

*Volume 29, Number 6*

*December, 1970*

# **SOVIET ATOMIC ENERGY**

**АТОМНАЯ ЭНЕРГИЯ  
(ATOMNAYA ÉNERGIYA)**

**TRANSLATED FROM RUSSIAN**



**CONSULTANTS BUREAU, NEW YORK**

# SOVIET ATOMIC ENERGY

*Soviet Atomic Energy* is a cover-to-cover translation of *Atomnaya Énergiya*, a publication of the Academy of Sciences of the USSR.

An arrangement with Mezhdunarodnaya Kniga, the Soviet book export agency, makes available both advance copies of the Russian journal and original glossy photographs and artwork. This serves to decrease the necessary time lag between publication of the original and publication of the translation and helps to improve the quality of the latter. The translation began with the first issue of the Russian journal.

## Editorial Board of *Atomnaya Énergiya*:

**Editor:** M. D. Millionshchikov

Deputy Director  
I. V. Kurchatov Institute of Atomic Energy  
Academy of Sciences of the USSR  
Móscow, USSR

**Associate Editors:** N. A. Kolokol'tsov

N. A. Vlasov

A. I. Alikhanov

V. V. Matveev

A. A. Bochvar

M. G. Meshcheryakov

N. A. Dollezhal'

P. N. Palei

V. S. Fursov

V. B. Shevchenko

I. N. Golovin

D. L. Simonenko

V. F. Kalinin

V. I. Smirnov

A. K. Krasin

A. P. Vinogradov

A. I. Leipunskii

A. P. Zefirov

Copyright © 1971 Consultants Bureau, New York, a division of Plenum Publishing Corporation, 227 West 17th Street, New York, N. Y. 10011. All rights reserved. No article contained herein may be reproduced for any purpose whatsoever without permission of the publishers.

Consultants Bureau journals appear about six months after the publication of the original Russian issue. For bibliographic accuracy, the English issue published by Consultants Bureau carries the same number and date as the original Russian from which it was translated. For example, a Russian issue published in December will appear in a Consultants Bureau English translation about the following June, but the translation issue will carry the December date. When ordering any volume or particular issue of a Consultants Bureau journal, please specify the date and, where applicable, the volume and issue numbers of the original Russian. The material you will receive will be a translation of that Russian volume or issue.

## Subscription

\$67.50 per volume (6 Issues)

Single Issue: \$30

2 volumes per year

Single Article: \$15

(Add \$5 for orders outside the United States and Canada.)

