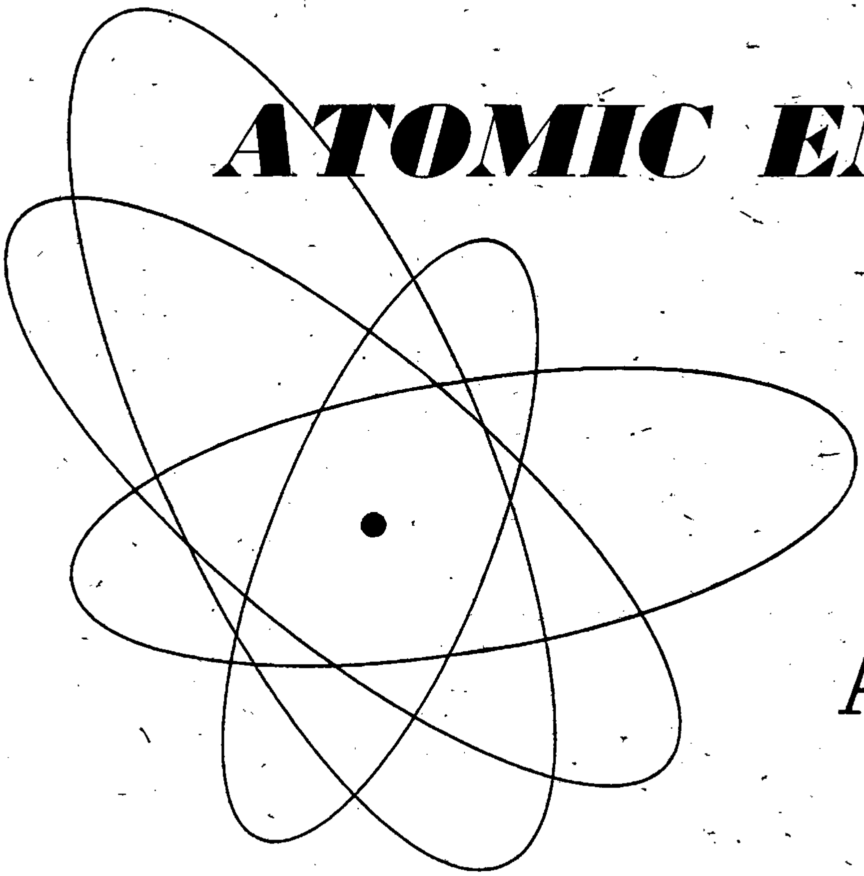
*Volume 10, No. 3*
*January, 1962*

# THE SOVIET JOURNAL OF
# ATOMIC ENERGY



Атомная
энергия

TRANSLATED FROM RUSSIAN

CONSULTANTS BUREAU

# Research by Soviet Experts Translated by Western Scientists

## Soviet Research on the LANTHANIDE AND ACTINIDE ELEMENTS, 1949-1957

An important contribution to the literature of nuclear chemistry, this collection of papers is a comprehensive presentation of Soviet research on the chemistry of lanthanides and actinides. The 106 reports included in this collection appeared in the major Soviet chemical journals translated by Consultants Bureau, as well as in the Soviet Journal of Atomic Energy, 1949-1957.

The five sections, totalling 657 pages, provide broad representation of contemporary Soviet research in this important aspect of nuclear science. This collection should be accessible to all nuclear researchers, whether theoretical or applied.

Each part may be purchased as follows:

| | |
|---|---|
| **Basic Chemistry** (25 papers) | $15.00 |
| **Analytical and Separation Chemistry** (30 papers) | $20.00 |
| **Nuclear Chemistry (and Nuclear Properties)** (32 papers) | $22.50 |
| **Geology** (10 papers) | $7.50 |
| **Nuclear Fuel Technology** (9 papers) | $7.50 |
| **Complete collection** | $65.00 |

## RADIATION CHEMISTRY, PROCEEDINGS OF THE FIRST ALL-UNION CONFERENCE MOSCOW, 1957

More than 700 of the Soviet Union's outstanding research scientists participated in this conference sponsored by the Academy of Sciences and the Ministry of the Chemical Industry. Each of the 56 reports read in the various sessions covers either the theoretical or practical aspects of radiation chemistry, and special attention is given to radiation sources used in radiation-chemical investigations. The general discussions which followed each report and reflected various points of view on the problem under analysis are also included.

| | | | |
|---|---|---|---|
| **Primary Acts in Radiation Chemical Processes** | | | |
| heavy paper covers | 5 reports, plus discussion | illustrated | $25.00 |
| **Radiation Chemistry of Aqueous Solutions (Inorganic and Organic Systems)** | | | |
| heavy paper covers | 15 reports, plus discussion | illustrated | $50.00 |
| **Radiation Electrochemical Processes** | | | |
| heavy paper covers | 9 reports, plus discussion | illustrated | $15.00 |
| **The Effect of Radiation on Materials Involved in Biochemical Processes** | | | |
| heavy paper covers | 6 reports, plus discussion | illustrated | $12.00 |
| **Radiation Chemistry of Simple Organic Systems** | | | |
| heavy paper covers | 9 reports, plus discussion | illustrated | $30.00 |
| **The Effect of Radiation on Polymers** | | | |
| heavy paper covers | 9 reports, plus discussion | illustrated | $25.00 |
| **Radiation Sources** | | | |
| heavy paper covers | 3 reports | illustrated | $10.00 |

*Individual volumes may be purchased separately.*

*NOTE: Individual reports from each volume are available at $12.50 each. Tables of contents sent upon request.*

**special price for the 7-volume set** .................................. $125.00

Payment in sterling may be made to Barclay's Bank in London, England.

**CONSULTANTS BUREAU**

**227 West 17th Street • New York, N.Y., U.S.A.**

THE SOVIET JOURNAL OF

# ATOMIC ENERGY

*A translation of ATOMNAYA ÉNERGIYA,*
*a publication of the Academy of Sciences of the USSR*

(Russian original dated March, 1961)

Vol. 10, No. 3 January, 1962

## CONTENTS

LETTERS TO THE EDITOR

| | |
|---|---|
| Annual subscription | $ 75.00 |
| Single issue | 20.00 |
| Single article | 12.50 |

# CONTENTS (continued)

NEWS OF SCIENCE AND TECHNOLOGY

BIBLIOGRAPHY

## NOTE

The Table of Contents lists all materials that appear in Atomnaya Énergiya. Those items that originated in the English language are not included in the translation and are shown enclosed in brackets. Whenever possible, the English-language source containing the omitted reports will be given.

Consultants Bureau Enterprises, Inc.

# THE SELECTION OF THE OPTIMUM PARAMETERS FOR AN ATOMIC ELECTRIC GENERATING STATION

A. Ya. Kramerov

Translated from Atomnaya Énergiya, Vol. 10, No. 3, pp. 211-221, March, 1961
Original article submitted June, 1960

A system of equations has been derived, giving a set of optimum parameters for an atomic electric generating station, which insure minimum cost of the electrical energy produced. It is assumed that the layout, materials, and type and elements of equipment have been previously selected, and that the problem is one of finding the optimum numerical values of the constructional and operational parameters of the elements of the station. Quite general approximate relationships are used to express the costs of the elements of the installation as a function of the parameters being sought. Attention is paid to the mutual relationships which exist among the parameters, through the equations which describe the processes going on in the station, as well as to the limitations which are imposed by the need for reliable operation.

The system of equations derived may be used to check the optimum parameters of various projected two-loop installations with nonboiling reactors, employing the maximum allowable fuel element temperatures. Examples are given to show the importance of the independent problem of expressing some of the optimum parameters in terms of other parameters obtained from individual equations of the system.

## General Conditions of Minimum Cost

The minimum cost of electrical energy occurs for the condition that the partial derivatives of the expression for the cost of 1 KWH ($c_e$), taken with respect to the independent parameters $x_k$, are equal to zero, thus:

$$F_k(x_k) = \frac{\partial \ln c_e}{\partial \ln x_k} = \sum_i cC'_i - (1+n)N'_b + nN'_{int} = 0. \tag{1}$$

Since the $x_k$'s are independent parameters the problem is to calculate the relations $\psi_m(x_k) = 0$ existing between them, which describe the physical processes taking place in the atomic generating station and thus give expression to the limiting conditions insuring reliable operation of the station.

In Eq. (1), $c_e = \frac{C}{\tau N_e} = \frac{\sum_i c_i}{\tau}$ is the cose of 1 kw-hr of electrical energy produced (here $N_0 = N_b - N_{int}$ is the useful electrical output, equal to the difference between the total output $N_b$ and the internal losses $N_{int}$. $C = \sum_i C_i$ is the cost of building and operating the station over its normal period of productivity $\tau$,* including fuel consumption); $c_i = C_i/C$ is the fraction of the total cost C represented by the ith component $C_i$; $n = N_{int}/N_0$ is the fraction of the energy consumed in internal losses. The logarithmic derivative of a quantity Y with respect to $x_k$ will be designated from now on by $Y' = \partial \ln Y/\partial \ln x_k$; thus: $N'_b = \partial \ln N_b/\partial \ln x_k$ and $N'_{int} = \partial \ln N_{int}/\partial \ln x_k$.

It follows from Eq. (1) that the logarithmic total differential of the cost of the station must be equal to zero for optimum parameters, thus:

$$d \ln c_e = \frac{dc}{c_e} = \sum F_k d \ln x_k = 0. \tag{2}$$

---

* It is to be understood that this period is not equal to the period of amortization of the equipment of the station.

The deviation of a given $F_k$ from zero is a measure of the fractional increase in cost per kw-hr over the minimum value, which is a feature gained by the use of "logarithmic" derivatives in the present paper.

Equation (1) gives the optimum parameters, which, generally speaking, may not satisfy all the inequalities $\psi_m(x_k) \gtrless 0$, which represent possible conditions for the construction and reliable operation of the generating station, but which are not taken into consideration in setting up the system (1). These inequalities should be replaced by equations; i.e., they should be used as "limiting" conditions and included among the conditions which are considered directly in looking for the optimum. If one of these conditions actually limits the system, it may have to be revised accordingly, and solved anew.

## The Relation of the Cost to the Parameters

In the following discussion it is assumed that the various types of elements in the station have been decided upon; i.e., the decisions have made as to suitable constructional layout and scheme of operation under the given conditions, the materials to be used, the number of parallel connected units, etc. Under these conditions, the cost of an element of the generating station is determined by the weight of material used and the complexity of fabrication, which, as a rule, depend only slightly on the parameters, except in those cases where a parameter change is accompanied by reducing the dimensions of an element down to something smaller; for example, changing the diameter of the fuel elements, which affects the cost of the fuel. In a rather well-known way, all this justifies the further step of representing the cost $C_i$ of an element of a fixed type of generating station in the form of a polynomial involving the weight of $G_i$, in particular the polynomial of the first degree:

$$C_i = \sum_i k_{ij} G_i^{n_{ij}} \simeq C_i^k + k_i G_i =$$

= a constant part (depending on the type of element) + a variable part (depending on the parameters, through the weight of the element), where $k_{ij}$ and $n_{ij}$ are constant coefficients: $C_i^k = k_{i0}$ represents the constant components of the cost: $n_{i0} = 0$; $k_{i1} = k_i$; $n_{i1} = 1$. Having assumed a linear relation between cost and the weight of equipment of fixed type, and bearing in mind that for a fuel cycle without fuel recovery the cost of 1 kg of fuel element depends linearly to the degree $\underline{m}$ (with $m \sim 1$) on the enrichment X of the fuel (term in X) and on the surface of 1 kg of fuel element to the degree $\underline{r}$ (term in the fuel element diameter $d_{fe}$), we obtain, instead of Eq. (1), the expression:

$$F_k = -a_Q Q' + a_{\text{int}} N'_{\text{int}} + c_{\text{fuel}} mX' + c^{x}_{SG} F - a_\eta \eta' + c^p_{I} p'_{I} + c^p_{II} p'_{II} - c_T \Gamma' - c_{ASS} r d'_{FE} + \\ + c^{x}_{R} S'_0 + c^{x}_{R} \frac{l_a}{L} l' + c^{x}_{PL} S'_{PL} m_{PL} = 0, \tag{3}$$

where $N_b = Q\eta_b$; $N'_b$; $N'_b = Q' + \eta'_b$; Q is the heat output of the reactor; $\eta_b$ is the gross efficiency: $a_Q = n + 1 - (c_T + c^x_{STGI}) = n + c_k + c^x_R + c^x_{SG} + c^x_P + c^x_{BL}$; $a_\eta = n + 1 - c_{EL}$; and $a_{\text{int}} = n + c^x_P$ are coefficients equal to the fractional change in cost of 1 kw-hr of electrical energy, corresponding with unit fractional change in heat output ($a_Q$), efficiency ($a_\eta$), and coolant circulating losses ($a_{\text{int}}$) respectively; $l_a/L$ is the fraction of the total reactor length L, proportional to the length of the active zone $l$; $c_{EL}$ is the variable part of the cost of the electric generating installation; $c^x_{STGI} = c_{EL} + c^Q_{STGI} + c^p_{STGI}$ is the variable part of the cost of the steam turbine generator installation (STGI): $c^x_P = c^v_P + c^p_P$ is the variable part of the cost of pumps; $c^x_{SG} = c^v_{SG} + {}^{pI}_{SG} + {}^{pII}_{S}$ is the variable part of the cost of the generator; $c^x_R = c^v_R + c^p_R$ is the variable part of the cost of the reactor; $c^x_{PL} = c^v_{PL} + c^p_{PL}$ is the variable part of the cost of piping in the first heat-exchange loop; $c^p_I = c^p_R m_R + c^{pI}_{SG} m^I_{SG} + c^p_P m_P + c^p_{PL} m_{PL}$ is the sum of the effective costs dependent upon the coolant pressure in the first heat-exchange loop taking account of the degree of dependance $m_i$; $c^p_{II} = c^{pII}_{SG} m^{II}_{SG} + \Sigma c^i_{STGI} m_i$ is the same thing for the elements which carry the pressure of the working part of the second heat-exchange loop; $c_{HM}$ is the cost of the nuclear fuel (heating material) consumed during the period of economical operation; $c_{FE}$ is the cost of the fuel elements consumed (along with the replaceable parts of the fuel channels); $c_{ASS}$ is the cost of making up the fuel element assemblies, consumed during the period of economical operation.

The meaning of the superscripts on the c's is as follows: $\underline{x}$ – variable part of the cost; $\underline{v}$ – variable part of the cost, which is proportional to the dimensions (volume) of the element; $\underline{p}$ – the same, but including the proportionality to the pressure by the factor $\underline{m}$. The subscripts show what element, system, or process the c's belong to, thus: I –

first heat-exchange loop; II – second heat-exchange loop; R – reactor, P – pump. The fractional costs, $c_i$, represent the fraction of the total cost of construction and operation of the station given by:

$$c_i = \frac{C_i}{\sum\limits_i C_i}.$$

The components entering into the optimizing conditions are the logarithmic derivatives Y', taken with respect to the desired independent parameters $x_k$, of the quantities Y, which serve to express the cost and the output. Some of these are "elemental" geometric quantities, such as the cross section of the reactor $S_0$, the diameter of piping $S_{PL}$, the equivalent diameter of the fuel emenets $d_{FE}$, and the length of the active zone $l$, some may be operating quantities, such as the pressure $p_I$ and $p_{II}$ in the first and second heat-exchange loops; some may be physical, such as the enrichment X, and the degree of burnout G; but at any rate they are good variables to use as the independent parameters that we are looking for;* the process being that the derivatives in question go to zero, except for the derivative of a given parameter with respect to itself, which is equal to unity, thus:

$$Y' = x_l' = \frac{\partial \ln x_l}{\partial \ln x_k} = 0 \quad \text{for} \quad k \neq l \text{ and} Y' = 1 \quad \text{for} \quad k = l. \tag{4}$$

The remaining Y values entering into Eq. (3) – the heat output Q, the steam generator surface F, the station efficiency, $\eta$, and the internal circulating losses $N_{int}$ – are all functions of the directly determined geometric, operational, and physical paramaters,* and in this sense are "secondary" parameters of the atomic generating station. Therefore, in what follows, we shall simply let these values be determined through the primary parameters as these are governed by the limitations placed upon them by a two loop generating station using nonboiling reactors. At the same time we are looking for their logarithmic derivatives $Y' = \partial \ln Y/\partial \ln x_k$ (entering into the condition $F_k = 0$), which are the coefficients standing before $(d \ln x_k)$ in the expression $d \ln Y = \sum\limits_k Y' d \ln x_k$. Substituting these derivatives into Eq. (3) yields the desired system of equations, defining the relations between the optimum parameters.

## Relations between the Primary and Secondary Parameters of the Atomic Generating Station

The relations between the parameters and the limitations placed upon them depend on the laws governing the physical processes taking place in the generating station, as well as on the constructional possibilities and the demands of reliable operation. The following results have been obtained from these relationships after a number of transformations and familiar simplifications.

Reactor heat output.

$$Q = Gc\,(T_{\max} - T_s)\, f^{-1}$$

and

$$d \ln Q = (1 - \varkappa B)\, d \ln G + \frac{T_{\max}}{T_{\max} - T_s}\, d \ln T_{\max} - \frac{T_s}{T_{\max} - T_s}\, d \ln T_s - f'_{X_F} d \ln X_F -$$
$$- \varkappa \left( \frac{h}{\alpha} - B \right) d \ln \varepsilon_{FE} + \varkappa (1 - B)\, d \ln d_{FE} + \varkappa \frac{h}{\alpha}\, d \ln \varepsilon + \varkappa B d \ln S_0. \tag{5}$$

c is the heat capacity of the coolant; $T_{max}$ is the maximum temperature of the fuel elements; $T_s$ is the boiling point of the working fluid in the steam generator; $f = K - \delta_{i_p} - \delta_{i_i} \times (X_F - 1)^{-1}$ is a coefficient equal to the ratio of the maximum temperature difference in the first loop $(T_{max} - T_s)$ to the coolant temperature rise in the reactor, $\Delta T = \bar{T}_1 - T_2$ (where $T_2$ is the temperature of the coolant on entering the reactor, and $\bar{T}_1$ is the temperature on leaving the reactor); $K = K_{\Delta T} K_{\theta} = (T_{max} - T_2)/\Delta T$ is a coefficient in which $K_{\Delta T} = \Delta T_{max}/\Delta T$ expresses the nonuniformity in coolant temperature rise along a reactor fuel channel, a quantity which is practically independent of

---

* It should be noted, that in a number of cases, the enrichment X is more conveniently determined as a function of other parameters of the reactor, which have to do with insuring criticality.

the choice of parameters which we are discussing; $K_\theta = (T_{max} - T_2)/\Delta T_{max}$ is the coefficient of overheating of the fuel elements, which, for a fixed distribution of fuel elements along the fuel channel depends only on the simple ratio $y = \Delta T_{max}/\theta$ (as can be seen, for example) from dimensional considerations; $\theta$ is the mean temperature differential between the fuel elements and the coolant; $\kappa = K/f$ $K'_y = K/f \times \sigma \ln K/\partial \ln y$; $f'_{X_F} = \partial \ln f/\partial \ln X_F$ and $B = (1 - St')\ \underline{h}/\alpha - 1$ – are coefficients determined by the "thermal engineering" of the first loop of the reactor; $St' = \partial \ln St/\partial \ln Pe$; $St = \alpha/\omega\gamma c$ is Stanton's criterion; $Pe = RePr = \omega d\gamma c/\lambda$ is Pekle's criterion; $\alpha$ is the coefficient of heat release from the surface of a fuel element to the coolant; $\underline{h}$ is the coefficient of heat release to the coolant from a point on the fuel element where the temperature $T_{max}$ is reached: $\epsilon_{FE} = S_{FE}/S_0$ is the fraction of the cross section of the active zone $S_0$ occupied by the cross section of fuel elements $S_{FE}$; $\epsilon = S/S_0$ is the fraction of the cross section of the active zone $S_0$ occuped by the cross section of coolant channels $S$; $\delta i_p$ and $\delta i_i$ are the fractions of the heat going into heating ($\delta i_p = \Delta i_p/\Delta i$) and evaporating ($\delta i_i = \Delta i_i/\Delta i$) the feed water to the steam generator; $X_F$ is the degree of cooling off of the coolant in the evaporational part of the steam generator (see below).

The value $d \ln T_{max} = 0$ holds, except for the case where the maximum surface temperature of the fuel elements is limited by the boiling point of the coolant; thus: $T_{max} = T_s(p_I)$. In the latter case (for water) we can use the empirical expression:

$$T_s - 273 = t_s \simeq 100 \sqrt[4]{p},$$

from which

$$d \ln T_{max} = d \ln T_s(p_I) \simeq \frac{1}{4}\,\frac{T_s(p_I) - 273}{T_s(p_I)}\, d \ln p_I.$$

Steam generator surface F. The exact expression for F and its partial derivatives with respect to the desired parameters is fairly complicated, since there are different components in the steam generator with different heat capacities and different temperature differentials $\theta_j$, including the heating differential $\theta_p$, the evaporation differential $\theta_i$, and the superheat differential $\theta_{SH}$. Simpler expressions are obtained by leaving out the heating and superheat components, or by equating the evaporation and superheat differentials. Then the mean temperature differentials will be equal for all these components; thus: $\theta_j = \bar{\theta}_p = \bar{\theta}_i = \bar{\theta}_{SH} = \delta i_i (\Delta T/\ln X_F)$ and the expression for the surface of the steam generator takes the form:

$$F = \sum_j F_j = \frac{Gc\Delta T}{\vartheta} \sum_j \frac{\delta i_j}{\alpha_j} = \frac{Gc}{\bar{\alpha}\delta i_i} \ln X_F. \tag{6}$$

Here

$$X_F = \frac{T_2 + (1 - \delta i_{SH})\Delta T - T_s}{T_2 + \delta i_p \Delta T - T_s} = \frac{\text{temperature differential entering evaporator}}{\text{temperature differential leaving evaporator}},$$

i.e., "the degree of cooling off" of the coolant in the evaporating part of the steam generator; $\bar{\alpha} = (\sum_j \delta i_j/\alpha_j)^{-1}$ is the mean heat transfer coefficient in the steam generator; $\delta i_j = \Delta i_j/\Sigma \Delta i_j$ is the fraction of the heat transferred in the jth component of the steam generator.

From Eq. (6), taking $\delta i_i$ to be constant, it follows that

$$d \ln F = d \ln G + d \ln (\ln X_F) - d \ln \bar{\alpha}.$$

For constant diameter and spacing of the tubes in the steam generator we can write

$$d \ln \bar{\alpha} = \frac{\partial \ln \bar{\alpha}}{\partial \ln Re}\, d \ln Re = \bar{\alpha}'_{Re} (d \ln G - d \ln S_{SG}),$$

where the criterion is given by $Re = wd_g/\nu = G/S_{SG}\ d_g/\gamma\nu$; $w = G/S_{SG}\gamma$ is the coolant velocity; $d_g$ is the hydraulic diameter; $S_{SG}$ is the coolant channel cross section in the steam generator; $\gamma$ and $\nu$ are respectively the specific gravity and viscosity of the coolant. In toto, we get the equation (approximately correct even for $\theta_p \neq \theta_i \neq \theta_{SH}$):

$$d \ln F = d \ln G (1 - \bar{\alpha}'_{Re}) + \bar{\alpha}'_{Re} d \ln S_{SG} + d \ln (\ln X_F). \tag{7}$$

The efficiency $\eta$. The thermal efficiency of an ideal regenerative cycle is

$$\eta_t = 1 - \frac{T_x \Delta S}{\Delta i},$$

where $T_x$ and $\Delta S$ are respectively the mean temperature and the reduction in entropy for withdrawal of heat from the cycle; $\Delta i$ is the increment in heat content in adding heat to the cycle. After rearrangement, and bearing in mind the approximate equality of the mean heat capacities of the working fluid

$$\bar{c}_p = \frac{\int_{T_1}^{T_2} c_p \, d \ln T}{\int_{T_1}^{T_2} d \ln T} \cong \frac{\int_{T_1}^{T_2} c_p \, dT}{\int_{T_1}^{T_2} dT},$$

we get

$$\eta_t = 1 - \frac{T_x}{T_s} c. \tag{8}$$

Here

$$c = 1 + \frac{\Delta i}{\bar{c}'_p T_s} \left[ \delta i_{\mathrm{P}} \left( 1 + \frac{2}{3} \frac{\Delta t_{\mathrm{P}}}{T_s} + \ldots \right) + \right.$$
$$\left. + \frac{\bar{c}'_p}{\bar{c}''_p} \delta i_{\mathrm{SH}} \left( 1 - \frac{2}{3} \frac{\Delta t_{\mathrm{SH}}}{T_s} + \ldots \right) \right],$$

where $\bar{c}'_p$ and $\bar{c}''_p$ are respectively the mean heat capacity of water and vapor; $\Delta t_{SH}$ is the superheat of the vapor.

In the absence of insufficient heating of the water or superheat of the vapor ($\Delta t_P = \Delta t_{SH} = \delta i_P = \delta i_{SH} = 0$), the correction factor c in Eq. (8) is equal to unity.

Usually $(c - 1) \ll 1$ and changes only slightly. Therefore we can consider that

$$d\eta_t = c \frac{T_x}{T_s^2} dT_s - \frac{T_x}{T_s} dc \simeq \frac{cT_x}{T_s} d \ln T_s$$

and

$$d \ln \eta_t = \frac{cT_x/T_s}{1 - cT_x/T_s} d \ln T_s = \frac{d \ln T_s}{T_s/cT_x - 1}, \tag{9}$$

and we can write $T_x$ everywhere, with the understanding that it means $cT_x$.

Power required for coolant circulation. Neglecting compressibility, we can write the following expression for the power consumed in coolant circulation, which does not reappear as electrical energy:

$$N_{\mathrm{int}} = \frac{1 - \eta_P \eta_b}{\eta_P} \frac{G}{\gamma} \Delta p = \frac{1 - \eta_P \eta_b}{\eta_P} \frac{G}{\gamma} \frac{\gamma}{2g} \sum_i \left( \frac{G}{S_i \gamma} \right)^2 L_i = \frac{1 - \eta_P \eta_b}{2g \eta_P} \frac{G^3}{\gamma^2} \sum_i \frac{L_i}{S_i^2}, \tag{10}$$

where $\eta_P$ is the efficienty of the pump; $\eta_b$ is the efficiency of the heat power installation; $\Delta p$ is the irreversible pressure drop in the first loop, G is the coolant flow; $L_i = (\lambda l_i / d_h + \xi_{\mathrm{local}})_i$ is the coefficient of resistance of the ith part of the path in order, having cross section $S_i$, length $l_i$, hydraulic diameter $d_h$, and total coefficient of local resistances $\xi_{\mathrm{local}}$; $\lambda$ is the coefficient of friction. Provisionally, we shall break the first loop down into sections, corresponding with the reactor, the steam generator, and the piping. The piping resistance depends principally on the local resistances, determined by the lay-out and construction of the loop, and hence is only slightly dependent on the parameters selected. Therefore we set $L_{PL}$ = const, which gives $d \ln L_{PL} = 0$. On the other hand, in the reactor and the steam generator, where there is an extensive heat-exchange surface, friction usually plays a substantial role. Therefore, after a number of transformations, we obtain

$$d\ln N_{\text{int}} = d\ln G\,[3+\lambda'(1-\xi_{\text{PL}})+(1-\bar{\alpha}')\,\xi_{\text{SG}}] - 2d\ln\gamma - 2\xi_{\text{PL}}\,d\ln S_{\text{PL}} - (2-\lambda')\,\xi_{\text{R}}\,d\ln S_0 - 3\xi_{\text{R}}\,d\ln\varepsilon +$$

$$+\xi_{\text{R}}(1-\lambda')\,d\ln\varepsilon_{\text{FE}} + \xi_{\text{R}}\,d\ln l + \xi_{\text{SG}}\,d\ln(\ln X_{\text{F}}) - \xi_{\text{SG}}(3+\lambda-\bar{\alpha}')\,d\ln S_{\text{SG}} \tag{11}$$

where $\xi_i = \Delta p_i/\Sigma\,\Delta p_i = \Delta p_i/\Delta p$ is the fraction of the ith component in the total resistance of the first loop; $\lambda' = d\ln\lambda/d\ln \text{Re}$; $\bar{\alpha}' = d\ln\bar{\alpha}/d\ln \text{Re}$.

## Concrete Optimum Conditions

To obtain the system of equations which gives the optimum values of the independent variables, we substitute into the optimum condition of Eq. (3) the values of $Q'$, $N_i'$, $\eta'$, $F'$, and $X'$, given by Eqs. (5), (7), (9), and (11) in the form of coefficients standing before the differentials of the corresponding independent parameters $G$, $T_s$, $p_{II}$, $p_I$, $X_F$, $S_{PL}$, $S_{SG}$, $S_0$, $\epsilon$, $\epsilon_{FE}$, $d_{FE}$, $l$, and $\Gamma$. Combining the coefficients standing before the differentials of each of these independent parameters, we obtain the concrete optimum conditions:

$$1)\;\; F_G = -a_Q(1-\varkappa B) + a_{\text{int}}\,[3+\lambda'(1-\xi_{\text{PL}})+(1-\bar{\alpha}')\,\xi_{\text{SG}}] + c^{\text{x}}_{\text{SG}}(1-\bar{\alpha}') = 0; \tag{12}$$

$$2)\;\; F_{T_s} = \frac{a_Q}{\frac{T_{\max}}{T_s}-1} - \frac{a_\eta}{\frac{T_s}{cT_{\text{x}}}-1} + c^p_{\text{II}}\,4\,\frac{T_s}{T_s-273} = 0. \tag{13}$$

This equation may be written in the form of a coefficient standing before $d\ln p_{II}$, starting with the relation $F_{p_{II}} = F_{T_s}\,d\ln T_s$, from which:

$$F_{p_{\text{II}}} = F_{T_s}\frac{d\ln T_s}{d\ln p_{\text{II}}} = \frac{1}{4}\,\frac{T_s-273}{T_s}\left[a_Q\left(\frac{T_{\max}}{T_s}-1\right)^{-1} - a_\eta\left(\frac{T_s}{cT_{\text{x}}}-1\right)^{-1}\right] + c^p_{\text{II}} = 0 \tag{13'}$$

(here and below $T_s = T_s(p_{II})$):

$$3)\;\; F_{p_{\text{I}}} = -\,a_Q\,\frac{1}{4}\,\frac{T_s(p_{\text{I}})-273}{T_s(p_{\text{I}})}\left(1-\frac{T_s}{T_s(p_{\text{I}})}\right)^{-1} + c^p_{\text{I}} = 0, \tag{14}$$

which holds for water coolant, if, as the maximum admissible temperature, we take $T_{\max} = T_s(p_I)$. If, however, the admissible temperature of the surface of a fuel element is $T_{\max} < T_s(p_I)$, it is a good idea to lower $p_I$ so as to make $T_s(p_I) = T_{\max}$. For a gaseous coolant:

$$F_{p_{\text{I}}} = c^p_{\text{I}} - 2a_{\text{int}}\frac{\partial\ln\gamma}{\partial\ln p_I} = c^p_{\text{I}} - 2a_{\text{int}} = 0, \tag{14'}$$

since for an ideal gas:

$$\frac{\partial\ln\gamma}{\partial\ln p_{\text{I}}} = \frac{\partial}{\partial\ln p_{\text{I}}}\ln\left(\frac{p_I}{RT}\right) = 1;$$

$$4)\;\; F_{X_F} = a_Q f'_{X_F} + a_{\text{int}}\frac{\xi_{\text{SG}}}{\ln X_F} + \frac{c^{\text{x}}_{\text{SG}}}{\ln X_F} = 0; \tag{15}$$

$$5)\;\; F_{s_{\text{PL}}} = -2a_{\text{int}}\xi_{\text{PL}} + c^{\text{x}}_{\text{PL}} = 0; \tag{16}$$

$$6)\;\; F_{s_{\text{SG}}} = -a_{\text{int}}\xi_{\text{SG}}(3+\lambda'-\bar{\alpha}') + \bar{\alpha}' c^{\text{x}}_{\text{SG}} = 0. \tag{17}$$

We also get the six coefficients standing before the differentials of the fundamental reactor parameters: $S_0$, $\epsilon$, $\epsilon_{FE}$, $d_{FE}$, $l$, $\Gamma$, upon which the initial enrichment X depends, which is what insures that the reactor will still be critical after running under optimum conditions to a fuel burn-out $\Gamma$. As before, setting $X'_{S_0} = \partial \ln X / \partial \ln S_0$; $X'_{\epsilon} = \partial \ln X / \partial \ln \epsilon$, etc., we have:

$$7)\ F_{S_0} = -a_Q \varkappa B - a_{\text{int}} \xi_{\text{R}} (2 - \lambda') + c_{\text{fuel}} m X'_{S_0} + c^{\text{x}}_{\text{R}} = 0; \tag{18}$$

$$8)\ F_{\varepsilon} = -a_Q \varkappa \frac{h}{\alpha} - 3a_{\text{int}} \xi_{\text{R}} + c_{\text{fuel}} m X'_{\varepsilon} = 0; \tag{19}$$

$$9)\ F_{\varepsilon_{\text{FE}}} = a_Q \varkappa \left( \frac{h}{\alpha} - B \right) + a_{\text{int}} \xi_{\text{R}} (1 - \lambda') + c_{\text{fuel}} m X'_{\varepsilon_{\text{FE}}} = 0; \tag{20}$$

$$10)\ F_{d_{\text{FE}}} = -a_Q \varkappa (1 - B) - a_{\text{int}} \xi_{\text{R}} (1 - \lambda') + c_{\text{fuel}} m X'_{d_{\text{FE}}} - c_{\text{ASS}} r = 0; \tag{21}$$

$$11)\ F_l = a_Q \varkappa + a_{\text{int}} \xi_{\text{R}} + c_{\text{fuel}} m X'_l + c^{\text{x}}_{\text{R}} \frac{l_a}{L} = 0; \tag{22}$$

$$12)\ F_{\Gamma} = c_{\text{fuel}} m X'_{\Gamma} - c_{\text{T}} = 0. \tag{23}$$

## Use of the System of Optimum Conditions

The system of equations $F_k = 0$ enables us to verify in how far a rational choice has been made for the basic parameters of an atomic generating station from the point of view of the cost of the electrical energy produced. For this purpose we determine the derivatives of the above coefficients in the form $F_k = \partial \ln c_e / \partial \ln x_k$. Each of the $F_k$'s is the difference between a sum of positive terms, $F_k^+$, giving the increase in the cost $c_e$ as the given parameter is increased, and a sum of negative terms, $F_k^-$, giving the decrease in the cost. At the strictly optimum point $F_k^+ = F_k^-$, i.e., $F_k = F_k^+ - F_k^- = 0$. The values of the station parameters can be considered sufficiently close to optimum, in the following two cases: first, when $| F_k | \ll 1$, and second, when $| F_k | \ll | F_k^+ |$ or $| F_k | \ll | F_k^- |$. The first case means that in the range which applies to the given generating station, appreciable fractional changes, $dx_k/x_k$, in the parameters correspond with only insignificant fractional changes in the cost of the electrical energy, i.e.,

$$\frac{\partial c_e}{c_e} = F_h \frac{\partial x_h}{x_h} \ll \frac{dx_h}{x_h}.$$

The second case means that the given parameter has been taken near the optimum value, regardless of the extent to which it affects the cost of energy generated. It is not necessary to fulfill the second condition, if the first condition is "sufficiently" fulfilled. However, this "sufficiency" is often difficult to evaluate, without having recourse to the second condition. If for any value of $F_k$, the largest of the sums of the positive or negative terms is very small, i.e., $| F_k^+ | \ll 1$ or $| F_k^- | \ll 1$, then over the range of variation in question, the given parameter has only a slight effect on the cost of electrical energy. In this case, the second condition may be left out of consideration, as far as $F_k$ is concerned.

With the help of the system of equations (12) – (23) it is in principle possible to solve the considerably more complicated problem of finding all of the optimum parameters for an atomic generating station of a desired type. The steps are as follows: a) orientational parameters are chosen from previous experience; b) estimates are made of the necessary cost and power requirements of the units of the station; c) approximate relations are set up for the variation of the power and cost of the station units as a function of the parameters chosen. Here everything can be expressed in terms of the costs and powers of step b), on the basis of the expressions derived previously for the necessary relationships (or similar expressions having the proper coefficients of the form $F_k$). Thus, for example, the cost of the elements whose weight is proportional to volume is $C_i = C_i^0 \, V_i/V_i^0$ [or if the pressure plays a role too, then $C_i = C_i^0 (V_i/V_i^0)(p/p_0)^{m_i}$]. Similarly, the cost of 1 kg of fuel element is given by the expression:

$$C_{\text{T}} = C_{\text{T}}^k + C_{\text{ASS}}^0 \left( \frac{d_{\text{FE}}^0}{d_{\text{FE}}} \right)^r + C_{\text{fuel}}^0 \left( \frac{X}{X_0} \right)^m.$$

where the index o refers to quantities previously chosen in accordance with steps a and b).

In addition to these cost factors, the system $F_k = 0$ also contains the fraction of the output consumed in circulating the coolant in the first loop, $n = N_i/N_p$, which may also be expressed in terms of the parameters we are looking for; thus:

$$n = \frac{n_b}{1-n_b};\ n_b = \frac{N_{int}}{N_b} = \frac{\frac{1-\eta_o\eta_b}{\eta_o}\frac{G}{\gamma}L\frac{\gamma}{2g}\left(\frac{G}{S\gamma}\right)^2 K_w^2}{\eta_b Gc\,(T_{max}-T_s)\,f^{-1}},$$

where $K_w = w_{max}/w$ is the ratio of the maximum to the mean coolant velocity in the reactor fuel channels; $L = \Sigma L_j(S/S_j)^2$ is normalized coefficient of resistance of the first loop; $\eta_b = \eta_{egm}(1 - cT_x/T_s)$ is the efficiency of the station (gross), and $f = \delta_{ii}/X_F - 1 + K - \delta_{ip}$ is a function already expressed in terms of $x_k$. To find the derivatives X' of the required fuel enrichment X with respect to the reactor parameters $d_{FE}$, $S_0$, $\epsilon$, $\epsilon_{FE}$, $l$, $\Gamma$, it is necessary to find a convenient expression for the criticality condition at the end of life: $\varphi(d_{FE}, S_0, \epsilon, \epsilon_{FE}, l, \Sigma) = 0$.

The expressions obtained for $c_i$, X', and n as a function of $x_k$ are substituted into the expressions $F_k = 0$, which obviously gives a system of equations relating the parameters to be selected, but which, in the general case, it is impossible to solve analytically. Even in special cases, the simultaneous solution for even a few optimum parameters meets with great difficulties. An approximate method of solution of this system of equations can be arrived at from the concrete features presented by the generating station, and is thus a subject requiring special consideration. However, in many cases, it is sufficient to take the separate equations of the system $F_k = 0$, and express the optimum values of some of the parameters (or the simple functions representing them) in terms of other parameters or their functions. This can be done, for example, with the coolant velocity, and the circulating power requirements. Sometimes it becomes clear from these expressions that some of the parameters have only a very slight effect on the optimum values of the others. This can appreciably reduce the number of parameters to be solved for simultaneously, and thus simplifies the work of finding them.

We shall consider several examples of the expressions for the optimum parameters under conditions in which the system of equations (12) – (23), derived above, is valid.

Coolant circulating power. From Eq. (12), the following expressions may be obtained for the optimum value of the power $N_{int}$ required to circulate the coolant in the first loop, along with the fraction which this power constitutes of the useful output, $n = N_{int}/N_0$.

$$n = \frac{1-\varkappa B}{2}\,\frac{c_K + c_R^X + c_{PL}^X}{1+\frac{k_o}{c_e\tau}}\cdot\left\{\frac{1+\frac{\bar{\alpha}' c_{SG}^X - \varkappa B\,(c_{SG}^X + a_{int})}{(1-\varkappa B)\,(c_K + c_R^X + c_{PL}^X)}}{1+\lambda'\frac{1-\xi_{PL}}{2} - \frac{1-\bar{\alpha}'}{2}\,\xi_{SG}}\right\};\ N_{int} = nN_o = n\frac{C}{c_e\tau}, \tag{24}$$

where $C = \sum_i C_i$, and $\Sigma\, C_i/C = \Sigma\, c_i = c_K + c_T + c_R^X + c_{SG}^X + c_P^X + c_{PL}^X + c_{STGI}^X = 1$; $c_i^X = C_i^X/C$ is the ratio of the variable part of the ith component to the total cost C; $c_K = C_k/C = \sum_i CK_i/C$ is the constant part of the capital cost, determined by the type of equipment, $c_T = C_T/C$ is running cost for fuel and operation over time $\tau$; $B = h/\alpha\,(1 + St') - 1$ (with limited surface temperature of the fuel elements, $h = \alpha$, and $B = St'$ gives the degree of change of the criterion St); $\kappa = K_y'\ K/f$; $(f = K - \delta_{ip} + \delta_{ip}/X_F - 1)$. Here we introduce the proportionality coefficient $k_p = c_P^X/N_{int}$ equal to the variable part of the cost of 1 $K_1$ of performance by the pumps in the first loop, and $c_e\tau = C/N_p = c_{KW} = c_T\tau$, the calculated expenditures in the production of the electrical energy, produced in time $\tau$.

On the strength of the relatively small values of $\bar{\alpha}'$, $c_{SG}^X$, B, $a_{int}$ and $\lambda'$ in Eq. (24), the factor in brackets is usually only slightly different from one, and the optimum cost fraction may be represented approximately in the form:

$$n = \frac{1-\varkappa B}{2}\,\frac{c_K + c_R^X + c_{PL}^X}{1+\frac{k_o}{c_e\tau}}. \tag{25}$$

Saturation temperature of the working fluid in the steam generator. From Eq. (13), we obtain the optimum value of the mean temperature for transferring heat to the working fluid (water) in the steam generator:

$$\frac{T_s}{T_x} = \frac{1}{2}\left(1-\frac{a_\eta}{a_Q}\right) + \sqrt{\frac{1}{4}\left(1-\frac{a_\eta}{a_Q}\right)^2 + \frac{a_\eta}{a_Q}\frac{T_{max}}{T_x} - c_{II}^p\,4\,\frac{T_s}{T_s-273}\left(\frac{T_{max}}{T_s}-\frac{T_s}{T_x}\right)\left(\frac{T_s}{T_x}-1\right)}. \tag{26}$$

In view of the rather weak dependence of the right side of this expression on $T_s$, solution by the method of successive approximation presents no great difficulties. If we neglect the effect of steam pressure on the cost of steam piping, i.e., if we set $c^P_{II} = 0$, then:

$$\frac{T_s}{T_x} = \frac{1}{2}\left(1 - \frac{a_\eta}{a_Q}\right) + \sqrt{\frac{1}{4}\left(1 - \frac{a_\eta}{a_Q}\right)^2 + \frac{a_\eta}{a_Q}\,\frac{T_{\max}}{T_x}}\,. \tag{27}$$

If, in addition, the quantity

$$\frac{a_\eta}{a_Q} = \frac{1 + n - c_{EL}}{1 + n - c_T - c^X_{STGI}}$$

is taken equal to unity, which is particularly true if we assume that the constant part of the capital costs plays a dominant role, i.e., $C_K \gg C - C_K$ (here $c_T \simeq c^X_{STGI} \simeq c_{EL} \simeq 0$) we obtain $T_s/T_x = \sqrt{T_{\max}/T_x}$, i.e., a familiar but obviously very inaccurate result, which corresponds, practically, with the condition of maximum output rather than minimum cost. The deviation of $c^P_{II}$ from zero and especially the deviation of $a_\eta/a_Q$ from unity, introduce substantial corrections into the optimum value of $T_s$. It will be noted that, if in the expressions for $a_\eta$ and $a_Q$, $n \ll 1$, and $c_{EL} \ll 1$, it is possible, in a very obvious way, to take account of the dependence of $a_Q$ on $T_s$. Then for $c^P_{II} = 0$, from Eq. (13), after rearrangement, we obtain the optimum value:

$$\frac{T_s}{T_{\max}} = \frac{\frac{T_{\max}}{T_x}}{1 - B}\left\{1 - \sqrt{1 - (1 - B)\left(1 + \frac{B}{\frac{T_{\max}}{T_x}}\right)}\right\},$$

where $D = C^0 - C^0_Q / C^0_Q\,(T_{\max}/T_x - T^0_s/T_x)$; is a quantity, independent of $T_s$, determined by the ratio of the constant $(C_0 - C^0_Q)$ and the variable ($C^0_Q$ at $T_s = T^0_s$) parts of the cost of the atomic generating station (assuming that all the independent parameters, except $T_s$, have been fixed). In the limiting cases where $D \to \infty$ (i.e., $C^0_Q = 0$, $C =$ = const) we again get for the optimum $T_s = \sqrt{T_{\max} T_x}$, the geometric mean temperature, insuring maximum output. For the more real case of $D \to 1$, the optimum value which we obtain from Eq. (28) is simply the arithmetic mean between the maximum fuel element temperature, $T_{\max}$, and the temperature at which heat is removed from the cycle, $T_x$, thus. $T_s = (T_{\max} + T_x)/2$, an expression, which, for many rough estimates, may be used with more, justification than $T_s = \sqrt{T_{\max} T_x}$.

Cooling of the coolant medium in the steam generator. The heating surface of the steam generator may be represented approximately in the form

$$F = \frac{1}{\delta i_i}\,\frac{Gc}{\bar{\alpha}}\ln X_F$$

(this expression is strictly true in the absence of warm-up and superheat components, or if the temperature differentials in all parts of the steam generator are equal).

From Eq. (15) and the expression

$$f = \frac{\delta i_i}{X_F - 1} + K - \delta i_o\left(\text{i.e., } f'_{X_F} = \frac{\partial \ln f}{\partial \ln X_F} = -\frac{X_F}{X_F - 1}\,\frac{\delta i_i}{\delta i_i + (K - \delta i_o)(X_F - 1)}\right)$$

we obtain the optimum value

$$X_F = 1 + \beta + \sqrt{\beta^2 + 2\beta(1 - b)^{-1}}\ \left(\text{for } b \ll 1,\ X_F = 1 + \beta + \sqrt{\beta^2 + 2\beta}\right), \tag{29}$$

where

$$\beta = \frac{1}{2}\,\frac{\delta i_i}{K - \delta i_o}\left(\frac{1}{b} - 1\right) = \frac{1}{2}\,\frac{\delta i_i}{K - \delta i_o}\left(\frac{a_Q \ln X_F}{a_{int}\xi_{SG} + c^X_{SG}} - 1\right);\quad b = \frac{a_{int}\xi_{SG} + c_{SG}}{a_Q \ln X_F}$$

(here, as before, a $a_{int} = n + c^X_P$; $a_Q = 1 + n - c_T + c^X_{STGI} = a_{int} + c_k\, c^X_{SG} + c^X_R + c^X_{PL}$).

Coolant velocity in the first loop. From Eqs. (16) and (17) it is possible to find quite convenient expressions for the optimum power expenditures in circulating the coolant, as well as for the coolant velocities in the piping of the first loop and the steam generator. Taking into consideration that the power required to circulate the coolant through the piping amounts to:

$$N_{PL}=\frac{1-\eta_b\eta_o}{\eta_o}\frac{G}{\gamma}\Delta p_{PL}=\frac{1-\eta_b\eta_o}{\eta_o}\frac{G}{\gamma}\left(L_{PL}\frac{\gamma}{2g}w_{PL}^{2}\right);\ G=\gamma S_{PL}w_{PL}$$

and that the variable part of the cost of the piping is proportional to the cross section to the power $m_{PL} \stackrel{\sim}{>} 1$;

$$C^{x}_{PL}=k_{PL}S_{PL}^{m_{PL}}$$

(here $k_{PL}$ is the proportionality constant), we find from Eq. (16) that for $m_{PL} = 1$ the optimum coolant velocity in the piping of the first loop is

$$w_{PL}=\left[\frac{g\eta_o}{\gamma(1-\eta_o\eta_b)}\frac{1}{L_{PL}}\frac{k_{PL}}{c_e\tau+k_o}\right]^{1/3}, \qquad (30)$$

where $L_{PL} = (\lambda L/d)_{PL} + \Sigma\xi^{PL}_{local}$ is the coefficient of resistance of the piping in the first loop, which is determined, basically, by the local resistances and is only slightly dependent on the numerical values of the parameters selected.

Coolant velocity in the steam generator. From Eq. (17) we obtain, in a similar way, the optimum expenditure in circulating the coolant through the steam generator

$$\frac{N_{SG}}{N_o}=\frac{\bar{\alpha}'}{3+\lambda'-\bar{\alpha}'}\frac{C^{x}_{SG}}{c_e\tau+k_o}\frac{1}{N_o}.$$

Remembering that

$$C^{x}_{SG}=k_{SG}F=k_{SG}\frac{Gc}{\delta i_1\bar{\alpha}}\ln X_F$$

and

$$N_{SG}=\frac{1-\eta_o\eta_b}{\eta_o}\frac{G}{\gamma}L_{SG}\frac{\gamma}{2g}w^{2}_{SG}$$

(here $k_{SG}$ is the proportionality constant), we obtain

$$w^{opt}_{SG}=\left(\frac{2g\eta_o}{1-\eta_o\eta_b}\frac{1}{L_{SG}}\frac{\frac{\bar{\alpha}'}{\bar{\alpha}}}{3+\lambda'-\bar{\alpha}'}\frac{k_{SG}}{c_e\tau+k_o}\frac{c\ln X_F}{\delta i_1}\right)^{\frac{1}{2}}. \qquad (31)$$

The ratio $\bar{\alpha}'/\bar{\alpha}=(Re/\bar{\alpha}^2)(d\bar{\alpha}/dRe)$ may with sufficient accuracy be replaced by the analogous ratio, which has not been applied to the coefficient of heat transfer from the coolant to the working fluid ($\bar{\alpha}$) but to the coefficient of heat transfer from the coolant to the heater surface ($\alpha_1$):*

$$\frac{\bar{\alpha}'}{\bar{\alpha}}\sim\frac{\alpha_1'}{\alpha_1}=\frac{0,8}{\alpha_1}=\frac{0,8}{\left(\frac{\alpha_1}{w^{0,8}_{SG}}\right)w^{0,8}_{SG}},$$

---

* This assumption is true enough for each individual part of the steam generator. Actually, for $\alpha_2$ = const, the derivative of the heat transfer coefficient $h = [1/\alpha_1 + 1/\alpha_2 + (\delta/\lambda)_{st}]$ with respect to the coolant velocity, Re, is equal to

$$h'_{Re}=\frac{\partial\ln h}{\partial\ln Re}=\frac{\partial\ln h}{\partial\ln\alpha_1}\frac{\partial\ln\alpha_1}{\partial\ln Re}=\frac{h}{\alpha_1}\alpha_1',$$

and the ratio $h'_{Re}/h=\alpha_1'\ \alpha_1$ (here $\alpha_1$ and $\alpha_2$ are the coefficients of heat release of the coolant and the working fluid: $(\delta/\lambda)_{st}$ is the thermal resistance of the pipe.

where, for water and gases, $\alpha_1 = 0.023\ \mathrm{Re}^{0.8}\mathrm{Pr}^{0.4} \times \lambda/d = \mathrm{const}\ /^{0.8}_{SG}$, i.e., $\alpha_1/w^{0.8}_{SG} = \mathrm{const}$ (relative to the velocity $w_{SG}$). Hence we obtain:

$$w^{\mathrm{opt}}_{SG} = \left( \frac{2g\eta_o}{1-\eta_o\eta_b} \frac{1}{l_{SG}} \frac{\frac{0{,}8}{(\alpha_1/w^{0,8}_{SG})}}{3+\lambda'-\alpha'} \frac{l_{SG}}{c_e\tau + k_o} \frac{c \ln X_F}{\delta i_i} \right)^{\frac{0{,}5}{1{,}4}} \tag{32}$$

(Here c is the heat capacity of the coolant.)

