KURCHATOV INSTITUTE'S CRITICAL ASSEMBLIES

A.YU. GAGARINSKIY
NRC "Kurchatov Institute"
Kurchatov square, 123182 Moscow, Russia

Since its establishment, the Kurchatov Institute of Atomic Energy (now National Research Centre "Kurchatov Institute") was always involved in R&D on nuclear reactors for various applications. This activity required dedicated critical facilities (whose number, design and purpose naturally varied with time).
This paper reviews the status of the Kurchatov Institute's experimental park that includes more than ten critical assemblies intended for R&D on power (VVER, RBMK, HTGR), ship and space reactors.

1. Introduction

Even the very first critical experiments Igor Kurchatov has performed in 1946 in the institute that now bears his name have confirmed unique advantages offered by so-called "zero power" reactors, or critical assemblies [1], that were widely used in experiments ever since. Thanks to their experiment-friendly range of kinetic response to varying critical conditions, as well as to their largely power-invariant neutronic parameters, critical assemblies enable realistic simulation of in-core neutronic processes.

In 1953, the Kurchatov Institute has launched its first critical assembly simulating a power reactor core to identify water-cooled and -moderated reactor parameters, such as critical mass, efficiency of control rods and temperature effects [2].

Since then, the Kurchatov Institute has performed thousands of experiments with uranium systems moderated by water, hydrogen-containing substances (zirconium hydride, polyethylene and their combinations), beryllium and graphite, with wide-ranging U-235 enrichments (to 96%) and moderator-to-uranium nuclear concentrations' ratios (Fig. 1) [3, 4].

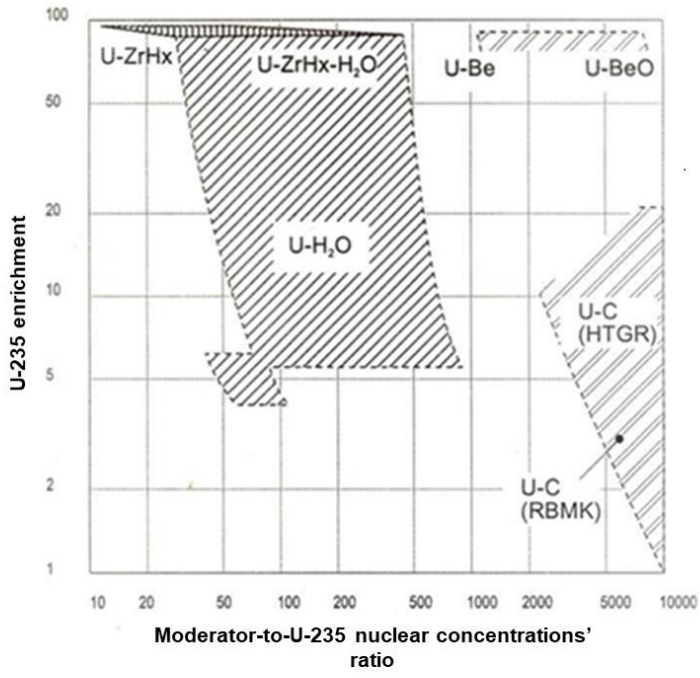

Fig. 1. ^{235}U enrichment and moderator-to-^{235}U uranium nuclear concentrations' ratio in critical experiments performed in the Kurchatov Institute

Experiments simulating future reactor core as accurately as possible to assess the key reactor parameters with minimal error had a long-lasting significance. As time went on, other research centres and even some plants and design organizations have joined the Kurchatov Institute in performing critical experiments, since these often were nothing else than fabrication quality tests and designer customization of actual cores. Such experiments yielded a major share of total criticality data; however, they often cannot be used for software improvement even at the state of the art.

On the other hand, experiments with critical assemblies having simple geometry, well-described composition and hence relatively low measuring errors (mostly due to uncertain knowledge of these very geometry and composition) yielded the “gold data pool” that enabled – and still contributes to – further development and improvement of computational software.

2. Benchmark experiments and international databases

Selection of reference – or benchmark – experiments performed on simple critical systems was launched in the 1960ies in order to ultimately produce a database to underlay reactor software verification (that proceeded from limited data arrays for many years).

