Additional Costs for Load-following Nuclear Power Plants

Experiences from Swedish, Finnish, German, and French nuclear power plants

Elforsk rapport 12:71

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ELFORSK

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Preface

This project is a continuation of a study carried out in 2011 (KK-007) on load-following capacities with nuclear power. Here, the focus is on additional costs related to load-following mode of operation. These costs are examined regarding fuel demands and different fuel-load patterns, component wear and tear, operational and maintenance costs, and long-term wear on structures. The information is collected from experience in Sweden in the 1980s, Finland, as well as recent experience including detailed studies carried out in France on PWRs and Germany on BWRs and PWRs.

The report is in English but a summary in Swedish follows.

Denna rapport är skriven på engelska, men en kort sammanfattning följer på svenska.

Sammanfattning

Denna rapport beskriver de extra kostnader som eventuellt tillkommer vid effektreglering av kärnkraftverk. Den typ av reglering som avses är lastföljning, typiskt vid nedgång i effekt nattetid och under helger. Denna typ av reglering har utförts i Sverige vid flera tillfällen under 1980-talet och även under "våtåren" i slutet av 1990-talet.

Eftersom Sverige har ca 50 % elproduktion från vattenkraft har behovet av lastföljande kärnkraft varit litet fram till idag. Dock, med en ökad intermittent elproduktion såsom vindkraft, introduktionen av solcellspaneler, aktiva kunder som tar beslut beroende på det aktuella elpriset, fler kablar till Kontinentaleuropa samt det tyska beslutet att avveckla landets kärnkraft vilket kan skapa brist på produktion i Tyskland ger det en större efterfrågan på lastföljning. Större fluktuationer i elpriset över dygnet och vardag/helg kommer att öka behovet av flexibel elproduktion och högst troligt är att anläggningar med möjlighet till flexibel elproduktion kommer då att ha fördelar. I detta sammanhang är det viktigt att se över kärnkraftens möjlighet till att vara en flexibel elproduktion.

Slutsatsen från rapporten är att vid en väl förberedd lastföljning tillkommer mycket små extra kostnader. De områden som undersökts är slitage, underhåll, personal, bränslekostnader och drift av anläggningen.

Eftersom en majoritet av de nordiska anläggningarna har modifierats och uppgraderats med nya turbiner, ny instrumentering och kontrollutrustning etc., behöver man se över varje individuell anläggning för att få en komplett bild av hur den anläggningen kommer att uppföra sig under lastföljning. Det är också nödvändigt att lokalisera driftområden som man ej ska befinna sig i längre tid under lastföljning. Sådana studier kan ge en extra kostnad i en övergripande förberedande fas till lastföljning.

Lastföljning är idag ett krav som ställs på de nordiska reaktorerna och därför är det intressant att utreda kostnaderna kring detta. Lastföljning är dock något som idag ytterst sällan praktiseras i de nordiska reaktorerna.

Det bör påpekas att även om kostnadsökningarna i absoluta tal inte blir så stora så blir påverkan på priset per producerad MWh väsentlig. Detta beror på att kärnkraften har höga fasta kostnader och lägre rörliga kostnader. T.ex. så är kärnkraftsskatten fast, kapitalkostnaderna är fasta, löner är fasta och stora delar av underhållskostnaderna är fasta.

Det finns ingen kostnad kopplad till utbildning av personal eftersom lastföljning redan ingår i personalens normala utbildning. Även härdövervakning ingår i utbildningen.

Extra kostnader vid behandling av bor i tryckvattenreaktorer i termer av elkonsumtion och vattenbehandlingskostnader är minimal men behöver tas hänsyn till vid perioder av regelbunden lastföljning.

Det är sammanfattat att om det planeras för lastföljning och regleringen av reaktoreffekten är gjord inom de på förhand beslutade gränserna så finns det inga hinder eller extra kostnader för lastföljning.

Angående manövrerbarhet av tryckvattenreaktorer så kan lastvariationsoperationer reducera säkerhetsmarginalerna för oavsiktliga transienter jämfört med vid baslastproduktion; detta refererar enbart till härdövervakning med borinjektion.

Tillgängligheten kan reduceras något som följd av effektreglering (mindre än 1,8 % för hela den franska kärnkraftsflottan), i huvudsak vid frekvensreglering med ökat underhåll av bl.a. styrstavsdrivdon. Inga studier tyder på minskad tillgänglighet på grund av enbart lastföljning.

Generellt kan lastföljning enklast utnyttjas i en kärnkraftpark med flera reaktorer där de olika reaktorerna nedregleras i serie. Då kan man begränsa intervallet som behöver regleras, exempelvis från 100 % till 70 %. Om ytterligare nedreglering behövs tas reaktor nummer två ned på samma sätt. Detta utnyttjas bland annat i Philippsburg i Tyskland.

En viktig slutsats från alla referenser i denna rapport är att lastföljning inte ska göras i en anläggning som har bränsleskador i härden. Detta har betonats från anläggningar med stor erfarenhet av bränsleskador (vilka dock inte orsakats av lastföljning), eftersom det antas att lastvariationer troligen förvärrar redan uppkomna bränsleskador.

Den huvudsakliga påverkan på en tryckvattenreaktor är avfall från borinjektionssystem med hänvisning till större vattenvolymer, vilket kan lösas genom effektiv återcirkulering. Ingen påverkan på bränslesäkerhet har setts (inga fel som är orsakade av lastföljning) och ingen påverkan på bränsleupparbetningsprocessen (utan betydelse för Sverige eller Finland).

Det huvudsakliga slitaget har setts på styrstavsmekaniken, vilket har tidigarelagt utbyte av dessa (typiskt vart tredje år för gråa styrstavar). Ökad inspektion och underhåll av tryckhållarens inlopp och utlopp som en följd av ökade temperaturvariationer har setts i Frankrike.

Vid pessimistiska beräkningar så ökar bränslekostnaden vid lastföljning i en kokarvattenreaktor med 17-23 %. Av den totala produktionskostnaden för en kWh från ett kärnkraftverk utgör bränslekostnaden ca 20 %. Därför kan bränslekostnaden totalt komma att bli 24 % av den totala produktionskostnaden för en kWh vid oplanerad lastföljning i en kokarvattenreaktor.

I den studie som gjorts här är antagandet att lastföljningen gjorts oplanerat under den första bränslecykeln vilket gör det till ett värsta fall. Om bränslecykeln är planerad för lastföljning så blir det inga ökade bränslekostnader vid lastföljning. Det ska dock påpekas att det är mycket svårt att planera den exakta effektregleringen under kommande driftsäsonger, varför en viss merkostnad för outnyttjat bränsle alltid kommer att finnas.

Det finns inga skillnader i behovet av färska bränsleknippen mellan scenarierna som inkluderar/exkluderar spektralskift. Detta som en följd av att idag drivs Forsmark med en styrstavsinställning som gynnar flexibilitet i anläggningen. Som en följd av detta är spektralskiftet lågt och påverkas inte av en ökad lastvariation. Därav är det bara små skillnader mellan de olika scenarierna vilket innebär att den ökade bränslekostnaden är oberoende av när i bränslecykeln som lastföljning görs.

För tryckvattenreaktorer blev den relativa ytterligare bränslekostnaden 25 %. Osäkerheten av behovet av ytterligare färska bränsleknippen motsvarar ±9 %. Vid applicerandet av ett pessimistiskt betraktande likt ovan för kokvattenreaktorer blir den resulterande bränslekostnaden för lastföljande tryckvattenreaktorer 25-34 % högre än dagens bränslekostnad.

Om man jämför bränslekostnaderna vid oplanerad lastföljning för kok- och tryckvattenreaktorer ser vi att den ytterligare bränslekostnaden är något högre för en tryckvattenreaktor. Därför, från ett strikt bränsleperspektiv, är det mer fördelaktigt att lastfölja med en kokvattenreaktor.

Summary

This report summarises possible additional costs due to power control of nuclear power. The type of manoeuvrability envisaged is load-following, typically lower power production during nights and weekends. This has been performed in Sweden in the 1980s, and during "wet years" (high precipitation) in the end of the 1990s.

As Sweden has approximately 50 % electric generation from hydropower, load-following of nuclear power has not been needed to a high extent in the past. However, with increased intermittent power production such as wind power, the introduction of solar panels, smarter customers that take decisions depending on actual energy price, more connecting cables to Continental Europe, as well as the German moratorium of nuclear power which can create a lack of power in Germany; a higher demand on load-following is foreseen. With larger fluctuations in the electricity price over 24 hours or week/weekend basis will increase the need of flexible electricity production.

It is believed that in the future, plants with flexible power production will have advantages since the request of power production will vary more than today. In this context the possibility for nuclear power plants in being flexible has to be overseen.

The conclusion from this report is that with a well-prepared load-following, there are very few additional costs. The areas investigated cover wear, maintenance, staffing, fuel costs, and operation.

As the a majority of the Nordic plants have been modified and updated with new turbines, new instrumentation and control etc., one has to look at each individual plant to get the complete picture of how that plant will behave during load-following. It is also needed to find power regions where one should not operate over longer periods during load-following. Such needed studies could bring an additional cost to the overall in preparation.

Load-following is today a requirement on the Nordic nuclear power plants and therefore it is of interest to investigate costs associated to this mode of operation. However, load-following is today very seldom performed among the Nordic nuclear power plants.

It should be noted that the increasing costs when load-following in absolute numbers are small; however, its influence on the price per produced MWh is significant. This is a consequence of that nuclear power plants have high fixed costs and low variable costs. For instance the tax of nuclear power is fixed, the capital costs are fixed, the salaries for the employees are fixed and large parts of the maintenance costs are fixed.

There is no cost associated with training of personnel as this is already part of normal operator education.

Additional costs due to the boron treatment in PWRs in terms of power consumption and water treatment costs are minimal, but need to be considered in detail for periods of regular load-following.

Turbine efficiency decreases and the risk for disturbance in operations could increase, but no such factors have hindered France and Germany to load-

follow with nuclear power. In France and Germany has even primary control been used regularly, i.e., frequency compensation to the electric grid on a time-frame of seconds. This is however not envisaged for Swedish power plants, and outside the scope of this report.

It is concluded that if the load-following is planned and the regulation is done within determined levels specific for the plant there is no hindrance or additional costs for load-following.

Regarding the manoeuvrability of PWRs, load variation operation could reduce safety margins of accidental transients, in comparison to base load operation; this refers only to boron control (injection/dilution).

The average capacity factor has been slightly reduced (less than 1.8 % for the entire fleet in France) when operating in primary (frequency) control, mainly due to increased maintenance of control rod drive mechanisms (CRDMs). However, no studies show decreased capacity factors solely due to load-following patterns.

In general, a site with several nuclear power plants could load-follow in a small interval of down-rated power, from 100 % to 70 %, starting with one reactor. If further down-regulation is needed, reactor number two is decreased in sequence. This is for example used at Philippsburg in Germany.

One important conclusion from all references in this study is that load-following should not be carried out with fuel damage in the core. This has been emphasised from plants with relatively large experience from fuel damages (however not due to load-following) as it is assumed that power changes is likely to worsen the fuel damage.

Main impact on PWR operation is the liquid waste from the boron injection system, referring to volume increase. This could be managed by improved re-circulation. No impact regarding fuel reliability has been seen (no failure associated to load variation) and no impact on spent fuel reprocessing (not of Swedish or Finnish concern). Operator training implements already load variation and close attention to core monitoring.

Main wear has been seen on the CRDMs, causing increased need of replacement (typically every three years for grey banks). Increased inspection and maintenance of the pressurizer inlet and outlet due to increased temperature variation frequency have been seen in France.

With a conservative approach, the fuel cycle cost of load-following for BWRs fall in the interval 17-23 % of additional fuel costs. Of the total production cost of a kWh produced from nuclear power the fuel cost is some 20 %. Therefore, the total fuel cycle cost can be 24 % of the total production cost of a kWh when the load-following is done in an unplanned manner for a BWR.

Here the assumption is that the load-following was made in the first fuel cycle in an unplanned manner which makes it to a worse case. If the fuel cycle is planned for load-following there will be no additional fuel costs. However, it is very difficult to predict the exact amount of power regulation that will take place during the upcoming operating periods. It is therefore reasonable to assume a certain additional cost for non-optimal fuel usage.

There is no difference in fresh fuel assembly demand between scenarios including/excluding spectral shifts. This is due to the fact that the current operating strategy in Forsmark with respect to control rod pattern is chosen to favour flexibility. As a consequence, the resulting spectral shift is low and hardly affected by increased power regulation. Accordingly, there are only minor differences between the different scenarios, meaning that the increased fuel cost is independent on when in the cycle load-following operation is used. This means that the reduction of spectral shift is moderate for the reactors at Forsmark, since they are already operated in a manner that disfavours spectral shift.

For PWRs the relative fuel cycle cost of the load-following scenario studied was calculated to 25 %. The uncertainty in demand of fresh fuel assemblies corresponds to a cost uncertainty of ±9 %. Applying a conservative approach, in analogy with the assumptions made above regarding the BWR case, the resulting relative fuel cycle cost of load-following for PWRs would then be in the interval of 25-34 %.

Comparing the cost of load-following for BWRs and PWRs we see that the cost is somewhat higher for PWRs. Hence, from a strict fuel cycle cost perspective, load-follow should preferably be performed by BWRs.

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1 Background to this study

Nuclear reactors are in Sweden traditionally run at full power. This project will investigate what costs are associated to a change in output during hours of the day when the load is low, for example during night-time. The parameters studied include operational impact, safety issues, and nuclear fuel issues; an analysis of the risks for shortened lifetime of nuclear plant equipment due to balancing operation is also discussed.

The first part of this project was carried out in 2011 and it concluded that it is technically feasible to load-follow using nuclear power, see Elforsk 12:08 [1]. This has already been shown in France using their Pressurised Water Reactors (PWRs); this mode of operation is in practice since 75 % of France's electricity production is generated from nuclear power.

As Sweden has approximately 50 % electric generation from hydropower, load-following of nuclear power has not been needed to a high extent in the past. However, with increased intermittent power production in the grid such as wind power, the introduction of solar panels, smarter customers that take active load decisions depending on actual energy price, more connecting cables to Continental Europe, as well as the German moratorium of nuclear power which can create a lack of power in Germany a higher demand on load-following is foreseen. A more competitive prizing of the electricity, with larger fluctuations over 24 hours or week/weekend basis will increase the need of flexible electricity production.

It is believed that in the future, plants with flexible power production are advantageous since the request of power production will vary more than today. In this context the possibility for nuclear power plants in being flexible has to be overseen.

Furthermore, decisions like the four electric grid areas that were decided in November 1, 2011, can cause even more incentives to vary the power produced in nuclear power plants. A flexible nuclear power production could be an important and substantial part of the Swedish energy market.

This study focuses on finding additional costs to the operation of nuclear power plant due to operating in load-following mode, instead of base load-power production. It should be noted that the means to load-follow with nuclear power differ between boiling water reactors (BWRs) and pressurised water reactors (PWRs) and therefore, both reactor concepts have been investigated.

