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AUTHOR: A.K. Krasin, V.A. Navumav, I.A. Savushkin, et al

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Physical Characteristics of the IRT-2000 Swimming-Pool Research

Reactor with Loop Channels, by

A. K. Krasin, V. A. Navumaw, I. A. Savushkin, R. I. Stralkow, A. I. Yarashevich

The IRT-2000 reactor installed in the Institute of Heat and Mass Exchange of the Academy of Sciences of the Belorussian SSR was put in operation in May 1962.

Water-cooled water-moderated reactors of the IRT type (sources 1 and 2 describe the reactor in detail) are simple in design, highly reliable, and safe, while providing great possibilities for experimental work in radiation chemistry, nuclear physics, and biology.

1. Work done using the experimental holes in the reactor is described in brief in the Supplement.

Since the IRT-2000 reactor is a prototype, its design did not provide for loop construction. The experimental capabilities of the IRT reactor are very much expanded when a loop channel is installed in the core. The physical characteristics of an IRT reactor with loop channels were, therefore, investigated.

1. Design changes made in individual units of the IRT-2000 reactor in order to install loop equipment.

A 90-mm diameter cavity was designed in the core center in order to facilitate working with loop equipment. Loop channels of different types could be installed. The installation of a cavity in the core made it necessary to alter the design of a number of the units placed in the reactor pool.

A 27-mm diameter hole, traversing the entire reactor vessel, was made in the lower core lattice, so the lower end of the loop channel could be fixed in place. Two mutually perpendicular cross-overs were cut in the upper core lattice, dividing the central fuel assembly into four fuel elements (fig. 1).

Reconstruction of the upper lattice facilitated safe spacing of the central fuel assemblies, and the installation of loop channel with diameters of up to 85-mm in the reactor core.

The design of the fuel assembly and the protective shield was changed in order to bring the loop channel out from the core. Two of the central supports for the fuel assembly were shortened 240-mm (fig. 1). A clamp was secured to the adjacent fuel assembly supports to replace the sections of the supports which had been removed. The opening in the protective shield below the central experimental hole was enlarged to 90-mm.

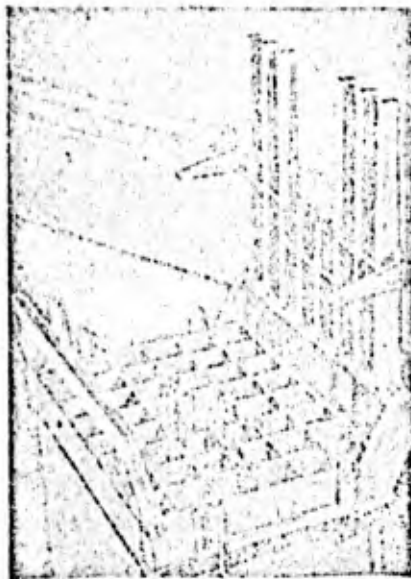


Figure 1. The redesigned core.

The reactor vessel was redesigned to enable the reactor to function and to install the loop channel. Since the steel framework had been partially cut out, the whole vessel was secured to the wall of the reactor pool with two brackets, and this reestablished adequate rigidity and stability.

The equipment included in the loop (pumps, heat-exchangers, compressors, etc.), the main circuit connections, and the auxiliary systems (purification, filling, etc.), were installed in a special room built in the area of horizontal experimental hole No. 10. The walls, floors, and ceilings of the work room for the loop installation were made of concrete aggregate with a density of 4.5 tons/cubic meter (t/m^3). The room was fitted with special ventilation, drainage, and pipelines for hot and cold water, and compressed air from the respective reactor systems. Demountable brackets, which carry the loop channel, are provided so the loop channel can be removed from the reactor pool.

The piping for the loop's primary circuit is placed in the inclined channels in the reactor's concrete biological shielding. Loop system control is exercised from a console above the work room for the loop system (fig. 2).

The alterations which must be made to install the loop are relatively easy to make because they can be made while the reactor is under construction.