Optimum ratio of coolant heating to the difference between the maximum temperature of the fuel elements, and the coolant temperature on leaving the reactor. From Eq. (21), we find that, at optimum, we should have $\kappa = -n_{\mathrm{eff}}$, where

$$\begin{aligned} n_{\mathrm{eff}} &= a_{\mathrm{int}}\, \xi_R (1-\lambda') + c_{ASS} r + c_{\mathrm{fuel}} m (-X'_{d_{FE}})] [a_Q (1-B)]^{-1} = \\ &= \left[ \xi_R \frac{1-\lambda'}{1-B} + \frac{c_{ASS} r + c_{\mathrm{fuel}} m (-X'_{d_{FE}})}{(1-B)\, a_{\mathrm{int}}} \right] \frac{a_{\mathrm{int}}}{a_Q} \end{aligned} \tag{33}$$

is a function of the basic cost ratios of the generating station: $\kappa = K'_w (K/f)$ is a function of the ratios of the characteristic temperature differences, expressed in terms of the operating conditions of the reactor fuel channels and the steam generator. In the expression for $\kappa$, the coefficient $K = T_{\max} - T_2/\Delta T$ gives the "superheat" of the fuel elements compared with the coolant, and is a familiar function of the parameter

$$y = \frac{\Delta T_{\max}}{\theta} = \frac{1}{2} \frac{h}{\alpha} \frac{S}{d_{FE}} \frac{S_{FE}}{S}; \qquad \frac{K}{f} = \frac{T_{\max} - t_2}{T_{\max} - T_s} = \frac{K}{K + \frac{\delta i_i}{X_F - 1} - \delta i_o};$$

$$f = \frac{T_{\max} - T_s}{\Delta T} = K + \frac{\delta i_i}{X_F - 1} - \delta i_o; \qquad X_F = 1 + \frac{\delta i_i}{\delta i_o} + \frac{T_{\max} - T_s}{\Delta T}.$$

Thus, having determined $\kappa = -n_{\mathrm{eff}}$ from Eq. (33), we can find the optimum value of $y = T_{\max}/\theta$, and the corresponding geometric quantities, in particular $l/d_{FE}$, as well as the optimum value of $K(y) = T_{\max} - T_2/\Delta T$, the "superheat" coefficient of the fuel elements. In the general case, y is expressed only approximately in terms of $\kappa$; in the special case, that the maximum fuel element temperature occurs at precisely that cross section where the maximum coolant temperature, $T_1 = T_2 + \Delta T_{\max}$ is reached (i.e., where the coolant leaves the fuel channel, we have

$$T_{\max} = T_2 + \Delta T_{\max} + K_L \bar{\theta}$$

(where $K_L = \theta_{\mathrm{exit}}/\bar{\theta} = \kappa_{\mathrm{exit}}/\bar{q}$ is the ratio of the heat flux, $q_{\mathrm{exit}}$, at the point where the coolant leaves the fuel channel, to the mean heat flux $\bar{q}$, which is equal to the ratio of the temperature drops $\theta$). In this case

$$K = K_{\Delta T} K_\theta = K_{\Delta T} \left( \frac{T_{\max} - T_2}{\Delta T_{\max}} \right) = K_{\Delta T} \left( 1 + K_L \frac{\bar{\theta}}{\Delta T_{\max}} \right) = K_{\Delta T} \left( 1 + \frac{K_L}{y} \right);$$

$$K'_y = \frac{\partial \ln K}{\partial \ln y} = -\left( 1 + \frac{y}{K_L} \right)^{-1} = -\frac{K_\theta - 1}{K_\theta}$$

and finally

$$\begin{aligned} K_\theta &= 1 + \frac{K_L}{y} = \frac{T_{\max} - T_2}{\Delta T_{\max}} = \frac{1 + \frac{n_{\mathrm{eff}}}{K_{\Delta T}} \left( \frac{\delta i_i}{X_F - 1} - \delta i_o \right)}{1 - n_{\mathrm{eff}}} = \\ &= \frac{a_Q + \left[ a_{\mathrm{int}} \xi_R \frac{1-\lambda'}{1-B} + \frac{c_{ASS} r + c_{\mathrm{fuel}} m (-X'_{d_{FE}})}{1-B} \right] \frac{\delta i_i (X_F - 1)^{-1} - \delta i_o}{K_{\Delta T}}}{a_Q - \left[ a_{\mathrm{int}} \xi_R \frac{1-\lambda'}{1-B} + \frac{c_{ASS} r + c_{\mathrm{fuel}} m (-X'_{d_{FE}})}{1-B} \right]}. \end{aligned} \tag{34}$$

For the purpose of finding convenient relationships between the optimum parameters, other equations (or groups of equations) of the system (12) – (23) may be transformed in a manner similar to the above. Here we have to keep in mind that the parameters selected must not exceed the limits set by the requirements of reliable operation and the possibilities offered for the construction of the station. In the general case, it is not known ahead of time which of these limitations will be the principal ones, i.e., which parameters should be taken as the limiting ones. Therefore, in the system of Eqs. (12) – (23), the only really limiting parameter was taken to be the fuel element temperature. It was practically always found profitable to utilize this limit to its full extent. The remaining parameters (or groups of them), determined from the system of equations, should be compared with the limiting admissible values, and in case of need set equal to these values (one at a time), with the corresponding corrections to the system of Eqs. (12) – (23) and its solution. Below we give basic limitations of a similar kind (for an atomic generating station with reactors where there is no boiling of the coolant) and a method of finding the form of the system of Eqs. (12) – (23) which corresponds with them.

The limitations that are most simply taken account of are the ones that are placed directly on the parameters being selected. If, for example, the parameter $x_1$, found from the system of Eqs. (12) – (23), exceeds the permissible limits $x_l \gtrless x_l^{\lim}$, it must be set everywhere equal to is limiting value ($x_l = x_l^{\lim}$; $d_{x_l} = d_{x_l}^{\lim} = 0$), the equation $F_1 = 0$ drops out of the system (12) – (23), the rest of the equations remain unchanged. This can happen in the following cases: 1) The cross section of the active zone $S_0$, and its height $l$ are limited by the dimensions of a reactor housing, D and L, which can be transported to the assembly point, or fabricated at the construction site; 2) the fraction of the cross section of the active zone, $\varepsilon$, occupied by coolant, is limited, in many reactors, by the need to achieve stability, the absence of undamped power oscillations, and the self-regulating action which comes from proper temperature and power coefficients of reactivity. This is especially true when using coolants which have large neutron interaction cross sections (for example: water); 3) the fuel burnout $\Gamma$ must not exceed the limiting value $\Gamma_{\lim}$ at which excessive structural changes appear in the fuel.

A more laborious transformation of the system of Eqs. (12) – (23) is required in those cases where the limitations are laid, not upon the $x_k$'s themselves, but upon some of the functions $y(x_k) = y_{\lim}$ (for example, the heat flux $q = q_{\lim}$). In such cases, it is convenient to introduce the function $Z = y/y_{\lim}$, which obviously has to be equal to unity if the limiting conditions are to be fulfilled. From the condition $d(\ln Z) = \sum_k (\partial \ln Z/\partial \ln x_k)\, d \ln x_k = 0$, we obtain the differential of any $l$-parameter, $d \ln x_l$, from the remaining parameters

$$d \ln x_l = -\sum_{k \neq l} \frac{\dfrac{\partial \ln Z}{\partial \ln x_l}}{\dfrac{\partial \ln Z}{\partial \ln x_l}}\, d \ln x_k$$

and further, we obtain the expression for

$$d \ln c_e = \sum F_h\, d \ln x_h = \sum_{h \neq l} F_k\, d \ln x_k + F_l \left( -\sum_{k \neq l} \frac{\dfrac{\partial \ln Z}{\partial \ln x_l}}{\dfrac{\partial \ln Z}{\partial \ln x_l}}\, d \ln x_k \right),$$

from which it is clear that the "new" $F_k = F_k^0$ (at $k \neq l$), may be expressed in terms of the former $F_k$:

$$F_k^0 = F_k - F_l \frac{\dfrac{\partial \ln Z}{\partial \ln x_k}}{\dfrac{\partial \ln z}{\partial \ln x_l}} = F_k - F_l \left( \frac{\dfrac{\partial \ln y}{\partial \ln x_k} - \dfrac{\partial \ln y_{\lim}}{\partial \ln x_k}}{\dfrac{\partial \ln y}{\partial \ln x_l} - \dfrac{\partial \ln y_{\lim}}{\partial \ln x_l}} \right). \qquad (35)$$

This gives the new conditions for the minimum in the calculated costs $c_e$, and the condition $Z = y/y_{\lim} = 1$ takes place of the "dropped-out" equation $F_l = 0$.

The fundamental limitations of this sort are, perhaps, the limitation on the heat flux at the surface of the fuel elements $q < q_{\lim}$, the coolant velocity in the reactor $\underline{w}$, and finally, the enrichment, X. Using Eq. (35) in these cases, we can find the altered conditions for the optimum, $F_k^0 = 0$.

# CORROSION RESISTANCE OF STEELS AND ZIRCONIUM ALLOYS IN BORIC ACID SOLUTIONS AT DIFFERENT TEMPERATURES

M. A. Tolstaya, S. V. Bogatyreva, and G. N. Gradusov

Translated from Atomnaya Énergiya, Vol. 10, No. 3, pp. 222-226, March, 1961
Original article submitted June 6, 1960

The present article describes the results obtained in investigating the corrosion resistance of steel 1Kh18N9T, zirconium alloys with 2.5 and 1.0% niobium, and carbon steel 20 in high-parameter solutions of boric acid. These materials were subjected to static tests in autoclaves with boric acid solutions which had different concentrations. Tests in solutions with boric acid concentrations of 0.23 and 1.13 g/liter were performed over periods of 1000 and 2000 hr at 335°C and under a pressure of 140 atm; in solutions with a boric acid concentration of 5.65 g/liter, the tests were performed over periods of 150 hr at 310°C and under a pressure of 100 atm. The possibility of using boric acid for the soft regulation of nuclear power reactors is demonstrated.

The article also provides the results obtained in investigating the effect of boric acid solutions on the corrosion of steels (carbon steel 20, alloyed steel Kh5M2, stainless steel Kh13, and austenite stainless steel 1Kh18N9T) at 40°C under conditions of free oxygen access. The obtained data provided a basis for recommending the industrial use of stainless steel OKh13 as the material for manufacturing storage tanks.

One of the possible methods of soft regulation and emergency shutdown of reactors with a water coolant is the introduction of water-soluble boron-containing compounds into the reactor water. Boric acid as well as some of its salts, for instance, aluminum tetra- and pentaborate,can be used for this purpose. Boric acid is the compound that apparently offers the greatest possibilities.

For the emergency shutdown of water-aqueous reactors, a boric acid solution with a boron concentration of approximately 1 g/liter can be introduced into the water in the first loop. Such a system will be used, for instance, in the Yankee atomic station (USA) [1]; it is of interest for a number of water-coolant reactors which are under construction or in the design stage.

The aim of the work described was the investigation of the effect of high-parameter solutions of boric acid on the corrosion resistance of structural materials in the first loop of water-aqueous reactors. At the same time, it was necessary to determine the efficiency with which boric acid is washed off the metal surface.

In performing the experiments, it also became necessary to check the corrosion of different steels which are used in the production of tanks for the storage of boric acid solutions.

## EXPERIMENTAL

The tests of materials in boric acid solutions with different concentrations and the parallel tests in high-purity water were performed under static conditions in autoclaves made of stainless steel 1Kh18N9T at saturation temperatures and under a pressure of 100 to 140 atm.

Pipe sections and plates of steel 1Kh18N9T, steel 20, and zirconium alloys with 1 and 2.5% niobium (materials used for the protective jackets of fuel elements and slugs) were used as specimens in these tests.

The surfaces of the specimens were subjected to different kinds of treatment: electropolishing, mechanical polishing, and etching. Moreover, in experiments with solutions containing 1 g/liter of boron in the form of boric acid, zirconium alloy specimens that were first tested in high-parameter water, i.e., specimens covered with thick protective zirconium dioxide ($ZrO_2$) layers, were investigated.

The tests of materials in boric acid solutions and the parallel tests in high-purity water at 40°C under atmospheric pressure were performed in aluminum tanks, which were placed in a thermostatically controlled device. The specimens used in these tests consisted of plates made of steels 1Kh18NGT, OKh13, Kh5M2, steel 20, and a zirconium alloy with 2.5% niobium (these specimens were used for checking the influence of the boric acid solution parameters on the detected effect of boron trapping by the metal surface). The media used for the investigation were high-purity water, which was poured into autoclaves and which had the following composition:

| | |
|---|---|
| Electrical conductivity, $10^{-6}$ ohm$^{-1}\cdot$cm$^{-1}$ | 0.4 – 0.6 |
| pH | 6.8 – 6.9 |
| $Cl^-$ concentration, mg/liter | 0.01 – 0.02 |
| Hardness, µg-eq/liter | 2 |

and boric acid solutions with different concentrations and pH values (Table 1).

TABLE 1. Characteristics of the Boric Acid Solutions Used

| Concentration, g/liter | | pH | |
|---|---|---|---|
| $H_3BO_3$ | B | Calculated | Determined by means of glass electrode at 25°C |
| 0.23 | 0.04 | 5.8 | 5.9 |
| 1.13 | 0.2 | 5.48 | 5.6 |
| 5.65 | 1.0 | 5.13 | 5.2 |
| 11.30 | 2.0 | – | 5.0 |

The analyses of solutions for determining their boron content were performed according to the photocolorimetric method by means of a carmine red indicator (the sensitivity of the method was 0.05-0.1 mg of boron per/liter.

After the specimens were tested in boric acid solutions, we checked whether boron penetrates the metal surface by using the spectrographic analysis method after "shavings" 0.01-0.05 mm thick were taken off the metal surface. Before this, the steel specimens were carefully rinsed in 3% NaOH, hot water, and acetone, while zirconium alloy specimens were rinsed in hot solutions of 5% NaOH, 5% HCl, water, and acetone.

The corrosion rate was determined according to the weighing method by determining the weight of specimens with an accuracy to 0.1 mg. Before weighing (before and after tests), the rinsed specimens were degreased in acetone and then dired and kept in a drier. A reduction weight was usually observed in steel specimens after the corrosion products were taken off by cathode etching in suitable media [2]. For zirconium alloy specimens, which were rinsed after tests in alkali, acids, and water, the corrosion rate was determined with respect to the increase in weight.

## EXPERIMENTAL RESULTS

The pH values of boric acid solutions are somewhat low (see Table 1), and, from this point of view, they can exert an aggressive action on steels. However, along with this, the oxidizing action of boric acid apparently increases with an increase in its concentration and an increase in the water parameter values. The interaction of these conflicting factors results in the fact that the corrosive action of boric acid solutions on metals is weakly pronounced under static conditions, although under dynamic conditions the flow velocity apparently can cause a certain increase in the solution's corrosive aggressiveness [3]. In order to determine the stability of boric acid, we also performed tests on the interaction with developed metal surfaces (by filling the autoclaves with steel or zirconium shavings). After a testing period of 24 to 48 hr at 310°C and under a pressure of 100 atm, the pH of the solution and the boric acid concentration did not change within the measurement accuracy limits, which indicated that boric acid water solutions in contact with the metals under investigation are stable at high temperatures.

It should be noted that the obtained corrosion rates in high-parameter and high-purity water (parallel tests) were lower than the corresponding rates which we have obtained earlier in semidynamic tests. Circulation of boric acid solutions can exert an even stronger influence on the corrosion rates, however, these values do not change to such an extent as to preclude the use of data obtained in static tests that are performed under different conditions for determining the effect of individual factors.

The low values of corrosion weight indices that are given in Tables 2 and 3 render quantitative generalizations difficult. Nevertheless, the sufficient reproducibility of weight analyses in these experiments made it possible to use a comparison of these quantities for substantiating the conclusions concerning the effect of boric acid concentrations on the stability of metals under various conditions.

The following dependences were observed in boric acid solutions with concentrations from 0.23 to 1.13 g/liter for pH = 5.8-5.5 at 335°C and under a pressure of 140 atm in correspondence with the data in Table 2.

TABLE 2. Corrosion of Specimens at 335°C and 140 atm. Static Tests in Autoclaves

| Material | Testing time, hr | Specimen surface treatment | Corrosion rate, g/m$^2$ hr | | |
|---|---|---|---|---|---|
| | | | high-purity water | high-purity water with addition of 0.23 g/liter $H_3BO_3$ | high-purity water with addition of 1.13 g/liter $H_3BO_3$ |
| 1Kh18N9T | 1000 | Untreated | 0.0005 | 0.0007 | 0.0007 |
| | 1000 | Mechanically polished | 0.0003 | 0.0009 | 0.0008 |
| | 1000 | Electropolished | 0.0001 | 0.0002 | 0.0006 |
| Zirconium alloy with 2.5% niobium | 2000 | Untreated | 0.0011 | 0.0011 | 0.0015 |
| | 2000 | Polished and etched | 0.0013 | 0.0012 | 0.0016 |
| Zirconium alloy with 1% niobium | 2000 | Polished and etched* | 0.0008 | 0.0010 | 0.0009 |
| | 2000 | Mechanically polished | 0.0015 | 0.0014 | 0.0011 |
| Steel 20 | 1000 | Untreated | 0.0040 | 0.0037 | 0.0041 |
| | 1000 | Electropolished | 0.0019 | 0.0019 | 0.0021 |
| | 1000 | Mechanically polished | — | 0.0035 | 0.0038 |

* The specimens were etched in a mixture of the following composition: 5% concentrated HF, 45% concentrated $HNO_3$, and 50% water.

TABLE 3. Corrosion of Specimens in a Boric Acid Solution with a $H_3BO_3$ Concentration of 5.65 g/liter (1.0 g/liter boron) at 310°C and 100 atm over a Testing Period of 150 hr

| Material | Specimen surface treatment | Corrosion rate (for 150 hr), g/m$^2$ hr |
|---|---|---|
| 1Kh18N9T | Untreated | 0.0030 |
| Zirconium alloy with 2.5% niobium | After testing in water at 310°C and 100 atm during 2000 hr (dense black film) | No weight changes observed |
| Zirconium alloy with 1.0% niobium | Same, but first etched | The same |
| | Same, but first mechanically polished | " " |
| Carbon steel 20 | Rust first removed by cathode etching in weak ammonia solution | " " |
| | Electropolishing | 0.0173 |

In the presence of boric acid, the corrosion rate of steel 1Kh18NGT specimens increased to a slight extent, while the corrosion rate of carbon steel 20 and zirconium alloys remained practically unchanged.

In accordance with the data given in Table 3 the following results were obtained in a boric acid solution with a higher concentration (5.65 g/liter $H_3BO_3$) for pH = 5.2 a temperature of 310°C, and a pressure of 100 atm over a testing period of 150 hr. The corrosion rate of steel 1Kh18NGT specimens hardly increased in comparison with the corrosion rate in boric acid solutions with lower concentrations, but with higher parameters (see Table 2); for the comparison, the results obtained for a 150 hr period were reduced to a 1000-hr testing period. The specimens were covered with a goldlike layer, which indicated that steel oxidation took place.

The corrosion of untreated specimens of carbon steel 20 was accompanied by an increase in weight and the formation of dense oxide films on the steel surface, while the corrosion of electropolished specimens was accompanied by a small weight loss. In the case of zirconium alloys which were first tested in high-parameter water, hardly any corrosion phenomena were observed under the given conditions.

TABLE 4. Corrosion at 40°C and 1 atm with Free Oxygen Access over a Testing Period of 310 hr

| Medium | Material | Surface treatment | Corrosion rate, $g/m^2$ hr |
|---|---|---|---|
| Boron acid solution with 11.4 g/liter concentration of $H_3BO_3$ (2.0 g/liter boron) | Steel 20 | Untreated | 0.1520 |
| | Steel 20 | Mechanically polished | 0.1200 |
| | Kh5M2 | By cutting tool | 0.0065 |
| | OKh13 | By cutting tool | 0.0035 |
| | 1Kh18N9T | Untreated | 0 |
| | Zirconium alloy | Untreated | 0 |
| High-purity water | Steel 20 | Untreated | 0.0810 |
| | Steel 20 | Mechanically polished | 0.0470 |
| | Kh5M2 | By cutting tool | 0.0120 |
| | OKh13 | By cutting tool | 0.0013 |
| | 1Kh18N9T | Untreated | 0 |

Table 4 provides the data obtained in testing the materials in a boric acid solution with an 11.3 g/liter concentration of $H_3BO_3$ for pH = 5 at 40°C and with free oxygen access. The data obtained in a parallel test in high-purity water make it possible to determine the effect of boric acid on the stability of the materials that were tested under the above conditions.

Under free oxygen access conditions, carbon steel 20 was subject to considerable corrosion at 40°C in a high-purity water as well as in a boric acid solution. In both media pitting corrosion was observed, which was more intensive in the case of specimens that were tested in high-purity water. In both cases, the corrosion products were friable, and they passed into the solution in considerable quantities.

Steel Kh5M2 corroded in both media at a markedly lower rate than carbon steel. Thus, under the above conditions, alloying with chromium even below the stability threshold results in a considerable protective effect. However, the corrosion of this steel was also accompanied by pitting.

Specimens of ferrite steel OKh13 corroded in both media at a very low rate, while the corrosion rate in a boric acid solution was somewhat higher. Pitting damage was not observed on the specimens.

Specimens of steel 1Kh18N9T and zirconium alloys were almost free from corrosion damage under the above conditions.

A spectrographic analysis, which was made after the specimens were thoroughly rinsed, showed that boron does not penetrate the steel surface during tests in high-parameter solutions of boric acid at 40°C. However, the surfaces of zirconium alloys, after they have been tested in high-parameter solutions of boric acid, absorb boron in amounts exceeding their maximum allowable content in the alloy ($5 \cdot 10^{-5}$ %) by two to three orders of magnitude. In testing zirconium alloy specimens in a solution with a high boron concentration, but at 40°C, the absorption effect was not detected. Obviously, boron penetrated the growing $ZrO_2$ oxide film that was formed on the zirconium alloy surface during its corrosion in water and in high-parameter solutions [4].

## SUMMARY

1. The possibility of using boric acid solutions for the soft regulation of processes in nuclear reactors was demonstrated.

2. The introduction of boric acid in high-parameter water for the purpose of emergency injection should hardly disturb the stability of all the tested materials to be used in the first loop.

3. No decomposition of boric acid was observed in high-parameter water. Boric acid could be readily washed off the surface of the materials tested. No penetration of the surface of steels by boron was detected; however, irreversible absorption of boron at the surface of zirconium alloys was observed.

4. Ferrite steel OKh13 can be recommended as the material suitable for manufacturing storage tanks.

## LITERATURE CITED

1. W. Shoupp et al., Transactions of the Second International Conference on the Peaceful Uses of Atomic Energy (Geneva, 1958). Selected reports by foreign scientists [Russian translation] (Atomizdat, Moscow, 1958) Vol. 8, p. 492.
2. M. A. Tolstaya, G. N. Gradusov, and S. V. Bogatyreva, Zavodsk. Laboratoriya 25, No. 10, 1249 (1959).
3. U. Makhu, Voprosy Yadernoi Énergetiki No. 1, 68 (1959).
4. B. Lustman and F. Kerze, Metallurgy of Zirconium [Russian translation] (IL, Moscow, 1959).

---

All abbreviations of periodicals in the above bibliography are letter-by-letter transliterations of the abbreviations as given in the original Russian journal. *Some or all of this periodical literature may well be available in English translation.* A complete list of the cover-to-cover English translations appears at the back of this issue.

---

# ON THE CHARACTER OF RESIDUAL DEFECTS IN DEFORMED AND NEUTRON-IRRADIATED MONOCRYSTALS

E. V. Kolontsova

Translated from Atomnaya Energiya, Vol. 10, No. 3, pp. 227-232, March, 1961
Original article submitted September 22, 1960

By using x-ray diffraction and, in part, the etching method, we investigated defects that appear due to the action of irradiation (in LiF and $\alpha$-quartz crystals) and deformation (in LiF, aluminum crystals, etc.). A certain generality in the character of crystal structure defects was established.

The changes in the physical properties of crystals subjected to neutron irradiation are to a certain extent similar to changes in the properties of crystals when they are subjected to plastic deformation. Our tests also showed an increase in hardness, the ultimate strength, and the elasticity modulus and a decrease in thermal and electrical conductivity, while similar changes in the impact strength, the kinetics of phase conversions, etc. were also observed [1-5].

In our experiments, we compared the character of defects in the structure of monocrystals that were subjected to plastic deformation and neutron irradiation. The investigations were performed by using x-ray diffraction, mainly by comparing the intensity distribution of anomalous (diffuse) scattering, and partially by using the etching method. In studying the shape of the diffuse scattering maxima, we used monochromatic radiation, which made it possible to estimate the intensity of individual maxima, since the photographing of x-ray patterns were performed with a control specimen [6 and 7]. LiF ($8 \cdot 10^{17}$; $2 \cdot 10^{18}$; $3 \cdot 10^{18}$ and $5 \cdot 10^{18}$ neutrons/cm$^2$) and $\alpha$-quartz monocrystals ($10^{17}$; $10^{18}$; $10^{19}$ neutrons/cm$^2$) were subjected to neutron bombardment, while ion-type monocrystals (LiF, NaCl, KCl, and AgCl) and metallic monocrystals (aluminum, zinc, cadmium, and tin) were subjected to plastic deformation by extension. The choice of specimens was determined by the properties of crystals on the one hand and by the investigation method on the other hand.

Experimental data indicate that the intensity of diffuse scattering in irradiated or deformed aluminum and $\alpha$-quartz monocrystals has a higher value. Thus, in $\alpha$-quartz that was irradiated in a beam of $10^{19}$ neutrons/cm$^2$, the intensity of diffusion maxima increased by a factor of approximately 1.5 [6], while in monocrystals of technically pure aluminum, which were deformed in extension by 7-10% (elongation), the intensity increased by approximately 15%.*

The beginning of a marked increase in intensity depends on the degree of deformation or on the total neutron flux value, respectively. This is quite natural, since, under the action of deformation or neutron bombardment, disturbances in the regular crystal structure must arise, while, as was shown in [9 and 10], the presence of statistically random distributed defects of a certain given type causes additional diffuse scattering, the distribution of which will be determined by the crystals's elastic characteristics. Thus, if the shape of diffuse scattering maxima does not change and the intensity increases, which is true for $\alpha$-quartz, pure aluminum, and technically pure aluminum crystals that are grown by using the method of treatment recrystallization [11], this means that defects with a statistically random distribution appeared in the crystals during the deformation or irradiation processes.

The analysis of changes in the shape of Laue maxima with a consideration of the additional anomalous scattering, as well as etching data, can be used for determining the character of these defects. Judging according to the observed broadening of Laue maxima and the intensity redistribution in them, we arrive at the conclusion that the action of deformation or irradiation [7 and 12] causes the division of a crystal into separate portions (fragments) which are slightly rotated with respect to each other. The presence of fragmentation in crystals is convincingly proved by photographs obtained by means of a narrow x-ray beam [13] and by the etching process [7].

---

* A sharper increase in the intensity of diffuse scattering in neutron irradiation was observed by the authors of paper [8] in diamond, silicon, and corundum monocrystals.

The fragmentation does not occur uniformily throughout the volume: In plastically deformed crystals, it is most strongly pronounced near the slip bands [13] and the dislocation bands [14 and 15], while in irradiated crystals it is most strongly pronounced in the surface layer, the depth of which depends on the total neutron flux value [7].

The fragmentation character is determined by the type of action on the crystal and the nature of the substance under investigation. For instance, a division of crystals into fragments limited by type (100) planes was observed in irradiated LiF crystals [7], while, as is known, the cohesive forces for planes of this type are at a minimum in NaCl-type crystals. Thus, it can be assumed that the stresses arising in a irradiated crystal are released by the crystals' fragmentation into separate portions along the "slackness sites." It is possible that internal stresses arise due to the accumulation of implanted lithium ions [16] and the formation of relatively large portions with a new orientation, which is observed in the irradiation of crystals (LiF) as well as in deformation (LiF and aluminum). The presence of sections with a new orientation is determined with respect to the appearance of additional interference maxima on radiograms of irradiated and deformed crystals. For small degrees of deformation or irradiation, these maxima are rather clearly defined (Fig. 1; see also Fib. 3b), while the majority of them is superimposed on a background of thermal diffusion maxima of the initial crystal. However, maxima which are located at random with respect to the interference maxima of the initial crystal are also observed. With an increase in the degree of deformation or irradiation, the number of additional interferences increases, while their clarity diminishes (Fig. 2).

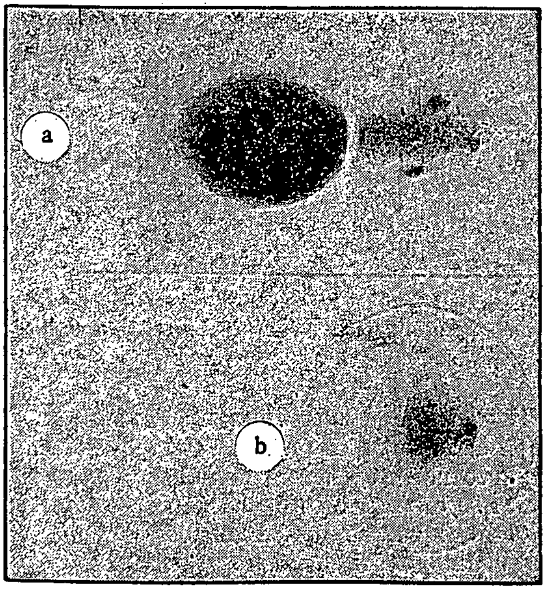


Fig. 1. Diffusion maxima of the (200) type. a) Technically pure aluminum monocrystal deformed by extension (2-3% elongation); b) LiF monocrystal irradiated with an intensity of $10^{18}$ neutrons/cm$^2$ (x 3.5).

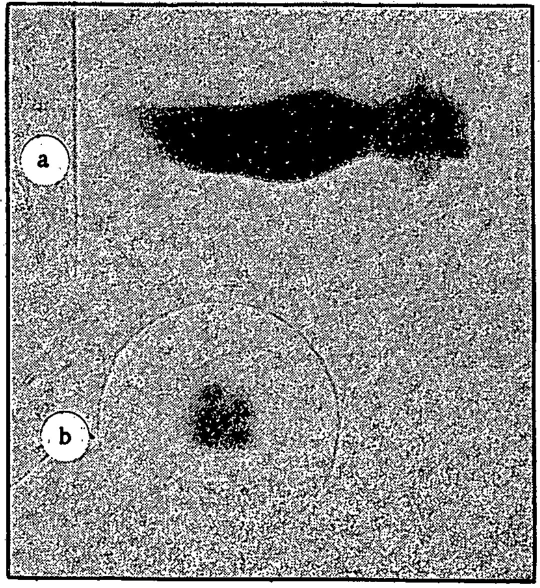


Fig. 2. Diffusion maxima. a) For aluminum, after the deformation was increased to 7% with respect to elongation; b) for LiF, after the total neutron flux was increased to $2.2 \cdot 10^{18}$ neutrons per cm$^2$ (x 3.5).

The appearance of clear additional interferences at the beginning of the action exerted on the crystal indicates the presence of relatively large portions in the crystal (up to $10^{-4}$ cm) with an orientation that is different from that of the initial crystal. The conclusion about the closeness of the orientation of the majority of such portions to the orientation of the initial crystal follows from the fact that the additional interferences are mainly superimposed on the background of diffusion maxima.*

The reduction in the clearness of interference maxima in irradiation and deformation processes can be probably explained by distortions which also appear in crystal portions with a new orientation, which is possible due to their additional fragmentation.

---

* It is possible that the appearance of additional interference maxima is caused by the so-called double Bragg reflection [17], but neither would this basically change the explanation of the results, since the secondary reflection of the x-ray beam becomes possible due to the appearance of individual portions inside the crystal with a crystal lattice orientation different from the initial ortientation.

A further increase in the degree of deformation and irradiation leads to the contraction of individual interferences into arc-shaped lines, while the extent of the lines depends on the nature and the state of the initial crystal for a given degree of deformation [12]. The number of lines that appear against the background of individual diffusion maxima also depends on the nature of the crystal. For all the irradiated LiF crystals and all the deformed monocrystals that we used (with the exception of technically pure aluminum, which was grown by using the method of collecting recrystallization), either one or two line maxima were observed (Fig. 3). In the case of some deformed monocrystals of technically pure aluminum, three lines were found (Fig. 4).

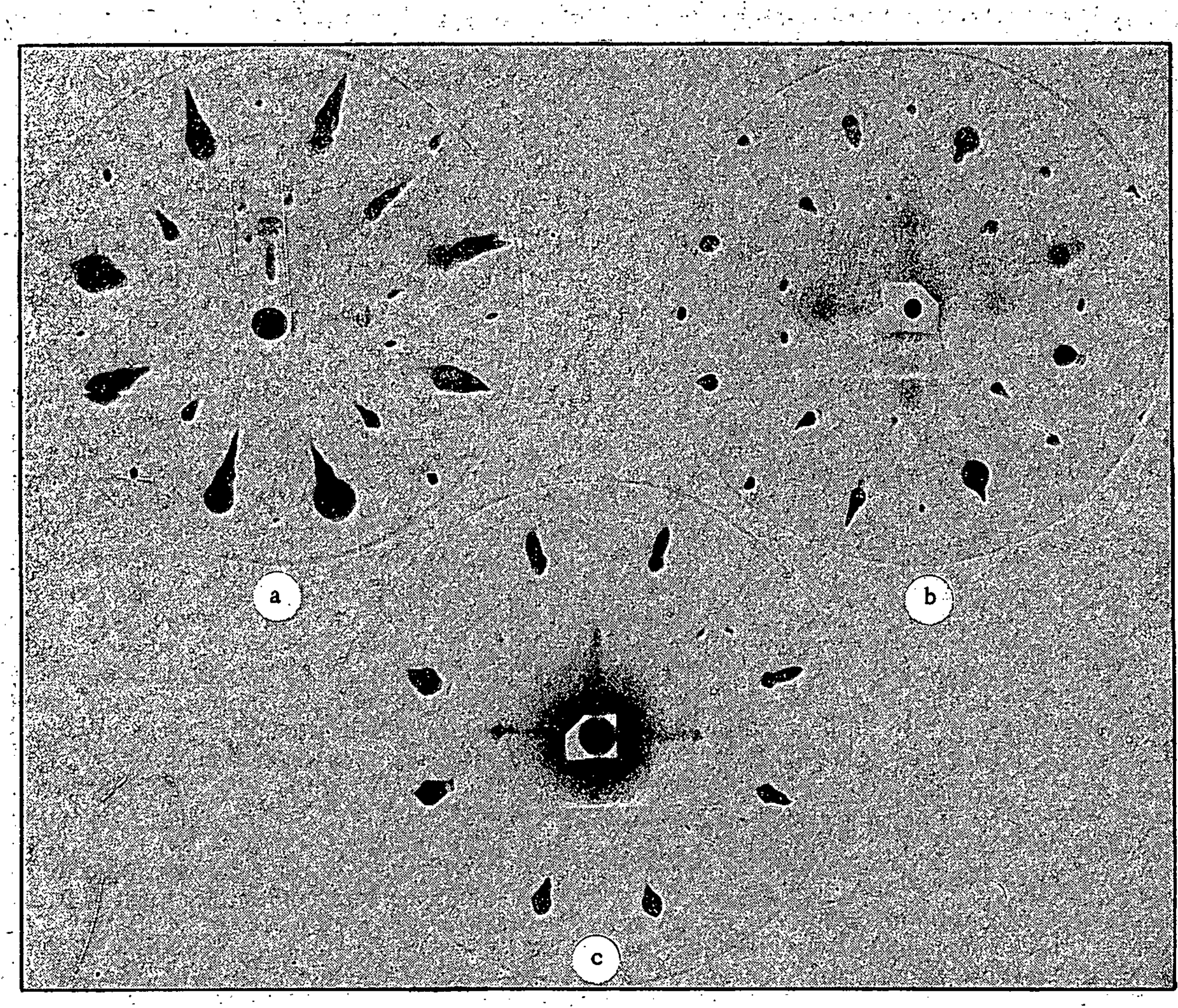


Fig. 3. Laue diagrams obtained for mixed molybdenum radiation. a) Deformed aluminum (7% elongation); b) LiF monocrystal deformed by compression; c) LiF monocrystal irradiated with an intensity of $3 \cdot 10^{18}$ neutrons/cm$^2$. The type [100] direction is parallel to the x-ray beam.

The appearance of line maxima in the shape of arcs of circles with different radii and a center which approximately coincides with the center of the radiogram indicates either the formation of sections inside the crystals that are slightly disoriented with respect to each other and with lattice parameters that are different from the lattice parameters of the initial crystal or, as was mentioned before, the possibility of secondary reflection of the reflected x-ray beam.* It is quite possible that both phenomena occur in deformed and irradiated crystals; however, this cannot be stated with certainty. Many difficulties are encountered in trying to separate these two effects, since the elimination of double Bragg reflection in using x-rays with ordinary wavelengths is apparently not possible. A theoretical separation of these effects by means of an accurate determination of the position of additional interferences that correspond to secondary reflection is also difficult, since exact calculation methods have not yet been developed.

---

* This phenomenon cannot be explained by the conditions under which the x-ray photographs were obtained, since the number of lines depends on the nature of the crystal and, moreover, the number of lines is the same for $K_\alpha$- as well as for $K_\beta$-radiation.

It should be noted that it is difficult to visualize such fragmentation which would cause the appearance of three clearly resolved maxima (see Fig. 4) in using only double Bragg reflection. It is also difficult to explain the appearance of all the additional interferences by parameter variations in individual crystal portions, if only for the reason that changes in the distance between the additional maxima in dependence on the reflection angle do not strictly follow the law which results from the constancy of average parameter changes throughout the crystal volume. The relatively large degree of parameter variation – approximately 3% – also causes some doubt.

Three different phenomena can possibly cause the appearance of sections with a new orientation: in the first place, fragmentation, which is clearly observable in deformation and irradiation; in the second place, the formation of displacement zones in irradiated crystals [18], which is seemingly due to local melting and subsequent crystallization of the substance. The orientation of the majority of these recrystallized regions must be close to the initial crystal orientation, since the surrounding initial crystal plays the role of inoculation in crystallization [4].

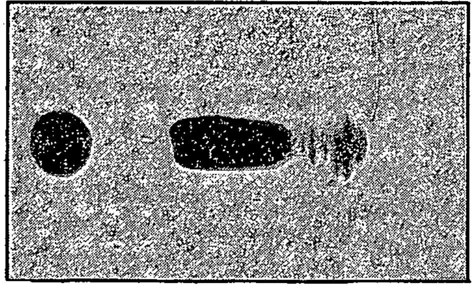


Fig. 4. Shape of type (200) interference maxima on the radiogram of an aluminum monocrystal that was 35% deformed by extension, which was obtained for mixed radiation (x 2).

In crystals deformed at room temperature, the reorientation of individual sections can follow the recrystallization pattern. Conditions that are favorable to this process are created near the slip and dislocation bands. Photographs obtained by means of an electron microscope confirm this point of view: Sections with regular etching pattern contours are observed near the slip bands, while the etching pattern contours are sharply distorted in the remaining sections of the [17]; the latter fact also applies to irradiated crystals [6]. It is possible that the cause of distortions is connected with the appearance of defects that are distributed statistically at random in the crystal, which makes it difficult to determine by etching the planes and directions in crystals in correspondence with the crystal chemistry of the specimen under investigation and the etching agent properties. However, it is possible that the distortion of etching pattern contours in deformed specimens is caused by slips resulting in the displacement of crystal sections with respect to each other, while in irradiation, specific defects, which are characteristic only for the irradiation process (for instance, segregation of lithium ions in an LiF crystal [15], shift zones [18], etc.), play the main role.

The analogous character of the appearance of residual defects in deformed and irradiated crystals still does not indicate that the cause of these defects is the same. The quantitative difference in the process of property restitution in crystal annealing is apparently connected with the difference between the causes of defects in deformation and irradiation, although, qualitatively, annealing or even "resting" at room temperature promote the "healing" of the crystal lattice of deformed as well as irradiated crystals [19].

It should also be mentioned that although the effects of deformation were investigated on LiF crystals, the effect similar to the effect of two-dimensional diffraction, which can be observed in irradiated LiF crystals, was not observed regardless of the indications that oriented defects that are located along the boundaries of slip packages are present in deformed aluminum and LiF crystals. It is possible that this difference is caused by the different number of oriented defects in deformation and in irradiation, since it is not possible to deform LiF crystals to a considerable extent at room temperature. However, it is possible that such defects as the segregation of lithium ions [15] or the accumulation of dislocation-type defects [7] play an important role in irradiated LiF crystals.

On the basis of what has been said above, the following conclusions can be drawn.

1. Point-type defects in the regular crystal structure which have a statistically random distribution appear in irradiated and deformed monocrystals; the presence of these defects causes an increase in the diffusion scattering intensity.

2. In the deformation process as well as in neutron irradiation, small sections whose orientation differs from the initial crystal orientation are formed in crystals. For the majority of these sections, the new orientation is close to the initial orientation.

3. The number of sections with the new orientation increases with an increase in the degree of deformation or irradiation. The beginning of reorientation depends on the nature of the crystal.

4. The crystal fragmentation that is observed in deformation and irradiation is not uniformily distributed throughout the crystal volume. For deformed crystals, the fragmentation is strongly pronounced near the slip and dislocation bands, while for irradiated crystals it is strongly pronounced in the surface layer, the depth of which depends on the total neutron flux value.

## LITERATURE CITED

1. Effect of Nuclear Radiation on the Structure and Properties of Metals and Alloys [in Russian] (Metallurgizdat, Moscow, 1957).
2. A. I. Zakharov, Usp. Fiz. Nauk 7, No. 4, 525 (1955).
3. S. T. Konobeevskii, V. I. Kutaitsev, and N. F. Pravdyuk, Transactions of the International Conference on the Peaceful Uses of Atomic Energy (Geneva, 1955) [in Russian] (Goskhimizdat, Moscow, 1958) Vol. 7, p. 582.
4. S. T. Konobeevskii, Atomnaya Énergiya No. 2, 63 (1956).*
5. A. I. Zakharov and O. P. Maksimova, Izv. AN SSSR, OTN 7, 3 (1958).
6. E. V. Kolontsova and L. A. Ignat'eva, Kristallografiya 4, No. 6, 56 (1960).
7. E. V. Kolontsova and M. I. Zhestovskaya, Kristallografiya 5, No. 1, 56 (1960).
8. S. T. Konobeevskii and F. P. Butra, Atomnaya Énergiya 5, No. 5, 572 (1958).*
9. K. Huang, Proc. Roy. Soc. A190, No. 1020, 102 (1957).
10. M. A. Krivoglaz, Zh. Éksperim. i Teor. Fiz. 34, No. 1, 204 (1958).
11. Yu. A. Bagaryatskii and E. V. Kolontsova, Kristallografiya 4, No. 6, 935 (1959).
12. E. V. Kolontsova, Zh. Éksperim. i Teor. Fiz. 21, No. 7, 821 (1951).
13. E. V. Kolontsova, Dokl. AN SSSR 93, No. 5, 795 (1953).
14. E. V. Kolontsova, I. V. Telegina, and G. M. Plavnik, Kristallografiya 1, No. 4, 419 (1956).
15. E. V. Kolontsova and I. V. Telegina, Kristallografiya 2, No. 5, 658 (1957).
16. A. Guinier and M. Lambert, Compt. rend. 246, No. 11, 1678 (1958).
17. H. Fricke and V. Gerold, J. Appl. Phys. 30, No. 5, 661 (1959).
18. D. A. Brinkmen, Effect of Nuclear Radiation on the Structure and Properties of Metals and Alloys [in Russian] (Metallurgizdat, Moscow, 1957) p. 5.
19. O. P. Maksimova and A. I. Zakharov, Collection: Problems in the Metallography and Physics of Metals [in Russian] (Metallurgizdat, Moscow, 1957) Vol. 5 p. 528.

All abbreviations of periodicals in the above bibliography are letter-by-letter transliterations of the abbreviations as given in the original Russian journal. *Some or all of this periodical literature may well be available in English translation.* A complete list of the cover-to-cover English translations appears at the back of this issue.

---

* Original Russian pagination. See C. B. translation.

# THE SEPARATION OF RADIUM FROM IMPURITIES BY MEANS OF AMMONIUM CARBONATE

N. P. Galkin, A. A. Maiorov, G. A. Polonnikova,
V. G. Shcherbakova, and L. V. Utkina

Translated from Atomnaya Énergiya, Vol. 10, No. 3, pp. 233-237, March, 1961
Original article submitted August 11, 1960

In the literature there is a reference to the use of $NH_4HCO_3$ in a technological system for the purification of chemical uranium concentrates [1]. However, the conditions in which this process is carried out have not been described in detail. Moreover, it is known that during the analysis of acid solutions containing uranium, the addition of ammonium carbonate makes it possible to separate uranium from iron and aluminum [2]. It is of interest to study this method of separating uranium from impurities in greater detail. In the present work an investigation was made of the dissolution of pure $(NH_4)_2U_2O_7$ in solutions of $(NH_4)_2CO_3$ and $NH_4HCO_3$, the separation of uranium from the solution in the form of $(NH_4)_4[UO_2(CO_3)_3]$ and the behavior of certain impurities in the salting-out of crystals of this carbonate complex.

## The Dissolution of Ammonium Diuranate in $(NH_4)_2CO_3$ and $NH_4HCO_3$ Solutions of Different Concentration

The dissolution of ammonium diuranate in $NH_4CO_3$ and $(NH_4)_2CO_3$ solutions is due to the formation of the complex $(NH_4)_4[UO_2(CO_3)_3]$:

$$(NH_4)_2U_2O_7 + 6(NH_4)_2CO_3 + 3H_2O \rightleftarrows 2(NH_4)_4[UO_2(CO_3)_3] + 6NH_4OH; \qquad (1)$$

$$(NH_4)_2U_2O_7 + 6NH_4HCO_3 \rightleftarrows 2(NH_4)_4[UO_2(CO_3)_3] + 3H_2O. \qquad (2)$$

A weighed sample of freshly prepared ammonium diuranate with 70% moisture content was added to a heated solution of $(NH_4)_2CO_3$ or $NH_4HCO_3$ of fixed concentration. The solid/liquid ratio was 1 : 1.2 (solid – weight of the moist $(NH_4)_2U_2O_7$). The experiments were carried out in a special vessel for solubility determination, placed in a thermostat. The temperature during the experiment was kept at 40 ± 0.1°C. Equilibrium was practically established in 1 hr.

As may be seen from Fig. 1, the solubility of ammonium diuranate in $(NH_4)_2CO_3$ solutions is less than in $NH_4HCO_3$ solutions. This may be explained by the effect of $NH_4OH$, which, being liberated according to reaction (1), displaces the equilibrium to the left.

With an increase in the $(NH_4)_2CO_3$ and $NH_3HCO_3$ concentration the uranium content in the solution first increases and then falls as a result of the salting-out effect of $(NH_4)_2CO_3$ and $NH_4CO_3$ [3]. To avoid the salting-out of $(NH_4)_4[UO_2(CO_3)_3]$ and obtain complete dissolution of ammonium diuranate, dilute solutions of $(NH_4)_2CO_3$ or, better, $NH_4HCO_3$ must be used. The amount of $(NH_4)_2CO_3$ or $NH_4HCO_3$ must correspond to the stoichiometric proportions according to reactions (1) and (2). In this case the total volume of liquid was calculated, taking into account the solubility of $(NH_4)_4[UO_2(CO_3)_3]$ in water at the given temperature [3]. For example, for complete dissolution of ammonium diuranate with 70% moisture content at 40°C in a 5% $NH_4HCO_3$ solution the solid/liquid ratio must be 1 : 5. Under these conditions the uranium concentration in the solution was ~ 40 g/liter.

## The Effect of Certain Factors on Crystallization of $(NH_4)_4[UO_2(CO_3)_3]$ from Solution

The salting-out of $(NH_4)_4[UO_2(CO_3)_3]$ by ammonium carbonate is due to the reduction in the solubility of the tricarbonate complex of uranyl in excess $(NH_4)_2CO_3$ [3]. We investigated a number of the most important practical

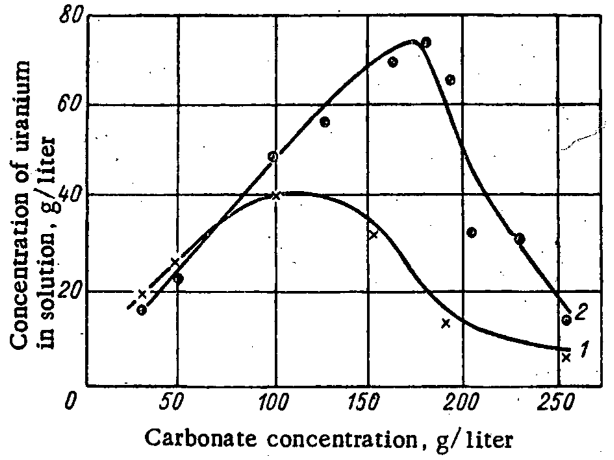


Fig. 1. Solubility of ammonium diuranate in $(NH_4)_2CO_3$ (curve 1) and $NH_4HCO_3$ (curve 2) solutions of different concentration.

