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ADDITIONAL PAPER

LOAD FOLLOWING BEHAVIOUR AND CYCLE DURATION FLEXIBILITY OF LIGHT WATER REACTOR POWER STATIONS

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LOAD FOLLOWING BEHAVIOUR AND CYCLE DURATION FLEXIBILITY OF LIGHT WATER REACTOR POWER STATIONS

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1. INTRODUCTION

Due to the very low fuel costs on the one hand and the comparatively high capital costs on the other hand, nuclear power plants so far have mainly been scheduled to be operated in the base load range. With an increasing portion of the total installed capacity being nuclear, participation of nuclear units not only in system frequency support but also in daily load cycle operation becomes necessary. Light water reactors (LWR) prove to be very well suited for following normal load changes of the supply system.

Similarly, although most utilities so far foresee a regular burnup cycle length of a certain, predominantly annual, duration a nuclear power plant must be capable of being operated also for irregular, shortened or prolonged cycle durations in order to meet grid flexibility requirements. Such requirements may result, e.g., from energy shortage due to an unanticipated need for repair or maintenance of another power plant in the grid. Especially the power stretch-out capability of a nuclear plant beyond the "natural" cycle end is of considerable importance to a utility.

2. LOAD FOLLOWING BEHAVIOUR

2.1 Typical Load Following Requirements of Utilities

For any utility, the daily load diagram clearly exhibits two power demand peaks, occurring late in the morning and early in the evening. A comparatively low power demand exists between midnight and early morning.

Future nuclear power plants have to be designed in such a way that they are capable of following the load demand of a grid with the required power change rates.

E.g., the nuclear capacity of Nordwestdeutsche Kraftwerke AG (NWK) will amount to more than 40 % of its total installed capacity after commissioning of the recently ordered 1300 MWe LWR which is scheduled for full power operation by late 1975 and which is the third nuclear power station NWK has a share in.

The purpose of this paper is to investigate the physics and system requirements of a nuclear plant and not to deal with mechanical aspects of fuel element design pertinent to load following operation.

Core power variation inherently is accompanied by reactivity changes, the main contributions being due to the fuel temperature (= Doppler) effect and to the transient xenon poisoning.

Fig. 1 shows the reactivity behaviour associated with a periodic operation of 18 h at full power and 6 h at 60 % power. Power reduction always results in a fuel temperature decrease leading to a reactivity increase which in turn is followed by a continuous reactivity decrease due to transient xenon build-up. The excess reactivity required for xenon override depends markedly on the power increase rate after part load operation. The less steep the power increase ramp the better the reactivity compensation of the negative Doppler effect by gradual xenon burn-out.

2.2 Load Following Capability of Light Water Reactors

2.2.1 Pressurized Water Reactors (PWR)

Reactivity control in a PWR is provided by

(1) boron acid dissolved in the reactor coolant (chemical shim)

(2) movable full length (and for very large reactors also some of partial length) neutron absorbing control rods of the cluster type (RCC), some of which can be "grey".

(3) Coolant temperature reduction towards end of life of a cycle offers an additional means of gaining reactivity because of the strongly negative coolant temperature coefficient.

The power output of a reactor is limited by thermal, hydraulic and metallurgical conditions that exist in the fuel rods which have the highest power rating and which are surrounded by the hottest coolant. Therefore, it is desirable to operate a reactor at full power with as low a control rod bank insertion as possible since their presence in the core results in power density distortions and, when inserted for an appreciable burnup period, also gives rise to a non-uniform burnup distribution; control rod removal could then create an unfavourable power distribution that might impose an undesirable restriction on the important economic aim of achieving a high average power density ($\sim$100 kW/l) and a fuel rating ($\sim$40 kW/kg U) typical for present PWRs.

A more uniform power distribution is accomplished by taking advantage of chemical shim control which compensates most of the operating reactivity requirements so that the core can be essentially kept free of control rods during full during full power operation. Since changing the concentration of the boric acid dissolved in the coolant is a slow process, boron is used only to compensate slowly varying reactivity effects such as the reactivity loss due to fuel burnup, xenon and samarium poisoning, and cold-to-operating moderator temperature change. Reactivity effects due to transient xenon poisoning can also be compensated by chemical shim control as long as the boron concentration does not become lower than, say, 150 ppm.

The more rapid reactivity changes required for Doppler effect compensation and safety shutdown are accomodated with RCC-rods having 20 fingers each.

Suitable combinations of the above mentioned means of control offer a high potential and flexibility for fulfilling a broad range of load following requirements within the following limits:

. ramp load changes 15 % per minute from 40 % to 100 % of nominal power.

. step load changes of $\pm$ 15 % of nominal power in the load range of 20 % to 100 %. These values have been experimentally verified with the Obrigheim Nuclear Power Station (KWO).

Siemens PWRs designed for load following operation are based on the following control philosophy.

The movable full-length control rods are subdivided into two or three functionally complementary groups of banks: P-(= Power), D-(= Doppler) and, if appropriate or desired, X-(= Xenon) bank, the latter consisting of "grey" (e.g. Inconel) rods.

