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Experimental Verification of Adiabatic Fuchs-Hansen Pulse Model

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Abstract

Systematic analysis of all pulse experiments performed in 6 years of pulse operation of Ljubljana TRIGA Mark-II reactor is presented. Deviations from linear adiabatic Fuchs-Hansen relations between pulse reactivity and maximum power and energy are explained. Principles for reducing systematic experimental errors and for increasing predictability of main safety related pulse parameters are derived.

1. Introduction

TRIGA Mark-II reactor at J. Stefan Institute was reconstructed for pulse mode operation in 1991. Six sets of pulse experiments have been performed since then. In total 92 pulses were performed. All pulsings were performed with compact homogeneous cores containing approximately 50 fuel elements (standard type, 20% enriched, stainless-steel cladding, 12w% uranium content). Detailed description of the reactor and its pulsing capability is presented in references [1, 2, 3]. The purpose of this paper is to present systematic analysis of measured parameters and to evaluate the validity of linear adiabatic Fuchs-Hansen (abbreviated: FH) pulse model normally applied in pulse safety analysis [1]. Statistical and systematic discrepancies are discussed and explained. Potential sources of experimental errors and deficiencies of analytical model are investigated.

2. Pulse parameter analysis

The most important pulse parameter is total energy produced in the pulse. Pulse energy is in our reactor recorded in two ways: from the nvt instrumentation channel (analog integration of the pulse signal) or using a computer program DASFGR integrating digitized pulse signal of the nvt channel [2]. The pulse energy is proportional to prompt reactivity according to FH model. Total energy recorded by DASFGR in dependence of reactivity is presented in Fig. 1 for all pulses. Spread of experimental dots around the linear fit with standard deviation of 1.6MWs can be observed. 1.6MWs is equivalent to approx. 10% of the pulse energy for the largest pulses. The fitted line is also shifted approx. 2MWs towards higher energy.

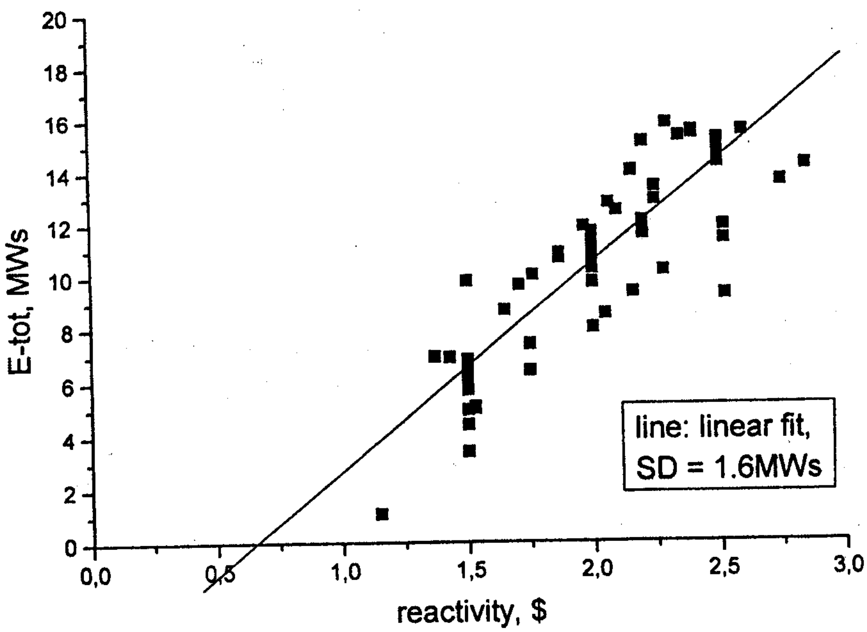

Fig. 1. Pulse energy recorded by DASFGR as a function of inserted reactivity for all pulses

2.1. Reproducibility of the pulse

The deviations from linearity can be explained by statistical and systematic effects. Statistical deviations are mainly due to limited reproducibility of the experimental conditions, for instance the position of the transient rod. An estimate of these effects can be obtained if observing a set of experimental data free of systematic errors. Since the systematic errors stem mainly from the changes in reactor properties due to operation between subsequent sets of pulses we can get an estimate of systematic error by observing the data within the same set. Fig. 2 shows total pulse energy as a function of reactivity for two sets of pulses performed in November 1991 and in March 1997.