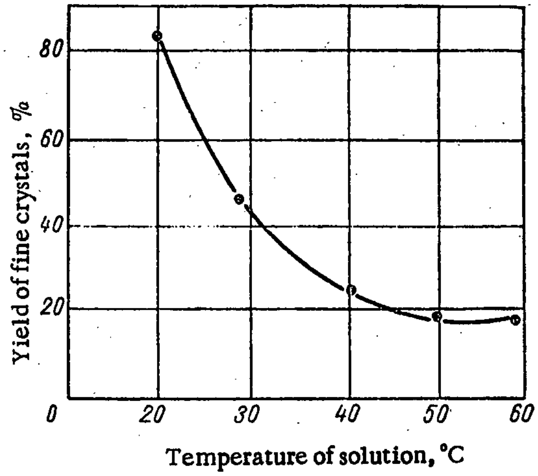


Fig. 2. The effect of temperature on the yield of fine crystals (size of the crystals $\leq 100\,\mu$); uranium concentration in the solution 30 g/liter; duration of addition of $(NH_4)_2CO_3$ 1.5 hr; speed of the stirrer 180 rev/min.

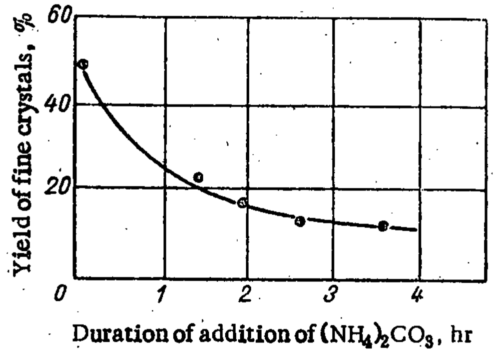


Fig. 3. The effect of the duration of the addition of $(NH_4)_2CO_3$ on the yield of fine crystals: uranium concentration in the solution 30 g per liter; speed of the stirrer 180 rev/min; temperature 40°C.

factors influencing crystallization : temperature, duration of addition of the salting-out agent, the uranium concentration in the solution, and the degree of mixing.

To compare the effect of the individual factors, the yield of coarse and fine crystals was determined by the sedimentation method. Crystals which settled out from a height of 25 cm in 1 minute in alcohol were assumed to be crude. The size of these crystals was 100 x 20 – 300 x x 60 $\mu$. The yield of fine crystals was found by the difference between the total amount and the amount of coarse crystals.

The experimental procedure was as follows: $(NH_4)_2CO_3$ was added for a fixed period with continuous stirring to a solution of $(NH_4)_4[UO_2(CO_3)_3]$ until the solution was saturated at the given temperature. After the completion of salting-out, the solution and the crystals were mixed for a further period. The total duration of the experiment was 3 hr. The precipitated crystals were filtered off and subjected to sedimentation analysis. The results of the experiments are given in Figs. 2-5. A photograph of the crystals is given in Fig. 6. A marked increase in the yield of fine crystals was observed with an increase in temperature, particularly from 20 to 40° (see Fig. 2). At the same time there was a considerable increase in the decomposition of $(NH_4)_2CO_3$.

With an increase in the duration of addition of $(NH_4)_2CO_3$ the number of fine crystals fell considerably (see Fig. 2). Thus, with rapid addition (2 min), the yield of fine crystals was 51%, while with slower addition (1 hr) it was 20%.

As may be seen from Fig. 4, the optimum uranium concentration in the solution must be taken as about 30 g/liter.

An increase in the speed of the stirrer from 60 to 180 rev/min leads to a nearly three-fold reduction in the yield of fine crystals (see Fig. 5). Faster stirring (450 rev/min) does not reduce the yield of fine crystals.

Figure 7 shows the variation of the uranium concentration in the solution during the salting-out of $(NH_4)_4[UO_2(CO_3]$. As may be seen from Fig. 7, the crystallization of the complex during the addition of $(NH_4)_2CO_3$ did not take place uniformly. Supersaturation of the solution was first observed. Rapid precipitation of $(NH_4)_4[UO_2(CO_3)_3]$ took place in

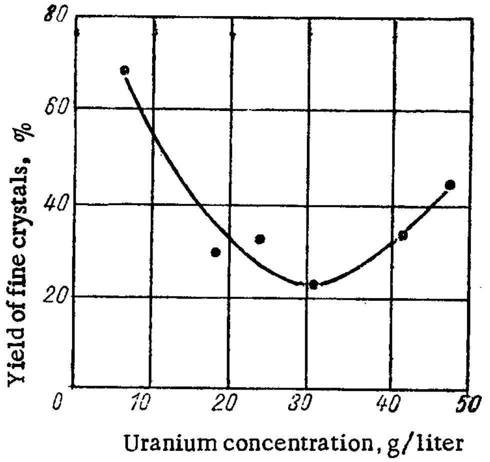


Fig. 4. The effect of the uranium concentration in the solution on the yield of fine crystals: duration of the addition of $(NH_4)_2CO_3$, 1.5 hr; speed of the stirrer 180 rev/min; temperature 40°C.

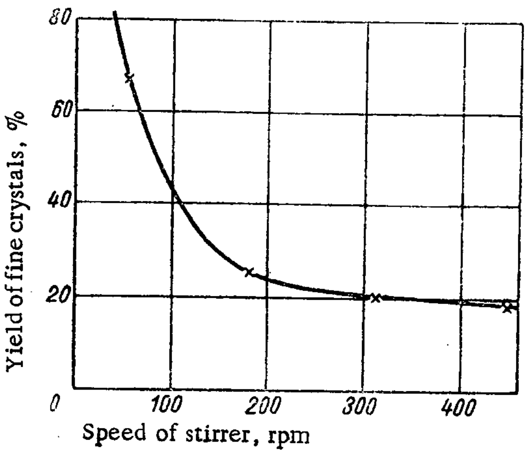


Fig. 5. The effect of the speed of the stirrer on the yield of fine crystals: uranium concentration in the solution 30 g/liter; duration of addition of $(NH_4)_2CO_3$, 1.5 hr; temperature 40°C.

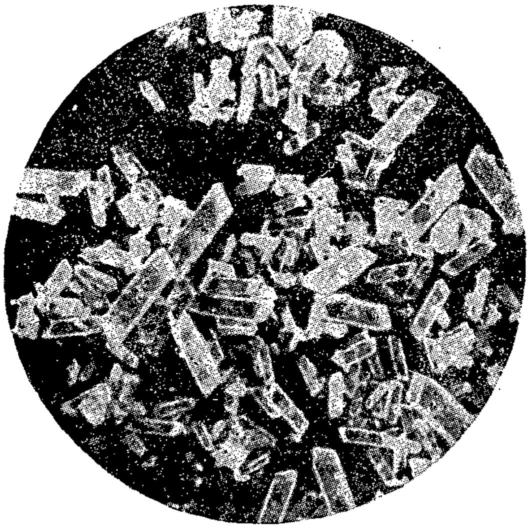


Fig. 6. $(NH_4)_4[UO_2(CO_3)_3]$ crystals (x 100).

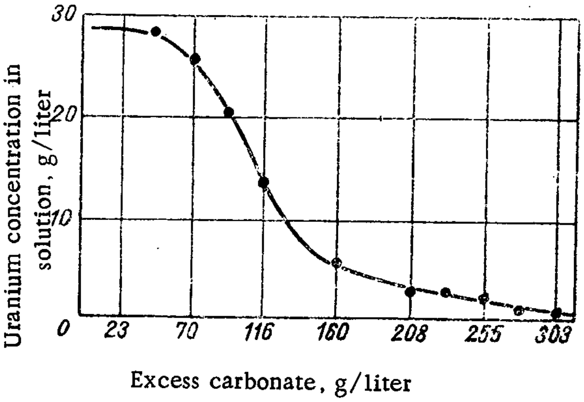


Fig. 7. Variation of the uranium concentration of the solution during the salting-out of $(NH_4)_4[UO_2(CO_3)_3]$.

the $(NH_4)_2CO_3$ concentration region of 70-150 g/liter. Further addition of $(NH_4)_2CO_3$ to a concentration of 300 g/liter caused fairly slow precipitation of the remaining uranium from the solution. Quantitative precipitation of uranium did not take place.

On the basis of these experiments the optimum crystallization conditions may be taken as: temperature 40°C, duration of addition of $(NH_4)_2CO_3$ 1 hr, uranium concentration in the initial solution 30 g/liter, speed of the stirrer 180 rev/min. To avoid supersaturation of the solution, crystallization is best carried out in the presence of a seeding compound. In addition, the $(NH_4)_2CO_3$, the amount of which must be sufficient to give a carbonate content of 300 g/liter in the solution, must be added at different rates: the first 40-50% must be added in 45 min, and the remainder in 15 min.

## The Behavior of Impurities during Precipitation of $(NH_4)_4[UO_2(CO_3)_3]$ from Solution

In each series of experiments the content of impurities varied widely. The initial solutions were prepared as follows. Impurities forming soluble compounds in a carbonate medium (sodium, copper, phosphorus, boron, etc.) were added to the $(NH_4)_4[UO_2(CO_3)_3]$ solution directly before crystallization. Other impurities (iron, manganese, aluminum) were precipitaed at the beginning, together with uranium, by ammonia. The ammonium diuranate obtained, containing one of these elements, was dissolved in a 5% $NH_4HCO_3$ solution. The undissolved residue was filtered and $(NH_4)_4[UO_2(CO_3)_3]$ was crystallized from the solution under optimum conditions. The crystals were filtered and washed with a saturated solution of $(NH_4)_2CO_3$. After the $(NH_4)_4[UO_2(CO_3)_3]$ crystals had been dried they were heated to the mixed oxide. The results of the experiments are given in Table 1.

TABLE 1. Separation of the Impurities in Uranium by Means of $(NH_4)_2CO_3$

| Impurities soluble in $(NH_4)_2CO_3$ | | | Impurities insoluble in $(NH_4)_2CO_3$ | | |
|---|---|---|---|---|---|
| Element | Content of impurity in initial solution, g/liter | Content of impurity in uranous-uranic oxide, as % of uranium | Element | Content of impurity in ammonium diuranate, as % of uranium | Content of impurity in uranous-uranic oxide, as % of uranium |
| Cu | 1,9<br>1,0<br>0,1<br>0,01 | 0,015<br>0,007<br>$<$0,0001<br>$<$0,0001 | Fe | 4,0<br>1,0<br>0,4 | 0,12<br>0,055<br>0,039 |
| B | 0,1<br>0,01<br>0,001 | $\geq 1\cdot10^{-4}$<br>$1\cdot10^{-4}$<br>$1\cdot10^{-5}$ | Mn | 5,0<br>0,52<br>0,16 | 0,059<br>0,012<br>0,0083 |
| V | 0,5<br>0,1<br>0,01 | 0,076<br>0,039<br>0,0032 | Al | 21,0<br>8,0<br>0,83 | 0,0059<br>0,0059<br>0,0048 |
| P | 2,0<br>1,0<br>0,1<br>0,01 | 0,20<br>0,165<br>$<$0,001<br>$<$0,001 | Cr | 8,06<br>0,83<br>0,08 | 0,115<br>0,077<br>$<$0,01 |
| Na | 10<br>5<br>1 | 0,012<br>0,007<br>0,001 | — | — | — |
| K | 10<br>5<br>1<br>0,1 | 16,6<br>7,9<br>1,64<br>0,102 | — | — | — |

TABLE 2. Purification of Ammonium Diuranate by Means of $(NH_4)_2CO_3$

| Product | Content, wt.% (converted to uranium) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Fe | Al | P | V | Mn | Cu | Cr | Si |
| Initial ammonium diuranate | 15,0 | 26,0 | 0,66 | 0,10 | 1,3 | 0,03 | 0,10 | 1,67 |
| Uranous-uranic oxide | 0,035 | 0,0059 | 0,012 | not detected | 0,035 | 0,0035 | 0,0047 | 0,0035 |

* The uranium content in the dry ammonium diuranate was 30.0%; in the uranous-uranic oxide, 84.0%.

From Table 1 it is seen that the majority of the elements (copper, boron, sodium, phosphorus, aluminum, etc.) are readily separated from uranium during the crystallization of the carbonate complex. Potassium, considerable amounts of which enter the crystals, is an exception. Thus, uranium can be separated by means of $(NH_4)_2CO_3$ not only from iron and aluminum, as already indicated in the literature, but also from a number of other elements. Data on the purification of dirty ammonium diuranate, which contained several impurities at the same time, agree well with this conclusion (Table 2). The initial ammonium diuranate containing 70% moisture was dissolved in a 5% $NH_4HCO_3$ solution with a solid/liquid ratio of 1:3.5. The other dissolution conditions were the same as described above. After the precipitated crystals of $(NH_4)_4[UO_2(CO_3)_3]$ had been washed and dried, they were calcined. The content of impurities in uranous-uranic oxide obtained in this way is indicated in Table 2.

## SUMMARY

1. The dissolution of ammonium diuranate in $(NH_4)_2CO_3$ and $NH_4HCO_3$ was investigated. It was found that to prevent salting-out of $(NH_4)_4[UO_2(CO_3)_3]$, the dissolution of the diuranate must be carried out in dilute solutions of $NH_4HCO_3$.

2. The optimum conditions for the crystallization of $(NH_4)_4[UO_2(CO_3)_3]$ from solution were established: temperature 40°C, uranium concentration in the solution of $(NH_4)_4[UO_2(CO_3)_3]$ about 30 g/liter, duration of addition of $(NH_4)_2CO_3$ 1 hr, speed of the stirrer 180 rev/min.

3. The efficiency of the separation of impurities from uranium by means of ammonium carbonate was investigated. It was shown that the separation of potassium by this method is unsatisfactory.

## LITERATURE CITED

1. Gelin, Mogard, and Nelson, Proc. Second International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1958. Selected Reports of Foreign Scientists [Russian translation] (Moscow, Atomizdat, 1959) 7, 417.
2. W. F. Hillebrand, et al., Practical Handbook of Organic Analysis [Russian translation] (Moscow, GNTI, 1957) 9, 478.
3. N. P. Galkin, A. A. Maiorov, and U. D. Vertyatin, Technology of the Processing of Uranium Concentrates [in Russian] (Moscow, Atomizdat, 1960).

# THE EFFECT OF RADIOACTIVITY OF SUBSTANCES ON THEIR PHYSICOCHEMICAL PROPERTIES

L. M. Kopytin and Yu. V. Gagarinskii

Translated from Atomnaya Énergiya, Vol. 10, No. 3, pp. 238-243, March, 1961
Original article submitted July 21, 1960

Radioactive substances have a number of features which can be explained by the effect of self-irradiation. Systems containing radioactive elements are in a nonequilibrium state. The fraction of particles (molecules, atoms, ions) having increased energy exceeds the equilibrium value in these systems. The regions of the substance in which there is retardation of the $\alpha$- and $\beta$-particles and the recoil atoms have a higher concentration than the equilibrium value of structure defects and increased free energy. These factors should affect the vapor pressure, solubility, dissociation pressure, equilibrium constants of chemical reactions, reactivity, specific heat, density, electrical conductivity, thermal conductivity and other properties of radioactive substances and also the character of their phase transformations. From this point of view a study is made of literature data on some properties of various radioactive substances.

It is known that the properties of solids change considerably due to irradiation by high-energy particles. It would be quite natural to expect that the physicochemical properties of substances containing radioactive elements and, consequently, constantly under the action of its own radiation, will differ from those properties the substances would have if they were not radioactive. The differences in the radioactive properties of isotopes of the same element (type of decay, energy of decay, specific activity) should cause, as well as the ordinary isotope effect, additional differences in the physicochemical properties of substances containing these isotopes.

A common feature of systems containing radioactive substances is their nonequilibrium state due to the constant formation in the mass of the substance of $\alpha$- or $\beta$-particles and recoil atoms, the process of retardation of which in the substance removes the system from the state of thermodynamic equilibrium. It is only possible to talk arbitrarily about the temperature of such a system, since there cannot be temperature equilibrium in it: during $\alpha$-decay in a radioactive substance thermal peaks are formed – local increases in temperature during short intervals of time of about $10^{-10} - 10^{-12}$ sec [1-5]; during $\beta$-decay, although it is not possible to talk of the presence of thermal peaks, a fraction of the particles (molecules, atoms, ions) with high energy exceeds the equilibrium value. In regions of a crystalline body, in which there is retardation of the particles and recoil atoms emitted during radioactive decay, different structure defects are formed (vacancies, intermediate atoms, etc.) in concentrations exceeding the equilibrium values.

The effect of self-irradiation on some heterogenous processes (absorption, catalysis, isotope exchange, solution) was studied in [6-8]. However, self-irradiation should cause a change in properties of radioactive substances such as the vapor pressure, the dissociation pressure, the equilibrium constants of chemical reactions, the reactivity, density, electrical conductivity, thermal conductivity, specific heat, mechanical properties, etc., and should also affect the character of phase transformations occurring in the radioactive substances.

In the study of radioactive substances a number of features have been detected which have not yet been satisfactorily explained. As far as we know, no attempt has been made to explain these features by the radioactivity of the substances although many of these features, in our opinion, can be explained in this way.

We will consider the effect of radioactivity on the vapor pressure. The saturated vapor pressure is determined by the fraction of molecules having energy sufficient to overcome the forces of adhesion and transfer into the gaseous phase. At temperatures much below the boiling point only a small fraction of the total number of molecules acquires this energy. In a system in which radioactive decay is taking place, the fraction of molecules having energy sufficient for transition to the gaseous phase is greater than the equilibrium value. In accordance with this in the stationary state the vapor pressure over a radioactive substance will be higher than the equilibrium value, corresponding to a given temperature. For radioactive substances in the crystalline state the presence of structure defects arising under the action of its own irradiation causes an increase in the free energy of the substances and, consequently, an increase in their vapor pressure.

It can be shown that the "vapor pressure – composition" diagram for a system containing a radioactive component should have a special character. We will consider a system of two substances A and B (substance B is radioactive) which would be ideal for nonradioactive substances. The experimentally measured vapor pressure of a pure radioactive component $P_B$ can be represented as $P_B^0 + \Delta P_B^0$, where $\Delta P_B^0$ is the increase in vapor pressure of the substance B caused by self-irradiation. The radioactivity of the component B will also affect the partial pressure of component A; therefore, the vapor pressure for intermediate compositions of such a system can be written $P + \Delta P$, $\Delta P$ is the increase in total pressure caused by the radioactivity of the substance B and composed of increases in the partial pressures of substances A and B, i.e.

$$\Delta P = \Delta P_A + \Delta P_B. \tag{1}$$

Assuming that the numbers of molecules A and B transferring into the gaseous phase under the action of self-irradiation are proportional to the molar fractions A and B, we obtain

$$\frac{\Delta P_A}{\Delta P_B} = \frac{N_A}{N_B}. \tag{2}$$

If we assume further that the total number of molecules transferring into the gaseous phase under the action of one act of decay is independent of the composition, then we can write

$$\Delta P = \Delta P_B^0 N_B. \tag{3}$$

From expressions (1-3) we obtain

$$\Delta P_B = \Delta P_B^0 N_B^2; \tag{4}$$

$$\Delta P_A = \Delta P_B^0 (N_B - N_B^2). \tag{5}$$

Consequently,

$$P_B = P_B^0 N_B + \Delta P_B^0 N_B^2; \tag{6}$$

$$P_A = P_A^0 N_A + \Delta P_B^0 (N_B - N_B^2); \tag{7}$$

$$P = P_A^0 + (P_B^0 - P_A^0 + \Delta P_B^0) N_B, \tag{8}$$

where $P_A^0$ and $P_B^0$ are the vapor pressures of the pure nonradioactive components A and B. The "vapor pressure – composition" diagram for such a system is shown schematically in Fig. 1. It is characteristic that in such a system the partial vapor pressure of the radioactive component has a negative, and the nonradioactive component has a positive, deviation from linearity; i.e., the deviations have opposite signs, which is not observed in the absence of radioactivity. These deviations compensate one another and the total vapor pressure in the system changes linearly with change in composition.* The tangent to the curve corresponding to expression (6) at the point $N_B = 0$ intersects the axis of pressures at $N_B = 1$; the section equal to $P_B^0$, i.e., a linear extrapolation of the data measured for small values of $N_B$ gives a value of vapor pressure of the substance B close to that which it would have if it were not radioactive.

We will consider the effect of radioactivity of the component B on the fractionation factor during distillation. In ideal systems the vapor pressure of pure components and the fractionation factor $\alpha$ are connected by a simple relationship

$$\alpha = \frac{P_A^0}{P_B^0}. \tag{9}$$

---

* The assumptions made in writing Eqs. (6)-(8) only hold in the first approximation; and the total vapor pressure in such a system, which would be ideal in the absence of radioactivity, cannot correspond to a linear dependence on composition.

In our case the fractionation factor, without allowing for the effect of radioactivity of the substance B in correspondence with relationship (9), would be equal to

$$\alpha = \frac{P_A^0}{P_B} = \frac{P_A^0}{P_B^0 + \Delta P_B^0}. \qquad (10)$$

It can readily be shown that the fractionation factor $\alpha$, due to the special character of the "vapor pressure – composition" curves expressed by Eqs. (6) and (7) with an allowance for the radioactivity of substance B, will be expressed by the equation

$$\alpha = \frac{P_A^0 + \Delta P_B^0 N_B}{P_B^0 + \Delta P_B^0 N_B}. \qquad (11)$$

It follows from Eqs. (10) and (11) that the content of radioactive substance in the distillate will be less than would be expected when only considering the vapor pressure of pure components.

Three isotopes of hydrogen with mass ratio 1:2:3 are considered ideal objects for studying the isotope effect on the physicochemical properties of substances, especially on the vapor pressure. However, the comparatively strong $\beta$-activity of tritium (the half life is about 12½ years) should affect the properties of this isotope and its compounds, and the effect of self-irradiation in this case is presumably comparable with the effect of the mass of the atom. For example, in [9] in which the vapor pressure was measured of almost 100% $T_2O$, it was noticed that the difference between the vapor pressures of $T_2O$ and $D_2O$ is much less than the difference between the vapor pressures of $D_2O$ and $H_2O$. This can easily be seen when comparing the boiling points of these modifications of water:

$H_2O$ (100.0°C); $D_2O$ (101.4°C); $T_2O$ (101.6°C).

The vapor pressures of HTO, calculated for the range 12-95°C as the geometrical mean of the vapor pressures of $H_2O$ and $T_2O$ [9], were much higher than the vapor pressures of HTO found by linear extrapolation of the partial vapor pressures of HTO over strongly diluted solutions of HTO in $H_2O$ [10]. The reason for this difference is intelligible when examining the diagram of Fig. 1. The existing experimental data on the vapor pressures of isotopes of elementary hydrogen are contradictory. The data of [11] obtained on a specimen of almost 100% $T_2$ and the data of [12] for a vapor pressure of HT and DT, obtained by linear extrapolation of the partial vapor pressures of HT and DT over their strongly diluted solutions to $H_2$ and $D_2$, respectively, are in the same ratio to one another as the data of [9] for $T_2O$ and [10] for HTO. However, the vapor pressures of HT found in [13] are much higher than those measured in [12].

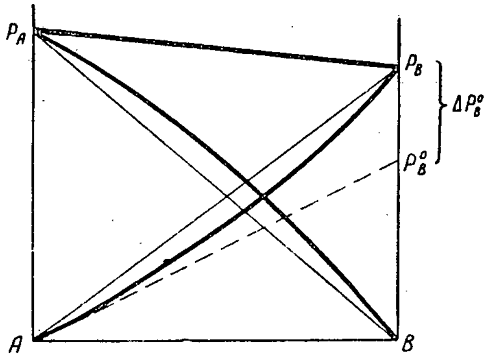


Fig. 1. "Vapor pressure – composition" diagram for a binary system of substances A and B in which substance B is radioactive.

The effect of self-irradiation on the vapor pressure of polonium ($Po^{210}$ $\alpha$-radiator with a half life of 138.4 days) should be very noticeable. It can be assumed that for this reason polonium has a comparatively low boiling point, which differs from the uniform increase in boiling point of elements of the main subgroup of the sixth group of the periodic table [14]: sulfur (444.6°C); selenium (684.8°C); tellurium (1390°C); polonium (962°C).

Comparing the vapor pressure curves of polonium and bismuth [15, 16] it can be concluded that the separation of polonium from bismuth by distillation should occur very readily. However, in practice it is found that polonium cannot be completely separated from bismuth even on repeated distillation. The author of [16] explains this by the formation in the bismuth-polonium system of intermetallic compounds or by the existence in this system of an azeotropic boiling mixture. However, it seems to us that this phenomenon is due to the radioactivity of the polonium. As can be seen from formula (11) in the case of radioactivity of one of the components, its fraction in the distillate should be less than that calculated from the vapor pressures of the pure components.

The relative effect of self-irradiation on the vapor pressure should decrease with increase in temperature. Therefore, for radioactive substances the curve for the dependence of the stationary pressure on the temperature will go higher and less deeply than the curve which would correspond to the equilibrium pressure. Therefore, the heat of vaporization calculated from the temperature dependence of the vapor pressure will be less than the true value for radioactive substances. For example, the heat of evaporation calculated in [15] for polonium is 24,597 ± ± 31 cal/g-atom. Dividing this value by the boiling point of polonium 1235°K, we obtain the Truton constant K = = 19.9 cal/deg-mole. Despite the fact that the true boiling point of polonium should be higher than 1235°K, the Truton constant for it is very small compared with similar constants for other metals, i.e., the value given for the heat of evaporation of polonium is low. The effect of self-irradiation on the dissociation pressure and on the vapor pressure should be similar. For example, it should be expected that the pressure of hydrogen over hydrides of radioactive metals will be higher than the equilibrium value.

The process of solution has a more complex character. During solution, as well as those factors which act during evaporation and dissociation, an important part can be played by other factors mentioned in [8], mainly the effect of electrical charges forming at the phase boundaries as a consequence of the continuous irradiation of charged particles by the radioactive substance on the structure of the double layer.

In the theoretical analysis of coprecipitation and fractional crystallization of radioactive substances [17-19] the effect of radioactivity has not yet been considered. Nevertheless it can play an important part here. In particular, the above-mentioned ideas on the effect of self-irradiation on the fractionation factor during distillation also hold with regard to the fractionation factor during isomorphic coprecipitation of radioactive substances. The solid phase should be enriched with a radioactive component to a larger extent than follows from the relative solubilities of the components. Therefore, the absence of parallelism between the change in fractionation factor and the ratio of solubilities of the corresponding salts, together with the reasons analyzed in [17, 18], can also be explained by the effect of self-irradiation.

We will deal with the features of phase transformations of radioactive substances. In the study of phase transformations of polonium it was found [20, 21] that the α- and β-phases of polonium can coexist over a wide range of temperatures.* In the study of phase transformations of freshly separated polonium by means of an x-ray spectrometer during heating and cooling of the specimen it was found [23] that the α- and β-phases of polonium coexist over the range 0-75°C. This wide range of temperatures of transformation cannot be explained by the presence in the specimen of lead formed by radioactive decay of polonium, since toward the end of the measurements [23] the lead concentration did not exceed 0.5%. The author of [20] is of the opinion that this phenomenon, as in the case of cobalt [24, 25], can be explained by the effect of the grain size on the transformation point. In fact, if the specimen is a collection of particles of different dimensions, then at low entropies of transformation and a large interphase surface energy this specimen has a transformation range rather than a point. However, it is known that in films obtained by the condensation of metals in vacuum the curve for the distribution of particles with regard to dimensions has a sharp maximum, i.e., all particles are obtained with almost the same size [26]. Consequently, the explanation given can hardly apply to the results of [20], in which the films of polonium were obtained by this method. However, it can be assumed that the reason for this phenomenon in polonium is connected with self-irradiation. For example, in [27, 28] it was shown that under the action of external irradiation by neutrons the low-temperature forms of $ZrO_2$ and $BaTiO_3$ change to high temperature forms at temperatures below their normal transformation points. This feature of the phase transformations of radioactive substances could be explained by the fact that the high-temperature phase which forms in the regions of local heating is hardened during further cooling of these regions below the transformation temperature. However, even for thermal peaks of separation this possibility is considered doubtful [29], since the time of existence of a peak (about $10^{-11}$ sec) is not so large compared with the period of thermal vibrations of atoms in the lattice (about $10^{-13}$ sec). The coexistence of phases of radioactive substances in the temperature range can be explained by the formation of structure defects in these substances under the action of self-irradiation. The assumption that the features of phase transformation of polonium are connected with radiation damage were already mentioned in [30], although this problem

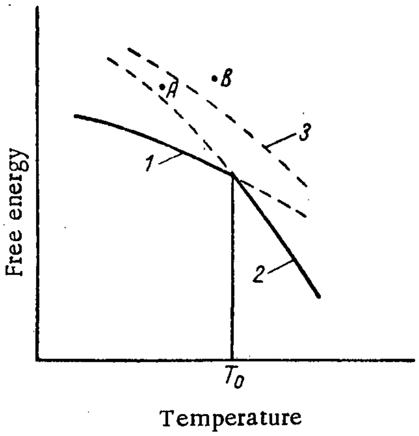


Fig. 2. Diagram of "free energy – temperature" for two mutually transforming phases of a radioactive substance; 1) α-phase; 2) β-phase; 3) metastable phase; A and B are the states of some regions passing through the thermal peak.

was not dealt with specifically. The effect of self-irradiation of radioactive substances on their phase transformations can be presented in the following way. The concentration of defects in regions passing through the state of the thermal peak considerably exceeds the equilibrium value; the intermediate atoms and vacancies deform the latter; therefore, these regions have increased free energy and are in the metastable state. In Fig. 2 the lines 1 and 2 show schematically the temperature dependence of the free energies of the $\alpha$- and $\beta$-phases respectively. Point A shows the state of the region passing through the thermal peak. In this state the free energy of this region exceeds the free energy of the metastable region at a given temperature of the $\beta$-phase and at temperatures below the normal point of transformation $T_0$ the transition of the deformed sections of the $\alpha$-phase to the $\beta$-phase can be thermodynamically favorable. These sections can therefore reduce their energy in two ways: by migration and recombination of the defects and by successive transformation of the deformed $\alpha$-phase to the $\beta$-phase, metastable under these conditions and then to the state of the $\alpha'$-phase. The actual path of this process depends on the corresponding activation energies. These discussions also hold for transition of the high-temperature phase from a disordered state to a stable state at temperatures above the normal transformation point. Therefore, if the transition of the disordered regions to the stable state is accomplished in the second way, then the two mutually transforming phases of the radioactive substance will have not a point, but a range of transformation.**

The possibility is not excluded of the formation under the action of irradiation of metastable structures, which generally do not have stable existence. If due to a thermal peak the region of the radioactive substance transfers to a state (point B on Fig. 2) in which its free energy exceeds the free energy of a certain metastable phase (line 3, on Fig. 2) then on the return of this region to the stable state there is a possible intermediate formation of this metastable phase also.

Instead of a melting point, radioactive substances should also have a more or less wide range of the solid-liquid state. It might be thought that the melting point taken for polonium (254°C) is the temperature lying close to the lower boundary of this range. The true melting point of polonium should be higher.

The ideas mentioned in this paper can also explain to some extent those features in the behavior of plutonium (the unusually large hysteresis, the comparatively large scatter of data obtained on different specimens of metal and the poor reproducibility of results for the same specimen [31]), which are observed during thermal analysis, measurements of electrical conductivity and dilatometric studies of plutonium.

The concentration of defects in a specimen of plutonium should depend on its previous history. When heating a specimen to a high temperature a considerable part of the structure defects will be annealed, and immediately after cooling the state of the specimen is close to the equilibrium state. Under the influence of the radioactive decay the state of the specimen at a low temperature (when the annealing of the defects is hindered) deviates from the equilibrium value with the accumulation of defects. When a specimen passes through a certain temperature T is states during heating and cooling will differ, since on passing downward through this temperature the concentration of defects in the specimen is higher than on passage upward, when a large part of the defects is annealed at high temperatures. This fact can presumably serve as the reason for considerable hysteresis in properties, sensitive to structure defects. The different degree of disordering of the structure of the same specimen of plutonium as a function of its previous history can be one of the reasons for the poor reproducibility of data when studying the properties of plutonium.

In conclusion the authors would like to thank A. A. Bochvar for reading the article and for his valuable comments.

## LITERATURE CITED

1. F. Seitz, Disc. Faraday Soc. 5, 271 (1949).
2. F. Seitz and J. Keller, Reports of the International Conference on the Peaceful Uses of Atomic Energy (Geneva, 1955) Vol. 7 [in Russian] (Moscow, State Chemistry Press, 1958) p. 747.
3. I. Brinkman, J. Appl. Phys. 25, 961 (1954).
4. S. T. Konobeevskii, Atomnaya Énergiya 2, 63 (1956).***
5. I. M. Livshits, M. I. Kaganov, and L. V. Tanatarov, Atomnaya Énergiya 6, 4, 391 (1959).***

---

* Naturally this statement does not contradict the phase rule which holds for equilibrium states.

** Since the entropy of transformation of metal phases does not usually exceed 3 cal/g·atom·deg, for a displacement of the transformation temperature, for example, by 30° it is sufficient to have an increase in free energy of 90 cal/g·atom. Assuming the excess energy of the defect equal to 10 ev [4], for a concentration of defects causing this increase we obtain a value of 1/2500.

*** Original Russian pagination. See C. B. translation.

6. V. I. Spitsyn, Izv. Akad. Nauk SSSR, Otdel. Khim. Nauk 11, 1296 (1958).
7. V. I. Spitsyn, Österr Chem. – Ztg. 60, 130 (1959).
8. V. I. Spitsyn, E. A. Torchenkova, and I. I. Glazkova, Doklady Akad. Nauk SSSR 132, 643 (1960).
9. M. M. Popov and F. I. Tazetdinov, Atomnaya Énergiya 8, 5, 420 (1960). *
10. A. Price, Nature 181, 268 (1958).
11. E. Grilly, J. Amer. Chem. Soc. 73, 843 (1956).
12. W. Libby and C. Barter, J. Chem. Phys. 10, 184 (1942).
13. J. Bigeleisen and E. Kerr, J. Chem. Phys. 23, 2442 (1955).
14. K. Bagnall, The Chemistry of the Rare Radioelements, London, Butterworths Scientific Publications, 1957, p. 84
15. L. Brooks, J. Amer. Chem. Soc. 77, 3211 (1955).
16. H. Weigel, Angew. Chemie 71, 289 (1959).
17. A. P. Ratner, Tr. Radievogo In-ta 2, 67 (1933).
18. A. Ratner, J. Chem. Phys. 1, 789 (1933).
19. V. G. Khlopin, Tr. Radievogo In-ta 4, 31 (1938).
20. C. Maxwell, J. Chem. Phys. 17, 1288 (1949).
21. W. Beamer and C. Maxwell, J. Chem. Phys. 17, 1293 (1949).
22. K. Bagnall and R. D'Eye, J. Chem. Soc. 4285 (1954).
23. J. Goode, J. Chem. Phys. 26, 1269 (1957).
24. O. Edwards and H. Lipson, J. Inst. Metals. 69, 177 (1943).
25. U. Dehlinger, Metallwirtschaft. 11, 223 (1932).
26. L. S. Palatnik and Yu. F. Komnik, Fizika Metallov in Metallovedenie 9, 374 (1960).
27. M. Wittels and F. Sherrill, J. Appl. Phys. 27, 643 (1956).
28. M. Wittels and F. Sherill, J. Appl. Phys. 28, 606 (1957).
29. Ch. Tucker and P. Senio, J. Appl. Phys. 27, 207 (1956).
30. R. M. D'Eye, J. Inorg. Nucl. Chem. 4, 367 (1957).
31. J. Ball, et al., Mem. Sci. Rev. Met. 57, 49 (1960).

All abbreviations of periodicals in the above bibliography are letter-by-letter transliterations of the abbreviations as given in the original Russian journal. *Some or all of this periodical literature may well be available in English translation.* A complete list of the cover-to-cover English translations appears at the back of this issue.

---

* Original Russian pagination. See C. B. translation.

# APPLICATION OF STABLE BORON ISOTOPES

S. P. Potapov

Translated from Atomnaya Énergiya, Vol. 10, No. 3, pp. 244-252, March, 1961
Original article submitted December 1, 1960

This article presents a brief survey of the basic applications of stable boron isotopes as materials with an altered isotope composition in cases where the differences between the nuclear properties of boron isotopes are used directly. The neutron flux transformation into heavy ionizing particles by means of the $B^{10}(n,\alpha)Li^7$ reaction and the large value of the effective thermal neutron cross section of this reaction make it possible to use $B^{10}$ in medicine, nuclear studies, and radiation chemistry. The differences between the neutron cross sections of $B^{10}$ and $B^{11}$ make it possible to use these isotopes in reactor construction and, in particular, to use $B^{10}$ in materials for control rods and reactor shields.

## Introduction

The rectification and chemical exchange methods are the basic boron isotope separation methods that are used for producing considerable quantities of these isotopes. In particular, the method of rectifying boron trifluoride [1] and boron trichloride [2], the method of the chemical exchange between boron trifluoride and its anisole complex [3], and some other methods are being used in practice or are under development in the USSR. The particulars of the above methods have been discussed in detail in [4]. Here, we shall note only certain factors which are decisive in determining the cost of the stable isotope $B^{10}$, which is most widely used at the present time.

1. The cost of the product is, in the first place, determined by the $B^{10}$ content. Figure 1 shows the dependence of the ration of the enriched product cost to the cost of a product with a concentration of 90% on concentration. It is obvious from the figure that the cost of products with a $B^{10}$ concentration exceeding 95% sharply increases. The curve was calculated by using the results obtained in [5] for a rectangular cascade, but it is also valid for other cascade shapes. Therefore, in practice, it is advisable to use enriched $B^{10}$, the choice of which is determined by the cost of producing $B^{10}$ with a given concentration as well as by the economic aspect of its application.

2. In the majority of cases, separating devices that are based on the above methods can be used without great expenditures for producing not only $B^{10}$, but also $B^{11}$. Correspondingly, the separation costs are distributed between these isotopes, and the cost of $B^{10}$ will be reduced approximately fivefold. It follows from the above that it is necessary to explore the possible uses of $B^{11}$, the practical utilization of which considerably lags behind that of $B^{10}$.

3. The cost of $B^{10}$ is to a considerable degree determined by the type of the chemical compound necessary for the actual utilization of this isotope in practice. In particular, elementary boron (or boron carbide $B_4C$) is necessary in certain cases where $B^{10}$ is used in reactor construction, while in isotope separation, $B^{10}$ is most often produced in the form of boron trifluoride (or in the form of its complex compounds with organic substances which readily dissociate in heating). However, sufficiently simple and efficient methods for obtaining elementary boron from boron trifluoride are still not available at the present time, which greatly increases the cost of $B^{10}$. Thus, according to data from [6], the cost of processing boron trifluoride for the production of elementary boron exceeds the cost of boron isotope separation by a factor greater than 1.5.

It should also be mentioned that the technology of producing boron-containing materials has not been sufficiently developed. For instance, in smelting boron steels that are used in reactor construction, approximately 50% of the boron that is introduced in the steel burns out [7]. Actually, these losses are much smaller in introducing $B^{10}$ into dispersion systems that are produced by using powder metallurgy methods [8]. Therefore, along with further improvements of boron isotope separation methods, it is necessary to improve the existing and to develop new, more perfect and efficient methods for producing elementary boron as well as various boron-containing materials and parts.

Stable boron isotopes are used as labeled atoms (tracers) and as materials with an altered isotope composition, where the differences between the nuclear properties of boron isotopes are used directly.

The application of boron isotopes as labeled atoms is not considered in the present article. We shall only mention that boron does not have radioactive isotopes which would be suitable as tracers in practice. Stable $B^{10}$ and $B^{11}$ isotopes are used for these purposes; in this they play an auxiliary role and provide only the means for investigations. As an example we can mention their application in studying the molecular structure of boric anhydride [9] and in investigating the growth of plants [10].

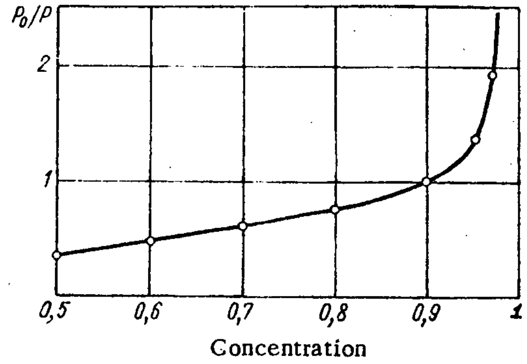


Fig. 1. Dependence of the relative cost of the enriched product on its concentration. P) Enriched product cost; $P_0$) cost of the 90% concentration product.

The present article is mainly concerned with the application of stable boron isotopes as materials with an altered isotope composition. Henceforth, for the sake of brevity, materials with enriched stable boron isotopes will be called "single-isotope materials."

## Application of Boron Isotopes as Single-Isotope Materials

The use of stable boron isotopes as single-isotope materials is based on the difference between the nuclear properties of these isotopes, in particular, the difference between their interactions with atomic nuclei and elementary particles.

For instance, the practical utilization of the reaction of interaction of boron isotopes with $\alpha$-particles, which is accompanied by the production of neutrons,

$$B^{10}(\alpha,\ n)N^{13} + 1{,}07\ \text{Mev, and}$$
$$B^{11}(\alpha,\ n)N^{14} + 0{,}15\ \text{Mev,}$$

is of considerable importance. These reactions are used for producing laboratory neutron sources (for instance, polonium sources) [11] as well as for analyzing boron-containing ores [12].

However, in the majority of cases, the practical application of boron isotopes is based on the differences between the nuclear properties of these isotopes, which are connected with the characteristics of their interaction with neutrons, in particular, thermal neutrons (see table).

Basic Characteristics of the Interaction of Stable Boron Isotopes with Thermal Neutrons

| Isotope | Content in natural boron, % | (n, α)-reaction cross section at 0.025 ev b | (n, γ)-reaction cross section at 0.025 ev, b | Energy of γ-radiation, Mev | Reaction of interaction with neutrons | Remarks |
|---|---|---|---|---|---|---|
| $B^{10}$ | 18,5 | 3820 [13] | 0,5 [13] | 4,47—11,43 [14] | 1) $B^{10}(n,\ \alpha)Li^{7*}+2{,}31$<br>2) $B^{10}(n,\ \alpha)Li^{7}+2{,}79$<br>3) $B^{10}(n,\ \gamma)\ B^{11}$ | Ratio of cross sections of reactions 1) and 2)<br>$\frac{\sigma_1}{\sigma_2} \simeq 0{,}925$ [15] |
| $B^{11}$ | 81,5 | — | $<50\cdot 10^{-3}$ [13] | 0,95—5,73 [16] | $B^{11}(n,\ \gamma)\ B^{12}$ [16]<br>($T_{1/2} = 0{,}019$ sec) | — |

It is obvious from the table that the light $B^{10}$ isotope is a good absorber of thermal neutrons. The absorption of neutrons by this isotope is relatively large even in the epithermal (intermediate) region [13], while, as can be seen from Fig. 2, the absorption cross section varies according to the $1/v$ law in a wide energy interval, where $v$ is the neutron velocity. The $B^{10}$ (n, $\alpha$) $Li^7$ reaction represents a particular case of light nucleus fission into $He^4$ and Li fragments. At the moment when they are generated, these fragments are partially or completely deprived of their electronic shells, and they move with a relatively low velocity, due to which they have a high ionizing ability. In 92.5% of the cases, the absorption of thermal neutrons by $B^{10}$ nuclei is accompanied by the emission of relatively soft $\gamma$-radiation with an energy of 0.478 Mev [15].

Due to the indicated properties of stable boron isotopes, boron and boron-containing materials have found widespread application, the efficiency of which becomes much greater if boron with a natural isotope composition is replaced by single-isotope materials with $B^{10}$ and $B^{11}$. We shall mention the basic fields where the above materials are used.

a) Medicine. The strong ionizing ability of $\alpha$-particles and $Li^7$ nuclei, which are produced in the capture of neutrons by the $B^{10}$ isotope, makes it possible to use boron in medical practice for the treatment of malignant tumors [17]. Certain boron-containing compounds accumulate in tumors in greater amounts than in healthy tissue. Therefore, if the diseased organ is irradiated with neutrons, the greatest amount of $\alpha$-particles and $Li^7$ nuclei, which destroy cancerous cells, are formed in the tumor as a result of the $B^{10}(n,\alpha)Li^7$ reaction. In order to secure the maximum biological defect, it is desirable to use $B^{10}$ with the greatest possible degree of enrichment.

The above treatment of cancer diseases was termed neutron-capture therapy. This method is especially useful and efficient in treating glioblastoma multiforme, which is one of the malignant forms of brain tumor that develop with the greatest rapidity [18].

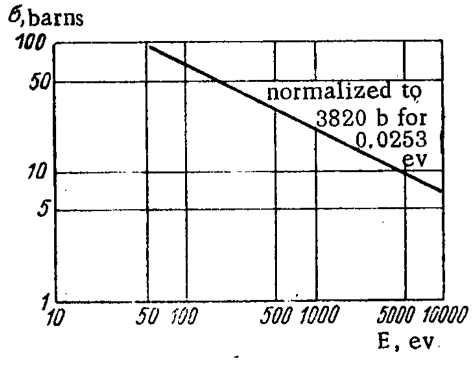


Fig. 2. Neutron absorption cross section of the $B^{10}$ isotope.

b) Nuclear physics equipment. The method of neutron capture therapy is based on the well-known phenomenon of neutron flux transformation into heavy ionizing particles as a result of the $B^{10}(n,\alpha)Li^7$ reaction. Due to the large thermal neutron absorption corss section of the $B^{10}$ isotope, the above transformation makes it possible to use boron to a great extent in nuclear physics equipment, in particular, in the construction of highly efficient neutron counters ("neutron data transmitters"). Ionization counters consisting of a chamber or a counting tube, where either gaseous $BF_3$ or thick boron layers on a metallic base-layer are introduced, gained the most widespread use. The use of the $B^{10}$ isotope instead of natural boron increases the sensitivity of counters four- to fivefold. Such counters are used not only in scientific research, but also in different branches of the national economy; for instance, in mineral prospecting [19].

$B^{10}$ is lately being used also in scintillation neutron counters. In some of them, slow neutrons are detected by recording the instantaneous 0.478-Mev $\gamma$-radiation by means of NaI (Tl) crystals. In other counters, for instance, in liquid boron counters, scintillations arising as a result of excitation by $\alpha$-particles and $Li^7$ nuclei are recorded. In scintillation counters, the scintillation time is shorter than the discharge time in ionization counters by approximately two orders of magnitude. Therefore, in the absence of $\gamma$-radiation, scintillation counters have advantages over gas ionization counters; for instance in measuring the neutron energy with respect to the flight time, where a high resolving power is required from neutron counters.

The application of $B^{10}$ in neutron detectors with semiconductor data transmitters should also be mentioned [20]. Such detectors can be used for determining the neutron energy. These data transmitters are so small that they do not distort the neutron spectrum.

c) Radiation chemistry. Not so long ago, the neutron flux transformation into heavy ionizing particles by means of $B^{10}$ had also been applied in radiation chemistry for acclerating radiation-chemical processes. As is known, nuclear reactors, which yield mixed radiation that also comprises neutrons besides intensive $\gamma$-radiation, are used, in particular, as ionizing radiation sources. With the aim of utilizing these neutrons with greater efficiency, it was proposed [21] to add enriched $B^{10}$ to the materials to be irradiated. Moreover, such admixtures, which are uniformily distributed throughout the material volume ("homogeneous admixtures"), reduce the probability of the formation of radioactive admixtures which is due to the neutron-activation of the substance to be irradiated.

In realizing such radiation-chemical processes, the role of boron atoms consists in the fact that they facilitate the "introduction" of heavy ionizing particles into the objects to be irradiated in the presence of a neutron field. In the case of surface irradiation, the particles would penetrate only a very thin layer a few microns thick. However, in some cases, the surface irradiation of materials by products of the $B^{10}(n,\alpha)Li^7$ reaction can also be usefully applied. The simple and original method of joining polymers by the localized action of neutron radiation is based on this effect [22]. The polymer surfaces to be joined, for instance, the surfaces of polystyrene and teflon, are wetted with a solution containing $B^{10}$ and are then irradiated in a sufficiently intensive neutron flux. Short-term heating (to a temperature of 1000°C) promotes the formation of polymer chains in the microvolumes along the tracks of ionizing particles; the polymer chains provide a firm bond between the polymer pieces (similar to spotwelding). Polymer pieces joined by using this method can withstand a load of over 100 $kg/cm^2$.

The possibility of using the $B^{10}(n,\alpha)Li^7$ reaction products for initiating radiation-chemical reactions in the gaseous phase should also be mentioned. At the present time, efficient and safe ionizing radiation sources that would be suitable for this purpose are still not available. The use of $\beta$- and $\gamma$-radiation sources is limted by the relatively low ionization density provided by $\beta$-particles and $\gamma$-rays. In using the existing sources of $\alpha$-particles, it is difficult to ensure adequate radiation protection in work. Moreover, the radiation yield of the existing types of plutonium $\alpha$-sources does not exceed $5 \cdot 10^5$ particles/$cm^2$.

Together with V. Gol'danskii et al., the author of the present article proposed an ionizing particle source for initiating gas reactions, the surface of which is covered with stable isotopes for the purpose of radiation protection, while the ionizing particles are generated only by the action of external neutron radiation on these isotopes. Sources of this type with the stable isotope $B^{10}$ ("boron sources") are most suitable for practical work. Such sources can be made, since there are known methods for producing boron glass wool and for depositing thin boron layers on metallic base-layers [23] and also because nuclear reactors can be used as neutron sources. Due to self-absorption in the boron layer, only these particles which are formed in a surface layer with a thickness of 0.4 $mg/cm^2$ can produce efficient ionization. For a thermal neutron flux of $10^{12}$ neutrons/$cm^2 \cdot$sec, $\sim 10^{10}$ ionizing particles can be produced per 1 $cm^2$ of a $B^{10}$ layer with the above thickness. In this, one-half of $B^{10}$ atoms will burn out in ~10 years. In particular, a multilayer radiator, through which the gas mixture to be irradiated is blown through, can be used as a boron source. The radiator consists of a set of flat surfaces or coaxial cylinders, which are covered with an isotope layer and which are spaced to allow the passage of gas. For sufficient total thickness of all isotope layers, the neutron flux can be almost completely absorbed in passing through the radiator. In this, the area of the surface emitting ionizing particles, for instance, in a boron radiator with a volume of 0.5 $m^3$, can attain ~2000 $m^2$ (for a boron layer thickness of 0.1 $mg/cm^2$).

