10.6 EVALUATION OF DESIGN CONSTRAINTS EFFECTS TO THE EFFICIENCY OF VVER FUEL CYCLE

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ABSTRACT

The paper discusses the influence of the reactor parameters limits for normal operation on the economical performance of VVER fuel cycles. It is shown for the typical VVER fuel cycles that decreasing the limits for the main power distribution parameters to 10% leads to decreasing the fuel components of the electricity cost price up to 4-5%. As the nowadays limitations are reached the dependence becomes weaker.

1 TASK FORMULATION

To explain the paper title, let’s emphasise that cycle efficiency is mainly effected by normal power distribution limits. The selection of the limits is aimed at:

- ensuring plant operation at rated power during the whole cycle;
- ensuring plant safety, i.e. design basis flow of the processes at normal operation and abnormal operation including design basis accidents.

Many papers discuss selection and optimisation of engineering solutions and parameters of power producing reactor. These issues are discussed most explicitly and adequately in relation to the comprehensive conditions in paper [1], though long time has passed since it was published.

The specific feature of this paper task is the fact that reactor, reactor core and fuel assembly designs, as well as reactor operation characteristics, have been already defined, while reactor operation parameters require defining the limits in order to select makeup fuel assemblies and arrange them in reactor core. The paper is focused at the following issues:

- discussion of normally accepted design basis limits for power distribution, which define the area of tolerable parameter values;
- evaluation of effect produced by power parameters to the efficiency of fuel cycle;
- evaluation of conservatism in selection of certain design basis limits for VVER.

2 DESIGN CONSTRAINTS FOR NORMAL OPERATION

As pointed out by paper [2], design constraints for normal operation are sufficient conditions, whose satisfaction ensure an acceptable flow of processes at any plant operating conditions including normal operation, as it is, anticipated operational occurrences and design basis accidents. The satisfaction of design constraints at normal reactor operation or design basis accidents ensures acceptable starting conditions for the beginning of transients.

If the core loading and reactor operation conditions were selected with account of design constraints, and safety analysis proved that technological and radiological safety criteria established by government regulatory documents [2 -7] were fulfilled, it will mean that the constraints meet the main goals.

There may raise the question of conservatism degree of the selected constraints. The nomenclature of constraints and the numerical values may be discussed. The paper discusses the constraints related to power distribution about the core. VVER design and operation typically refer the constraints for the following functionals to such kind of constraints:

q_{FA} - FA power, or FA relative power, K_q;

q_{tvel} - rod power, or relative rod power, K_r;

K_v - relative power of FA section;

q_l - linear heat rate;

t_T , t_{cl} - fuel temperature and temperature of clad outer surface;

Profile is the profile of axial power distribution in hot channel;

Offset is an integral axial offset of core power.

Before proceeding to individual discussion of each constraint, it is necessary to point out that the parameters limited by design basis limits are bound with each other in actual reactor; and the constraint of any of them typically result in automatical constraint of other parameters. Later, this will demonstrated by Figure 1.

The optimisation of the constraints is mainly understood as a coupled set of constraints with a certain variety of values within this set. Further along, the paper discusses the task of selecting the above set of constraints.

Let's discuss each of the mentioned constraints individually. The latest designs of VVER-440 and VVER-1000 do not limit FA power (q_{FA}). Earlier, the constraint of this functional was used as indirect constraint of rod power. At that, it was assumed that the inhomogeinity of rod-wise power inside was close (or equal) to a maximum value. As calculation methods improved, there appeared a possibility of evaluating the power distribution inside a certain FA; and since FA power can be determined by in-operational measurements, rod power can be determined on the basis of calculated data.

Fuel assembly power, as it is, can be limited due to the effect of the released power produced to the coolant flow in FA (the flow decreases as power rises). However, the power effects the coolant flow not too much, and the flow in FA can be associated with the power of the most stressed rod. This relationship allows, as necessary, to limit the residual power density and FA radioactivity.