At full power operation the whole bank of (black) control rods (P-bank) is used to compensate small power and coolant temperature variations. Their insertion depth can be kept as low as roughly 5 %. The P-bank is essentially stationary and independent of the power level since the average coolant temperature is maintained constant (see steady-state part load diagram, Fig. 5) so that the P-bank performs only minor movements. The small insertion depth of the P-bank avoids axial power density distortions.

For discussing load follow operation control it is useful to distinguish between two subsequent time intervals during a burnup cycle.

A. Time interval extending from beginning of life (BOL) of a burnup cycle over 75 - 90 % of the total cycle length, the interval endpoint depending on the actual load follow requirement

During this operational period the Doppler reactivity effect $\Delta\varsigma_{\mathrm{Doppl.}}$ resulting from power reduction will be compensated by a D-bank, consisting e.g. of 4 rods. The axial position of the D-bank is strongly power dependent. The bank is inserted as far as possible in order to avoid axial power and burnup distortions. The resulting slight radial p o w e r d e n s i t y distortion can easily be tolerated during part load. Radial b u r n u p distortions are practically negligible. For the Stade Nuclear Power Plant KKS (See Fig. 2 for core cross section and D- and X-bank positions) Fig. 3 shows the load weighted radial power form factor F'_{xy} at a burnup state corresponding to 210 full power days. F'_{xy} is defined as the ratio of maximum integral rod rating at the actual power level over average integral rod rating at full power, vs. time, related to a daily load cycle (40 % power during a period of 6 hours at night) as plotted in the upper part of the figure. The arrows indicate insertion and witdrawal, respectively, of the D_1-bank. Note that the locations of the highest - rated fuel elements at part load differ from those at full power as indicated by fuel element identification marks.

In order to firmly establish that there is no appreciable effect on power density distribution due to local burnup perturbations possibly caused by periodical D-bank insertions, an extreme case, characterized by the pessimistic assumption that the D_1-bank will be fully inserted for a period of 12,5 days (140 th to 152,5 th day of the cycle) at 40 % power, has been calculated with the two-dimensional burnup-code MEDIUM [1]. The result is shown in Fig. 4. Evidently, upon withdrawal of the D_1-bank, the radial power form factor is only slightly higher than before D_1-bank insertion, the increment vanishing gradually with increasing burnup. Periodical d a i l y load cycling clearly will be even more harmless, since burnup perturbation caused by D-bank insertions during shorter part load periods will remain very low and will almost completely disappear during full power operation periods. Additionally, radial burnup distortions could be further reduced, if at all necessary, by periodically exchanging one D-bank against another one (e.g. D_1 against D_2).

During the time interval discussed the transient xenon reactivity $\Delta\rho_{Xe}$ following power reduction is compensated by chemical shim control.

B. Time interval before end of life (EOL) of a burnup cycle

Towards the end of a burnup cycle when the boron concentration, and as a result the boron removal rate, is too low to follow the xenon reactivity transient, reactivity can be gained by a temporary coolant temperature reduction taking advantage of the strongly negative coolant temperature coefficient of reactivity at EOL. (For the Obrigheim Nuclear Power Station KWO the measured coolant temperature reactivity coefficient at EOL of the first cycle was $(-40 \pm 3) \cdot 10^{-5}\ {}^{o}C^{-1}$ as compared to a predicted value of $-42 \cdot 10^{-5}\ {}^{o}C^{-1}$.) The high reactivity potential of PWRs at EOL is shown in Fig. 5 as a function of core power together with the pertinent coolant part load diagrams.

As a result, load-follow operation can be performed at natural EOL of a cycle by imposing slight restrictions on the transition from part load to full load by terminating fast load increase at a power level somewhat below full power. The reactivity required is gained by coolant temperature reduction to the necessary extent as shown in Fig. 5 and by the Doppler effect. Due to the fast xenon burnout at this elevated power level full power can be subsequently attained within less than a few hours depending on the level and the duration of the part load as shown in Fig. 6.

In case that the design rate of power increase after part load operation is demanded by the utility for end of cycle also, grey RCC-rods (X-bank), e.g. made of Inconel, are provided. They are fully inserted towards EOL of a burnup cycle thereby providing the necessary amount of reactivity for xenon override. A slight reactivity and burnup penalty has to be accepted in this case.

Fig. 7, which again is a result of a two-dimensional burnup calculation, shows that full insertion of the X-bank, as designed for KKS (see Fig. 3), 280 equivalent full power days after start up of the first cycle does not lead to an undue radial power density distortion; the radial power form factor increases only slightly, gradually decreasing afterwards. A one day load follow operation is then performed with the X-bank inserted. The combined D- and X-bank control strategy is indicated by the arrows. Note that the grey rods are moved sequentially in partial banks consisting of, e.g., 4 rods each.

A block diagram of the Siemens PWR control system is shown in Fig. 8. It demonstrates the simplicity of this system for a PWR equipped with the above described P-, D- and X-banks. Reactor power follows the turbine load. The coupling is governed by the control of the average reactor coolant temperature. Its measured value will be compared with its setpoint in accordance with the steady-state part load diagram shown in Fig. 5 [2]. Deviations result in movements of the P-bank according to their burnup and load program depending setpoints. The next control element is the D-bank. The setpoint of the D-bank position varies with the reactor power via a function generator. Final control elements are the boron injection and removal systems, respectively, and the X-bank. Whether the one or the other method, or a combination of both, is selected depends on the burnup state within a cycle (see 2.2.1 A. and B.).

