MULTI-PULSE OPERATION OF IGRIK REACTOR

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Presented are research results of operation of pulse homogeneous solution research complex IGRIK [1] in the multi-pulse mode with a sequential input of reactivity. Factors effecting on the parameters of the realized pulses in the multi-pulse mode are determined experimentally. Physical features of the IGRIK reactor operation in the multi-pulse mode are shown, and potentialities to realize several variants of generation of a sequential pulse string are shown.

Studied are the dependences of the obtained characteristics of fission pulses in the given mode on the initial conditions and methods of pulse realization.

Introduction

The IGRIK pulsed reactor was put into operation in 1976. It has a core in the form of uranyl-sulfate solution in light water [1, 2]. The solution is delivered to the core body with the use of a dosing pump.

The IGRIK reactor operates in three main operating modes: static, quasi-pulse and pulse.

The pulse mode is realized through the fission of uranium nuclei by instantaneous neutrons with simultaneous ejecting four pulse rods (PR) from the core. The total reactivity margin of PR equals 6 $\beta_{\text{eff}}$. To realize the required energy-release the initial level of the core fuel solution is changed. The energy-release per pulse constitutes 5\(\times\)60 MJ, with the pulse width varying between 20 and 2.4 ms.

The quasi-pulse mode is a modified pulse mode, wherein the pulse is formed owing to the delayed neutrons. The value of input reactivity ranges within 0.5\(\times\)1.2 $\beta_{\text{eff}}$ above the delayed neutrons critical state. In this case the pulse width varies from several tens of seconds to 0.02 s.

In the static mode, the reactor can operate at the power of up to 30 kW for an unrestricted length of time. The set power level is achieved by pouring the required amount of fuel solution into the core body. The decreased power level is compensated by adding the fuel solution from the storage balloon.

Reactor is mostly used to produce single fission pulses. Each following impulse is generated usually after several hours after the previous. However, for some nuclear-physical experiments it is necessary series of sequential fission pulses, divided by a small period of time.

The present paper considers variants of the consequent one-by-one ejection of all four PR to obtain four or more fission pulses. With this pulse realization it is possible to obtain both common pulses and quasi-pulses.

Therefore, of primary importance for this operation mode are factors that influence on the system reactivity and, finally, on the pulse generation. To these factors can be referred the following items:

- The “start” state of the reactor (the initial subcriticality of the system)
- The fuel solution state (initial pressure in the core body, the solution temperature, as well as the level of gas saturation of solution before the pulse).
- The time interval between fission pulses.
- Energy-release realized in the previous pulses of this series.

Taking into account the influence of the above factors, as well as the ranges of their variations and limitations imposed by them, it is possible to use the multi-pulse mode of the IGRIK operation more fully.

1 Features of the multi-pulse mode. Possibility for obtaining a pulse series.

In the production of several pulses, the PR weight (except for the first) is reduced from pulse to pulse due to changes in configuration and composition of the core.
Generation of pulses with energy release ~10 MJ is accompanied with the heating up of the solution (the static temperature coefficient of reactivity quenching constitutes about $0.03\beta_{eff}/^\circ C$). The reactor after the pulse falls in the state below the delayed criticality even when the dispersed fuel returns to the initial geometry. The inertial pressure in solution is not high, so that gas-vapor bubbles are present in the solution and along with its temperature broadening define core dispersion dynamics and reactor self-quenching [3].

It may be considered that the realization of the 1st pulse is followed by generation of radiolytic gas bubbles, and heating-up and dispersion of fuel solution. In about 1s the fuel turns back to the initial geometry by action of gravity, and the system reactivity grows. Moreover, the radiolytic gas bubbles partly leave the solution, the maximum temperature of the solution falls and the system returns to the state close to the delayed neutrons critical state (low critical state - LCS).

Effectiveness of the PR, ejected after the first pulse is sufficient to compensate change of reactivity caused by the fuel heating and leading reactor in the state of prompt criticality without adding additional volume of solution into the vessel.

Therefore, there is a possibility to generate the subsequent fission pulses after a space of time sufficient to mix up the fuel and to return it to the initial critical geometry. By this instant of time the core has a sufficiently powerful internal neutron source, and so the rate of reactivity input during generation of the subsequent fission pulses should be sufficiently high. The rate of reactivity input by one pulse rod of the IGRIK reactor equals approximately $15\beta_{eff}/s$.

2 Registration of pulse parameters

The uniform-scaled registration of pulses was performed with a record-keeping system that allows for all necessary measurements in preparation to the pulse, as well as registration, mathematical treatment of the shape of every pulse, and output of an operative record. For detectors we used neutron chambers of KNK-15 and KNT-54 types working in the current mode.