## CONSULTANTS BUREAU, NEW YORK AND LONDON



227 West 17th Street  
New York, New York 10011

Davis House  
8 Scrubs Lane  
Harlesden, NW10 6SE 1  
England

# SOVIET ATOMIC ENERGY

A translation of *Atomnaya Énergiya*

Volume 29, Number 6

December, 1970

## CONTENTS

	Engl./Russ.
On the Sixtieth Birthday of Boris Sergeevich Dzhelepov, Corresponding Member of the Academy of Sciences of the USSR. . . . .	1177
Turbulent Heat and Mass Exchange – M. D. Millionshchikov . . . . .	1178 411
Special Aspects of the Deformation of Uranium Subjected to Tensile Stain at a Constant Velocity – A. I. Voloshchuk, V. F. Zelenskii, Yu. F. Konotop, and Yu. T. Miroshnichenko . . . . .	1184 416
Subbarrier Neutron Fission of Pu <sup>238</sup> (E/T) – S. B. Ermagambetov and G. N. Smirenkin . . . . .	1190 422
Design of Cascades for Separating Isotope Mixtures – N. A. Kolokol'tsov, V. P. Minenko, B. I. Nikolaev, G. A. Sulaberidze, and S. A. Tret'yak. . . . .	1193 425
Storage of Multiply-Charged Ions in a Relativistic Electron Bunch – M. L. Iovnovich and M. M. Fiks . . . . .	1199 429
Energy Balance in the Plasma in Apparatuses of the "Tokamak" Type – Yu. N. Dnestrovskii and D. P. Kostomarov . . . . .	1205 434
 <b>REVIEWS</b>	
Thermodynamics of the Uranium–Carbon, Uranium–Nitrogen, and Plutonium–Carbon Systems – V. V. Akhachinskii and S. N. Bashlykov . . . . .	1211 439
 <b>ABSTRACTS</b>	
Slowing Down of Resonance Neutrons in Matter. Communication 4 – D. A. Kozhevnikov and V. S. Khavkin. . . . .	1220 448
Investigation of the Calibration Characteristics of a Radiation Thermodiverter in High-Intensity Fields of Ionizing Radiations – V. S. Karasev, S. S. Ogorodnik, and Yu. L. Tsoglin . . . . .	1221 449
Calculation of Photoneutron Distribution by Monte Carlo Method – A. A. Morozov and A. I. Khisamutdinov . . . . .	1222 449
Precision System for the Determination of Oxygen by Fast Neutron Activation – I. P. Lisovskii and L. A. Smakhtin . . . . .	1223 450
VVR Reactor Semiautomatic Activation Analysis System – I. P. Lisovskii, L. A. Smakhtin, N. V. Filippova, and V. I. Volgin . . . . .	1223 450
Method of Attenuating Radial Betatron Oscillations in Cyclic Accelerators – L. A. Roginskii and G. F. Senatorov. . . . .	1224 450
Permanent Electromagnet with Built-in Radioisotope Thermoelectric Direct Converter – A. Kh. Cherkasskii and V. S. Makarov . . . . .	1225 451
 <b>LETTERS TO THE EDITOR</b>	
Experimental Study of the Characteristics of the IR-100 Research Reactor – L. V. Konstantinov, I. N. Martem'yanov, V. A. Nikolaev, A. A. Sarkisov, V. F. Sachkov, A. V. Sobolev, S. V. Chernyaev, and I. S. Chesnokov . . . . .	1227 453

**CONTENTS**

(continued)

Engl./Russ.

Effect of the Flow Velocity of a Vapor-liquid Mixture of Coolant, and of Vapor Content, on Surface Heat-Transfer Coefficient in Boiling of Water Inside Tubes - F. F. Bogdanov. . . . .	1229 454
Neutron Yield from Thick Targets Bombarded with 11.5 and 23.5 MeV Protons - V. K. Daruga and E. S. Matusевич . . . . .	1233 456
A Method of Determining the Iron Content of Corrosion Product Deposits - B. A. Alekseev, N. N. Kozhenkov, and G. A. Kotel'nikov. . . . .	1235 458
Group Separation of Fission Products by the Chromatographic Method - L. N. Moskvín and N. N. Kalinir. . . . .	1236 458
Experimental Verification of the Radiation-Chemical Method for Producing Tetrachloroalkanes - A. A. Beér, P. A. Zagorets, V. F. Inozemtsev, L. S. Maiorov, V. I. Slavyanov, G. A. Artyushov, I. F. Sprygaev, and V. A. Novozhilov . . . . .	1240 461
Use of Xenon Proportional Counter Escape Peaks for X-Ray Radiometric Analysis of Tungsten in Ores - N. G. Bolotova, V. V. Kotel'nikov, and E. P. Leman. . . . .	1243 463
Diagnostics of an Electron-Ion Bunch Using Bremsstrahlung - M. L. Iovnovich, V. P. Sarantsev, and M. M. Fiks . . . . .	1245 465
Excitation of Radial Betatron Oscillations by a Longitudinal Accelerating Field - Yu. S. Ivanov, A. A. Kuz'min, and G. F. Senatorov . . . . .	1248 467
<b>NEWS</b>	
Liege May 1970 International Symposium on Modern Electric Power Generating Stations - P. A. Andreev. . . . .	1251 470
June 1970 Princeton Symposium on Plasma Stabilization by Feedback and Dynamical Techniques - D. A. Panov. . . . .	1253 471
June 1970 Zakopane Symposium on Nondestructive Materials Testing Equipment and Techniques Using Nuclear Radiations - A. Maiorov. . . . .	1256 473
The Saturn-1 Plasma Machine - V. A. Suprunenko. . . . .	1259 474
The Anglo-Soviet Plasma Physics Experiment - V. V. Sannikov. . . . .	1260 475
GKIAÉ-JINR Agreement on Scientific and Technical Collaboration - V. Biryukov. . . . .	1262 475
<b>BRIEF COMMUNICATIONS</b> . . . . .	1263 476
<b>INDEX</b>	
Author Index, Volumes 28-29, 1970. . . . .	1267
Tables of Contents, Volumes 28-29, 1970 . . . . .	1273

