UNCERTAINTIES IN THE ANALYSIS OF WATER INGRESS ACCIDENT FOR THE HTGR CORES

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Abstract

Behaviour of the reactor major physical characteristics during the accident related to the water/steam ingress into the core, resulted from the steam generator (SG) loss of integrity has been analysed on the example of the VGM reactor with the pebble bed core designed in the USSR. The header tube instantaneous double-ended rupture without interaction of the outgoing flows has been considered due to the uncertainties of its failure process. Calculation of water quantity discharged into the core has been made under the following assumptions:

1). Accumulation of water in liquid state in the core is eliminated inasmuch as the fuel elements and helium temperature exceed water boiling temperature at a pressure of about 5 MPa;

2). Chemical interaction of water with graphite is not taken into account;

3). Moisture sensors fail to be actuated.

The calculation results of the water mass variations in the core vs. time, as well as reactivity changes caused by water ingress into the core have been given in the paper.

The need to take into account reactivity changes caused by the front edge of the steam/helium mixture, that defines the neutron power increase rate has been shown in the paper.

Changes of the reactivity compensation members' efficiency at a steam/water ingress into the core and reflector both in hot and cooled down reactor have been evaluated.

The paper carries requirements for experimental investigations intended to prove the adequacy of the reactivity compensation members' efficiency in the accident under consideration.

Introduction

The spectral characteristics of HTGR cores with low-enriched uranium (LEU) fuel and graphite moderator provide the prevailing action of neutron slowing down effects at the steam-helium mixture ingress during the steam generator depressurization resulted in a potential reactivity increase.

The availability of rather thick graphite reflectors, where the neutron spectrum is more soft than in the core provides restriction of reactivity increase.

In this connection the calculation of reactor reactivity at water ingress should be made by the aid of computer codes which adequately treat both the variation of the neutron energy during their slowing down, and the thermalization processes. It is also evident, that estimation of the reactivity variation calculation error in this accident is possible using only the results of correctly conducted physical experiment.

To obtain the representative results of the physical experiments, the detailed information not only about a potential amount of water ingress and about the dynamics of its penetration that determines the reactor power dynamics, is required.

The paper aims to study uncertainties in water ingress inventory, in reactivity increase value, which made of the accident designing conditions, and also in results of VGM reactor dynamic calculation.

1. Modelling of water ingress accident

In the accident analysis it is assumed, that the instantaneous rupture of the steam generator header is occurred.

The calculation of water ingress into the core is made under the following assumptions:

1. accumulation of water in liquid state in the core is avoided, inasmuch as the core and helium temperature is higher than the water boiling temperature;

2. chemical interaction of water with graphite is not taken into account;
During the steam generator depressurization, the increase of water inventory in the core is recurred in cycles. The core and reflector filling with moisture, transported by the circulating helium front edge, is proportional to the time of steam-helium mixture penetration through the core and water and steam flowrates flowing out of the steam generator.

The steam mass increase at the second and successive edges is occurred within the time required for the steam-helium mixture to pass through the primary circuit, taking into account variation of water and steam flowrates leaving the steam generator, as well as the steam-helium mixture variations in the path due to the circulator isolation.

Following the coolant direction, the steam-water mixture first enters the side reflector and then passes to the top reflector and reactor core. Depending on the accident modelling scenario different water inventory enters the reactor. If it is assumed, that the moisture sensors are actuated, then the circulator would be isolated and water mass in the core would change according to dependence 1 shown in fig.1 (design basis accident scenario). The maximum moisture inventory in the core in this case would be ~80 kg. Such moisture inventory would be accumulated at the circulator coastdown and failure to close of return valve. At the scheduled circulator isolation and the return valve actuation ~10 kg of water enters the core.

In this case the moisture sensors are not actuated and the circulator is not isolated, the water mass would be accumulated according to dependence 2 shown in fig.1 (beyond design basis scenario). The maximum credible water inventory in the core in this case would be, if all free volume is filled with steam. The steam mass in this case would depend on the steam density, that in its turn, would depend on the average temperature of the pebble bed. At the average temperature of fuel elements about 600°C the maximum water inventory in the core would be about 400 kg. During the circulator operation at nominal speed water inventory initially entered the core within ~1 s would be ~9 kg.

Fig.1 Water inventory changes in the core

1. circulator coast-down
2. running circulator
2. Reactivity changes at water ingress into the core

To estimate reactivity changes during water passing through the core the WIMS-24 program has been used, by the aid of which one-dimensional reactor analysis was performed, taking into account changes of the reflector features and those of the core along its height, regardless of the actual fuel and moderator arrangement.

The reactivity changes vs time have been normalized to the absolute reactivity value, obtained from the calculations of reactor filled with a specified water inventory. The reactor calculations were made by the aid of two-dimension computer complexes NEKTAR-VIANKA /2,3/ and GAVROSH /4/ taking into account heterogeneous fuel and moderator arrangement in the fuel elements, that have been experimentally tested on the physical facility GROG /5/ on models of the pebble bed core.