2 Introduction to load-following

Most of the currently operating nuclear reactors were designed to have strong capabilities to change power output during operation. Nuclear power plants (NPPs) in France and Germany operate regularly in load-following mode [2, 3]. They participate in the primary and secondary frequency control, and some units follow a variable load-programme with one or two large power changes per day. In France, load-following is needed in order to balance daily and weekly power variations in electricity supply and demand since nuclear energy represents a large share of the national mix (75 %). In Germany, load-following became important in recent years when a large share of stochastically varying sources of electricity generation (e.g. wind) was introduced to the national mix.

Most often nuclear power generation is considered as base load-power, i.e., 100 % production all the time. However, with a very low demand at night-time or during weekends, it could be preferable to go down in power during these periods. This is what is defined as acting load-following. There are also several other modes of regulating power, such as primary (frequency control on a time-frame of seconds) and secondary regulated (demand from market to regulate power on an hourly basis).

The economic consequences of load-following are mainly related to the reduction of the load-factor of a power plant. In the case of nuclear power, fuel costs represent a small fraction of the electricity generating cost, especially compared to other thermal plants. Thus, operating at higher load-factors is profitable for NPPs as they cannot make savings on fuel costs while not producing electricity.

There are different methods of varying the power output from a nuclear power plant: adjusting control rods, for PWRs adjusting boron concentration to the primary cooling water or, for BWRs, adjusting the main recirculation pumps (MRCPs). The additional costs due to these methods are discussed in this report, in terms of increased maintenance and risk of outage or failures. See Elforsk 12:08, [1] for how it is done to load-follow a nuclear power plant in practice.

The minimum requirements for the manoeuvrability capabilities of modern reactors (Generation III+) are defined by the utility requirements which are based on the requirements of the grid operators. According to the current version of the European Utility Requirements (EUR) the nuclear power plant (NPP) must be capable of a minimum daily load-cycling operation between 50 % and 100 % of rated power (Pr), with a rate of change of electric output of 3-5 % Pr/minute, see [4, 5].

The regulatory factors are in Sweden set by the Transmission System Operator (TSO) Svenska Kraftnät in the Grid Requirement SvKFS 2005:2 [6], based on demands specified in Nordel 1975 [7]. It is stated that the PWRs should be able to manoeuvre at 5 %/min, and the BWRs should be able to operate at 10 %/min within 30 % of full effect (in the area of 60-90 % of full effect).

3 Experience from load-following

From the previous report (Elforsk 12:08) an overview of experience from all over the world was given [1]. The main countries regarding load-following experience listed there were France and Germany, why these countries have been studied more in detail in this report. Information on these countries have been found in two recently published reports, see [2] and [3]. Some details from previous experience in Sweden and Finland are also investigated further below.

In this project, several interviews and meetings have been held with a number of specialists listed in section 9.2. Several sites have been visited as well: Ringhals (BWR and PWR), Forsmark (BWR), Philippsburg in Germany (BWR and PWR) and Nogent-sur-Seine in France (PWR). It should be noted that Ringhals and Philippsburg are sites with both BWRs (R1[1], KKP1[2]) and PWRs (R2-R4, KKP2) on the same site. This is of interest when comparing the two techniques with respect to power control and load-following capabilities.

Another factor to consider is the use of two or more reactors during power control. Experience at KKP was exemplified in an EnBW report [8] where this strategy to use units in sequence for load-following avoids going down in power too low, as this decreases the efficiency of turbines among other effects.

Below follows a summary of the previous operating experiences of load-following in Sweden, Finland, Germany, and France.

3.1 Swedish experience

Sweden has load-followed in the past. Mainly in the early 1980s and in the end of the 1990s, see Elforsk 12:08 [1] for more details. The operations since, have focused on full operation at maximum power, including power up-rates. This is in part caused by the earlier political decision in 1981[3] to shut down reactors by 2010. As this is no longer the case since the political decision 2010 to allow a maximum of 10 nuclear plants in Sweden, a more elaborate operation is now possible.

In addition to load-following operation, tests of primary control of power output were carried out at Forsmark, and are mentioned in [9]. Some power oscillations occurred, and this type of operation was therefore abandoned.

Other examples of early investigations include causes of automatic emergency shutdowns at Forsmark between the years 1985 and 1988. Shutdowns related to power changes were due to the turbine power controller logics, i.e., equipment with which the turbine output power was controlled [10]. This controller unit was at that time mechanically controlled which made it sensitive and

[1] R = Ringhals
[2] KKP = KernKraftwerk Philippsburg
[3] A prior referendum was held in March, 1980.

vulnerable, and was difficult to pilot when power changes were needed. The mechanical construction of this regulator caused therefore a potential risk for disturbances such as automatic shutdown in case of power control and manipulation of the turbine. The turbine regulator was re-designed in the mid-1990s and is now electronic, which is much more reliable and easier to use for power control. Therefore, today the plant is more controllable for load-following operations.

3.2 Finnish experience

Loviisa houses two Soviet-designed VVER-440/213 PWR reactors, each with a capacity of 496 MW. The reactors at Loviisa NPP went into commercial operation in 1977 and 1980 respectively. The plant is operated by Fortum Oyj.

At Loviisa daily load-following and load-following at weekends are prohibited according to the technical specifications and safety rules (in Finnish TTKE) if not a special permit has been granted by STUK (the safety authority in Finland) [11]. In 1981 IVO (former name of Fortum) investigated the possibility of load-following and applied for a permit to load-follow. The permit was granted with the conditions that:

- Maximum 3 unrestricted regulations every year.
- Maximum 7 regulations with maximum 100 MW per plant every year.

Due to the limitations above the regulations has been concentrated to churchly holidays and other exceptions.

3.3 German experience

A visit to Philippsburg (one BWR and one PWR) was carried out in September 2012 to meet with specialists from EnBW nuclear power and from the power plant (See Appendix B).

Fig. 1. Philippsburg Nuclear power plant site (EnBW) [12].

EnBW has about 20 000 employees, of which 1 800 in EnKK, which is the nuclear part of EnBW. The employees work at Neckarwestheim, Obrigheim and Philippsburg (KKP). About 800 employees work at KKP, where two units reside. Unit 1 is a 926 MW BWR (now in final shut-down since the German moratorium March 16, 2011) and unit 2 is a 1 468 MW PWR operating until 2019. In the past, EDF (Electricité de France) had 45 % of the shares of EnBW until the beginning of 2011 when this part was sold to the region Baden-Württenberg.

Load-following has been used at the BWR (KKP1) since the early 1980s, while the PWR (KKP2) started later with load-following operations. Below are examples of actual power output from KKP1 in 2009 (See Fig. 2 and Fig. 3). The figures illustrate primary control from 100 % to approx 95 % and regular load-following down to approx 70 % during nights and weekends. All reports of operation are available from VGB, see [20].

In general, German BWRs have better manoeuvrability than the PWRs according to [2]. The older German PWRs used black control rods (called D-banks) in a set of 4 rods, in combination with boron regulation (for xenon compensation) [3].

The mean temperature is kept constant in German PWR designs (as is the case for the newer EPR by AREVA as well) [2]. This means that during reactor power decrease the inlet temperature increases slightly to compensate for the decrease in outlet temperature.

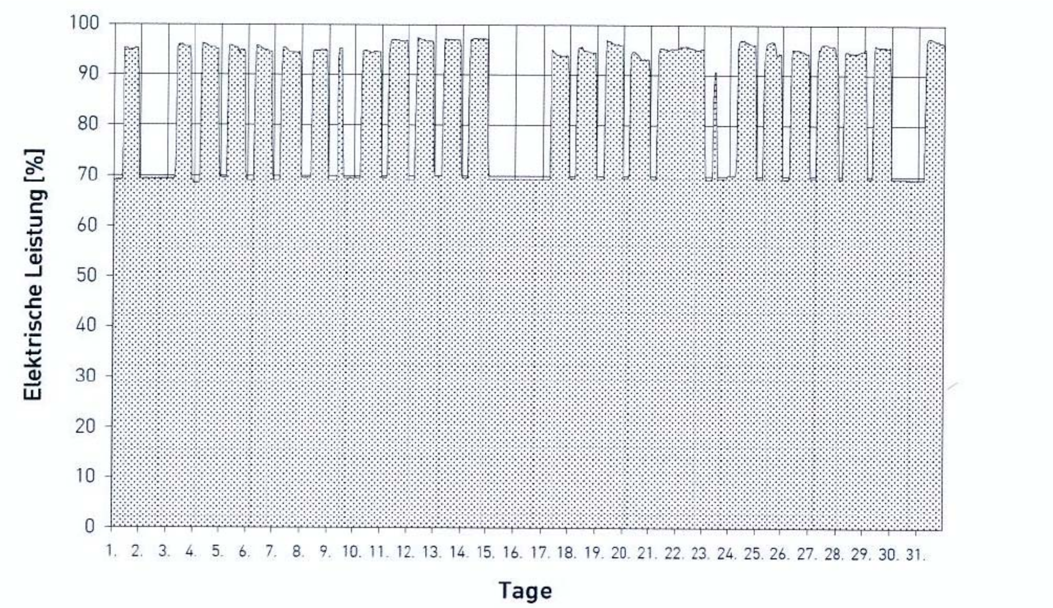


Fig. 2. Power production (in % of rated power, 926 MW) for August 2009 at Philippsburg unit 1 (BWR).

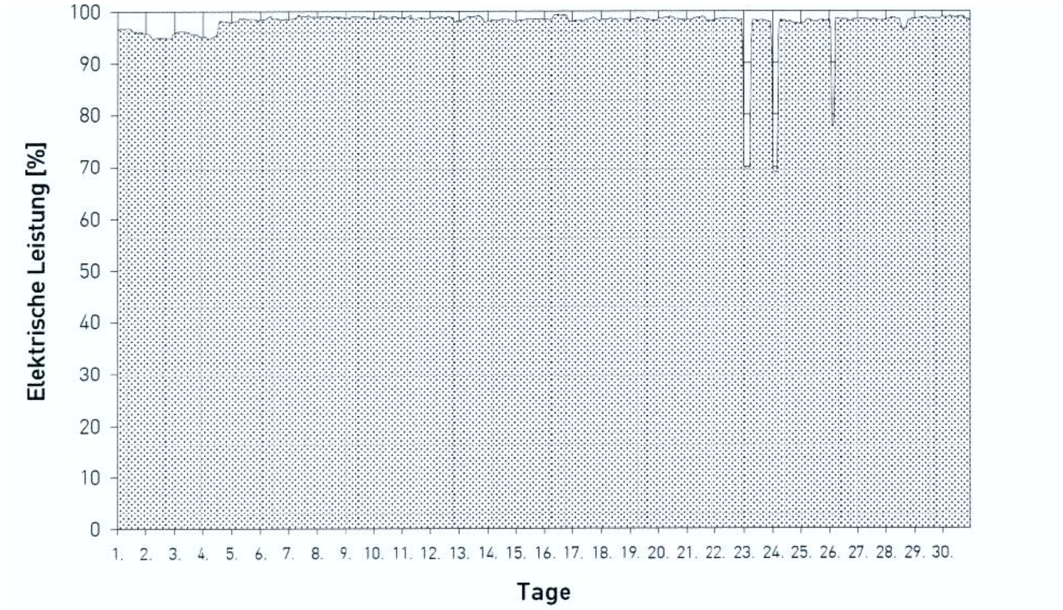


Fig. 3. Power production (in % of rated power, 926 MW) for November 2009 at Philippsburg unit 1 (BWR).

The Philippsburg BWR and PWR plants have regularly load-followed since their construction. In general, no additional costs have been estimated due to this mode of operation.

However, the political decisions play an important role in how to operate the plants. In the beginning of the millennium a decision was taken to phase out nuclear by letting the plants operate up to a production limit. The result was that the power plants had to plan the output well to make best use of the stipulated power production for each unit. However, in 2010 new signals from the German government that it would be possible to continue with nuclear power in Germany made companies believe that full power was the most optimal as long as the spot prices were high. So, the need or interest for load-following is often closely coupled to the energy politics and how the energy market is working, (state controlled or de-regulated). See also details in chapter 5 on the conclusions from the German experience of this power production operation.

3.4 French experience

A visit to EDF (Electricité de France), the PWR at Nogent-Sur-Seine, and Areva was carried out in November 2012, see Appendix C.

Fig. 4. Nuclear power plant at the Nogent-sur-Seine site, where two PWRs (1 300 MW each) with their cooling towers to the left are operating.

EDF operates 58 nuclear power plants (NPPs) in France, mainly divided into three types of PWRs: 900 MW, 1300 MW and N4 reactors (newer 1400 MW plants). In France, Framatome (now Areva NP) constructed all nuclear power plants, of which two basic PWR-types, i.e., 900 MW and 1300 MW of generation power, were delivered to EDF. Therefore, France can be considered as the "home market" of Framatome and no other competitor was able to enter that market.

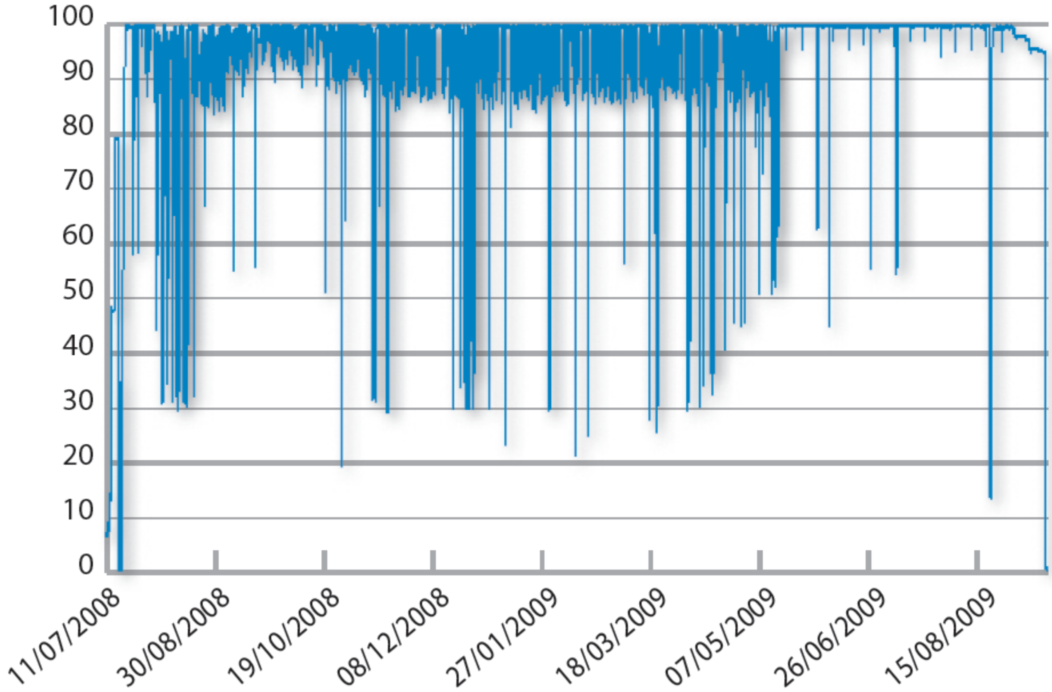
The first PWRs in France (900 MW) were designed to perform base-load operation, i.e., constant maximum power production. However, several were later modified to perform load-following and other controllability [2].