Additionally the start state of the reactor (subcritical multiplying system reactivity) was determined by the transient analysis method with “discharging” the neutron source.

3 Measuring results

When refining the mode of generation of a series of sequential pulses, their parameters were determined for various start states of the system, various rods used to input the excess reactivity, and various time intervals between “shots” of PR from the core.

For each sequential pulse, the energy release realized, half-height width, runaway period, and reactivity were determined. The reactivity for the 2nd and following pulses were calculated based on the runaway period without considering the change in neutron lifetime in the heated core.

3.1 Measurement of the interval between the 1st and the 2nd inputs of reactivity

As the previous studies have shown, it is impossible to realize the 2nd pulse on the IGRIK reactor within $0 \div 0.7$ s after the 1st pulse [2, 4]. Ejection of one PR from the core after 0.7s will result in realization of a quasi-pulse. However, the parameters of this pulse will vary greatly depending on the time interval after the 1st pulse. The further growth of the interval between the 1st and the 2nd ejections of PR results in the increase in energy-release of the 2nd (the comparison was made for the two reactivities $1.5\beta_{eff}/s$ and $1.3\beta_{eff}/s$ input in 1st pulse). The 1st pulse was realized by a shot of the 1st PR on command “0” of a program device (time commands unit – TCU), the 2nd pulse was realized by ejection of one more PR in the 1.8-3.7s time interval. The shapes of first two pulses are presented in Fig.1, and the results of measurement of their parameters – in Table 1, where $\theta$ – width, $\tau$ – runaway period, $\rho$ - reactivity, $Q$ – energy release.
Fig. 1 The 1\textsuperscript{st} and the 2\textsuperscript{nd} pulses depending on the time of the repeated reactivity input

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<tr>
<td>1 pulse 2 p-se</td>
<td>12.2</td>
<td>438</td>
<td>35</td>
<td>39</td>
<td>10.2</td>
<td>330</td>
<td>36.5</td>
<td>30</td>
<td>34</td>
<td>31</td>
</tr>
<tr>
<td>2 pulse 2 p-se</td>
<td>7.1</td>
<td>12.4</td>
<td>10.6</td>
<td>8.6</td>
<td>6.32</td>
<td>11</td>
<td>11.2</td>
<td>8.4</td>
<td>9.9</td>
<td>7.6</td>
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<td>P, $\beta_{\text{eff}}$</td>
<td>1.51</td>
<td>1.29</td>
<td>1.34</td>
<td>1.4</td>
<td>1.57</td>
<td>1.31</td>
<td>1.3</td>
<td>1.4</td>
<td>1.36</td>
<td>1.47</td>
</tr>
<tr>
<td>Q, MJ</td>
<td>9.0</td>
<td>6.6</td>
<td>9.37</td>
<td>3.69</td>
<td>9.2</td>
<td>7.0</td>
<td>7.6</td>
<td>5</td>
<td>6.72</td>
<td>5.25</td>
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With a larger excess of reactivity introduced initially (pulses 2013 and 2007), the system after the 1\textsuperscript{st} pulse is transferred to the deeply subcritical state, and the repeated input of reactivity results in realization of the 2\textsuperscript{nd} pulse with a lower energy-release, although the value of introduced reactivity in the 1\textsuperscript{st} pulse (№ 2039) and the 2\textsuperscript{nd} (№ № 2013 and 2007) was the same and equals $1.5\beta_{\text{eff}}$.

The decrease of energy output and increasing of the 2\textsuperscript{nd} pulse width is explained with the fact, that by the moment of this pulse generation there is a sufficiently “strong” neutron source and PR effectiveness is not realized completely because of low reactivity introduction speed.

Moreover, the value of the reactivity quenching coefficient in the 2\textsuperscript{nd} pulse depends on the pressure of radiolytic gas over the mirror of fuel solution, saturation of fuel with radiolytic gas, and fuel temperature after the 1\textsuperscript{st} pulse. The parameters of the 2\textsuperscript{nd} pulse obtained depend on the level of completion of all transient processes in the core after the 1\textsuperscript{st} pulse, i.e. on the time interval between the pulses.
3.2 Change in reactivity introduced in the 1\textsuperscript{st} pulse

When refining the mode of generation of sequential pulses, their parameters were determined subject to the input of various values of excess reactivity 1.07\(\beta\text{eff}/\text{s}\) to 1.51\(\beta\text{eff}/\text{s}\) introduced in the 1\textsuperscript{st} pulse.