2. Computations for physical characteristics.

A model of the loop channel was used for the qualitative calculation of the homogeneous steel-water mix which would be most unfavorable, so far as reactor reactivity was concerned.

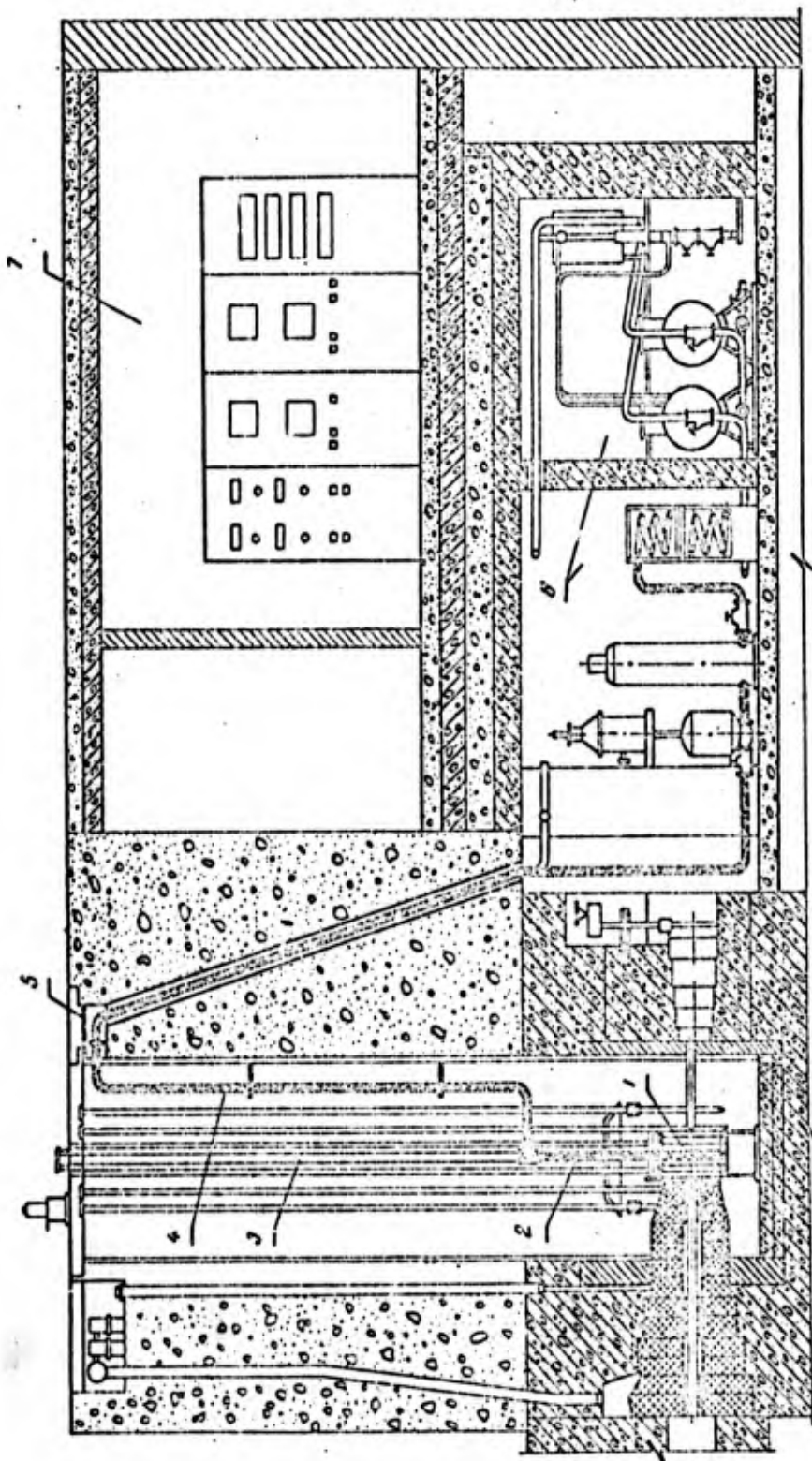


Figure 2. Arrangement of the IRT-2000 loop installation. 1 - core; 2 - loop channel; 3 - charging tube; 4 - piping; 5 - loop recess; 6 - equipment room; 7 - control console.