An estimate of the pulse reproducibility is obtained if the pulses performed at (presumably) same transient rod position and reactivity in the same set are compared. Such are, for example, four pulses performed at 2.2$ on the curve corresponding to pulse operation in March 1997 in Fig. 2.

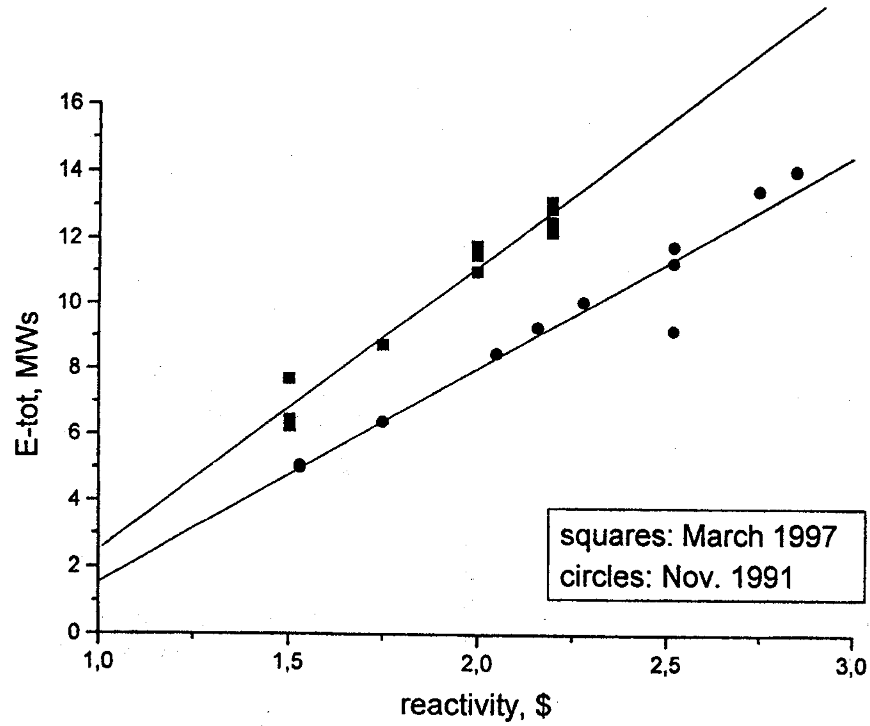

Fig. 2. Total pulse energy as a function of reactivity for pulse operation in November 1991 and March 1997.

However, note that the spread of experimental values at 2.5$ on the curve corresponding to November 1991 experiments is not due to the same effect. Taking into account the sequence of pulsing and eliminating all sources of errors it can be derived that in this case the reason for deviation from linearity is Xenon poisoning of the reactor due to pulsing. The pulse corresponding to the lowest point (9MWs) at 2.5$ was performed as the last in the sequence. Approximately 90MWs energy was produced in all previous pulses performed in the same day. The accumulated energy corresponds to 400s of operation at 250kW. The energy and maximum power produced in the last pulse indicate that actual pulse reactivity was not 2.5$ but approx. 2.2$. The reduction of reactivity matches the xenon effect typical for ≈ 10min of operation at full power if it is taken into account that there is no xenon burn-up in the periods between pulses. However it should be noted that xenon directly influenced pulse reactivity only in the set of pulses in November 1991 as this was the only pulsing performed from subcritical reactor. In all other pulses Xenon may have only indirect effect by influencing pulse rod worth through flux redistribution due to repositioning of other control rods compensating xenon build-up. However, this effect is probably small as it can not be clearly extracted from the pulse data and makes part of the statistical error.

2.2. Systematic errors

Excluding Xenon effect it can be observed from Fig. 2 that the reproducibility error is much smaller than systematic errors. The following main sources of systematic errors and deviations are identified:

- pulse channel calibration and sensitivity of the detector on the local flux variations
- transient rod reactivity curve and influence of other control rods
- fuel burn-up due to long term steady state operation between pulsing
- modifications in core configuration.

The first two effects are well known also from steady state operation and can be reduced by careful calibration of instrumentation, by measuring transient rod taking into account interference with other rods (e.g. by rod swap method) and by introducing correction factor for flux distribution effects. They are elaborated in ref. [4] and will not be pursued here particularly because they are estimated to be smaller than the effects due to burn-up and other changes in the core.

