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Investigation of isentropic compression and equations of state of fissionable materials

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Abstract. **In 1957, to enable the experimental study of fissionable materials at pressures of tens and hundreds of atmospheres, a new approach, which came to be known as the "Nonexplosive Chain Reaction" method, was suggested at VNIIEF. Based on compressibility data obtained with the NCR and shock wave methods, the equations of states of plutonium and uranium at record high pressures and densities were constructed.**

In recent years, the term 'hydronuclear experiments' has been used at the Geneva negotiations on the comprehensive ban of nuclear tests and in publications in the open press. This term was introduced by the American side and describes the possibility of using nuclear charges with a small yield (less than four pounds of TNT (trinitrotoluene) equivalent) in shock experiments.

A similar method invented and used at the Russian Federal Nuclear Centre – VNIIEF is named the 'method of nonexplosive chain reactions (NCR). This paper reports on the origin of this technique and investigations performed in the early years of the Soviet nuclear program by application of the method.

The key problem in the 1950s was equations of state of fissionable materials. Chemical explosives compressing spherical structures produced a high energy density at the system centre. States of materials under pressures of tens of millions of atmospheres generated in the active zone (in fissionable material) had not yet been investigated and belonged to a fundamentally new field of science.

In calculations of compressed states, the system of equations describing the hydrodynamics of compressed materials should be solved, and one of its components is the equation of state, which establishes the relation among density, pressure, and internal energy. Sufficiently accurate data as required for constructing equations of state of fissionable materials could be derived only from experimental measurements.

Experimental research on the properties of plutonium and uranium using shock compression was begun by L V Al'tshuler, K K Krupnikov, and S B Kormer in 1949 – 1954 and continued in the departments under their direction. This research yielded information about their Hugoniots and shapes of the low-compression portions of their isentropes.

The topical issue, however, was the investigation of isentropic or nearly isentropic compression of these materials under maximum pressures in the active zone. It was obvious that the best and straightforward method for these experiments would be compression of a spherical structure. But how could information about compression in the active zone at the centre of an exploded charge be derived?

The technique for measuring the compression of fissionable materials was suggested at VNIIEF in 1957 by the authors of this note and named, following Yu B Khariton's recommendation, the method of nonexplosive chain reactions (NCR). The underlying idea of the technique was to conduct explosive experiments with charges containing fissionable materials, but without a notable yield of nuclear energy. It turned out that such experiments made possible conducting the most accurate and complete measurements concerning the equations of state of fissionable materials. In NCR experiments, the hydrodynamic stage of nuclear charge compression is studied in a certain range of the active zone mass in which the released nuclear energy is so small that it has little effect on the processes of compression and expansion of the active zone.

The rate of neutron multiplication and, hence, the integral number of fissions in an explosive experiment is directly related to the maximum compression of the active zone. The numerical parameters relating the number of neutrons due to fissions detected in the experiment and the maximum density are derived from hydrodynamic and neutron-flow calculations of tested structures.

Thus, an NCR experiment is designated to study compression of an active zone by the energy released from a chemical explosive, whereas information about the resulting compression is derived from the number of detected neutrons generated in the active zone.

The first NCR experiments (March 1958) on investigation of the uranium isentropic compression confirmed the feasibility of the new technique. In 1960 – 1963 extensive experimental and theoretical research was carried out. The main results of this research were measurements of the isentropic compressibilities of uranium and plutonium under the highest record pressures.

The equations of state of fissionable materials constructed in 1964 described all the available measurements obtained in both Hugoniot studies and NCR experiments with active zone compression.

By setting out the principal features and application prospects of the NCR technique, one of the authors (Ya B Zel'dovich) dreamed of establishing a priority of Russian

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science. The solution of such a complex problem as the construction of the equations of states for fissionable materials in the ranges of high pressures and densities was the result of all-out team-work by a host of scientists and engineers working in different fields.

Besides the authors of the method, the physicists A B Sel'verov, B L Glushak, A A Gubkin and A K Shanenko took part in the feasibility studies of NCR experiments, interpretation of measurements, and formulation of equations of states of plutonium and uranium, and the theorist E S Pavlovskiĭ in calculations of neutron flows.

New techniques of physical measurements were developed and parameters of chain reactions in NCR experiments were recorded by the group of physicists V M Gorbachev, E K Bonyushkin et al. under the direction by Yu S Zamyatnin and A I Veretennikov, heads of departments.

The selection of the forms of the equations of state was based on the work by S B Kormer, who suggested an equation of state including electronic components and variable specific heat of the lattice.

Theoretical work by D A Kirzhnits and N N Kalitkin in Moscow provided the basis for a physically coherent description of experimental data on the isentropic compressibility of fissionable materials in wide ranges of pressure and density.

A lot of hydrodynamic parameters of various tested charge structures and neutron flows in them were calculated by mathematicians I A Adamskaya, A I Sokolova, I F Sharova, and in the first years of the research by A K Semendyaev and A V Zabrodin, research officers at the Institute of Applied Mathematics.

The first test-site experiments were directed by E A Negin, chief designer, and I F Turchin, head of department. The laboratory experiments with explosives were performed at the department directed by L M Timonin.

The painstaking efforts made in constructing the equations of state of fissionable materials, which was of paramount importance for designers of nuclear charges, have proven to be worthwhile, thanks to constant support by the management of VNIIEF, especially B G Muzrukov, director of the nuclear centre, Yu B Khariton, scientific director, E A Negin, chief designer, and D A Fishman, first deputy of chief designer.