It was found that a cylindrical channel, 75-mm in diameter, contained 2.8-kg of steel (1Kh18N9T), and that this was approximately the weight of steel in many of the different designs for a loop channel.

Installation of the loop channel in the center of the core required removal of four fuel assemblies (figs. 1, 3 b). The free space around the channel can be filled by inserts made of moderator material, or by specially shaped fuel assemblies.

The computations were made for a cylindrical geometry of 5 zones; zone 1 - the loop channel; zone 2 - the insertion zone; zone 3 - the core; zone 4 - the side reflectors for the core cells (graphite or water); zone 5 - the side reflectors (the water in the reactor pool).

The condition that the size-shape factor for the core be invariable was the basis for the transition from the real core to the cylindrical one. The height of the model used for the computations was taken as equal to the equivalent height for the core.

A 3-group method, similar to that described in reference [3], was selected. The equations for neutron balance for the 3-group approximation, obtained on the basis of the diffusion approximation for a kinetic equation, are in the form

$$D_j \nabla^2 \Phi_j(r) - \Sigma_j \Phi_j(r) + \sum_{k=1}^{j-1} \Phi_k(r) \Sigma_{jk} + \chi_j Q_j(r) = 0;$$

$$Q_j(r) = \sum_{l=1}^3 (\nu_l \Sigma_l)_j \Phi_l(r),$$
(1)

where

Φ_j is integrated flux for the j^{th} group;

χ_j is the integral for the fission spectrum for the j^{th} group;

Σ_j is the complete cross-section for the j^{th} group;

Σ_{jk} is deceleration cross-section of the j^{th} group with respect to the k^{th} .

The other symbols are conventional.

Groups with the following limits have been separated out at the energy intervals in order to separate out the effects caused by the influence of fast neutron leakage on the reactor's critical mass, and by the resonance absorption of moderated neutrons:

$$j = 1300 \text{ keV} < E < \infty ;$$

$$j = 2 \quad E_{\text{limit}} < E < 300 \text{ kev};$$

$$j = 30 < E < E_{\text{limit}};$$

(E_{limit} is the limit between the Maxwell and Fermi spectra, determined in accordance with [4]).

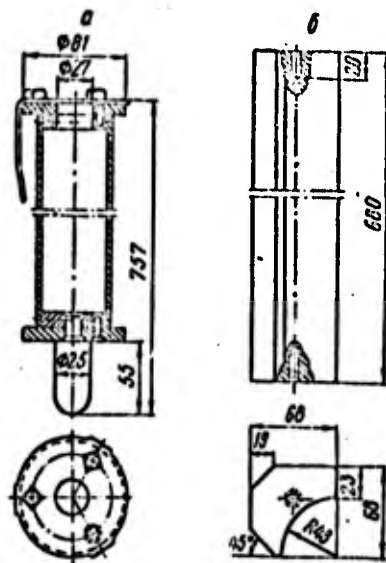


Figure 3. Loop channel simulator (a) and insert (b).

The average group cross-sections for core and reflector materials, with the exception of the cross-sections for uranium and water, were obtained by reducing the 10-group system of constants, described in detail in reference [5], to a 3-group system, using the following formulas

$$\begin{aligned} \Sigma_{a1} &= \left(\sum_{l=1}^5 \Phi_l \Sigma_{al} \right) / \sum_{l=1}^5 \Phi_l, \quad \Sigma_{12} = \left(\sum_{l=1}^5 \Phi_l \sum_{k=6}^9 \Sigma_{lk} \right) / \sum_{l=1}^5 \Phi_l, \\ D_1 &= \left(\sum_{l=1}^5 D_l \Phi_l \right) / \sum_{l=1}^5 \Phi_l, \quad (\nu_f \Sigma_f)_1 = \left[\sum_{l=1}^5 (\nu_f \Sigma_f)_l \Phi_l \right] / \sum_{l=1}^5 \Phi_l, \end{aligned} \quad (2)$$

where

l is the number of the group in the 10-group approximation.