The Russian press date (podpisano k pechati) of this issue was 11/16/1970. Publication therefore did not occur prior to this date, but must be assumed to have taken place reasonably soon thereafter.

ON THE SIXTIETH BIRTHDAY OF BORIS SERGEEVICH  
DZHELEPOV, CORRESPONDING MEMBER OF THE  
ACADEMY OF SCIENCES OF THE USSR



The Editorial Staff of Atomnaya Énergiya congratulate Boris Sergeevich Dzheleпов on his sixtieth birthday and wish him health and a successful continuation of his scientific and organizational activities on behalf of nuclear physics in the Soviet Union.

---

Translated from Atomnaya Énergiya, Vol. 29, No. 6, December, 1970.

© 1971 Consultants Bureau, a division of Plenum Publishing Corporation, 227 West 17th Street, New York, N. Y. 10011. All rights reserved. This article cannot be reproduced for any purpose whatsoever without permission of the publisher. A copy of this article is available from the publisher for \$15.00.

## TURBULENT HEAT AND MASS EXCHANGE

M. D. Millionshchikov

UDC 523.542

Turbulent heat and mass exchange in layers close to a wall has been studied by many authors [1, 3]. This problem has become especially important since it was discovered that the usual approach would not explain the observed heat and mass exchange for values of Prandtl's number  $P$  (the ratio of the molecular coefficient of kinematic viscosity to the thermal conductivity  $\nu/\kappa$ ) much larger than unity.

Some materials for which these processes have been experimentally investigated have Prandtl numbers of order 3000 or more. Deissler [1] analyzed experimental data for a wide range of values of  $P$  (0.5-3000), and developed a special theory of heat and mass exchange which, with the appropriate choice of certain constants, yields results in good agreement with experimental results in this range.

Deissler considers the laminar sublayer to be a region of interaction between molecular and turbulent exchange characterized by the distance from the wall and the kinematic viscosity. A logarithmic profile is used in the region of developing turbulence, and in this way a better quantitative description of the velocity profile is obtained than when a linear profile is used in the laminar sublayer and a purely logarithmic profile.

However this method does not yield a theory for the dependence of heat and mass transfer on Prandtl's number including small values.

Deissler also described the variation of Nusselt's number for large Prandtl numbers by taking it to be proportional to the Prandtl number raised to the power  $1/4$ .

Another position was taken concerning heat and mass exchange by L. D. Landau and V. G. Levich [2]. Their theory agrees with that of P. L. Kapitsa [4, 5], in that they consider that there are stable liquid-motion waves in layers close to a wall. The thermal conduction is very low in the viscous layer for large Prandtl numbers, and so the turbulent pulsations in this layer lead to turbulent transfer comparable to molecular transfer at distances from the wall considerably smaller than the thickness of the hydrodynamic laminar sublayer. Hence the thickness of the thermal (or diffusion) laminar sublayer, i.e., the layer in which turbulent exchange may be neglected, is in general a function of the molecular thermal conductivity. The very general assumptions of the theory can be stated as follows:

- 1) The longitudinal component of the pulsation velocity  $u'$  varies like the mean velocity, i.e., it is proportional to the distance from the wall;
- 2) the pulsation frequency is independent of the distance from the wall;
- 3) the correlation between the transverse velocity component and the transverse transfer scale is independent of the distance from the wall.