2.2.2 AEG Boiling Water Reactor

The control system of the AEG BWR is schematically shown in Fig. 9. The system employs the so called "forward control". It uses the comparison between the required electrical power output and the actual power output as a direct means to determine the necessary adjustment in reactor power. The change of reactor power is accomplished in two ways:

a) by means of changing the speed of the coolant recirculation pumps,
b) by moving the control rods.

Since the AEG BWR employs pressure vessel internal pumps with low inertia, the variation of pump speed can be accomplished at a fast rate. The subsequent change in recirculation flow and its influence on steam volume fraction in the core causes a change in reactor power at a rate of ± 1 % per second in the range from 40 % of rated power upwards.
A typical example for the dependency between reactor power level and coolant throughput is shown in Fig. 10. The points shown indicate measured values from the Lingen power station while the underlayed lines quote the predicted dependency. The excellent agreement indicates the applicability of this mechanism.

By means of control rod moving, the power level also can be changed. This works with the rate of 10 % per minute in the range from 10 % of rated power upwards.

By combining the 2 mechanisms mentioned, the reactor power over the full range from 10 to 100 % load can be automatically adapted to changes in power demand as shown in Fig. 11. As can be seen, each power level is attainable by different combinations of control rod positioning and pump speed. At partial load operation the pump speed normally will lay in the range between lines c and b of Fig. 11. In this way any requirement in load change can first fastly be adapted for by means of flow control. If the limit of the flow control range is reached, rod movement is initiated and is maintained until the pump speed is brought back into the middle range. The region between 90 and 100 % of rated power is covered only by means of flow control for the following reason: Beside its fast action, flow control also has the feature of practically not influencing the power distribution in the core over a wide range. Additionally the decrease in power due to a reduction in recirculation flow always is stronger than the decrease in cooling capability. Therefore in the upper power range the maneuvering by means of flow control is a safe way and avoids disturbances in power distribution.

In addition to adapting ramp changes in the required power output as afore described, also step changes of 10 % can be coped with. This is done by making use of the energy stored in the steam volume between core exit and turbine entrance. If a step requirement occurs, the system pressure set point is lowered in order to open the inlet valve of the turbine. The concurrent behaviour of reactor power, generator output, neutron flux, system pressure, and steam flow as a function of time is shown in Fig. 12.

Summed up, it can be said that the combined recirculation flow and rod control enables the system to cope with ramp load changes of:

ramp load changes of:	± 10 %/min	from 10 % of rated power upwards (rod control)
	± 1%/sec	from 40 % of rated power upwards (flow control) according to Fig. 3

step load changes of: $\pm$ 10 %   from 40 % of rated power upwards

fully automatically. These features provide an excellent capability for load following.
The coupling between coolant recirculation and reactor power by means of the core void content reactivity interconnection also provides an inherent safety to the system in case of pump failure. With regard to the adaptability to load patterns, the capability for overriding Xenon built up is of importance. Fig. 13 shows the relationship between burnup reserve in the core and the capability to reach full power again after a period of zero load. It is based on the assumption that the reactor has been on full load for an extended period of time before. These conditions are much more unfavourable than normal operational demand will be since short reductions to zero load are seldomly required and some partial load scheme is more likely. Nevertheless, Fig. 13 shows that for most combinations even then the 100 % level can be reached again without delay after start up. For the most unfavourable condition of zero burnup reserve, after 8 hours of shut down (maximum Xenon build up) the level of 60 % of rated power can be reached without delay, and then it takes roughly 3 hours of steady power increase to come back to 100 % of rated power. This means that there is hardly any countable restriction in the flexibility of the load following scheme even at the end of the burn up cycle. This statement is further supported by the results of a parametric study as shown in Fig. 14. Based on the assumption of a load pattern consisting of longer operation at rated power, ramp decrease to partial load, constant partial load operation for a certain time and subsequent ramp increase to full load it shows the minimum partial load level to be maintained, if the increase to full load is not be hindered by Xenon build up, as function of burnup reserve. For instance is even at end of cycle a ramp decrease of 1 hour, 6 hours at about 50 % of rated power and a ramp increase of 1 hour back to full load possible without being hindered by means of Xenon buildup.

3. CYCLE DURATION FLEXIBILITY OF LIGHT WATER REACTORS

3.1 Typical Requirements for Cycle Length Flexibility

In addition to load following flexibility of nuclear power stations, the capability of extending or shortening of burnup cycles is of considerable importance to every utility in order to meet grid requirements. In this context one should clearly distinguish between foreseeable and unforeseen events.

Utility requirements foreseeable in good time (e.g. long range planning for a specified equilibrium burnup cycle length or for a transition from an originally ensivaged cycle length to a new one) can always be met by suitable variations of fuel element discharge and reload batch volumes or/and suitable adjustment of feed enrichment. This can be done without deteriorating the power density distribution at the beginning of the subsequent cycle and without adversely affecting the average discharge burnup.

