Guidelines for Writing Report

On Reactor Exercise at VR1 Prague

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Abstract

These guidelines are intended for the university students taking part in a training course at the research reactor VR-1 organised jointly by the Czech Technical University in Prague and the Royal Institute of Technology, KTH, in Stockholm. Upon completion of this training course, the students are supposed to submit a scientific report in the framework of the educational course Nuclear Reactor Physics, SH2600, at KTH. The current manual aims at making the process of writing the final report seamless and fast.

Key words: nuclear reactor, training course, scientific report.

Contents

Chapter 1

Introduction

The reactor exercise at VR-1 finalises the educational process in the framework of the Nuclear Reactor Physics course in KTH. It is thus an essential step in successfully passing this course. The present document focuses on what a guiding teacher expects to see in a student's report.

Very generally, the student should demonstrate a firm knowledge of reactor physics grounds and the ability to apply this knowledge in selected areas and for specific tasks. Another learning objective of any Master's programme at KTH is the student's capacity to produce scientific documents in general and scientific reports and papers in particular. Upon passing this course, the student becomes one step closer to his/her final goal in the selected master's programme – writing an MSc thesis. That's why this report gives an excellent opportunity to obtain a preparatory experience in organising the material in a form suitable for a master's thesis.

There are quite many detailed documents introducing the reader to scientific writing [2] . That's why, these guidelines do not give direct instructions about language, style, structure etc. However, the current manual follows general requirements about writing scientific documents especially what regards structure, style, captions etc. Hence it may be used as an example for preparing scientific reports. Because of this, several pictures such as Figure 1, Figure 2 and Figure 3, a table for example Table 1, and equations for instance Eq. (3.1) and (3.2), are given in this document. The section Appendices was included exactly for the same reason. Otherwise, the mentioned above examples may seem unnecessary.

The most general and important guidelines are summarized as follows.

- Any erroneous statement will be treated as an error.
- Any missing relevant compulsory chapter will be treated as an error. See section 2.3 "Reporting Individual Exercise" for the list of compulsory chapters.
- When copying formulas be critical; manuals and textbooks may have typos. When writing or copying formulas, make sure that various terms have correct signs and physical units.
- Be aware that same symbols are often used for completely different quantities or variables, for example, the symbol n typically stands for the neutron density in the reactor physics context, but the same symbol n may be used to denote the neutron detector count rate etc.
- Be critical against your own writing; avoid unclear or curious statements such as, "Neutrons control a reactor".
- When your report is ready for submitting, it is strongly recommended that you read your own manuscript once again taking on the role of a picky reviewer.

Chapter 2

Background

This chapter provides a very brief introduction to the reactor VR-1, it gives also a list of the selected exercises in the framework of the training course. Finally, the chapter describes how to organise the material when reporting on a separate exercise.

2.1 VR-1 Reactor

The VR-1 reactor was specifically designed for training university students, preparing industry experts, for performing Research-and-Development, R&D, work as well as for promotional activities in the nuclear industry. It was commissioned on December 3 in 1990 at the Czech Technical University in Prague.

Figure 1: NRC Chairman Stephen Burns visiting the VR-1.

The VR-1 training reactor is a pool-type, light water reactor based on enriched uranium, at the Czech Technical University in Prague. The neutron moderator is light demineralized water, which is also used as a neutron reflector, as biological shielding, and as a coolant. Heat is removed from the active core by natural convection.

2.2 Training course at VR-1

Training is focused on areas such as reactor physics, neutronics, dosimetry, nuclear safety and Instrumentation and Control, I&C, systems. Teaching blocks focusing on the environmental protection are prepared especially for students of natural science and pedagogy. Depending on the curriculum and orientation of individual faculties, the training is performed in the regular weekly schedule or in the form of batch courses two to five days long. The specific content of the courses is compiled according to the requirements of the teachers from various faculties.

The present reactor exercise assumes visiting and spending two full days at the VR-1 reactor. The reactor administration offers a broad variety of educational activities. The following experiments have been selected for the KTH students in 2019:

1) Reactivity measurement (Source Jerk method and Rod Drop method).

