NEUTRON FLUX MEASUREMENT UTILIZING CAMPBELL TECHNIQUE

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ABSTRACT

Application of the Campbell technique for the neutron flux measurement is described in the contribution. This technique utilizes the AC component (noise) of a neutron chamber signal rather than a usually used DC component. The Campbell theorem, originally discovered to describe noise behaviour of valves, explains that the root mean square of the AC component of the chamber signal is proportional to the neutron flux (reactor power). The quadratic dependence of the reactor power on the root mean square value usually permits to accomplish the whole current power range of the neutron flux measurement by only one channel. Further advantage of the Campbell technique is that large pulses of the response to neutrons are favoured over small pulses of the response to gamma rays in the ratio of their mean square charge transfer and thus, the Campbell technique provides an excellent gamma rays discrimination in the current operational range of a neutron chamber. The neutron flux measurement channel using state of the art components was designed and put into operation. Its linearity, accuracy, dynamic range, time response and gamma discrimination were tested on the VR-1 nuclear reactor in Prague, and behaviour under high neutron flux (accident conditions) was tested on the TRIGA nuclear reactor in Vienna.

1 INTRODUCTION

The Department of Nuclear Reactors, Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague operates the nuclear reactor VR-1 [1]. This reactor with maximum power about 5kW is used mainly for educational purposes. The reactor is equipped with a neutron flux measurement system based on the uncompensated wide range fission chambers RJ1300 (from Poland); the system operates either in pulse range for low reactor power or in two DC current ranges (more and less sensitive) for high reactor power. This measuring system covers the whole reactor power range (in the order of $10^{10}$) with a safety reserve, but it is necessary to set accurately the transitions between pulse and more sensitive current ranges and between more sensitive and less sensitive current ranges. Furthermore, the neutron chambers are also sensitive to gamma rays. The influence of gamma rays in the pulse range is suppressed by discrimination. In conventional DC current ranges, it
is not possible to remove the influence of gamma rays on the neutron flux measurement. After
the reactor is operated with high power for a longer period, and then the power is decreased to
a lower value, while the power measurement remains still in the current range, then the
gamma rays substantially deteriorate the accuracy of the measurement.

In order to reduce the number of current ranges for the neutron flux measurement and to
improve the gamma discrimination in the current range of the uncompensated neutron
chamber, it was decided to investigate the Campbell technique, to design a neutron flux
measurement channel based on this technique and to test its properties.

2 THEORETICAL BASICS OF CAMPBELL TECHNIQUE

The Campbell technique for the neutron flux measurement is based upon Campbell’s
theorems [2,3,4,5]. The first theorem states that the mean value of the current from a source of
random current pulses is directly proportional to the average pulse rate and the mean charge
per pulse if all pulses have the same circuit’s response to a single pulse of a unit charge:

$$\overline{I(t)} = \int_{t=0}^{\infty} h(t) \, dt \sum_{i=0}^{m} \overline{n_i} \cdot \overline{q_i}$$  \hspace{1cm} (1)

where $\overline{n_i}$ is directly proportional to the average pulse rate, $\overline{q_i}$ the mean charge per pulse and
$h(t)$ the circuit’s response to a single pulse of a unit charge.

The second theorem describes that the variance of the current from the source of
random current pulses is proportional to the average pulse rate and the mean square charge
per pulse:

$$\overline{I(t)^2} - \overline{I(t)}^2 = \int_{t=0}^{\infty} h(t)^2 \, dt \sum_{i=0}^{m} \overline{n_i} \cdot \overline{q_i^2}$$  \hspace{1cm} (2)

where $\overline{n_i}$ is the average pulse rate and $\overline{q_i^2}$ the mean square charge per pulse.