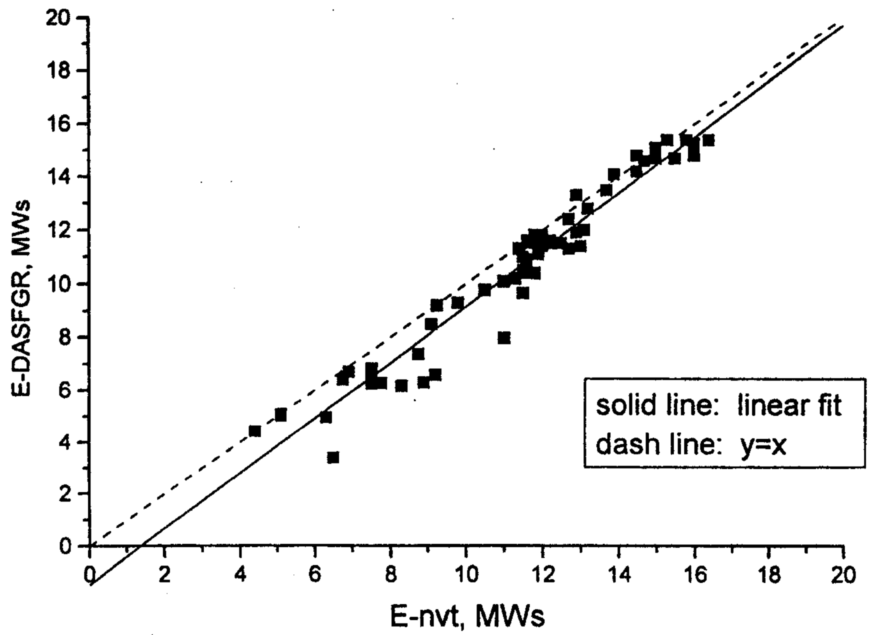

Fig. 3. Relation between pulse energy reading of nvt channel instrumentation and DASFGR for all pulses

All effects listed above influence mainly the slope of the energy-versus-reactivity curve, however, they do not explain its shift. The shift to higher energy is always observed (see Fig. 1 and 2) even if the curve is linear and the scattering is small. There are two reasons for the shift:

1. FH model is appropriate only for reactivity much larger than prompt reactivity (1$). Neglecting of experimental points at low reactivity (below 2$) would yield steeper linear fits as can be derived from Figs. 1 and 2.

2. FH model linear relation between energy and reactivity holds for the energy released in the pulse assuming that power drops to zero immediately after the pulse. However, there is always some energy generated after the pulse particularly in small pulses where reactor does not automatically become subcritical and has to be shut down. The power after the pulse is in the order of MW, time interval between the pulse and the scram is in the order of seconds, total effect is therefore in the order of MWs. The effect is stronger on the nvt channel reading than on the DASFGR result where major part of the delayed energy can be numerically subtracted. Figure 3 shows the relation between pulse energy reading from DASFGR and nvt instrumentation. It can be observed that nvt readings exceed DASFGR readings for approx. 1MWs in average.

However, neither the delayed energy effect can be completely compensated nor the validity of FH model for small reactivities can be improved. For this reason there is still some shift in linear fit curves in Figs. 1 and 2 in spite of results being processed with DASFGR. We can see that the delayed energy is the reason for the shift from the fact that the same effect can not be observed on maximum pulse energy presented in Fig. 4.