2) Control rod calibration.

3) Critical experiment – approaching critical state (Prediction of the reactor critical state by inverse rate method).

4) Influence of temperature effects on behaviour and operation of nuclear reactor.

5) Reactor behaviour in critical, supercritical, and subcritical state with and without the external neutron source.

2.3 Reporting Individual Exercise

The above six exercises fall into different and relatively independent topics thus turning an individual account on a separate exercise into a scientific mini article. It is hence a good idea to allocate a separate chapter for every exercise/experiment which in turn calls for a certain format such as IMRAD, which is widely accepted in the scientific community:

- **Introduction**; may also be entitled Background, Theoretical Background or simply Theory. Here the author states: objectives (may be educational); theoretical model of the physical phenomena studied including equations; simplifications and assumptions and other relevant material.
- **Methods and Materials** section details how the author has obtained experimental results. It may include a brief description of physical installations, detectors and other relevant instrumentation. A good idea is also to explain why the experiment was performed in this particular way.
- **Results** section provides raw (uninterpreted) data collected as well as processed (interpreted) data. The latter can include fitting, interpolation, extrapolation or any other methods of deriving new scientific information. The data is typically organised in a form of easy-to-read tables, graphs, pictures.

  Discussion section considers whether or not the obtained data (uninterpreted and/or interpreted) meets the objectives declared in the introduction and supports the stated hypotheses. It may also give evaluated uncertainties as well as judge the implications of the findings, potential limitations of the experimental design, etc. A missing chapter for example Discussion will be interpreted as an error.

Chapter 3

Reactivity Perturbation Experiments

The major learning outcome of this exercise is understanding how to measure experimentally the most important reactor parameters such as reactivity, prompt-neutron lifetime and effective delayed neutron fraction. Two reactivity perturbation experiments will be studied in the chapter, namely the rod drop and the source jerk methods. Each experiment relies heavily on the point reactor model. In this simplified formalism, the shape of the neutron flux and density distributions are ignored. The reactor is therefore reduced to a point.

3.1 Theoretical background

Everything in exact sciences begins with definitions and assumptions. It is a good starting point first to formulate the essence of the point kinetics approximation (model) for example as

$$\phi(\mathbf{r},E,t)=\psi(\mathbf{r},E)\cdot T(t). \tag{3.1}$$

In other words, we assume that the neutron flux distribution is separated into a product of the shape function, ψ, and the amplitude function, T.

In order to describe details of the two reactivity experiments declared previously, it is worth to start with the concept of reactivity, for example

$$\rho\equiv\frac{k-1}{k}. \tag{3.2}$$

It goes without saying that various reactivity units must be explained here as well as other related concepts should also be defined in this subsection, for example prompt and delayed neutrons, delayed neutron precursors, two variants of the point kinetics equations, namely with one-delayed neutron group and many (6 or 8) delayed neutron groups. The new recommended 8-group structure is given in Appendix A.

Table 1: Thermal delayed neutron yield and half-life data for ^{235}U, 6 groups

Group	Half-life $T_{1/2}$ [s]	Mean-life time τ [s]	Decay constant λ[s^{-1}]	Ratio β_j/β	Mean energy [MeV]
1	55.72	80.39	0.0124	0.033	0.25
2	22.72	32.78	0.0305	0.219	0.46
3	6.22	8.97	0.111	0.196	0.40
4	2.30	3.32	0.301	0.395	0.45
5	0.610	0.88	1.14	0.115	0.42
6	0.230	0.33	3.01	0.042	–

Any other preparatory theoretical derivations together with probably further assumptions, which will be used in numerical evaluations, should be formulated here. In particular, the formula that will be used in the reactivity measurement must be formulated.

3.2 Rod drop and source jerk experiments

Any relevant and important information clarifying the rod drop and source jerk experiments is welcome here. For instance, it could be as follows:

- Description of the initial reactor state;
- Sequence of the steps done;
- Specification of the control rods involved (position, type, etc.);
- Specification of the detectors and other instrumentation involved;
- Specification of the movements done;
- Specification of the physical variables being measured;
- References to the formulas involved;
- Description of the mathematical methods involved.