The time dependence of the reactor power when the reactivity is introduced by the 1\textsuperscript{st} PR in several centers above the high critical state (HCS) may be traced on the example of realization of a series of pulses №№ 2023, 2029, and 2037. The 3\textsuperscript{rd} pulse is the maximum by amplitude and energy-release in all cases wherein the reactivity is introduced in several cents above the prompt criticality.

As the inputted reactivity in the 1\textsuperscript{st} pulse rises, the amplitude of the 2\textsuperscript{nd} pulse growths and the amplitude of the 3\textsuperscript{rd} pulse falls. So it is possible to obtain three pulses with approximately identical amplitudes. This is seen on the example of realization of the series of pulses №№ 2039 and 2041 (see. Table 2 and Fig. 3). The growth of the energy-release realized in the 1\textsuperscript{st} and the 2\textsuperscript{nd} pulses results in a gradual increase in fuel solution temperature and its saturation with radiolytic gas. This, in turn, leads to the increase of effective feedback and the decrease in amplitude of the 3\textsuperscript{rd} pulse.

![Fig. 2 Realization of several variants of sequential pulse generation](image-url)
Table 2 Parameters of sequential pulses depending on the reactivity input in the 1\textsuperscript{st} pulse

<table>
<thead>
<tr>
<th>Parameter</th>
<th>( #2023 )</th>
<th>( #2029 )</th>
<th>( #2037 )</th>
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<tbody>
<tr>
<td>( \theta, \text{ms} )</td>
<td>145 26 21 22</td>
<td>139 25 8.5 22</td>
<td>70 26 19.5 46.5</td>
</tr>
<tr>
<td>( \tau, \text{ms} )</td>
<td>41.3 11.1 6.8 22.4</td>
<td>35 12.4 5 32</td>
<td>17 7.4 7.6 41.7</td>
</tr>
<tr>
<td>( \rho, \beta_{\text{eff}} )</td>
<td>1.07 1.32 1.52 1.16 1.1 1.28 1.7 1.1 1.21 1.49 1.47 1.07</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( Q, \text{MJ} )</td>
<td>6 1.3 8 2.5 5.9 1.3 8.8 5 4.7 2.6 4.5 6</td>
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</table>

*numbers in the table correspond to pulses realized by inputting the recurrent PR*

3.3 Consecutive pulses, carried out by PR ejection during power overshoot.

After each sequential pulse (beginning from the 2\textsuperscript{nd} pulse) a power overshoot is observed, which is to say that the system returns to the critical state. In pulses \( \#2036 \) and \( \#2043 \) (fig/2) four almost identical pulses, caused by alternate ejection of PR, and power overshoot after them were obtained.

In this case the interval between the pulse and the power overshoot decreases with increase in pulse number. This means that after the pulse the system with the heated core quickly returns to the critical state. The heating of fuel solution results in the increase in volume of the core and increase of a flat layer over the experimental channel, and consequently, in the increase in reactivity in the given geometry. Thickness of this layer before the 1\textsuperscript{st} reactivity input is about 5cm.

A power overshoot after the 1\textsuperscript{st} pulse was not observed. The attempt to reveal it led to the increase of the interval between the 1\textsuperscript{st} and the 2\textsuperscript{nd} reactivity inputs in pulses \( \#2044 \) and \( \#2045 \) (Fig.2). The result was also negative, which is to say that the system with three injected PRs (after generation of the 1\textsuperscript{st} pulse) can not approach to the prompt neutron critical state.

Then an attempt was made to simulate a series of sequential pulses realized by the PR injection only. In start 2045, the reactivity was input in the moment of the power overshoot after the recurrent pulse. As a result the series obtained includes tree approximately identical pulses and a high 4\textsuperscript{th} pulse. Then a series of pulses was observed, which amplitudes decrease with time. Furthermore, the reactor turned to the static mode of operation and was transferred to the subcritical state by PR injection.

If all PRs are injected after the latest pulse, there are no further power overshoots and four sequential pulses will be obtained. Every of the pulses are conditioned by input of reactivity by the pulse rod. The time interval between the 1\textsuperscript{st} and the 2\textsuperscript{nd} reactivity inputs may be varied from 2 to 4 s (may be more, but it should be additionally studied). Between the further reactivity inputs the intervals are fixed. This mode can be used for the tasks, which require similar time between pulses or time intervals between pulses is not regulated.

3.4 Variation of parameters of sequential pulses

The next stage of the work included studies of the reactor operation in the multi-pulse mode with the constant reactivity input in the 1\textsuperscript{st} pulse and change in the sequence of ejection of PRs from the core.