At high pulse rates no individual pulses can be detected due to the overlapping of the
pulses. The result is a fluctuating chamber current. If the chamber is used in the DC regime,
then the mean value of the fluctuating current is given by the equation (1). Since the
Campbell technique utilizes only the AC component of the current, then the mean value of the
current may be considered zero. For one type of radiation (e.g. neutrons) current pulses with
only one value of average charge is considered. In this case the equation (2) becomes:

$$\overline{I(t)^2} = \overline{n} \cdot \overline{q^2} \int_{t=0}^{\infty} h(t)^2 \, dt$$  \hspace{1cm} (3)

where $\overline{n}$ is the average pulse rate and $\overline{q}$ the average charge.

The mean square (ms) or the square of the root mean square (rms) value of the AC
current is proportional to the average pulse rate and thus also to the neutron flux. The
necessary dynamic range of the rms evaluation is only the square root of the neutron flux
(power) range; e.g. for the power range $10^6$ the rms range is only $10^3$. 

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The mean square value of the current is also proportional to the square of a charge per pulse. This means that larger pulses produce a greater contribution to the mean square value of the current than smaller ones. This fact provides the opportunity for discrimination between large neutron and small gamma pulses of the neutron chamber. The discrimination ratio \( D \) is defined as the ratio of neutron sensitivity \( S_n \) to gamma sensitivity \( S_\gamma \):

\[
D = \frac{S_n}{S_\gamma} \quad (4)
\]

For the system operating in the DC mode, the discrimination ratio \( D_{DC} \) is:

\[
D_{DC} = \frac{S_{n,DC}}{S_{\gamma,DC}} = \frac{\bar{n}_n \cdot q_n}{\bar{n}_\gamma \cdot q_\gamma} \quad (5)
\]

where \( S_{n,DC} \) is the DC neutron sensitivity, \( S_{\gamma,DC} \) the DC gamma sensitivity, \( \bar{n}_n \) the average neutron pulse rate, \( \bar{q}_n \) the average charge per neutron pulse, \( \bar{n}_\gamma \) the average gamma pulse rate, \( \bar{q}_\gamma \) the average charge per gamma pulse.

For the mean square (Campbell) system, the gamma discrimination ratio can be expressed:

\[
D_{ms} = \frac{S_{n,ms}}{S_{\gamma,ms}} = \frac{\bar{n}_n \cdot \bar{q}_n^2}{\bar{n}_\gamma \cdot \bar{q}_\gamma^2} \quad (6)
\]

where \( S_{n,ms} \) is the mean square neutron sensitivity, \( S_{\gamma,ms} \) the mean square gamma sensitivity, \( \bar{n}_n \) the average neutron pulse rate, \( \bar{q}_n^2 \) the mean squared charge per neutron pulse, where \( \bar{n}_\gamma \) the average gamma pulse rate, \( \bar{q}_\gamma^2 \) is the mean squared charge per gamma pulse.

As the mean squared charge is approximately equal to the square of the average charge, the improvement of gamma discrimination is:

\[
\frac{\bar{n}_n \cdot \bar{q}_n^2}{\bar{n}_\gamma \cdot \bar{q}_\gamma^2} \approx \frac{\bar{n}_n \cdot \bar{q}_n^2}{\bar{n}_\gamma \cdot \bar{q}_\gamma^2} = \frac{\bar{q}_n}{\bar{q}_\gamma} \approx 1000 \quad (7)
\]

The ratio \( \bar{q}_n / \bar{q}_\gamma \) is about 1000, and thus the improvement of the mean square (Campbell) system gamma discrimination is expected in the order of \( 10^3 \).
3 DESIGN OF THE NEUTRON FLUX MEASUREMENT CHANNEL WITH CAMPBELL TECHNIQUE