It's not a bad idea to display some raw data, for example as in *Figure* 2.

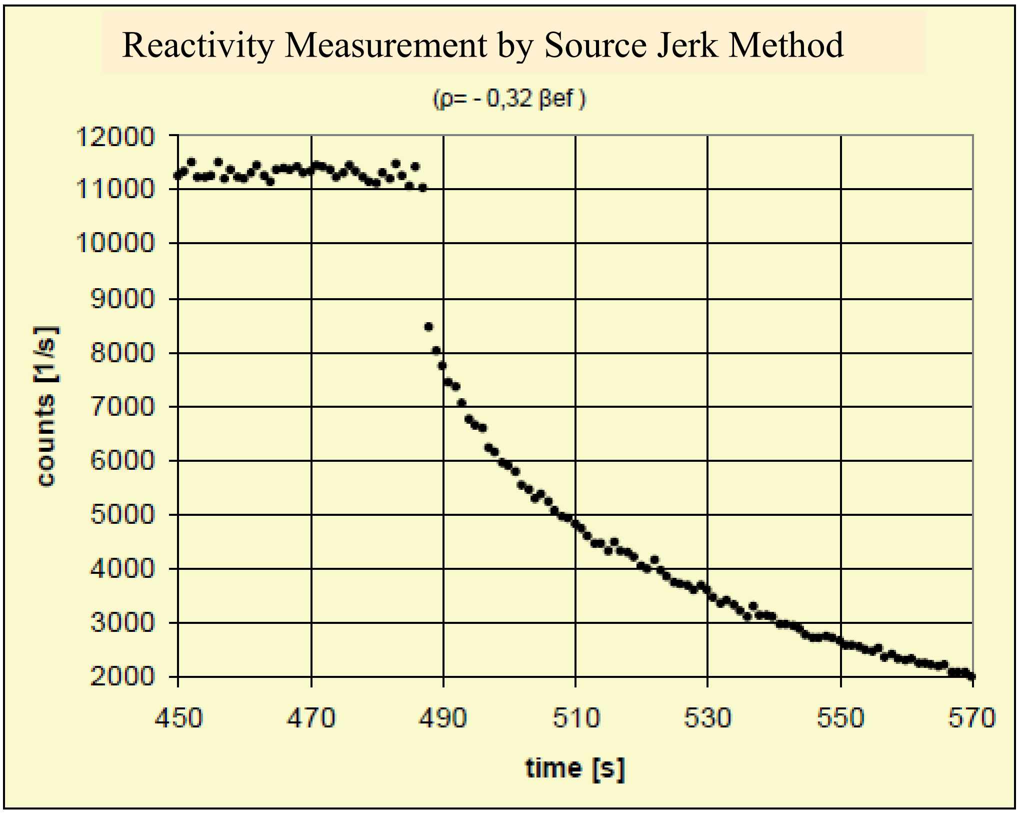

Figure 2: Neutron time rate evolution

3.3 Results and assignments

The following assignments and reactor parameters should be performed:

1) Describe the measurement – (1 assignment);
2) The control rod worth by both methods – (2);
3) Discuss the precision of both methods and analyse possible inaccuracies of both methods, for example background influence – (1);
4) The reactor period corresponding to the insertion of a positive reactivity by the movement of R2 – (1);
5) Determine the reactivity based on the data in Table 6.1 in ref. [1] – (1);

As seen above, the total number of assignments, $N = 6$. The assignments related to the description, discussion, comparison and analysis may be reported in other suitable sections of the present exercise, for example in 3.4 Discussion.

3.4 Discussion

First of all, it is expected here a brief analysis whether or not the declared in the introduction objectives are reached. More in detail, the following questions/tasks may be answered/performed:

- Compare the values from both methods and discuss possible differences between them;
- Discuss the precision of both methods and analyse possible inaccuracies of both methods (background influence);
- Compare the values of the reactor period found by different methods;
- Discuss the precision of the methods used and analyse possible inaccuracies.

Chapter 4

The general structure of the present chapter is similar to that of Chapter 3, i.e. it follows the IMRAD format as described in Section 2.3, Reporting Individual Exercise. This comment is common for the subsequent chapters and thus will not be further mentioned.