The EDF goals in the 1970s was to improve the manoeuvrability of the nuclear fleet to allow for rapid load-following (from 100 % to 30 % of rated power, Pr), frequency control (±5 % of Pr), rapid return to normal operation at 5 % Pr/min and improving stability in operation, e.g., reducing unplanned shutdowns (scrams). The different modes of operation were licensed in the beginning of the 1980s, starting with an experimental period of tests using mode A (boron concentration adjustment) in 1982, mode G (grey control rods) in 1983, combination of the modes in 1984, followed by an operating period starting in 1985 with following the grid frequency (delivering primary control), see section 4.1.2 below.

Fuel damage linked to load-following cycles was examined in detail between 1982 and 1986. Data indicated that even if the number of load-following manipulations increased from 200 to 1500 times, the number of fuel rod defects stayed the same or even decreased (from 1 to 0.5 defected fuel rods per campaign).

During operation, 60 days are reserved for coast-down operation (at about 85 % of the fuel cycle), in which the plant is not operating in load-following mode. Instead, an outage optimisation schedule is implemented to stretch the operating cycle if needed. The fuel cycle is between 12 and 16 months in France.

An example of power control from a French nuclear power plant during one year is shown in Fig. 5.



Courtesy of Électricité de France (EDF).

Fig. 5. One years' power history from a French PWR in % of rated power [2] from July, 2008 – August, 2009.

3.5 Conclusions on experience from load-following

Load-following has been part of normal operations in many countries of the world. Examples from Sweden, Finland, Germany, and France show good performance during these periods. France and Germany also use nuclear power in frequency control mode (primary power regulation). The main reasons for load-following in Sweden and Finland have been due to limits in hydropower usage, such as during "wet years" and during periods of coast-down (end of fuel cycle).

Main impact on PWR operation is the liquid waste, referring to volume increase, which could be managed and re-circulated. No impact regarding fuel reliability has been seen (no failure associated to load variation) and no impact on spent fuel reprocessing[4]. Operator training implements already load variation and close attention to core monitoring.

[4] Spent fuel reprocessing is not a concern for Sweden and Finland.

4 Manoeuvring capability

The manoeuvring capability of the Nuclear Power Plants (NPPs) is set by two dominating factors, technical and regulatory. As compared to fossil fuelled plants, nuclear plants can regulate much faster, as the fossil plants operate at much higher temperatures. In general, the main concern for structural materials is corrosion, especially at the hot water outlet. Each degree causes a big difference in material changes.

4.1 Regulatory demands

The regulatory factors are in Sweden detailed in the grid requirement SvKFS 2005:2 [6] where the demands are set for new built plants as well as parts of today's plants where the new installed parts affect the regulatory demands [6]. The regulatory demands when the Swedish NPPs were built can be found in Nordel 1975 [7]. However, the set demands on the manoeuvring capability are basically the same in [6] and [7]. The PWRs should be able to manoeuvre at 5 %/min within 30 % of full effect in the area of 60-90 % of full effect, and the BWRs should be able to operate at 10 %/min within the same power range. It should be noted that the grid requirement specifically says that power levels at unfavourable operation points (power levels) over a longer period should be avoided. All load-following operation is carried out with purchase agreement between the plant and SvK, and it is always up to the plant operator to allow for power variations, if safe operation can be assured.

Below we will explain the regulatory demands in Germany and France, with examples from the plants Philippsburg and Nogent-sur-Seine.

4.1.1 German regulation - Philippsburg

If the plants Philippsburg 1 (KKP1) or Philippsburg 2 (KKP2) have to reduce the output power due to disturbances in the plants, it has to be reported to the TSO by phone. Also, the report ”Betriebsanweisung” (Operating Instructions, see Appendix B) has to be filled and recorded. In the report it has to be stated when the problems will be solved and when the plant can reconnect to the grid. The report is sent to the TSO, see [12].

KKP2 has to run at full power at least 48h a week in order to be able to determine the stable full load operation point with enough accuracy. Also, when the power has been lowered and then returned to full power, 24 hours has to elapse before the power can be lowered again according to the regulatory demands in Germany, [12].

Concerning the power control, three modes are used in Germany. For Phillipsburg 1 and 2 this translates to:

- Primary (frequency) control
- Secondary control
- Load-following and Minute-reserve

Primary Control

Primary control is requested for a limited time by fax from the TSO. Primary control is for KKP1 possible in two steps, 11 and 22 MW (of 926 MW) as shown in Table 1. For KKP2 is primary control possible in three steps, 10, 20, and 30 MW (of 1 468 MW), see Table 1.

Table 1. The steps for primary control in Philippsburg 1 and 2.

Stufe	Primärregelungsstufen	
	KKP1	KKP2
1	11 MW	10 MW
2	22 MW	20 MW
3		30 MW

For KKP1 primary control is not possible at the same time that the output power is less than 74 % of maximum power ~670 MW.

Secondary Control

Secondary control is requested for during a limited time by fax from the TSO. Secondary control for KKP1 and KKP2 is possible in steps of 30 MW/min, see Table 2.

Table 2. The steps for secondary control in Philippsburg 1 and 2.

	KKP1	KKP2
Leistungshub	-30 MW	-30 MW
Gradient	30 MW/min	30 MW/min

Load-Following

Load-following is possible with a notice of 5 h in advance in Germany.

Normally this is done according to a predetermined table; see Table 3, where it is shown how the operator reduces the effect progressively between KKP1 and KKP2. First the operations at KKP1 normally go to 74 % of full power MW, see Stufe 1. Thereafter, KKP2 is used down to 70 %, see Stufe 2.

After that, further decrease of KKP1 is effectuated, see Stufe 3, and finally further decrease of KKP2 is effectuated, see Stufe 4.

Table 3. The steps for load-following in Philippsburg 1 and 2.

	Leistungsreduktion			
Stufe	KKP1		KKP2	
	um max.	auf	um max.	auf
1	230 MW	74 %	0 MW	100 %
2	230 MW	74 %	430 MW	70 %
3	600 MW	30 %	430 MW	70 %
4	600 MW	30 %	800 MW	45 %

Minute-Reserve

Also a so-called Minute-reserve exists in Germany. This is a special case of load-following where the TSO demand fast power regulation. The TSO can at maximum demand a decrease or increase of 90 MW for KKP1 and 100 MW for KKP2. This power control should be possible within 7.5 minutes after order from the TSO and it should be finished after another 7.5 minutes. This means that the TSO can adjust power to a maximum of 90+100 MW within 15 minutes from the two reactors in Philippsburg. In France a similar mode also exists.

4.1.2 French regulation - Nogent-sur-Seine

ASN (Authorité de Sûreté Nucléaire) is the nuclear safety authority in France. They require that all modifications to plants are validated by tests, such as those undertaken in the 1970s to improve flexibility of power control of the French nuclear fleet.

The French NPPs have now different types of modes for the controllability. Mode A is used in the oldest 900 MW reactors (constructed in the early 1970s) and is based on boron regulation, which means boronisation and dilution of the cooling water in the reactor primary circuit.

Mode G was later added to the nuclear fleet (for most 900 MW and 1 300 MW PWRs) and is based on control rod adjustment with ”black” and ”grey” banks. The grey control rod banks are several times less efficient than normal (black) control rods; the reactivity adjustment is less abrupt. The first tests with grey banks were carried out in Tricastin in 1981.

All EDF NPPs operating in flexible power variation mode can carry out:

- Frequency control : ± 2 %[5] (immediate effect)
- Remote control : ± 5 % (energy balance between zones, managed by the Grid Regulator)
- Daily load variation (typically 6 hours at 50 % power during the night)
- Load decrease down to zero (plant disconnected from the grid, but at hot conditions, able to rapid load increase)
- All power ramps can be performed at 5 %/min (mode G)

Primary Control and secondary control

The power from one unit is divided into three parts, with three set values (P_0, k, P_s) according to: $P = P_0+k*(f_0-f_{actual}) + N*P_s$, where P_0 is a set point given by the operator between 37 % and 93 % of maximal power (P_{max}) of the unit (load-following), $k*(f_0- f_{actual})$ corresponds to 2 % of P_{max} of (automatic primary control)[6], and P_s corresponds typically to 5 % of P_{max} (automatic secondary control). The value N is varying from -1 to 1 and is obtained from the TSO, which is Résaux de Transmission d’Electricité (RTE) in France. For a

[5] In percentage of rated power, Pr.

[6] f_0 is nominal frequency, 50.00 Hz, and f_{actual} is the actual grid frequency.

1 300 MW plant, 27 MW is used for primary control, and about 70 MW of secondary control, with the reactor running at 1 200 MW.

The primary frequency control is used for short-term adjustment of the electric grid, to stabilise production and demand in the time frame of seconds. Typically, dP = k*df with k~50 % P/Hz, which means that for a frequency change of df = 50 mHz in the electric grid, the power needs to change by 2.5 % of full power [2].

Load-following

Load-following control is typically used on an hourly basis for power-regulating between day and night, or over a weekend in steps of 1-5 % of full power per minute. In France, the main ramping speed is below 1.5 %/min, see [2]. The main load-following power model is "12-3-6-3", which means operation for 12h at 100 % Pr, followed by 3h power decrease, 6h at 50 % Pr, and finally 3h power increase. This can be carried out during 85 % of the fuel cycle for PWRs.

4.2 Technical aspects

The technical aspects of how to regulate the power of NPPs is described in Elforsk 12:08 [1] together with the technical limitations.

In the BWRs today the manoeuvring is carried out with the main cooling pumps down to a power of about 60-70 %. This is exemplified in Fig. 6, with the pump minimum speed, which is reached at 60 % reactor power in this example. This limit varies however slightly for different power plants.

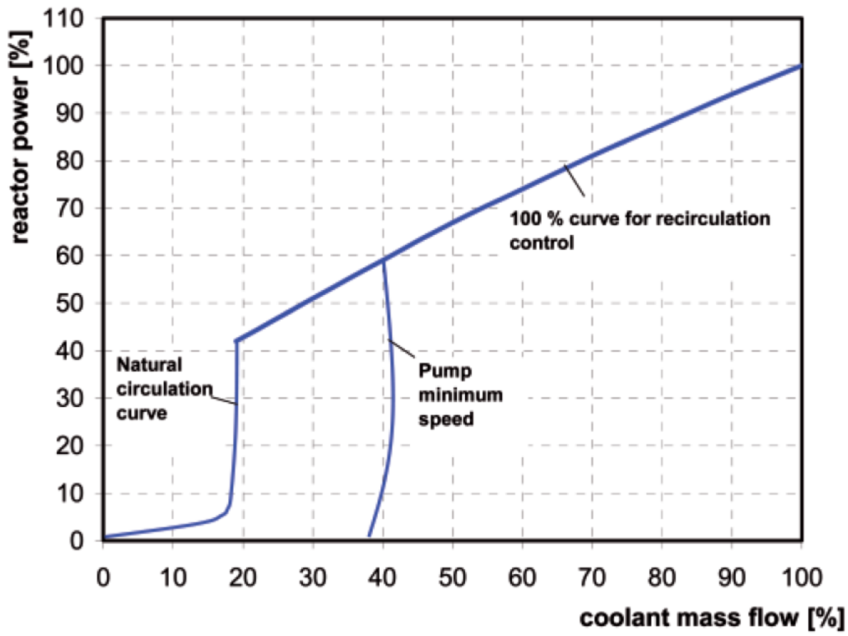


Fig. 6. Schematic characteristic curve for recirculation control (BWR) [3].

For PWRs the manoeuvring is made by increasing the boron concentration and/or inserting the control rods, either the "normal" black rods or less efficient grey rods.

The limiting physical aspects of varying the power in a light water reactor (BWR and PWR) can be summarised as, see [2]:

- Counter-reactions
  - Less efficient neutron moderation due to increased temperature of the primary coolant decreases reactor power.
  - Decreased reactivity due to the Doppler effect[7] caused by change in fuel temperature.
  - Change in the power distribution in the core.
- Fission product poisoning
  - Xenon is a reactor poison as it absorbs neutrons. At power changes, the equilibrium is changed due to a shift in time with respect to the reactor power and is therefore a significant challenge for the manoeuvrability of the plant.
- Fuel burn up
  - As the fuel is consumed the reactivity drops, and the manoeuvrability changes
  - Boron is used to compensate for the high reactivity at the beginning of the cycle (BOC).
  - Burnable absorbers, which are neutron absorbing materials that are consumed during the fuel cycle, increase the reactivity in the end of the cycle (EOC).

The neutron poisoning by xenon, ^{135}Xe, is a dominant factor to why the reactor power cannot be increased too fast as the effect is shifted in time with respect to reactor power. It has a very large neutron-capture cross section and decays with a half-life of 9.1 hours. The delay in reactivity change comes from the fact that ^{135}Xe is produced from decay of fission products such as iodine, ^{135}I (half-life of 6.6 hours).

The concentration of ^{135}Xe and the associated negative reactivity decreases (and pass by a minimum of about 3 hours) when the power of the reactor is increased. The concentration of ^{135}Xe and the associated negative reactivity increase (and pass a maximum after about 7-8 hours) when the power of the reactor is reduced. See also Fig. 7 with examples of poisoning at different times in the fuel cycle.

[7] Neutrons are lost as the absorption in ^{238}U increases with temperature due to a strong resonance (peak) in the cross section (probability) of neutron capture.

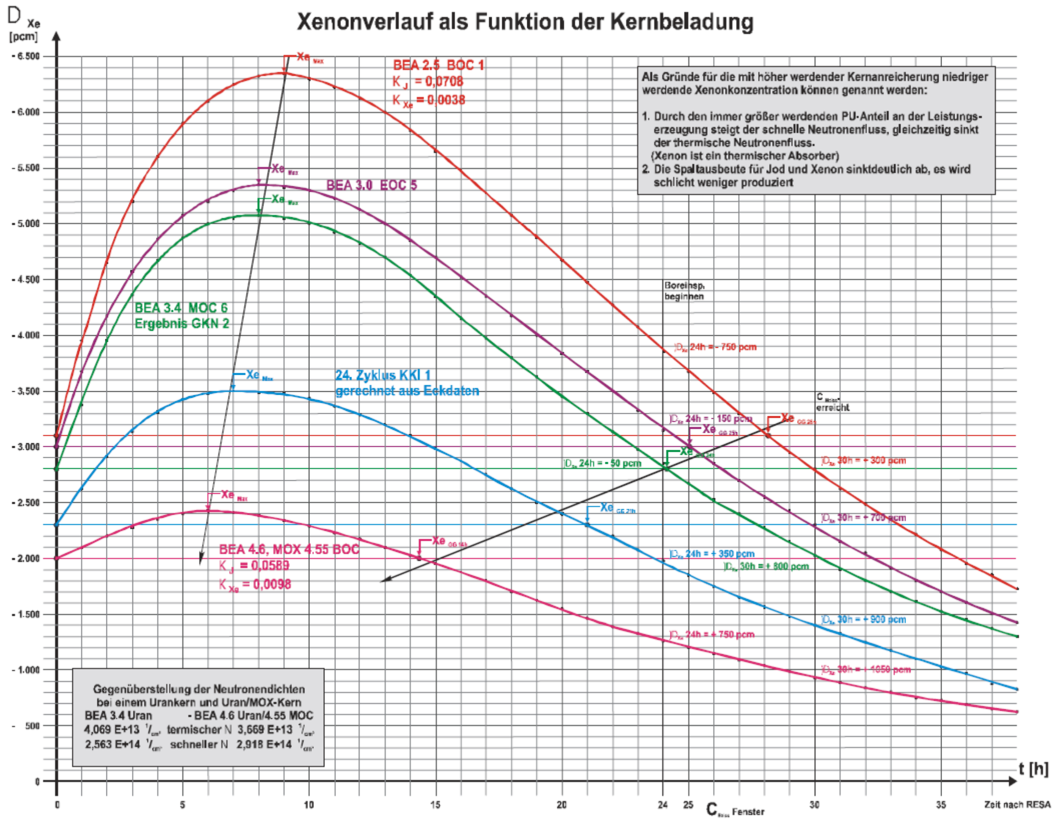


Fig. 7. Xenon peak after power change [14].