In the 10-group approximation, the 5th group has a lower limit of 300 kev, while that for the 9th group is E_{limit} .

Similar formulas were used to determine the average cross-section for the

second group. The neutron spectrum for the IRT reactor, obtained for a core without a reflector, was computed by weighting the function of the flux qualitatively. The effect of the reflector on the flux spectrum was taken into consideration by substituting equivalent dimensions for the real core dimensions. Then the flux spectrum is in the form

$$\Phi_l = \left(\lambda_l + \sum_{k=1}^{l-1} \Phi_k \Sigma_{kl} \right) / (\Sigma_l + \lambda^2 D_l).$$

Since fast neutron leakage and resonance absorption for U^{238} and U^{235} nuclei have the greatest effect on the reactivity of the water-moderated water-cooled IRT reactor, a more rigorous approach was taken by averaging the cross-sections for water and uranium. It was assumed that inaccuracy in determination of the interaction between neutrons and water would only result in errors in the value given the diffusion coefficient for the fast neutron group. Therefore, the magnitudes of Σ_{aj} , Σ_{12} , Σ_{23} , and D_2 for water were computed using formulas of the type in (2), while that of the diffusion coefficient, D_2 , for the fast neutron group was determined by the coincidence between the neutron group age and the experimental value obtained for fission neutron age in water. The experimental value for age for an indium resonance energy $\tau = 27.68 \pm 0.1 \text{ cm}^2$, given in reference [6], was used. Introducing the correction factor for age, equal to

$$\Delta v = \int_{E_{lim}}^{1.44} D(u) du / \xi \Sigma_s(u) = 0.92 \text{ cm}^2,$$

we have

$$\tau + \Delta\tau = D_1 \lambda_1 / (\Sigma_{12} + \Sigma_{a1}) + D_2 \left(\lambda_2 + \lambda \frac{\Sigma_{12}}{\Sigma_1} \right) / (\Sigma_{23} + \Sigma_{a2}). \quad (3)$$

Formula (3) is used to find D_1 .

The method given in reference [7] was taken into consideration when deriving the constant for the reactor pool water area; since this method includes neutron leakage through the horizontal experimental holes.

Group cross-sections for uranium isotopes were computed with consideration given to the self-shielding effect in the approximation of narrow resonances [8]. Average microscopic cross-sections of thermal neutron groups were taken from reference [4]. Distribution of the neutron flux through the assembly was considered in the computations made for the microscopic cross-sections of a thermal neutron

group. Thermal neutron flux depression in the fuel element was computed using the successive generations method [9], and diffusion approximations were used in the case of the moderator and the construction materials. The system of multigroup equations at (2) was solved quantitatively on a "Ural-1" electronic computer using the method of successive approximations for the sources.