Under these assumptions, the longitudinal velocity pulsations satisfy the relation [2]

$$u' \sim v_* \frac{y}{\delta_0},$$

where  $v_*$  is the dynamic velocity and  $\delta_0$  is the thickness of the hydrodynamic laminar sublayer.

The transverse velocity component corresponding to heat and mass transfer, estimated from the continuity condition for the flow has, in the layer close to the wall, the order

$$v' \sim v_* \left( \frac{y}{\delta_0} \right)^2.$$

Translated from *Atomnaya Énergiya*, Vol. 29, No. 6, pp. 411-426, December, 1970. Original article submitted August 28, 1970.

© 1971 Consultants Bureau, a division of Plenum Publishing Corporation, 227 West 17th Street, New York, N. Y. 10011. All rights reserved. This article cannot be reproduced for any purpose whatsoever without permission of the publisher. A copy of this article is available from the publisher for \$15.00.

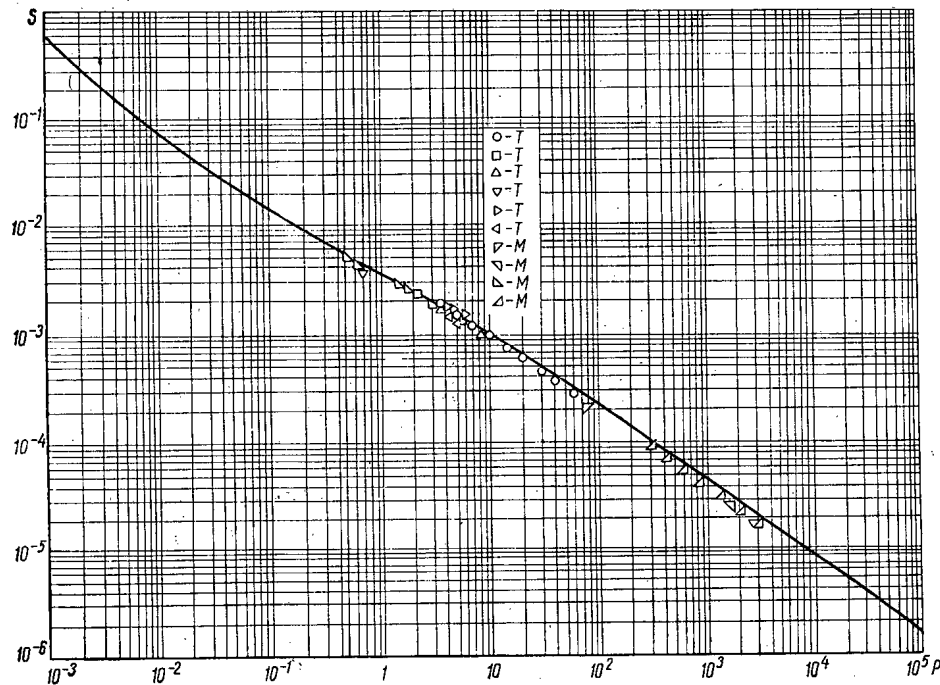


Fig. 1. The Stanton number  $S$  vs the Prandtl number  $P$  for the Reynolds number  $R = 10,000$ .

The transfer path in the transverse direction is proportional to  $v'$ , i.e., it depends on  $y$  in the same way as the transverse velocity component and is proportional to  $y^2/\delta_0$ .

The transverse heat transfer is proportional to the product of the transverse velocity component and the mean transverse transfer path:

$$\chi_T \sim v_* \delta_0 \left( \frac{y}{\delta_0} \right)^4,$$

where  $\chi_T$  is the turbulent thermal conductivity.

Determination of  $\delta_0$  from the relation

$$v \sim v_* \delta_0,$$

yields

$$\chi_T = \text{const } v \left( \frac{y}{\delta_0} \right)^4.$$

Now taking the distance  $y = \delta_0'$  from the wall as the thickness for which the turbulent thermal conductivity is of the order  $\chi$  (the molecular thermal conductivity), we obtain V. G. Levich's formula

$$\delta_0' = c \delta_0 P^{-1/4}. \quad (1)$$

This relation directly yields the limit formula for the thermal conductivity law for large  $P$  [2], which is confirmed by Deissler's experimental data. No limit formula can be obtained for small or intermediate values of  $P$ .