Now, let's proceed to rod power. The constraint of rod power is the most logical constraint and, typically, the most important of the constraints used to limit the power distribution. This constraint much influences the most of the processes typical for equilibrium and transient conditions of heat decay. So, for example, the constraint of rod power is one of the defining conditions in analysis of the bulk of the conditions of safety analysis. And, in order to demonstrate the availability of the rod power constraint, it is necessary to simulate every condition where such constraint plays a significant role.

Rod power is bound with linear heat rate; it is an integral parameter of power density, and to much extent, defines the coolant flow parameters and the parameters that characterise clad status. In particular, rod power alongside with axial power profile defines the departure from nucleate boiling ratio.

Evaluation and constraint of FA section relative power (K_v) gives a good opportunity for limiting the linear heat rate (q_l) that we are going to discuss now. For VVER case, this constraint is closely bound with rod power constraint, and stipulated by two physics causes.

Firstly, the satisfaction of this constraint ensures reliable heat decay from rod surface. At normal operation and anticipated operational occurrences, the avoiding of nucleate boiling, non-excursion of rated clad temperature, and absence of fuel melting are ensured. For certain accidents, the absence of fuel melting and steam-zirconium reaction are ensured, and constraint of fuel enthalpy in maximally stressed rod sections is also ensured.

Secondly, the constraint of linear heat rate versus fuel burnup in fuel rod is bound with the fact that at a certain linear heat rate gas release into cladding suddenly increases, which deteriorates the rod strength parameters.

Now, let's discuss fuel temperature and clad temperature constraints. Since at VVER operation at nominal parameters, fuel temperature shows a significant margin to melting temperature, further, fuel temperature is excluded from discussion.

Let's focus at the temperature of clad outer surface (t_{cl}). The constraint of the temperature can be considered at one and the same time as Safety criterion, and as Design basis limit. The problem makes the extent of substantiation of such constraint. As the authors are informed, the constraint is not caused by the discussion of any physics process, but it reflects the state of affairs, which is realised at VVER reactors in the course of long-term successful operation. The limitation used to work fine, so let's not change it. As far as we know, PWR design has no clad temperature constraint. For example, paragraph 4.4.2.11.5 of safety analysis report for Westinghouse AP 1000 reactor [8] says: "Since the thermal-hydraulic design constraints DNB, adequate heat transfer is provided between the fuel clad and the reactor coolant so that the core thermal output is not limited by considerations of clad temperature".

It is necessary to point out here that as per our analysis, the constraint for t_{cl} for VVER-1000 is a significant limitation of possibility to increase linear heat rate and, to some extent, rod power.

Finally, let's discuss the profile of axial power distribution about the core, and axial offset. The profile of axial power distribution about the core is an important reactor parameter, and, together with maximal linear heat rate, defines the departure from nucleate boiling ratio. To ensure safety analysis, the VVER design uses several typical power profiles plotted in such a manner that their extreme point crosses a linear heat rate limiting curve. Safety analysis calculations are conducted for several typical power profiles in such a way that the normal operation limiting requirement is requirement that the calculated power profile were close to one of the selected typical profiles. This requirement is satisfied by determining tolerable positions for CPS control rods. Speaking in general, the application of typical profiles in safety analysis is too much conservative. It would be much more correct to "bind" a profile to a cycle moment and perform applicable simulation of transients and accidents.

3 SAFETY AND EFFICIENCY

As it was earlier said, the findings of efficiency analysis prove that rigid design constraints result in realization of less efficient fuel cycles that show higher safety quality. Thus, the selected design constraints shall ensure plant operation at a rated power level with reasonable balance between conservatism, which ensures safety, and efficiency. With accumulation of experience in safe operation of this type of fuel cycles, design constraints can shift within the range of extreme tolerable values. At that, it is must be taken into consideration that usually the limitation of only one power density parameter approaches to the ultimate value. Other parameters, though bound with this constraint, have a certain variation freedom, which can be used to advantage when selecting them. We draw the attention again to the fact that safety analysis shall evaluate the finally selected set of design constraints for sufficiency. Further, we give a comparison of fuel cycles from economic point of view, where fuel cycles differ in tolerable values of design constraints (K_q, K_r, K_V and q_l). The comparison is made for VVER-440 and VVER-1000 fuel cycles and presented in a generic form.