The main disadvantage of such ionizing particle sources is the necessity of using a sufficiently intensive neutron flux. With the aim of utilizing neutrons with the greatest efficiency, the above sources can be used as component parts of neutron sources without, however, resorting to additional neutron consumption (for instance, in the shields of reactors intended for radiation-chemical processes).

d) Reactor construction. In contrast to the cases considered above, if stable isotopes are used in reactor construction, the generation of particles as a result of neutron absorption by the $B^{10}$ isotope plays not a positive, but a negative role, since it leads to a reduction in the radiation stability of boron-containing materials.

The use of boron isotopes in reactor construction is based on utilizing the difference between their nuclear properties and, in particular, the above-indicated particularities of the interaction between the $B^{10}$ isotope, and neutrons. Due to these features, natural boron containing 18.5% $B^{10}$ with $\sigma_{E = 0.025\ ev} = 755$ b has the following advantages as a neutron absorber over other elements that have large neutron capture cross sections (in barns, for E = 0.025 ev), such as:

| | |
|---|---|
| gadolinium | 46,000 |
| samarium | 5500 |
| europium | 4600 |
| cadmium | 2550 |
| dysprosium | 1100 |

1. Availability (second only to cadmium).

2. Highly penetrating $\gamma$-radiation, such as the radiation produced in neutron capture by elements with medium and heavy atomic weights, in particular, cadmium, does not appear in neutron absorption by boron. This can be explained by the small cross section of the $(n,\gamma)$-reaction (radiative capture) in boron isotopes (see table).

3. The cross section of the $B^{10}(n,\alpha)Li^7$ reaction does not have resonances in the epithermal region (see Fig. 1), while the cadmium neutron capture cross section varies less favorably (after resonance at 0.18 ev, it diminishes rapidly). Therefore, boron neutron absorbers are very efficient in a sufficiently wide energy interval.

The indicated advantages of boron offer great possibilities for using the most diverse boron-containing materials in reactor construction: boron steels, borides, boron carbides, etc. [24]. The efficiency of these materials becomes much higher if boron enriched with the $B^{10}$ isotope is added to them. Moreover, in certain cases, the use of $B^{10}$ for these purposes is not only desirable, but also necessary.

As an example, we shall consider the use of boron-containing materials for reactor control rods. If a control rod is to be sufficiently efficient, it is necessary that it intensively absorbs the reactor neutrons (that it is "black" with respect to the neutrons) or that it has a sufficiently great surface area. Neutron absorption in the rod is determined by the criterion $N\sigma t$ [25], where N is the number of the absorber's nuclei per 1 $cm^3$ of the material, $\sigma$ is the neutron absorption cross section which is averaged with respect to the energy spectrum of the reactor neutrons, and t is the thickness of the rod's boron-containing layer.

The dependence of the rod surface area on the criterion $N\sigma t$ is shown in Fig. 3, from which it is obvious that the surface area and, consequently, the dimensions of the rod sharply increase with a reduction in neutron absorption.

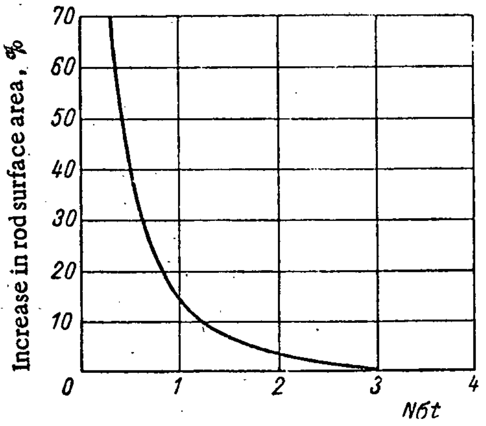


Fig. 3. Dependence of the surface area of rods on the degree of their neutron absorption.

In the majority of cases, the dimensions of control rods are limited. Therefore, it is necessary to increase their absorbing ability by introducing a large amount of boron into the material of which they are made. However, with an increase in the relative boron content, the mechanical properties of these materials deteriorate. For instance, boron steel is often used in reactor control rods [26 and 27]. By means of boron additions amounting to a few hundredths of a percent, the mechanical properties of steel can be improved, which is similar to the case of alloying steel with carbon: Its resistance to mechanical aging, the heat-resistance, and some other properties are improved. However, for larger boron additions, the mechanical properties of steel deteriorate to a considerable extent. Such steel is not readily amenable to rolling and it becomes very hard and brittle [28] (Fig. 4), although its heat resistance remains rather high, due to which it is possible to use absorbing rods made of this steel is cases where cooling is not provided [29].

Thus, in order to augment the neutron absorption in boron steel, considerably large boron additions are desirable. However, the boron content in steel must be small if its technological properties are to be preserved. This contradiction can be reduced to a considerable extent if, instead of natural boron, its stable isotope $B^{10}$ is used. If the $B^{11}$ isotope, which is useless from the point of view of neutron absorption, is removed from steel, then, for the same boron content, the neutron absorption in steel can be increased more than fivefold. Conversely, if an assigned absorbing ability of boron steel is to be secured, the relative boron content in it can be reduced more than fivefold if the stable isotope $B^{10}$ is used instead of boron with the natural isotope composition. The mechanical properties of steel can be much improved, as, for instance, in the case where the amount of the boron addition is reduced from 1% to 0.2% (see Fig. 4).

Great advantages are also to be obtained if natural boron is replaced by boron enriched with $B^{10}$ when used as an "addition that burns out," which is introduced in the reactor core for compensating excess reactivity at the beginning of a period of operation. Such additions were used in the reactors of the atomic icebreaker Lenin [30]. The use of absorbers that burn out considerably improves the fuel element operating conditions and it makes it possible to reduce the number of control rods. The use of boron enriched with $B^{10}$ instead of natural boron makes it possible to considerably reduce the amount of the additions to be introduced and, consequently, to reduce the changes in the mechanical properties of the materials to which boron is added [31].

In certain cases, for instance, in small-size devices [32], enriched $B^{10}$ can be used as a component in shielding materials, such as boral and boroxal [33], a polyethylene with boron, etc. The use of $B^{10}$ in shielding materials has a number of advantages. While having low specific gravity, a $B^{10}$ layer with a given thickness provides a 20 to 500 times as effective protection from neutron radiation as a layer of lead and concrete with the same thickness.* By placing a boron-containing material around the core, it is possible to improve the reactor core thermal shielding,

---

* The efficiency of actual boron-containing materials that are used for shielding (for instance, polyethylene with $B^{10}$) is correspondingly lower.

i.e., to reduce the thermal stresses that arise in it due to the heat release in the absorption of neutron- and $\gamma$-radiation. Finally, biological protection is secured and improved by introducing $B^{10}$ into the shielding materials. This can be explained by the fact that, due to the absorption of neutrons by the $B^{10}$ isotope which is accompanied by the emission of soft $\gamma$-radiation (0.478 Mev), the neutron capture in structural materials, in particular, steel [34], which produces high-energy $\gamma$-radiation, is reduced.

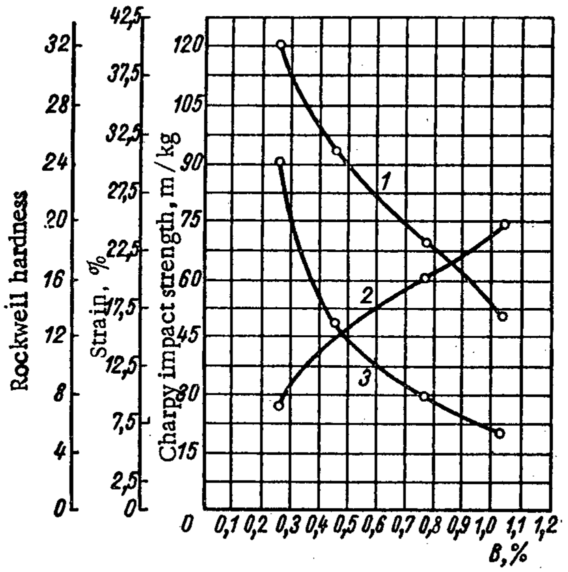


Fig. 4. Dependence of the mechanical properties of stainless austenite steel (18% chromium, 10% nickel, and 0.5% carbon) on the boron content. 1) Strain; 2) hardness; 3) impact strength.

It should also be mentioned that, due to the advantages of $B^{10}$ as a neutron absorber, this isotope can be used for the so-called antiactivation coatings [35]. The deposition of a thin coating layer that contains $B^{10}$ on the surfaces of parts makes it possible to prevent their activation by neutron irradiation in certain cases.

As was mentioned above, the mechanical properties of boron steels deteriorate considerably if their relative boron content increases. This can be explained by the fact that the solubility of boron in metals is very low. In connection with this, various methods for producing materials with a higher boron content, in particular, dispersion systems, which are produced by using the powder metallurgy method, are presently under development. In this respect, materials made of enriched boron that is dispersed in titanium [8], which have satisfactory mechanical properties for $B^{10}$ contents of up to 15%, are of considerable interest.

Such systems also have certain advantages in solving technical problems connected with increasing the radiation stability of materials. As is known, materials whose atom nuclei are subject to fission in a neutron field are most prone to radiation damage. The $B^{10}(n,\alpha)Li^7$ reaction represents a peculiar case of light nucleus fission. The "fragments" ($He^4$ and $Li^7$ nuclei) which are formed as a result of the reaction capture electrons at the end of their run and are thereby transformed into helium and lithium atoms, which occupy a volume approximately 20 times as large as the initial boron atoms [36 and 37]. Helium accumulates in the shape of bubbles, thereby causing the appearance of cracks and defects in the material's structure. Such radiation damage becomes especially serious under high-temperature conditions, when the evolution of gases becomes several times as large as before (for instance, in using boron-containing materials in reactor control rods).

It became evident that the above-mentioned materials with $B^{10}$ dispersed in titanium have a relatively high radiation stability for integral flux values of up to $\sim 4.6 \cdot 10^{20}$ neutrons/$cm^2$. The irradiation of specimens with 3.8% $B^{10}$ ( the depletion of $B^{10}$ amounts to 1.9%) in an integral flux of $2.39 \cdot 10^{20}$ neutrons/$cm^2$ does not cause damage to the material's structure. Similar results were also obtained for materials with enriched $B^{10}$ that is dispersed in steel [38].

Besides adding the $B^{10}$ isotope to materials that are made by using the powder metallurgy method, there are also other ways of increasing the radiation stability of boron-containing materials, among which the introduction of boron into boron-containing metal ceramics should be mentioned. Some of these metal ceramics, for instance, boron carbide in a ceramic with aluminum oxide ($B_4C - Al_2O_3$) [39] retain their initial volume almost without changes during the irradiation process without developing cracks. For an almost 100% depletion the diameter of a cylindrical specimen containing 2.2% $B_4C$ by weight in $Al_2O_3$ increased only by 1.2%, while the specimen's length did not change. The porosity of this specimen was from 15 to 35%.

In contrast to $B^{10}$, the heavy isotope $B^{11}$ has a very small neutron capture cross section (see table). Due to this property, $B^{11}$ can be used for developing boron-containing materials that weakly absorb neutrons [40]. For instance, if $B^{11}$ is added to boron steel with the aim of increasing its heat resistance, its neutron absorption hardly increases in comparison with ordinary stainless steel.

## SUMMARY

Thus, there is at present a possibility of considerably widening the use of boron isotopes in scientific research, technology, medicine, and other branches of the national economy. This is now possible due to the existence of sufficiently developed methods for boron isotope separation, which makes it possible to organize their production on an industrial scale. The greatest amounts of these isotopes, in particular, the $B^{10}$ isotope, are required in reactor construction. Therefore, a necessary condition for the successful application of stable boron isotopes is the development of simple and sufficiently efficient methods for producing these isotopes in elementary form and for introducing them into materials suitable for use in reactor construction. In other words, the development of inexpensive and readily available materials with $B^{10}$ and $B^{11}$ which would satisfy the strict requirements with repsect to the thermophysical and mechanical properties and which would have high radiation stability is now becoming an especially pressing problem.

## LITERATURE CITED

1. Yu. K. Myulenfordt, G. G. Zivert, and T. A. Gagua, Collection: Production of Isotopes, Powerful Gamma-Devices, Radiometry, and Dosimetry [in Russian] (AN SSSR Press, Moscow, 1958) p. 129.
2. N. N. Sevryugova, O. V. Uvarov, and N. M. Zhavoronkov, Dokl. AN SSSR 126, 1044 (1959).
3. G. M. Panchenkov, V. D. Moiseev, and A. V. Makarov, Zh. Fiz. Khim. 31, 1851 (1957).
4. N. N. Sevryugova, O. V. Uvarov, and N. M. Zhavoronkov, Atomnaya Énergiya 9, No. 2, 110 (1960).*
6. G. Miller et al., Report No. 1836 presented by USA to the Second International Conference on the Peaceful Uses of Atomic Energy (Geneva, 1958).
7. E. Houdremont, Special Steels [Russian translation] (Izd. Inostr. Lit., Moscow, 1960) Vol. 2, p. 1585.
8. L. Prus et al., Nucl. Sci. and Engng. 6, No. 3, 167 (1959).
9. T. A. Sidorov and N. N. Sobolev, Optika i Spectroskopiya 3, No. 6, 560 (1957).
10. J. McMurtrey and H. Engle, Plant Physiol. 28, No. 1, 127 (1953).
11. Experimental Nuclear Physics [Russian translation] (Izd. Inostr. Lit., Moscow, 1955) Ed. by E. Segre, Vol. 2, p. 310.
12. I. N. Plaksin, V. N. Smirnov, and L. P. Starchik, Dokl. AN SSSR 128, No. 6, 1208 (1959).
13. Atlas of Neutron Cross Sections [in Russian] (Atomizdat, Moscow, 1959).
14. L. V. Groshev et al., Atlas of the Spectra of Thermal Neutron Radiative Capture $\gamma$-Radiation [in Russian] (Atomizdat, Moscow, 1958).
15. G. Duren and H. Rosenwasser, Phys. Rev. 93, 831 (1954).
16. F. Ajzenberg-Selove and T. Lauritsen, Nucl. Phys. 11, 1, 111 (1959).
17. Atomics Engng Technology 7, 429 (1956).
18. K. Kholnen, Atomic Energy in Medicine [in Russian] (Atomizdat, Moscow, 1959) p. 142.
19. V. K. Khristianov, G. I. Panov, and A. A. Chernova, Geokhimiya, No. 2, 3 (1957).
20. Nucleonics 18, No. 2, 57 (1960).
21. British Patent No. 802552; W. Davidson and J. Geib, J. Appl. Phys. 19, 427 (1948).
22. I. M. Barkalov, V. I. Gol'danskii, and B. G. Dzantiev, Author's certificate No. 129 015, 1960.
23. N. S. Gorbunov, Diffusion Coatings for Iron and Steel [in Russian] (AN SSSR Press, Moscow, 1958) p. 108; B. Rossi and G. Staub, Ionization Chambers and Counters [Russian translation] (Izd. Inostr. Lit., Moscow, 1951).
24. H. Cowen, Nucl. Sci. and Engng. 4, No. 34, 11 (1959).
25. H. Stevens, Nucl. Sci. and Engng. 4, No. 3, 373 (1958).
26. Stal' No. 3, 269 (1959).
27. T. Middleham et al., Iron and Steel 30, No. 12, 526 (1957).
28. L. Prus, E. Byron, and J. Thompson, Nucl. Sci. and Engng. 4, No. 3, 415 (1958).
29. N. A. Dollezhal', A. K. Krasin, N. A. Nikolaev, A. N. Grigor'yants, and G. N. Ushakov, Transactions of the Second International Conference on the Peaceful Uses of Atomic Energy (Geneva, 1958). Repots by Soviet Scientists [in Russian] (Atomizdat, Moscow, 1959) Vol. 2, p. 15.
30. A. P. Aleksandrov, I. I. Afrikantov, A. I. Brandaus, G. A. Gladkov, B. Ya. Gnesin, V. I. Neganov, and N. S. Khlopkin, Transactions of the Second International Conference on the Peaceful Uses of Atomic Energy (Geneva, 1958). Reports by Soviet Scientists [in Russian] (Atomizdat, Moscow, 1959) Vol. 2, p. 60.
31. W. Ray, W. Neisz, and H. Cooper, Nucl. Sci. and Engng. 4, No. 3, 386 (1958).
32. Chem. Engng. 64, No. 5, 176 (1957).
33. J. Warde, Mater, and Methods 4, No. 2, 121 (1956).
34. D. L. Broder et al., Atomnaya Énergiya 8, No. 1, 49 (1960).*

---

* Original Russian pagination. See C. B. translation.

35. Usine Nouvelle, February 27, 1958, p. 37.
36. W. Anderson, Nucl. Sci. and Engng. 4, No. 3, 357 (1958).
37. D. Dunning, W. Anderson, and P. Mertens, Nucl. Sci. and Engng. 4, No. 3, 402 (1958).
38. C. Leiten, B. Beaver, and A. Richt, J. Nucl. Mater. 1, No. 2, 136 (1959).
39. W. Barney, G. Schmel, and W. Seymour, Nucl. Sci. and Engng. 4, No. 3, 439 (1958).
40. M. Legal, Rev. techn. CFTH, No. 25, 47 (1957).

---

All abbreviations of periodicals in the above bibliography are letter-by-letter transliterations of the abbreviations as given in the original Russian journal. *Some or all of this periodical literature may well be available in English translation.* A complete list of the cover-to-cover English translations appears at the back of this issue.

---

# INVESTIGATIONS OF THE RADIATION PURITY OF ATMOSPHERIC AIR AND OF THE RIVER NEVA IN THE REGION OF BERTH TESTS OF THE ATOMIC ICEBREAKER LENIN

Yu. V. Sivintsev, V. A. Knizhnikov, E. L. Telushkina,
and A. D. Turkin

Translated from Atomnaya Énergiya, Vol. 10, No. 3, pp. 253-258, March, 1961
Original article submitted September 7, 1960

During the berth tests of the atomic icebreaker Lenin, we investigated the amount of radioactive substances in the air of the central section holds, in the icebreaker's mainmast, as well as in the atmospheric air, river water, and flora and fauna in the region adjoining the test location. The investigation results indicate that the nuclear power plant of the atomic icebreaker Lenin is provided with a highly efficient radiation protection system, due to which the operation of this vessel is completely safe for the servicing personnel, the berth location, and the stationing of the icebreaker and the ships following in its wake.

As a rule, the operation of any nuclear power plant is accompanied by the discharge of artificially radioactive isotopes into the surrounding medium. In connection with this, much attention was paid to the development of a perfect radiation protection system [1] which would make it possible to reduce the discharge of gaseous and liquid radioactive waste from the vessel. In one of the papers devoted to the problem of radiation protection in atomic icebreakers, the concentrations of radioactive gases and aerosols in air that is pumped out of the central section (CS) holds where the three nuclear reactors are located were calculated. An analysis showed that the primary coolant loops are the basic sources of gas and aerosol activity in the case of bidistillate leakages. Moreover, the activation of argon in the air by the neutron flux in the immediate vicinity of the reactor can be important. According to the calculations performed, the available radiation protection system allowed the presence of negligibly small amounts of radioactive gases in the air of the CS holds under normal operating conditions of the nuclear power plant (of the order of hundredths of the respective maximum allowable concentrations).

During the berth tests of the atomic icebreaker, which lasted from August 6th to September 14th, 1959, we investigated experimentally the contamination of the CS holds by radioactive gases and aerosols and the gas activity that is discharged by means of the special CS ventilation system through the mainmast.

The first measurements showed that the concentration of radioactive gases in the air of the CS holds was extremely low (of the order of $10^{-11}-10^{-10}$ C/liter) and that it was below the measurement range of highly sensitive stationary gas dosimetry devices. Due to this fact, further measurements were mainly performed by means of extensible air-sampling chambers, which consisted of cylindrical polyethylene bags with plastic bases. Two banks of cylindrical counters, one of which was intended for measuring the $\beta$-activity of the gas and the other for controlling the $\gamma$-background, were mounted on one of the bases. If necessary, an adapter with a filter or a case with an end-type counter can be mounted on the opposite base. During the berth tests, we used cylindrical STS-5 counters and BFL-5 end-type counters, which made it possible to measure $A^{41}$ activities equal to $2\cdot10^{-11}$ C/liter and $10^{-10}$ C/liter, respectively.

For determining the concentration of radioactive aerosols, a known volume of air was drawn through an FP-type filter. The activity of the filter was then measured in the laboratory.

In investigating the concentration of radioactive gases, most attention was paid to the investigation of air that is discharged through the mainmast. Samples were taken by means of tubes through which a portion of the air was drawn from the mainmast. For the purpose of checking the calculated activated argon concentrations, we analyzed samples taken from the air ducts that draw the air from under the protective lids of the reactors.

The measurements showed that, over the entire period of berth tests of the atomic icebreaker's nuclear power plant, the specific activity of discharged air did not exceed $10^{-9}$ C/liter. Measurements of the specific activity of the air discharged through the mainmast made it possible to establish that there is a definite relationship between the total power level of the operating nuclear reactors and the specific air activity. On the basis of this, we made an approximate estimate of the activity discharged by a single reactor operating under normal conditions at a 100% power level. The conditions which existed on September 5, 1959, when the power levels of the plants were 45, 40, and 20%, corresponded to this case. The specific activity of the air discharged through the mainmast was equal to $2 \cdot 10^{-10}$ C/liter on that day. Since, for this ventilation system, the air discharge amounts to approximately 70,000 $m^3$/hr, the activity discharged through the mainmast during the operation of a single plant at 100%-power is equal to 0.014 C/hr. An analysis of samples taken under the above conditions from the CS holds (thermal control data transmitters, the main circulation pumps, etc.) indicated activity values that were close to the chamber's sensitivity limit, which is equal to $2 \cdot 10^{-11}$ C/liter.

The specific gas activity in air ducts under the reactor shielding lids was equal to $10^{-9}$ C/liter. Its half life (1.8 hr) corresponded to the half life of $A^{41}$.

When the nuclear energy plant operates under normal conditions, radioactive argon is generated in the channels of the emergency protection rods and in the automatic regulator channels. This assumption was confirmed by a burst of gas activity after the emergency protection system was actuated (as a result of the expulsion of air from the corresponding channels).

The gas contamination was different in the case where primary coolant leakages appeared. Thus, in cases where the active bidistillate from the first loop partially penetrated the room of the protection control system (PCS) servomotors, the gas activity in this room increased to $3.1 \cdot 10^{-8}$ C/liter; the activity was caused by isotopes with half lives of the order of 5 to 7 hr. Consequently, the air contamination was in this case due to inert radioactive gases which were originated by fragments ($Kr^{85}$, $Kr^{88}$, and $Xe^{135}$).

The reactivity of samples of long-lived $\beta$-active aerosols which were taken from the CS holds in no case exceeded the natural radioactivity of air.

Regardless of the fact that negligibly small concentrations and amounts of radioactive gases and aerosols were expected to be found in the air discharged from CS, a network of external dosimetry service control posts was organized in the vicinity of the location where the berth tests of the atomic icebreaker were performed. The main task to be performed at these posts was a thorough investigation of the external medium for an experimental determination of the degree to which the radioactive substances discharged from the atomic icebreaker influence the air, water, flora, and fauna in the vicinity of the discharge location.

For the purpose of collecting data on the background content of naturally radioactive elements, work on studying the external medium activity levels was started two months before the beginning of the atomic icebreaker berth tests. The external dosimetry service operated until the icebreaker left the Neva River.

A specially constructed device was used for measuring the amount of $A^{41}$ in atmospheric air. Its data transmitter consisted of a lead unit with two banks of STS-5 counters (five counters in each bank), one of which registered the $\beta$-radiation of the gas as well as the background, while the other was screened from $\beta$-particles and was sensitive only to the background. By means of a telescopic rod, the data transmitter could be placed at a distance of 1.5-2.5 m from the ground. The sensitivity of the device was $10^{-11}$ C/liter. Measurements performed by means of this device over a period of two months made it possible to establish experimentally that the concentration of $\beta$-active gases in no case exceeded in the atmospheric air near the location where the atomic icebreaker was tested the sensitivity of the device (i.e., $10^{-11}$ C/liter). The above value is lower than the maximum allowable $A^{41}$ concentration in atmospheric air.

Simultaneously with the determination of the $A^{41}$ concentration near the atomic icebreaker, we measured the $\gamma$-radiation dose rate before the tests were started, during the period when they were performed, and after the icebreaker sailed. Over 100 measurements were made; they were performed at locations to leeward of the atomic icebreaker at distances from 30 m to several kilometers. It was established that the $\gamma$-radiation dose rate in this region varied from 12 to 20 $\mu$r/hr. This corresponded to the natural background $\gamma$-radiation of this locality.

The amounts of $\beta$-active long-lived and short-lived aerosols in atmospheric air were determined by using the aspiration and the sedimentation methods. For determining the concentration of long-lived $\beta$-active aerosols by the aspiration method, the samples were taken at five fixed posts. Four of them were located at a distance of 200 to 300 m in various directions from the icebreaker. One device was installed 25 km from the city at Krasnoe Selo, and it served for taking control samples.

The sampling of long-lived aerosols from atmospheric air was performed by drawing air through a filter made of the highly efficient thin-fibered cloth FPP-15, which had a surface area of 0.573 $m^2$ and was placed on the surface of a hollow cylinder made of a metallic grid. After 38,000 to 76,000 $m^3$ of air was drawn through the cloth at an average rate of 425 $m^3$/hr, the filter was calcined in a crucible at 500 to 600°C, after which the ash activity was measured. We took 168 samples, of which 77 were taken during the period preceding the starting of the reactors, while the remaining samples were obtained after the operating power level was attained in the reactors. The measurement results are given in Fig. 1.

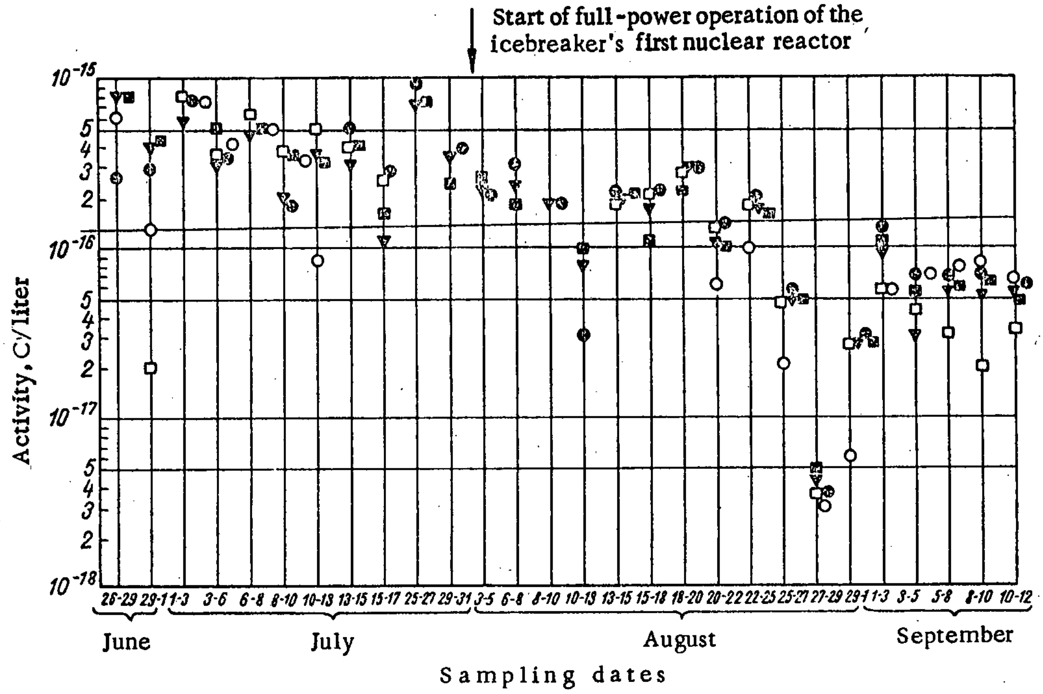


Fig. 1. Concentration of long-lived β-active aerosols in atmospheric air during the berth tests of the atomic icebreaker Lenin (at distances of 500 to 700 m from the mooring place). Sampling stations: ○) control; □) first; ▲) fourth; ◉) seventh; ▣) tenth.

It is obvious from the obtained data that the concentration of long-lived β-active aerosols in atmospheric air varied from $2.0 \cdot 10^{-17}$ to $1.2 \cdot 10^{-15}$ C/liter before the tests of the atomic icebreaker were started, while during the period when the reactors were in operation at full power, these concentrations did not exceed $3.7 \cdot 10^{-16}$ C/liter.

The distribution of samples with respect to specific activity indicates that, before the tests were started, the concentration of β-active aerosols was in most cases equal to several $10^{-16}$ C/liter units, while during the time when the nuclear reactors operated at full power, concentrations of the order of $10^{-17}$ C/liter were most often encountered. Thus, a comparison of the activities of long-lived β-active aerosols in samples taken before and during the berth tests of the atomic icebreaker indicates that the aerosol concentrations in atmospheric air did not increase.

For determining the concentrations of short-lived β-active aerosols, atmospheric air was drawn through an FPP-15 filter with a 12.5 $cm^2$ area at a rate of 120 to 150 liters/min. The samples were taken at distances of 200 to 300 m from the atomic icebreaker to leeward of the discharge location. Investigations showed that the concentrations of short-lived β-active aerosols varied from $1.4 \cdot 10^{-14}$ to $1.8 \cdot 10^{-13}$ C/liter during the observation period, while their half life was 35-40 min, which coincided with the half life of the naturally radioactive fission products of radon, which is always present in the atmosphere [2].

The recordings of the amount of β-active aerosols precipitated from the atmospheric air were performed at 14 fixed posts, of which 12 were located in different directions from the atomic icebreaker within a 2-km radius.

Two observations posts were located at a considerable distance from the icebreaker: at Krasnoe Selo and at Koltushi (20 km from the city). The samples obtained at these posts were used as control samples. For the collection of radioactive deposits at these posts, we installed 50 x 60-cm galvanized iron vessels with edges 10 cm high at a distance of 4 to 10 m from ground; the vessels were lined with filter paper. After the end of the exposure period, which amounted to seven days, the contents of the vessels were calcined in crucibles at a temperature of 500-600°C, after which the activity of the ashes was determined. We took 169 samples in all, 92 of which were taken before the reactors were set in operation, while the remaining 77 samples were taken after the reactors started to operate at full power. It follows from the obtained data that the amount of $\beta$-active aerosols that precipitated from the atmosphere varied from $2 \cdot 10^{-11}$ to $3.8 \cdot 10^{-9}$ C/m$^2$ over a 24-hr period before the tests were started; during the operation of the nuclear reactors at full power, the amount of aerosols in the samples did not exceed $3.7 \cdot 10^{-9}$ C/m$^2$ per day. Thus, the amount of radioactive aerosols in atmospheric air did not increase after the icebreaker's reactors were set in operation.

The performed investigations showed that the amounts of $\beta$-active aerosols that settled out of the atmosphere did not differ from the background concentrations during the berth tests of the atomic icebreaker.

The complex of investigations performed in the river also included radioactivity tests of the water, the bottom deposits, plankton, benthos, and periphyton. The samples were taken at eight posts: 1) at a distance of 50 m ahead of the ship's bow; 2) at a distance of 50 m behind the ship's stern; 3) to port of the ship; 4) at a distance of 0.5 km upstream from the vessel; 5) at a distance of 0.5 km downstream from the vessel; 6) in the middle of the river in line with the vessel; 7) at a distance of 2000 m upstream from the vessel; 8) at a distance of ~10 km beyond the city boundary. At the first five posts, the observations were performed systematically, and at the other posts they were performed periodically.

At all posts, 3 liters of water were sampled for the radiometric investigations. During the initial investigation period, surface (0.5 m from the surface) and bottom (0.5 m from the bottom) samples were analyzed simultaneously. Thereafter, due to the identity of the obtained results, only the surface water was investigated. The treatment of samples and the measurement of the reactivity of the preparations obtained from water, plankton organisms, silt, benthos, and overgrowths were performed in the following manner. A water sample (3 liters) was completely evaporated and the activity of the residue was measured. The sensitivity of the method was $3 \cdot 10^{-12}$ C/liter. The activity of plankton samples was measured after drying. In dependence on the weight of a sample which was deposited on a base-layer, the sensitivity of the method varied from $1.0 \cdot 10^{-7}$ to $5.0 \cdot 10^{-8}$ C/kg of air-dry weight. In order to improve the sensitivity and to check the obtained results, the measured plankton samples from several posts were combined into a single sample, after which a thick-layer specimen was made or the same mixture was calcined and a thin-layer specimen with a higher specific activity was prepared from the ashes. In this case, the sensitivity of the method was somewhat higher; it was $1.0 \cdot 10^{-8}$ to $1.0 \cdot 10^{-9}$ C/kg of air-dry weight.

The radioactivity of silt was determined by measuring thick-layer samples. The sensitivity of the method was $\sim 4 \cdot 10^{-9}$ C/kg of air-dry weight.

Benthos and overgrowth samples were prepared in the shape of thick-layer preparations or by calcining and depositing the ashes in thin layers on a base. The sensitivity of the method was $\sim (1.0\text{-}5.0) \cdot 10^{-9}$ C/kg of moist weight. Water plants were calcined and their activity was measured. The sensitivity of the method was of the order of $5.0 \cdot 10^{-9}$ C/kg of moist weight.

The analysis of 105 water samples showed that its specific activity was not constant; it changed from $2.0 \cdot 10^{-11}$ to $1.2 \cdot 10^{-12}$ C/liter (Fig. 2). It is characteristic that these changes were simultaneously observed at all posts and, consequently, they were not connected with the presence of the icebreaker. Another peculiarity of these variations was also the fact that, beginning with the second half of July, the specific water activity dropped to a value which was two to three times as low as before and remained at this level until the middle of September, i.e., during the entire period of testing.

As was shown by measurements, the radioactivity of the bottom deposits at different points of the section investigated was practically equal for all the points over a period of three months; it was equal to $(1.3\text{-}5.7) \cdot 10^{-8}$ C/kg before the tests and $(2.1\text{-}5.5) \cdot 10^{-8}$ C/kg after the nuclear reactors were set in operation.

Hydrobionts were chosen for radiometric investigations in connection with the fact that they represent some of the most highly sensitive indicators characterizing the contamination level of river waters by radioactive substances. The measurements performed on benthos plankton organisms and periphyton showed that along with the seasonal variation of the form of plankton, its specific activity also changed from $(8\text{-}37)\cdot10^{-8}$ C/kg of air-dry weight in June – July to $(0.7\text{-}11)\cdot10^{-8}$ C/kg in August – September, 1959. These changes reflect the variations in the river water activity.

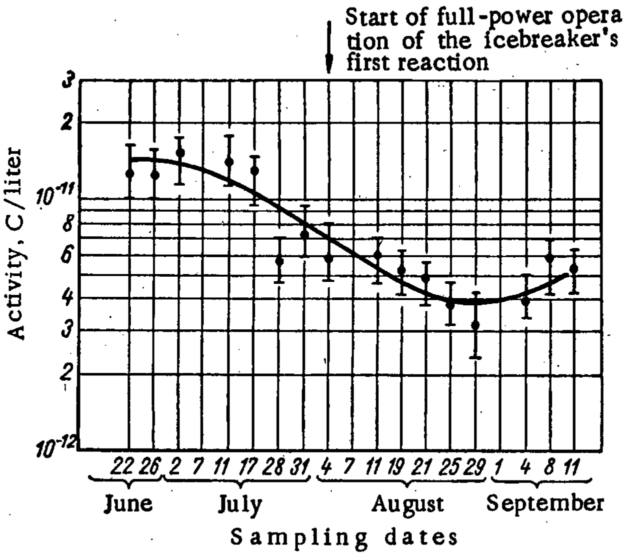


Fig. 2. Concentration of $\beta$-active substances in the water of the Neva River over the period from June 22th to September 11th, 1959 (average values for all posts).

The small amounts of the obtained bottom fauna specimens, which were the result of the paucity of the Neva River bed, did not permit accurate measurements of the amount of $\beta$-emitters in the benthos over a greater section of the river. Nevertheless, on the basis of the obtained results, it can be stated that the radioactive substances detected in bottom organisms in amounts of the order of $10^{-8} - 10^{-9}$ C/kg are not connected with the operation and the location of the atomic icebreaker and that they have a different origin.

The specific activity of the overgrowths, which were mainly represented by green confervoid algae as well as water plants, represented mainly by pond weeds and confervoid algae, was approximately $1.5\cdot10^{-8}$ C/kg of moist weight. Neither in this case was there found any connection with the operation and the location of the vessel.

Thus, the analysis of 474 samples which were taken from the Neva River during the berth tests of the atomic icebreaker made it possible to state that the content $\beta$-active substances in the river water, bottom deposits, and the tissue of hydrobiontswas at the level of the background which was observed in recent years in this region [3]. The detected variations in the activity level of the water and plankton had a seasonal character, and they were independent of the location of the vessel and the operating conditions of the nuclear power plant.

## SUMMARY

1. During the berth tests of the atomic icebreaker Lenin, we measured the amounts of radioactive substances in the air and holds of the central section and in the icebreaker's mainmast as well as in atmospheric air, river water, flora, and fauna in the vicinity of the testing site.

2. When the nuclear power plant of the atomic icebreaker operated under normal conditions, the concentration of radioactive gases in the CS holds did not exceed $4\cdot10^{-10}$ C/liter; it was due to $A^{41}$ and was, on the average, equal to $10^{-11}$ C/liter, and which corresponded to 0.01 of the maximum allowable concentration of this isotope in the air in working rooms.

3. The average concentration of $A^{41}$ in the air discharged into the atmosphere through the mainmast was $8\cdot10^{-11}$ C/liter; this concentration did not exceed $2\cdot10^{-10}$ C/liter. This corresponded to a total argon discharge of 0.014 C/hr during the operation of a single reactor at 100%-power.

4. Primary coolant leakages occurred during the tests. In this, the concentration of radioactive gases in the PCS servomotor room increased to $3\cdot10^{-8}$ C/liter; it was due to isotopes generated by fission fragments with half lives of the order of 5 to 7 hr ($Kr^{85}$, $Kr^{88}$, and $Xe^{135}$).

5. The concentration of $\beta$-active aerosols in the air in CS holds in no case exceeded the natural background activity values.

6. No contamination of the atmospheric air, river water, bottom deposits, and hydrobionts by $\beta$-active substances in excess of the background values was observed.

7. Variations in the activity level of the atmospheric air, water of the Neva River, and hydrobionts in the vicinity of the berth of the atomic icebreaker Lenin during the period from June 15th to September 14, 1959 have

a seasonal character, they are not connected with the vessel's location, and they are independent of the nuclear plant's operation. It is characteristic that, in correspondence with seasonal changes, higher radioactivity levels in air, water, and hydrobionts were observed mainly before the tests were begun.

Thus, it has been proved experimentally that the nuclear power plant of the atomic icebreaker Lenin is provided with a highly efficient radiation protection system, due to which the operation of this vessel is completely safe for the servicing personnel, berthing location, and the base from which the icebreaker and the convoy of ships following it operate.

## LITERATURE CITED

1. Yu. V. Sivintsev and B. G. Pologikh, Transactions of the Second International Conference on the Peaceful Uses of Atomic Energy (Geneva, 1958). Reports by Soviet Scientists [in Russian] (Atomizdat, Moscow, 1959) Vol. 2, p. 87.
2. Yu. V. Sivintsev, Background Irradiation of the Human Organism [in Russian] (Atomizdat, Moscow, 1960).
3. Soviet Scientists on the Subject of Dangers of Nuclear Weapons Tests [in Russian] (Atomizdat, Moscow, 1959) Ed. by A. V. Lebedinskii.

# LETTERS TO THE EDITOR

## PRODUCTION OF MONOENERGETIC BEAMS OF ACCELERATED PARTICLES

F. R. Arutyunyan and I. P. Karabekov

Translated from Atomnaya Énergiya, Vol. 10, No. 3, pp. 259-260, March, 1961
Original article submitted August 24, 1960

The production of high-intensity monoenergetic beams by using the existing methods involves considerable difficulties. Electrostatic accelerators which are stabilized by means of special devices [1 and 2] provide currents equal to $I_{max} \simeq 100\ \mu a$ with an energy spread of $(2\text{-}4) \cdot 10^{-4}$; however, their stabilization systems have considerable operational drawbacks [3]. Cascade generators [4], which provide currents of 5-10 ma, have a considerable pulsation factor even if symmetrical circuits are used, while the accelerating voltage stability is equal to the supply source voltage stability.

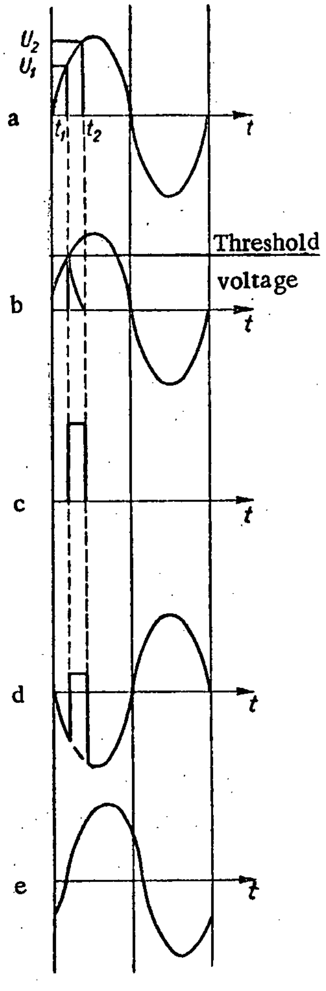


Fig. 1. Voltage and pulse time diagram. Voltages: a) anode – cathode; b) discriminator input voltage and the pulse provided by the discriminator; c) accelerating voltage; d) modulating electrode voltage; e) heating voltage.

Accelerators using pulsed voltage and resonance accelerators have an energy spread in the accelerated beam that is equal to several percent.

The present article explores the possibility of producing monoenergetic pulsed beams with an energy spread between pulses that is not worse than $10^{-4}$ for rather large pulsations in the supply circuit. A high-voltage power transformer or a transformer cascade can serve as the accelerating voltage source.

A sinusoidal voltage with the frequency f is applied to the accelerating gap. The particles are accelerated during the time $\Delta t = t_2 - t_1$ (Fig. 1a). For this, the beam will have an energy spread $\Delta E = e\,[U(t_2) - U(t_1)]$, where U is the accelerating gap voltage, and a repetition frequency that is equal to the supply circuit frequency. If the energy spread between pulses is to remain constant, in varying the amplitude on the frequency of the supply voltage, it is necessary automatically to provide such a phase of particle injection into the accelerating gap for which the accelerating voltage remains constant.

A gas-discharge phase discriminator [5] would make it possible to fix the periodical voltage phase with an accuracy to ± 1.5' for a frequency of 50 cps and an angular interval from 20 to 70°. In dependence on the input voltage amplitude, the discriminator can fix with the above accuracy phases for which $u = U_m \sin \varphi_{discr} = \text{const}$. This would result in a maximum energy spread $\Delta E/E = \pm 10^{-4}$ between the pulses.

The diagram illustrating the acceleration of particles by using this method is given in Fig. 2. The voltage from a high-voltage transformer is supplied to a three-electrode gun. The voltage necessary for blocking the beam, which can also be an alternating voltage that is shifted 180° with respect to the anode voltage, is fed to the gun's modulating electrode (see Fig. 1d). After the accelerating gap voltage has attained the assigned value, a pulse with the duration $\tau$, which unblocks the gun, is provided by means of the gas-discharge phase discriminator (see Fig. 1c). The capacitance of capacitor C, which is connected in parallel to the accelerating gap, serves for maintaining the assigned voltage spread $\Delta U_{acc}$ $U_{acc}$ during acceleration; it is found by using the equation

$$C \gg \frac{\tau}{R_i \frac{\Delta U_{acc}}{U_{acc}}},$$

where $R_i$ is the gun's internal resistance. The value of capacitance C is determined by the assigned particle energy spread in the beam.

In this accelerating system, there is no energy spread in the beam due to the ac feed of the gun's heating, since the phase shift between the supply voltages is constant. The complete time diagram of the voltages and pulses that act in the system is given in Fig. 1.

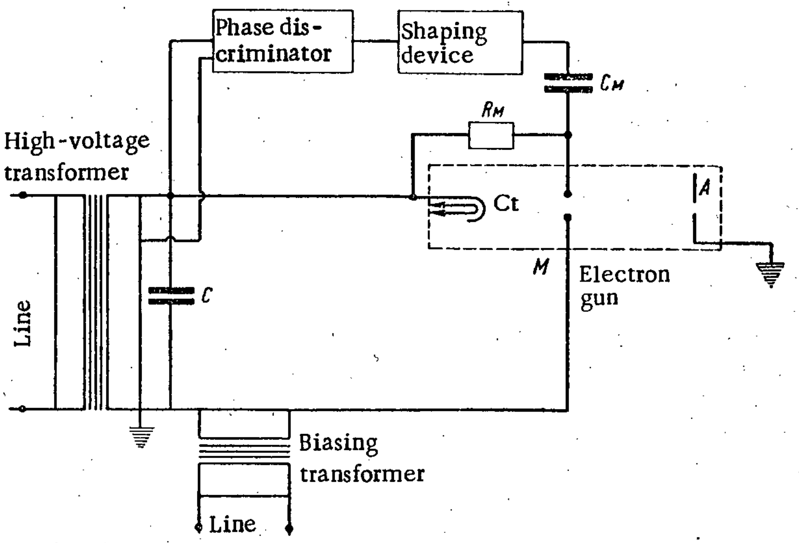


Fig. 2. Schematic diagram of particle acceleration. A) anode; Ct) cathode; M) modulating electrode; $C_M$) coupling capacitor; $R_M$) modulator load resistor.

The proposed accelerating method makes it possible to obtain intensive particle beams that are almost completely monoenergetic, while the beam current is limited only by the focusing properties of the electron gun.

The maximum energy to which the particles can be accelerated by using the proposed method is limited only by the possibility of connecting a large number of transformers and cascades. For instance, for producing a beam with an energy of 100 kev and $\Delta E/E \simeq \pm 10^{-4}$ with a beam current of 1 amp, a pulse duration of $10^{-7}$ sec, and a repetition frequency of 50 cps, it is necessary to provide a high-voltage transformer with an effective voltage of 100 kv, and an installed power capacity of 30 kva, and a capacitor with a capacitance of 0.01 $\mu f$. It is obvious that the proposed accelerator has the following advantages: 1) The beam is monoenergetic to a high degree (not worse than $10^{-4}$); 2) it is possible to produce several beams with accurately assigned energy ratios by means of the same supply device; 3) the circuit is relatively simple and inexpensive (there are no high-voltage kenotrons, the number of high-voltage capacitors is small, and there are no stabilizing devices).

## LITERATURE CITED

1. B. V. Baev, P. E. Vortnikov et al., Dokl. AN SSSR 101, No. 4, 637 (1955).
2. V. G. Blovchenko, B. M. Gokhberg, and V. M. Morozov, Dokl. AN SSSR 101, No. 6, 1023 (1955).
3. B. Millar, R. Bailay, and L. Churchill, J. Scient. Instrum. No. 10, 34 (1957).
4. B. S. Novikovskii, Atomnaya Énergiya 4, No. 2, 175 (1958).*
5. I. P. Karabekov, Pribory i Tekhnika Éksperimenta No. 2, 83 (1960).

---

* Original Russian pagination. See C. B. translation.

# CROSS SECTION OF THE (d,p) REACTION ON VARIOUS NUCLEI

M. Z. Maksimov

Translated from Atomnaya Énergiya, Vol. 10, No. 3, pp. 260-262, March, 1961
Original article submitted June 18, 1960

Due to its large cross section the (d,p) reaction is one of the basic reactions that are used in studying the internal properties of nuclei [1] and in preparing radioactive isotopes [2]. A great deal of experimental and theoretical work was devoted to this reaction. The experimental angular distributions of protons in this reaction are in good agreement with the results predicted by theory [1]. However, the calculation of absolute cross sections (in particular, with the yield of a given isotope) is not yet possible, although such attempts were repeatedly made [3 and 4]. The obtained expressions are very complicated, and they contain undetermined parameters.

In studying the mechanisms of nuclear reaction processes on deuterons and the preparation of radioactive isotopes, it is desirable to have simple relationships which would make it possible quickly to determine the possibilities of a given reaction. In connection with this and what has been said above, it would be of interest to generalize the theoretical [1, 3, and 4] and the experimental [3, 5, and 6] data on the (d,p) reaction and to obtain such relationships by using a semiempirical method. An analysis of these data shows, in the first place, that the cross section of the (d,p) reaction, which is accompanied by the formation of a given isotope, can be represented in the shape of curve 1 (see figure) in dependence on the deuteron energy:

$$\sigma_{d,p} \simeq C_{d,p} P(E_d - E_d^{\text{eff}}). \tag{1}$$

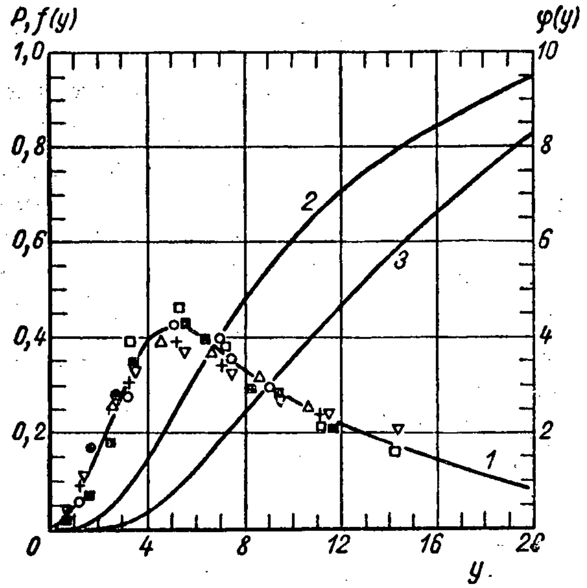


Diagram of the functions. 1) P(y) (some experimental data were also plotted); 2) $f(y)$; 3) $\varphi(y)$. Cross section designations: □) $Na^{23}$; ■) $Fe^{54}$; ▽) $Co^{59}$; +) $Cu^{63}$; △) $Br^{81}$; ●) $Ag^{197}$; ○) $Bi^{209}$.