Before turning to new constructions, we recall that, for  $P = 1$ , the laminar and thermal layers have the same thickness. We thus set  $c = 1$  in (1), i.e., we have

$$\delta_0' = \delta_0 P^{-1/4} \text{ for } P \gg 1. \quad (2)$$

For Prandtl numbers smaller than unity, both the tangential turbulent stresses and the turbulent transfer of heat and mass are negligibly small within the limit  $\delta_0$  of the laminar sublayer.

Hence, for  $P > 1$ , the value of  $\delta_0'$ , which is the distance from the wall at which turbulent heat and mass transfer begin, is equal to the thickness  $\delta_0$  of the hydrodynamic laminar sublayer:

$$\delta_0' = \delta_0 \text{ for } P < 1. \quad (2')$$

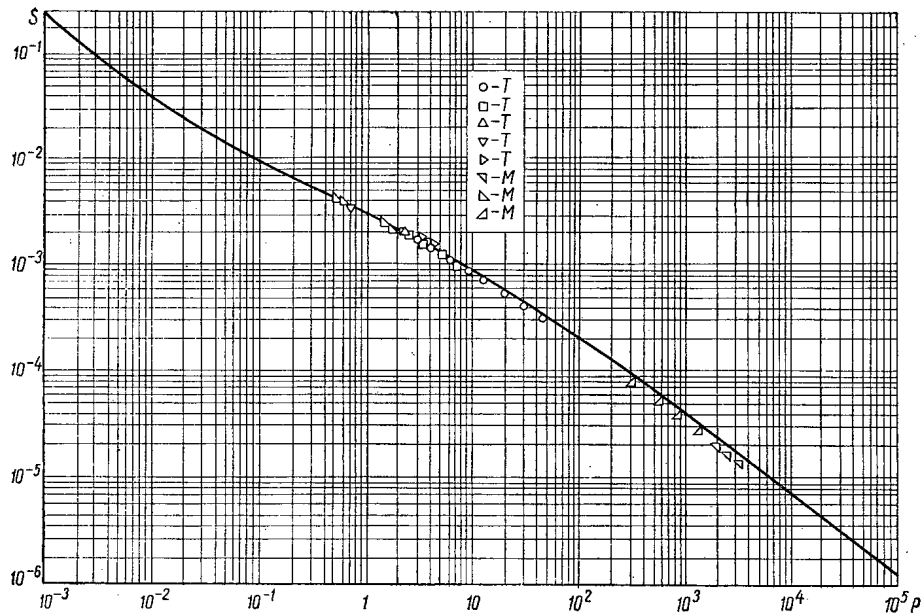


Fig. 2. The Stanton number  $S$  vs the Prandtl number  $P$  for the Reynolds number  $R = 25,000$ .

It should be noted that the constant in (1) which is taken to be unity is the only experimental quantity obtained from thermal measurements used in the following reasoning.

The investigation in [6, 9] of turbulent flow in a tube and the resistance laws shows that the superposition of molecular viscosity and the various forms of turbulent viscosity leads to a very accurate description of the behavior of the velocity and the resistance coefficients, not only for strongly developed turbulence but also for the range of Reynolds numbers in which the influence of molecular viscosity may not be neglected. This fact is a basis for assuming that the use of the superposition principle for molecular and turbulent exchange might also yield useful results in connection with problems concerning heat exchange and mass exchange.

These two problems are completely analogous, and for the sake of definiteness we consider the heat-exchange problem and then, by changing notation, we obtain the corresponding results for the mass-exchange problem.

Let  $q$  be the heat flux towards a plane wall, and let the flow be parallel to the wall with velocity  $u(y)$ .

