REACTOR OPERATION EXERCISE

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1 Introduction

Objectives of the exercise

This exercise is aimed at making the student familiar with the

- construction,
- operation,
- nuclear and technological measuring systems, and
- control system

of nuclear reactors. A further goal is training the students the most important reactor maneuvers.

Steps to achieve the objectives

In order to achieve the above goals, students will

- Learn how a nuclear reactor is controlled (measuring chains, control rods, etc.).
- Study and perform maneuvers, such as reactor startup, power increase and decrease, automatic and manual operation, shutdown.
- Study the method of inserting or removing reactivity into or from the reactor core by moving the control and safety rods.
- Learn how the safety systems intervene in case an error (either human or electronic) occurs.
- Study the water circulation system, which is separated into primary and secondary parts; when and how these equipment should be operated.
- Obtain information on the systems measuring technological parameters and their role in the safe operation of the reactor.

Preliminary conditions of the exercise

- Students should have sufficient knowledge in reactor physics.
- They should have some general knowledge on the most important major components (core, control, cooling) of a nuclear reactor.

2 Theoretical background – short summary

Definition of terms

Multiplication factor (k)

The multipliction factor is the ratio of the number of neutrons present in the reactor in a neutron generation to that of a previous generation. The two types of multiplication factors are infinite (k_∞) and effective (k_{eff}). k_∞ is defined as

$$k_\infty = \frac{n_h}{n_0}$$

where

n_0 is the number of neutrons entering a given neutron generation in a reactor of infinite size

n_{h} is the number of neutrons proceeding from the same neutron generation to the susequent one, in the same infinite reactor.

The effective multiplication factor is derived from k_∞ by taking into account that a portion of the neutrons escape through the boundaries of the system:

$$k_{eff} = P \cdot k_\infty$$

where

P is the so called escape probability, i.e. the percentage of neutrons which do not escape through the boundaries of the reactor of finite dimensions.

The concept of criticality

A nuclear reactor is critical if self-sustaining nuclear chain reaction is achieved without external neutron sources. In this state k_{eff} is equal to 1. In a similar manner can one define the states subcritical and supercritical:

$k_{\mathrm{eff}} = 1 \Rightarrow$ reactor is critical;

$k_{\mathrm{eff}} < 1 \Rightarrow$ reactor is subcritical;

$k_{\mathrm{eff}} > 1 \Rightarrow$ reactor is supercritical.

Reactivity

The reactivity is the relative deviation of the effective multiplication factor from 1, i.e.:

$$\rho = \frac{k_{eff} - 1}{k_{eff}} \cdot 100 \ (\%)$$

Similarly to the definition of super- and subcriticality one can state that

for $\rho = 0$ the neutron flux is constant with time,

for $\rho > 0$ the neutron flux increases with time,

for $\rho < 0$ the neutron flux decreases with time.

The time dependence of the variation of the neutron flux is determined by the ratio ρ/β_{eff} rather than the percentage value of the reactivity. β_{eff} is the percentage of the contribution of the delayed neutrons to criticality. This is why a reactivity unit is defined as

$$\rho\,[\text{dollars}] = \frac{\rho[\%]}{\beta_{eff}[\%]}$$

This quantity has units of dollars ($). If ρ = 1 $, the reactor is so called prompt critical, i.e. critical even without the delayed neutrons. This state must be avoided since in a prompt critical reactor the reactor period or doubling time (see next paragraph) becomes very short.

Reactor period and doubling time

Reactor period T_p is the time necessary for the neutron flux to grow to e times its original value.

Doubling time T_{2X} is the time necessary for the neutron flux to double its original value.

One can easily show that

$$T_{2X} = \ln 2 \cdot T_p$$

3 Procedures

Summary of the tasks to be performed

Operations prior to startup

- Switch on the control system
- Perform the prescribed tests
- Inspect the reactor core
- Check and put into operation the necessary technological equipment

Nuclear operations

- Startup, run to a given power level
- Manual and automatic operation at a given power level
- Change power
- Shut down the reactor

3.1. Tasks prior to nuclear startup

a) *Switching on the control system*

- The control system named “Logic” is put under voltage by turning on the start key “Mains”.
- The excitation voltage of the supporting magnets of the control rods is turned on by means of the key “Ready”.

b) *Measurement of the drop time of the safety rods.* (Note: it is very important, and therefore a safety requirement that the drop time of the rods should be less than 500 ms.)

c) *Checking and testing of the nuclear measuring chains.*

d) *Inspecting the reactor core and performing manipulations in the reactor vessel*

- Before startup, the reactor core must be visually inspected for irregularities or potential loose parts etc.
- Samples to be irradiated should be inserted into the vertical irradiation channels.
- Tools and equipment needed for the specified research problem/project should be set in.

The last two activities are done corresponding to the reactor operation schedule of the given day.

d) *Checking the technological equipment and putting them into operation, as required by the reactor schedule/program of the given day.*

Concerning the technological equipment, we do not go into detail here. The supervisor of the exercise will show students all the important components in reality. However, three issues are brought up in brief here:

- Cooling of the primary water can be done by operating the primary circuit (using the primary pumps), either alone or in parallel with the secondary loop. The necessity of the cooling is determined by the reactor program, mainly the time and maximum power of the operation. In most cases, if the reactor is operate under about 10 kW and not for a very long time, cooling is usually not turned on.
- The primary water can also be warmed up. This can be done using a heater built into the primary loop. Warming is only necessary if the temperature of the water in the reactor vessel is below 20 °C, or if needed by a specific experiment.
- The primary water can also be purified using built-in ion exchangers. This is only required if the parameters that determine the quality of the water exceed certain limits.