Unforeseen events can result from a need, e.g., for a premature termination or an extendend operation, respectively, of a burnup cycle (power stretch-out), possibly coupled with a demand for a certain specified length of the subsequent cycle. Premature termination of a current cycle without requirement for an unduly long subsequent cycle length is also possible by properly adjusting the fuel element reload batch volume.

3.2 Potential of Light Water Reactors Regarding Cycle Duration Flexibility

3.2.1 Siemens Pressurized Water Reactors

Numerous calculations supported by operational experience have shown that PWRs have a high degree of cycle duration flexibility.

Utility requirements for a specified equilibrium burnup cycle duration t_{cycl} [d] can be easily fulfilled by selecting the appropriate fraction $\frac{1}{Z}$ of the total number of core fuel elements to be discharged and replaced by fresh ones at the end of an operational period. This can be done without adversely affecting the average discharge burnup $\overline{Bu}$ /$\overline{M}$Wd/t/ and the average specific fuel power $\overline{P}_U$ /$\overline{M}$W/t/, respectively, as is evident from the following relationship:

$$t_{cycl} \cdot Z = \frac{\overline{Bu}}{\overline{Pu}}$$

Both $\overline{B}_u$ and $\overline{P}_U$ should be kept high in order to achieve low fuel cycle costs.
Fig. 15 illustrates the correlation between average discharge burnup $\overline{B}_u$, reload batch volume fraction $\frac{1}{Z}$ (Z = cycle number) and equilibrium feed enrichment e.
The transition from a planned (Z =) four cycle operation (KKS) to a three cycle operation is presented in Table 1. The central column refers to the case where, after "natural" end of life (EOL) of the first cycle (420 d), 52 instead of 40 out of a total of 157 fuel assemblies will be discharged leading, if this pattern is continued, to an equilibrium cycle duration of approximately 300 equivalent full power days (EFPD) instead of the originally envisaged 230 EFPD. A reduced cycle length has been interspersed by loading only 40 instead of 52 fresh fuel elements at the end of the 6^{th} cycle resulting in a duration of 233 EFPD in the 7^{th} cycle. Upon resuming a three cycle operation by discharging again 52 fuel elements at the end of the 7^{th} cycle equilibrium burnup conditions are reached already in the subsequent cycle.

The left hand column of Table 1 refers to a termination of the first cycle 46 days before the natural end of life under the simultaneous requirement of an extended second cycle. Again, one third of the fuel assemblies has been discharged. As can be seen, this case would lead to a slight burnup loss in the subsequent two cycles. Such a burnup loss could be avoided if less than 52 fuel assemblies were discharged; if this cannot be done because of a desired extended second cycle, this burnup loss can be compensated by stretching the subsequent cycle or by re-using, in later cycles, some of the fuel that was prematurely discharged during the first cycle.

The right hand column of Table 1 refers to a power stretch-out of the first cycle by 44 EFPD beyond the normal end of life. In this case burnup is gained. The additional excess reactivity required for stretch-out operation is obtained by lowering both the reactor output and the average coolant temperature according to the part load diagram shown in Fig. 5. The average coolant temperature can be reduced with a sufficiently high rate ($\sim 55^{\circ}C/h$) to an adequately low level ($\sim 260^{\circ}C$). Reactor control becomes simplest as soon as full power operation is no longer possible due to lack of reactivity. In principle the reactor can then be left with all control rods removed, that is, without any external control. Due to its negative reactivity coefficients it remains critical and follows during power stretch-out the operational curves of steam temperature and average coolant temperature with maximum thermal efficiency.

Fig. 16 illustrates the optimal stretch-out operation of a 650 MWe PWR of the KKS-type beyond the normal end of the cycle. By reducing the reactor power gradually from 100 to 65 %, more than 50 equivalent full power days can be gained corresponding to a core burnup increase of 2000 MWd/t. If the subsequent burnup cycle is to have the duration of an equilibrium cycle, approximately 10 - 12 fresh fuel assemblies should be loaded in addition to the regular reload batch.

As can be seen from Table 1, no problems will be encountered with regard to achieving a flat radial power distribution at start up of the cycle following a shortened of extended cycle. This is due to the excellent fuel management flexibility of PWRs, resulting from the fact that PWR cores are controlled by an uniformely distributed neutron poison (chemical shim) allowing power operation with control rods almost completely withdrawn so that, in connection with the fact that each fuel assembly is able to hold a RCC bundle, the effects of otherwise necessary control rod programming need not be accounted for in fuel management considerations.

Since the need of matching a nun-uniform loading and fuel cycling to a complicated non-uniform control rod distribution is eliminated, one has substantially increased freedom in the choice of possible fuel management alternatives. Flexibility of fuel management is further increased by the fact that fuel assemblies, due to their 90^{o}-symmetry, can be rotated around their axes before being reshuffled.