Control Rod Calibration

Upon doing this exercise, the students will learn the influence on reactivity when inserting a neutron absorber into the reactor core. More specifically, the following learning outcomes will be achieved:

- Reactivity characteristics of control rods including integral and differential control rod worth.
- Maximum available positive reactivity reserve (excess reactivity).
- Shut-down reactivity.
- Theoretical relation with other quantities of reactor physics.
- Various types of control rods.
- Various methods of control rod calibration.

Calibrating control rods is of vital importance for the safe operation of a nuclear reactor. Every experimental measurement consists of moving a preselected control rod to the next position and reading a neutron detector response

4.1 Introduction

As usual, initial definitions are expected here such as what the reactor control system is, why we need control rods, which materials are suitable for manufacturing control rods. It's not bad idea to give also a classification of control rods.

An important question, to be answered, is how we are going to characterise the effectiveness of control rods (variables, units, curves), and what we expect to obtain having done this experiment. To this end, it worth to define:

- Control rod calibration curve;
- Integral control rod worth;
- Differential control rod worth;
- Mutual control rod calibration.

4.2 Theory

As before, all relevant physical variables should be defined here as well as all theoretical methods, models, assumptions etc. should be explained, in particular the Inverse Rate Method and the Dynamic Determination Method.

4.3 Calibration experiment

The title is self-explanatory i.e. a detailed description of the experiments is expected here together with raw data.

4.4 Results and Assignments

As before any processed data in a form of tables, diagrams and curves are expected here. More specifically, the following assignments and reactor parameters should be performed:

1) Describe the measurements – (1);
2) Calibrate one of the control rods R1 or R2 using the Inverse Rate method – (1);
3) Plot the calibration curves and determine their equations (fit to a polynomial) of the calibration curve – (1 curve + 1 polynomial = 2 assignments);
4) Determine the differential control rod worth for R1 or R2 – (1);
5) Using the results, determine in which part of the core, the control rod has the largest influence on reactivity and explain why – (1).

The number of assignments is totalling to $N = 6$.

4.5 Discussion

Discuss the importance of the obtained results. Determine also in which part of the core the control rad has the largest influence on reactivity and explain why.

Chapter 5

Critical Experiment

The major learning outcome is understanding how to set a subcritical reactor into the critical state. Additionally, students will learn:

- The principle design of a thermal reactor;
- The function of main reactor components;
- Basic design of a digital reactor instrumentation and control system.

Approaching the critical state is an extremely important experiment directly related to safety because every nuclear reactor undergoes this procedure several times during its lifetime. Typically, this critical experiment is performed as a series of measurements. Every measurement consists of moving a preselected control rod to the next position and then measuring a detector response (pulses/s) to an external source. When writing the final report, the students plot the experimental results and extrapolate them to identify the critical configuration (control rod position).

5.1 Introduction

As the title suggests, the student is expected here to explain the meaning of being critical in the nuclear reactor context. It should be explained why and when we put a reactor into a critical state, what potential safety risks of doing so are. Finally, the student concludes on the importance of doing this experiment for all newly commissioned reactors.

5.2 Theory

The student is expected here to define physical variables characterizing a critical state of a nuclear reactor as well as important physical properties that crucially influence such variables. It is good to name possible steps that gradually move a reactor towards a critical state. Supporting formulas and graphs are welcome here.

5.3 Approaching critical state at VR-1

Clearly, a detailed account of the steps undertaken during this critical experiment at VR-1 is needed here together with supporting sketches, graphs etc. Raw data as well as the fitting procedures (if any) should be also describe here.

5.4 Results and Assignments

The results of the fitting, smoothing etc. procedures should be presented here. Any other predicted, evaluated etc. parameters may be also given. In detail the assignments here are as follows:

1) Describe the experiment – (1);
2) Find the critical position of control rod R1 or R2 – (1);
3) Using graphical extrapolation, determine the next position of a control rod R1 or R2 depending on the particular experiment – (1);
4) Compare the critical position from your experiments with the position in the critical reactor – (1);
5) Discuss potential discrepancies between the evaluated and the actual critical positions – (1).