The requirements for the future neutron flux measurement channel were derived from experience with contemporary neutron flux measurement system of the VR-1 nuclear reactor. The VR-1 neutron flux measurement system consists of the RJ1300 uncompensated fission chamber which is connected to one pulse channel and two DC current channels. The pulse channel measures the neutron flux in the power range from zero to 0.5 W (on the VR-1 reactor, 0.5 W corresponds to the neutron chamber response rate of approximately $5 \times 10^4$ pulses/sec.), the more sensitive current channel from 0.5 W to 500 W, and the less sensitive current channel from 500 W to 5 kW. The intention was to substitute the two current channels with only one Campbell channel with improved gamma discrimination compared to the DC current channels. The required power range of the intended Campbell channel for accurate measurement was set from 0.5 W to 10 kW, the indication during accident conditions to at least 50 kW. The measured power during accident conditions (above 10 kW power) have to be greater than power safety limit 7.5 kW.

![Block diagram of neutron flux measurement channel](image)

**Figure 1** Block diagram of neutron flux measurement channel

First experiments with the Campbell technique were conducted with modified amplifier of the contemporary pulse channel and a digital oscilloscope with the rms AC voltage measurement [6]. The quadratic dependence of the neutron flux on the rms value was checked. The results of these experiments were very satisfactory and encouraged the author to investigate deeper the Campbell technique and to design a neutron flux measurement channel using the Campbell technique for the current range measurement. It was decided to develop our own electronic circuits using state of the art components. The block diagram of the neutron flux measurement channel is shown in Fig. 1.

The neutron flux measurement channel consists of two parts. One part operates in the pulse range of the chamber (lower part of the figure), the other in the current range utilizing the Campbell technique (upper part of the figure). The high voltage power supply provides 500 V DC for the neutron chamber. A voltage corresponding to the current flowing through the resistor R is coupled to the voltage amplifier by the capacitor C. The resistance was selected to get a reasonable voltage loss on the resistor R during the maximal DC current through the chamber. A preamplifier with very low noise and high bandwidth amplifies the...
AC part of the chamber signal. A relay on the input of the preamplifier permits usage of test signals for checking of the measurement channel. The high voltage power supply, resistor R, capacitor C and preamplifier are common for the pulse and Campbell subsystems. The output of the preamplifier is divided into both the pulse range and the current Campbell range. The pulse system consists of amplifier and comparator for gamma discrimination.

The following part of the contribution deals only with the Campbell subsystem. The amplifier has frequency characteristics from 5 kHz to 200 kHz according to the recommendation in [5]. Different frequency ranges were also tried, but the best results were achieved with the above-mentioned range. Experiments with a current amplifier were also carried out, but its noise signal was higher than the voltage amplifier noise signal in the described arrangement.

The next stage of the Campbell subsystem is the rms unit. The rms unit measures the root mean square value of the AC input signal from the amplifier, and its output is the appropriate DC voltage. The rms unit contains the integrated circuit for analogue rms calculation AD638, which possesses excellent parameters – noise, accuracy, dynamic range. The properties of the rms unit were checked and the results were fully satisfactory.

The last part of the Campbell subsystem contains a voltage/frequency (U/f) converter that converts the DC rms voltage to frequency. The reason for using the U/f converter is the fact that the control and safety system of the VR-1 nuclear reactor has inputs for frequency measurement of input values. The U/f converter with maximum frequency up to 500 kHz uses the integrated circuit AD654. The linearity of the U/f converter in the expected dynamic range was successfully tested.

The final appearance of the realised neutron flux measurement channel described above is shown on the figure 2.
4 NEUTRON FLUX MEASUREMENT CHANNEL TESTS