3.2 Nuclear operation of the reactor

a) Starting the reactor and increase power to a specified level

Self-sustaining chain reaction in the reactor is started by moving the neutron absorbing (control and safety) rods, which are incorporated into the reactor core, at a given rate and direction and making use of the startup neutron source. The operator is able to adjust the desired state of operation by moving the control rod(s) by means of the control mechanism according to information obtained from the nuclear channel(s).

Steps of the startup procedure are as follows:

1) The startup neutron source has to be inserted into the core.
2) The safety rods should be pulled out, one after the other
3) The core condition should be checked by means of the nuclear pulse channels.

4) Thereafter the reactor is ready to start, however, in terms of reactor physics, it is still subcritical.

Steps of making the reactor critical:

1) The first operation is to pull the manual control rod to approximately core mid-height.
2) Observing the $T_{1/2}$-instruments of the nuclear pulse channels with adequate pauses after transient jumps, the automatic control rod is pulled out stepwise from the core.
3) During the pulling of the automatic control rod, the reactor goes critical.
4) Pulling out the rods is accompanied by a continuous increase of neutron flux (power). In this state the reactor is slightly supercritical.
5) At a power of about 5 to 10 W, the neutron source should be removed from the reactor core.

In the startup range up to about 50 W, the nuclear pulse channels give information about the status of the reactor. On the other hand, a proper overlapping of the pulse and DC channels ensures that e.g. the channel used to measure the power is also operable from about 1 W.

Steps of achieving the desired power level:

1) Adjustment of the required power increase rate, i.e. the doubling time $T_{1/2}$ by adequately pulling out the automatic control rod; the power increases to the desired level.
2) Nearing the desired power level, the increase rate has to be reduced by slightly pushing back the automatic control rod. Stopping at a specified power is equivalent to a multiplication factor of 1, i.e. reactivity is zero, thus the reactor is in critical condition.

b) "Manual" and "automatic" modes of operation at a given power

At the desired power, the reactor may be operated either "manually" or "automatically".

- Manual operation means that maintenance of the critical condition requires to constantly observe the instruments and repeatedly move one of the control rods up or down at a low rate. In general, however, manual operation of the reactor is restricted to the periods of power increase and power decrease or at a power too low for the automatic control to be effective.
- In automatic operation, the automatic control rod itself moves slightly up and down in order to maintain the prescribed power level. Note: The automatic rod should be around its mid-height position.

Switching from manual to automatic or vice versa can be done by pushing the appropriate button on the control desk. Adequate operation of the automatic power control can be tested by slightly moving the manual control rod up and down. If the automatic mechanism is efficient, it will compensate for the changes due to the motion of the manual rod.

c) Changing of the power

Power modification is possible either in automatic or in manual operation modes. In general, only slight changes are performed in the automatic operation mode (e.g, from 1 to 1.2 kW).

In most cases, power is increased in manual mode. In this case, if previously the reactor was operated automatically, automatic power control has to be switched off by pressing the "Manual" button.

Thereafter any control rod may be pulled up to make the reactor supercritical. However, in most cases the automatic rod is used for this maneuver. These operations must be done in accordance with the limits and conditions required by the technical specifications of operation.

Power reduction may also be done either in automatic or in manual mode of operation. Here, however, rods are lowered to introduce negative reactivity into the core, thus moving the reactor from critical to subcritical condition; the power decreases.

General remark: it is important that the nuclear measuring devices should always work in the appropriate range, continuously providing the operator with all the necessary information on the state of the reactor.

d) Shutting down the reactor

Shutting down the operating reactor is performed by pushing the safety and control rods into the core. Shutting down may be "slow", in which case all four rods get into the reactor core by their servomotors. In this case the electromagnets supporting the rods do not release them, so as soon as all the rods are in, they may immediately be pulled out, hence the reactor may be immediately started.

Immediate or safety shutdown comes about either

- if an error occurs e.g. in the control system, electronics, etc. or there is a loss of electricity;
- the operator wants to increase power too quickly, i.e. at a rate which is prohibited by the safety systems, or the power exceeds a certain upper limit.

In both of these cases, the supporting electromagnets release the rods to drop in the reactor core. The safety rods fall freely since they move in air-filled tubes. The fall is even accelerated by springs.

- upon deliberate voltage cutting in the supporting electromagnets by pressing the safety button named "BV", causing them to release the rods that fall into the reactor core, immediately shutting down the reactor.

After rods have dropped, the final shutting down is made by

- removing the key "Ready" from the control desk, cutting thereby the circuit of the supporting magnets;
- turning and removing the "Mains" switch in order to turn off the "Logic".

If primary or secondary equipment were in use during the operation, these should also be switched off.

During the exercise, the operations will be discussed with the supervisor. In course of the operations, each maneuver will be explained by the operator.

4. Questions for revision

1) Define the following terms:
    - Multiplication factor
    - Reactivity
    - Doubling time
    - Critical reactor
    - Prompt supercriticality
2) List the steps that one must perform before the nuclear startup of the reactor.
3) What are the most important steps during startup?
4) What happens if the operator (or student) wants to increase power too quickly?
5) Can the power be increased in “Automatic” mode of operation?
6) In which part of the reactor are electromagnets used?
7) How can the reactor be shut down?