3.2.2 AEG Boiling Water Reactor

According to the definitions given in 3.1, one should distinguish between the unforeseen need for extended operation and the need for changes which can be adapted for well in advance. The unforeseen need for extended operation leads to the so called "power stretch-out" (derating) operation. With the boiling water reactors in operation in Germany (VAK, KRB, KWL) ample experience of derating performance has been gathered due to the demand of the utility companies to extend the respective cycle. The significant feature of this mode of operation is that all control rods are fully withdrawn, and that the reactor power drops at a rate necessary to gain the reactivity loss due to burnup by means of decreasing fuel temperature (Doppler coefficient) and void content. In Fig. 17, a comparison is shown between the prediction of the derating performance and measurements at the Lingen reactor (KWL). For the Lingen reactor as well as for similar measurements in KRB and VAK, the numerical value of the rate of change has been about 0,35 % of power level per day. Calculations of the rate of change for present day design with an average power density of 51 KW/l (Lingen: 38 KW/l) yield a value of about 0,50 % of power level per day. The stretch-out can be further extended if a decrease of feed water temperature is initiated, thus decreasing the void content in the core additionally. The corresponding change of power level after begin of stretch-out operation is shown in Fig. 18. The feedwater temperature decrease is accompanied by a decrease in plant efficiency of several percent. Nevertheless in certain cases stretch-out operation will bring substantial savings in fuel costs due to higher burnups to be achieved at the same initial enrichment. The boiling water reactor of present day design can for instance be operated from the begin of stretch-out operation for additional 100 days, and during this time will drop to roughly two thirds of rated power level. This gives ample reserve for unforeseen needs to extend the operation beyond the scheduled fuel cycle length. The subsequent cycle has to be adjusted in reload enrichment and/or reload batch volume to make good for part of the additional burnup.

If changes in cycle duration and sequence are foreseen well in advance before the start of the next cycle, adjustments can be made by adjusting either the enrichment or the amount of the reload bundles or both. Studies of economics for different types of cycle patterns make it seem most appropriate to keep the enrichment of the reload bundles constant and only to adjust the number of reload bundles.

If this is done, the range between 6000 resp. 8000 hours per cycle yields a final bundle burnup between 28400 resp. 26800 MWd/t U. Since presently the economical optimal burnup for BWR bundles is about 27500 MWd/t U and the optimum is rather flat, these deviations are tolerable. The corresponding number of bundles to be exchanged during reload is about one figth resp. one fourth of the total core inventory. These figures show that the adaptibility of a given core to different fuel loading schemes is established rather simply by changing the number of reload bundles of the same enrichment. It is important that these adaptions can be made without introducing unpermissible power shapes within the core. The chessboard reload pattern allows the replacement of almost one third of all bundles with fresh fuel, without thermally overloading certain areas within the core. This is possible, because each control rod cell consisting of the control rod and the 4 surrounding elements can easily adapt one new bundle. Additional new bundles can be placed in the edge zone of the core which due to neutron leakage has lower power density compared to the inner region. Exact figures of corresponding cycle length number of reload bundles, percentage of these bundles with respect to the total core inventory and average discharge burnup are given in Table 2, referring to a BWR plant with a thermal rating of 2292 MW and a total amount of 532 bundles in the core.

References

/̲1̲/ M. Wagner: Siemens Internal Report
/̲2̲/ W. Aleite: VGB-Kernkraftwerks-Seminar, Essen, 1970 (published 1971)

Variation of Burnup Cycle Duration for a 650 MWe PWR (KKS)

F: radial power form factor at beginning of life
D: cycle duration (d)
E: number of discharged fuel assemblies
$\overline{Bu}$: average burnup of discharged batch (MWd/kg)

		shortened cycle	normal cycle	extended cycle
1st cycle	F	1.30	1.30	1.30
	D	374	420	464
	E	52	52	52
	$\overline{Bu}$	14.4	16.1	17.7
2nd cycle	F	1.36	1.37	1.44
	D	273	248	220
	E	52	52	52
	$\overline{Bu}$	23.0	23.7	24.3
3rd cycle	F	13.6	1.36	1.34
	D	301	307	312
	E	52	52	52
	$\overline{Bu}$	30.5	30.7	30.8
4th cycle	F	1.40	1.37	1.38
	D	302	303	305
	E	52	52	52
	$\overline{Bu}$	31.1	31.0	30.7
5th cycle	F	1.37	1.34	1.36
	D	301	296	294
	E	52	52	52
	$\overline{Bu}$	31.8	31.8	31.9

continued

6th cycle	F	1.33	1.33	1.32
	D	299	299	299
	E	52	40	52
	$\overline{Bu}$	31.6	33.2	31.6
7th cycle	F		1.36	
	D		233	
	E		52	
	$\overline{Bu}$		31.4	
8th cycle	F		1.44	
	D		305	
	E		52	
	$\overline{Bu}$		31.5	
9th cycle	F		1.32	
	D		297	
	E		52	
	$\overline{Bu}$		31.6	
10th cycle	F		1.34	
	D		299	
	E		52	
	$\overline{Bu}$		31.5	