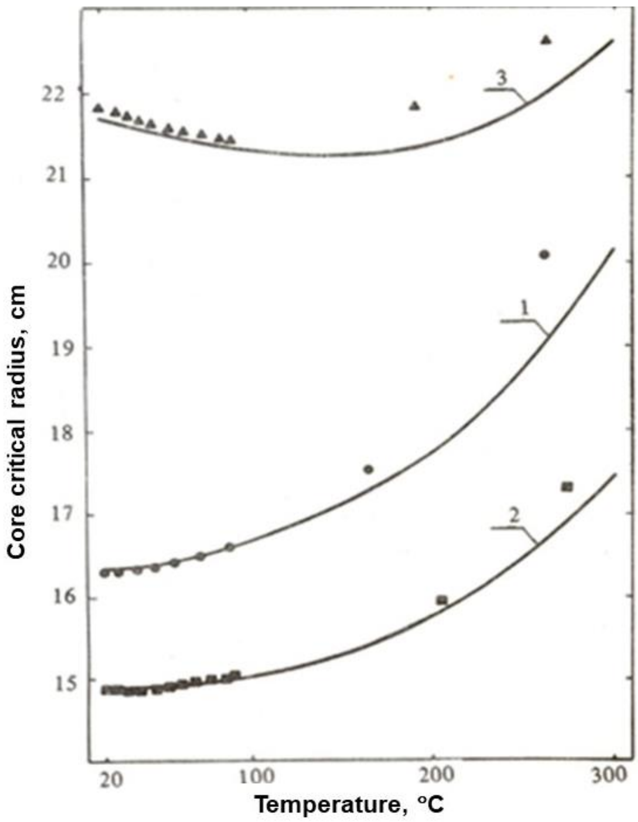

Fig. 2. Critical radius of hexagonal fuel rod bundles depending on temperature:
1 – • – $\rho_H/\rho_5 = 49$; 2 – ■ – 331; 3 – ▲ – 614 (points = experiment; lines = computation)

For example, measurements of critical parameters of uniform U-water bundles consisting of U dioxide rods performed at temperatures ranging between 20 and 280°C can illustrate this class of experiments. These measurements – suggested by the author and performed by the research team he headed in the Kurchatov Institute in late 1970ies [5] – were unique in the world practice, as it turned out later. In these experiments, high excess reactivity that varied with the critical assembly heatup in a pressure vessel was compensated by the central core section moving relative to a fixed circle of rods. Critical size of “unexcited” uniform lattices were identified by aligning the moving core section with the fixed one; i.e. in fact the temperature when “correct-geometry” cores became exactly critical was actually measured. Fig. 2 shows respective data for hexagonal lattices consisting of rods enriched to 10% of U-235 at three different ratios of hydrogen and U-235.

In 1992, the U.S. Department of Energy has initiated – and Idaho National Laboratory has suggested and implemented – a new data selection approach called Criticality Safety Benchmark Evaluation Project (CSBEP) [6, 7], whose main idea was to collect all available – and meeting some specific requirements – experimental criticality data, convert them into some standard format and organize their evaluation by independent experts. In 1995, this initiative has developed into the International Criticality Safety Benchmark Evaluation Project (ICSBEP) performed under the auspices of the Organization for Economic Cooperation and Development in order to preserve the hard-won data of the 20th century’s “nuclear legacy” (including military experimental data that were declassified at that time) and to prevent their irretrievable loss with the demise of their authors.

The rate of data contribution to the ICSBEP database was at its highest in late 1990-ies – early 2000ies, and naturally died out by 2010, when archive data fit for the project came to the end. By 2014, this database included data on over 5000 configurations of critical (and even some subcritical) systems provided by 20 countries including Russia, which joined the project in 1994 and became its second largest (after the United States) contributor providing over 15% of its total data (this share is much higher if we consider uranium systems only).

At the same time, the imperative need to preserve all reactor physics experimental data including measuring methods and techniques became increasingly obvious. Therefore, in 1999 the Nuclear Science Committee of the OECD Nuclear Energy Agency (NSC/NEA/OECD) has launched its International Reactor Physics Experiment Evaluation Project (IRPhEP) [7], as a logical follow-up and extension of the ICSBEP. In 2003, the IRPhEP became NEA’s official project aiming to compile a pre-evaluated reactor physics benchmark dataset to be used for next-generation reactor design and safety evaluation. As by 2014, the IRPhEP database included the data yielded by 136 experiments performed on 48 critical assemblies in 20 countries (including Russia and the Kurchatov Institute) [8].

3. Neutronic experiments and critical assemblies of the Kurchatov Institute

Most of Russian critical experiments of relatively simple geometry and composition were performed between 1960ies and early 1980ies by just four nuclear research centres to develop various reactors and other facilities required at the time. The IPPE has mostly focused on U and Pu fast neutron systems (and, to smaller extent, on liquid-salt and uranium-water ones), while VNIIEF and VNIITF, starting from late 1990ies, have published the data of a large series of critical experiments that involved quasi-homogeneous assemblies of simple geometry with highly enriched metallic U and Pu-239. The Kurchatov Institute, as mentioned above, has performed experiments with uranium systems moderated by water, hydrogen-containing substances (zirconium hydride, polyethylene and their combinations), beryllium and graphite.

Below follows a brief overview of Kurchatov Institute’s critical experiments from their “golden age” to the present day, including the evolution of relevant experimental base, whose current status is shown in Table 1 [9].