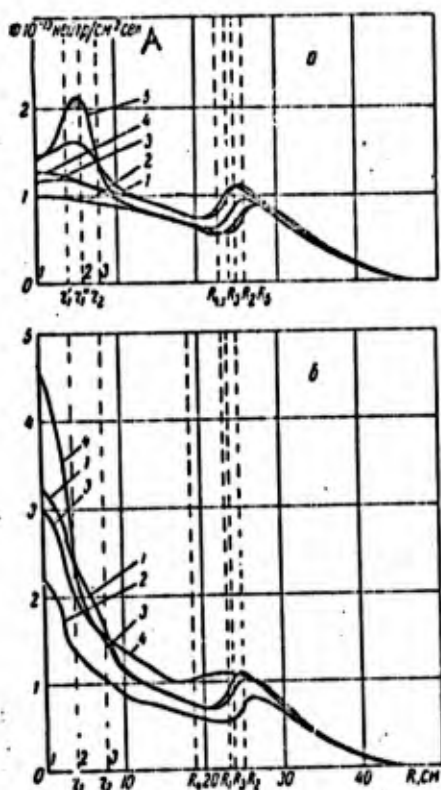


Figure 4. Thermal neutron flux in a 1000 kw IRT reactor with loop channels (a); with cavity at center of core filled with water (b). 1 - beryllium oxide; 2 - aluminum; 3 - graphite; 4 - fuel assembly; 5 - water; R_i - critical radii, $i = 1, 2, 3, 4, 5$; r_1' is the radius of the loop channel area with inserts 1, 2, 3, 5; r'' is the radius of the loop channel area with insert 4; r_2 is the radius of the insert areas 1, 2, 3, 4, 5. A - neutrons/cm²/second.

The results of the computations made for absolute neutron flux for 1000 kw, and for the critical mass for the IRT reactor with loop channels surrounded by various inserts, are shown in Figure 4 and listed in Table 1. The effect of the graphite thermal column was taken into consideration in the various data listed with respect to critical mass and reactivity margin. The effect of the

thermal column was evaluated using a flat model, the lead screen taken into consideration. The maximum "effect" of the thermal column is observed in the case of core cells being fully charged with fuel assemblies, and is equal to 1.38% K_{eff} , the minimum when the core contains 26 assemblies surrounded by a water moderator, and is equal to 0.3% K_{eff} . The results of the computations agree well with the experimental ones (see Table 2).

Table 1. Critical Mass and Reactivity Margin Computations for an IRT Reactor with Loop Channels

Insert zone filling	Core cell reflector	Critical mass (no. assemblies/kg U^{235})	Reactivity margin with core fully charged, %
Fuel assemblies	Graphite	30.9/3.94	5.8
Fuel assemblies	Water	34.2/4.36	5.8
Beryllium	"	34.0/4.34	5.1
Beryllium oxide	"	34.4/4.39	4.8
Graphite	"	35.3/4.50	4.2
Aluminum	"	38.0/4.85	2.1
Water	"	39.7/5.07	1.4

Table 2. IRT-2000 Reactor Critical Masses

Critical Mass (no. assemblies/kg U^{235})		Type reflector		Note
Computed	Experimental	core cells (no. cells)	outside core shell	
20.3/2.57	<20*/2.47	graphite - 28	water	Core without loop channel and inserts
28.0/3.55	25.8/3.27	graphite - 2 water - 20	water with experimental horizontal loops	"
38.0/4.85	37.3/4.76	water - 11	"	Core with loop channel and aluminum inserts

* According to data in reference [1].

An examination made of the errors which were possible during the critical mass computations (such as incorrect calculation of microscopic cross-sections, neutron age in water, etc.) revealed that the range of maximum errors in the critical mass was $\pm 10\%$.

#3. Experimental Test of the Physical Characteristics of the IRT-2000 Reactor ¹

(1. Critical experiments conducted under the guidance of Yu. G. Nikalayev of the I. V. Kurchatav IAE [Atomic Energy Institute]).

A critical test, designed to verify the effect of the loop channel installed in the IRT reactor, was carried out and the critical load for the reactor was determined using a loop channel simulator. The simulator (fig. 3a), made of 1Kh18N9T steel, and weighing 2.63 kg, was installed in a water cavity 90-mm in diameter. The water cavity was formed by aluminum inserts installed in the four central core cells (fig. 3b). The reactor went critical when 38 fuel assemblies were in place (fig. 5a) and the automatic control rods were completely inserted in the core. Extrapolation using inverse counting curves reveals that the critical state will be reached with the control rods raised and 37.3 fuel assemblies ($4.76 \text{ kg of } U^{235}$) charged.