The developed neutron flux measurement channel was carefully tested. The first series of tests was carried out to check the dynamic range, linearity and accuracy of the measurement. The measured data from the Campbell channel were compared with data acquired from the neutron flux measurement channel of the reactimeter at the VR-1 reactor which, for the neutron flux measurement, is equipped and set identically as the control and safety system of the nuclear reactor VR-1. The reactor during the measurement was ‘fresh’ to avoid gamma influence on the DC current measurement. The frequency from the Campbell channel output was measured by a universal counter, which was connected by the IEEE488 bus to a personal computer. The RS232 serial output from the neutron flux measurement channel of the reactimeter was read by a personal computer equipped with a serial terminal program, and the received data were stored to a file. The evaluation of the experiments was carried out by the MS Excel software. The test result is shown in Fig. 3. The deviation of the neutron flux (power) measurement was less than ±3% in the whole-expected power range (0.5 W to 5 kW). The Campbell channel threshold for power measurement due to DC offset, electronic noise, influence of alpha particles, etc. is about 0.01 W (corresponds to $10^3$ pulses/sec. on the VR-1 reactor), and reasonable accurate measurement from 0.05 W ($5.10^3$ pulses/sec.- accuracy about 5%).

![Figure 3](image)

**Figure 3** Linearity of neutron flux (power) measurement on VR-1

The following tests were concentrated on the gamma discrimination. Because of the impossibility to measure direct gamma background, the following experiment for the gamma discrimination test was prepared. The reactor was operated near the maximum power for a longer period to get a higher gamma background, and then the power was quickly reduced either by control rod movement or the reactor scram. The neutron flux was measured by the DC current, pulse and Campbell channels, and the three values from these channels were compared. The experimental results after the reactor scram are shown in Fig. 4. The reactor was operated for about 30 minutes at the power of 5 kW to get considerable gamma background. Then was the reactor scrammed. The DC current channel gives up to 100 times greater power value than the pulse and Campbell channels due to the influence of the gamma background. The gamma discrimination of the Campbell and pulse channels is very similar. The deviation at the end of the diagram is caused by the noise in the Campbell channel (noise...
comparable with $0.01 \, \text{W})$. The experimental results confirm the excellent gamma discrimination of the Campbell channel.

![Gamma discrimination measurement on VR-1](image1)

**Figure 4** Gamma discrimination measurement on VR-1

The time response of the Campbell channel was also investigated. The input of the Campbell channel was driven by the noise signal from an arbitrary waveform generator, and the rms DC voltage signal was measured by a digital oscilloscope. The amplitude of the input noise signal was magnified 10 times (power increase 100 times due to square dependence), and time response was measured. The delay of the Campbell channel response was approximately 0.1 second, which is fully satisfactory.

![Behaviour while high neutron flux on TRIGA](image2)

**Figure 5** Behaviour while high neutron flux on TRIGA

Behaviour of the Campbell channel during an extremely high neutron flux (simulation of accident conditions) was checked on the TRIGA reactor in Atomic Institute Vienna. The TRIGA reactor maximum power is 250 kW. The fission chamber RJ1300 was situated on the TRIGA reactor in such a position that the same dependence of the reactor power on the neutron chamber response was achieved as on the VR-1 reactor. The experimental results are represented in Fig. 5. The power measurement is linear approximately to 20 kW, then the
deviation of the measurement is increasing, but there is no decrease in power, which is important for the reactor safety. The measurement above 20 kW is inaccurate, but the measured values are substantially beyond the safety power limit (7.5 kW) of the VR-1 reactor.

5 CONCLUSION

During the activities described in this paper, a neutron flux measurement channel utilizing Campbell technique based on the root mean square evaluation of the AC current component from a wide range fission chamber was designed and put into operation. The properties of the channel – linearity, accuracy, time response, dynamic range and behaviour during high neutron flux in simulated accident conditions were carefully checked, and the acquired test results were in accordance with expectations and set requirements. Also, the gamma discrimination of the Campbell channel was evaluated as fully satisfactory. This Campbell channel is now ready for neutron flux measurement in experiments carried out on the VR-1 reactor. The neutron flux measurement utilizing the Campbell technique is also prepared for students as an experimental task during practical training on the nuclear reactor. Further activities will concentrate on the solution of automatic testing before the reactor start-up and the licensing of the channel for future utilization in the control and safety system of the VR-1 nuclear reactor.

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7 REFERENCES