Here, $C_{d,p}$ values are expressed in barns, and they depend only on the target nucleus properties, while $E_d^{\text{eff}}$ is determined by the equation

$$E_d^{\text{eff}} = \frac{0{,}96\, Z_A}{A^{1/3}+0{,}8}(1-\alpha) - 0{,}028\, Z_A - 0{,}65 \text{ Mev}, \tag{2}$$

where

$$\alpha = 1{,}78\left[\frac{2AZ_A}{A+2}\left(A^{1/3}+0{,}8\right)\right]^{-1/3}.$$

It is obvious from the figure that the experimental data actually lie close to the smooth curve P(y) within the measurement error limits, which are equal to 20-30%. We shall also give here the expression for extraction from a thick target. By using Eq. (1) and the range vs energy curve [7], we obtain:

$$B_{d,p} \simeq \frac{2{,}3\cdot 10^{-3}}{Z_A^{3/4} E_d^{1/4}} C_{d,p}\left[\varphi(y) + E_a^{\text{eff}} f(y)\right], \tag{3}$$

where $y = E_d - E_d^{\text{eff}}$; the functions $f(y) = 2.07\cdot 10^{-1} \times \times \int_0^y P(y)\,dy$ and $\varphi = 2.07\cdot 10^{-1} \int_0^y yP(y)\,dy$ are shown in the figure.

The $C_{d,p}$ coefficients were determined by using Eqs. (1)-(3) and the experimental data [2, 3, 5, 6, and 8]; they are given in the table, from which it is obvious that, for the majority of nuclei, these coefficients are close to unity (1-0.6). For $K^{41}$ and $Fe^{58}$, the experimental values are apparently much lower. For $Bi^{209}$, this coefficient has a low value because only a five-day activity was measured. If we take into account the spins of the basic state of $Bi^{210}$ (I = 5) and of two isomeric states (I = 1) and (I = 1), the fact that lower values were obtained can be explained by the appearance of the 6/17 factor. A similar situation is observed in the case of the $U^{235}$ (d,n) reaction, and it should also apply to the $Co^{59}$ (d,p) and $Na^{23}$ (d,p) reactions; but in these cases, transitions from isomeric states into the basic states are virtually not forbidden.

Values of the $C_{d,p}$ Coefficient for Different Nuclei

| Nuclei | $c_{b,\,p}$, b | Nuclei | $c_{d,\,p}$, b | Nuclei | $c_{d,\,p}$, b |
|---|---|---|---|---|---|
| $C^{12}(d,n)$ | 0,23 | $Fe^{68}$ | 0,12* | $Au^{197}$ | 0,65 |
| $Na^{23}$ | 1,05 | $Co^{59}$ | 0,69 | $Hg^{204}$ | 0,65** |
| $Si^{30}$ | 0,70* | $Cu^{63}$ | 0,61 | $Tl^{205}$ | 1,1** |
| $P^{31}$ | 0,67 | $Br^{81}$ | 1,00 | $Pb^{208}$ | 0,63 |
| $Cl^{37}$ | 0,93* | $Sr^{88}$ | 0,92 | $Bi^{209}$ | 0,27 |
| $K^{41}$ | 0,40* | $Pt^{196}$ | 0,40** | $U^{238}$ | 0,68 |
| $Fe^{54}(d,n)$ | 0,37 | $Pt^{198}$ | 0,87** | $Np^{237}$ | 0,25 |

* Yields from thick targets were used [2].

** Cross sections for $E_d \lesssim$ 9 Mev were used [3]; the other data were borrowed from [3, 5, 6, and 8] for $E_d >$ 10 Mev.

As for the (d,n) reaction, the effect of stripping is here less pronounced than in the (d,p) reaction, since a deuteron must approach the nucleus rather closely in order to transfer its proton to the nucleus, which is apparently equivalent to intermediate nucleus formation. It should be noted that the experimental data for medium nuclei [8] also lie sufficiently close to the smooth curve 1, while their absolute values are, as a rule, one-half to one-fourth as large as the absolute values of the (d,p) reaction. For heavy nuclei and for large deuteron energies (> 10 Mev), besides stripping and compound nucleus formation, it is also necessary to take into account the direct knocking-out of intranuclear nucleons. This is indicated by the weak dependence of the (d,n) reaction cross section on energy and by the small value of this cross section [6].

Thus, the Eqs. (1)-(3) that are given here, together with the data in the figure and the table, make it possible to determine without much difficulty the (d,p) reaction yields from a thin and a thick target, which is very important in practical work as well as in studying the mechanisms of nuclear reaction processes.

In conclusion, the author extends his thanks to V. I. Shevchenko and P. P. Dmitriev for the useful discussion.

## LITERATURE CITED

1. A. Sitenko, Usp. Fiz. Nauk 67, 377 (1959).
2. W. Garrison and J. Hamilton, Chem. Rev. 49, 237 (1951); I. Gruwerman and P. Kruger, Int. J. of Appl. Rad. and Isot. 5, 21 (1959); V. Gol'danskii and E. Leikin, Transformations of Atomic Nuclei [in Russian] (AN SSSR Press, Moscow, 1958).
3. D. Peaslee, Phys. Rev. 74, 1001 (1948).
4. V. Neudachin, I. Teplov, and B. Yur'ev, Transactions of the All-Union Conference on Medium- and Low-Energy Nuclear Reactions [in Russian] (AN SSSR Press, Moscow, 1958) p. 222; G. Abraham, Proc. Phys. Soc. A 67, 273 (1954).
5. P. Kafalas and J. Irvine, Phys. Rev. 104, 703 (1956).
6. W. Ramler et al., Phys. Rev. 114, No. 154, 163 (1959).
7. M. Maksimov, Zh. Éksperim. i Teor. Fiz. 37, 127 (1959).
8. N. Vlasov et al., Atomnaya Énergiya 2, No. 2, 169 (1957);* O. D. Brill' and L. V. Sumin, Atomnaya Énergiya 7, No. 4, 377 (1959).*

---

* Original Russian pagination. See C. B. translation.

# THEORY OF THE EFFECTIVE CROSS SECTIONS OF HEAVY NUCLEI IN THE REGION OF PARTIAL NEUTRON RESONANCE OVERLAPPING

A. A. Luk'yanov and V. V. Orlov

Translated from Atomnaya Énergiya, Vol. 10, No. 3, pp. 262-264, March, 1961
Original article submitted April 27, 1960

In [1], we presented a general theory of effective group cross sections in an infinite homogeneous medium [1]. A simple method for calculating the cross sections in the region of partial resonance overlapping is described below.

The effective cross section in an infinite homogeneous medium is given by the relationship [1 and 2]

$$\langle \sigma_x (E) \rangle = \frac{\int\limits_{E_1}^{E_1+\varepsilon} \frac{\sigma_x}{\sigma}\, dE'}{\int\limits_{E_1}^{E_1+\varepsilon} \frac{1}{\sigma}\, dE'}, \tag{1}$$

where $\sigma$ and $\sigma_x$ are the total cross section and the reaction cross section, respectively, and $\epsilon$ is a certain energy interval within which the collision density changes little. Besides the effective cross section $<\sigma_x(E)>$, we shall also determine the average cross section in the $(E_1, E_1 + \epsilon)$ interval:

$$\overline{\sigma_x (E)} = \frac{1}{\varepsilon} \int\limits_{E_1}^{E_1+\varepsilon} \sigma_x (E')\, dE'. \tag{2}$$

We are interested in the energy region where the actual cross section slightly differs from the average cross section:

$$\frac{|\sigma - \bar{\sigma}|}{\bar{\sigma}} \ll 1.$$

By using the identity $\sigma = \bar{\sigma} + (\sigma - \bar{\sigma})$, we obtain

$$\frac{\sigma_x}{\sigma} = \frac{\sigma_x}{\bar{\sigma} + (\sigma - \bar{\sigma})} = \frac{\sigma_x}{\bar{\sigma}} - \frac{\sigma_x (\sigma - \bar{\sigma})}{\bar{\sigma}^2} + \ldots; \tag{3}$$

$$\frac{1}{\sigma} = \frac{1}{\bar{\sigma}} - \frac{\sigma - \bar{\sigma}}{\bar{\sigma}^2} + \ldots \tag{4}$$

By substituting Eqs. (3) and (4) in expression (1), we obtain:

$$\langle \sigma_x (E) \rangle \simeq \overline{\sigma_x (E)} - \frac{\overline{\sigma_x \sigma} - \bar{\sigma}_x \bar{\sigma}}{\bar{\sigma}}. \tag{5}$$

The calculation of average cross sections is given in [3 and 4]. Our problem consists in calculating a correction for the average cross section which would have a dispersive character. It is obvious from Eq. (5) that this correction determines the effective cross section dependence on the absorber's concentration in the medium as well as on temperature.

For a certain energy, we shall represent the cross sections as the sum of the contributions of individual resonances:

$$\sigma_x (E) = \sum_{\gamma} \sum_{m=-\infty}^{\infty} \sigma_{x\gamma}^{m} (E - E_m), \tag{6}$$

where m is the mth resonance, which is measured in the positive and the negative directions from a certain $E_0$ value which corresponds to a resonance that is closest to the energy. Similarly, for the total cross section, we have:

$$\sigma(E)=\sum_{\gamma}\sum_{m=-\infty}^{\infty}\sigma_{r\gamma}^{m}(E-E_m)+\sigma_{s_{\text{pot}}}=\sigma_r+\sigma_{s_{\text{pot}}}. \qquad (7)$$

(7)

The index $\gamma$ pertains to the determined system of resonance levels, which are characterized by the total spin I and by parity. For determining the cross section, we shall use the usual form

$$\sigma_{x\gamma}^{m}(E)=\sigma_{x\gamma}^{0m}\,\psi\left(\frac{E-E_m}{\Gamma}\,2;\ \frac{\Gamma}{\Delta}\right), \qquad (8)$$

where $\sigma_{x\gamma}^{0m}$ and $\psi$ are the cross section at the maximum and the Doppler function, respectively [5].

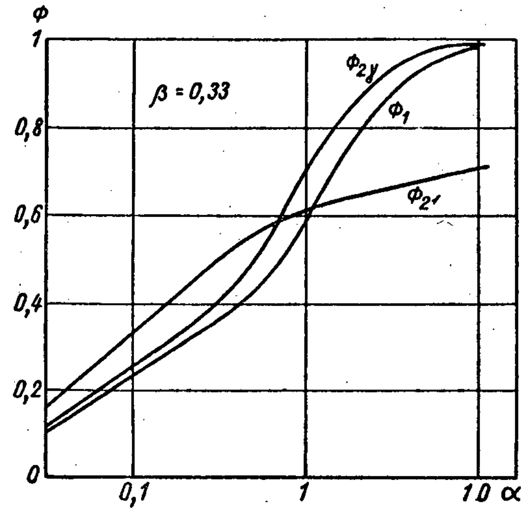
We shall consider the case in which we are interested: where the Doppler width is greater than the total resonance width, which is characteristic for heavy nuclei. In this case, the resonance shape is sufficiently accurately described by the function

$$\psi\left(\frac{E-E_m}{\Gamma}\,2;\ \frac{\Gamma}{\Delta}\right)\simeq\frac{\sqrt{\pi}}{2}\,\frac{\Gamma}{\Delta}\exp\left[-\frac{(E-E_m)^2}{\Delta^2}\right]. \qquad (9)$$

Let $\bar{D}_I$ be the average distance between the levels of a given spin I and parity in the energy interval under consideration. We shall assume that the levels are equidistant. It can be shown that a consideration of the scattering of $D_I^m$ values leads to a difference of not more than 4-5% in the average cross section value. A much greater contribution is introduced by taking into account the distribution of the above resonance widths [1, 3, and 6].

In the equidistant level approximation, the expression for the reaction cross section can be written as

$$\sigma_x(E)\simeq\sum_{\gamma}\sum_{m}\alpha_{\gamma}^{xm}\,e^{-(y+mb_I)^2}, \qquad (10)$$



The $\Phi_x$ function for one ($\Phi_1$) and two ($\Phi_{2f}$, $\Phi_{2\gamma}$) reaction channels

$$\alpha=\left(\frac{\langle\Gamma_\gamma\rangle}{\langle\Gamma_n\rangle}\right);\quad \beta=\left(\frac{\langle\Gamma_\gamma\rangle}{\langle\Gamma_f\rangle}\right).$$

and

$$\alpha_{\gamma}^{xm}=\frac{\sqrt{\pi}}{2}\,\frac{\Gamma}{\Delta}\,\sigma_{x\gamma}^{0m};\quad y=\frac{E-E_0}{\Delta};\quad b_I=\frac{\bar{D}_I}{\Delta}.$$

We shall now calculate the average value of the product:

$$\bar{\sigma}_x\bar{\sigma}_r=\sum_{\gamma\gamma'}\sum_{mm'}\alpha_{\gamma}^{xm}\,e^{-(y+mb_I)^2}\,\alpha_{\gamma'}^{rm'}\,e^{-(y+mb_I')^2}. \qquad (11)$$

By averaging the $\alpha_{\gamma}^{xm}$ coefficients with respect to the distribution of the above widths and neglecting small changes $\alpha_{\gamma}^{xm}$ within energy changes in the $\epsilon \ll E_1$ interval under consideration, we obtain

$$\overline{\sigma_x\sigma_r}=\frac{\Delta}{\varepsilon}\left[\sum_{\gamma\gamma'}\overline{\alpha_{\gamma}^{x}}\,\overline{\alpha_{\gamma'}^{r}}\int\limits_{\left(\frac{\varepsilon}{\Delta}\right)}\Theta^2\left(b_I\ \frac{y}{b_I}\right)dy+\sum_{\gamma}\left(\overline{\alpha_{\gamma}^{x}\alpha_{\gamma}^{r}}-\overline{\alpha_{\gamma}^{x}}\,\overline{\alpha_{\gamma}^{r}}\right)\int\limits_{\left(\frac{\varepsilon}{\Delta}\right)}\Theta\left(\sqrt{2}\,b_I\ \frac{y}{b_I}\right)dy\right] \qquad (12)$$

The function

$$\Theta(u, z) = \sum_{m=-\infty}^{\infty} e^{-u^2(z+m)^2} \qquad (13)$$

represents a periodical function with the period z = 1. We shall expand this function into a Fourier series [7 and 8]:

$$\Theta(u, z) = \frac{\sqrt{\pi}}{u} \sum_{\nu=-\infty}^{\infty} e^{-\frac{\pi^2\nu^2}{u^2}} e^{2\pi i\nu z}. \qquad (14)$$

This sum converges quickly for $u < \pi$ or, in our case, for $\overline{D}_I < \pi\Delta$, which is valid for heavy nuclei if $E > 1$ kev. We shall retain two terms of Eq. (14):

$$\Theta(u, z) \simeq \frac{\sqrt{\pi}}{u}\left(1 + 2e^{-\frac{\pi^2}{u^2}} \cos 2\pi z\right). \qquad (15)$$

By substituting expression (15) in (12), we finally obtain after integration:

$$\overline{\sigma_x\sigma} - \overline{\sigma}_x\overline{\sigma} = \sum_{\gamma} \overline{\sigma}_{\gamma}^{x}\overline{\sigma}_{\gamma}^{r}\left\{2\exp\left[-\left(\frac{2\pi}{b_I}\right)^2\right] + \frac{b_I}{\sqrt{2\pi}}\frac{\Phi_x}{S_x}\right\}. \qquad (16)$$

The $S_x$ and $\Phi_x$ functions take into account the effect of the distribution of the above widths on the cross section value [6]. The value of $S_x$ was borrowed from [3]; we calculated the function for one and two reaction channels (see figure):

$$\Phi_x(E) = \left\langle\frac{\Gamma_n^2\Gamma_x}{\Gamma}\right\rangle \Big/ \frac{\langle\Gamma_n\rangle^2\langle\Gamma_x\rangle}{\langle\Gamma\rangle} - \left\langle\frac{\Gamma_n\Gamma_x}{\Gamma}\right\rangle \Big/ \frac{\langle\Gamma_n\rangle\,\langle\Gamma_x\rangle}{\langle\Gamma\rangle} \qquad (17)$$

From our determination of the effective cross section (5), it is readily seen that the dependence of the cross section on temperature enters only $b_I$, while the dependence on the moderator concentration enters $\overline{\sigma}$. By using partial cross sections, which were calculated in [4] for unblocked cross sections, we determined the effective cross sections by taking into account resonance blocking for an infinite $U^{235}$ lump ($\sigma_{spot}$ = 10 b) at 300°K:

| $E$, kev | $\overline{\sigma}_f$ | $\overline{\sigma}_\gamma$ | $\langle\sigma_f\rangle$ | $\langle\sigma_\gamma\rangle$ |
|---|---|---|---|---|
| 1 | 12,75 | 8,46 | 6,88 | 4,51 |
| 2 | 9,66 | 6,08 | 6,45 | 4,47 |
| 5 | 6,43 | 3,70 | 5,51 | 3,24 |
| 7 | 5,94 | 3,27 | 5,39 | 2,97 |
| 10 | 5,05 | 2,67 | 4,82 | 2,51 |
| 50 | 2,30 | 0,67 | 2,29 | 0,67 |

The effect of resonance blocking is considerable for energies of up to 10 kev; for higher energies, the resonances overlap, and the cross section becomes smooth.

The above method of calculating the cross section dispersion in the region of partial resonance overlapping for heavy nuclei is of definite interest. Any $\langle f(\sigma)\rangle$ function that is averaged over the energy interval $\epsilon$ which contains many resonances can be represented in the following form:

$$\langle f(\sigma)\rangle \simeq f(\overline{\sigma}) - \left.\frac{d^2 f}{d\sigma^2}\right|_{\sigma=\overline{\sigma}} (\overline{\sigma^2} - \overline{\sigma}^2). \qquad (18)$$

By using the obtained expression for dispersion in the energy region where the actual cross section differs only slightly from the average cross section, it is easy to find the diffusion factor value for an infinite medium [1] and to analyze experiments on transmission for a rather wide incident neutron spectrum with many resonances, etc.

The above method can be conveniently used in estimating temperature effects in fast and intermediate neutron systems. We determined the ratio of $U^{238}$ and $U^{235}$ concentrations in an infinite medium at 300°K for which the total temperature effect becomes positive:

$$\frac{\varrho_8}{\varrho_5} \leqslant 0{,}675.$$

This result is more probable than the result obtained in [2], where the value of this ratio was found to be 1.87.

## LITERATURE CITED

1. A. Luk'yanov, and V. Orlov, Collection: Neutron Physics [in Russian] (Gosatomizdat, Moscow, 1961 – in preparation).
2. D. Gertsel', Transactions of the International Conference on the Peaceful Uses of Atomic Energy (Geneva, 1955) [in Russian] (AN SSSR Press, Moscow, 1958) Vol. 5, p. 564.
3. A. Lane and J. Lynn, Proc. Phys. Soc. A 70, 557 (1957).
4. R. Rae and B. Margolis, Phys. Rev. 112, 492 (1958).
5. A. Akhiezer and I. Pomeranchuk, Some Problems in the Theory of the Nucleus [in Russian] (Gostekhteoretizdat, Moscow, 1948) p. 248.
6. C. Porter and R. Thomas, Phys. Rev. 104, 483 (1956).
7. R. Courant and D. Hilbert, Methods of Mathematical Analysis [Russian translation] (Gostekhteoretizdat, Moscow, 1951) Vol. 1, p. 69.
8. I. Ryzhik and I. Gradshtein, Tables of Integrals, Series Sums, and Products [in Russian] (Gostekhteoretizdat, Moscow, 1951) p. 318.

# FAST NEUTRON CAPTURE CROSS SECTIONS FOR NIOBIUM, NICKEL, AND IRON

Yu. Ya. Stavisskii and A. V. Shapar'

Translated from Atomnaya Énergiya, Vol. 10, No. 3, pp. 264-265, March, 1961
Original article submitted August 23, 1960

We used the method of the instantaneous γ -radiation recording for measuring the energy dependence of fast neutron radiative capture cross sections for a natural mixture of niobium, nickel, and iron isotopes. The T(p,n) reaction was used as the neutron source. The protons were accelerated in a Van de Graaff generator. The average neutron energy spread was ± 20 kev. A scintillation counter with a $CaF_2$ crystal was used as the detector. Annular geometry was used in measurements. The measurement method and the processing of the experimental data have been treated in detail in [1]. The energy dependence of the neutron radiative capture cross section was determined by comparison with the $U^{253}$ fission cross section curve that was given in [2]. The experimental error for individual points did not exceed 10% for niobium and 15% for nickel and iron. For determining the absolute cross section magnitude, we used the neutron radiative capture cross sections for an energy of ~400 kev, which were obtained in [3]; they were equal to 65 mb for niobium, 8.3 mb for nickel, and 5 mb for iron.

The results of our measurements, together with the results obtained in [3-6], are given in Figs. 1-3.

In [1], we dealt with the problem of the effect of possible changes in the γ -radiation spectrum on the measurement results.

It should be noted that, if the niobium cross section is averaged with respect to many overlapping levels, the average distance between the levels for nickel and iron is comparable to the energy resolution of the method.

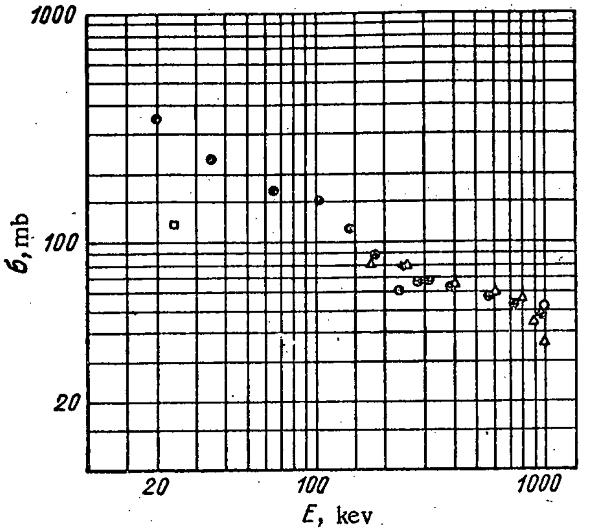


Fig. 1. Energy dependence of the fast neutron radiative capture cross section for niobium. Data: ⊛) present paper; △) [3]; □) [5]; ○) [6].

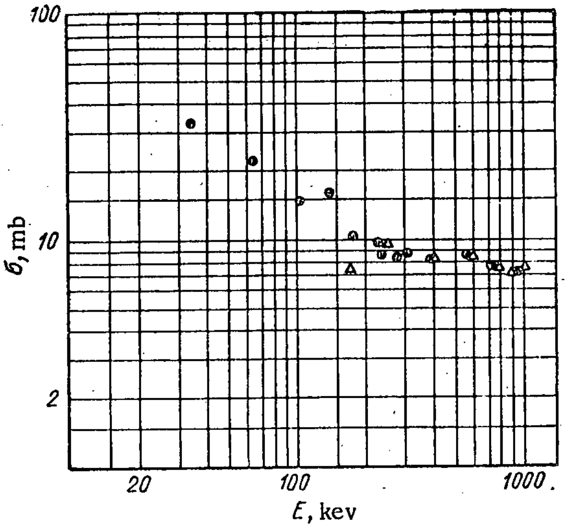


Fig. 2. Energy dependence of the fast neutron radiative capture cross section for nickel; Data: ⊛) present paper; △) [3].

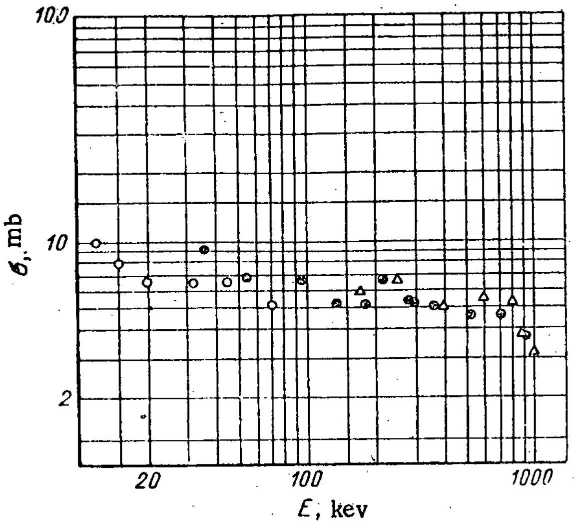


Fig. 3. Energy dependence of the fast neutron radiative capture cross section for iron. Data: ⊛) present paper; △) [3]; ○) [4].

It is obvious from the figures that the radiative capture cross sections weakly depend on energy in the 150-1000 kev interval. This is apparently connected with the considerable influence of the capture of neutrons having an orbital moment different from the zero moment as well as with a possible increase in radiation width with an increase in energy [7].

In conclusion, the authors extend their thanks to A. I. Leipunskii and O. D. Kazachkovskii for their interest in this work.

## LITERATURE CITED

1. Yu. Ya. Stavisskii and A. V. Shapar', "Fast neutron capture cross sections for Mo, W, Nb, Ni, and Fe." Report to the Second Conference on Low-Energy Nuclear Physics (Moscow, 1960).
2. D. J. Hughes and R. B. Schwartz, Neutron Cross Sections [Russian translation] (Atomizdat, Moscow, 1959).
3. B. Diven, Transactions of the Second International Conference on the Peaceful Uses of Atomic Energy (Geneva, 1958). Selected reports by foreign scientists [in Russian] (Atomizdat, Moscow, 1959) Vol. 2, p. 233.
4. A. I. Isakov, Yu. P. Popov, and F. L. Shapiro, Zh. Éksperim. i Teor. Fiz. 38, 989 (1960).
5. V. N. Kononov, Yu. Ya. Stavisskii, and V. A. Tolstikov, Atomnaya Énergiya 5, No. 5, 564 (1958).*
6. D. Hughes, W. Spatz, and H. Goldstein, Phys. Rev. 75, 1781 (1949).
7. I. V. Gordeev and V. S. Stavisskii, "Energy dependence of the radiation and fission width for $U^{235}$, $U^{233}$, and $Pu^{239}$ in the incident neutron energy region from 1 kev to 1 Mev." Report to the Second Conference on Low-Energy Nuclear Physics (Moscow, 1960).

---

* Original Russian pagination. See C. B. translation.

# SOME REMARKS CONCERNING THE DETERMINATION OF THE PHOTONEUTRON YIELD OF THICK SPECIMENS

V. I. Gomonai, D. I. Sikora, and V. A. Shkoda-Ul'yanov

Translated from Atomnaya Énergiya, Vol. 10, No. 3, pp. 265-266, March, 1961
Original article submitted August 31, 1960

The photoneutron yields of thick specimens of some elements under the action of monoenergetic electron beams in the 10-35 Mev energy region were measured almost simultaneously in the experiments described in [1 and 2]. However, the methods used in these experiments differed from each other to a certain extent. In [1], a thick-walled lead Faraday cylinder with a bottom thickness of up to 20 radiation lengths served as the electron beam monitor and as the photoneutron source at the same time. In [2], a thin-walled ionization chamber that was filled with hydrogen served as the monitor. Photoneutron yields of thick lead targets, which were placed behind the ionization chamber, were measured. The thickness of each target was equal to approximately six radiation lengths. The experimental data from [1 and 2] are given in Fig. 1.

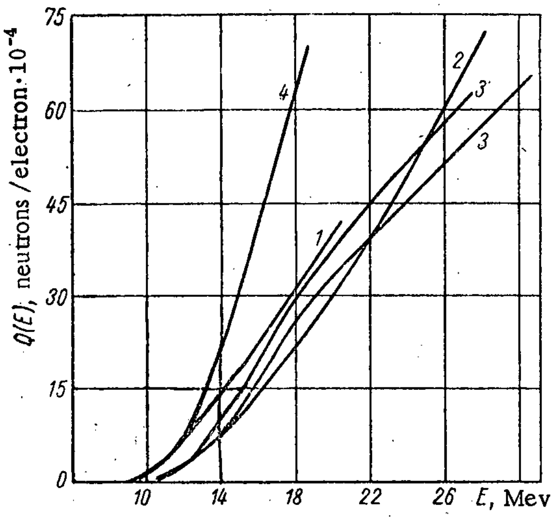


Fig. 1. The incident electron energy dependences of lead photoneutron yields that were obtained experimentally with respect to the excitation functions given in [3 and 4] (curves 3, 3', and 4).

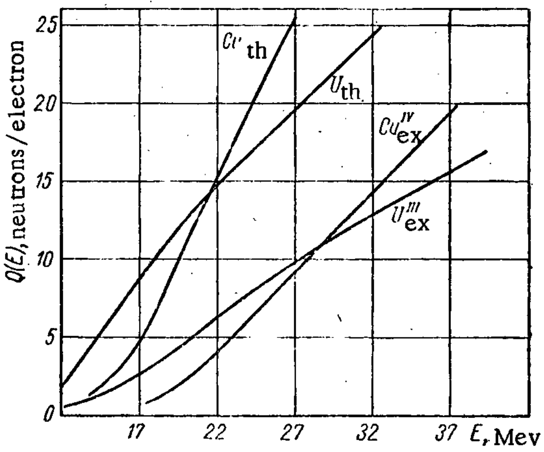


Fig. 2. Comparison of experimentally and theoretically calculated photoneutron yields of uranium and copper. One scale division represents $2.0 \cdot 10^{-4}$ neutrons/electron for copper and $1.0 \cdot 10^{-4}$ neutrons/electron for uranium.

On the basis of the data on the excitation functions of ($\gamma$,n)-reactions in lead that were published in [3 and 4], we calculated photoneutron yields of an infinitely thick target by using the Belen'kii–Tamm spectrum. The results, which are given by curves 3, 3', and 4, are shown in Fig. 1 (see also [5]). In our calculations that were published in [5] (see curve 3, Fig. 1) as well as in the present article (see curve 3', Fig. 1), it was assumed that the value of the ($\gamma$,n)-reaction cross section in lead for the energy region from 22 to 30 Mev remained constant and equal to the value which it assumes in the 18-22 Mev energy interval [4]. In contrast to the curve given in [5], curve 3' in Fig. 1 was also calculated by means of the Belen'kii–Tamm equilibrium spectrum, while the cross section of pair formation was obtained by using the equation [6]

$$\sigma_{\text{pair}}=\sigma_{\text{B.H.}}+4{,}0+\frac{46}{\omega},$$

where $\sigma_{\text{B.H.}}$ is the cross section of pair formation according to the Bethe–Heitler theory, and $\omega = E/m_0c^2$ (E is the electron energy, and $m_0c^2$ is the electron rest energy). Thus, in correspondence with the calculations given in [6], we took into account the higher values of the Bethe–Heitler cross section of pair formation in heavy elements, which are a consequence of the inaccuracy of the Born approximation for heavy elements. Figure 1 indicates that the recently published experimental data [2] confirm our earlier conclusion [1] that the published values of the excitation functions of (γ,n)-reactions in lead [3] are much higher than the actual ones. Moreover, by comparing the theoretical photoneutron yield curve 3' with the experimental curves 1 and 2, we arrive at the conclusion that an increase in the photoneutron formation cross section in lead apparently must be observed at energies above 21 Mev. This influence follows from a comparison between the theoretical curve 3' (where the value of the (γ,n)-reaction cross section in the energy region above 21 Mev was assumed to be constant) and the experimental curves 1 and 2.

It should be noted that, although the shapes of the experimental curves 1 and 2 generally agree, the difference between the absolute yield values exceeds the measurement error (± 15%). Partially, this can be explained by the fact that the photoneutron yield values obtained in [2] were somewhat lower due to the lesser thickness of targets in these measurements in comparison with the target thicknesses in [1]. According to the estimate of the authors of [2], these values are lower by approximately (5 ± 3%) than the yield values for an infinitely thick lead target and for an electron energy of 34 Mev.

The magnitudes of the above difference in other elements can be estimated by considering Fig. 2, which provides theoretical data on photoneutron yields for infinitely thick targets [5] and experimental data for targets with finite thicknesses [2].

Attempts to characterize the photoneutron yield dependence on energy by using a spectrum which is integrated over the depth and which is different from the Belen'kii – Tamm equilibrium spectrum did not produce satisfactory results [2]. Thus, the Belen'kii–Tamm equilibrium spectrum can be successfully used for calculating photoneutron yields in the above-considered energy region within the limits of the presently allowable errors in measuring the cross section of (γ,n)-reactions.

## LITERATURE CITED

1. V. M. Grizhko et al., Zh. Éksperim. i Teor. Fiz. 38, 1370 (1960).
2. W. Barber and W. George, Phys. Rev. 116, 1551 (1959).
3. K. Montalbeti, L. Katz, and I. Goldemberg, Phys. Rev. 91, 659 (1953).
4. M. Toms and W. Stephens, Phys. Rev. 108, 77 (1957).
5. V. I. Gomonai, I. Yu. Krivskii, and V. A. Shkoda-Ul'yanov, Atomnaya Énergiya 7, No. 5, 476 (1959).*
6. H. Davies, H. Bethe, and L. Mazimon, Phys. Rev. 93, 788 (1954).

# CALCULATION OF MUTUAL SHIELDING OF LUMPS IN A TIGHT LATTICE

N. I. Laletin

Translated from Atomnaya Énergiya, Vol. 10, No. 3, pp. 267-269, March, 1961
Original article submitted September 22, 1960

In reactor calculations it is often necessary to evaluate integrals of the form:

$$\int\limits_{V_j} \frac{dV}{V_j} \int\limits_{V_i} \frac{dV'}{4\pi} |\mathbf{r}-\mathbf{r}'|^n f(\theta;\ \varphi)\, e^{-\int\limits_{\mathbf{r}}^{\mathbf{r}'} \Sigma(\mathbf{r}'')\, dr''} \qquad (1)$$

The regions of integration $V_i$ and $V_j$ may be the volume of all the lumps in an infinite lattice, or the volume occupied by the moderator, or the volume of the whole lattice; r and r' are radius vectors; θ and φ are the angles which the vector r – r' makes with the z and x axes; and Σ(r) is the total macroscopic neutron interaction cross section

---

* Original Russian pagination. See C. B. translation.

of the material in the vicinity of the point $\underline{r}$. An integral of this type is used, for example, to express the value $P_C$:

$$P_c = \int\limits_{V_2} \frac{\Sigma_2 dV}{V_2} \int\limits_{V_2} \frac{dV'}{4\pi} \frac{e^{-\int\limits_{\mathbf{r}}^{\mathbf{r}'} \Sigma(\mathbf{r}'')\,dr''}}{|\mathbf{r}-\mathbf{r}'|^2} \tag{2}$$

which may be considered to be the probability that a neutron will experience its first collision in the lump, if we assume that neutrons are born only in the lumps and that the density of neutron sources is constant. Here $V_2$ is the volume of all the lumps, and $\Sigma_2$ is the total cross section for neutron interaction with the material in the lumps.

The quantity $P_2$ is used to calculate the fast neutron multiplication factor in heterogeneous reactors, the effect of inelastic scattering on neutron moderation, the heat produced from the absorbtion of radiation in the active zone, etc.

An integral of the same form is used to express the quantity $P_1$:

$$P_1 = \int\limits_{V_2} \frac{\Sigma_2 dV}{V_1} \int\limits_{V_1} \frac{dV'}{4\pi} \frac{e^{-\int\limits_{\mathbf{r}}^{\mathbf{r}'} \Sigma dr''}}{|\mathbf{r}-\mathbf{r}'|^2}, \tag{3}$$

where $V_1$ is the total moderator volume. This quantity may be considered to be the probability that a neutron will experience its first collision in the lump, if the neutrons are born only in the moderator, and the density of sources is constant. The quantity $P_1$ may be used to calculate the mutual shielding of the lumps, in the expression for the volume part of the resonance absorbtion. The integral $P_1$ is easily brought into relationship with $P_C$. In fact:

$$P_1 = \int\limits_{V_2} \frac{\Sigma_2 dV}{V_1} \int\limits_{V_1} \frac{dV'}{4\pi} \frac{e^{-\int\limits_{\mathbf{r}}^{\mathbf{r}'} \Sigma dr''}}{|\mathbf{r}-\mathbf{r}'|^2} = \int\limits_{V_2} \frac{\Sigma_2 dV}{\Sigma_1 V_1} \left[ \int\limits_{V_1+V_2} \frac{\Sigma(\mathbf{r}')\, e^{-\int\limits_{\mathbf{r}}^{\mathbf{r}'} \Sigma dr''}\, dV'}{4\pi |\mathbf{r}-\mathbf{r}'|^2} - \int\limits_{V_2} \frac{\Sigma_2 e^{-\int \Sigma dr''}\, dV'}{4\pi |\mathbf{r}-\mathbf{r}'|^2} \right] = \frac{\Sigma_2 V_2}{\Sigma_1 V_1} - \frac{\Sigma_2 V_2}{\Sigma_1 V_1} P_c = \frac{x_2}{x_1}(1-P_c). \tag{4}$$

Here $x_2 = 4\Sigma_2 v_2/S$ is the hydraulic diameter of the lump, measured in neutron mean free path lengths: $v_2$ is the volume of one lump; S is the surface area of a lump; $x_1 = 4\Sigma_1 v_1/S$ is the mean distance between lumps in mean free path lengths; $v_1$ is the moderator volume associated with one lump. Here we are taking into consideration the fact that:

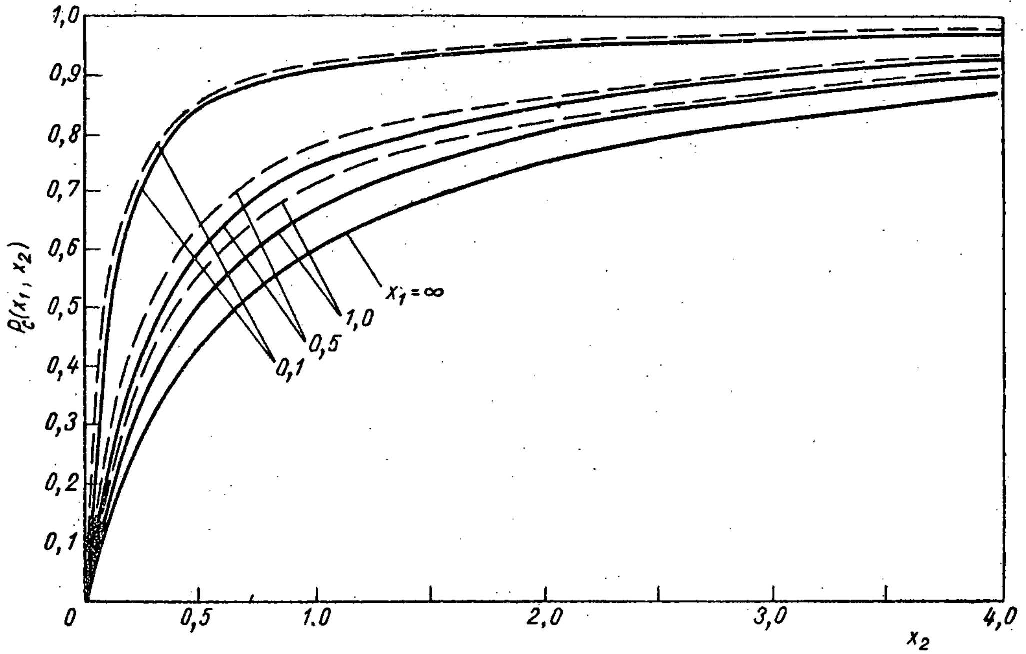
$$\int\limits_{V_1+V_2} \frac{\Sigma(\mathbf{r})\, e^{-\int\limits_{\mathbf{r}}^{\mathbf{r}'} \Sigma dr''}\, dV}{4\pi |\mathbf{r}-\mathbf{r}'|^2} = 1.$$

If the lumps are located sufficiently far from one another ($x_1 \gg 1$), the region of integration $V_2$ of the integrals (2) and (3) practically coincides with the region of integration $v_2$, and the integration over $V_1$ may be replaced by integration over an infinite volume. Evaluating the integrals (2) and (3) in this case presents no difficulty. For $x_1 \lessgtr 1$, the integrals of type (1) are evaluated only in a few special cases. Thus, for example, for a heterogeneous medium consisting of infinite plane-parallel sheets of two different kinds:

$$P_c(x_1; x_2) = 1 - \frac{2}{x_2} \int\limits_0^1 \frac{\left(1 - e^{\frac{-x_2}{2u}}\right)\left(1 - e^{\frac{-x_1}{2u}}\right)}{1 - e^{-\frac{x_1+x_2}{2u}}}\, u\,du, \tag{5}$$

where $x_1 = 2\Sigma_1 t_1$; $x_2 = 2\Sigma_2 t_2$.

For a heterogeneous medium with lumps of arbitrary shape, the integrals of the type being considered may be evaluated for the case when the lumps are located chaotically with respect to one another, so that the probability of a neutron colliding with a lump and traversing a definite distance within it does not depend upon the probability of collision with another lump. For example, an integral of type (1) is evaluated by determining the effective longitudinal neutron diffusion coefficient of heterogeneous media with cylindrical lumps of arbitrary cross section[1].



The integral $P_c$ ($x_1$; $x_2$) for a medium with fuel elements in the form of plane layers. ——— fuel elements parallel to one another; – – – – fuel elements in disordered array.

In media with a chaotic arrangement of lumps, we obtain for $P_c$ the following expression:

$$P_c = 1 - \frac{x_1}{x_2}\left\{1 - \int_0^{2\pi}\int_0^{\pi} \frac{\sin\theta\, d\theta\, d\varphi}{4\pi\left[1 + \frac{4}{x_1}\int_0^{\infty}\psi(x,\theta,\varphi)\left(1 - e^{-\Sigma_2 x}\right)dx\right]}\right\}. \tag{6}$$

Here $\underline{x}$ is the neutron path length in the lump in the absence of interaction between the neutron and the material of the lump; $\psi(x, \theta, \varphi)dx$ is the probability of a given value of $\underline{x}$ for a neutron with the direction determined by the angles $\theta$ and $\varphi$. In particular, for a medium with circularly cylindrical parallel lumps:

$$P_c(x_1; x_2) = 1 - \frac{4}{\pi}\int_0^1 \frac{\int_0^1 \sqrt{1-u^2}\, e^{-x_2\frac{u}{v}}\, du}{\left(1 + \frac{4}{\pi}\frac{x_2}{x_1}\int_0^1 \sqrt{1-u^2}\, e^{-x_2\frac{u}{v}}\, du\right)} \frac{v\, dv}{\sqrt{1-v^2}}, \tag{7}$$

where $x_2 = \Sigma_2 d$; $x_1 = \Sigma_1 d/p$; $p = v_2/v_1$; $\underline{d}$ is the diameter of the lump. Then, at $x_1 \ll 1$, and $x_2 \ll 1$;

$$P_c(x_1; x_2) \simeq \frac{x_2}{x_1 + x_2} = \frac{\Sigma_2 v_2}{\Sigma_1 v_1 + \Sigma_2 v_2},$$

and at $x_1 \gg 1$:

$$P_c(x_2) \simeq 1 - \frac{4}{\pi}\int_0^1 \frac{v\,dv}{\sqrt{1-v^2}} \int_0^1 du \sqrt{1-u^2}\, e^{-x_2 \frac{u}{v}}$$

For a medium with lumps in the form of infinite sheets, arranged at different angles to one another (all lumps parallel to the z axis):

$$P_c(x_1;\, x_2) = 1 - \frac{2}{x_2}\int_0^1 \frac{u\left(1-e^{-\frac{x_2}{2u}}\right)du}{1+\frac{2u}{x_1}\left(1-e^{-\frac{x_2}{2u}}\right)} \tag{8}$$

Here $x_2 = 2\Sigma_2 t_2$; $x_1 = 2\Sigma_1 t_1$.

It is not difficult to show that Eqs. (5) and (8) give identical results at $x_1 \ll 1$, and $x_2 \ll 1$, namely:

$$P_c \approx \frac{\Sigma_2 v_2}{\Sigma_1 v_1 + \Sigma_2 v_2}\,.$$

and likewise, at $x_1 \gg 1$:

$$P_c \approx 1 - \frac{2}{x_2}\left[1 - E_3\left(\frac{x_2}{2}\right)\right], \quad E_n(y) = \int_1^\infty \frac{e^{-yt}\,dt}{t^n}$$

Direct calculation shows that the numbers obtained from Eqs. (5) and (8) do not differ greatly over the whole range of variation of $x_1$ and $x_2$ (see figure). This fact enables one to assert that the use of Eq. (7) for a medium with circularly cylindrical lumps in an ordered array (square, triangular, or other lattice) does not lead to any great error. The values of $P_c(x_1;\, x_2)$, obtained from Eq. (7), are given in the table.

Values of $P_c^{\text{cyl}}(x_1;\, x_2)$, Calculated from Equation (7)

| $x_1$ | $x_2$ | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0,2 | 0,4 | 0,6 | 0,8 | 1,2 | 1,6 | 2,0 | 3,0 | 4,0 | 6,0 | 8,0 |
| 0,2 | 0,5314 | 0,6947 | 0,7741 | 0,8209 | 0,8737 | 0,9027 | 0,9210 | 0,9464 | 0,9595 | 0,9729 | 0,9796 |
| 0,4 | 0,3875 | 0,5596 | 0,6571 | 0,7197 | 0,7955 | 0,8396 | 0,8684 | 0,9096 | 0,9314 | 0,9538 | 0,9653 |
| 0,6 | 0,3175 | 0,4832 | 0,5852 | 0,6544 | 0,7420 | 0,7951 | 0,8305 | 0,8824 | 0,9104 | 0,9396 | 0,9546 |
| 0,8 | 0,2762 | 0,4340 | 0,5366 | 0,6087 | 0,7030 | 0,7619 | 0,8019 | 0,8616 | 0,8942 | 0,9286 | 0,9462 |
| 1,2 | 0,2294 | 0,3744 | 0,4750 | 0,5489 | 0,6499 | 0,7156 | 0,7614 | 0,8316 | 0,8707 | 0,9124 | 0,9339 |
| 1,6 | 0,2038 | 0,3397 | 0,4376 | 0,5114 | 0,6154 | 0,6848 | 0,7342 | 0,8109 | 0,8544 | 0,9011 | 0,9254 |
| 2,0 | 0,1876 | 0,3169 | 0,4124 | 0,4858 | 0,5912 | 0,6629 | 0,7145 | 0,7958 | 0,8424 | 0,8928 | 0,9190 |
| 3,0 | 0,1648 | 0,2839 | 0,3750 | 0,4471 | 0,5536 | 0,6283 | 0,6831 | 0,7714 | 0,8229 | 0,8791 | 0,9086 |
| 4,0 | 0,1530 | 0,2662 | 0,3545 | 0,4254 | 0,5321 | 0,6081 | 0,6646 | 0,7568 | 0,8111 | 0,8709 | 0,9024 |
| 6,0 | 0,1408 | 0,2475 | 0,3325 | 0,4019 | 0,5083 | 0,5856 | 0,6438 | 0,7401 | 0,7976 | 0,8614 | 0,8951 |
| 8,0 | 0,1345 | 0,2378 | 0,3210 | 0,3894 | 0,4954 | 0,5733 | 0,6324 | 0,7309 | 0,7901 | 0,8560 | 0,8910 |
| ∞ | 0,1153 | 0,2073 | 0,2838 | 0,3486 | 0,4525 | 0,5315 | 0,5930 | 0,6986 | 0,7637 | 0,8372 | 0,8766 |

## LITERATURE CITED

1. N. I. Laletin, Proc. Second International Conference on the Peaceful Uses of Atomic Energy (Geneva, 1958). Reports of Soviet Scientists, Vol. 2 [in Russian] (Atomizdat, Moscow, 1959) p. 634.

# EFFECTIVENESS OF A SYSTEM OF ABSORBING ELEMENTS SYMMETRICALLY ARRANGED IN A RING IN THE ACTIVE ZONE OF A REACTOR WITH REFLECTOR

**V. I. Nosov**

Translated from Atomnaya Energiya, Vol. 10, No. 3, pp. 269-270, March, 1961
Original article submitted October 11, 1960

In a previous paper,* the author obtained the two-group approximation for the criticality conditions of a homogeneous thermal reactor with a system of absorbing rods equally spaced in a ring in the active zone, or in the radial reflector.

In the same paper, results were given for calculations on a system of amsll diameter rods ($d \ll R_{core}$). In this case, it is possible to neglect the azimuthal dependence of the neutral flux at the surface of the rods in the criticality equation, and confine attention to the first term in the series expansion in k.

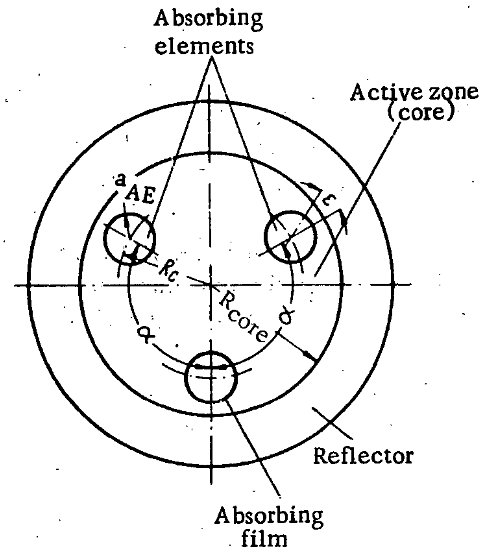


Fig. 1. Diagram of arrangement of absorbing elements in the active zone of reactor with reflector. ($R_c = 0.585\ R_{core}$, where $R_c$ is the distance between the center of the absorbing element and the center of the reactor).

In the present paper, we discuss the results of calculations on a system of absorbing elements of large dimensions, symmetrically arranged in a ring in the active zone of a reactor with reflector (Fig. 1). The absorbing element is a thin absorbing film, filled with active-zone material. It is assumed that the film is absolutely black to thermal neutrons and does not absorb or moderate fast neutrons. In fixing the boundary conditions at the surface of the absorbing element, account is taken of the moderation and neutron multiplication occurring inside.

The critical equations for the case in question are given by Eq. (14) of the previous paper:

$$\left.\begin{aligned}&\sum_{k=0}^{\infty}\sum_{m=0}^{\infty}\sum_{n=0}^{\infty}(B_{1m}F_{nNmk}+B_{2m}\Phi_{nNmk})\times\\&\qquad\times\cos k\omega=0;\\&\sum_{k=0}^{\infty}\sum_{m=0}^{\infty}\sum_{n=0}^{\infty}(B_{1m}H_{nNmk}+B_{2m}R_{nNmk})\times\\&\qquad\times\cos k\omega=0,\end{aligned}\right\}\tag{1}$$

where $B_{1m}$ and $B_{2m}$ are arbitrary constants: $F_{nNmk}$, $\Phi_{nNmk}$, $H_{nNmk}$, and $R_{nNmk}$ are suitable functions of the radius of the absorbing element $a_{AE}$, the radius of the reactor $R_p$, the radius of the active zone $R_{core}$, the properties of the multiplying medium and the reflector [N is the number of absorbing elements, n is the index of the series giving the azimuthal dependance of the neutron flux in the reactor, and m and k are indices of the series giving the azimuthal dependance of the neutron flux on the surface of the absorbing elements (angle ω)].

If we limit the approximation to the kth order, we get a system of $2(k+1)$ linear, homogeneous, algebraic equations, which must be solved for $2(k+1)$ unknowns (all the terms with $m > k$ must be omitted).

The critical condition for the problem is given by setting the determinant of the system of equations equal to zero.