4 CYCLE EFFECTIVENESS AS EFFECTED BY PARAMETERS OF REACTOR POWER DISTRIBUTION

In order to avoid a complicated and ambiguous optimization of core loadings, we implemented the task the following way. For the mode of VVER-440 and VVER-1000 steady-state refuellings we selected individually the makeup FAs and varied the number of periphery burnt out FAs in the core. The map of loading was formed by way of rod power minimization. Prices were determined proceeding from world prices for reactor fuel with accounting of natural uranium price, cost of separative work unit (SWU), FA production price, expenditures for waste recycling or long-term storage. Figure 1 gives a summarized dependence of fuel component of price versus K_q, K_r, K_V and q_l. As reflected by the dependence, we can make a conclusion that the fuel component of price changes by 5 % if K_q is changed by 0.15, and q_l by ~ 50 W/cm. Similar conclusion may be made from the dependence of fuel component of price on margin coefficients in relation to functionals K_q, K_r, K_V and q_l. As the nowadays limitations are reached the dependence becomes weaker.

5 INVESTIGATION OF PROBABILITY OF REDUCING THE CONSERVATISM IN CONSTRAINTS FOR POWER DISTRIBUTION DURING OPERATION

Here we try to answer the following question: if there any possibility of shifting to less conservative constraints for core loadings in terms of ensuring the satisfaction of Safety Criteria, and whether the adopted constraints for rod power and linear load are really ultimate tolerable constraints.

Evidently, the answer to the question is the competence of reactor plant Designer and Constructor and depends on several factors, they are: adequacy extent in describing a thermal hydraulic model of reactor plant, scenario of the expected transient (including the sequence of actuating the executive elements and delay in protective and locking system), computer codes used and their errors, etc.

Nevertheless, with the assistance of Kurchatov Institute experts Tsyganov S.V. and Nikonov S.P. and using code ATHLET it was calculated three conditions, which are the most sensitive to power distribution constraints and which can appear in VVER-1000 operation. These are the following conditions: normal operation at nominal power, disabling all reactor coolant pumps at nominal power, and great leakage of the primary coolant caused by the rupture of main coolant pipeline. To summarise the follow-up conclusions made from the analysis of simulating the above mentioned conditions, it may concluded that VVER-1000 design basis constraints for normal operation reactor parameters ensure the satisfaction of applicable Safety Criteria.

For the conditions of normal operation and anticipated operational occurrences, the following requirements will serve as Safety Criteria:

- departure from nucleate boiling ratio exceeding a unity;
- clad temperature less than 352 – 355 °C;
- fuel temperature less than melting temperature;
- limited number of damaged fuel rods.

For the condition with pipe break, Safety Criteria will be the following:

- clad temperature less than 1200 °C;
- fuel temperature less than melting temperature, fuel enthalpy at maximum stressed rod section is $\leq$ 200 cal/g;
- limited depth of clad oxidation and amount of reacted zirconium.

The calculations of normal operation condition and calculations of transients by code ATHLET showed that the limitation of rod power and linear load have at least a 10 % margin for the discussed anticipated operational occurrences. Clad temperature at steady state reactor operation turned out to be the most limiting factor that limits the possibility of increasing the power density(q_l and q_{tvel}). The maximum clad temperature at steady state reactor operation makes 352 – 355 °C.

CONCLUSIONS

The paper analyses the dependence between the fuel component of output power price and the limitations of core parameters that characterize power distribution. The paper proves that more severe limitations for power inhomogeinity result in less efficient fuel cycles.

The second half of the paper deals with investigation of problem of sufficient justification of adopted limitations for VVER power distribution. The methodological studies used by the paper authors prove the availability of reducing the conservatism of power distribution limitations, should it be based on the analysis of all Safety Criteria excluding normal operation clad temperature. The paper proposes to study individually the justification rate of the used limitation for clad temperature.