Vital technical aspects to manoeuvre the power of an NPP are:

- good reactivity measurement system is needed, this is not a concern for more modern plants, however for older plants the measurement system can be somewhat coarse.
- The main cooling pumps need to be finely regulated to control the reactor power.
- Good start/stop sequences for the condensate and feedwater pumps. For instance that one pump shuts down at low flow and thus avoids cavitation risks.
- The control rods have to be finely manoeuvrable in order to control the reactor power.
- The boron systems have to be sensitive in order to control the reactivity of the core.

4.2.1 Start-up sequence

A typical start-up sequence is illustrated in Fig. 8, when the plant has been shut down for two different timeframes, 1-24h and 1-7 days. The start up takes longer time when the reactor has been shut down for a longer time, this is due to the fission poisoning. Note in particular the stabilisation times, where the reactor has to "rest" to reach a more equilibrium state [6]. The time for start up after 1-7 days of shut down could be in the range of 20 h, while for a shutdown of 1-24 h the start up could be in the range of 7 h.

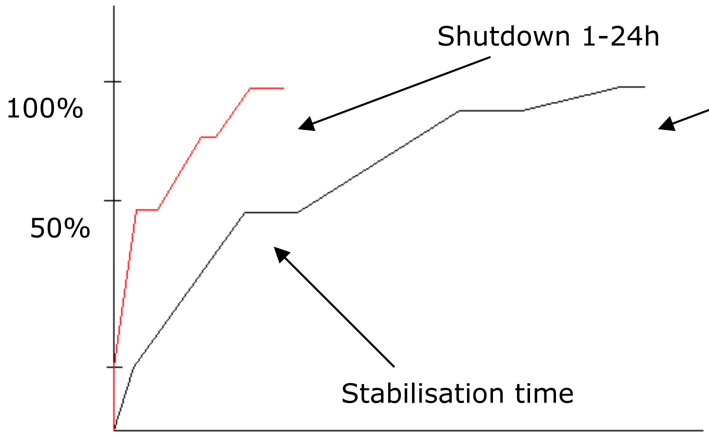


Fig. 8. Start-up sequence, reactor power as function of time (arbitrary units). Note the difference in speed for the ramp-up in power.

4.3 European Utility Requirements (EUR)

The European Utility Requirements (EUR) organisation aims at harmonization and stabilization of the conditions in which the standardized Light Water Reactor nuclear power plants to be built in Europe will be designed and developed. EUR was created in 1991 by utilities in Belgium, France, Germany, Spain, and the UK to establish a more open specification of what is needed of a nuclear reactor.

The EUR states the requirements for future NPPs (i.e., generation III+ reactors) where the EUR is adopted. The stated requirements are that [4]:

- The unit should be capable of continuous operation between 50 and 100 % of its rated power Pr (but not below the minimum power level).
- The standard plant design shall allow the implementation of scheduled and unscheduled load-following operation during 90 % of the time of the whole fuel cycle.
- The unit may be required to participate in emergency load variations.
- The unit shall be capable of taking part in primary control of the grid.
- The unit shall be able to contribute to grid restoration.

The US-based Electric Power Research Institute (EPRI) has similar requirements, as detailed in [5].

4.4 Design transient specification

The safety requirement for the core in an NPP is that the power should be allowed to be reduced to a subcritical level where the thermal power can be handled by the decay heat and pressure release systems. This means that the fastest reduction of the power is through scram[8]. However, every change in the power is a thermal transient and thus adds strain to the Reactor Pressure Vessel.

The allowed thermal transients are defined and stated in the Design Transient Specification, DTS, see also Elforsk 12:08 [1]. The current DTSs for the BWRs in Sweden has been recalculated in the power uprate programmes and are now based upon a life length of 60 years. The work is ongoing for the PWRs in their power uprate programmes.

At Ringhals the power changes involved in down-regulating are discussed in the licensing document on transient budget, and are referred to as "2.2a" and "2.2b" in the licensing document. The original total number permitted were in the order of $2x10^4$ times of ramping up and down the power (for the 40 year transient budget), with the power change of 5 % per minute except for stationary variations of ±2 % [18]. For secondary control this is the limited number of rampings.

EDF made a study on the possible amplitude of load-following transients that do not affect the transient budget. The study provided a number in the order of 7 % of nominal power; EDF keeps their load-following for frequency control within this range.

The pressure vessel of the Finnish Loviisa Unit 1 has been successfully heat annealed in 1996 in order to release embrittlement caused by neutron bombardment and impurities of the welding seam between the two halves of the vessel. After such an operation the DTS is recalculated for the RPV to be licenced for longer operating time. The operating licenses for both Loviisa units have been renewed for a 50 year lifetime, Loviisa-1 to 2027 and Loviisa-2 to 2030.

PCI - Pellet-Cladding Interaction has been touted as a problem regarding load-following; however there are no PCI requirements for H1[9] operation and H2[10] transients according to [28]. PCI threshold values are however provided by the fuel suppliers. These limit values act to ensure availability during the operating cycle. If the limit values are contained, the fuel supplier provides a warranty that no PCI related fuel damage will occur.

PCI related fuel damages occurred in the 90's, since then better core monitoring systems have been introduced to avoid these types of incidents.

For a BWR the DTS is not affected as long as the power is regulated in the "blue area" of the operation diagram, see Fig. 9. However, at about 65 % reactor power, dependant on the plant, fission poisoning appears and the manoeuvrability is impaired.

[8] Full insertion of the control rods in order to get the reactor in full safe mode, i.e., zero power.
[9] H1 is normal mode of operation.
[10] H2 is mode with expected transients.

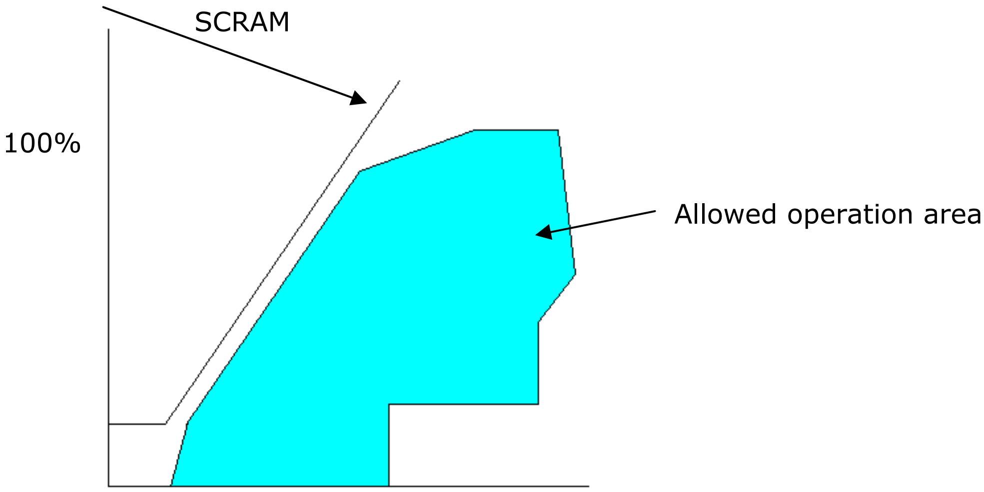


Fig. 9. Operation area, with reactor power as function of main coolant flow.

Fig. 10 shows the operation area (reactor power as function of axial power ratio between upper and lower core) for a PWR using the A mode and G mode (regulating with grey control rods). As found in the figure, the area at G mode is larger and thus easier to manoeuvre within.

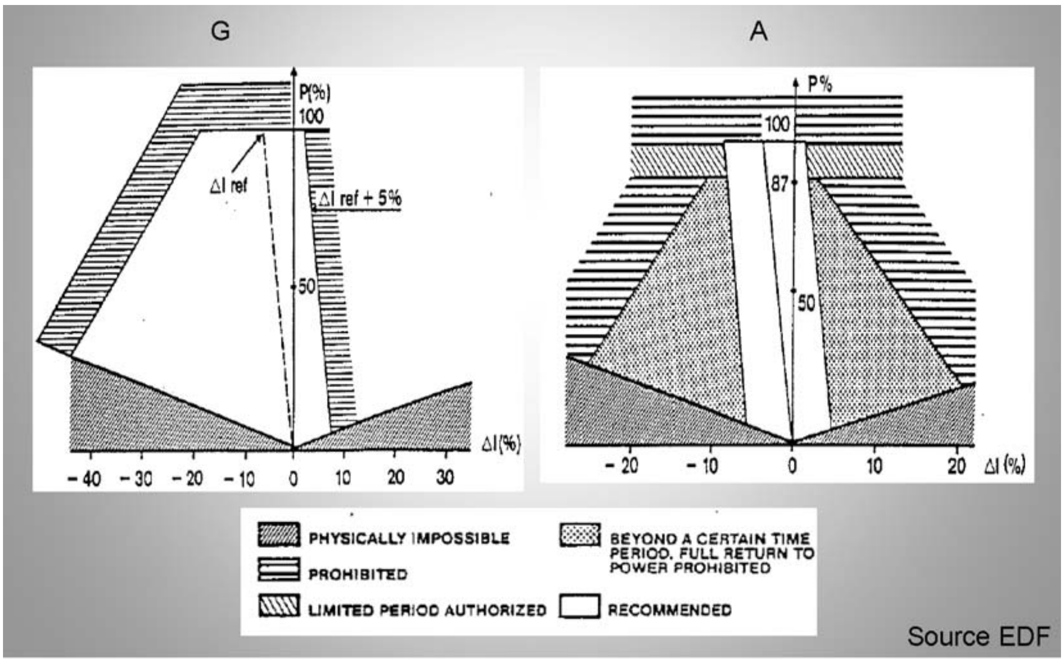


Fig. 10. Operation diagram PWR, with reactor power as function of axial power (delta flux).

If the DTS needs to be recalculated it could be a large work dependant on the available information, up a 100 man years of work. If data has been collected for the plant of historic occurred transients and if pertinent data for the transients in the DTS is available, the work is more in the size of a couple of months of work.

Regarding the effect of load-following at Ringhals on the DTS: "The transient budget should normally not be changed due to the types of variations that comes from load-following as long as the temperature changes are marginal (± 0.5 °C) at normal ramp-up or ramp-down (3-4 MW/min). However, the PWRs at Ringhals have an upper temperature change limit of 28 °C/h [19]. For a BWR, the power changes should not impose on temperature changes of 40 °C/h in order to violate the STF (Säkerhetstekniska driftförutsättningar, the technical safety specifications).

Every occurrence from the STF has been logged; this implies that important archived material can be found for the historic transients. Regarding the load basis for the transients a lot of work has been done in the power uprate programs. This means that if the DTS has to be recalculated the work is more in the region of months of work than years.

4.5 Conclusions on Manoeuvring capability

The manoeuvring capability of the Nuclear Power Plants is set by two dominating factors, technical and regulatory.

It is concluded that if the load-following is planned and the regulation is done within determined levels specific for the plant there is no hindrance or additional costs for load-following.

Regarding the manoeuvrability of PWRs, load variation operation could reduce safety margins of accidental transients, in comparison to base load operation; this refers only to mode A core monitoring (boronisation/dilution).

Time spent at intermediate load should be thoroughly controlled and must comply with technical specifications.

The average capacity factor has been slightly reduced (less than 1.8 % for the entire fleet in France) due to load-variation operation, mainly due to unexpected or increased maintenance.

Main wear has been seen on the control rod drive mechanism (CRDM), causing increased need of replacement (typically every three years for grey banks), see also appendix C. It should be noted that the CRDM is used mainly for frequency control, which means that the needs of replacement should be of lesser concern for load-following operation without primary control.

Increased inspection and maintenance of the pressurizer inlet and outlet due to increased temperature variation frequency is a result of load-following.

5 Cost considerations in nuclear power plants

In this chapter follows a summary of discussions held with different nuclear operators in Sweden, Finland, Germany, and France.

Several specialists have been contacted in this study; see a complete list in section 9.2. A short questionnaire was prepared for the discussions with Ringhals (RAB), Forsmark (FKA), Oskarshamn (OKG), Fortum, EnBW and EDF (see Appendix A). The questions were divided into four parts: general, operation, maintenance, and training. Specific questions for PWRs were also added for the meetings with Ringhals, Fortum, EnBW, and EDF.

5.1 General

The main reason to load-follow is to keep the power balance in the grid. In Sweden this is the responsibility of the TSO (Svenska Kraftnät, SvK) to make sure that there is a balance between production and consumption. There is always a difference in power needs at night/day and weekday/weekend. There could also be a difference due to outage of other plants, and years with well-filled hydropower stations.

For the nuclear plant Loviisa, the power reduction request comes from Fortum's Physical Operations Trading unit, based on very low demand of electricity e.g. during summer or spring floods. At Loviisa these occasions has happened several times every year between 2000 and 2002.

At Forsmark the general order in which the three reactors were used for load-following was decided on a common weekly meeting, and depended on specific operation situations in each reactor; fuel issues, power history etc.

There is a lack of comparative studies of plants operated at full power and plants regularly load-following. At Ringhals, Forsmark and Oskarshamn studies have been carried out to find the most vulnerable components while operating at reduced power. There are also studies that discuss what power regions to avoid for optimal use of the plant together with consequences when operating at these areas that can cause higher wear and tear [9,24,26].

5.2 Operation

There are in general no operational difficulties in load-following operation. The plants are designed to regulate power and there are no problems in running the plants at lower power. However, some power ranges need to be avoided and certain limits cannot be surpassed. These limits are plant specific and need to be understood for each coupled system, core-turbine-generator. If these limits are not followed, unnecessary wear on components is possible which could increase maintenance costs. Also, this can result in that the allowable number of transients is decreased.

First of all it is important to regulate power, up and down, slow enough in order to avoid unnecessary stresses on material and fuel. In addition, there is also a need to stay out of power ranges for longer time that are unfavourable. These unfavourable power ranges are for example where different systems automatically are connected or where vibrations can occur due to critical flow speeds etc.

As there is no longer any habitual experience of load-following in Sweden and since many of the plants have been modified, re-designed and renewed, especially recent power up rates, there will be a need to analyse where these critical power ranges are for each and every plant.

One important conclusion from all references in this study is that load-following is not carried out with fuel damage in the core. This has been emphasised from plants with relatively large experience from fuel damages (however not due to load-following) as it is assumed that power changes is likely to worsen the fuel damage.