Table 1

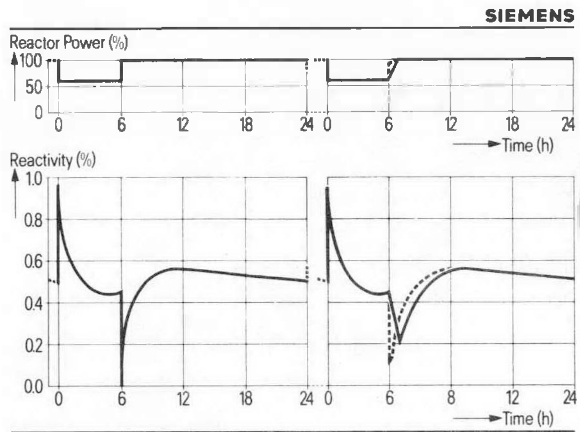
cycle length [EFPH]	number of reload bundles	percentage of total core *)	discharge burnup [MWd/t]
6000	107	0,21	28400
6500	117	0,22	28000
7000	128	0,24	27600
7500	139	0,26	27200
8000	151	0,284	26800

*) total core inventory = 532 bundles

Relationship between number of reload bundles, cycle length and average discharge burnup (2292 MW thermal BWR)

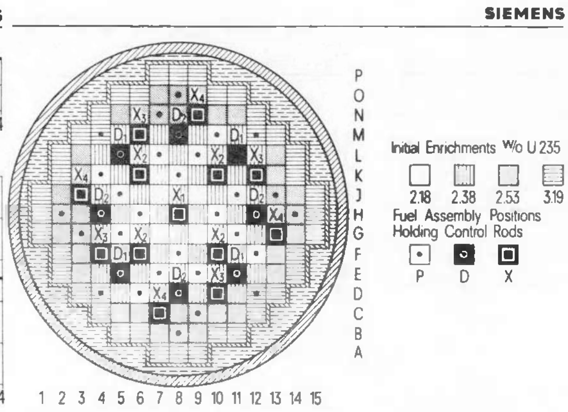
AEG E 3 108 e

Table 2



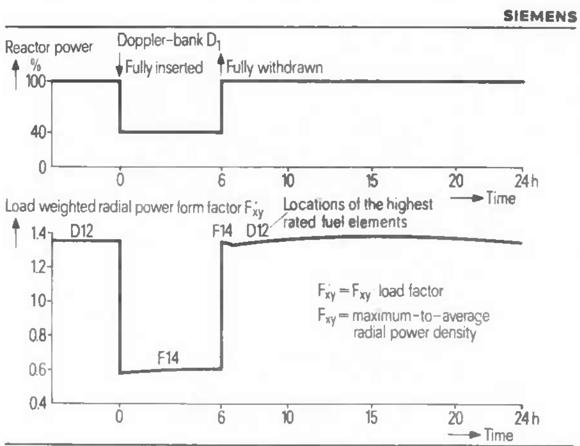
Reactivity Behaviour during Daily Load Cycle Operation (PWR) ERT12 71695e

Fig. 1



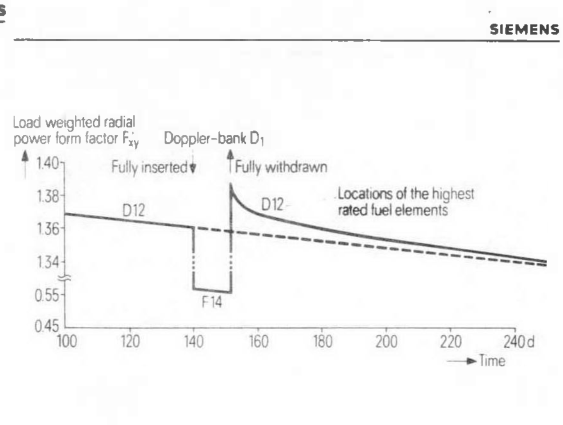
Core Cross Section of a 650 MWe PWR Showing Doppler- and Xenon-Control Bank Positions ERT12 71450e

Fig. 2



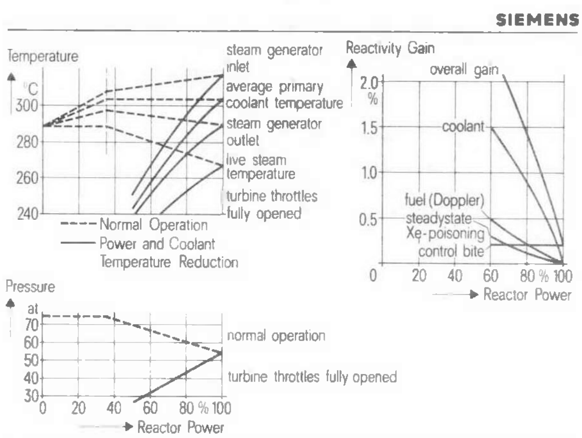
Radial power form factor during daily load cycle operation with transient xenon poisoning compensated by boron (PWR). 210 days after beginning of live ERT12 71465e

Fig. 3



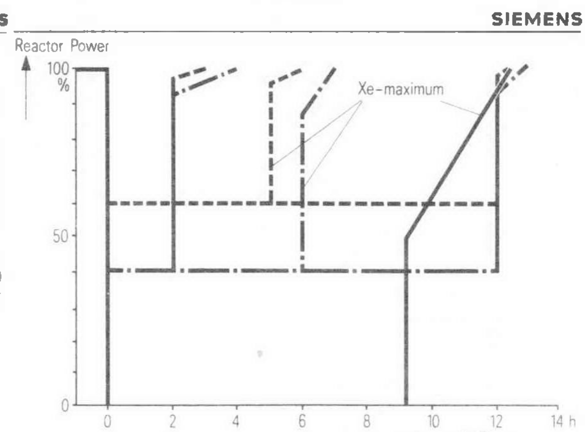
Radial power form factor after extended Doppler-bank insertion, PWR ERT12 71451e