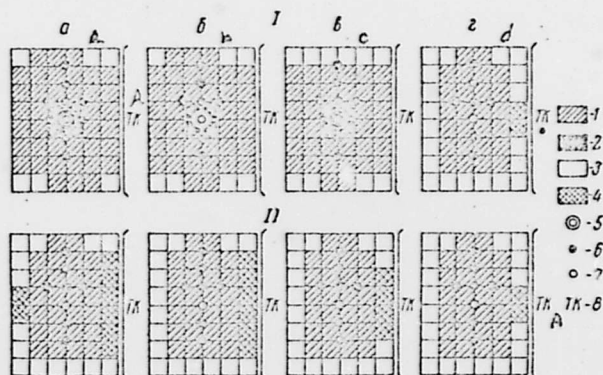


Figure 5. Cartograms showing core charges. (I - critical tests with central cavity filled differently; II - tests to determine effect of reflector material on the reactivity margin, ρ). 1 - fuel assemblies; 2 - aluminum; 3 - water; 4 - graphite; 5 - steel simulator; 6 - control rod channels; 7 - central channel; 8 - thermal column. a - $\rho = 153\%$; b - 100; c - 0.55; d - 0.14%. A - thermal column.

The effect of the loop channel simulator on reactor reactivity was determined by a critical experiment without a steel simulator in the water cavity. The reactor went critical with 37 fuel assemblies (fig. 5b) in place and the automatic control rods only partially inserted in the core. Extrapolation showed that a state of compensation can be reached with 36.3 fuel assemblies loaded ($4.63 \text{ kg of } U^{235}$). Experimental results show that the insertion of the loop channel steel simulator in the water cavity of the core center increases the reactor's critical load by only one fuel assembly, that is by $128 \text{ g of } U^{235}$.

Experiments without the loop channel in the water cavity were conducted not only to determine critical loads, but also to study the possibility of forming an effective neutron "trap" in the core of the IRT reactor. The correspond "flash-up" of the thermal neutron flux in the water cavity was measured by the activity of a copper wire placed in the central experimental hole, and between fuel elements of adjacent fuel assemblies. Measurements showed the thermal neutron flux in the center of the water cavity surrounded by aluminum inserts to be higher than at the nearest of the fuel assemblies by a factor of 2.5.

The effect of the neutron "trap" on reactor reactivity was determined by a critical test with cylindrical aluminum inserts in the core rather than in the central water cavity. Now the reactor went critical with $3\frac{1}{4}$ fuel assemblies (fig. 5c), or $4.3\frac{1}{4}$ kg U^{235} . A comparison between the two critical experiments showed that forming a water neutron trap in the IRT reactor increases the reactor's critical mass by at least 2 to 3 fuel assemblies.

A number of experiments were made to determine the effect of the reflector on the reactivity margin when working with mixed water-graphite reflectors. Without a loop channel the reactor went critical with 26 fuel and 2 graphite assemblies in place on the thermal column side (fig. 5d), and the automatic control rods partially inserted in the core (the "weight" of the rod sections in place equalled 0.14%). Subsequent core loading was in steps, two graphite assemblies per step. Results are shown in Figure 5. Comparison of the reactivity margins proves that each additional assembly adds its effect. The maximum effect exerted by one assembly is not in excess of 0.265%. If the water reflector is replaced completely by graphite the reactivity margin increases 3.5%.

The results of the critical tests indicated were used to prove the correctness of the method.

4. Discussion of the Results.

The results of tests for critical mass (Table 2, Figure 5), reactivity margin (Table 1, Figure 5), and neutron flux (fig. 4), can be used to estimate the experimental possibilities of an IRT-2000 reactor with a loop channel.

The results of the computations and of the critical tests demonstrate that it is, in principle, possible to put a loop channel in the center of the core. The "weight" of the construction material used for a loop channel, 2.63 kg of steel, is that of one fuel assembly (fig. 5d), so different types of loop channels can be built.