Fig. 2 shows reactivity changes vs time at the front edge of the steam-helium mixture and during subsequent water penetration into the reactor core.

Initially the reactivity is proportional to water inventory entered the core. The maximum reactivity increase in the hot reactor at the ingress of ~80 kg of water is about 0.4% Δk. Calculations by the V.S.O.P. program indicate, that reactivity increase for such water inventory is ~0.6% Δk. In case of 400 kg steam ingress into the core, the reactivity increase is ~2% Δk and ~2.4% Δk according to the operational data /6/.

So, uncertainties of reactivity changes calculations obtained by the aid of different programs are in the range of 20-30%.

The calculation analysis revealed, that at water ingress into the side reflector reactivity is changed insignificantly. The reactivity compensation rods efficiency in the side reflector is also changed negligibly.

At water ingress into the core, due to reduction of neutrons leakage in direction of the side reflector, efficiency of the reactivity compensation rods is decreased (at a ~400 kg water ingress it is decreased by > 10%).

![Fig. 2 Reactivity changes during the accident with water ingress](image)

1. isolated circulator
2. running circulator
3. steady reactivity increase
3. Power and temperature changes during the accident with water ingress into the core

To analyse the power and temperature dynamics a simplified reactor model has been used, in which the core was divided into 10 sections and presented as 3-zone cylindric channel with fuel in the central part, surrounded by moderator and gas.

The power balance equations of the model are the following:

\[
\frac{d(mc)_j}{dt} = JF_F(T_j-T_f) - \frac{1}{\kappa_F} (T_j - T_f) \\
\frac{d(mc)_j}{dt} = \kappa_F m_c(T_j - T_f) - \kappa_F(T_j - T_f) \\
\frac{d(T_j)}{dt} = -\frac{W}{A_f}(T_j-T_f) + \frac{k_Fa_f}{A_f} (T_j - T_f)
\]

where, \( W \) - coolant flow velocity, \( F \) - heat transfer coefficient, \( F \) - perimeter, \( A_f \) - cross-section, \( j \) - specific gravity, \( A_f, P_f \) - surface area, \( A_f \) - section length, \( C \) - heat capacity.

6 groups of delayed neutrons are treated in the kinetics equation:

\[
\frac{dN_i}{dt} = \frac{1}{2} (x_i - \beta_{th}) \frac{N_i}{N(t)} + \sum_{i=1}^{6} \lambda_i C_i \\
\frac{dC_i}{dt} = \frac{1}{2} (x_i - \beta_{th}) \frac{N_i}{N(t)} - \lambda_i C_i \\
\]

Total reactivity comprises temperature effects of fuel (\( \beta_f \)) and moderator reactivity (\( \beta_m \)) with the worths, corresponding to reactor with the average temperature:

\[
\beta = \frac{1}{2} \frac{1}{\xi} \sum_{i=1}^{6} \beta_i C_i \frac{N_i}{N(t)} + \beta_m \frac{N_i}{N(t)} + \beta_f \frac{N_i}{N(t)}
\]

It was assumed, that the relative space power distribution \( N/A(t) \) during the accident, did not change.

Fig. 3 shows the reactor power distribution at water ingress into the core and changes of the fuel and coolant maximum temperatures.

As is evident from fig.3, reactor power is changed substantially depending on the dynamics of water accumulation in the core. At the circulator isolation (curve 1) the reactor becomes subcritical due to the temperature feedbacks, and in case of the circulator operation at nominal speed during 300 s the reactor goes...
over to a new power level (curve 2). It is also clear to what extent it is necessary to take into account reactivity changes at the front edge of the steam-helium mixture entering the reactor.

Supposing that the reactivity is increased steadily in accordance with the water inventory in the core (fig.2 curve 3), then the reactor power would reach the setting of the emergency protection actuation \( (1.2 N_m) \) within \( ~80 \) s, instead of \( ~30-40 \) s, obtained from the dynamics analysis taking into account the actual cyclic reactivity changes. The difference in fuel temperature provided by this time delay is about 100°.

Conclusion

Results of the analysis revealed, that depending on conditions of the accident with the steam generator depressurization, the water inventory in the core could vary between 10 and 80 kg in the design basis scenario and could reach \( ~400 \) kg in the beyond design basis scenario.

Changes of the positive reactivity increase corresponding to those scenarios is \( (0.05 - 0.41) \% \) and \( ~2\% \) accordingly.

Substantial reactivity changes occurred during the accident and significant discrepancies in results of its analysis made by the aid of different computer codes \( (20 - 30 \%) \), required verification of physical models used in the analysis of the reactor multiplication factor with the different water inventory, including the maximum one, in the core and side reflectors.

The latter circumstance necessitated conduct of experiments on the critical assemblies simulating reactor conditions, aimed to substantiate the sufficiency of the reactivity compensation members arranged in the side reflector.

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