Fig. 4



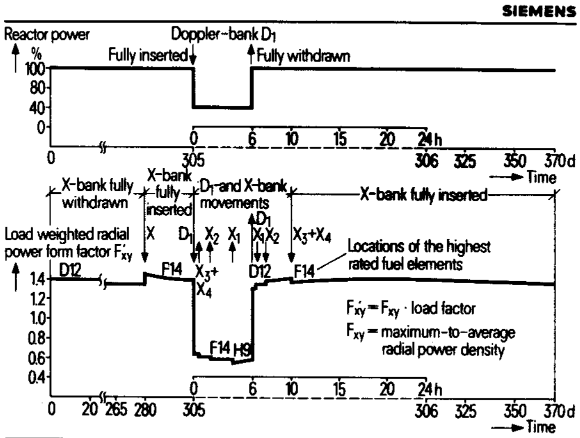
Temperature and Pressure Part Load Diagram and Reactivity Gain vs Reactor Power for a PWR ERT12 71454e

Fig. 5



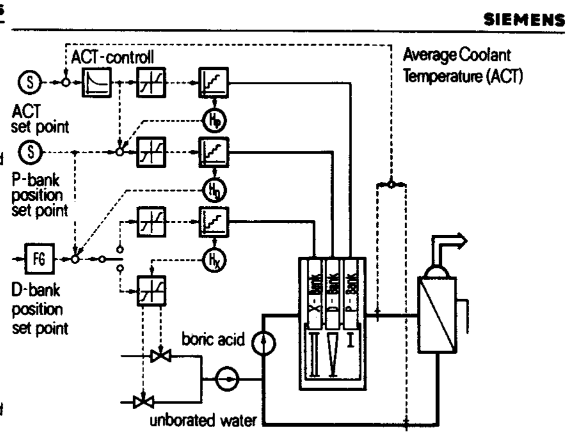
Most Unfavourable Load Increase Restrictions of a PWR at End of Cycle after Scram and Different Part Load Levels ERT12 71485e

Fig. 6



Radial power form factor during daily load cycle operation with transient xenon poisoning compensated by xenon-bank, PWR

Fig. 7



Block Diagram of a Siemens PWR Control System

Fig. 8

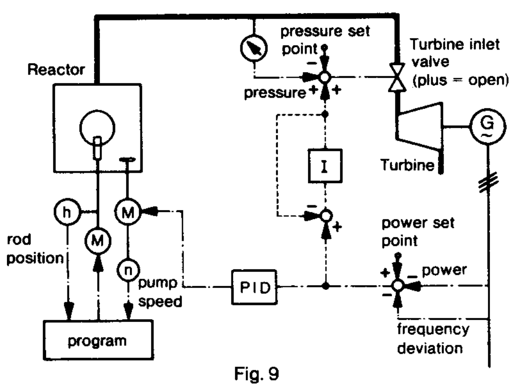


Fig. 9 Schematic of direct cycle BWR control system

AEG E3 100e

Fig. 9

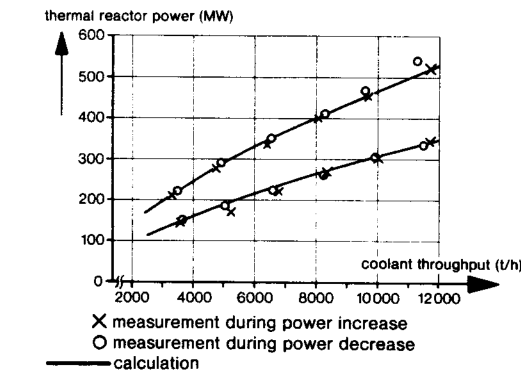


Fig. 10 Recirculation flow control characteristic (control rods at constant position)

AEG E3 101e

Fig. 10

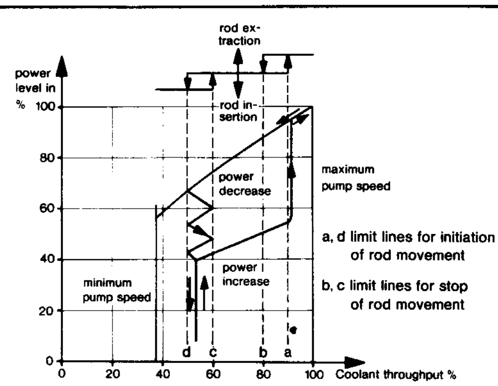


Fig. 11 Combined operation of recirculation flow control and rod control (typical example of power maneuvering)