Fuel damage was brought up in the previous study Elforsk 12:08 [1] as caused by load-following. The reference report by Hundt et al. [15] has been found referring to very old information. For example, reported fuel damage due to primary power control was seen in 1977 at Gundremmingen which was not specifically due to load-following.

Fuel related costs are mainly discussed in chapter 6. However it was pointed out in [6] that the annual refuelling outage has taken longer time than expected, also the following stretch-out/coast-down has been shorter than expected. This results in a deviation in power from the optimal cycle end point.

According to Fortum [6], there is always a risk of disturbances in operation due to power changes. An example is that the flow changes in pumps and valves from the optimal working point. This increases the risk for an urgent shut-down and delay to restore power levels.

5.3 Maintenance and re-design

The main conclusion from the different responses in this study regarding maintenance and re-design is that load-following cause a minimal additional wear in the plant, except for control rod drivers in frequency control operation. In general, at low power (<60 % of rated power) more wear can be seen in a plant, due to for example vibrations and changes in temperature. This is mainly due to the fact that the plants optimal working point is at full power, and the farther one operates from that point, the worse it is, in terms of efficiency, pump capacity, position of control rods etc, [1]. However, to load-follow down to about 60 % of rated full power does not cause any problems when plant specific power ranges are avoided. After longer periods in certain ranges, some relays can start to flip which means that a lot of signals are sent in different systems that could cause an overload in signals with further risk of disturbances.

The condensate- and main feedwater pumps are used to pump the water back from the turbine condenser to the reactor core in a BWR. The pumps also increase the pressure of the feedwater so that the pressure is maintained in the reactor pressure vessel. This is done in two steps where the condensate pumps is the first step and the feedwater-pumps is the second. Forsmark 3 and Oskarshamn 3 have three pumps of each pump type, of which two (of each) are always in operation during normal (100 % power) operation. The third pump is considered as a reserve pump.

During the 1980s and 1990s the Swedish plants were partly load-following to obtain sufficient balance in the grid. In the end of the 1980s Forsmark 3 had been load-followed to a much larger extent than what was planned for at the time of construction. Therefore, some actions were taken, such as minimising cavitational issues resulting in vibrations of the condensate- and the feedwater pumps that could appear due to lower flow. The simple solution was to make use of only one pump (instead of two) at low power operation, see [25]. The “one pump solution” has also been implemented at the twin reactor Oskarshamn 3, where similar vibration problems were also noted.

Answers from Ringhals regarding additional maintenance costs confirms that as long as the power regulation is limited to 60 % of full power no additional wear is expected. That is, as long as the two turbines can keep running, it does not influence the operation. However, dumping steam from the plant in one turbine string (that is, running the reactor at 100 % but only using 50 % of thermal power to the turbines) could result in condensation on turbines and unnecessary wear of the piping and the condensation pool.

Vibration problems regarding load-following has earlier also occurred in Germany at Philippsburg and Neckarwestheim. Specific wear and tear was noted in some cases on condenser pump wheels due to the same issues as in Forsmark and Oskarshamn. The issue has however been resolved.

The Loviisa power plants in Finland are two VVER PWRs designed for part load operations. Anything from 50 to 100 % load can be maintained indefinitely and thus there are no issues with load-following. However the operators understand there is risk at reducing the power more than 100 MW (20 %) for each unit since the flow routes change and possibly the high pressure pre-heaters are bypassed. If the flow routes do not get changed, no maintenance issues are found. The discussion above is, however, based on very little experience, as Loviisa has not participated in load-following for the past 10 years.

In France where the load-following primarily is regulated with the control rods an increased maintenance is necessary for the CRDMs due to the high utilisation of the component. In French nuclear power plants there is also an increased inspection and maintenance of the pressurizer inlet and outlet due to increased temperature variation frequency.

5.4 Training of personnel

No additional training is needed in case of load-following operation, as this is part of the regular training schemes. The adjustment of power is included in the normal duties for the operators in the control room. Power control is also part of the yearly training sessions in the simulator. Therefore, no additional cost is needed regarding training and experience.

One improvement that could be needed is to introduce additional core supervision capability in the control room. An example is how to compensate for xenon poisoning in the core and the monitoring of the axial power.

5.5 Cost differences between BWRs and PWRs

If nuclear power plants are load-following within the limits that are set for power regulating, there is a small additional wear to the different components involved since some components are used at either a different (not optimal) operational point or at a higher utilisation, such as the CRDMs. Also there are differences in what components that are involved at different plants.

The main difference in terms of power regulation between BWRs and PWRs is the use of boron in PWRs, and hence a possible cost for this operation could be assumed. The evaporation itself causes a small power reduction since the evaporator uses house steam. Possibly there are some minor costs due to water treatment, but this depends mainly on what boron system that is used. It should be noted that at beginning of cycle (BOC) the boron concentration is over 700 ppm, and is used at a rate of 2-3 ppm per day. At end-of-cycle (EOC) about 10 ppm remains and the manoeuvrability is limited.

There is however a solution of not using boron in PWRs. In French reactors, grey control rods are employed as well, see chapter 4.2. The advantage of these control rods is that they do not cause an uneven axial power distribution as normal control rods do, see chapter 6.1. It should be noted that a continuous boron treatment system (boron concentration adjustment) is needed for power regulation, such as the boron thermal regeneration system (BTRS) by Westinghouse [16]. This is not present at all PWRs. Rather, boron is treated in batches when need be.

The fact that BWRs have steam (void) inside the core (as opposed to PWRs), gives an opportunity to optimise fuel for spectral shift. This means that the neutron spectrum becomes harder, and plutonium breeding can be improved and used in the end of the fuel cycle, see also chapter 6.

A general issue for both plant configurations is the risk of wear in control rods if used in the power regulation. This could for example be due to neutron irradiation at unfavourable positions of the control rod structure. However, this is not of relevance for load-following operation.

5.6 Conclusions on Cost Considerations in NPPs

The main lesson learned is that if load-following is planned in advance and within given limits, there are no problems in this mode of operation. There are very few additional costs correlated to load-following for maintenance nor operation and training. However, regular primary (frequency) control does influence the wear in CRDMs and hence the maintenance intervals and the outage duration.

As the plants have been modified and updated with new turbines, new instrumentation and control etc., one has to look at each individual plant to get the complete picture of how that plant will behave during power control. It is also needed to find power regions where one should not operate over longer periods during load-following. Such needed studies could bring an additional cost to the overall in preparation.

There is no cost associated with training of personnel as this is already part of normal operator education. However increased core monitoring is foreseen.

Additional costs due to the boron treatment in PWRs in terms of power consumption and water treatment costs are minimal, but need to be considered in detail for periods of regular load-following.

6 Fuel economy

The fuel cycle costs associated with load-following operation have here been investigated for both BWRs and PWRs. Fuel utilization and the number of fresh assemblies needed in the subsequent operating periods have been analysed for different load-following scenarios. Six consecutive operating periods (cycles) were included in the BWR analysis. The focus in this report has mainly been on BWR operation, since the cost initially was anticipated to be larger due to the possible reduction of spectral shift, i.e., less capability to build up fissionable isotopes, due to load-following operation in BWRs.

It should be noted that the calculations and associated costs in this study are reactor specific. Since the additional fuel cost largely depends on the number of cycles during which the fuel assemblies normally stays in the core, the relative fuel cycle cost of load-following will vary for different reactors.

6.1 Introduction

For each operating period (cycle) of a nuclear power plant, both PWRs and BWRs, the distribution of the uranium enrichment and burnable absorber[11] in the fresh fuel to be loaded into the core is designed to fit the specific cycle. The number of fuel rods with burnable absorbers, and the concentration of the burnable absorber, are adjusted to fit the core inventory and the planned cycle length properly. Consequently, both previous and coming cycles have significant impact on the nuclear design of the fresh fuel as well as the actual core.

Load-following operation implies that the fuel will not be utilized as was originally planned for, i.e., the number of full power operating hours and hence the total cycle length will decrease with load-following operation. Furthermore, for BWR core design, the reactor is always assumed to be operated in a predetermined way with respect to the axial position of the control rods and the velocity of the coolant mass flow. The balance of control rod positions and coolant flow velocity is somewhat flexible as long as operation stays within the operating regime, see Fig. 11.

[11] A neutron absorbing substance that is consumed during reactor operation. Insertion of burnable absorbers aims to compensate for the reactivity reduction due to burnup of the fuel rods.

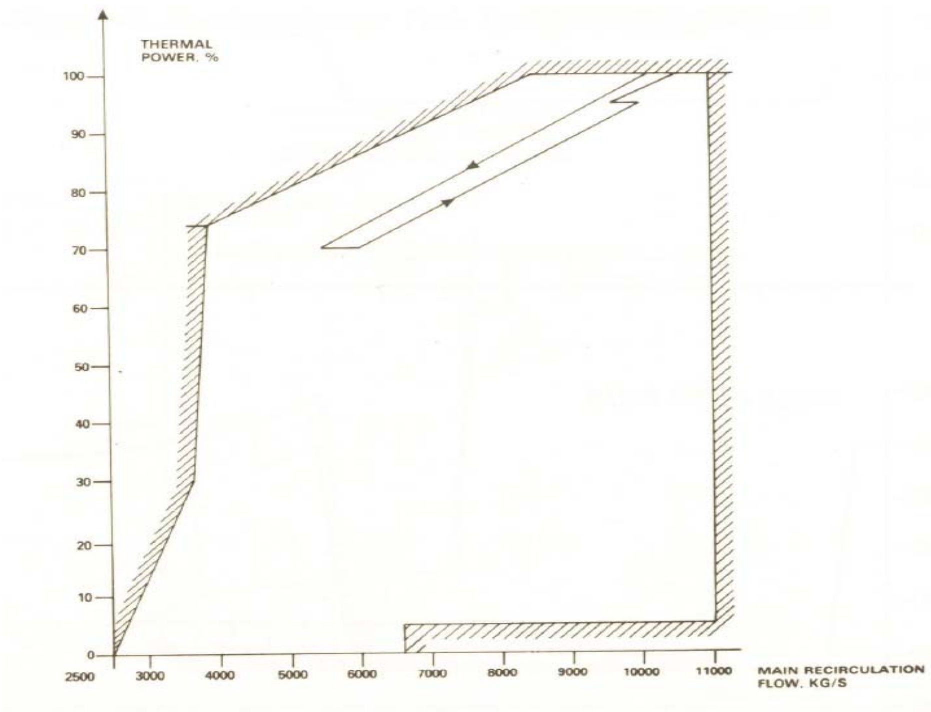


Fig. 11. Schematic operating regime of a BWR. The arrows indicate a load swing down to 70 % power, see [22].

Operation at an optimal point within the operating regime creates economical benefits, i.e., spectral shift in a BWR. A lower coolant flow velocity at the beginning of the operating period gives a larger amount of steam in the core. Since steam does not slow down the neutrons as effectively as fluid water, more fast neutrons are present in the core. This result in effective breeding of ^{238}U into the fissile material ^{239}Pu, which makes it possible to operate the cycle at the rated power level for a longer time. This is known as spectral shift.

With load-following operation the reactor will occasionally be operated at less optimal conditions to facilitate power regulations. Accordingly, load-following is anticipated to result in a less economical operating scheme with respect to spectral shift.

In PWRs there is no boiling in the core and hence no spectral shift. Therefore, the main focus of the calculations will be on BWRs in this investigation.

6.2 Multicycle analysis

In order to quantify fuel cycle costs associated with load-following operation, four different multicycle scenarios have been studied. Each scenario consists of six consecutive cycles. For each scenario, the number of fresh fuel assemblies needed for each cycle was analysed and compared to the energy output. If there is an increased cost connected to load-following operation, this would be seen as a lower energy output per fresh fuel assembly. Each of the four scenarios starts with the same reference core which is treated in different ways:

1. the full reference cycle (including coast down[12]),
2. the reference cycle -20 % cycle length,
3. the reference cycle operated at 60 % power first half,
4. the reference cycle operated at 60 % power second half.

For the first scenario, the reference core is simulated with a coast down period at the end of the operating period. In the other scenarios no coast down period is included for the operating period of the reference core due to the reduction in cycle length. The five consecutive cycles are computed with a coast down period for all scenarios.

The first scenario is intended as a reference scenario where the core is operated as planned.

The aim of the second scenario is to estimate the cost of overloading the core, i.e., use a larger number of fresh fuel assemblies than is needed to achieve the resulting shorter cycle length. This scenario reflects load-following operation during weekends, i.e., a power reduction from the nominal power to 60 % power for two days a week which results in a 20 % reduction of total energy.

The third and fourth scenarios are used to investigate the influence of a worsened utilization of spectral shift. It is assumed that a load-following operation mode at the beginning of the cycle (scenario three) should give a worsened fuel economy compared to using load-following operation during the end of the cycle (scenario four). This is because the action to produce more fissile ^{239}Pu by allowing more water to boil in the core can mainly be done during the first half of the cycle (when the reactivity at the bottom of the core is still high enough to maintain the nuclear chain reaction). Any difference between regulating the power the first and the second half of a cycle would be an indicator for the importance of the change in spectral shift. Operating at 60 % power during half of the cycle is intended to reflect load-follow operation all week nights plus weekends.

6.3 BWR core design

For the BWR multicycle analysis, the Forsmark 1 nuclear power plant was chosen, which contains 676 fuel assemblies. It is important to clarify that the number of fresh fuel assemblies needed to achieve a certain cycle length is not a fixed number. Depending on the length of the previous cycle, the type of fresh fuel assembly and their average enrichment, cycle specific safety limits etc., the number of fresh fuel assembly required varies. It should also be pointed out that minimizing the number of fresh fuel assemblies used for a

[12] Coast down is the action that permits the reactor power level to decrease gradually as the fuel in the core does not have enough remaining reactivity to produce full power. A coast down period of a few weeks generally occurs towards the end of the operating period.

certain cycle length is not the only priority; operational flexibility is normally of a similar priority in core design today.

Furthermore, in this load-following investigation, the level of optimization for all core designs, except the reference core, are somewhat lower. It takes weeks to fulfil a complete core design that satisfies all safety and operational restrictions associated with a specific cycle. Here, only the most limiting safety parameters are regarded in order to find the correct number of fresh fuel assemblies for each cycle. However, there still remains an uncertainty of approximately ± 2 fuel assemblies per cycle.

6.3.1 BWR fuel demand results

In Table 4, the results of the four scenarios for BWR are presented as the number of fresh fuel assemblies required (#FA). The cycle length is specified in EFPH (equivalent full power hours). Different cycle lengths are used for the first (10370 EFPH) and the subsequent cycles (8750 EFPH), the difference in cycle length is because the figures are from the actual production plan. For the subsequent five cycles the cycle length is averaged to 8750 EFPH. However, the results would be similar for small alterations of the cycle length.