Initially, an attempt was made to prove the possibility of repeatability of the sequential pulse string. For this purpose we realized starts \( \#2039 \) and \( \#2040 \). The time dependence of the detector
signal (which is proportional to the reactor power) at the same start state $\rho_{st}=-0.26\beta_{eff}$ and the same pulse realization are presented in Fig. 4. Pulses obtained are equal both by energy-release and by amplitude. The only distinction was in the shape of the power overshoot after the 3rd reactivity input (surges for 5 s).

In pulse №2041, the 2nd pulse was realized at the same start state of the reactor as in pulses №№ 2039, 2040, but with an alternative method of realizing pulses (the reactivity input happened with the same time intervals as in pulses № 2039 and 2040, but the sequence of PR ejection in pulse №2041 was replaced). Another time dependence of the reactor power was obtained. This demonstrates the different efficiency of PRs depending on the relative positions (see Table 3, Fig.3). In this case the efficiency of the 2nd PR rose, and the 2nd pulse occurred to be 40 % greater by energy-release than the 2nd pulse in start №2040.

It should be mentioned, that after the peak of the second pulse a power overshoot is observed: pulse №2046, (Fig.1), pulses №№ 2039, 2040 (Fig.3) (for quasi-pulses it is observed at the rear front of the second pulse №2007 (Fig.1) №2037 (Fig.2)). Increasing the interval between 1st and 2nd pulses №2043 (Fig.1) and at the different method of pulse realisation (another order of PR ejection) №2041 (Fig.3) such power overshoot is not observed.

The overshoot at the trailing edge of the 2nd pulse (see Fig. 2) might not be explained by the low rate of reactivity input. But it is developed in 150 ms after the 2nd reactivity input, when the PR has being already fully ejected from the core. These distinctions may be explained either by different efficiency of the 2nd and the 3rd PRs or by difference states of the system after ejection of two pulse rods in different variants (adjacent or axi-symmetrically located PRs).

![Fig.3 Recurrence of the consequent pulse series](image)

<table>
<thead>
<tr>
<th>Table 3 Parameters of sequential pulses</th>
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<tr>
<td>№2039</td>
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<td>1 pul</td>
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<td>$\theta$, ms</td>
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<td>$\rho$, $\beta_{eff}$</td>
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<td>$Q$, MJ</td>
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CONCLUSIONS

The conducted research work has resulted in experimental data that give an estimate of the processes taking place in the reactor core during realization of the mule-pulse mode. These data made possible to determine potentialities for the IGRIK reactor to operate in this mode, the range of changes in pulse parameters, as well as to reveal restrictions applied by the physical processes and design philosophy of the installation.

The sequential ejection of four PRs from the core results in generation of a series of pulses and quasi-pulses. The parameters of pulses, beginning from the 2nd, depend only on the parameters of the 1st pulse and time interval between reactivity outputs, which can be governed when turning the reactor to the start point.

The parameters of the 2nd pulse were determined depending on the time interval between the 1st and repeated inputs of reactivity. As the 1st pulse with the required parameters is realized, the system returns to the state close to the critical state with outcome to a certain power level ("tail" after the 1st pulse). The value of the "tail" is determined by the time of injection of PR into the core. Thus, in 3.7 s after the 1st fission pulse, the energy-release in the "tail" equals ~36% of the energy-release in the 1st pulse. Within 3.7 s a transition over HCS was not observed.

Ejection of one more PR from the core within up to 1.8 s after realization of the 1st fission pulse will result in realization of a quasi-pulse. However, the parameters of this pulse will vary greatly depending on the input reactivity in the 1st pulse and on the time of realization of the 2nd fission pulse.

In the process of refinement of the multi-pulse mode, the dependence of the parameters of the series of sequential pulses on different values of input reactivity was studied, making possible to realize the series of sequential pulse with required parameters.

At the IGRIK reactor a series of four sequential fission pulses with approximately equal parameters was obtained. Within the interval 1÷5 s after the 1st reactivity input it is possible to realize three more pulses by ejecting sequentially the three PR from the core within a definite time interval.

A method was obtained for putting the IGRIK reactor to the start state. The method based on measurements with a record-keeping system allows the system subcriticity to be determined with an accuracy of part of a “cent”. The parameters of sequential pulses are reproducible with the use of the same PR traffic control program. The total input reactivity does not exceed the permitted value $\bar{\beta}_{\text{eff}}$.

Thus, the problem of obtaining the recurrence in the series of sequential pulses is solved, providing for the stable operation of the IGRIK reactor in multi-pulse mode.

REFERENCES