AEG E3 102e

Fig. 11

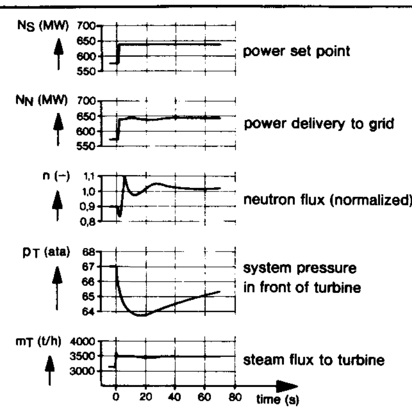


Fig. 12 Transient response of system parameters in case of stepwise increase in power demand (pressure setpoint variation activated)

AEG E3 103e

Fig. 12

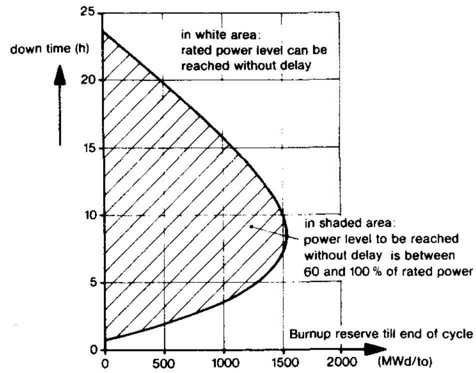


Fig. 13 Permissible down-time after shut down if undelayed reaching of full power is required

AEG E3 104 e

Fig. 13

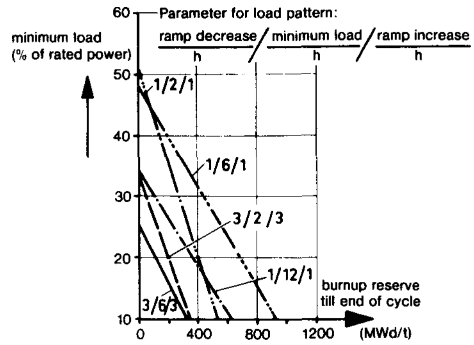
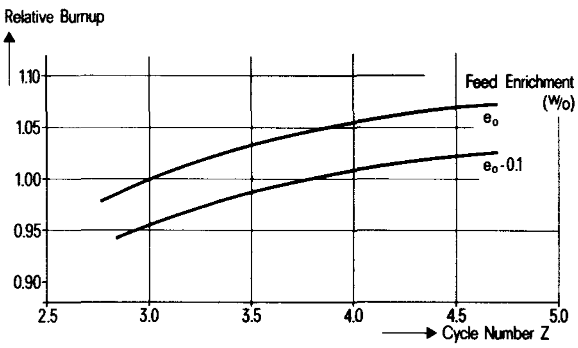


Fig. 14 Minimum partial load after ramp decrease from full power operation if after subsequent ramp increase full power is to be reached without restriction

AEG E3 105 e

Fig. 14

SIEMENS

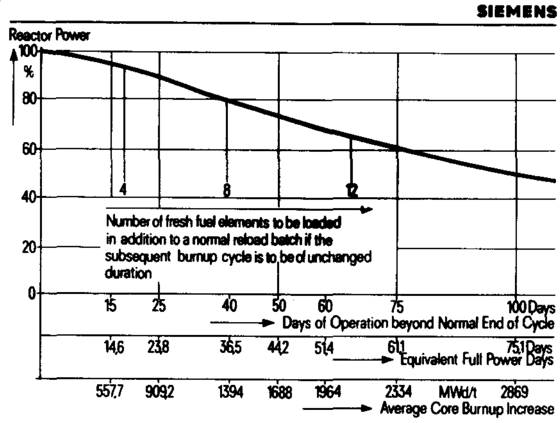


Relationship between Average Discharge Burnup and Cycle Number for Different Feed Enrichments, PWR.

ERT12 71453e

Fig. 15

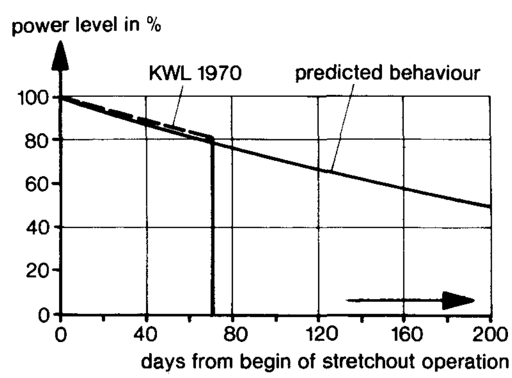
SIEMENS



Stretchout Operation of a PWR

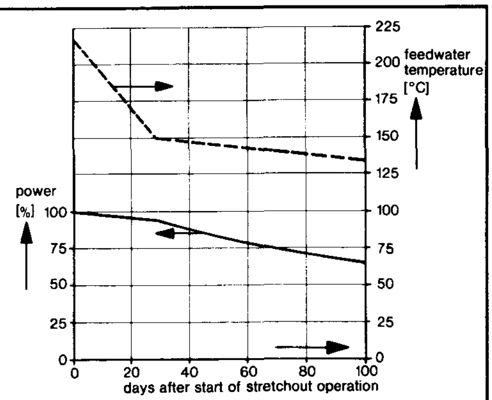
ERT12 71487e

Fig. 16



AEG KWL stretchout operation 1970 E3 106 e

Fig. 17



Power and feedwater temperature as a function of time after begin of stretchout operation

AEG E3 107e

Fig. 18