Table 4. Cycle lengths (EFPH) including coast down operation and fuel demand (#FA) for the four scenarios.

	scenario 1 Reference		scenario 2 (20%)		scenario 3 (60% 1st half)		scenario 4 (60% 2nd half)	
cy. No	EFPH	#FA	EFPH	#FA	EFPH	#FA	EFPH	#FA
1	10370	136	8000	136	8000	136	8000	136
2	8750	126	8750	94	8750	96	8750	96
3	8750	118	8750	118	8750	118	8750	118
4	8750	122	8750	122	8750	122	8750	122
5	8750	120	8750	122	8750	122	8750	122
6	8750	120	8750	118	8750	120	8750	120
Total:	54120	**742**	51750	**710**	51750	714	51750	**714**

For cycle one, the reference cycle, the same number of fresh fuel assemblies was used for all four scenarios, only the cycle length and power level is altered. Of interest for our analysis is the energy output (in EFPH) per fresh fuel assembly (FA). According to the last row in Table 4, the ratio for the reference case is 72.94 EFPH/FA and for scenario two the ratio is 72.89 EFPH/FA, i.e., less energy output per fuel assembly is achieved for the load-following scenario. It should be noted that after the second cycle, the difference in number of fresh fuel assemblies compared to the reference scenario is within the uncertainty of ± 2 fuel assemblies.

For the third and fourth scenario, which are simulated with more control rod presence and a lower coolant flow during half of the cycle, the energy output per fresh fuel assembly is 72.48 EFPH/FA. Two additional fresh fuel assemblies are needed for the second cycle of scenario three/four compared to that of scenario two. This difference is within the uncertainty of the simulations.

The fact that there is no difference in fresh fuel assembly demand between scenario three and scenario four indicates that the expected loss in fuel economy due to spectral shift is insignificant. This is due to the fact that the current operating strategy in Forsmark with respect to control rod pattern is chosen to favour flexibility. As a consequence, the resulting spectral shift is low and hardly affected by increased power regulation. Accordingly, there are only minor differences between the different scenarios, meaning that the increased fuel cost is independent on when in the cycle load-following operation is used.

6.3.2 Spectral shift operation

Due to the fact that the observed impact of spectral shift was smaller than expected, a minor study was performed in an attempt to estimate the effect of spectral shift. Simulations of a two cycles were done. One of the cycles optimized the spectral shift utilization and the other did not make use of this feature. The end of cycle reactivity was compared between the two simulations and made it possible to estimate the spectral shift effect.

The outcome of this exercise shows that the total core reactivity is decreased equivalent to approximately four fresh fuel bundles when maximum use of spectral shift is practiced. But, as pointed out in section 6.3.1, flexibility is favoured today. Hence, our study shows that today, there is no worsened fuel economy due to losses in spectral shift associated with load-following operation.

6.4 PWR fuel demand results

Since there is no spectral shift present for PWRs, the increase in fuel cost due to load-following operation was anticipated to be smaller than for BWRs. A minor study with a scenario one and two has been performed for Ringhals 4 in order to see if the results correspond to the BWR results. It is somewhat more difficult to see actual differences in fuel demand for a PWR, in this case Ringhals 4, since the core only contains 157 fuel assemblies (a PWR fuel bundle contains more than twice as many fuel rods and almost three times as much Uranium as a BWR fuel bundle), and core design is performed in quarter symmetry, i.e., the number of fresh fuel assemblies cannot be changed with less than four assemblies.

As a consequence, a rather large decrease in cycle length is required to make it possible to unload four fresh fuel assemblies. Instead, one, two or three year old fuel assemblies are unloaded to match the cycle length. The unloaded fuel assemblies are then stored in the fuel pool for future cycles.

The difference in fuel demand between scenario one and two corresponds reasonably well with the results from the BWR simulation. As mentioned above, it is more difficult to meet cycle length variations in a PWR. Accordingly, the resulting fuel cycle cost is slightly higher for PWRs than BWRs, see section 6.5.3. The cycle lengths are taken directly from the production plan and hence only the sum of cycle two to five are presented in Table 5.

Table 5. Cycle lengths (EFPH) including coast down and fuel demand (#FA) for the two PWR scenarios.

	Scenario 1 Reference		Scenario 2 (20 %)	
cy. No	EFPH	#FA	EFPH	#FA
1	9014	44	6931	44
2-6	39869	236	39838	228
Total:	48883	**280**	46769	**272**

6.5 Economic evaluation of load-following operation

Based on the results presented in sections 6.3.1 and 6.4, the effect of load-following on the fuel cycle cost has been evaluated both for BWRs and PWRs. It should be noted that the calculations and associated costs in this study are reactor specific. Since the additional fuel cost largely depends on the number of cycles the fuel assemblies stays in core before it is considered spent, i.e., the system number, the relative fuel cycle cost of load-following will vary for different reactors.

6.5.1 BWR with 20 % shorter cycle length

In this case, no actual load-following operation with lower power than nominal and flow adjustment and/or insertion of control rods was simulated in the core calculations. The full power operation of the first cycle was simply shortened by 20 % compared to the first cycle in the reference case. In the following five cycles the lengths were exactly the same as in the reference case. The difference in energy output of the first cycle due to the load-following operation was 2370 EFPH. A coast down period of 370 EFPH was included for the reference scenario.

The resulting difference in fuel demand over six cycles was calculated to 32 fuel assemblies (FA). As has been pointed out above the uncertainty in this figure is ± 2 FA.

With this information the marginal fuel cycle cost for the resulting energy difference was calculated to 2159 GWh. With current fuel cost for 32 FAs for Forsmark 1 this would result in a certain marginal fuel cycle cost per kWh specifically for this reduction in energy production due to load-following operation.

As we will see, this cost is actually the savings due to the reduced number of fresh fuel assemblies that will be inserted into the reactor core for the following cycles after the first cycle where the load-following occurred.

The reference fuel cycle cost was then calculated by dividing the current fuel cost per kgU by the expected discharge burnup, i.e., the average total thermal energy production per kgU, and then divide with the efficiency to obtain the fuel cost per kWh electrical. The resulting reference fuel cycle cost was thus obtained and the difference in fuel cycle costs was calculated. Note that the difference is valid only for the energy reduction due to load-following operation during the initial cycle and not for the entire electricity production in the initial cycle.

By dividing these fuel cycle costs a relative cost saving may be obtained. The finesse with this is that the dependency of differences in fuel prices thus is eliminated. The resulting relative fuel cycle cost saving was calculated to 95 % for this case. That is, the surplus in number of fresh fuel assemblies inserted in the initial cycle, due to the unplanned load-following, will be largely compensated by a reduced demand of fresh fuel assemblies in the following cycles. In this case almost all, i.e., 95 %, of the fuel cycle cost will be regained in this way. Hence, as not all of the cost is regained, there is a cost associated with load-following that equals 5 % of the reference fuel cycle cost.

If the load-following operation was planned in advance, before the core design of the initial cycle, the fuel reloading would be adjusted and 100 % of the fuel cycle cost for the corresponding energy reduction will be saved. However, it is very difficult to predict the exact amount of regulated power for the upcoming operating period(s). It is therefore reasonable to assume that no matter how well planned the operating period is, there will always be an additional cost associated with non-optimised usage of the fuel when load-following operation is practiced.

The cost of 5 % is valid only if consideration to the energy difference of the initial cycle is taken directly in the core design for the following cycle after the cycle when load-following operation was used. Otherwise the fuel cycle cost would be much higher. This is not always possible as the unplanned load-following operation may occur at the very end of the cycle where there might not be enough time to redesign the core.

As mentioned above, the uncertainty in fuel demand is ±2 FA. It means that the fuel cycle cost might be at least twice as high, 10 %, as two fuel assemblies here would correspond to about 5 %. Also, comparing the demand in number of FAs specifically for cycle six in the reference case with corresponding cycle of case two, we notice that they still differ. This might imply that the transient in FA demand is not finished after the sixth cycle. Hence, if yet another cycle was studied, the resulting difference in FA demand might decrease with two FA resulting instead in a fuel cost of 10 % for this case.

6.5.2 BWR with load-following operation at 60 % power for half of the cycle

In this case, load-following operation at 60 % power was performed for half of the initial cycle. In the core calculations this was achieved by flow adjustment and insertion of control rods. Two cases were studied. In case three, the first half of the cycle was operated at 60 % power and in case four the second half was operated at 60 % power. The object of this was partly to see the worth of the spectral shift effect. Both these cases will thus result in the same amount of electricity generated for the initial load-following cycle. Also the initial cycle of scenario two generates the very same amount of electricity. In the following five cycles no load-following was assumed and the cycle lengths were exactly the same as in the reference case. Hence, the difference in energy output of the first cycle due to the load-following operation was 2370 EFPH in all three power regulated scenarios.

The resulting difference in fuel demand over six cycles was calculated to 28 fuel assemblies (FA) for scenarios three and four. Also for these cases the uncertainty is about ±2 FA.

With this information the marginal fuel cycle cost for the resulting energy difference due to load-following was calculated in the same way as for scenario two. The reference fuel cycle cost is the same as for scenario two and the resulting relative fuel cycle cost saving was calculated to 83 % for both these cases. Hence, the cost for load-follow is 17 % of the reference fuel cycle cost specifically for the energy reduction due to load-follow.

As mentioned above the uncertainty in fuel demand is ±2 FA. It means that the fuel cycle cost might increase to 23 %, see discussion about conservatism in section 6.6, as two FA in these cases corresponds to about 6 %.

6.5.3 PWR with 20 % shorter cycle length

In this case, no actual load-following operation with lower power than nominal was simulated in the core calculations. The full power operation of the first cycle was simply shortened by 20 % compared to the same cycle in the reference case. In the following five cycles the lengths were exactly the same as in the reference case. Hence, the reduction in cycle length due to load-following operation was 2114 EFPH including coast down operation for the first cycle in the reference case.

The resulting difference in fuel demand over six cycles was calculated to eight fuel assemblies (FA). The uncertainty in this figure may be ±1 FA.

With this information the marginal fuel cycle cost for the resulting difference in electricity generation was calculated to 1985 GWh_e. With current fuel cost for eight new fuel assemblies for Ringhals 4, this results in a certain marginal fuel cycle cost per kWh_e specifically for this reduction in electricity generation due to load-following operation.

The reference fuel cycle cost was then calculated by dividing the current fuel cost per kgU by the discharge burnup. Discharge burnup is defined as the average total thermal energy production per kgU. The ratio is divided by the efficiency, to obtain fuel cycle cost per kWh_e. The resulting reference fuel cycle cost was thus obtained and the difference in fuel costs for the two different scenarios was calculated. Note that the difference is valid only for the reduction in electricity generation due to load-following operation during the initial cycle and not for all of the electricity generated in the cycle.

By dividing these fuel cycle costs, the relative cost saving is obtained for this case and the dependency of differences in fuel prices was eliminated. The resulting relative fuel cycle cost saving was calculated to 75 % for this case. Hence, the surplus in fresh fuel assemblies that were inserted in the first cycle, due to the unplanned load-following reducing the cycle energy output, will be largely compensated by a reduced demand of fresh fuel assemblies in the following cycles. In this case 75 % of the fuel cycle cost was regained. Hence, the cost associated with load-follow equals 25 % of the reference fuel cycle cost for Ringhals 4.

As mentioned above the uncertainty in fuel demand for PWRs is one fuel assembly (FA). It means that the fuel cycle cost might decrease to 16 % or increase to 34 %, as one FA here corresponds to 9 %. Hence, 34 % may then be regarded as the maximum relative fuel cycle cost. It might be interesting to study more cycles to see if the difference in number of fuel assemblies would change or not. Comparing the demand in number of fuel assemblies specifically for cycle four to five in the reference case with the corresponding cycles for case two, we notice that they still differ. This might imply that the transient in FA demand is not quite finished after cycle six.

6.5.4 Comparison of the results to the rule of thumb

The rule of thumb of the industry [21] states that the equilibrium cost of the surplus of fresh fuel assemblies inserted in a core when it was designed, compared to what the fuel demand would be for the cycle energy (including load-following), may be calculated by dividing the cost of the extra fuel assemblies with the system number, N. The system number corresponds to the number of cycles the fuel assemblies (FA) spend in the core for equilibrium conditions. It may be calculated by dividing the core size in number of FA with the number of fresh FA in the refuelling.

The system numbers for the data in question for the six cycles in this study have been calculated. The inverse of the system number is then the relative fuel cycle cost according to the rule of thumb. The results in this study based on core calculations are compared to the rule of thumb in Table 6.

Table 6. Comparison of our results with the rule of thumb described in [21].

Reactor:	**BWR, Forsmark 1**		**PWR, Ringhals 4**
	Scenario 2 (20 % shorter cycle length)	**Scenario 3/4 (operation at 60 % power during half of the cycle)**	**Scenario 2 (20 % shorter cycle length)**
N (system number)	5,7	5,7	3,5
Cost increase, % (1/N, rule of thumb)	18	18	29
Cost increase, % (in this study)	5	17	25
Difference between the rule of thumb and our results	*-12*	*0*	*-4*

We see that the agreement between the results and the rule of thumb is fairly good but somewhat worse for scenario two of the BWR calculation.

However, as mentioned in section 6.5.1, considering the uncertainty in the calculations, the cost for scenario two of the BWR calculation might increase to 10 %, meaning the results would be closer to what the rule of thumb suggests. Based on the assumption that the rule of thumb gives a hint of the correct costs, the result for case two probably should be 10 %. Studying yet another cycle might show this. A cost of 10 % would also mean a more conservative value for the fuel cycle cost of load-follow performed according to the assumptions in this case two.

6.6 Conclusions of the economic evaluation

A difference in the resulting relative fuel cycle cost for BWR, when load-following operation was practiced by reducing the power to 60 % of the nominal power for half of the cycle, as compared to the case when the cycle energy output is simply shortened by 20 %, was noticed. In case three and four, when load-following operation was actually simulated in the core calculations, the nominal fuel cycle cost was calculated to 17 % as compared to just 5 % in case two.

As discussed above, the uncertainty in the demand of fresh fuel assemblies corresponds to a cost uncertainty of ±6 % and ±5 % respectively for these figures.

As it is unrealistic that load-follow would not increase the fuel cycle cost at all, the -5 % uncertainty variation for case two would not be valid and may thus be disregarded. As discussed above the +5 % scenario for case two may very well be the more realistic one if calculations for more cycles were performed. The relative fuel cycle cost for this case may thus be concluded to be 5-10 %.

Hence, considering the uncertainty for case three and four, the fuel cycle cost would be in the interval of 11-23 % for load-following operation. With a conservative approach also for these cases, the fuel cycle cost of load-following may fall in the upper part of this interval, which is 17-23 %. The agreement with the rule of thumb, suggesting 18 %, is very good and seems to support this assumption. These cases would probably be the more realistic scenarios with regard to load-following and as they are more conservative regarding the fuel cycle cost we believe they should be applied for BWRs. It should be noted that there is no difference in the increased cost for scenario three and scenario four, meaning that the cost is independent on when in the cycle, load-following operation is utilised. This means that the reduction of spectral shift is moderate for the reactors at Forsmark, since they are already operated in a manner that disfavours spectral shift.

For PWRs the relative fuel cycle cost of the load-following scenario studied was calculated to 25 %. The uncertainty in demand of fresh fuel assemblies corresponds to a cost uncertainty of ±9 %. Applying a conservative approach, in analogy with the assumptions made above regarding the BWR case, the resulting relative fuel cycle cost of load-following for PWRs would then be in the interval of 25-34 %. Hence, this would be in good agreement with the rule of thumb stating 29 % for this case.