Figure 2 and the table give the results of calculations on the change in effectiveness of a system of three absorbing elements as a function of radius to the kth order of approximation. The ordinates of the curve are the difference, $\Delta k_{eff}$, between the effective multiplication factor in the reactor without absorbing elements, $k_{eff}$, and with

---

* V. I. Nosov, Atomic Energy 2, No. 4, 262 (1960).

absorbing elements, $k'_{eff}$. Here $k_{eff}$ is calculated for a reactor in which the channels formed by withdrawing the absorbing elements are filled with active-zone material. For any value of $k'_{eff} < k_{eff}$, a value was taken for the radius of the absorbing element such that, in the given approximation, the critical equation of the reactor with the system of absorbing elements went to zero. The values of the radii of the absorbing elements were found for the three degrees of approximation k = 0, k = 1, and k = 2 (in all cases n = 2). To show what effect the number of terms taken in the series in n has on the radius of the absorbing element, calculations were also made for n = 0 and k = 0.

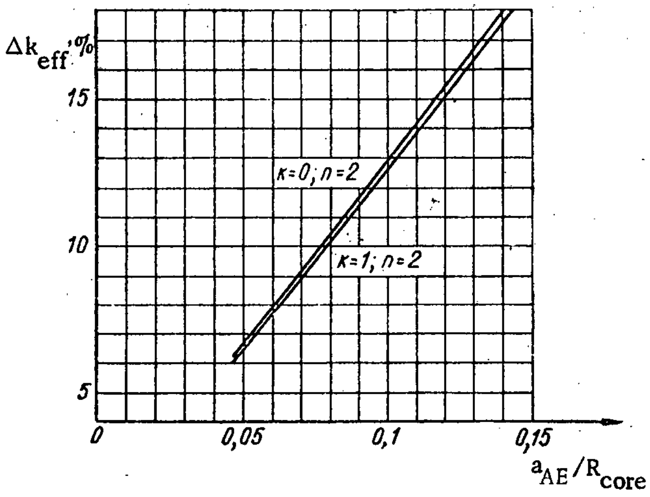


Fig. 2. Change in effectiveness of a system of three absorbing elements as a function of radius of element. Nomenclature same as Fig. 1.

Values of the Radius of the Absorbing Element, Calculated to Various Degrees of Approximation

| $\Delta k_{eff}$, % | $a_{AE}/R_{core}$ | | | |
|---|---|---|---|---|
| | κ=0; m=0; n=0 | κ=0; m=0; n=2 | κ=1; m=1; n=2 | κ=2; m=2; n=2 |
| 13,56 | 0,1051 | 0,1051 | 0,1073 | 0,1076 |
| 9,56 | 0,0737 | 0,0737 | 0,0750 | 0,0750 |

It follows from an examination of the table, and the curves of Fig. 2, that even for large diameters of the absorbing element, the first order approximation k = 1 gives good accuracy. In the critical equation for the reactor system of three absorbing elements, the angular dependance of the neutron flux in the reactor may be neglected, i.e., we may take n = 0. Thus, for example, the values of the radius of the absorbing element ($a_{AE}/R_{core}$) at k = 1 and k = 2 are equal to 0.1073 and 0.1076 respectively (for n = 2), and the curves of Fig. 2 for these approximations run together.

Thus it follows from what we have said, that numerical solutions of the criticality equations can be limited to the two first terms of the series in k and n for rather large absorber diameters (~0.3 $R_{core}$).

All the numerous and difficult calculations were made by R. V. Kuleva to whom the author is very much obliged.

# ON THE APPROXIMATE SOLUTION OF THE TRANSPORT EQUATION BY THE METHOD OF MOMENTS

Sh. S. Nikolaishvili

Translated from Atomnaya Énergiya, Vol. 10, No. 3, pp. 271-272, March, 1961
Original article submitted August 25, 1960

Our object is to calculate the energy distribution of neutrons at a given distance from a point isotropic source situated in an infinite homogeneous medium. The problem is solved by the method of moments, whose essence consists in the following. From the kinetic equation describing the slowing down and diffusion of neutrons, some of the first even-space moments of the function desired are determined. Afterwards an approximate representation of this function is constructed with the same exact first even moments [1].

In this paper the representation indicated is constructed by taking into consideration the asymptotic behavior of the solution; the first three moments of the approximating function are used.

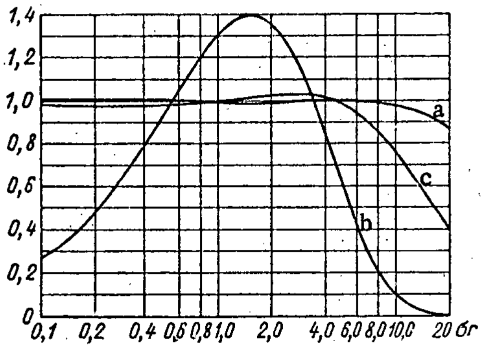


Fig. 1. Results of solving Eq. (5) by different approximate methods for $\omega = 0.3$.

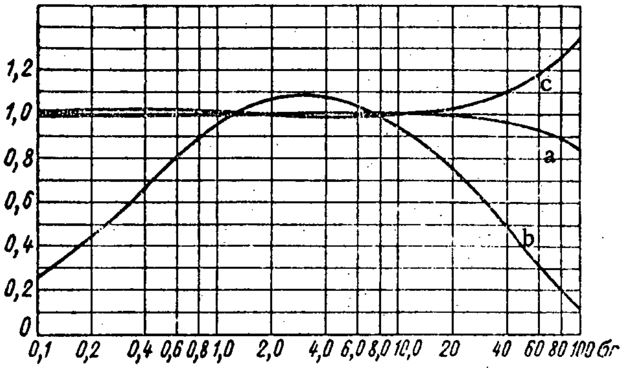


Fig. 2. Results of solving Eq. (5) by different approximate methods for $\omega = 0.9$.

Suppose $\Phi(r)$ is a nonnegative function defined in the interval $(0, \infty)$. We assume that the first three even moments of this function are known:

$$\mu_n = \frac{1}{n!} \int_0^\infty r^n \Phi(r)\, dr, \quad n = 0,\ 2,\ 4.$$

We take

$$\Phi(r) \approx \tilde{\Phi}(r) = A r^{\nu-1} e^{-\alpha r} \tag{1}$$

and choose the parameters $\nu$, $\alpha$ and A so that the three first moments of the function $\tilde{\Phi}(r)$ coincide with the known moments of $\Phi(r)$. This problem has a solution for every nonnegative function, with all parameters of the representation (1) being real positive numbers defined consecutively from the relations

$$\nu = \frac{5p - 1 + \sqrt{1 + 14p + p^2}}{2(1-p)}, \quad p = \frac{\mu_2^2}{6\mu_0\mu_4}; \tag{2}$$

$$\alpha = \sqrt{\frac{\nu(\nu+1)}{2} \frac{\mu_0}{\mu_2}}; \tag{3}$$

$$A = \frac{\mu_0 \alpha^\nu}{\Gamma(\nu)}, \tag{4}$$

and $\Gamma(\nu) = \int_0^\infty x^{\nu-1} e^{-x}\, dx$ is Euler's $\gamma$-function.

By way of an example of the use of the formula (1), we consider the problem of the space distribution of neutrons emitted by a point isotropic source. For simplicity we assume that the scattering indicatrix is spherically symmetric. The transport equation in this case has the form [2]

$$\mu \frac{\partial \varphi}{\partial r} + \frac{1-\mu^2}{r} \frac{\partial \varphi}{\partial \mu} + \varphi = \frac{\omega}{2} \int_{-1}^{+1} \varphi(r, \mu')\, d\mu' + \frac{\delta(r)}{8\pi r^2}. \tag{5}$$

The distribution sought is determined by the function

$$4\pi r^2\varphi_0(r) = 4\pi r^2 \int_{-1}^{+1} \varphi(r, \mu)\, d\mu.$$

Separating out the nonscattering part of the neutron field, we represent the function $4\pi r^2\varphi_0(r)$ in the form

$$4\pi r^2\varphi_0(r) = e^{-r} + \Phi(r). \tag{6}$$

For moments of the function $\Phi(r)$ according to Eq. (5) we shall have

$$\mu_0 = \frac{\omega}{1-\omega};\quad \mu_2 = \frac{\omega(2-\omega)}{(1-\omega)^2};\quad \mu_4 = \frac{\omega(23-27\omega+9\omega^2)}{9(1-\omega)^3}.$$

Consequently, for $4\pi r^2\varphi_0(r)$ in accordance with what was said, we obtain

$$4\pi r^2\varphi_0(r) \approx e^{-r} + \frac{\omega}{1-\omega}\,\frac{\alpha^{\nu}}{\Gamma(\nu)}\, r^{\nu-1} e^{-\alpha r}, \tag{7}$$

$\nu$ and $\alpha$ are determined with the help of Eqs. (2) and (3), in which

$$p = \frac{3}{2}\,\frac{(2-\omega)^2}{23-27\omega+9\omega^2}.$$

The results of the calculations for the values $\omega = 0.3$ and $\omega$ 0.9 are represented in Figs. 1 and 2, where distance from the source is measured as the abscissa in units of mean free path, and the ratio of the approximate values of the function $4\pi r^2\varphi_0(r)$ found by formulas (7)-(9) to the exact values of this function (curves a, b, and c respectively) are measured on the ordinate axis. To determine the accuracy of formula (7) the values of $4\pi r^2\varphi_0(r)$ are cal-also by the formula

$$4\pi r^2\varphi_0(r) \approx 3re^{-\sqrt{3(1-\omega)}\,r} \tag{8}$$

and

$$4\pi r^2\varphi_0(r) \approx e^{-r} + \frac{3\omega r}{2-\omega}\, e^{-\sqrt{3\frac{1-\omega}{2-\omega}}\,r} \tag{9}$$

Formula (8) gives the solution of the problem in the diffusion approximation. Formula (9), proposed in [3], may be obtained if $\Phi(r)$ on the right side of Eq. (6) is represented in the form

$$\Phi(r) = ae^{-kr}$$

and a and k are chosen so that the first two even moments of $\Phi(r)$ will be exact.

The method of moments with the use of representation (1) was employed to solve several problems concerning the spacial energy distribution of fast neutrons in various media. The results of the calculations will be published separately.

The author expresses his thanks to G. I. Marchuk for his constant interest in this paper and for many valuable remarks.

## LITERATURE CITED

1. H. Goldstein, Fundamental Aspects of Reactor Shielding, London – Paris, 1959.
2. K. Case, F. de Hoffmann, and F. Placzek, Introduction to the Theory of Neutron Diffusion, Washington, D. C. 1953.
3. C. Grosjean, Nuovo Cimento 6, 1262 (1956).

# THE GROWTH OF VAPOR BUBBLES MOVING IN A VOLUME-HEATED FLUID

V. K. Zavoiskii

Translated from Atomnaya Énergiya, Vol. 10, No. 3, pp. 272-274, March, 1961
Original article submitted June 7, 1960

In order to write the equations of the kinetics of a boiling homogeneous reactor it is necessary to known the growth law of vapor bubbles moving in a volume-heated fluid. In this paper it is shown that the rate of growth of a moving bubble under moderate thermal loads is determined principally by the rate of heat transfer to it from the surrounding fluid by means of convection.

We assume that the rate of growth of a moving bubble, as also of a stationary one [1], is actually determined only by the rate at which heat is supplied to it. Then an increase in the energy of the bubble in unit time will equal to the magnitude of heat flow from the fluid into the vapor through the entire separation surface:

$$r\gamma'' \frac{dV}{dt} = \int \lambda \left( \frac{\partial T}{\partial R} \right)_R dS, \tag{1}$$

where r is the heat of evaporation; $\lambda$ the coefficient of heat conduction in the fluid; $\gamma''$ the density of vapor; V, S, R the volume, surface and radius of the bubble respectively at the moment t; and $(\partial T/\partial R)_R$ is the temperature gradient in the fluid at the bubble surface.

According to [2]:

$$\int a \left( \frac{\partial T}{\partial R} \right)_R dS = k_1 \left( \frac{au}{R} \right)^{1/2} R^2 \Delta T, \tag{2}$$

where $k_1$ is a constant coefficient; a the coefficient of temperature conduction, equal to $\lambda/c\gamma'$ ($c$, $\gamma'$ are the heat capacity and fluid density respectively); u the surfacing velocity of the bubble; and $\Delta T$ the temperature difference between the fluid far from the bubble and that at its surface.

Combining expressions (1) and (2), we obtain

$$\frac{dV}{dt} = k_1 \frac{c\gamma'}{r\gamma''} \left( \frac{au}{R} \right)^{1/2} R^2 \Delta T. \tag{3}$$

Bubbles of sufficiently large dimensions (R = 2 – 15 mm) will surface with a constant velocity. Such bubbles will be deformed and, by their radius, we understand the radius of the spherical bubble of the same size. The magnitude of the overheating $\Delta T$ is also to be considered constant all along the path of motion of the bubble. In fact, in [1] it is shown that the temperature of the water at the surface of a bubble sufficiently accurately coincides with the temperature $T''$ of saturated vapor at the given pressure. Therefore $\Delta T = T' - T''$ (where $T'$ is the temperature of the water far from the bubble). On the other hand in [3] it was established that under conditions of regular circulation, the difference between the temperature of the water and the temperature of the saturated vapor, calculated from the hydrostatic pressure of a column of liquid at the given point, varies slowly with height. We have confirmed this conclusion by controlled measurements under conditions of disorganized circulation. Thus in expression (3) the dimension of the bubble is the only quantity varying with time.

Let z be the distance traversed by the bubble in its vertical ascension. Since dz = udt and $R^{3/2} \sim V^{1/2}$, we obtain, by integrating (3),

$$V^{1/2} - V_0^{1/2} = k_2 \frac{c\gamma'}{r\gamma''} \left( \frac{a}{u} \right)^{1/2} \Delta T (z - z_0), \tag{4}$$

where $z_0$ is the distance at which the bubble created attains a volume $V_0$.

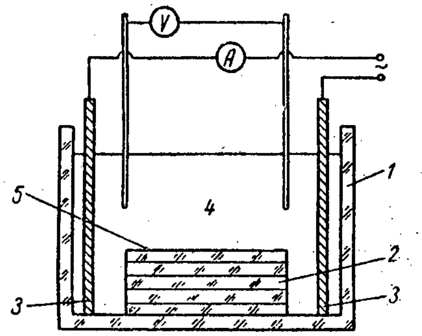


Fig. 1. Apparatus for photographing vapor bubbles: 1) rectangular glass vessels; 2) displacer made from glass plates; 3) electrode; 4) photographed area; 5) plane on which the vapor bubbles are formed; A and V – ammeter and voltmeter.

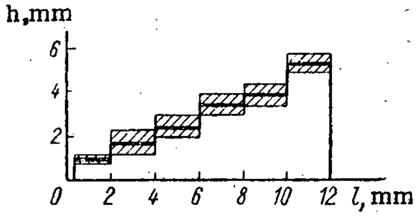


Fig. 3. Ratio of the longitudinal $l$ and transverse h dimensions of a deformed bubble in one of the photographs.

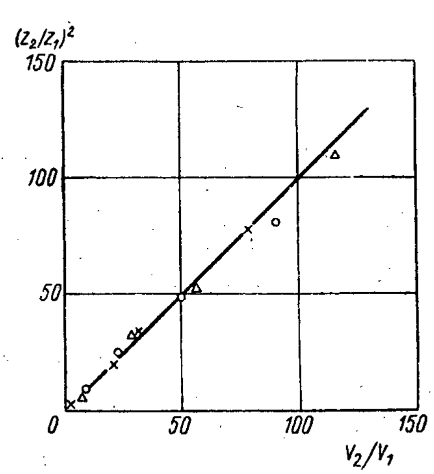


Fig. 2. Dependence of the ratio of mean volumes of vapor bubbles at different layers on the square of the ratio of distance tranversed by them in the liquid. Under powers (kv/$l$) of: △) 0.4; ○) 0.6; × 3.8.

If $V_0 << V$ and if one may discount the distance to the birth place of the bubble ($z_0 = 0$), then

$$V = k_2^2 \left(\frac{c\gamma'}{r\gamma''}\right)^2 \frac{a}{u} \Delta T^2 z^2. \qquad (5)$$

We apply this equation to the case of a boiling liquid in which all bubbles are created in a single plane ($z = 0$). At a distance z from the bottom of the vessel we consider a small volume bounded by two horizontal sections at a distance $\Delta z$ from one another. The total volume of all bubbles in this volume will be

$$VNs\Delta z = k_2^2 \left(\frac{c\gamma'}{r\gamma''}\right)^2 \frac{a}{u} \Delta T^2 z^2 Ns\Delta z,$$

where N is the number of bubbles per unit volume; and s is the cross-sectional area of the vessel. Dividing both sides of this expression by $s\Delta z$, we obtain

$$\varphi = k_2^2 \left(\frac{c\gamma'}{r\gamma''}\right)^2 \frac{a}{u} N\Delta T^2 z^2, \qquad (6)$$

where $\varphi$ is that portion of the volume occupied by vapor at the height z.

The verification of Eq. (5) was accomplished by measuring the dimensions of the vapor bubbles in boiling water by photographs. A rectangular glass vessel (Fig. 1) was filled with water and two metallic plates (electrodes) were positioned inside. A contraction of the cross section of liquid between the electrodes was brought about by the placement of glass displacers as shown, as a result of which the flux density attained its greatest magnitude in this section and practically all of the vapor was formed there. The vapor bubbles were produced on the horizontal surface of the displacer. Bubbles of electrolytic gas arising on the electrodes, and rising along them, did not enter the portion of liquid boiling in the contracted section.

The experiments were carried out at atmospheric pressure. The power varied from 0.4 to 3.8 kv/$l$. The fluid volume (above the displacer) was 2$l$.

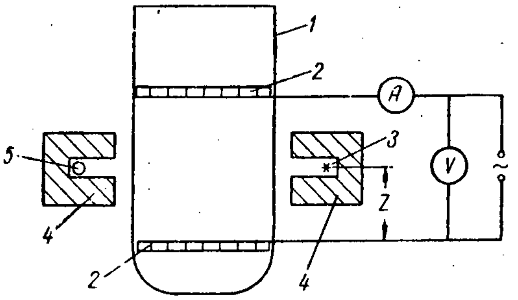


Fig. 4. Apparatus for measuring the volume vapor capacity: 1) cylindrical glass vessel; 2) electrodes; 3) $\gamma$-ray source; 4) lead shielding; 5) counter; A and V are an ammeter and voltmeter.

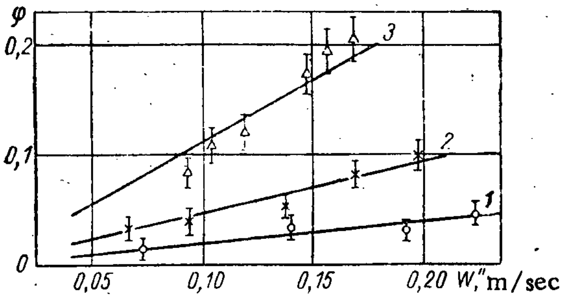


Fig. 5. Dependence of volume vapor capacity $\varphi$ on reduced vapor velocity W" above the electrodes for three distances z from the lower electrode (mm): 1) 60; 2) 110; 3) 180.

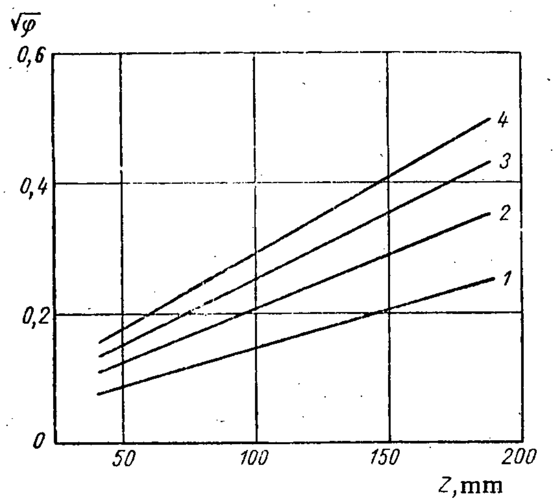


Fig. 6. Dependence of $\sqrt{\varphi}$ on distance z for four reduced vapor velocities (m/sec): 1) 0.05; 2) 0.10; 3) 0.15; 4) 0.20.

To carry out the photography, the fluid volume above the displacer was separated into horizontal layers of height 1 cm. In each layer the amount of bubbles were counted and the mean volume of bubbles was calculated. The error in determining the dimension of the large and medium sized bubbles did not surpass 1-3%, and for the small ones 5-10%. Thus the ratio of mean volumes of bubbles in different layers $V_2/V_1$ was found, and also the mean square ratio of the distance of these layers from the displacer surface $(z_2/z_1)^2$. The points found in this manner (Fig. 2) lie on the straight line corresponding to Eq. (5).

It was established that the transverse dimension of a bubble increases approximately proportionally to its longitudinal dimension (Fig. 3). From the experimental data the coefficient $k_1$, entering into Eq. (2), was calculated. It turned out that $k_1 \approx 11$, which coincides well with the magnitude found in [2]. This indicates the suitability of Eq. (2) to the calculation of the heat flow in a moving vapor bubble of sufficiently large dimension.

Equation (6) was verified with the aid of an apparatus for the measurement of volume vapor capacity (Fig. 4). In a vessel with diameter approximately 200 mm filled with water to a height of around 250 mm, there were placed two horizontal electrodes chosen from some metallic thin strips, arranged with a chord and strengthened reinforced among themselves by a strip bent into a circle. The area of each electrode did not exceed 3% of the area of the vessel cross section, and, as shown in the control experiment, the upper electrode did not exert a significant influence on the exit of the vapor from the liquid. At the same time the apparatus guaranteed a heating which was sufficiently uniform over the volume of the liquid between electrodes, and the bubble formation proceeded over the entire surface of the lower electrode. Control measurements showed that in the interval of reduced vapor velocity* studied, the density of the vapor-water mixture was the same over the entire vessel section.

The density of the vapor-carrying mixture was determined by directing beams of $\gamma$-rays from $Co^{60}$ through the space between electrodes at various heights. The results of the measurements are given in Fig. 5. The straight lines are constructed by the method of least squares.

Figure 6 is obtained as a result of cutting Fig. 5 along lines of constant reduced vapor velocity. The linear dependence of $\sqrt{\varphi}$ on distance, traversed in the water by vapor bubbles is given by Eq. (6).

---

* Reduced vapor velocity means that calculated over the entire vessel section.

For more intensive fluid motion, the rising velocity of a bubble will be determined also by the rate of heat transfer to it and may be found from expression (1). Of course in this case also the heat flux to the bubble will depend on the velocity of the flow of the fluid about it.

In conclusion I with to thank V. G. Levich, V. M. Byakov for their helpful discussions of the results, and also V. N. Vorob'ev, S. V. Goncharov, G. I. Savel'ev, A. F. Semin for their help at various stages of this project.

## LITERATURE CITED

1. M. Plesset and S. Zwick, J. Appl. Phys. 25, 493 (1954).
2. V. G. Levich, Physicochemical Hydrodynamics [in Russian] Fizmatgiz, Moscow, 1959, p. 465.
3. P. Zmola and R. Bailey, Trans. ASME 78, 881 (1956).

# ON THE THEORY OF HASIGUTI, SAKAIRI AND SUGAI CONCERNING THE IRRADIATION-INDUCED GROWTH OF α-URANIUM

Yu. N. Sokurskii

Translated from Atomnaya Énergiya, Vol. 10, No. 3, pp. 274-275, March, 1961
Original article submitted October 29, 1960

In reference [1], a theory by Hasiguti, Sakairi and Sugai concerning the radiation growth of α-uranium was reported. The authors of this theory proposed that, under the influence of stresses set up by local heating in the region of thermal spikes, twinning would occur along the $\{130\}\ \langle 3\bar{1}0\rangle$ systems. In addition, they assumed that "the average deformation for various twins of the $\{130\}\ \langle 3\bar{1}0\rangle$ type is evidenced by elongation in the [010] direction and contraction in the [100] direction." The internal stresses which arose from such local twinning had to be relieved by a corresponding deformation of the surroundings through interstitices and vacancies which, in the long run, led to an irreversible plastic deformation.

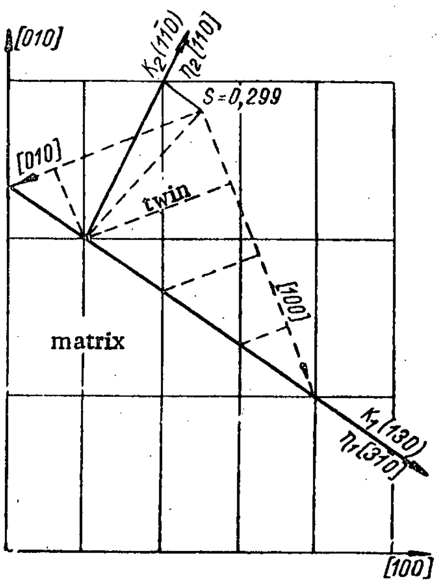


Fig. 1. Junction plane of twin and matrix lattices for twinning along the (130) $[3\bar{1}0]$ system.

However, the basic assumption of the theory that the average deformation for various types of $\{130\}\langle 3\bar{1}0\rangle$ twins is elongation in the [010] direction and contraction in the [100] direction appears incorrect.

As is well known [2], (130) twins are characterized by the following elements: $K_1(130)$; $\eta_1[3\bar{1}0]$; $K_2(1\bar{1}0)$; $\eta_2[1\bar{1}0]$; $S = 0.299$. The junction plane of the twin and matrix lattices is shown in projection on the ab plane in Fig. 1 for twinning along the (130) $[3\bar{1}0]$ system. In Fig. 2, the deformations which occur for twinning along the (130) and a crystallographically equivalent plane are presented in the usual fashion. As is obvious from this figure, the general result of twinning along the $\{130\}\ \langle 3\bar{1}0\rangle$ systems is a contraction of the crystal along the [010] axis and an elongation in the [100] direction, which contradicts the initial assumption made by the authors of the theory under discussion.

Since deformation by twinning is unipolar, the tensile stresses which act along the [010] axis cannot give rise to elongation of the crystal along the [010] axis (in Fig. 2, the regions of possible contraction and elongation for $\{130\}$ twinning are indicated). Thus, regardless of the nature of the stress condition in the region close to a fission spike, α-uranium crystals cannot elongate in the [010] axis direction by means of $\{130\}\ \langle 3\bar{1}0\rangle$ twinning.

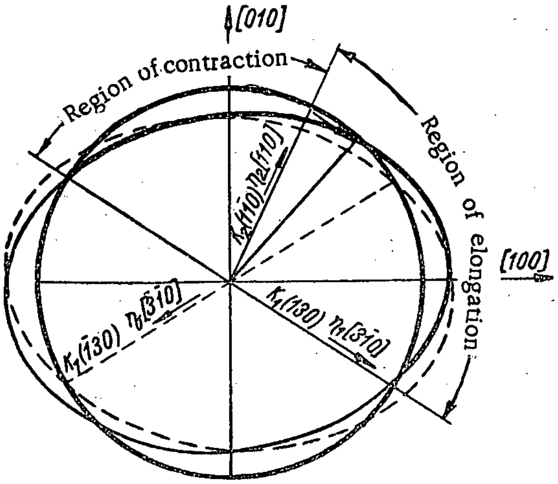


Fig. 2. Deformations associated with twinning: —— along the (130) plane; – – – – along a crystallographically equivalent plane.

From the standpoint of the physical processes which occur in the region of a fission spike, it is doubtful whether the arguments of the authors are correct. The time for formation and growth of a thermal spike ($\tau \simeq 10^{-11}$ sec) is much too short to expect the appearance of large-scale twins whose formation requires a considerable time.

Assuming that twin formation proceeds with the speed of sound, $\underline{c}$, we obtain its maximum diameter, approximately equal to $\tau c = 10^{-6}$ cm. It is doubtful that such twins would be stable. Theories based on the processes of atomic displacement and "agitation" which take place in the region of a fission spike seem more perspicuous.

## LITERATURE CITED

1. Hasiguti, Kiyoura, Proceedings 2nd International Conference on the Peaceful Uses of Atomic Energy (Geneva, 1958). [in Russian] Selected Foreign Scientific Reports, Vol. 6, Moscow, Atomizdat, 1959, p. 83.
2. R. Cahn, Acta Metallurgica 1, 176 (1953).

---

# PHASE COMPOSITION IN NICKEL-RICH ALLOYS OF A NICKEL-MOLYBDENUM-BORON SYSTEM

P. T. Kolomytsev and N. V. Moskaleva

Translated from Atomnaya Énergiya, Vol. 10, No. 3, pp. 276-277, March, 1961
Orignal article submitted September 12, 1960

Materials which contain nickel, molybdenum, boron and other elements have a wide practical application. In particular, steels which contain approximately one percent by weight of boron can be used for the production of shielding; and if there is more than two percent by weight of boron, they can be used for the production of control rods. Thus the phase composition of alloys which contain significant quantities of boron is of interest.

The results of an investigation of nickel-base alloys containing up to 22-33 at.% of molybdenum and up to 25-33 at.% of boron are reported in this paper.

For the melt, the charge materials described in reference [1] were used plus molybdenum in powdered form containing 99.7 wt.% of molybdenum, 0.2 wt.% of oxygen, 0.002 wt.% of nickel, and 0.01 wt.% of iron. All alloys were melted in aluminum oxide crucibles in an argon atmosphere. Burn-up of nickel, molybdenum, and boron is slight for a melt under pure argon; thus, the composition of the alloys was that of the charge.

The alloys studied were subjected to annealing for 100 hr at 1000°C with subsequent cooling in air. An increase in annealing time did not lead to a change in phase composition, as was determined by studies of microstructure and measurements of microhardness and by x-ray analysis.

Electrolytic etching and thermal coloration by heating with a high-frequency current were used to bring out microstructure [2].

Measurement of microhardness was carried out on a PMT-3 apparatus. Using cobalt $K_\alpha$ radiation, qualitative x-ray powder analysis was done. Powders from high-boron-content alloys were prepared by grinding castings; in low-boron-content alloys, the boride phase was separated electrochemically by the method described in [3].

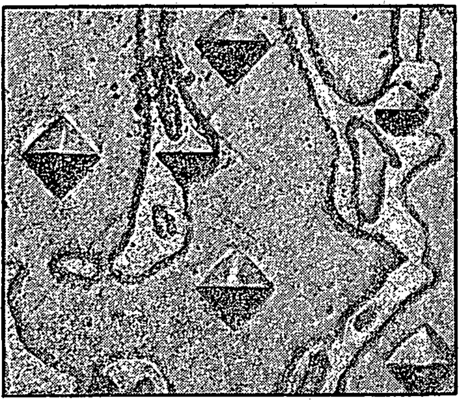


Fig. 1. Microstructure of alloy containing 5.29 at.% boron and 2.98 at.% molybdenum (x 500). $Ni_3B$ inclusions have a microhardness of 1145 kg/m$^2$. Solid-solution matrix $\gamma$ is less hard.

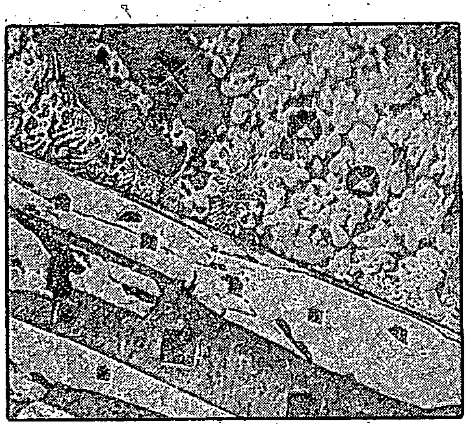


Fig. 2. Microstructure of alloy containing 20.4 at.% boron and 17.3 at.% molybdenum (x 400). Light component with small imprints – phase M (microhardness 1540 kg per mm$^2$). $Ni_3B$ and the solid-solution $\gamma$ (dark component) often form a eutectic.

Fig. 3. Microstructure of alloy containing 30.8 at.% boron and 32 at.% molybdenum (x 500). Light component – phase M.

It is possible to divide the alloys in the region studied into four groups according to phase composition. To the first group belong alloys with the structure of a homogeneous solid solution having a nickel base and containing not more than 0.02-0.03 at.% of boron. Alloys containing no more than 10 at.% of molybdenum, in whose structure there is the compound $Ni_3B$ in addition to the solid solution, belong to the second group. For alloys of this group, the two-phase structure is characteristic (Fig. 1). X-ray analysis of the precipitate electrochemically separated from this alloy confirms the judgement concerning the presence of only one boride phase – $Ni_3B$. An increase in boron content of the alloys, with molybdenum content kept fixed, leads to an increase in the solid-solution lattice period, since, in this situation, boron binds nickel and molybdenum is forced into the solid solution. To alloys of the third group belong the three-phase alloys in which, besides the solid solution and $Ni_3B$, there is a third phase which we call phase M. The typical structure of these alloys is shown in Fig. 2. In the case of electrochemical precipitation from alloys of this group in electrolytes, which usually are used for the separation of carbides from nickel alloys [3], $Ni_3B$ is dissolved to a significant degree, and lines characteristic of phase M are seen mainly in radiographs of the precipitates. In radiographs of the precipitates which are obtained by precipitation from alloys of the third group in an electrolyte, reflections from the planes of the rhombic $Ni_3B$ lattice are observed. The structure of alloys of the fourth group containing more than 10 at.% of molybdenum consists of two phases: nickel-base solid solution and phase M.

For low boron content, phase M is seen as a dispersed component, but large inclusions of phase M are developed in the case of a significant boron content in the alloy structure (Fig. 3).

Phase M is a ternary nickel-molybdenum-boron compound, as was shown by the results of qualitative x-ray analysis of the phase (separated from the alloys and synthesized).

As a result of the determination of the composition of phase M and the investigated alloys, it seems possible to present an isothermal section of the nickel corner of the nickel-molybdenum-boron ternary system at 1000°C (Fig. 4).

In these studies, very long exposures at high temperature were not used; thus, it is possible that for equilibrium alloys the boundary which separates alloys of the second and third groups will be displaced a little to the left toward alloys with a lower molybdenum content.

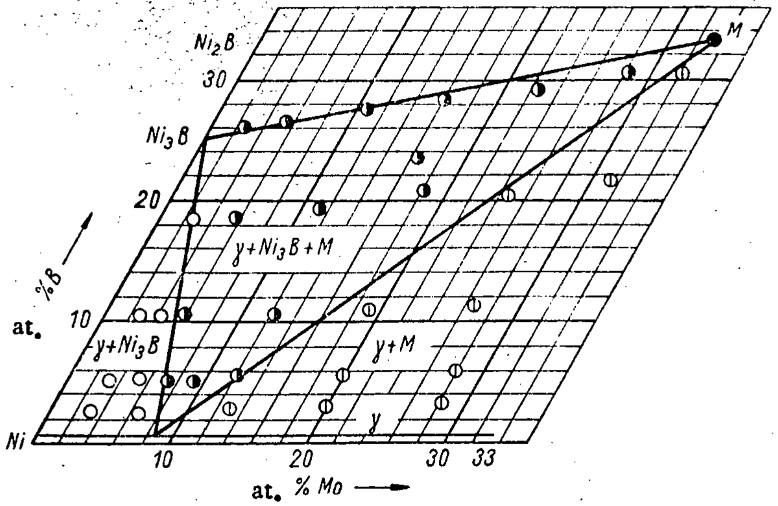


Fig. 4. Isothermal section of the nickel corner of the nickel-molybdenum-boron system at 1000°C. Alloys: ○ – $\gamma$ + $Ni_3B$; ◑ – $\gamma$ + $Ni_3B$ + + M; ⦶ – $\gamma$ + M.

## LITERATURE CITED

1. P. T. Kolomytsev, Izv. AN SSSR, Otd. tekhn. n. Metallurgiya i toplivo No. 3, 83 (1960).
2. P. T. Kolomytsev and S. A. Strekopytov, Metallovedenie i termicheskaya obrabotka metallov, No. 4, 56 (1960).
3. N. M. Popova, Carbide Analysis of Steel [in Russian] Oborongiz, 1957.

---

# SEPARATION OF URANIUM FROM IMPURITIES BY MEANS OF AMMONIUM SULFITE

N. P. Galkin and G. A. Polonnikova

Translated from Atomnaya Énergiya, Vol. 10, No. 3, pp. 277-279, March, 1961
Original article submitted August 4, 1960

An indication of the possibility of using ammonium sulfite, $(NH_4)_2SO_3$, for the separation of uranium from impurities first appeared in the literature in 1843 [1]. However, there was no detailed description of the separation method in this or subsequent papers. In our opinion, ammonium sulfite could be used in laboratory practice for the separation of uranium from uranium-containing products contaminated by impurities. The conditions for ammonium diuranate repurification were studied in the present work. To this end, the solubility of pure ammonium diuranate in ammonium sulfite solution with respect to its dependence on a number of factors and the conditions for precipitation of uranium from ammonium sulfite solution were studied.

We investigated the effect of $(NH_4)_2SO_3$ concentration, of temperature, and of the ratio T : L (T – wet diuranate weight) on the solution of ammonium diuranate in the presence of $(NH_4)_2SO_3$. Solution depended on the formation of a stable complex [2] in accordance with the reaction

$$(NH_4)_2U_2O_7 + 4(NH_4)_2SO_3 + 3H_2O \rightleftharpoons 2(NH_4)_2[UO_2(SO_3)_2] + 6NH_4OH.$$

The experiments were carried out in the following manner: a weighed batch of pure ammonium diuranate having 56% moisture content was placed in thick-walled test tubes to which was added a fixed quantity of freshly

TABLE 1. Boiling of Ammonium Uranylsulfite Solution

| Length of boiling, hr | pH | Concentration of uranium in solution g/liter | Concentration sulfite ion | Remarks |
|---|---|---|---|---|
| 0 | 7,5 | 25,8 | 224 | Separation of crystalline precipitate |
| 2 | 6,0 | 9,3 | 54 | |
| 5 | 5,5 | 2,9 | — | |

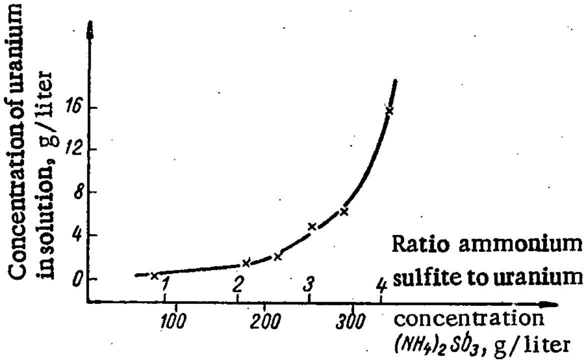


Fig. 1. Effect of $(NH_4)_2SO_3$ concentration on $(NH_4)_2U_2O_7$ solubility at 80°C and T : L = 1 : 2.

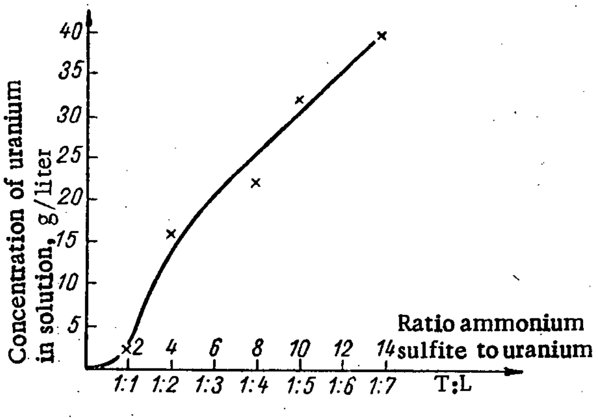


Fig. 3. Effect of temperature on $(NH_4)_2U_2O_7$ solubility in 320 g/liter $(NH_4)_2SO_3$ solution for T : L = = 1 : 2.

TABLE 2. Chemical Analysis of Ammonium Uranylsulfite Solution

| | U | $SO_3$ | $NH_3$ | U : $SO_3$ : $NH_3$ |
|---|---|---|---|---|
| Calculated for $(NH_4)_2[UO_2(SO_3)_2]$, % . . . . . . | 51,05 | 34,34 | 7,3 | 1 : 2 : 2 |
| Measured, % . . | 49,9 | 32,65 | 8,08 | 1 : 1,96 : 2,26 |

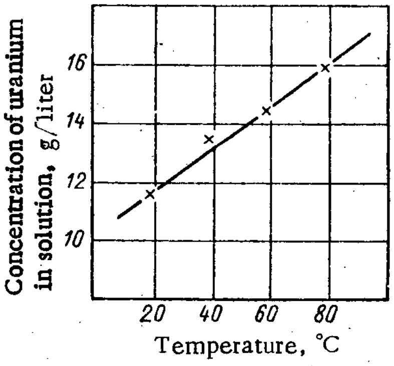


Fig. 2. Effect of the ratio T : L on $(NH_4)_2U_2O_7$ solubility in 320 g/liter solution of $(NH_4)_2SO_3$ at 80°C.

prepared $(NH_4)_2SO_3$ solution [3]. The test tubes were sealed with stoppers and fastened on a disc which was placed in a thermostatically controlled oven. Rotation of the disc in a vertical plane mixed the contents of the test tubes. The dissolving was carried on for two hours.

The results of the experiments, presented in Figs. 1-3, showed that ammonium diuranate solubility increased both with increase in temperature and with increase of the ammonium-sulfite-to-uranium ratio (for values two and greater). The highest uranium concentration in the solution which was reached during the course of the experiments turned out to be 39.2 g/liter for an ammonium-sulfite-to-uranium ratio of 14. Further increase of $(NH_4)_2SO_3$ solution volume led to complete solution of the ammonium diuranate. It is possible to increase the diuranate solubility by neutralizing with sulfurous acid, which yields ammonia. The addition of 0.5 M $H_2SO_3$ to 1 mole uranium increased the uranium content in solution from 16 to 28 g/liter, and the addition of 1 M $H_2SO_3$ to 1 mole uranium increased the uranium content to 52 g/liter (T : L = 1 : 2).

It was possible to precipitate uranium from the ammonium sulfite solution by boiling [1]. During boiling, the volume of solution was kept constant. A precipitate appeared at pH 6 one hour after initiation of solution boiling (Table 1): it consisted of large transparent yellow crystals. From the data of Table 2, it is obvious that the composition of the precipitate approximates that of the double sulfite of uranium and ammonia described in reference [2].

For repurification, we used moist ammonium diuranate, the composition of which is presented in Table 3. Solution was carried out under optimal conditions: saturated $(NH_4)_2SO_3$ solution (concentration 320 g/liter at a temperature of 80°C and ammonium-sulfite-to-uranium ratio 13.6 (T : L = 1 : 2). The insoluble residue was filtered off and the solution boiled for 5 hr. The precipitated crystals were washed twice with 10% $(NH_4)_2SO_3$ solution, dried and heated to 800-900°C for the purpose of producing uranium oxides.

TABLE 3. Effectiveness of Ammonium Sulfite Method for Diuranate Purification

| Product | Content, wt. % | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | U | Fe | Mn | Cu | Al | P | Ca | Co | As | $H_2O$ |
| Initial ammonium diuranate. . . . . | 36,0 | 11,2 | 0,15 | 0,06 | 1,4 | 0,34 | 0,46 | 0,006 | 0,3 | 61 |
| Uranium oxides. . . . . | 83,3 | 0,045 | 0,006 | 0,01 | 0,01 | 0,02 | 0,1 | $<0,0001$ | 0,1 | — |

As is evident from Table 3, oxides are obtained which contain an insignificant quantity of impurities as a result of the ammonium sulfite method.

## LITERATURE CITED

1. P. Berthier, Ann. chim. Phys. 7, (3), 76 (1843).
2. V. Kohlschütter, Liebigs Ann. Chem. 311, 1 (1900).
3. Yu. B. Karyakin, Pure Chemical Reagents [in Russian] Moscow, Goskhimizdat, 1955.

---

# QUANTITATIVE SPECTRAL ANALYSIS OF THE ISOTOPIC COMPOSITION OF BORON

B. V. L'vov and V. I. Mosichev

Translated from Atomnaya Énergiya, Vol. 10, No. 3, pp. 279-281, March, 1961
Original article submitted August 3, 1960

The most prevalent method of determining the isotopic composition of boron is the mass-spectrometric method [1-5]. However, because of its complexity and relatively low output, it is hardly possible to consider this method for bulk analysis. Activation methods for the determination of the isotopic composition of boron are experimentally complicated and require the presence of neutron sources [6, 7]. Analysis for isotopic composition of boron by infrared absorption spectroscopy of $BF_3$ [8] is limited by the need for converting the sample to $BF_3$. The determination of boron isotopic composition by analysis of the atomic emission spectrum requires the use of special sources for spectral excitation and very complicated interferometric apparatus, since the isotopic shift in the boron atomic spectrum is very small [9].

This paper proposes the determination of the isotopic composition of boron by means of the electron-vibrational emission spectra from the BO molecule in which the isotopic displacement is sufficiently great and can be resolved by the usual spectral apparatus. We observed the BO spectrum by vaporization of many boron-containing compounds (elemental boron, boron oxide, boron carbide, metallic borides) in a carbon arc burning in air. In view of the lack of other boron compounds enriched in $B^{10}$, development of the quantitative method was carried out on samples of amorphous, elemental boron with an active material content of ~85 wt.%.

The discharge proved to be unstable for vaporization of powdered boron samples in an alternating current arc. In addition, sputtering of the sample was observed, as a result of which a weak BO spectrum was produced. Change in electrode shape and material did not give noticeable improvement in results. Nor did the introduction of KCl, $KNO_3$, and NaCl lead to an increase in intensity of the BO spectrum. Only the use of a direct current arc as an excitation source permitted the production of sufficiently intense spectra. It should be noted that a change in arc current, within the range 4-25 amp, and the use of an oxygen jet did not give a noticeable change in spectral intensities, although the speed of sample burning was thereby increased.

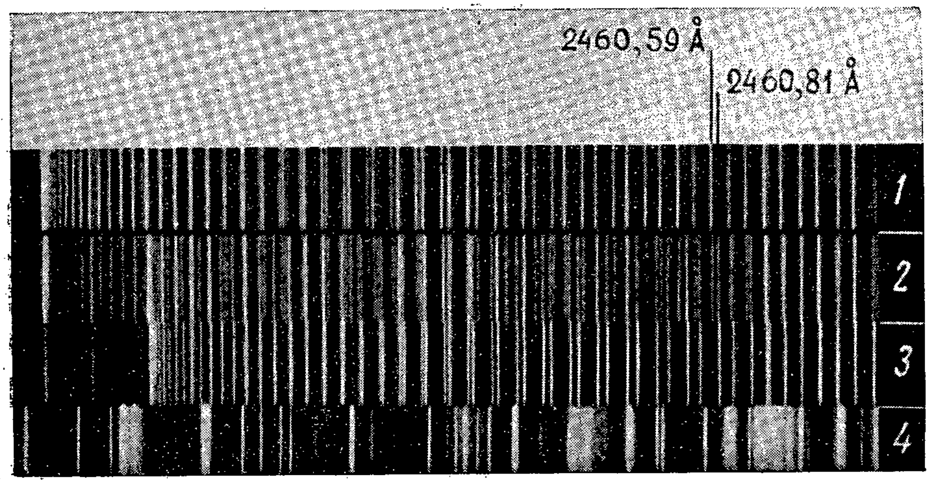


Fig. 1. Spectrum of a portion of the 0-1 band of BO in a direct current arc: 1) 19.2 at.% $B^{10}$; 2) 51.2% $B^{10}$; 3) 83.8% $B^{10}$; 4) Fe.

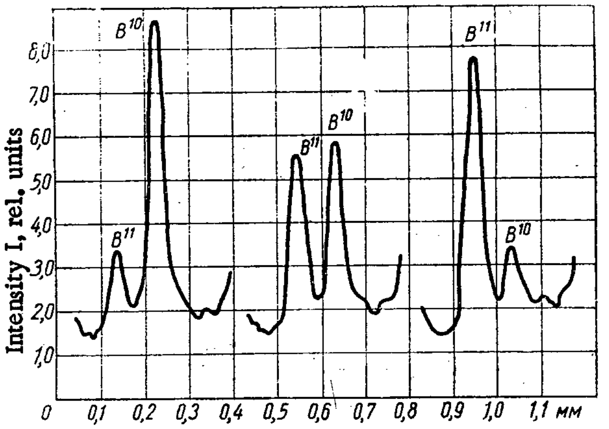


Fig. 2. Photomicrograms of $B^{10}$ and $B^{11}$ analytical lines for samples with $B^{10}$ content (at.%) of 83.3, 51.2, and 19.2.

A 7 mg analyzed sample of boron was put in a channel in a carbon electrode and vaporized in a direct current arc with a 9-10 amp current and 3 mm separation. Depth of the channel was 3 mm, diameter was 2.5 mm. The upper portion of the electrode was ground down to a 4 mm diameter. The opposing electrode was ground to a cone. The material-containing electrode was the anode. The BO spectra were photographed in the 2400-2500 A region with a KS-55 spectrograph having quartz optics and a 7 $\mu$ slit width, using 90 sec exposures. For conversion from density to intensity, the iron spectrum was photographed through a nine-step filter. The photographic materials used were "spectral" plates [type II sensitivity, 16 GOST (All-Union State Standard) units].

The spectrum associated with the BO molecule is seen in the 2000-8500 A region and has two band systems: $\alpha$-band ($A^2\Pi - X^2\Sigma$ transition) in the 3100-8500 A region, and the $\beta$-band ($B^2\Sigma - X^2\Sigma$ transition) in the 2000-3600 A region [10, 11]. Examination of the $\beta$-band showed that the 0-1 BO band with bands heads for $B^{11}O$ at 2437.10 A and for $B^{10}O$ at 2440.71 A was the most suitable for analysis. Utilization of the heads of this band for analysis was impossible because of the superposition of the rotational structure of the $B^{11}O$ band on the band head of the $B^{10}O$ band. Therefore, we investigated the structure of these bands and, as a result, chose two lines lying close together which were free of superpositions with wavelengths of 2460.59 A for $B^{11}O$ and 2460.81 A for $B^{10}O$ (Fig. 1). The dispersion of the KS-55 spectrograph in the 2460 A region is about 2.4 A/mm, which proved to be completely sufficient for the resolution of the two chosen lines. In Fig. 2, there are shown photomicrograms of the analytical $B^{11}O$ 2460.59 A and $B^{10}O$ 2460.81 A lines which represent the result of photometric evaluation of the spectra from samples with different isotopic compositions.

