mail: w.zimmer@atomwirtschaft.de