Insert material surrounding the loop channel effects critical mass, essent-

ially (Table 1). Considering the variations tested (water, graphite, beryllium, beryllium oxide, and aluminum), it can be said that minimum critical mass occurs when the loop channel is surrounded by beryllium, and does so at 3/4 assemblies. The maximum critical mass, 39.7 fuel assemblies, was observed when the loop channel was surrounded by water. Thus, installation of a loop channel in the core increases critical mass for this reactor by from 6 to 14 fuel assemblies, depending on the material surrounding the channel (when water is the reflector in the core). Concrete selection of the material used to surround the loop channel will depend on the aims of the loop experiments. There are many experiments (radiation chemistry experiments, for example) which require maximum thermal neutron flux, so the cavity must be surrounded by water (fig. 4). It should be noted that in this case the reactivity margin is not high enough to compensate for poisoning¹ (see Table 1), so some of the fuel assemblies must be replaced with assemblies with higher U²³⁵ contents in the TVEL [fuel elements]. When maximum run is the basic requirement, the loop channel must be surrounded either by fuel assemblies, or by graphite, or beryllium, inserts. As Table 1 shows, the reactor with loop channel has relatively low reserves when poisoning is taken into consideration. However, it should be noted that the loop channel can be removed from the core and the latter can be filled once again with fuel assemblies when the loop experiments are concluded.

1. The investigation revealed that the reduction in the reactivity margin for a 1000 kw IRT reactor because of poisoning was 1.95%.

An effective neutron "trap" results when the cavity formed in the center of the core of an IRT reactor is filled with water. When the water cavity is surrounded by fuel assemblies, the result is a 2000 kw neutron "trap" which will handle about $1 \cdot 10^{14}$ neutrons/cm²/second. Formation of a neutron "trap" increases critical mass by about 5 fuel assemblies.

Conclusions

1. Critical tests and physical-neutron computations revealed that it is possible to install a loop channel containing about 3 kg of steel in the IRT reactor.

2. The results of the work done make it possible to select the optimum type of material for use in surrounding the loop channel to provide for maximum run of the reactor with the loop channel in place, or to obtain maximum thermal neutron flux.

3. Filling the cavity in the center of the core with water results in the IRT reactor having a neutron "trap" with very intense thermal neutron flux; at 2000 kw $1.0 \cdot 10^{14}$ neutrons/cm²/second.

4. The design changes which must be made to accommodate for the loop system are relatively easy to make, and can be recommended for inclusion in IRT reactors which are to be built in the future.

SUPPLEMENT

A Brief Description of the Investigations Made Using the Experimental Holes in the Reactor

All of the horizontal holes in the reactor are currently in use and the following experiments have been made.

Hole No. 1. Measurement of the $\gamma - \gamma$ coincidence with the (n, γ) reaction using scintillation spectrometers.

Hole No. 2. Investigation of the spatial distribution of the flux spectrum emitted by the reactor in different organic mediums.

Hole No. 3. Neutron diffraction studies of polarized neutrons of magnetic structures and magnetic form factors in intermetallic manganese compounds.

Hole No. 4. Measurement of the γ -ray spectrum for the (n, γ) reaction of various isotopes.

Hole No. 5. Study of the frequencies of the oscillation spectrum of atoms in a solid crystal lattice using neutron scattering.

Hole No. 6. Study of the coincidence of γ -rays with the conversion electrons of the (n, γ) reaction, and investigation of the conversion electron spectrum.

Hole No. 7. Investigation of the kinetic characteristics of fission fragments in the case of fission of polarized neutrons.

Hole No. 8. A neutron diffraction study of the degree of reversibility of ferrite systems of different compositions.

Hole No. 9. Study of the effect of small, intermediate neutron doses on the physiological functions, and the metabolism, of animals, as well as the investigation of the effect of intermediate neutrons on microorganisms.

Hole No. 10 is an exception. It has the lowest neutron flux at the output and is led out to the work room for the loop system. It will not be used in the near future.

The investigations using the horizontal holes in the reactor were carried out by the Institutes and Departments of the Academy of Sciences of the Belorussian SSR and the Belorussian State University.