A considerable background was observed in the region of the selected lines; therefore, the determination of the line intensities for $B^{11}O$ at 2460.59 A and for $B^{10}O$ at 2460.81 A was carried out with regard for the background. To this end, the background density to the right and left of the lines and between the lines was measured. The background densities were converted to intensity, and for each line the average background intensity was calculated and then subtracted from the total line intensity. Background intensity depends strongly on the spectrograph slit width. With a 7 $\mu$ slit width, high resolution was achieved for the chosen lines without loss of spectral intensity. In the situation where the spectrograph slit was more than 7 $\mu$, a sharp increase in the background was seen, and line intensities were considerably reduced for exposures of spectra with less than a 7 $\mu$ slit.

Density of the analytical lines and background was measured on a MF-4 microphotometer using a scale of adjusted densities. For the conversion from density to intensity, a characteristic curve was constructed in a W −log I coordinate system. In the density range −1.0 to 1.0, the function $W = f(\log I)$ corresponded to a straight line with slope ~2 for the photographic plates used and the selected developing conditions (D-11 developer, developing time 6 min at 19°C). The linearity of the characteristic curve and its large slope allowed a reduction of the error arising from the conversion of photometry data to line intensity. For speeding up the calculations, one can use tables which relate the values of adjusted density to line intensity, depending on the slope of the characteristic curve.

TABLE 1. Dependence of Line Intensity Ratios on Isotopic Concentration Ratios

| Sample number | $I_{B^{11}O}/I_{B^{10}O}$ | $C_{B^{11}}/C_{B^{10}}$ |
|---|---|---|
| 1 | 4,18 | 4,21 |
| 2 | 1,81 | 1,85 |
| 3 | 0,94 | 0,95 |
| 4 | 0,49 | 0,49 |
| 5 | 0,24 | 0,20 |

TABLE 2. Reproducibility of Experimental Results for Given $B^{10}$ Content

| Sample number | $C_{B^{10}}$, at. % | $\sigma_{abs}$, at.% | $\sigma_{rel}$, at.% |
|---|---|---|---|
| 1 | 19,5 | 0,63 | 3,2 |
| 2 | 35,6 | 1,80 | 5,0 |
| 3 | 51,5 | 1,50 | 3,0 |
| 4 | 67,2 | 1,60 | 4,9 |
| 5 | 80,8 | 0,99 | 5,1 |

Table 1 gives a comparison of the average values of the intensity ratios, $I_{B^{11}O}/I_{B^{10}O}$, which were obtained from 50 measurements on ten plates for each elemental boron sample, with the isotopic concentration ratios $C_{B^{11}}/C_{B^{10}}$. The isotopic composition of the final samples was determined by the mass-spectrometric method; average samples were prepared by mixing the last samples in various proportions. As can be seen from the table, for the first four samples a sufficiently good agreement of the $B^{11}$ and $B^{10}$ concentration ratios with the ratios of the $B^{11}$ and $B^{10}$ line intensities at 2460.59 A and 2460.81 A is observed. This shows that, in the range of $B^{10}$ concentrations from 19.2 to 67.2 at.%, an uncalibrated determination of the isotopic composition of boron is possible; that is, the relation

$$\frac{I_{B^{11}O}}{I_{B^{10}O}} = \frac{C_{B^{11}}}{C_{B^{10}}}. \tag{1}$$

is valid for that range. A preliminary calibration or the introduction of the corresponding correction is necessary for higher $B^{10}$ content. Deviation of the line intensity ratios from concentration ratios for high $B^{10}$ content is explained, it appears, by an insufficiently accurate calculation of the background around the $B^{11}O$ line. Unfortunately, we were unable to choose a method for calculating background which was valid for all ranges of boron concentration ratios. However, in a comparatively small interval of concentrations of one of the isotopes (10-15 at.%), it is always possible to select a method for background calculation such that Eq. (1) remains valid.

Table 2 presents data on the spectral determination of $B^{10}$ content and also the absolute ($\sigma_{abs}$) and relative ($\sigma_{rel}$) standard deviation of an individual measurement (for the isotope of lower concentration), characterizing the reproducibility of the experimental results. Each value is an average of 50 determinations on 10 plates. $B^{10}$ content was calculated according to Eq. (1) taking account of the average background. It should noted that for a quadruple determination of isotopic composition, the measurement error is correspondingly reduced by a factor of two; that is, it amounts to ± 2% on the average.

The virtues of the method appear to be its simplicity and its satisfactorily high capacity. In 6 hr, two operators can analyze ten samples, making quadruple exposures of the spectra.

The method developed is applicable, in principle, to the determination of the isotopic content of various solid boron compounds.

## LITERATURE CITED

1. G. M. Panchenkov and V. D. Moiseev, Zh. fiz. khim. 30, No. 5, 1118 (1956).
2. C. Melton et al., Analyt. Chem. 28, 1049 (1956).
3. G. A. Semenov and Yu. A. Zonov, Zh. anal. khim. 14, No. 1, 137 (1959).
4. P. Bentley and A. Hamer, Nature 182, No. 4643, 1156 (1958).
5. V. Shyuttse, Zh. éksperim. i teor. fiz. 29, No. 4, 486 (1955).
6. H. Wanke and E. Monse, Z. Naturforsch. 10a, 667 (1955).
7. D. Dutina, Analyt. Chem. 30, 2006 (1958).
8. A. A. Mal'tsev, E. N. Moskvitina, and V. M. Tatevskii, Data of the Tenth Conference on Spectroscopy I. [in Russian] L'vov, Izd. L'vov Univ. 1957, p. 172.
9. E. Burke, Phys. Rev. 99, No. 6, 1839 (1955).
10. R. Mullikin, Phys. Rev. 25, 259 (1925).
11. A. A. Mal'tsev, Yu. Ya. Kuzyakov, and V. M. Tatevskii, Data of the Tenth Conference on Spectroscopy I. [in Russian] L'vov, Izd. L'vov Univ. 1957, p. 475.

# NEWS OF SCIENCE AND TECHNOLOGY

## IX SESSION OF THE LEARNED COUNCIL OF THE JOINT INSTITUTE FOR NUCLEAR STUDIES

V. Biryukov

Translated from Atomnaya Énergiya, Vol. 10, No. 3, pp. 282-303, March, 1961

The regular IX sesstion of the Learned Council of the Joint Institute for Nuclear Studies at Dubna was held November 21-24, 1960. The Learned Council heard reports from laboratoty directors, vice directors, and the administrative director of the Institute, reviewed scientific and financial plans projected for 1961, and discussed plans involving additional construction activities.

The Director of the High-Energy Laboratories, Academician V. I. Veksler, gave a report on the balance of work during 1960. In line with the decision of the Council and the Laboratory, much work was accomplished in increasing the operating time of the synchrophasotron (the Dubna proton synchrotron) and improving its operating stability. The intensity of the charged-particle beam was increased to $10^{10}$ protons per pulse. A number of high-energy facilities and shielding devices were designed to improve the reliability of the accelerator supplies system performance, and were put into effect. Instruments and circuits worked out to stabilize beam intensity at a desired level, to stabilize pulse length, etc., were of enormous importance in this regard. Accelerator improvements also included work along the line of improved target systems. A new linear accelerator-type injector unit was designed and fabricated, and is presently being run through preliminary tests. Extensive work on new techniques were completed in the Laboratory during the year 1960. The Drafting Bureau of the Institute and the Laboratory staff developed an arrangement for automatic processing of plates of particle tracks in particle-recording chambers. This arrangement is designed to fit into the Kiev computer system installed in the Theoretical Physics Laboratory. A report was given at the VIII session of the Learned Council on the start-up of a new type of electron accelerator, the ring phasotron [a synchrocylotron, cf. JAE 9, No. 2, p. 146 (1960)*]. The possibilities opened up by the use of a novel accelerator of this type are now being probed experimentally. The audience listened with intense interest to a report of work now in progress for designing channels producing monoenergetic beams of fast particles.

The results of basic research experiments carried out on the Dubna proton synchrotron during 1960 were reported on at the Rochester (USA) Conference on High-Energy Physics held during late August, 1960 [cf. JAE 10, No. 1, p. 80 (1961)*]. Some of the findings had already been made public at the VIII session of the Learned Council of the Dubna Institute. One of the important conclusions was obtained in a series of experiments probing nucleon structure. The study of angular distributions of particles in inelastic pion-nucleon and nucleon-nucleon collisions showed that the distribution of nucleons in the center-of-mass system is strongly anisotropic, independently of the multiplicity of pion generation, the maximum corresponding to the initial direction of motion of the nucleons. Some interesting and unexpected results were disclosed in a study of angular distribution of particles in the formation of $\Lambda^0$ and $\Sigma$-hyperons. The distribution of these particles in the high-energy regions is similar to the aforementioned nucleon distribution, in contrast to the almost isotropic distribution at the threshold of hyperon production. An analysis of the data obtained provided ground for the inference that particles carrying a baryonic charge are formed in peripheral collisions at high energy ranges.

Several research projects completed at the High-Energy Laboratory were devoted to the study of elastic nucleon-nucleon scattering, and nucleon interactions with fast K-mesons. Xenon and propane bubble chambers were used to study longitudinal polarization of $\Lambda^0$-particles generated in the course of interactions between pions and nucleons at energies of 7.8 and 3 Bev. These experiments were carried out with the object of testing conservation of parity in the production of strange particles. The results obtained apparently attest to the presence of polarization, but are still not sufficiently reliable to justify unambiguous conclusions.

The 1961 schedule of scientific research at the High-Energy Laboratory envisages further investigation of the problem of parity conservation in strong interactions, the processes of generation and decay of strange particles in pion-nucleon encounters, correlation effects in the production of strange particles, the properties of $K_2^0$-mesons, nucleon structure, etc. A project on weak interaction studies is also proposed, particularly an approach via

---

* Original Russian pagination. See C. B. translation.

investigations of regularities in K-decay, mass differences of K-mesons, and so forth. The projected plan of technical research efforts is also of quite large scope.

The Director of the Nuclear Problems Laboratory, Dr. of Phys. Math. Sci. V. P. Dzhelepov, reported to the Learned Council on the results of the most outstanding scientific research work accomplished on the synchrocyclotron of the Laboratory during 1960. The work of this research team attracted sustained interest on the part of physicists of various countries at the last Rochester conference.

In harmony with the research program required to determine the amplitude of nucleon-nucleon scattering at 650 Mev, Laboratory physicists undertook a complicated experiment devised to study triple scattering of protons by protons in that energy range, determined the correlation of the normal components of polarization in proton-proton interactions for the angle 90°, and came up with information of major importance on the contributions made by various forces. The coefficient of spin correlation was also measured for angle 90° at a proton energy of 315 Mev. These data were analyzed in common with data reported from Berkeley. A study of polarization effects in nucleon-nucleon collisions is being pursued further. Results of a reduction of experimental data on elastic n-p scattering were also presented at the Rochester Conference, with the idea of determining the constant of pion-nucleon interaction by means of a new method taking the two poles into account.

A portion of the important work of the Laboratory during 1956 has already been reported on, at the VIII session of the Learned Council. There were results of nuclear photoemulsion studies on pion-pion interactions, work on cerifying the strictness of conservation of isotopic spin in the reaction $d + d \to \pi^{0} + \alpha$, experimental data on angular distribution of pions, and values of the production cross section of mesons by nucleons in a state of zero isotopic spin, as well as results of measurements of the value of the Panovsky ratio, using a new technique.

The reporter dwelt in detail on investigations underway at the Laboratory into pressing current problems in the field of weak interactions. Experiments devised to determine the constant of muon-nucleon coupling by studying the processes of muon capture by nuclei are being carried on. Angular neutron distributions were measured in muon capture in calcium, to throw some light on a variant of muon-nucleon interaction. Processing of the first data obtained reveals that the contribution of a pseudoscalar variant to the effective interaction exceeds theoretical prediction by a factor of two. These investigations are being continued. In studying hyperfine structure (by measuring in $\mu \to l$-decay) due to spin coupling of a $\mu$-meson with the electron shell of atoms, it was demonstrated that this phenomenon is observed in mesic atoms of the transition elements, the actinides, and the lanthanides. Interesting experiments were conducted during 1959-1960, in collaboration with the staff of the Institute of Theoretical and Experimental Physics of the Academy of Sciences of the USSR, on radiationless transitions in heavy $\mu$-mesic atoms. Scintillation spectrometry was employed for this purpose to study the spectra of mesic x-ray photons emitted by $\mu$-mesic atoms in Pb and Bi isotopes and in the nuclides $Th^{232}$, $U^{235}$, and $U^{238}$. An analysis of the spectra revealed a hitherto unobserved mechanism functioning in heavy $\mu$-mesic atoms and involving radiationless transitions where the energy of transitions is imparted directly to the nucleus. Other research projects worthy of special note are the study of processes occurring in $\mu$-mesic atoms and $\mu$-mesic molecules, attempts to determine radiation corrections for the magnetic moment of the $\mu$-meson, determinations of direction of muon spin, etc.

The Laboratoty is also pursuing investigations of the spectra of nuclear radiations from neutron-deficient nuclides formed by irradiation of heavy-atom targets by beams of particles shot from the synchrocyclotron. Experimental workers have seven beta-ray spectrometers of various types and categories of precision at their disposal for this work; scintillation spectrometry techniques are in use. The spectra of several neutron-deficient isotope species were studied during 1960, the existence of several new nuclides was established, decay schemes were plotted and elaborated for several nuclei. Several research institutes in the Soviet Union, plus institutes in Poland and Czechoslovakia, cooperated in this phase of the work.

A portion of the Laboratory staff is participating in experiments being carried out on the proton synchrotron. A Wilson chamber placed in a magnetic field is being used to study the properties of $K_2^0$-meson decay; the data obtained in these experiments indicate the possibility of extending the selection rule $\Delta T = \pm \frac{1}{2}$ to processes of decay where leptons take part. Nuclear photoemulsion techniques are being used in continued research on the angular and energy distributions of secondary particles in p-p and p-n collisions in the energy neighborhood of 10 Bev.

Theoretical work accomplished during 1960 included an examination of the problem of extracting theoretical information from experiments using neutrino beams of mesonic nature, carrying out an analysis of deuteron scattering of gamma photons, and scattering of gammas by more complex nuclei over a wide range of energies below the meson production threshold, etc.

A sizable amount of work was carried out at the Laboratory on improving the synchrocyclotron, and on development of new accelerators. The prominent place is occupied by work related to the design of new experimental equipment. A facility with a liquid-hydrogen and deuterium bubble chamber in a magnetic field was successfully inaugurated and put to work on a beam of pions; final adjustments are being completed on a 200-liter capacity propane bubble chamber, and a 64-channel pulse-height analyzer and discharge-track chamber have been designed. Current work is also directed at polarization targets and semiconductor particle detectors.

Member of the Board of Directors of the Theoretical Physics Laboratory N. N. Bogolyubov spoke on theoretical research and studies in a wide variety of directions directly related to experimental work. The staff of this Laboratory are engaged in highly interesting work on dispersion relations and spectral representations. The fundamental work in this direction was reported on at the conference on dispersion relations theory convened in May,1960 under Joint Institute for Nuclear Studies' auspicies [cf. JAE 9, No. 1, p. 71 (1960)*]. Development of various problems in quantum field theory, the study of strong interactions, and the structure of nucleons were the subjects competing for prominent places in the attention of the staff of theoretical physicists. Calculations related to experiments being conducted by physicists on the Joint Institute's accelerators are highly significant to experimental workers; these include calculations on proton synchrotron particle beams, the angular and energy distributions and beam intensities of antinucleons, gamma quanta, neutrinos, and strange particles; calculations based on models of central and peripheral $\pi N$- and NN-collisions, etc. Work on applications of the theory of the superfluid state of the nucleus to the study of various problems is also proceeding successfully. The reporter took note of some lines of work in which theoreticians collaborating with experimental workers have carried out an analysis of experimental accelerator data. These efforts include studies of interactions between $\pi$-mesons and nucleons with nucleons, processes involving mesic atoms and mesic molecules, problems of parity conservation in strong interactions, and many others.

The work of the Theoretical Physics Laboratory was reported on at the Rochester conference on high energy physics, and drew high praise from the international scientific community.

N. N. Bogolyubov made a special point of the program of theoretical research on high-energy neutrino physics carried out at the Theoretical Physics Laboratory and at the Nuclear Problems Laboratory. The Rochester conference demonstrated that high-energy neutrino research is one of the most vital and promising problems in advanced physics.

The successful development of the Joint Institute computing center is proceeding apace in the Laboratory of Theoretical Physics. The Laboratory obtained in 1960, in addition to the services of the Ural computer now being used, two new electronic computers. The Laboratory staff had introduced significant improvements into components of the Kiev computer, enabling the machine to successfully solve specific problems encountered in processing experimental data. N. N. Bogolyubov reported that both of the new computers will go into service in early 1961. Intense work is proceeding on building up a library of standard programs for those computers.

The Laboratory's research schedule for 1961 envisages research efforts based on the outlines of the over-all program followed by the Laboratory for the past several years.

The members of the Learned Council heard a report by the Director of the Neutron Physics Laboratory, Corresponding Member of the Academy of Sciences of the USSR I. M. Frank, on work aimed at the building of a pulsed nuclear reactor, on the main Laboratory buildings, and on the development of new physics and electronics equipment. The Learned Council approved the Laboratory's 1961 work schedule and stressed the need for supplying the Laboratory with new equipment.

The report by the Director of the Nuclear Reactions Laboratory, Corresponding Member of the Academy of Sciences of the USSR G. N. Flerov, dealt with work on building accelerators for multiply charged ions, and on the completion of major structural and assembly operations in the Laboratory. Among the major operations to be carried out by the Laboratory during 1961, the Learned Council noted experiments on the synthesis of new transuranium elements, and the development of new equipment and new express techniques for isolation of transuranium elements.

The Vice-Director of the Institute, Prof. Wang Hang-Chang, spoke on the development of international ties. He reported that institutes in Bulgaria, Hungary, East Germany, China, Poland, Rumania, and Czechoslovakia participated in the scientific research carried out with the aid of nuclear emulsions irradiated in the proton synchrotron during 1960. Coordination of this work, generalization of the results of scientific investigations, and irradiation of the emulsions were carried out by a special committee headed by Prof. V. Petrzhilka. In July,1960, the committee undertook for the first time to draw up a balance sheet of the research using nuclear photoemulsions which has been conducted by the member nations of the Joint Institute, and made a selection of the most outstanding work for

---

* Original Russian pagination. See C. B. translation.

presentation to the Rochester conference, while introducing further refinements in the research agenda. Collaboration in bubble chamber research work is also being developed. The first batch of several thousand plates taken on the propane chamber in a pion beam at 7 Bev was sent to Warsaw, Budapest, Berlin, and Bucharest. Collaborative work will soon be initiated on processing plates obtained with the xenon bubble chamber. A committee on collaborative efforts in bubble chamber techniques was authorized under the chairmanship of the Vice-Director of the High-Energy Laboratory I. V. Chuvilo. Irradiation of preparations on the synchrocyclotron is being continued for purposes of radiochemical and spectroscopic research underway in Poland and Czechoslovakia.

In addition to those conferences already referred to, the Dubna Joint Institute for Nuclear Studies was also host to the III Conference on the Nuclear Spectroscopy of Neutron-Deficient Isotopes, and the conference on problems of cyclotron design for acceleration of multiply charged ions. The 1961 agenda calls for conferences on bubble chamber research, on automation of processing of nuclear emulsions data and plates of chamber tracks, conferences on weak interactions, on nuclear spectroscopy, slow neutrons, and on the theory of dispersion relations, the structure of elementary particles, and properties of strange particles.

Many members of the Joint Institute staff have completed trips to member nations of the Institute for the purpose of participation in gatherings and seminars, reading of lectures, exchanges of experience, and other activities. Members of the Institute took part in the conferences on high-energy physics which met at Rochester and Weimar, in the conference on the uses of isotopes in physics and industry at Copenhagen, in a symposium on chemical effects in nuclear transformations in Prague, in a symposium on inelastic interactions in Vienna. Several theoretical physicists and experimental physicists attached to the Institute staff spent several months in work at CERN, in the UAR, and at the Institute of Theoretical Physics in Copenhagen.

The Vice-Director of the Joint Institute, Prof. É. Dzhakov, spoke on the work of scientific colleagues from member nations of the Institute (aside from the USSR). The number of these colleagues has increased considerably during the past year. Furthermore, many colleagues arrived for short stays with the object of acquainting themselves with particular problems and experimental facilities. At present, there are guest colleagues from the various member nations of the Joint Institute participating in almost all of the scientific research teams and drafting bureaus where new equipment is being devised. They are playing an active part in the investigations being carried out at the Institute, and are making a significant contribution to the Institute's activities.

The Learned Council also reviewed the budget and personnel situation, and building plans for the Joint Institute for 1961, the status of groups working on rival projects, and confirmed the new staffs of subsidiary bodies administering the various laboratories under the Institute.

Panel sessions were hold for topics in low-energy nuclear physics during the course of the IX session of the Learned Council. Reports were delivered at these sessions on the results of 1960 conferences, such as the Dresden workshop on reactor physics and reactor engineering, the Balaton colloquium on problems of low-energy nuclear physics, and the nuclear spectroscopy workshop convened at Dubna. The panel noted the fruitful labor of these conferences and the great interest manifested in them by many research institutes attached to the Dubna Joint Institute. The Chairman of the low-energy nuclear physics section, Corresponding Member of the Academy of Sciences of the USSR I. M. Frank, reported on the projected work plans for the section. The section adopted a resolution to hold workshops for an exchange of experience in cyclotron operation and cyclotron research (scheduled for Krakow, April-May,1961), on scientific research topics to be pursued with the aid of the accelerator for multiply charged ions (at Dubna, May,1961), on nuclear spectroscopy of neutron-deficient nuclei (Dubna, June,1961), on physical research using slow neutrons (Dubna, October,1961), and on problems related to sources of polarized ion beams and polarized targets (Dubna, early 1962). The plan for collaborative research efforts involving the Dubna Institute and research institutes of the member nations, in the field of low-energy physics, calls for work on the spectroscopy of neutron-deficient nuclides, the study of photoelectric phenomena, the investigation of solids and fluids by cold neutron scattering techniques, development of an ironless beta-ray spectrometer, and common work in the development of new radio and electronics equipment.

## CONFERENCE ON REPRESENTATIVES OF 12 GOVERNMENTS

V. Biryukov

Translated from Atomnaya Énergiya, Vol. 10, No. 3, p. 285, March, 1961

The regularly scheduled session of the Committee of Authorized Representatives of member governments of the Joint Institute for Nuclear Studies was held on November 25-26, 1960, at Dubna.

The main report was made by the Director of the Joint Institute for Nuclear Studies, Corresponding Member of the Academy of Sciences of the USSR D. I. Blokhintsev, who drew up a balance sheet of the Institute's work over the period 1956-1960, and outlined the plan of development of the Institute projected for the incoming five-year period. The committee took note of the successful completion of the plan of development and of the scientific research work conducted by the various laboratories of the Institute during 1960, and approved the work schedule for 1961 which had previously been accepted by the Learned Council. The resolution stressed the notable assistance rendered by the USSR, as well as by Poland, Czechoslovakia, and the German Democratic Republic,in the construction and equipment of both new and old laboratories at the Institute. The committee took special note of the important achievements scored in the development of ties between the Joint Institute and scientific instititutions in various countries, and made a recommendation to broaden the practice of sending colleagues on leave to institutes in various countries to promote exchanges of experience and joint research efforts.

A perspective plan of development for the Institute covering the incoming 1961-1965 period was presented by the Board of Directors and duly approved. This plan envisages maintenance of the fundamental direction of activity already pursued by the Institute: fundamental research in the field of elementary particle physics (the structure of particles, primarily of nucleons, study of the laws of particle production and interaction) and the physics of the atomic nucleus. The most important work called upon to bring to fruition a development program in physical research of such depth and scope is that of stepping up the intensity of beams of accelerated particles in the Institute's major facilities, the synchrocyclotron and proton synchrotron machines, and also further development of automated processing of experimental material.

On the basis of a report made by the Administrative Director of the Institute, V. N. Sergienko, the committee adopted a resolution approving the 1960 financial report, the 1961 financial plan, and the construction and personnel-staff plans of the Institute.

The terms of the incumbent Vice-Directors of the Institute having reached their end, new elections were held. Elected Vice-Directors of the Joint Institute for the incoming period were: Prof. Heinz Barwich, Director of the Central Nuclear Research Institute of the German Democratic Republic, and Corresponding Member of the Rumanian Academy of Sciences Tudor Tanasescu.

## SYMPOSIUM ON INELASTIC NEUTRON SCATTERING IN SOLIDS AND FLUIDS

M. G. Zemlyanov

Translated from Atomnaya Énergiya, Vol. 10, No. 3, pp. 285-287, March, 1961

An international symposium on inelastic scattering of slow neutrons in solids and fluids convened in Vienna in October, 1960. The symposium was attended by about 120 scientists from 24 countries and two international scientific bodies, viz.,Euratom and the Dubna Joint Institute for Nuclear Studies. Fifty papers were delivered to the gathering.

All of the papers presented to the symposium may be grouped under four general headings: 1) theoretical questions in inelastic interaction between slow neutrons and both magnetic and nonmagnetic substances; 2) research on processes of neutron slowing-down to low energies (neutron thermalization); 3) work on neutron spectrometric technique applicable to experiments on inelastic scattering of slow neutrons; 4) results of experimental investigations in inelastic neutron scattering in solids and fluids.

The major attention in the theoretical papers was devoted to the further development of the general method [suggested by Van Hove, Phys. Rev. 95, 249 (1954)] of interpretation of slow neutron scattering data referable to solid and fluid scatterers, in terms of pair space-time correlation functions. This method, distinguished by great generality of approach, is comparatively new, and has undergone intensive development during the past years.

A paper presented by P. Egelstaff (Britain), entitled "Theoretical justification for the low of thermal neutron scattering," demonstrated that this method can be used to extract information on the distribution function of frequencies from data on slow neutron scattering by polycrystalline specimens of coherently scattering substances. Of particular interest are the papers first to appear on the subject of correlative functions of the effect of the finite lifetime of phonons and magnons on neutron scattering, based on the same method (R. Elliot et al., Britain).

In addition, several papers were presented which had no direct relation to correlation functions and instead developed some "old-fashioned" theoretical concepts. For example, the reports by W. Marshall (Britain) and R. Stewart (USA) analyzed the possibility of interpreting cross sections for noncoherent scattering and coherent scattering within the framework of the Debye model, with specially assigned parameters dependent on the temperature of the scatterer. It was demonstrated, in a paper submitted by L. V. Tarasov (USSR), that the cross section for noncoherent scattering is proportional, within the accuracy of some thermal factor, to the frequency distribution function, in the case of an isotropic scatterer (polycrystal) of arbitrary symmetry (one atom per unit cell).

In the reports devoted to thermalization of neutrons, the brunt of the attention was given to studies of thermalization in intensely cooled hydrogen-containing media. These investigations provided some idea of the dynamics of the media at low temperatures, on the one hand, and on the other hand showed the possibilities of obtaining intense fluxes of cold neutrons. At the present time, two possibilities of increasing the intensity of cold neutrons have been determined: lowering the temperature of the neutron gas in a small volume of reactor moderator, and building a special-purpose nuclear reactor with an intensely cooled moderator (L. Borst, USA).

The neutron spectrometry methods used in experiments on inelastic scattering differ both in the technique used to produce monoenergetic beams of incident neutrons and in the technique used for measuring the energy of the scattered neutrons. At the present time, the following methods of neutron spectrometry are the ones in most common use:

| Separation of primary neutrons | Study of scattered neutrons |
|---|---|
| Polycrystalline filter | Mechanical time-of-flight chopper (1) |
| Crystal monochromator | Crystal spectrometer (2) |
| Rotating single crystal | Time of flight (3) |
| Crystal monochromator | Polycrystalline filter (4) |
| Multirotor mechanical beam chopper | Time of flight (5) |
| Linear electron accelerator | Time of flight (6) |

Method (1) is in use at Brookhaven (USA) and in Stockholm; it provides maximum transmission compared to rival techniques. However, the accuracy of the end results is restricted to a considerable degree by the large spread in the primary line of the incident neutrons. Moreover, when this method is used the range of energy measurements of the incident neutrons is narrowed down. Method (2) is the one used at Chalk River (Canada); good resolution may be had with this method, but transmission is poor. The use of a single crystal to separate out the primary line makes it possible to vary the energy of the incident neutrons over a rather wide range, thus making much more complete information available on the dynamics of the material. Method (3) is employed at Chalk River and at Warsaw; the method of a rotating crystal serves to define the monochromatic line of primary neutrons, to vary their energies over a wide range, and to facilitate investigations of the energy distribution of the scattered neutrons at several angles simultaneously. Method (4) is being used in Canada (at Chalk River) and in West Germany. It is used to study large energy transfers in inelastic scattering; the transmission obtained is sufficient for carrying on in-pile experiments with a neutron flux of $\sim 10^{13}$ neutrons/cm$^2$ • sec. Method (5) is used at Chalk River, Harwell, and Idaho Falls (USA). The use of multirotor (two-rotor, three-rotor, and four-rotor) mechanical choppers makes it possible to define a narrow monochromatic line of incident neutrons, to vary the energies of primary neutrons over a wide range, to materially reduce the background contributed by admixtures of fast neutrons in the incident beam, and to effect investigations of the energy distribution of neutrons scattered at different angles, simultaneously. Method (6) is the one used in California. Researches will be soon initiated on inelastic scattering of neutrons, using the Harwell linear electron accelerator. The papers delivered made it clear that a linear electron accelerator (without a subcritical target) possesses the same advantages as a thermal reactor with respect to neutron intensity. In addition, an accelerator has some advantages over reactors, for example the lower background of fast neutrons, greater opportunities for the use of cryogenic techniques in producing cold neutrons, lower level of activation of the equipment used, and others. Use of a subcritical target increases the neutron flux almost 10 times.

The symposium heard experimental results of a study of inelastic neutron scattering on several solids: aluminum, vanadium, graphite, zirconium hydride, lithium hydride, sodium hydride, palladium hydride, iron, silicon, and lead. A paper by P. Egelstaff and S. Cocking (Britain and Canada) on scattering by graphite, which is a predominantly coherent scatterer, showed how information on the distribution function of frequencies can be extracted as in the case of experimental data referable to a polycrystalline specimen. The distribution function obtained for graphite agrees with the results of theoretical calculations by Boldok. It was demonstrated, in a paper by S. Thurberfield and P. Egelstaff (Britain) based on preliminary data, that a change in the temperature of a vanadium specimen results in a modification of the frequency spectrum and effective Debye temperature.

Experimental researches on the dynamics of the liquid state of matter dealt in the main with water. The presence of a peak at ~0.06 ev energy was definitively established in the inelastic neutron scattering spectrum. The peak is due to decelerated rotation of the $H_2O$ molecule as a whole in the potential field of neighboring molecules. The width of this peak is slightly larger than previously supposed. An appreciable broadening of the primary line of incident neutrons is observed for elastically scattered cold neutrons. This broadening may provide some idea of the nature of diffusion flow of $H_2O$ molecules. Investigations of the dynamics of liquid helium involving the use of inelastic neutron scattering were discussed in a review paper on the existing literature in the field (H. Palevsky, USA, "Cold neutron scattering experiments in liquid helium.")

The proceedings of the symposium will be published by the International Atomic Energy Agency during the first half of 1961.

## SYMPOSIUM ON PHYSICS RESEARCH WITH PILE-PRODUCED NEUTRONS

### A. M. Demidov

Translated from Atomnaya Énergiya, Vol. 10, No. 3, pp. 287-288, March, 1961

A symposium on this topic, organized by the International Atomic Energy Agency, met in October,1960 in Vienna. Reviews of research programs carried out at reactor centers in various countries were presented along with papers discussing techniques and findings of individual researches. Fifty-five reports were presented in all, including 7 reports by the Soviet delegates. About 150 persons were in attendance. The major questions discussed at the symposium were problems in nuclear physics, solid state physics, and physics of fluids.

Review papers were devoted to physical research on the NRU and NRX (Chalk River) reactors, the CP-5 (ANL, USA), the MTR (Idaho, USA), the ORNL reactor (USA), the LPTR reactors (Livermore, USA), the EL-2 and EL-3 (at Saclay, France), the FRM (West Germany), the JRR-1 (Japan), PT (Institute of Physics, Rumania), the EWA (Poland), BR-1 (Belgium), JEEP (Norway), and others. In addition to the review papers, separate individual papers were presented on some aspects of reactor research, including physical experiments using the OWR (Los Alamos, USA), MITR (Massachusetts, USA), DIDO and BEPO (Harwell, Britain), L-54 (Frankfort-am-Main, West Germany), VVRSzH (Hungary), IRT AN SSSR (USSR), and other reactors in the USSR.

A special session was devoted to the use of pulsed reactors for physical research and for comparing them to pulsed accelerators used as neutron sources. As a rule, data was reported on neutron flux levels in the reactor core, and experimental holes were discussed. A central place in the reports was occupied by descriptions of new techniques and instruments. Results of measurements were reported only as an illustration of the performance of the instruments.

Solid state physics and fluid physics research on reactors are being pursued in the direction of inelastic neutron scattering studies and slow neutron diffraction studies. Problems concerning inelastic scattering of neutrons in solids and fluids were discussed in a symposium in October, 1960 (see previous article this issue). Reports on this topic were dealt with only briefly in review papers presented at this symposium.

Several reports on neutron spectrometers and experimental facilities were also presented. A paper by B. Jacquerot "Neutron cooling and a facility for production of cold neutrons" provided a description of a cryogenic arrangement built into the Saclay EL-3 heavy-water reactor; this arrangement was designed to produce intense fluxes of cold neutrons. A report by P. Egelstaff discussed a four-rotor neutron beam chopper which proved far superior to the one-rotor type in shaping a neutron pulse, greatly reducing background due to fast neutrons, and broadening the range of available neutron energies. Data on various types of crystal spectrometers were given in many of the papers. The spectrometers discussed were designed for single crystals and double crystals, rotating crystal, bent quartz, and beryllium crystals.

Neutron diffraction studies of the crystalline, and especially of the magnetic, structure of solids were the subject of a number of papers (G. Cable et al., USA, J. Hastings, USA, A. Erpen, France; V. N. Bykov et al., USSR; B. Brockhouse et al., Canada; J. Haaidkop, Netherlands; K. Blinowski, Poland). These reports provided a wealth of fresh data on the position and arrangement of light atoms in crystals, on the magnetic structure of salts, metals, and alloys. Hastings' paper briefly discussed the question of the use of polarized neutrons to probe magnetic structures.

Several current problems in nuclear physics found reflection in the symposium: decay of polarized neutrons, measurement of capture cross sections, neutron scattering and fission cross sections, study of the characteristics of neutron resonances, studies on the nuclear fission process (including aligned nuclei), measurement of neutron flux levels, study of gamma-ray spectra appearing in the capture of thermal and resonance neutrons, and fission neutrons.

Research on the decay of polarized neutrons has been underway for sometime now at the CP-5 reactor at Argonne National Laboratory. Cobalt mirrors are used to polarize the neutrons. The accuracy achievable in determining degree of polarization of the neutrons was recently increased to 95 ± 5%. Similar research is underway at the Chalk River NRU reactor. In this case, neutrons are polarized by means of a Co-Fe alloy crystal. The degree of polarization is 93%. Data obtained on correlations between direction of electron flight and direction of neutron spin displayed close agreement with the CP-5 reactor data, and were in harmony with the assumption as to V—A-coupling with the ratio of coefficients $C_A/C_V = -1.20 \pm 0.12$.

At Brookhaven and Oak Ridge national laboratories, efforts are underway to improve neutron effective cross section ($\sigma_t$) data in the region of thermal energies for $B^{10}$, $U^{233}$, $U^{235}$, $Pu^{240}$ and several other nuclides, as well as fission cross sections for $U^{233}$ and $U^{235}$. In particular, values $\sigma_t = 695 \pm 2$ barns (Brookhaven) and $\sigma_t = 693 \pm 5$ barns (Oak Ridge) were reported for $U^{235}$ at a neutron velocity of 2200 meters/sec. Values reported for $U^{235}$ also include $\sigma_f = 591 \pm 6$ barns (Brookhaven) and $\sigma_f = 587 \pm 6$ barns (at the BR-1 reactor, Mol, Belgium).

A large number of gamma-ray spectrometers boasting 0.01-0.05% resolution have been built during the past few years for studies of gamma-ray spectra obtained in thermal neutron capture. Reports on Magnetic Compton spectrometers used at the OWR reactor at Los Alamos and the Soviet IRT reactor were delivered to the symposium, which also heard papers on two-crystal diffraction gamma-ray spectrometers (Chalk River) a bent-crystal spectrometer with Cauchois geometry (LPTR and MITR reactors, USA) and Du Mond geometry (CP-5 reactor, USA, and FRM reactor, West Germany). $\gamma - \gamma$ angular and time correlations are being investigated at a large number of reactors. Circular polarization of gammas in the capture of polarized thermal neutrons is being studied in Canada and Norway. A description of two spectrometers designed for analyzing internal conversion electrons resulting from thermal neutron capture was presented to the symposium. One of them is being operated at the IRT reactor and the second is slated to be in operation at the FRM (West German) reactor by the end of 1960. Two facilities have been set up at the CP-5 reactor for measuring gamma-ray spectra resulting from resonance neutron capture. In one case, monochromatization of neutrons is brought about with a fast beam chopper, and in another case by the method of reflection from a beryllium crystal.

On the basis of the symposium materials and ensuing discussions, the opinion took shape that the basic trends in reactor physical research for the next period will be investigations of inelastic scattering of slow and cold neutrons in solids and liquids, neutron diffraction, especially diffraction on magnetic structures, and gamma-ray spectra resulting from capture of thermal neutrons and resonance neutrons.

The symposium materials will be made available in published form by the International Atomic Energy Agency in early 1961.

## INTERNATIONAL COLLOQUIUM ON RADIOACTIVE ISOTOPE APPLICATIONS IN CONSTRUCTION

Translated from Atomnaya Énergiya, Vol. 10, No. 3, pp. 289-290, March, 1961

An international colloquium on applications of radioactive isotopes in construction work was held at Leipzig (German Democratic Republic) in September,1960. Scientists and specialists from Bulgaria, Britain, Hungary, the German Democratic Republic [East Germany], Poland, USSR, and the German Federated Republic [West Germany] took part in the colloquium. The total attendance was about 300.

The colloquium was organized by the Leipzig construction trades school. The task of the colloquium, as defined by the reactor, Prof. Steiger, in his introductory remarks, consisted in strengthening international collaboration between scientists working in the field of peaceful uses of atomic energy, and in the exchange of scientific and technical experience in isotope applications in the construction field.

The lion's share of the reports presented to the colloquium dealt with tracer applications in quality control of concrete and concrete mixes and reinforced concrete products. Reports by Pohl (Leipzig construction trades school), Honig (Institute of Concrete Constructions, Brno, Czechoslovakia), and Ferristor (Britain) shed light on problems involved in the use of soft scattered gamma radiation (0.5 Mev) for gamma radiography of reinforced concrete products. This method is used for quality control of the products and to determine the position of reinforcement rods in concrete blocks by nondestructive means. Stereoscopic gamma radiography using two advantageously placed sources of radiation gives a greater definition and better localizing of reinforcements or flaws. The use of gamma radiographic techniques is greatly simplified in practice by exposure nomograms compiled for different concrete mixes, with photographic film sensitivity and activity of the radiation source ($Co^{60}$, $Cs^{137}$, and $Ir^{192}$) taken into account.

Employment of radioactive tracers to determine the quality of concrete batches was discussed in reports by Menkhoff (Institute of construction machinery and building production, Aachen, German Federated Republic), Galambos (Hungarian research institute of architecture and excavations, Budapest), Jurenka (Research institute for building materials, Prague), and Bundarski (Construction institute, Warsaw). These papers discussed determination of concrete density and quality control by means of both scattered and direct gamma radiations. A portable radiometric equipment employing scintillation counters was designed for this purpose, aiding in quality control of concrete products under production conditions. Bundarski reported on comprehensive applications of radiometric and ultrasonic techniques in quality control of reinforced concrete products (this paper was co-authored by colleagues Ya. N. Basin and R. A. Makarov of the USSR Academy of Construction and Architecture). The paper submitted by Jurenka dealt with the state of research and development progress in equipment for humidity measurements of concrete mixes and components, in addition to monitoring of concrete density. The equipment developed will make it possible to determine moisture content (hydrogen content) of concrete mixes in terms of the flux density of slow neutrons released as the concrete mixture slows down fast neutrons.

A paper sumitted by Stein (Advanced transportation school, Dresden, German Democratic Republic) discussed a large variety of modifications of instruments designed to determine the density and moisture content of soils under both field and laboratory conditions. The instruments determine density and moisture content of soils in terms of the intensity of absorption of direct and reflected gamma radiations as they pass through the soil specimen.

A report by L. A. Sukhova (Asbestos Cement Research Institute, USSR) and Heiman (Vakuumtronik factory, Dresden) offered data on the use of instruments employing radioactive-radiation sources for monitoring and process control applications in construction work. Sukhova gave an account of the use of radioactive level gages, density gages, noncontacting load cells, ect., in process control and automation in asbestos cement plants. Heiman's paper discussed designs of radioactive level gages for determining the level of coal dust and cement in in-plant hoppers and bins.

Several papers were devoted to applications of tracer atoms in different avenues of investigation. Kost (Bautechnologischer Institute, Jena-Burgau, German Democratic Republic) reported data on tracer applications of the radioactive isotope $Cr^{51}$ in studying intermixing of material in the rotating kiln of a cement factory. Honig reported on research work underway in Brno and Bratislava using tracers to study mixing of concrete in a concrete mixer. The radioactive isotope $Ca^{45}$ was introduced as tracer, in the form of calcium sulfate.

Galambos reported on tracer applications in the study of the process of cement flow through pneumatic conveying channels. Experience in using short-lived radioactive isotopes as tracers in studying water seepage through a stone-rubble dam on the Drava river was elucidated in a paper presented by Novak (Water works administration, Brno). A paper by Grosche (Hochtechnische Schule, Stuttgart, West Germany), data were presented on the use of the radioactive isotope $Br^{82}$ as tracer in studying the performance of drainage and sewerage installations and for determining rate of water flow through a canal.

Construction topics of special interest associated with industrial applications of radioactive and ionizing radiations were treated in several papers. Lucke (Institute of Structural Materials, Weimar, German Democratic Republic) presented a detailed treatment of the question of changes in the crystal lattice of concrete and losses in elastic strength in response to bombardment by a high-level flux of gamma and neutron pile radiation. Schibora (Bureau of designers of nuclear facilities, East Germany) reported on radiation shielding characteristics and fundamental hygiene and health physics requirements affecting the design of nuclear reactor shielding installations. The basic viewpoints held on organization of dosimetric services in nuclear installations were presented in the paper. Wuckel (Institute of Applied Physics of Pure Materials, Dresden) gave a report on modification of the properties of artificial materials through bombardment with high-energy radiations. Koch (Institute of Applied Radioactivity of the German Academy of Sciences, Leipzig) dwelt on several special problems in the technology and design of interior shielding and protective coatings for laboratories working with nonenclosed radioactive materials. Krumbiegel (Institute of Fissionable Materials, German Academy of Sciences, Leipzig) delivered a paper on the possibilities open to the use of stable isotopes in the chemistry of structural materials.

The basic parameters and technical data relating to the first nuclear electric power station in the German Democratic Republic were presented in a paper by Patzelt (Bureau of designers of nuclear facilities).

S. Ya. Vartazarov (Institute of Power Works Construction [Orgenergostroi] USSR) made a presentation on radioactive isotope and nuclear radiations applications in power construction in the Soviet Union.

An exhibit of radiometric equipment was open to visitors in the hall where sessions were held. Participants at the colloquium had the opportunity of visiting the Institute of Applied Radioactivity.

The materials of the papers presented and discussions will be made available in printed form as the proceedings of the colloquium.

## WEST GERMAN ATOMFORM CONFERENCE

Yu. Mityaev

Translated from Atomnaya Énergiya, Vol. 9, No. 3, p. 291, March, 1961

An Atomic Forum was organized in West Germany in May, 1959. The tasks outlined for the Forum embrace publicity and dissemination of scientific and technical achievements in the use of atomic energy, furthering of the development of atomic energy on the part of West German firms, establishment of contacts and exchange of information with foreign and international organizations, the organization of exhibits, conferences, conventions, etc. The activities of the Forum are being supervised by a board of 32 German specialists. The control board includes prominent scientsts such as the famous physicist W. Heisenberg [1].

The first technical conference of the Atomforum took place at Karlsruhe in October,1960. Over 80 papers were presented by German specialists and scientists on various aspects of nuclear energy applications [2]. Over a thousand German scientists and specialists participated in the deliberations of the conference [3].

Several introductory presentations stresses the use of nuclear energy and the nuclear power development program in West Germany, the participation of West Germany in the execution of various international projects, and current problems in nuclear physics research. The remaining papers, covering six general topics, were heard at separate panel discussions.

Most of the papers presented were devoted to power reactor projects underway in West Germany. Plans for a water-hydrogen boiling-water reactor, an experimental high-temperature gas-cooled reactor with spherical graphite-clad fuel elements, heavy water reactors burning natural uranium fuel, a uranium-graphite reactor of the Calder Hall type (carbon dioxide gas coolant), and the development program set up around a nuclear power station with a liquid sodium coolant reactor came under discussion. Several papers discussed marine propulsion reactors. Competing with review papers were concrete presentations of nuclear power engine plans using a boiling-water reactor or an organic-cooled and organic-moderated reactor.

In reports touching on reactor control, problems of reactor dynamics, analog methods for simulating control processes, and electronic reactor simulators were discussed. Several papers described the control loops adopted for West German reactors now in the design stage. One report was devoted to the significance of the most important nuclear physics constants in reactor design.

The conference also discussed the various materials used in reactor design as nuclear fuel, coolants, moderators, structural materials, and biological shielding materials. Reports dealing with these problems were all of a concrete character, except for several review papers. Some idea of the topics taken up in the reports may be garnered from the following breakdown of fundamental problems treated in the papers:

– methods for producing reactor-grade graphite (gastight and water-impermeable graphite) and properties of reactor-grade graphite manufactured in West Germany;

– production and properties of steels and alloys used in reactor design (alloys with boron and europium additives, cobalt content in reactor steels, corrosion and welding of steels);

– fissionable and fertile materials (processing of spent nuclear fuel; position of West Germany in Europe in the fabrication of fuel elements);

– materials employed in building shielding against radioactive radiations.

Reports on measuring techniques may be broken down into two groups. The first group includes papers discussing the various types of electronic equipment used in outfitting nuclear reactor installations and physics laboratories. Papers under the second grouping described various instruments whose operating principles are associated with the use of nuclear energy. As an example, we may cite a paper on a noncontacting device designed to determine coating thickness, and a device for measuring fluid density.

Many of the papers were devoted to radioactive isotope applications in scientific research and in industry.

The use of isotopes in chemistry and biochemistry, in hydrology, in the study of semiconductors, in steel production, etc. was discussed. The use of cyclotrons for fabrication of radioactive isotopes also came up. Some papers dealt with problems in radiochemistry and radiation chemistry, as for example radiation-chemical transformations of aldehydes.

Some of the papers were devoted to safety problems in atomic enterprises, processing and burial of radioactive wastes, and particularly processing of radioactive waste waters.

Geological and hydrological problems arising in the burial of radioactive wastes in the ground and safety in the performance and start-up of nuclear reactors (primarily research reactors), shielding of personnel from inhalation of contamined air, and results of materials tests were discussed.

Finally, the last group of papers discussed some of the ancillary equipment designed for nuclear reactors and isotope laboratories: charge-recharge devices, gas filters, viewing windows and periscopes, master-slave manipulators and other remote control devices, demonstration and training equipment used for training junior and medium-rank staff members.

## LITERATURE CITED

1. Brennstoff – Wärme – Kraft XI, No. 9, 452 (1959).
2. Erste technische Tagung. Anwendung der Kernenergie. Karlsruhe, Oktober, 1960.
3. Atomkernenergie V, H. 9, 450 (1960).

## BRIEF COMMUNICATIONS

Translated from Atomnaya Énergiya, Vol. 9, No. 3, pp. 302-303, March, 1961

USSR. Solemn ceremonies were observed in Moscow on the occasion of laying a foundation for a monument to the outstanding Soviet physicist, three times awarded the tital Hero of Socialist Labor, and winner of the Lenin and Stalin prizes, Academician Igor' Vasil'evich Kurchatov. Scientists, engineers, and workers representing the Party and Soviet circles in the capital were present at the ceremonies.

East Germany. The nation's first nuclear power station, based on a water-cooled water-moderated reactor of 70 Mw(e), is being built at Reinsterg. The reactor is scheduled for start-up in 1962. Preparatory work is going on in the design of a second improved reactor of the same type.

At the Central Institute for Nuclear Physics in Berlin, tests have been completed for the building of a zero-power research reactor intended for exponential experiments and determination of lattice parameters.

Iran. A swimming-pool type research reactor facility of 5 Mw power is being planned for Teheran University.

Malagasy. A contract has been signed with the French Commissariat de l'Energie Atomique according to the terms of which the Commissariat obtained rights for exploring uranium ore deposits in Western Madagascar. The Commissariat proposes spending 360 thousand pounds sterling on prospecting activities. It also plans to produce 500 tons of uranium ore annually in the southwestern part of Madagascar.

United Arab Republic. Construction of a hot laboratory is expected to reach completion during the autumn of 1961. Laboratory equipment is being furnished by Norwegian firms. It is expected that a pool-type reactor of 2 Mw power will be started up sometime during 1961. The reactor was built with the aid of the Soviet Union in accordance with a contract signed in 1956 between the Soviet Union and the UAR. Plans also call for building a plant for extracting uranium from ores, and a heavy water production plant.

# BIBLIOGRAPHY

## NEW LITERATURE

### Books and Symposia

Translated from Atomnaya Énergiya, Vol. 9, No. 3, pp. 304-311, March, 1961

Kratkii spravochnik inzhenera-fizika Yadernaya fizika. Atomnaya fizika. [Concise Engineer's and Physicist's Handbook. Nuclear and Atomic Physics]. Moscow, Gosatomizdat, 1961. 520 pages. 1 ruble, 22 kopeks.

The handbook contains 13 sections. The first section furnishes information on neutron interactions with nuclei, the fission process, neutron sources, and particle recording techniques. The second section offers reference material on the diffusion of monoenergetic neutrons, slowing down of neutrons, neutron multiplication in an infinite medium; fundamental quantities and equations for finding critical reactor dimensions are given, with calculations for control rods, and calculations of the isotope composition of nuclear fuel. The third section is devoted to reactor structural materials. The fourth and fifth sections deal with reactor design and shielding against reactor radiations. A classification of reactors is given; fundamental data on various reactors being planned, under construction, or already in operation in the capitalist countries are given; the major considerations involving biological shielding of nuclear facilities are elucidated.