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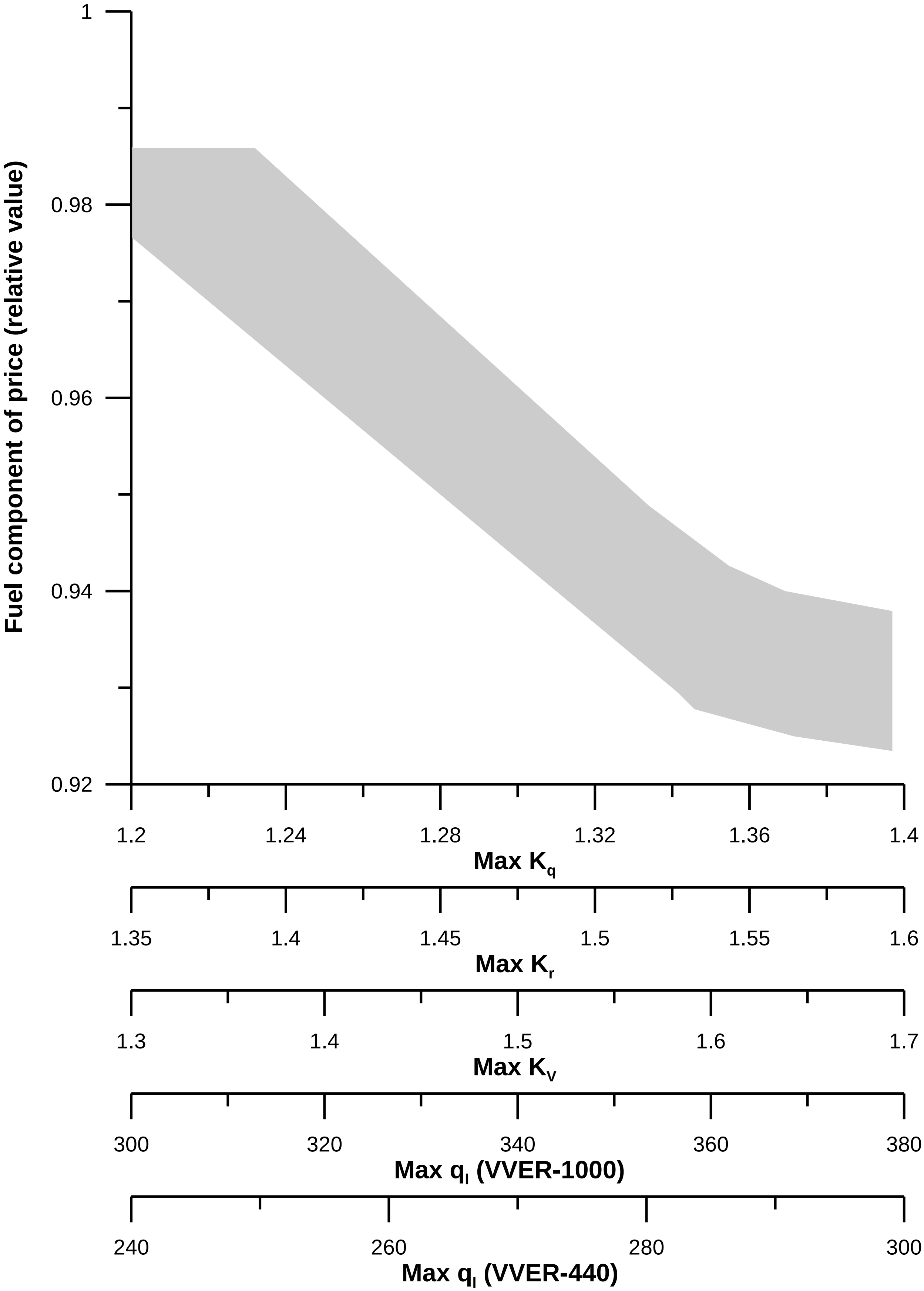

Fuel component of price (relative value)
1
0.98
0.96
0.94
0.92
1.2
1.24
1.28
1.32
1.36
1.4
Max K_q
1.35
1.4
1.45
1.5
1.55
1.6
Max K_r
1.3
1.4
1.5
1.6
1.7
Max K_V
300
320
340
360
380
Max q_l (VVER-1000)
240
260
280
300
Max q_l (VVER-440)

Fig. 1