The relative fuel cost of 25 % is valid only if consideration to the energy difference of the initial cycle is taken directly in the core design for the next cycle following the cycle with load-following operation. Otherwise the cost would be higher. It is not always possible to do this, as unplanned load-following may occur at the very end of the cycle where there might not be enough time to redesign the core. For PWRs this would be more unlikely, though, as load-following at the end of the operating period should be avoided due to boron concentrations near zero[13].

It should be noted here that if the load-following was planned in advance, before the core design of the initial cycle, the reloading will be adjusted and 100 % of the fuel cost for the corresponding energy reduction would be saved. However, it is very difficult to predict the exact amount of regulated power for the upcoming operating period(s). It is therefore reasonable to assume that no matter how well planned the operating period is, there will always be an additional cost associated with non-optimised usage of the fuel when load-following operation is practiced.

Comparing the cost of load-following for BWRs and PWRs we see that the cost is somewhat higher for PWRs. As we have seen this is consistent with what the rule of thumb would suggest. Since the system number is lower, the cost will consequently be higher. This we think may also be partly explained by the fact that large fuel assembly operations are required for PWRs, i.e., loading/unloading of at least four fuel assemblies as compared to two fuel assemblies for BWRs. Furthermore, one fuel assembly for a PWR contains 2.7 times more Uranium compared to one fuel assembly for a BWR.

Hence, from a strict fuel cycle cost perspective, load-follow should preferably be performed for BWRs.

It should once again be noted that the calculations and associated costs in this study are reactor specific. Since the additional fuel cost largely depends on the number of cycles the fuel assemblies stays in core before it is considered spent, i.e., the system number, the relative fuel cycle cost of load-following will vary for different reactors.

The costs are relative to a reference fuel cycle cost for normal operation without load-following and are thus applicable only for the energy loss due to load-following operation during the cycle. For example, if load-follow operation is practiced during 20 % of the cycle, the increased cost of 5-10 % is only valid during this time period.

[13] To reduce the power in a PWR, neutron absorbing boron is generally inserted in the primary coolant water. Towards the end of the operating period the boron concentration is low at full power operation. If boron is then inserted to reduce the power, it is difficult to regain full power production due to the low boron concentrations then needed.

7 Risks

7.1 Introduction

This chapter discusses the risks associated with load-following. The risks are mentioned in other chapters but are treated here also to get a more complete picture. Risk in this chapter is defined as in a Vattenfall definition concerning business risks (Enterprise Risk Management). “Risk is the possibility that an event will occur and adversely affect the achievement of objectives, which can prevent value creation or erode existing value.” This includes safety risks, economic risks and other risks.

There are a number of factors which might be seen as risks. However, during the work resulting in this Report only a limited number of risks was found to be relevant. Some other possible risks were related to older equipment which does not exist in today’s Units or to operating procedures which are not followed today. This chapter discusses factors which are relevant to consider as risks related to load-following for the existing Units in Sweden.

This chapter does not make quantitative statements of the risk, only a qualitative discussion.

7.2 Damaged fuel

Quick changes of temperature will always mean a stress to the material involved. Changes of power in the reactor will cause changes of temperature to the fuel elements. This has been foreseen in the design of the reactors and in the design of the fuel. There are specifications for the permissible speed of change of power and thus temperature. Operating procedures are also specified as to what is permitted regarding changes.

As long as those specifications are followed there are no indications that unhurt fuel is damaged in any way by load-following. Temperature changes sufficiently slow will not cause new damage to the fuel.

However, if there is a crack or other deviation from the original structure of the element, there are many indications that the crack does get more serious by load-following or other reason for temperature change. So, damaged fuel may well be even more damaged. A crack in the fuel is often noticed by an increasing activity in the reactor cooling water. If this does happen then load-following with this Unit should be avoided until the faulty element has been replaced during an overhaul or maintenance action.

7.3 ”Under-loading” of fuel

A possible scenario is where a certain amount of load-following is forecasted for a year. One or more reactor(s) is loaded with fuel based on this forecast. If the year then turns out differently than forecasted, the load-following may be less than expected. More energy than planned is then used from the fuel. If this occurs, perhaps in more Units than one, the energy left might not be sufficient for full power operation in the end of the season. Such a situation could lead to a lack of electricity and increasing prices for a period.

This is a limited economic risk. The "under-loading" must be large in order to make a significant contribution to the power balance. For example with 20 % "under-loading" which is not realized the output from the Unit due to coast-down will start 63 days earlier then planned which will give a significant reduction in the end. However, 20 % is very much and not likely.

This risk always exists whether we have load-following or not since there are other possible reasons for "under-loading" a reactor. Normally this risk is small but still a risk.

7.4 Component wear

The same is valid as in subchapter 7.2 above: as long as restrictions for power levels and speed of power change are kept within specifications there are no indications that increased component wear takes place. It should however be noted that by correcting power variation by control rods, an additional wear can be assumed, and hence an increased maintenance need.

7.5 Reactor Pressure Vessel transients

Each reactor has a maximum allowed transient "budget". It could be argued that load-following will increase the transients and thus consume the budget for transients. However since this is planned for in the original budget, and in the case of sufficiently slow and limited power changes some load-following transients do not have to be accounted for. So this is not a risk worth considering.

7.6 Increased risk of operational disturbances

Every deviation from normality will increase the possibility that something unwanted will occur. A stable operation causes less operational measures by operators and thus fewer opportunities to make mistakes. However, this may also be regarded as increased training compared to a situation in the control room when nothing disturbs a calm situation. There are no indications that load-following has caused more errors and there are also no indications that load-following has caused an increase of disturbances or failures of equipment. So this does not seem to be a risk.

8 Conclusion

This study has analysed and quantified possible additional costs that can arise when not operating nuclear power as base load power. Several different issues were examined, such as general plant layout, training of personnel, maintenance costs, additional fuel costs and re-design needs.

In principle there are very few additional costs due to load-following if the operations are planned well in advance, such as the fuelling, and that critical power ranges are avoided for longer periods. This means that reactors need to be analysed individually, as there are specific modifications on all plants, compared to the original design.

It should be noted that mainly all nuclear power plants today were designed to be used at least in load-following mode, in some cases also for primary control in the grid. This means that no major re-design is necessary.

However, a complete analysis of each individual plant is necessary if planning for a regular load-following operation with one or more reactors. This is due to the fact that load-following has not been used regularly as operational mode and all the plants have been modified in the power uprate and lifetime extension programs.

For Swedish measures, BWRs are in general easier to power control than PWRs. This is mainly due to the need of boron inclusion in PWRs (as Sweden is not using other control rods than the normal ones for shutdowns and major power changes). The regulator of the power on a PWR is also coupled to the generator, rather than the core power, which means that there is a risk for mismatch between actual power and needed power.

As the a majority of the Nordic plants have been modified and updated with new turbines, new instrumentation and control etc., one has to look at each individual plant to get the complete picture of how that plant will behave during load-following. It is also needed to find power regions where one should not operate over longer periods during load-following. Such needed studies could bring an additional cost to the overall in preparation.

Load-following is today a requirement on the Nordic nuclear power plants and therefore it is of interest to investigate costs associated to this mode of operation. However, load-following is today very seldom performed among the Nordic nuclear power plants.

It should be noted that the increasing costs when load-following in absolute numbers are small; however, its influence on the price per produced MWh is significant. This is a consequence of that nuclear power plants have high fixed costs and low variable costs. For instance the tax of nuclear power is fixed, the capital costs are fixed, the salaries for the employees are fixed and large parts of the maintenance costs are fixed.

There is no cost associated with training of personnel as this is already part of normal operator education.

Additional costs due to the boron treatment in PWRs in terms of power consumption and water treatment costs are minimal, but need to be considered in detail for periods of regular load-following.

Turbine efficiency decreases and the risk for disturbance in operations could increase, but no such factors have hindered France and Germany to load-follow with nuclear power. In France and Germany has even primary control been used regularly, i.e., frequency compensation to the electric grid on a time-frame of seconds. This is however not envisaged for Swedish power plants, and outside the scope of this report.

It is concluded that if the load-following is planned and the regulation is done within determined levels specific for the plant there is no hindrance or additional costs for load-following. However, the exact amount of power reduction that will take place during the upcoming operating periods is very difficult to predict. It is therefore reasonable to assume a certain increased fuel cost due to non-optimised fuel usage.

Regarding the manoeuvrability of PWRs, load variation operation could reduce safety margins of accidental transients, in comparison to base load operation; this refers only to boron control (injection/dilution).

The average capacity factor has been slightly reduced (less than 1.8 % for the entire fleet in France) due to load-variation operation, mainly due to unexpected or increased maintenance.

In general, a site with several nuclear power plants could load-follow in a small interval of down-rated power, from 100 % to 70 %, starting with one reactor. If further down-regulation is needed, reactor number two is decreased in sequence. This is for example used at Philippsburg in Germany.

One important conclusion from all references in this study is that load-following should not be carried out with fuel damage in the core. This has been emphasised from plants with relatively large experience from fuel damages (however not due to load-following) as it is assumed that power changes is likely to worsen the fuel damage.

Main impact on PWR operation is the liquid waste, referring to volume increase, which could be managed and re-circulated. No impact regarding fuel reliability has been seen (no failure associated to load variation) and no impact on spent fuel reprocessing (not of Swedish or Finnish concern). Operator training implements already load variation and close attention to core monitoring.

Main wear has been seen on the CRDMs, causing increased need of replacement (typically every three years for grey banks). Increased inspection and maintenance of the pressurizer inlet and outlet due to increased temperature variation frequency have been seen in France.

With a conservative approach, the fuel cycle cost of load-following for BWRs fall in the interval 17-23 % of additional fuel costs. Of the total production cost of a kWh produced from nuclear power the fuel cost is some 20 %. Therefore, the total fuel cycle cost can be 24 % of the total production cost of a kWh when the load-following is done in an unplanned manner for a BWR.

Here the assumption is that the load-following was made in the first fuel cycle in an unplanned manner which makes it to a worse case.

There is no difference in fresh fuel assembly demand between scenarios including/excluding spectral shifts. This is due to the fact that the current operating strategy in Forsmark with respect to control rod pattern is chosen to favour flexibility. As a consequence, the resulting spectral shift is low and hardly affected by increased power regulation. Accordingly, there are only minor differences between the different scenarios, meaning that the increased fuel cost is independent on when in the cycle load-following operation is used. This means that the reduction of spectral shift is moderate for the reactors at Forsmark, since they are already operated in a manner that disfavours spectral shift.

For PWRs the relative fuel cycle cost of the load-following scenario studied was calculated to 25 %. The uncertainty in demand of fresh fuel assemblies corresponds to a cost uncertainty of ±9 %. Applying a conservative approach, in analogy with the assumptions made above regarding the BWR case, the resulting relative fuel cycle cost of load-following for PWRs would then be in the interval of 25-34 %.

It should be noted here that if the load-following was planned in advance, before the core design of the initial cycle, the reloading will be adjusted and 100 % of the fuel cost for the corresponding energy reduction would be saved. However, the exact amount of power reduction that will take place during the upcoming operating periods is very difficult to predict. It is therefore reasonable to assume a certain increased fuel cost due to non-optimised fuel usage.

Comparing the cost of load-following for BWRs and PWRs we see that the cost is somewhat higher for PWRs. Hence, from a strict fuel cycle cost perspective, load-follow should preferably be performed by BWRs.

9 References

Below are references to reports listed, as well as a list of specialists that have been helpful in the preparation of this report. Thank you for your valuable help in making this project possible!

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9.2 Contacts and sources of information

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Appendix A

Date	Stockholm 2012-08-29	Vattenfall R&D AB
Security class	Medium [C2]	Evenemangsg. 13C
Our Reference	Timmy Sigfrids, Hans Henriksson	SE-16956 SOLNA
	Johan Sandström	SWEDEN

Questionnaire regarding Load-following NPPs

Below follows some questions to discuss during our meeting. If you have relevant studies/reports that you can share with us, that would be appreciated. What we are interested in are to find out costs to load-follow (LF) with nuclear power.

General
- Why did you load-follow?
- How often (regularly or occasionally)?

- Are there studies carried out on comparisons between periods with constant full power, and periods with LF? Comparison between plants with and without LF?

Maintenance
- What major components do you see a high wear in that you can relate to the load-following? (Main re-circulation pumps, valves, turbines, machinery)

- What costs does the LF imply for the overall maintenance?

- Do you have specific maintenance due to LF? Is the outage time longer after periods of LF? More tests needed during outage? Do you need more service staff?

- Was there any re-construction needed for LF? Are there any modifications to the original reactor design?

Operation
- Did you have any disturbances in operation (availability) you can relate to LF, or what disturbances do you have a higher risk of when load-following?

Did you have any limits in LF due to your transient budget?

Is there a comparison of additional fuel costs involved?

- Have you had any problems with fuel damages due to LF?

- What fuel-cycle do you have and do you fuel according to LF?

For PWRs:
- How does the cost of boron affect LF?

- Is there additional environmental costs related to LF? Examples being additional low-level waste (due to boron/water purification and water management).

Training
What additional training is needed for operators/personnel due to LF?

What are the needs for more staff (operators) during LF operation?

Vattenfall Research and Development AB,
Stockholm, 29 Aug 2012

Miscellaneous
We prepared an overview report (in Swedish) in 2011 regarding load-following. We have used M. Hundt et al, Universität Stuttgart (2009) and H. Ludwig et al., int Journal for Nuclear Power vol. 55 no 8, aug/sept 2010. Are you familiar with these two reports?

Hundt referred to fuel damage due to LF. Did this occur in Phillipsburg I?

We would be grateful to discuss these issues with you soon.

Appendix B

Visit to EnBW and Philippsburg (Germany)

A visit to Philippsburg (one BWR and one PWR) was carried out in September 2012 where we met with staff from EnBW nuclear power generation (Jörg Storbeck and Tim Vogel, EnBW Karlsruhe) and from KKP unit I (Roman Zofka, head of unit I, deputy head of unit 2), Frank Witte (head of operations), and Julia Korn, (visitor guide)

Fig. 12. Philippsburg unit 1.

EnBW has about 20000 employees, of which 1800 in the EnKK (nuclear part of EnBW). These work at Neckarwestheim, Obrigheim and Philippsburg (KKP). About 800 employees work at KKP, where two units reside, unit 1 is a 926MW BWR (now in final shut-down since 16 March 2011) and unit 2 is a PWR still operating until 2019. EnBW owns 25 % of the German grid (TransNetBW is the ITO) in the region of Baden- Württemberg. In the past, French EDF had 45 % of EnBW until the beginning of 2011 when it was sold to the region Baden-Württenberg.

Operation

Load-following has been used at the BWR (KKP 1) since the early 1980s, while the PWR (KKP 2) started later with LF. Three modes of power control were used at Philippsburg 1:

- Primary (frequency) control: 0 to 11 MW change (of 926 MW),
- Secondary (minute reserve) is used in a 90 MW interval
- Load-following is demanded with a 5h notice. Normally the operations go to 70 % of full power. Thereafter, unit 2 was used down to 70 %. After that, further decrease of unit 1 was effectuated.

Anlage 1 Ereignisbericht

EnBW Kraftwerke AG

EnBW

Ereignisbericht

Kraftwerk: .... Block/Anlage: ....
Erstellt am: .... Erstellt von: ....