Assembly name	Assembly type	Thermal power, kW	Physical startup year	Remark
SF-1	U – H_2O	0.1	1961	Modernized in 1996
Efir-2M	U – H_2O	0.1	1973	Long-term shutdown

SF-7	U – H_2O	0.1	1975	Modernized with life extension to 2029
Maket	U – D_2O	0.1	1977	Reconstructed in 1983
Grog	U – C	0.1	1980	Long-term shutdown
Astra	U – C	0.1	1981	Modernization with electric heatup planned
RBMK	U – C	0.02	1982	
Narcisse-M2	U – ZrH_x	0.01	1983	Permanent shutdown
PIK (phys.model)	U – H_2O	0.1	1983	
Delta	U – H_2O	0.1	1985	Modernized with life extension to 2029
V-1000	U – H_2O	0.2	1986	Life extended to 2029
P	U – H_2O	0.2	1987	Modernized with life extension to 2029
Kvant	U – H_2O	1.0	1990	
SK-phys	U – H_2O	0.6	1997	
RP-50 (Aksamit)	U – H_2O – ZrH_x	0.1	2013	

Table 1. Kurchatov Institute's critical assemblies as of 2017

NPP reactors

NPP reactor research developed along several lines. Critical experiments with water-moderated assemblies to validate VVER reactor physics have started in 1950ies from several assemblies allowing for full-scale study of VVER-440 and VVER-1000 reactor cores.

An important achievement regarding VVER lattices were high-precision experiments performed under scientific guidance and supervision of the Kurchatov Institute in Hungary and Czechoslovakia on ZR-6 and LR-0 critical assemblies, respectively. It should be noted that ZR-6 experiments have set a pattern for many experimental groups, since they have included a detailed study of how the uncertainties associated with core geometry, composition, etc., impact on neutronic parameters [10].

Today the Kurchatov Institute has three critical assemblies (P, SK-phys and V-1000) tailored to solve the tasks of evolutionary development of VVERs, including their very latest generation, so-called SUPER-VVER. The list of experiments already performed or planned on these assemblies includes:

- spectral shift simulation;
- identification of neutronic parameters of systems containing various fuels (U-Gd, U-Er; recovered U, ceramic- or steel-clad “tolerant” fuel, etc.);
- effect of higher steam content on multiplication properties of the core (for larger VVERs);
- identification of neutronic parameters of systems with square lattices (TVS-K fuel for PWRs).

Multiple critical experiments were also performed with U-graphite assemblies allowing for varied fuel content (metallic U or uranium dioxide), U-235 enrichment (from natural level to 2.4%), lattice pitch and water content in channels – including the experiments with less graphite per cell and erbium burnable poison. The RBMK assembly continues to provide scientific support to operating RBMK reactors (that generate a half of the country's total electricity) to further improve their safety and economy (tests of new scram rods and profiled assemblies, subcriticality tests, etc.). Testing at the Kurchatov Institute's RBMK assembly is a mandatory prerequisite for any component to be loaded into the core of operating RBMK-1000.

High-temperature gas-cooled reactors

Since early 1980ies, the Kurchatov Institute operates its Grog and Astra critical assemblies intended for simulation of high-temperature gas-cooled reactors (HTGRs) and other uranium-graphite reactors of varied core geometry, structure and composition, with spherical and cylindrical fuel elements enriched up to 21% of U-235.

In particular, multiple experiments were initially performed at the Astra to validate some safety parameters of Russian HTGR designs (VG-400, VGM and others). Later, international projects such as GT-MHR (Russia and USA) and RBMR (South Africa) used the Astra for high-precision experiments with circular cores.

Astra's plans for the next few years (so-called Hot Astra Project) are as follows:

- equipment modification and experiments with electric heatup;
- compilation of a new database to validate multi-physical approaches to future reactor designs.

Ship and space reactors

However, most systems explored in the Kurchatov Institute belong to small nuclear facilities intended for various applications [11]. Respective critical assemblies were moderated by water, zirconium hydride or beryllium, consisted of different fuel rods enriched from 5 to 96% of U-235, and had hydrogen-to-U-235 concentration ratios and temperatures ranging from 25 to 1000 and from 20 to 300°C, respectively. For the very first time, the Kurchatov Institute has published its criticality data related to hydrogen- and beryllium-moderated assemblies of simple geometry at the 3rd Geneva Conference on Peaceful Uses of Atomic Energy. Subsequent publications were somewhat sporadic. Nevertheless, many of these experiments had simple geometry and well-described fuel composition, and were therefore included in the benchmark database.