The total number of assignments is thus $N = 5$.

5.5 Discussion

First of all, a brief analysis is expected here, whether or not the objectives, declared in the introduction, are reached. More in detail, the following should be done:

- Find the critical position of control rods R1 and R2;
- Using graphical extrapolation, determine the next position of control rods R1 and R2;
- Compare the critical position evaluated in your experiments with the actual position in the critical reactor;
- Discuss potential discrepancies between the evaluated and actual positions;
- Discuss the importance of safety measures undertaken while approaching the critical state.

Chapter 6

Reactivity Feedback

The major learning outcome is observation and understanding of the time-dependent behaviour of a nuclear reactor in response to either planned change in the reactor conditions or to unplanned and abnormal conditions, which is of utmost importance to the safe and reliable operation of nuclear reactors. More specifically, the students will learn practical determination of the fuel temperature coefficient, FTC, which is of highest significance in the reactor stability. Moreover, it is generally considered even more important than the moderator temperature coefficient, MTC. The fuel temperature coefficient is also called the prompt temperature coefficient, PTC, because it causes an immediate response on changes in fuel temperature.

6.1 Introduction

A general definition of reactor dynamics and its relationship to the reactor control and stability is expected here. It is a good idea to stress in what respect the reactor dynamics differs from the reactor kinetics. It is also relevant to identify the most important physical processes and phenomena that determine long term time behaviour of nuclear reactors.

6.2 Theoretical Outline

It is a good starting point to define first the concept of feedback in general and its role in nuclear reactors in particular as well as how we are going to characterise various kinds of feedback (reactivity coefficients). It is also recommended to identify principal physical phenomena that influence the reactor behaviour through feedback as well as to name the most important reactivity coefficients. State simplified models (four- and six-factor formulas) that allow to give at least qualitative predictions. Explain the involved physical quantities.

6.3 Void and Temperature Reactivity Effect Measurement

Obviously, a detailed account of the steps undertaken during experimental measurements at VR-1 is needed here together with supporting sketches, graphs etc. raw/processed data should be also presented here.

6.4 Results and Assignments

The found void coefficient for various fuel assemblies should be reported here. More specifically the following should be done:

1) Describe the measurement – (1);
2) Measure the negative and positive void coefficients – (2);
3) Plot the negative and positive void coefficients – (1);
4) Discuss the importance of Doppler broadening – (1);
5) Define and discuss the importance of the Moderator-to-Fuel ratio, define the concepts of under moderated and over moderated reactor – (1);
6) Theoretically compare the fuel and moderator temperature coefficients paying attention to how fast the feedback come into effect – (1).

The number of assignments sums up to $N = 7$.

6.5 Discussion

As usual, it is expected here a brief analysis of whether or not the objectives, declared in the introduction, are reached. Discuss also if the observed reactor behaviour meets our expectations.

Chapter 7

Reactor behaviour in critical, supercritical and sub critical state with and without the external neutron source

This chapter is based on students' discussions and observations gained through this training course. Hence it may be written in a free format reflecting the author's preferences. The experience acquired when performing these experiments might be very helpful here especially the experience obtained in the kinetics and dynamics measurements. It is perhaps a good idea to start this chapter classifying the time-dependent behaviour of nuclear reactors by the time scale as:

- Short-term, of order 1 min;
- Medium-term, of order 1 day;
- Long-term, of order 1 year.

Identify when the point reactor kinetics is valid and when we must account for feedback. It goes without saying that all topics stated in the title of this chapter should be reflected in the chapter body. The grading is based on the following:

1) Define and discuss the importance of various concepts of criticality, prompt/delayed-subcritical/critical/supercritical – (1);
2) Describe the reactor behaviour in the critical state with/without external source – (2);
3) Describe the reactor time dependent behaviour in the subcritical state with and without external source – (2);
4) Identify the situations when the nuclear operator sets a reactor on the supercritical state (which one according to the classification in item 1) – (1).

The number of assignments $N = 6$.