Ereignisart

Ausgefallene Leistung: ....(MW) Totalausfall: Ja ☐

Bei FW-Erzeugung
Fernwärmeversorgung bleibt gewährleistet: Nein ☐

Unfall mit Personenschaden Ja ☐

Genehmigungsrelevant Ja ☐ Noch zu klären ☐

Öffentlichkeitswirksam Ja ☐

Sonstiges:

Ereignisbeschreibung

Ereigniseintritt/-beginn Datum: Uhrzeit:

Voraussichtliches Ende Datum: Uhrzeit:
oder
voraussichtliche Dauer, wenn das Ende nicht abschätzbar ist. Stunden: oder Tage:

Ereignisbeschreibung (Stichworte):

Maßnahmen:

Verteiler, Fax-Nr.:

KWG T:	9400 – 1 23	ETG DI:	951 – 1 75 04		
KWG TT:	9400 – 1 01	KWG TK:	9400 – 1 08	KWG TC:	9400 - 1 12

Die Abläufe der kraftwerksinternen Alarm- und Notfallpläne und sonstige Regelungen zur Information über Ereignisse bleiben vom Ereignisbericht unberührt.

Appendix C

Visit to EDF, Nogent-sur-Seine, and Areva (France)

A visit was carried out to EDF, Nogent-sur-Seine and Areva in November, where discussions with the utility, plant operators and reactor vendors were carried out.

Fig. 13. Nogent-sur-Seine unit 1 and 2.

EDF meeting

A meeting with EDF was held at EDF offices in Saint-Denis and at the nuclear reactor site Nogent-sur-Seine about 80 km east of Paris, see Agenda at the end. EDF summarised the experience of operating NPPs in load-following mode and primary (frequency) control from the 1970s to today, in a presentation that discussed the modifications done to the plants, and exemplified the fleet planning and optimisation depending on availability and electric grid market. Factors affecting generation master plan when NPP are on-line include demand forecast, share of nuclear power, dispatch capability (plant availability), geographical localization, non nuclear generation flexibility capabilities (Hydropower in France), economics.

Core adjustment is performed by varying three parameters:

- Reactor coolant temperature: Slight power deviations not filtered by turbine-generator can be absorbed by allowing free variation of coolant temperature but additional means are necessary to avoid large temperature variations
- Control rod position: Control rod movements generate fast core reactivity but cause power distribution disturbances and add mechanical loads on components
- Boron concentration: Boron concentration variations have little effect on power distribution but action is time-delayed and its effectiveness decreases along fuel cycle

The EDF goals in the 1970s was to improve the manoeuvrability of the nuclear fleet to allow for rapid load-following (from 100 % to 30 % of rated power, Pn), frequency control (5 % Pn), rapid return to normal operation at 5 % Pn /min and improving stability in operation, e.g. by reducing unplanned shutdowns (scrams). The different modes of operation where licensed in the beginning of the 1980s, starting with an experimental period of tests using mode A (boron concentration adjustment) in 1982, mode G (grey control rods) in 1983, combination of the modes in 1984, followed by an operating period starting in 1985 with grid following (primary control).

Fuel damage linked to load-following cycles was examined in detail between 1982 and 1986. Data indicated that even if the number of load-following manipulations increased from 200 to 1500 times, the number of fuel rod defects stayed the same or even decreased (from 1 to 0.5 defected fuel rods per campaign).

Concerning design transients, 12000 authorized load increases and decreases at 5 % Pn/min were split in 10000 normal and 2000 with cooling transients. However, transients during frequency control are not counted as such.

Before implementing the flexible nuclear power operation, several on-site tests were performed in the 1980s on seven 900 MW NPPs for 200 LF transients. The test phases included fuels, verification of equipment and procedures of adequacy.

The main parameters that were monitored include axial power distribution as ΔI, which is the ratio of upper and lower power level in the core (ΔI_{ref} ± 5 % for 95 % of the transients), the average temperature control (max value <3.7°C), maximum power (LF stopped if power increased to over 96 %), and liquid waste volumes (one LF cycle 50 %, 8 hours generated between 20 m^3 BOC to 100 m^3 EOC).

The equipment qualification tests included component fatigue due to frequency control in control rod drive mechanism (CRDM), control rods, RCC guide tubes, and fuel assembly response to power changes. Mechanical impact on primary components was proven to be small: pressure/temperature variations are slow and limited. This result however required time and efforts, and modifications of the original design to limit the wear of some singular areas (such as the pressurizer). It is still necessary to check that the actual loading doesn’t exceed the design transient provision.

During operation, 60 days are reserved for coast-down operation (at about 85 % of the fuel cycle), in which the plant is not operating in load-following mode. Instead, an outage optimisation schedule is implemented to stretch the operating cycle if need be. The fuel cycle is between 12 and 16 months. All EDF NPPs operated in flexible power variation mode can carry out:

- Frequency control :+/- 2 % (immediate response)
- Remote control :+/- 5 % (energy balance between zones, managed by the Grid Regulator)
- Daily load variation (typically 6 hours at 50 % power during the night)
- Load decrease down to zero (plant disconnected from the grid, but at hot conditions, able to rapid load increase)

- All power ramps can be performed at 5 %NP/min (grey mode)

The power from one unit is divided into three parts, with three set values (P_0, k, P_s) according to: $P = P_0+k*(f_0-f) + N*P_s$, where P_0 is a set point given by the operator between 37 % and 93 % of rated power, P_r, of the unit (load-following), $k*(f_0-f)$ corresponds to 2 % P_r (automatic primary control), and P_s corresponds typically to 5 % P_r (automatic secondary control). The value N is varying from -1 to 1 and is obtained from the TSO, which is Résaux de Transmission d'Electricité (RTE) in France. For a 1300 MW plant, 27 MW is used for primary control, and about 70 MW of secondary control, with the reactor running at 1 220 MW.

Visit to Nogent-sur-Seine

The visit to Nogent-sur-Seine (see photo above) included a short presentation of the site (two 1300 MW_e PWRs in phase of start-up for unit 1 and outage for unit 2), simulator-session with operation in load-following and primary control mode, visit to control room and turbine hall. The simulator session gave hands-on understanding of the operation using "grey" control rods (mode G), see photo), and boron compensation of xenon peaks. Details on the different modes of operation were also given.

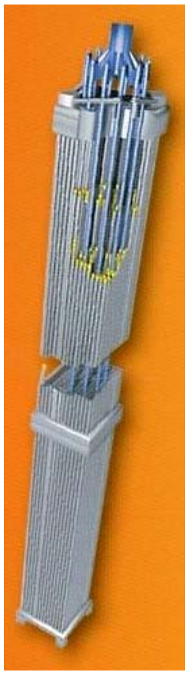

Fig. 14. PWR fuel assembly (left) with the rod cluster control assembly (RCCA) handle and the 24 rods beside. RCCA (blue) inserted in fuel assembly (right).

The figure above shows the PWR fuel assembly with rod cluster control assembly (RCCA) handle and 24 rods inside (blue). "Grey" RCCAs consist of 8 (normal) rods made out of AgInCd and 16 stainless steel rods (no neutron absorption weight). Black RCCAs consist of 24 AgInCd rods.

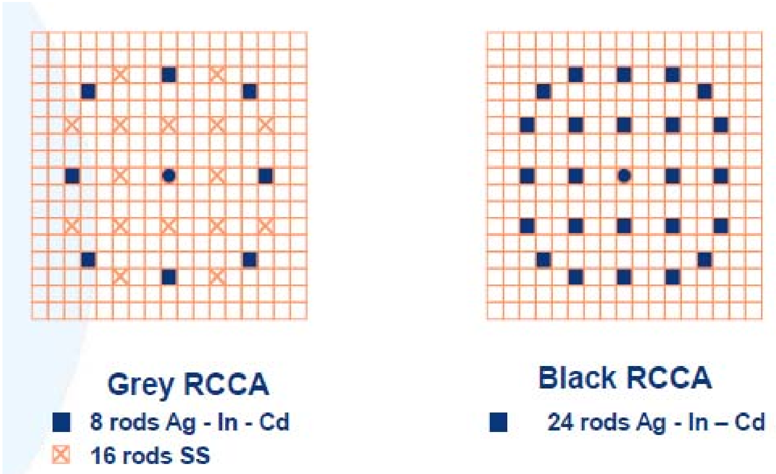

Fig. 15. Fuel assembly layout with typical design of grey and black RCCAs.

The simulated reactor operation consisted of primary (frequency) control from maximum power, which means that the reactor first has to decrease power by by about 92 MW for sufficient margin to P_{max} (1320 MW). That means that P_0 in the formula above was 93 %. This value is communicated to EDF optimisers every morning at 7 am together with availability and status of the plant (see operation sheet at the end of the appendix). The decrease was ramped with 40MW/min (3 %/min) but other ramp speeds were available as well. The fastest was 200 MW/min (15 %/min) which had to be carried out manually. After that, the reactor goes into automatic mode and corrects turbine with frequency on the generator (variations from 1500 rpm, which corresponds to 50Hz). Note that 1 rpm corresponds to 33 mHz frequency change, so more precise monitors are used for the regulation. The control is carried out with grey RCCA complemented by RCCAs in the R-bank (regulating temperature). It should be noted that the average core temperature decreases with reactor power in these PWRs, contrary to German PWRs for example. Secondary control was also carried out, in which the N-value (see formula above) is changed from the TSO. In the simulator, this was applied from the simulator supervisor.

Another simulation consisted of a load-following pattern, with minimum load, down to 260 MW reactor power. This is however lower than what is allowed in primary control mode (37 % of nominal reactor power) so no frequency control was carried out. Now, both black (normal) and grey control rods were used. As the power was substantially changed, some boron injection was needed to compensate for axial power offset and xenon poisoning in the core. As core temperature decreases with power, the R-bank had to be withdrawn to adjust (increase) for that. However, when almost fully withdrawn the boronisation compensated. It was also possible to withdraw some grey control rods for compensation by manually adjust power.

Conclusions

One issue is how to educate/explain for safety authorities that nuclear power can be flexible power. EDF tested and modified the systems for about 15 years to reach a validated model of flexible power control that also was accepted by ASN (Autrorité de Sûreté Nucléaire) the nuclear safety authority in France.

It should also be noted that about 10 units in France (900 MW_e PWRs) are operating at full power since 2000, for comparison of operating experience between "flexible" and "non-flexible" operation.

The main component affected by load-following is the CRDM and need increased maintenance. A mechanical adaptation of the original design to cope with a high number of steps was needed as well as a monitoring system to count the number of steps.

Other issues include:

- Load variation operation reduces safety margins of accidental transients, in comparison to base load operation with A-mode core monitoring (boronisation/dilution).
- Main impact on reactor operation is the liquid waste (average volume increase about 2500 m^3/unit/year).
- No impact regarding fuel reliability (no failure associated to load variation) and no impact on spent fuel reprocessing.
- Time spent at intermediate load is followed and must comply with technical specifications.
- Capacity factor is reduced by load variation operation, mainly due to unplanned events
- Operator training implemented for load variation include close attention to core monitoring).
- CRDM replacement (typically every 3 years for grey banks). R bank CRDM (temperature control) are less worn out.

Meeting with Areva

The meeting with Areva was carried out at their main offices in La Défense. Experience from recent assessments of modifying a nuclear fleet into a more flexible power generation was presented. Issues on load-following and primary control were brought up, such as CRDM mechanism, fretting wear, pressurizer thermal fatigue and so on.

The issue whether old plants could be modified has recently been assessed in Korea on Westinghouse PWR plants. Areva has also been involved in projects with Ringhals, and has therefore some knowledge of the situation in Swedish PWRs. They have for example looked at load-following sequences on 100 % - 50 % - 100 % power over-night, which is a plausible scenario for Swedish operation as well.

The different operating modes were discussed as well. The A-mode (boron concentration adjustment) is used in some old PWRs and the N4 (1450 MW) reactors, due to French pellet-cladding-interaction (PCI) regulations. Mode G is the common mode used in almost all French PWRs and is described above, Mode X was an advanced mode that has never been used in operation. Instead, a mode T has been proposed for new reactors, such as the EPR. This mode uses a larger RCCA of 36 rods, all consisting of B_4C and AgInCd (i.e., no grey steel rods) instead of the 24 rods in the old design. Five different banks are then used for power control, divided in a power bank and a heavy bank.

Finally, the 3D core monitoring system Magelan was presented. This has been validated the last 8 years and is to be included in the EDF operated PWRs soon. The main advantage is that the axial profile and neutron poisoning can be monitored on-line.

Agenda of meetings

Monday 19 November 2012
10 h 00Welcome
10 h 30 EDF Presentations
– Ph. Lebreton (History 1980-1988),
– H. Hupond (design, performances, modifications),
– S. Feutry (operation).
12 h 30 Lunch
14 h 00 IAEA : Flexiblops technical report status.
14 h 30 Q&A session
16 h 00 Departure to Provins [mini van]
18 h 00 Arrival in à Provins
Evening
Hôtel Restaurant Aux Vieux Remparts. Dinner at Hotel on EDF

Tuesday 20 November 2012
08 h 00 Departure to NOGENT NPP
08 h 30 Arrival at NPP public information center
08 h 45 Meeting with M. Lecouf et M. Castagnié
General questions
09 h 30 Control room simulator live session, real time load-following operation
11 h 30 Access registration for on site visit
12 h 00 Lunch with M. HervéMaillard, Nogent NPP General Manager
13 h 30 Tour Control room & Turbine hall
15 h 00 End of visit
18:00 Arrival in Paris, drop off

French Operating Instruction:

Situ7h CNPE / Nogent Tranche 1 / le 09/11/2012 03:38:44

Tranche (EDP) :	**Nogent Tranche 1**	**Contrat de performance des tranches J+1, J+2 (situ 7h)** Document destiné à fournir à la permanence journalière du COPM-CPO les informations nécessaires à l'optimisation des moyens sur les journées (J+1) et (J+2)
Rédacteur :	Laurent VAIRET	
Date J :	09/11/2012	

Productible site : A renseigner en cas de contraintes externes actives.

Productible site (valeur nette à 13h)	J+1 :	J+2 :

Etat des performances (valeurs à 07h00) : **Indiquer les performances potentielles, indisponibilités inclues mais essais exclus.**

		J+1	J+2
Puissance maximale disponible nette (MW) / heure du maxi		724 / 18:50	724 / 18:50
Rpm à Pcmax		0	0
Aptitude au réglage primaire de fréquence (O ou N) [1]		non	non
RPmax		0	0
Pr (Réserve secondaire) : 1/2 bande de réglage (en +/- MW)		0	0
Minimum Technique Courant (valeur nette)		0	0
Minimum Technique Théorique (valeur nette)		0	0
Aptitude au suivi de charge (O ou N)		non	non
Aptitude aux arrêts programmés (O ou N)		non	non
Vitesse de variation de charge (en MW/mn)	Baisse rapide	0	0
	Montée rapide	0	0
	Baisse normale	0	0
	Montée normale	0	0
Baisse ou montée spécifique	Plage de puissances		
	Pente (MW/mn)		
	Palier		

[1] si RPM=0 à Pcmax, préciser si aptitude au réglage primaire pour un point de consigne inférieur à Pcmax = 97,6 % Pn (cas des tranches en limitation de puissance)

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