As regards ship reactor experiments, starting from the early 1960ies, the Kurchatov Institute has deployed eight universal critical assemblies, including a high-temperature one (with working coolant temperature of 300°C and pressure of up to 200 kg/cm^2) and a high-flux one (with neutron flux of up to ~10^9 cm^{-2}·s^{-1}. The latter – Kvant – is currently in high demand as a reference thermal neutron source for calibration of in-core detectors, irradiation of test samples, etc. Today four of these assemblies (SF-1, SF-7, Delta and Kvant) continue operating to minimize computer simulation errors and to confirm full-scale core parameters.

Fig. 3. Critical assembly simulating RP-50 thermionic converter

For space reactor experiments, the Kurchatov Institute previously had the Narcisse critical assembly, where it has performed comprehensive experiments simulating the reactors with direct conversion of heat to electricity. Presently the Institute is actively operating its new critical assembly launched in 2013 – the only one built in this century to meet the new requirements of the space industry [12]. Intended for study of RP-50 thermionic converter, this assembly uses highly enriched fuel (96% of U-235), control rods with B-10-enriched boron carbide, and metallic beryllium / beryllium oxide reflectors. Current plans are to start moderating this assembly with zirconium hydride instead of water.

It should be noted that the data yielded by these – and other – experiments performed at almost all critical assemblies of the Kurchatov Institute have been included in ICSBEP and IRPhEP international databases.

Conclusion

National Research Centre “Kurchatov Institute” preserves all capacities – such as assemblies, nuclear fuel, instrumentation and qualified personnel – necessary for critical experiments. Such experiments – though not very numerous, but highly accurate and well documented – stay in demand due to continued development of new reactor facilities and assurance of safe operation of existing ones. These trends correspond to world practices, where the successfully developing IRPhEP Project does not focus on preserving and consolidating the available data only, but also identifies areas that need new data, as well as plans for further experiments.

Multiple startups of VVERs-1000 confirm that Russian experts, including the Kurchatov ones, are in good position to contribute to this expanding international base of multi-physical (i.e. neutronic plus thermohydraulic) experimental benchmark data.

References

1. I.V. Kurchatov, I.S. Panasyuk. In: “Some papers of I.V. Kurchatov Institute of Atomic Energy”. Energoatomizdat, Moscow, 1982, pp. 7–26 (in Russian).
2. G.A. Gladkov, Yu.V. Nikolski. USSR’s first water-water critical assemblies. *Atomnaya Energiya*, v. 90, Issue 2, February 2001, pp. 88–90 (in Russian).
3. A.Yu. Gagarinski. Critical benchmark experiments in RRC Kurchatov Institute. *Atomnaya Energiya*, v. 84, Issue 6, June 1998, pp. 495–501 (in Russian).

4. A.A. Bykov, A.Yu. Gagarinski, E.S. Glushkov et al. Programs of Experiments with Critical Assemblies at the Russian Research Centre “Kurchatov Institute”. *Nuclear Science and Engineering,* v. 145, 181–187 (2003).
5. A.Yu. Gagarinski, N.A. Lazukov, D.A. Mastin et al. Reactivity temperature effects in uniform U-water critical assemblies in the range of 20–280°C. *Voprosy Atomnoi Nauki I Techniki*, Issue 5(18), Moscow, NIKIET, 1981, pp. 113–117 (in Russian).
6. J. Blair Briggs. The Activities of International Criticality Safety Benchmark Evaluation Project (ICSBEP). *Journal of Nuclear Science and Technology*, Suppl. 2, pp. 1427–1432, August 2002.
7. J. Blair Briggs, John D. Bess, Jim Gulliford. Integral Benchmark Data for Nuclear Data Testing through the ICSBEP & IRPhEP. International Conference on Nuclear Data for Science and Technology, INL/CON–12–26696, March 2013.
8. John D. Bess, J. Blair Briggs, Jim Guilford, Ian Hill. Current Status of the IRPhEP and ICSBEP (August 2014). THTR Conference, Portland, Oregon, August 4008, 2014.
9. M.V. Kovalchuk, V.I. Ilgisonis, Ya.I. Strombach, A.S. Kurski, D.V. Andreev. Development of experimental reactor base in NRC Kurchatov Institute: from the start of F-1 to the 60th jubilee of IR-8. *Voprosy Atomnoi Nauki I Techniki*, Issue 3, 2017, pp. 4–17 (in Russian).
10. Experimental Studies of the Physics of VVER-Type Uranium-Water Lattices. In: Proc. Temporary International Team, v.1, Academial Kiado, Budapest, 1984.
11. A.Yu. Gagarinskiy. High-precision neutronic experiments in NRC Kurchatov Institute. *Atomnaya Energiya*, v. 120, Issue 4, 2016, pp. 191–197 (in Russian).
12. V.A. Usov, N.P. Moroz, G.V. Kompaniets. Basic results of physical startup tests of the AKSAMIT critical assembly simulating RP-50 thermionic converter. In: Innovative nuclear energy designs and technologies, NIKIET, October 2014.