The sixth section offers reference material on plasma physics and thermonuclear reactions; information is given on nuclear fusion reactions, cross sections of elementary interactions, the motion of charged particles in electromagnetic fields, the kinetics of various plasma processes, the fundamentals of magnetohydrodynamics, method for confinement and heating of a plasma, etc. The seventh section (charged particle accelerators) offers, alongside other information, a classification of accelerators and tabular data on accelerators. The eighth chapter contains reference material on dosimetry and tolerance levels for ionizing radiations. The ninth section presents the fundamental engineering characteristics of measurements instrumentation.

The tenth and eleventh sections provide the necessary information relating to the nuclear geology and radiochemistry. Problems associated with the production and use of radioactive isotopes are elucidated in the twelfth section. This section presents a table of the characteristics of the most abundant isotopes, brief descriptions of instruments for monitoring and automatic process control, plus radiation sources. The thirteenth section concentrates information of a general nature, systems of units, and information on physics and mathematics.

Atomnyi ledokol "Lenin." [The atomic icebreaker LENIN]. Leningrad, Lenizdat, 1960. 172 pages. 50 kopeks.

The book constitutes a symposium of the articles written by those who participated in the design and building of the nuclear propulsion icebreaker "Lenin."

This symposium contains the articles: Academician Yu. A. Shimanskii "Brilliant victory of Soviet science and engineering," A. I. Bobrov, "A nuclear giant built by the efforts of the entire nation," V. I. Negatov, "The first-born in a nuclear fleet," B. E. Klopotov et al., "The task posed by the Motherland has been fulfilled with honor," A. I. Gorbushin et al., "Building the hull of the nuclear ship," N. D. Dvornikov et al., "Completion of the maiden voyage meeting strict requirements," S. A. Chernykh and I. S. Darbkin, "The success of the venture was assured by the high level of productive technique," P. A. Ponomarev and A. N. Stefanovich, "In close contact with the shipbuilders," and P. I. Ukhanov et al., "The voice of those to whom peace is dear."

The articles comprising the symposium successively describe the stages passed in building the ship, and shed light on the advantages of the nuclear propulsion icebreaker in performance. In view of the fact that the book was conceived as a popular edition written for the broadest readership, the design of the icebreaker and its nuclear power installation are described in general terms. Considerable stress is placed on the materialization of the fruitful labor of the many thousands engaged in building the "Lenin."

The book is written is lively and engaging popular language and is well illustrated; it will be read with deep interest by a broad spectrum of readers.

Korroziya reaktornykh materialov. [Corrosion effects on reactor materials]. Moscow, Atomizdat, 1960. 284 pages. 1 ruble, 93 kopeks.

This is a symposium including 29 articles devoted to the mechanism of corrosive processes occurring in nuclear reactors under specific high-temperature and high-pressure environmental conditions. The first section of the symposium considers the procedures resorted to in research on corrosion and electrochemical processes in water at high temperatures and high pressures. The articles in the second section describe the effect of composition of water on the corrosion behavior of various structural materials. The third section is devoted to an investigation of the mechanism of corrosion cracking and the effect of external and internal factors on corrosive attack under stress conditions in austenitic stainless steels. The effect of the composition of steel, heat-treatment of steel, and composition of the environmental medium on the development of intercrystalline corrosion in water at high temperatures and pressures constitute the subject matter of the fourth section. The fifth section takes up research on the corrosion behavior of austenitic steels, low-alloy steels, aluminum and its alloys, and zirconium alloys, as well as the effect of slits and fissures and contacts with other metals on the effectiveness of corrosive attack processes; cleanup of corrosion products from a reactor loop is also considered in this section.

Zil'berman, Ya. I. Osnovy khimicheskoi tekhnologii isskustvennykh radioaktivnykh elementov [Fundamentals of the chemical technology of artificial radioactive elements]. Moscow, Gosatomizdat, 1961. 336 pages. 1 ruble, 32 kopeks.

This book provides a systematized outline of information on the chemical technology of artficial radioactive elements and especially information on processing of nuclear fuel.

The production technologies of artificial nuclear fuel in reactors and the technology of plutonium extraction from spent uranium and of uranium-233 from irradiated thorium are described.

The theoretical foundations of isolation of a trace constitutent from a carrier and the chemistry and technology of separation of plutonium and uranium-233 by coprecipitation techniques on carriers are among the topics discussed. Flow sheets of the process of separation and purification of uranium and plutonium using carrier coprecipitation techniques are also discussed.

A brief accounting is given of the viewpoint of various research workers on the nature of radiocolloids, and the conditions governing the formation of radiocolloids of various elements are discussed.

Three chapters of the book deal with problems associated with extraction by organic solvents. In addition to solvent extraction, the chapters take up such problems as separation of radioactive elements through ion exchange and electrochemical separation methods.

Some basic questions arising in the building and equipping of radiochemical plants and laboratories and in the processing of gaseous, liquid, and solid hot wastes are elucidated.

The chemical and biological effects of ionizing radiations are discussed, and basics of shield shielding calculations for gamma-ray exposure are given.

The book is based on a lecture course given by the author at the Leningrad Lensovet Technological Institute and at the Zhdanov Leningrad University.

Praktikum po primeneniyu izotopov i izluchenii v sel'skom khozyaistve. [Practical handbook on uses of isotopes and radiations in agriculture].

This handbook, edited by Prof. V. V. Rachinskii, Doctor of Chemical Sciences, was published by the K. A. Timiryazev Order of Lenin Moscow Agricultural Academy, and appears in a series of installments.

The following installments became available during 1959-1960:

A. O. Furman Radiometriya [Radiometry]. Part one. 1959. 96 pages. 30 kopeks. First of a series.

A. O. Furman. Radiometriya. Part two. 1960. 106 pages. 25 kopeks.

V. V. Rachinskii, A. G. Treshchov, I. V. Kolosov, T. P. Shipt. Tekhnika zashchity pri rabote s radioaktivnymi veshchestvami [Shielding techniques for handling of radioactive materials]. 1959. 36 pages. 13 kopeks. Fourth in the series.

V. V. Rachinskii, A. G. Treshchov, I. V. Kolosov. Radiokhimiya [Radiochemistry]. 1960. 100 pages. 30 kopeks. Fifth in the series.

V. V. Rachinskii, L. G. Yaglova, Ya. V. Mamul', Zh. A. Medvedev. Primenenie methoda mechenykh atomov v fiziologii i biokhimii rastenii [Applications of the labeled-atom technique in plant physiology and biochemistry]. 1960. 25 kopeks. Sixth in the series.

V. A. Emel'yanov, V. V. Rachinsiii. Primenenie yadernykh izluchenii v pochvovedenii i melioratsii [Applications of nuclear radiations in soil science and land reclamation]. 1960. 96 pages. 30 kopeks. Seventh in the series.

The numbers of the handbook series which have appeared to date may be acquired by writing to the radioisotope laboratory of the Academy (Moskva, A-8, Timiryazevskii proezd, 6). C.O.D.

## Articles from the Periodical Literature

### I. Nuclear Power Physics

Neutron physics and reactor physics. Hot plasma physics and controlled fusion. Physics of acceleration of charged particles.

Doklady akad. nauk SSSR 134, No. 5 (1960)

A. A. Barmin, V. V. Gogosov, 1041-1043. The piston problem in magnetohydrodynamics.

Yu. G. Prikorov, 1058-60. Note on recording of plasma energy losses.

Zhur. tekhn. fiz. XXX, No. 11 (1960)

V. E. Golant, 1265-1320. Ultramicrowave techniques in plasma research.

I. F. Kvartskhava et al. 1321-28. Instability of an induction theta pinch.

A. P. Komar, S. P. Kruglov, 1369-80. A quantometer for measuring energy flux of bremsstrahlung from betatrons and synchrotrons, and study of energy flux at $E_{\gamma \max} \leq 1000$ Mev.

Izvestiya akad. nauk Uzbek. SSR, Seriya fiz.-matem. nauk No. 4 (1960).

G. M. Avak'yants, 89-92. Note on light scattering by a plasma.

Pribory i tekhnika éksperimenta No. 5 (1960)

I. Ya. Chasnikov et al., 15-19. Measurement of multiple scattering on tracks of protons of ~10 Gev energy.

A. A. Rimskii-Korsakov, O. V. Lozhkin, 20-23. Identification of particles in nuclear emulsion by the scale method.

E. M. Balabanov, Yu. S. Smirnov, 23-27. Comparative study of symmetrical and conventional circuits for a cascade generator.

A. N. Serbinov, V. I. Moroka, 27-32. A high-frequency ion source with a honeycomb evacuation system.

N. I. Leont'ev et al., 97-99. An omegatron with an inhomogeneous magnetic field.

N. I. Leont'ev, Yu. K. Udovichenko, 100. Data display for an energy absorption resonance in the omegatron.

L. P. Khavkin, 101-106. Plutonium radioactive ionization pressure gage.

N. D. Morgulis, R. I. Marchenko, 106-108. Several ionization techniques for measuring very high vacuums.

V. I. Mikhailov, 117-19. A portable high-voltage source.

A. S. Vovenko et al., 119-21. Cerenkov counter uses total internal reflection.

Yu. Ya. Lapitskii, I. N. Slivkov, 121-23. New instrument monitors beam at exit end of accelerator.

I. E. Konstantinov, V. A. Strakhova, 124-126. A Compton scintillation gamma-ray spectrometer with increased efficiency.

V. V. Ovechkin et al., 127-28. New technique for calibrating a scintillation gamma-ray spectrometer.

I. P. Karabekov et al., 129. New Geiger-Müller counter pulse facility.

I. D. Rapoport, 130-31. On enhancement of the sensitivity of the photographic method for recording dense showers of charged particles.

A. F. Dunaitsev et al., 133. Measurement of energy of negative pions with a star detector.

Advances Phys. 9, No. 36 (1960)

T. Ericson, 425-511. Statistical model of the nucleus and nuclear level densities.

Energia Nucleare 7, No. 11 (1960)

G. Felcher, M. Musci, 772-92. Investigation of the dynamics of solids and liquids by the technique of slow-neutron spectrometry.

Industries Atomiques IV, No. 9-20 (1960)

J. Combrission, 53-57. Dynamical polarization of nuclei.

M. Cambornac, 71-75. Constant-supply supplies for the electromagnets used in the SATURN synchrocyclotron.

Nucl. Instrum. and Methods 8, No. 3 (1960)

J. Burgerjon, W. Weidemann, 261-71. The Pretoria cyclotron. Second report.

T. Nagy et al., 327-30. Electron drift velocity in argon, nitrogen, and argon mixtures.

Nucl. Phys. 19, No. 5 (1960)

G. Mani et al., 535-49. Cross sections of the Al(n,p), Al(n,$\alpha$), and Al(n,2n) reactions.

Nucleonics 18, No. 11 (1960)

J. Marion, 184-85. Gamma-ray calibration energies.

Nuovo Cimento XVII, No. 6 (1960)

J. Linhart, 850-63. Theory of fusion reactions in an unconfined plasma.

Progr. Theoret. Phys. 24, No. 3 (1960)

U. Ueda, M. Sawamure, 519-28. Electrical polarizibility of the neutron.

Technical Digest II, No. 6 (1960)

J. Fuksa, 30-38. Instruments in applied nuclear physics.

## II. Nuclear Power Engineering

Theory of nuclear reactors and reactor calculations. Reactor design. Operation of nuclear reactors and nuclear electric power stations.

Avtomatika i telemekhanika (mosk. inzh.-fix. inst.) No. 1 (1960)

P. I. Popov, 5-15. An analysis of several systems for automatically controlled start-up of nuclear reactors.

Yu. I. Topcheev, 16-43. Methods for analyzing nuclear reactor control response in stepped and linear variation of reactivity.

Liteinoe proizvodstvo No. 11 (1960)

V. G. Faddeev et al., 27-29. Casting the rudder for the nuclear incebreaker "Lenin."

Sudostroenie No. 9 (1960)

--- 74-75. On the superstructure of the atomic ship "Savannah." (from the foreign literature).

Atomkernenergie 5, No. 11 (1960)

H. Kornbichler, 397-400. Static hydraulic stability of boiling-water reactors.

M. Angelopoulos, 401-406. Computation of linear extrapolation length on the surface of an infinite coated plate.

H. Bergwaldt, H. Harder, 406-412. Approximation method of one-group and multigroup numerical calculations for an irregular reactor core lattice.

Atomwirtschaft 5, No. 11 (1960).

H. Benzler, 518-22. Optimization of cooling process for improved gas-coolant reactors.

Energia Nucleare 7, No. 10 (1960)

S. Tassan, 673-84. Methods for measuring the physical core parameters in heterogeneous reactors, using exponential experiments.

B. Montagnini, 724-35. Extension of variational calculus techniques to determination of extrapolation length for fuel elements and absorbers.

E. Gatti, V. Svelto, 736-38. "Machine time" in time to amplitude conversion.

Energia Nucleare 7, No. 11 (1960)

S. Barabaschi et al., 793-796. New facility measures operating time of reactor scram rods.

Jaderná Energie VI, No. 11 (1960)

J. Beran, 361-364. Note on the problem of contamination of gas in the primary loop by corrosion products.

J. Brit. Nucl. Energy Conf. 5, No. 4 (1960)

J. Richards, 227-39. Nuclear energy for marine propulsion engines.

R. Murdoch, H. Kearsey, 252-63. Study of the hydraulic characteristics of aqueous slurries with $ThO_2$.

--- 305-25. Discussion on the A. Bowden and J. Dramm article "Design and testing of large gas pipes" published in J. Brit. Nucl. Conf. 5, 49 (1960).

Nucl. Energy No. 151 (1960)

E. Okrent, 562-67, 571. Requirements for lubricant materials used in nuclear seagoing vessels.

--- 572-74. Observation of purity specifications in nuclear reactor operation.

H. Kleijn, 575. The reactor at the University of Delft.

Nucl. Engng. 5, No. 55 (1960)

--- 542-46. Development of nuclear industry in West Germany, Switzerland, Sweden, Norway, Spain, Portugal, Denmark, and Austria.

M. Ziegler, 547-48. French nuclear industry.

W. Reyseger, 551-52. Nuclear industry in the Netherlands.

J. Van der Spek, 553-54. Nuclear industry in Belgium.

F. Castelli, 554-56. A program of atomic energy development in Italy.

D. Hartley, 557-60. Slender tubular plates for high-pressure heat exchangers.

--- 562. Graphite reflector for the ZED-2 reactor.

--- 563-64. Fuel reloading operations at Bradwell.

Nucl. Power 5, No. 56 (1960)

J. Burkett, 97-101. Research work at the atomic energy research center at Winfrith Heath.

B. Emmerson, 102-105. Operating experience with the JASON reactor.

A. Stead, F. Latham, 107-108. Measurement of liquid metal level in a reactor cooling system.

D. Booth, 110-13. Xenon poisoning in two-shift operation.

Nucl. Sci. and Engng. 8, No. 4 (1960).

A. Colomb, 298-93. Photoneutrons and control of a swimming-pool reactor.

R. Bennett, R. Heineman, 294-99. Measurement of neutron rethermalization corss section in graphite.

R. Ritchie, H. Eldridge, 300-11. Attenuation of thermal neutron flux by absorbing foils.

R. Leipziger, L. Altamari, 312-14. Equipment for measuring the specific surface area of irradiated coarse-grained powders.

N. Kallay, 315-25. Dynamic programming and design of nuclear reactor control systems.

J. Carter, 326-39. Feedback mechanism in the EBR-1 Mark III reactors.

W. Godsin, 340-45. Monitoring temperatures of fuel irradiation capsules according to change in thermal conductivity.

A. Weinberg, 346-60. Some aspects of the development of a liquid-fuel reactor.

W. Pettus, 361-62. On the Dancoff effect in lattices with $H_2O$-$D_2O$ moderator.

S. Strauss, 362-363. Surface tension of liquid metals at the melting point.

M. Levin, 363-64. Generalized concept of the resonance integral.

J. Chernick, 365. Breeder reactor economics.

Nucleonics 18, No. 11 (1960)

--- 148-53. Power reactors and experiments (tabulated data).

W. Farmer, 162-65. Thermal properties of reactor materials.

K. Mayer, 166-67. Reactor materials costs.

R. Hankel, 168-69. Stress and temperature distributions in fuel elements.

S. Menkes, 170. Heat transfer from reactor core to coolant.

P. Huebotter, 176-77. Nuclear fuel burnup conversions.

H. Baucom, 198-200. Nuclear data for reactor studies.

--- 209. Factors for converting radioactive decay constants.

Nucleonics 18, No. 12 (1960)

D. Dickey, 80, 82. A human-engineered reactor control panel.

J. Russell, 88 ff. Relative worth of control materials determined by using boron equivalents.

T. Pashos et al., 94 ff. A method for comparing reactor control materials.

L. Hatch et al., 102-103. Reactor roundtable: fluidized bed for rocket propulsion.

Technical Digest II, No. 11 (1960)

T. Margulova, 12-19. Effect of heat-transfer circuit on corrosion in the operating loops of a nuclear power station.

## III. Nuclear Fuel and Materials

Nuclear geology and primary ore technology. Nuclear metallurgy and secondary ore technology. Chemistry of nuclear materials.

Geol. rudn. mestorozhdenii No. 5 (1960)

A. I. Zubov, 6-24. Uranium-containing solid bitumens.

Doklady akad. nauk SSSR 134, No. 6 (1960)

V. G. Vlasov, V. N. Strekalovskii, 1384-86. Interaction between hydrogen and uranium trioxide.

Zhur. anal. khim. 15, No. 5 (1960).

V. A. Mikhailov, 528-33. Investigation of the solubility of phenylarsonates of zirconium, thorium, and uranium.

L. M. Moiseeva et al., 561-63. Gravimetric determination of trace amounts of beryllium in ores and dressed ores.

P. N. Palei, Chang Wen-Tsing, 598-600. Complexometric determination of plutonium (IV) using arsenazo reagent as indicator.

Zhur. neorgan. khim. 5, No. 10 (1960)

L. V. Lipis, G. B. Pozharskii, 2162-66. Absorption spectra of plutonium (III) halides.

L. V. Lipis et al., 2190-2203. Complex sulfates of plutonium (IV) and alkali metals.

V. V. Golovnya et al., 2204-10. Cerium (IV) and uranium (IV) acido complexes.

P. N. Palei, N. I. Udal'tsova, 2315-18. On the solubility of EDTA in water, chlorate solutions, sodium chloride and potassium chloride solutions.

V. B. Shevchenko et al., 2340-53. Liquid-liquid extraction of trihydroxyglutaric acid into TBP.

V. B. Shevchenko et al., 2354-62. Solvent extraction of uranium (VI) from nitrate solutions, using tri-n-octylamine.

Zhur. neorgan. khim. 5, No. 11 (1960)

A. K. Babko, V. S. Kodenskaya, 2568-74. Study of equilibrium states in a solution of uranyl carbonate complexes.

Zhur. prikladnoi khim. 33, No. 10 (1960)

B. N. Laskorin, V. F. Smirnov, 2172-79. Uranium extraction from phosphate solutions.

Zhur. strukturnoi khimii 1, No. 3 (1960)

L. N. Kovba, A. N. Golubenko, 390-92. The compound $LiUO_2$.

Zhur. fiz. khim. 34, No. 8 (1960)

A. M. Trofimov, L. N. Stepanova, 1837-42. Radiochemical study of ion exchange on swelling ion exchange resins.

V. Ya. Leonidov et al., 1862-65. Specific heat of hexavalent uranates of calcium and barium at high temperatures.

Radiokhimiya II, No. 5 (1960)

V. M. Vdovenko et al., 531-36. Solvent extraction of nitrates of various metals by mixed solvent systems.

M. F. Pushlenkov et al., 537-40. Effect of the nature of diluents used on the TBP extraction of uranyl nitrate.

E. N. Patrusheva et al., 541-48. Extraction of rare-earth fission products by organophosphorus compounds.

I. A. Lebedev et al., 549-58. Determination of the composition and stability constants of oxalate, nitrate, and sulfate complexes of Am(III) and Cm(III) by the ion exchange method.

E. A. Kanevskii, L. A. Fedorov, 559-67. Kinetics of oxidation of U (IV) in solution by chlorates and persulfates of ammonia and by hydrogen peroxide.

V. I. Levin et al., 596-602. Isolation of carrier-free $Co^{58}$ from neutron-irradiated nickel, by the extraction method.

V. I. Shamaev, 624-29. Analysis of several impurities in selenium and tellurium by neutron activation.

Uspekhi khimii XXIX, No. 11 (1960)

A. D. Maddock, 1388-1405. Astatine.

Chem. and Engng. News 38, No. 41 (1960)

R. Ellis, 96 ff. Production and applications of fused salts.

Energia Nucleare 7, No. 11 (1960)

B. Brigoli, 761-68. Modern distillation techniques. II.

G. Perona, 769-71. Reactor fuel elements (account of 1959 New York conference and 1960 Vienna conference).

Industries Atomiques IV, No. 9-10 (1960)

--- 97 ff. Review of research on uranium-molybdenum alloys.

Jaderná Energie VI, No. 10 (1960)

K. Svoboda, 326-32. Hot atom chemistry. I. Historical review and physics of the process of ejection of a hot atom.

J. Cifka, 333-40. Hot atom chemistry. II. Reaction in liquids and gases.

K. Panek, 341-46. Hot atom chemistry. III. Reaction in the solid phase.

V. Cermák, Z. Herman, 347. Reactions of ions with molecules in $N_2$, $O_2$, CO, $SO_2$, $CO_2$, COS, and $CS_2$ atmospheres.

J. Brit. Nucl. Energy Conf. 5, No. 4 (1960)

R. Alexander et al., 264-71. The second uranium processing plant at Springfield.

H. Page et al., 272-84. Processing of uranium ore concentrates and process wastes into a purified uranyl nitrate solution at the Springfield plants.

E. Hawthorn, 285-304. A process for treating fluidized solid materials by the dry method in $UF_4$ production at the Springfield plants.

Kernenergie 3, No. 9 (1960)

O. V. Udarov et al., 866-68. Separation of boron isotopes.

M. Glazunov, V. Kiselev, 869-70. Mass-spectrometric analysis of fission products of uranium-cesium and rubidium.

I. Maass, 883-87. Concept of mass-spectrometric measuring probes.

Tschang Tsing-Lien, 892-97. Densimetric techniques in heavy-water analysis.

H. Birkenfeld, 901-906. Precise mass-spectrometric analysis of isotopes.

H. Birkenfeld, 910-13. Analysis of heavy water (deuterium) with the Soviet MI-1301 mass spectrometer.

G. Haase, 915-17. Mathematical techniques in mass spectrometry.

Nucl. Instrum. and Methods 8, No. 3 (1960)

G. Eichholz, 320-26. Continuous monitoring of uranium content in leaching solutions.

Nucl. Power 5, No. 56 (1960)

——— 79-90. Review of reactor materials.

O. Plail, 91-96. Irradiation techniques in nuclear fuel testing. I.

Nucl. Sci. and Engng. 8, No. 4 (1960)

A. Hall, 283-88. Solubility of Al—Pu in the solid state, and diffusion studies.

Nucleonics 18, No. 11 (1960)

S. Paprocki, R. Dickerson, 154-61. Mechanical and physical properties of structural materials and reactor fuels.

Nucleonics 18, No. 12 (1960)

D. Thomas et al., 104 ff. Irradiation stability of thoria slurries.

Research XIII, No. 11 (1960)

L. Blackman, 441-48. Properties of graphite. II. Thermal and electronic properties.

Research XIII, No. 12 (1960)

L. Blackman, 492-502. Properties of graphite, III. Crystalline compounds and irradiated graphite.

## IV. Nuclear Radiation Shielding

Radiobiology and radiation hygiene. Shielding theory and techniques. Instrumentation.

Pribory i tekhnika éksperimenta No. 5 (1960)

I. B. Keirim-Markus et al., 35-40. General-purpose RUS-3 scintillation radiometer. Bulletin I. Measuring panel.

V. F. Kuz'min, S. S. Matyukhin, 46-52. Quick-acting electronic counter with printer attachment.

B. N. Raevskii et al., 62-64. Transistorized decade counter.

Yu. A. Nemilov et al., 81-85. On photomultiplier stability.

V. V. Matveev et al., 86-89. Variation in anode current of a phototube multiplier acted upon by a magnetic field.

Razvedka i okhrana nedr No. 10 (1960)

R. S. Belova, I. I. Yankovskii, 54-55. Some problems in radiation shielding in oilwell logging operations.

Archives Environmental Health 1, No. 4 (1960)

C. Straub, 302-10. Studies in radioactive contamination of a locality.

Archives Environmental Health 1, No. 5 (1960)

E. Christofano, W. Harris, 438-60. Industrial hygiene in uranium purification operations.

Atomkernenergie 5, No. 11 (1960)

H. Meurers, 416-18. Continuous monitoring of atmospheric fallout.

R. Jaeger, 425-28. Symposium on problems in radiation dosimetry.

Atomwirtschaft 5, No. 11 (1960)

L. Lassen, 511-18. Decontamination of air; removal of radioactive aerosols.

Chem. and Engng. News 38, No. 47 (1960)

--- 66. Fission-product detector in the air stream at the exit of a nuclear ramjet aviation engine.

Energia Nucleare 7, No. 10 (1960)

--- 691-96. Signal-to-noise ratio and resolving time of pulse amplifiers for nuclear detectors.

F. Arecchi et al., 697-700. Statistical restrictions on photoelectrons for slow scintillation counters.

F. Gadda, G. Redaelli, 701-704. High-efficiency GM counter for measuring flow of a radioactive fluid.

F. Gaini et al., 705-16. A nuclear magnetometer.

G. Felcher et al., 738. Note on the problem of absolute graduation of a Ra-Be source.

Health Physics 4, No. 1 (1960)

E. Edelsack et al., 1-15. Experimental studies of bremsstrahlung from a thick target emitting energies at 1.0, 1.5 and 2.0 Mev.

S. Kondo, 21-24. Neutron sensitivity of silver-activated phosphate glass.

J. Spaa, 25-31. An instrument for stepwise measurements of dust in air.

G. Ziegler, D. Chleck, 32-34. Fading of latent image in film badges.

G. Dunning, 35-41. Short-lived fission products in radioactive fallout.

C. Cook, 42-51. Energy spectrum of fallout gamma radiation.

J. Davis et al., 55-61. Correlation analysis of the relationship between meteorological variables and radioactivity in the atmosphere.

A. Aten et al., 62. Radioactive iodine determination in milk following a reactor accident.

W. Happer, R. Birkhoff, 62-63. Angular characteristic of a partially shielded cylindrical dosimeter.

A. Jones, 64-68. Portable gamma-ray dosimeter with sonic alarm.

E. Watts, 68-69. Lead slurry for low-energy shielding.

Industries Atomiques IV, No. 9-10 (1960)

P. Pilet, 59-65. Isotopes and reactions in cages.

R. Wahl, 76-82. Electronic instrumentation of atomic research centers.

C. Nordau, 83-89. Some problems arising in the Radiobiological Service of the scientific and technical research control body.

D. Duivenstijn, 119-22. Measurements of weak beta radiation.

Jaderná Energie VI, No. 11 (1960)

O. Novakova, J. Silar, 365-78. Determination of very low activities of gamma emitters by means of scintillation detectors.

F. Behounek, J. Koci, 379-82. Sensitive gamma background and sensitive detector for gamma background and beta contamination of surfaces.

F. Vitek, Z. Dienstbier, 383-85. Exponential model of biological separation of radioisotopes, and it use in computing absorbed radiation dosage.

J. Brit. Nucl. Energy Conf. 5, No. 4 (1960)

J. Watson, 240-49. Performance of ionization chambers operating on alternating current, at high flux densities.

T. Ryves, 250-51. Use of a liquid scintillation beta counter.

Nucleonics <u>18</u>, No. 11 (1960)

E. Troubetzkoy, H. Goldstein, 171-73. Gamma rays from thermal neutron capture.

P. Zweifel, 174-75. Neutron self-shielding.

S. Katcoff, 201-208. Fission-product yields from neutron-induced fission.

S. Ellis, R. Ellis, 210. Conversion factors for radiation dosimetry.

Nucleonics <u>18</u>, No. 12 (1960)

J. Carruthers et al., 84 ff. Low-temperature electrometer circuit.

Technical Digest <u>II</u>, No. 11 (1960)

V. Santholzer, 33-38. Results of systematic fallout measurements.

V. Radioactive and Stable Isotopes

Labeled atoms techniques. Uses of radioactive radiations. Direct conversion.

Vestnik mashinostroeniya No. 11 (1960)

A. I. Nisnevich, 16-22. What's new in the field of radioactive tracer applications in studying wear on machine parts.

Vysokomelekulyarnye coedineniya <u>2</u>, No. 10 (1960)

S. A. Azimov et al., 1459-62. Grafting of some monomers onto natural silk and caprone by gamma irradiation.

Geol. rudnykh mestorozhdenii, No. 5 (1960)

G. A. Gumanskii et al., 123-24. Use of emission radiography for studies of paragenetic interrelations between minerals and material composition of high-Z elements.

Gidrotekhnicheskoe stroitel'stvo No. 11 (1960)

S. Ya. Vartazarov, 17-21. Applications of radioactive isotopes and nuclear radiations in quality control of prefab reinforced concrete in hydraulic engineering construction.

Zavod. laboratoriya <u>26</u>, No. 10 (1960)

S. Z. Bokstein et al., 1111-14. Investigation of the recrystallization process in iron by tracer techniques.

Izvestiya akad. nauk Armyan. SSR. Geol. i geograf. nauki <u>13</u>, No. 3-4 (1960)

T. I. Gvaita, Ya. G. Ter-Oganesov, 57-63. Radioactive techniques in prospecting for rare and disperse elements.

Izvestiya akad. nauk SSSR. Otdel. tekhn. nauk. Énergetika i avtomatika No. 5 (1960)

V. G. Segalin, 104-15. On an anomalous phenomenon of absorption of penetrating radiations by a multicomponent (multilayered) substance, and applications in instrument design and automation.

Izvestiya vyssh. ucheb. zaved. Pishchevaya tekhnol. No. 4 (1960)

V. V. Pal'min, L. T. Alekhina, 75-77. Study of irradiation conditions of beef by $Co^{60}$ to improve its organoleptic properties.

Izmerit. tekhnika No. 10 (1960)

U. Ts. Andres et al., 27-28. Measurement of spped of fall of bodies in liquid by the radiometric method.

Kauchuk i rezina No. 9 (1960)

I. Ya. Poddubnyi et al., 5-15. Vulcanizing of polydimethylsiloxane rubber by gamma radiation.

Kolloidnyi zhur. <u>22</u>, No. 5 (1960)

M. P. Volarovich, 524-34. Tracer investigation of properties of peat and processes occurring in peat.

Yu. S. Zaslavskii et al., 593-98. Tracer investigation of electrokinetic processes and sedimentation in disperse systems.

N. V. Churaev, 631-38. Tracer applications in the study of moisture transport processes in peat.

Master uglya No. 10 (1960)

V. Goroshko, 23. Applications for radioactive radiations. Use of radiometric separators for mechanizing sorting out of waste rock and dressing of coal.

Ogneupory No. 10 (1960)

A. S. Frenkel' et al., 460-67. Tracer atom applications to the study of diffusion of iron oxide into chromomagnesite refractories.

Stal' No. 11 (1960)

V. A. Machkovskii, M. M. Khil'ko, 995-96. Radiometric investigation of the fettling process and of wear on hearths in open-hearth furnaces.

Stanki i instrument No. 10 (1960)

S. N. Korchak, 26-28. Tracer isotope applications in the choice of grinding lubricants and cooling fluids.

Trudy Kazakh. nauchno-issled. inst. mineral. syr'ya No. 2 (1960)

I. P. Koshelev et al., 96-115. Photoneutron method for investigating boreholes in deposits of rare and exotic metals.

I. S. Zhevlakov, O. V. Shishakin, 116-24. Effectiveness of the photoneutron method for determining beryllium content in ore specimens.

Ugol' No. 10 (1960)

V. G. Segalin, A. A. Rudanovskii, 36-39. Radioactive transducer aids in controlling coal-face undercutter.

Tsvet. metally No. 10 (1960)

P. F. Groshev, 71-78. Tracer isotope study of wear resistance of draw plates.

Énergomashinostroenie No. 11 (1960)

B. A. Speranskii, 44-47. Detection of flaws in steel parts with the betatron (experience outside the USSR).

Atomkernenergie 5, No. 11 (1960)

F. Thielman, 412-15. Special techniques in the manufacture of radioactive preparations for measurements, based on shaping of preparations into plastic foil.

H. Moser, W. Rauert, 419-25. Tracer applications in hydrology.

Kernenergie 3, No. 9 (1960)

J. Muhlenpfordt, 816-22. The role of stable isotopes in research.

Nucl. Energy No. 151 (1960)

--- 583-85. Radioactive wastes disposal problems.

# Soviet Journals Available in Cover-to-Cover Translation

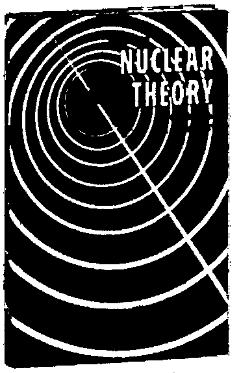
| ABBREVIATION | RUSSIAN TITLE | TITLE OF TRANSLATION | PUBLISHER | TRANSLATION BEGAN | | |
|---|---|---|---|---|---|---|
| | | | | Vol. | Issue | Year |
| AĖ | Atomnaya ėnergiya | Soviet Journal of Atomic Energy | Consultants Bureau | 1 | 1 | 1956 |
| Akust. zh. | Akusticheskii zhurnal | Soviet Physics – Acoustics | American Institute of Physics | 1 | 1 | 1955 |
| | Antibiotiki | Antibiotics | Consultants Bureau | 4 | 1 | 1959 |
| Astr(on). zh(urn). | Astronomicheskii zhurnal | Soviet Astronomy—AJ | American Institute of Physics | 34 | 1 | 1957 |
| Avto(mat). svarka | Avtomaticheskaya svarka | Automatic Welding | British Welding Research Association (London) | | 1 | 1959 |
| | Avtomatika i Telemekhanika | Automation and Remote Control | Instrument Society of America | 27 | 1 | 1956 |
| | Biofizika | Biophysics | National Institutes of Health* | | 1 | 1957 |
| | Biokhimiya | Biochemistry | Consultants Bureau | 21 | 1 | 1956 |
| Byull. ėksp(erim). biol. i med. | Byulleten' ėksperimental'noi biologii i meditsiny | Bulletin of Experimental Biology and Medicine | Consultants Bureau | 41 | 1 | 1959 |
| DAN (SSSR)<br>Dokl(ady) AN SSSR | Doklady Akademii Nauk SSSR | The translation of this journal is published in sections, as follows: | | | | |
| | Life Sciences | Doklady Biochemistry Section | American Institute of Biological Sciences | 106 | 1 | 1956 |
| | | Doklady Biological Sciences Sections (Includes: Anatomy, biophysics, cytology, ecology, embryology, endocrinology, evolutionary morphology, genetics, histology, hydrobiology microbiology, morphology, parasitology, physiology, zoology sections) | American Institute of Biological Sciences | 112 | 1 | 1957 |
| | | Doklady Botanical Sciences Sections (Includes: Botany, phytopathology, plant anatomy, plant ecology, plant embryology, plant physiology, plant morphology sections) | American Institute of Biological Sciences | 112 | 1 | 1957 |
| | Chemical Sciences | Proceedings of the Academy of Sciences of the USSR, Section: Chemical Technology | Consultants Bureau | 106 | 1 | 1956 |
| | | Proceedings of the Academy of Sciences of the USSR, Section: Chemistry | Consultants Bureau | 106 | 1 | 1956 |
| | | Proceedings of the Academy of Sciences of the USSR, Section: Physical Chemistry | Consultants Bureau | 112 | 1 | 1957 |
| | Earth Sciences | Doklady Earth Sciences Sections (Includes: Geochemistry, geology, geophysics, hydrogeology, mineralogy, paleontology, petrography, permafrost sections) | American Geological Institute | 124 | 1 | 1959 |
| | | Proceedings of the Academy of Sciences of the USSR, Section: Geochemistry | Consultants Bureau | 106-123 | 1<br>6 | 1957-<br>1958 |
| | | Proceedings of the Academy of Sciences of the USSR, Sections: Geology | Consultants Bureau | 106-123 | 1<br>6 | 1957-<br>1958 |
| | Mathematics | Doklady Soviet Mathematics | The American Mathematics Society | 131 | 1 | 1961 |
| | Physics | Soviet Physics—Doklady (Includes: Aerodynamics, astronomy, crystallography, cybernetics and control theory, electrical engineering, energetics, fluid mechanics, heat engineering, hydraulics, mathematical physics, mechanics, physics, technical physics, theory of elasticity sections) | American Institute of Physics | 106 | 1 | 1956 |
| | | Proceedings of the Academy of Sciences of the USSR, Applied Physics Sections (does not include mathematical physics or physics sections) | Consultants Bureau | 106-117 | 1 | 1956-<br>1957 |
| Derevoobrabat. prom-st'. | Derevoobrabatyvayushchaya promyshlennost' | Wood Processing Industry | Timber Development Association (London) | | 9 | 1959 |
| | Ėlecktrosvyaz | Telecommunications | Massachusetts Institute of Technology* | | 1 | 1957 |
| Ėntom(ol). oboz(renie) | Ėntomologicheskoe obozrenie | Entomological Review | American Institute of Biological Sciences | 38 | 1 | 1959 |
| Farmakol. (i) toksikol(ogiya) | Farmakologiya i toksikologiya | Pharmacology and Toxicology | Consultants Bureau | 20 | 1 | 1957 |
| FMM | Fizika metallov i metallovedenie | Physics of Metals and Metallography | Acta Metallurgica* | 5 | 1 | 1957 |
| Fiziol. zhurn. SSSR (im. Sechenova) | Fiziologicheskii zhurnal im. I. M. Sechenova | Sechenov Physiological Journal USSR | National Institutes of Health* | | 1 | 1957 |
| Fiziol(ogiya) rast. | Fiziologiya rastenii | Plant Physiology | American Institute of Biological Sciences | 4 | 1 | 1957 |
| | Geokhimiya | Geochemistry | The Geochemical Society | | 1 | 1958 |
| FTT | Fizika tverdogo tela | Soviet Physics—Solid State | American Institute of Physics | 1 | 1 | 1959 |
| Izmerit. tekh(nika). | Izmeritel'naya tekhnika | Measurement Techniques | Instrument Society of America | | 1 | 1959 |
| Izv. AN SSSR, O(td). Kh(im). N(auk) | Izvestiya Akademii Nauk SSSR: Otdelenie khimicheskikh nauk | Bulletin of the Academy of Sciences of the USSR: Division of Chemical Sciences | Consultants Bureau | | 1 | 1952 |

*continued*

| | | | | | | |
|---|---|---|---|---|---|---|
| Izv. AN SSSR, O(td). T(ekhn). N(auk): Met(all). i top. | (see Met. i top.) | | | | | |
| Izv. AN SSSR Ser. fiz(ich). | Izvestiya Akademii Nauk SSSR: Seriya fizicheskaya | Bulletin of the Academy of Sciences of the USSR: Physical Series | Columbia Technical Translations | | 1 | 1954 |
| Izv. AN SSSR Ser. geofiz. | Izvestiya Akademii Nauk SSSR: Seriya geofizicheskaya | Bulletin (Izvestiya) of the Academy of Sciences USSR: Geophysics Series | American Geophysical Union | | 1 | 1954 |
| Izv. AN SSSR Ser. geol. | Izvestiya Akademii Nauk SSSR: Seriya geologicheskaya | Izvestiya of the Academy of Sciences of the USSR: Geologic Series | American Geological Institute | | 1 | 1958 |
| Kauch. i rez. | Kauchuk i rezina | Soviet Rubber Technology | Research Association of British Rubber Manufacturers | 18 | 1 | 1959 |
| | Kinetika i kataliz | Kinetics and Catalysis | Consultants Bureau | 1 | 3 | 1960 |
| | Koks i khimiya | Coke and Chemistry USSR | Coal Tar Research Association (Leeds, England) | | 1 | 1958 |
| Kolloidn. zh(urn). | Kolloidnyi zhurnal | Colloid Journal | Consultants Bureau | 14 | 1 | 1952 |
| | Kristallografiya | Soviet Physics – Crystallography | American Institute of Physics | 2 | 1 | 1957 |
| Metalov. i term. obrabot. metal. | Metallovedenie i termicheskaya obrabotka metallov | Metal Science and Heat Treatment of Metals | Acta Metallurgica | 6 | 1 | 1958 |
| | Metallurg | Metallurgist | Acta Metallurgica | | 1 | 1957 |
| Met. i top. | Metallurgiya i topliva | Russian Metallurgy and Fuels | Eagle Technical Publications | | 1 | 1960 |
| Mikrobiol. | Mikrobiologiya | Microbiology | American Institute of Biological Sciences | 26 | 1 | 1957 |
| OS | Optika i spektroskopiya | Optics and Spectroscopy | American Institute of Physics | | 6 | 1959 |
| | Pochvovedenie | Soviet Soil Science | American Institute of Biological Sciences | | 1 | 1958 |
| | Priborostroenie | Instrument Construction | British Scientific Instrument Research Association | | 1 | 1959 |
| Pribory i tekhn. éks(perimenta) | Pribory i tekhnika éksperimenta | Instruments and Experimental Techniques | Instrument Society of America | | 1 | 1957 |
| Prikl. matem. i mekh. | Prikladnaya matematika i mekhanika | Applied Mathematics and Mechanics | American Society of Mechanical Engineers | | 1 | 1958 |
| PTÉ | (see Pribory i tekhn. éks.) | | | | | |
| | Problemy Severa | Problems of the North | National Research Council of Canada | | | |
| Radiotekh. | Radiotekhnika | Radio Engineering | Massachusetts Institute of Technology* | 12 | 1 | 1957 |
| Radiotekh. i élektronika | Radiotekhnika i élektronika | Radio Engineering and Electronics | Massachusetts Institute of Technology* | 2 | 1 | 1957 |
| | Stanki i instrument | Machines and Tooling | Production Engineering Research Assoc. | | 1 | 1959 |
| | Stal' | Stal (In English) | Iron and Steel Institute | | 1 | 1959 |
| Stek. i keram. | Steklo i keramika | Glass and Ceramics | Consultants Bureau | 13 | 1 | 1956 |
| Svaroch. proiz-vo | Svarochnoe proizvodstvo | Welding Production | British Welding Research Association | | 4 | 1959 |
| Teor. veroyat. i prim. | Teoriya veroyatnostei i ee primenenie | Theory of Probability and Its Applications | Society for Industrial and Applied Mathematics | | 1 | 1956 |
| Tsvet. Metally | Tsvetnye metally | Nonferrous Metals | Primary Sources | | 1 | 1960 |
| UFN | Uspekhi fizicheskikh Nauk | Soviet Physics – Uspekhi (partial translation) | American Institute of Physics | 66 | 1 | 1958 |
| UKh | Uspekhi khimii | Russian Chemical Reviews | The Chemical Society (London) | | 1 | 1960 |
| UMN | Uspekhi matematicheskikh nauk | Russian Mathematical Surveys | London Mathematical Society | 15 | 1 | 1960 |
| Usp. fiz. nauk | (see UFN) | | | | | |
| Usp. khim(ii) | (see UKh) | | | | | |
| Usp. matem. nauk | (see UMN) | | | | | |
| Usp. sovr. biol. | Uspekhi sovremennoi biologii | Russian Review of Biology | Oliver and Boyd | | 48 | 1959 |
| Vest. mashinostroeniya | Vestnik mashinostroeniya | Russian Engineering Journal | Production Engineering Research Assoc. | | 4 | 1959 |
| Vop. gem. i per. krovi | Voprosy gematologii i perelivaniya krovi | Problems of Hematology and Blood Transfusion | National Institutes of Health* | | 1 | 1957 |
| Vop. onk. | Voprosy onkologii | Problems of Oncology | National Institutes of Health* | | 1 | 1957 |
| Vop. virusol. | Voprosy virusologii | Problems of Virology | National Institutes of Health* | | 1 | 1957 |
| Zav(odsk). lab(oratoriya) | Zavodskaya laboratoriya | Industrial Laboratory | Instrument Society of America | 25 | 1 | 1959 |
| ZhAKh Zh. anal(it). khimii | Zhurnal analiticheskoi khimii | Journal of Analytical Chemistry USSR | Consultants Bureau | 7 | 1 | 1952 |
| ZhETF<br>Zh. éksperim. i teor. fiz. | Zhurnal éksperimental'noi i theoreticheskoi fiziki | Soviet Physics–JETP | American Institute of Physics | 28 | 1 | 1955 |
| ZhFKh Zh. fiz. khimii | Zhurnal fizicheskoi khimii | Russian Journal of Physical Chemistry | The Chemical Society (London) | | 7 | 1959 |
| ZhMÉI Zh(urn). mikrobiol. épidemiol. i immunobiol. | Zhurnal mikrobiologii, épidemiologii i immunobiologii | Journal of Microbiology, Epidemiology and Immunobiology | National Institutes of Health* | | 1 | 1957 |
| ZhNKh<br>Zh(urn). neorgan(ich). khim(ii) | Zhurnal neorganicheskoi khimii | The Russian Journal of Inorganic Chemistry | The Chemical Society (London) | | 1 | 1959 |
| ZhOKh<br>Zh(urn). obshch(ei) khimii | Zhurnal obshchei khimii | Journal of General Chemistry USSR | Consultants Bureau | 19 | 1 | 1949 |
| ZhPKh<br>Zh(urn). prikl. khimii | Zhurnal prikladnoi khimii | Journal of Applied Chemistry USSR | Consultants Bureau | 23 | 1 | 1950 |
| ZhSKh<br>Zh(urn). strukt. khimii | Zhurnal strukturnoi khimii | Journal of Structural Chemistry | Consultants Bureau | 1 | 1 | 1960 |
| ZhTF<br>Zh(urn). tekhn. fiz. | Zhurnal teknicheskoi fiziki | Soviet Physics–Technical Physics | American Institute of Physics | 26 | 1 | 1956 |
| Zh(urn). vyssh. nervn. deyat. (im. Pavlova) | Zhurnal vysshei nervnoi deyatel'nosti (im. I. P. Pavlova) | Pavlov Journal of Higher Nervous Activity | National Institutes of Health* | | 1 | 1958 |

*Sponsoring organization. Translation through 1960 issues is a publication of Pergamon Press.

# *3 titles of immediate interest!*



## LECTURES ON NUCLEAR THEORY

**by L. Landau and Ya. Smorodinsky**

Translated from Russian

A concise presentation by these world-famous Soviet physicists of some of the basic concepts of nuclear theory. Originally published at $15.00 per copy.

*". . . a real jewel of an elementary introduction into the main concepts of nuclear theory . . ."*—NUCLEAR PHYSICS

*". . . a decidedly worth-while addition to any experimental nuclear physicist's library."*—E. M. Henley, PHYSICS TODAY

**cloth** **108 pages** **$5.25**

*Order from:* **PLENUM PRESS** **227 W. 17th Street,** **New York 11, N.Y.**

---

*— of major interest to all researchers in low-temperature physics.*

## A SUPPLEMENT TO "HELIUM"

**By E. M. Lifshits and E. L. Andronikashvili**

Translated from Russian

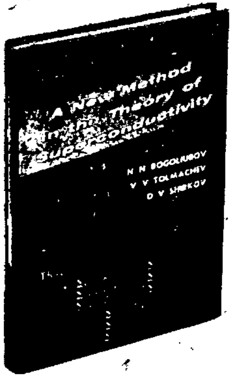
This notable volume consists of two supplementary chapters, by these outstanding Soviet physicists, which were added to the Russian translation of W. H. Keesom's classic book "Helium."

The first chapter, by Lifshits, presents a concise resume of the Landau theory of superfluidity. The second chapter reports in considerable detail the experimental work conducted by Peter Kapitza and E. L. Andronikashvili.

**cloth** **167 pages** **illustrated** **$7.50**

*Order from:* **CONSULTANTS BUREAU** **227 W. 17th St.** • **New York 11, N. Y.**

---



## A NEW METHOD IN THE THEORY OF SUPERCONDUCTIVITY

**By N. N. Bogoliubov, V. V. Tolmachev and D. V. Shirkov**

Translated from Russian

The Soviet authors put forth a systematic presentation of a new method in the theory of superconductivity, developed as a result of the research of N. N. Bogoliubov and V. V. Tolmachev—based on a physical and mathematical analogy with superfluidity. This new method is an immediate generalization of the method developed by Bogoliubov in formulating a microscopic theory of superfluidity. The authors give calculations for the energy of the superconducting ground state using Frohlich's Hamiltonian, as well as of the one-fermion and collective elementary excited states. A detailed analysis of the role of the Coulomb interaction between the electrons in the theory of superconductivity is included. The authors also demonstrate how a system of fermions is treated with a fourth-order interaction Hamiltonian and establish the criterion for its superconductivity.

**cloth** **121 pages** **illustrated** **$5.75**

*Order from:* **CONSULTANTS BUREAU** **227 W. 17th St.** • **New York 11, N. Y.**

---

*Descriptive folders upon request.*

# RESEARCH by Soviet EXPERTS

**Translated by Western Scientists**

## SPECTRA AND ANALYSIS

### by A. A. Kharkevich

The first handbook directed toward acousticians and others working in those fields which require the analysis of oscillations—ultrasonics, electronics, shock and vibration engineering. This volume is devoted to the analysis of *spectral concepts* as they are applied to oscillations in acoustics and electronic engineering, and to a discussion of the methods of spectral analysis. Contents include KOTEL'NIKOV'S theorem for bounded spectra, the spectra and analysis of random processes, and (in connection with the latter) the statistical compression of spectra.

**cloth** **236 pages** **$8.75**

## ULTRASONICS AND ITS INDUSTRIAL APPLICATIONS

### by O. I. Babikov

This work is concerned with ultrasonic control methods which are applied in industry, and also with the action of high-intensity ultrasonic oscillations on various technological processes. Considerable attention is devoted to ultrasonic pulse methods of flaw detection and physicochemical research. It is an invaluable aid to scientific researchers, engineers, and technicians working in fields which make use of ultrasonic methods industrially, as well as being a convenient reference for a broad category of readers who might wish to become acquainted with the current state of ultrasonic instrumentation.

**cloth** **265 pages** **$9.75**

*Tables of contents upon request*

**CONSULTANTS BUREAU**
**227 West 17th Street • New York 11, N.Y. • U.S.A.**