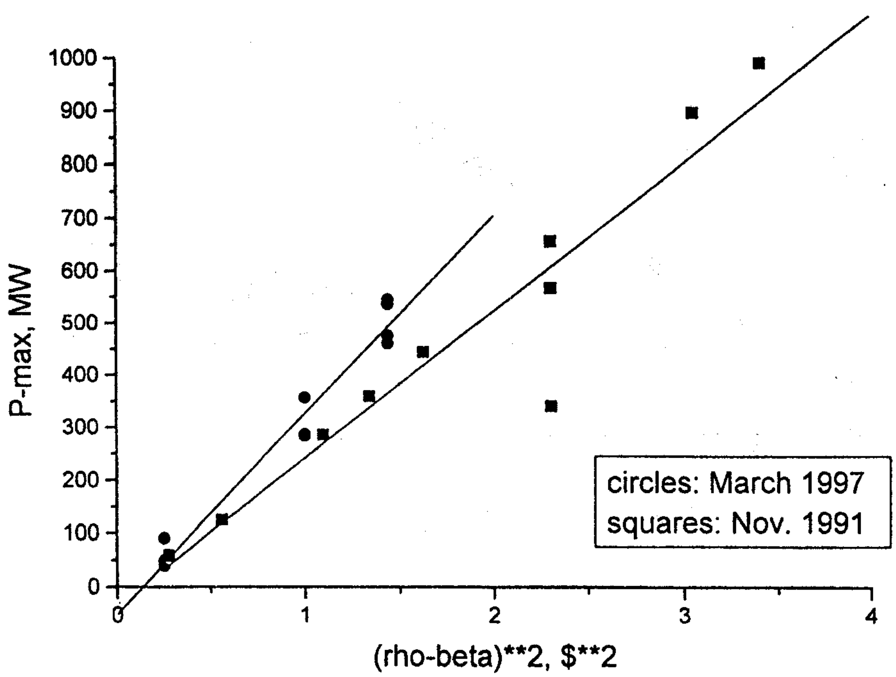

Fig. 4. Maximum pulse power (DASFGR) in dependence of squared prompt reactivity for two sets of pulses

2.3. Effects of burn-up and core modifications

The effects of burn-up and core modifications can not be considered as errors as they do not influence the reproducibility of the results in a closed set of pulses. Rather they should be interpreted as differences due to changes in reactor properties influencing the pulse parameters (e.g. change of effective α_f due to burn-up) and can be predicted.

According to FH approximation the pulse energy E and maximum power P_{max} are inversely proportional to fuel temperature reactivity coefficient α_f and proportional to prompt reactivity ρ_p and its square, respectively:

$$E \propto \frac{\rho_p}{\alpha_f} \quad , \quad P_{max} \propto \frac{\rho_p^2}{l_p \alpha_f} \quad ,$$

where l_p denotes prompt neutron life time. The slopes of $E(\rho_p)$ and $P_{max}(\rho_p{}^2)$ lines presented in Figs. 2 and 4, respectively, may depend on ρ_p, α_f and l_p. However, the ratio of the slopes of the curves, corresponding to two different sets of pulses in the same diagram is approximately equal in case of $E(\rho_p)$ and $P_{max}(\rho_p{}^2)$, meaning that there is the same parameter causing difference in the slopes of E and P_{max}. It is not probable that this is reactivity ρ_p because it appears as linear term in energy formula and as square in the P_{max}. Since all curves in Figs. 2 and 4 are well linear the only possibility remains that the error in ρ_p would be in form of multiplication factor, equal for ρ_p and $\rho_p{}^2$, which could be true only if this factor was 1.

The only remaining parameter appearing in both expressions for E and P_{max} is α_f. It is well known [5] that effective fuel temperature reactivity coefficient depends on several parameters such as enrichment, temperature and burn-up. As it is core averaged it implicitly depends also on core structure: number and type of fuel elements, loading pattern, number of irradiation channels, position of control rods, etc. The same fuel elements and similar core loading pattern were used in all pulse experiments. Implicit effects are for this reason relatively small and difficult to extract from statistical error.

The direct effect of burn-up is much stronger than its implicit consequences. Calculations of α_f show [5] that its absolute value at temperatures above 30°C decreases with burn up. For 100°C it is 7.5pcm/°C at zero burn-up and 4.5pcm/°C at 14% burn-up. The difference grows approximately proportionally with temperature. It can be estimated that 1% of burn-up produces approx. 3% reduction of α_f relative to the value at zero burn-up. E and P_{max} are increased for the same amount due to this effect as they are inversely proportional to α_f. The difference in core burn-up between two sets of pulses presented in Figs. 2 and 4 is approximately 5% (1991 core was fresh) producing approximately 15% total difference in the slopes of the lines fitting the data of the same set. The estimate is in good compliance with the observation.

3. Conclusions

Systematic analysis of pulse experiments shows that there are several effects influencing the accuracy of pulse parameter measurements. In addition to the technical specifications and limitations for pulse mode operation the following principles are to be observed to reduce the inaccuracies and systematic errors and to increase predictability of the pulse experiment:

- transient rod calibration taking into account influence of other control rods
- using of similar core configuration as in the previous set of pulse experiments
- avoiding pulsing from subcritical state
- taking into account fuel burn-up in predictions and in analysis of the results
- taking use of numerically improved results of prompt energy by DASFGR in addition to nvt readings.

Reproducibility of pulse results will also be improved by installing a new transient rod positioning indicator.

References

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