References

[1] J. Rataj, Reactor Physics Course at VR-1 Reactor

[2] D. Grishchenko, I. Mickus, Guidelines for Writing a Scientific Report

[3] , I. Mickus, D. Grishchenko, Report Requirements

[4] Rudstam, G. et al. (2002), Delayed Neutron Data for the Major Actinides, Volume 6, NEA/WPEC-6, NEA/OECD

[5] Simmons, B.E. and King, J.S. (1958), A pulsed technique for reactivity determination, Nuclear Science and Engineering, 3, pp. 595-608

[6] Berglöf, C. (2010), On Measurement and Monitoring of Reactivity in Subcritical Reactor Systems, PhD thesis, TRITA-FYS 2010:18, KTH, Stockholm, Sweden

Appendices

Appendix A

New Eight-Group Precursor Structure

Subgroup 6 of the NEA Working Party on International Evaluation Co-operation, NEA/WPEC-6 [4] recommends nowadays a new eight-group precursor structure to improve both the analysis of the in-pile reactivity measurements and the reactor kinetics calculations. The new eight-group structure is characterised by the same set of half-lives for all fissioning isotopes and for fission induced by neutrons of different energies. The recommended isotope-independent and energy-independent half-lives and corresponding mean-lives and decay constants are given in the next [4] .

Table 2: Recommended Halve-lives, 8 groups

	Group:	1	2	3	4	5	6	7	8
Half-life	$T_{1/2}$ [s]:	55.6	24.5	16.3	5.21	2.37	1.04	0.424	0.195
Mean-life time	τ [s]:	80.21	35.35	23.52	7.52	3.42	1.50	0.612	0.281
Decay constant	λ [s^{-1}]:	0.0125	0.0283	0.0425	0.1330	0.2925	0.6665	1.635	3.555

Appendix B

Prompt Decay Constant Fitting Method

In case when delayed neutrons may be neglected, the point reactor kinetic equations read as

$$\frac{dn(t)}{dt} = \alpha n(t).$$

Here, we have defined the prompt neutron decay constant by

$$\alpha \equiv \frac{\rho - \beta}{\Lambda}.$$

By injecting short pulses of source neutrons in a subcritical core, the prompt neutron decay constant may be found [5] . With the knowledge of β and Λ, the reactivity, ρ, and hence the multiplication factor, k, can be found. One source neutron pulse is not sufficient for determining the prompt neutron decay constant α, that's why a pulsed neutron source is needed. Then the reactivity in dollars may be rewritten in a form

$$\rho_{\$} \equiv \frac{\rho}{\beta} = \alpha \frac{\Lambda}{\beta} + 1.$$

that is suitable [6] for an indirect experimental determination of the reactivity measured in dollars, $\rho_{\$}$. The "indirect experimental determination" means here that Λ and β are evaluated through a Monte Carlo computer code.

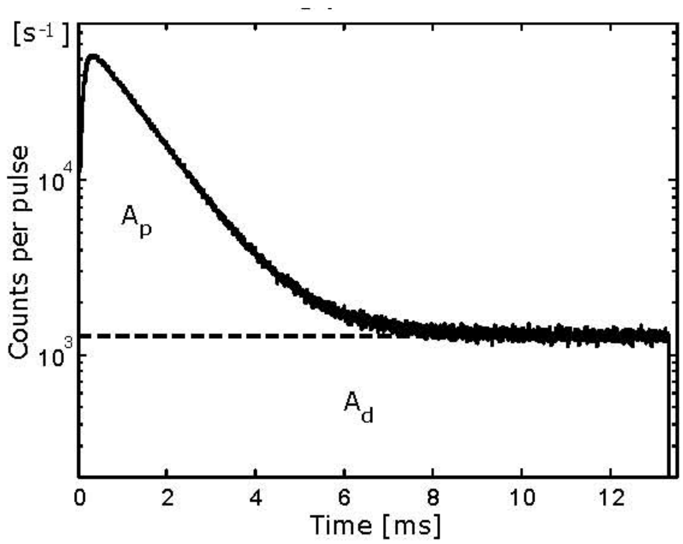

Figure 3: Prompt and delayed neutron Areas