Then

$$q = -(\kappa + \rho c_p \varepsilon_T) \frac{dT}{dy}, \quad (3)$$

where  $T$  is the absolute temperature,  $T = T(y)$ ;  $\kappa = \rho c_p \chi$  is the molecular thermal conductivity;  $\varepsilon_T$  is the coefficient of turbulent mass exchange; and  $c_p$  is the specific heat at constant pressure.

According to Reynolds' hypothesis

$$\varepsilon_T = \nu_T,$$

where  $\nu_T$  is the kinematic turbulent viscosity.

Generalizing Reynolds hypothesis, we have †

$$\varepsilon_T = a' \nu_* (y - \delta'_0).$$

Our generalization lies in the fact that the thickness  $\delta'_0$  of the thermal laminar layer is not in general equal to the thickness  $\delta_0$  of the laminar sublayer for the velocity field, and the quantity  $a'$  is defined as follows:

$$\begin{aligned} a' &= \text{const} = a && \text{for } y > \delta'_0; \\ a' &= 0 && \text{for } y \leq \delta'_0. \end{aligned}$$

†cf. [6, 7].



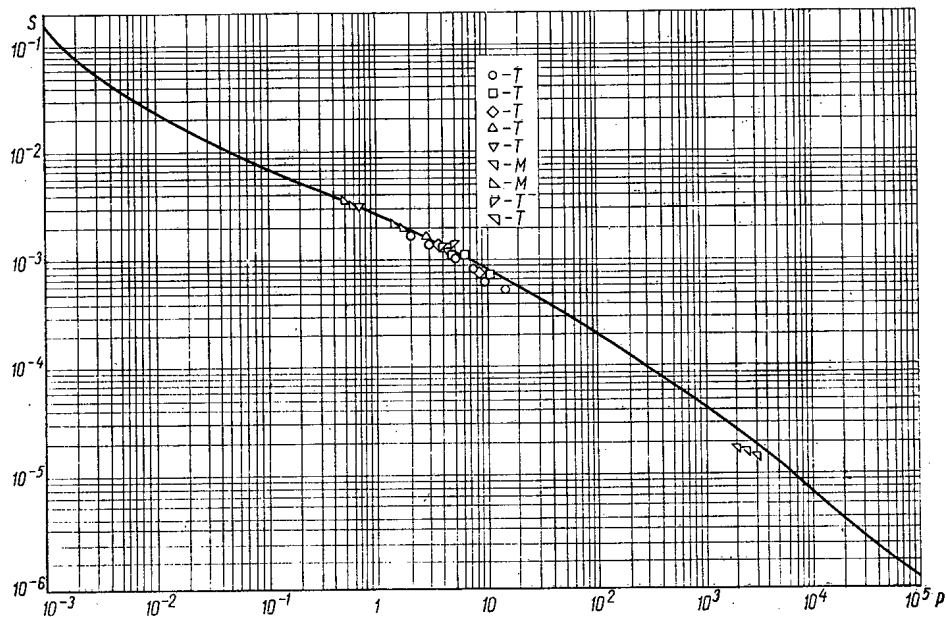


Fig. 3. The Stanton number  $S$  vs the Prandtl number  $P$  for the Reynolds number  $R = 50,000$ .

By integrating (3) we obtain a relation determining the temperature distribution:

$$\frac{\Delta \bar{T}}{\beta} = \frac{1}{a'} \ln [1 + a' P (\eta - \delta')] + \delta' P, \quad (4)$$

where

$$\beta = \frac{q}{\rho c_p T_0 \nu_*}; \quad \eta = \frac{y \nu_*}{\nu}; \quad T_0 = T(0);$$

$$\delta = \frac{\delta_0 \nu_*}{\nu}; \quad \delta' = \frac{\delta'_0 \nu_*}{\nu}; \quad \Delta \bar{T} = 1 - \frac{T}{T_0}.$$

Relation (4) is analogous in form to the relation

$$\frac{u}{\nu_*} = \frac{1}{a} \ln [1 + a (\eta - \delta)] + \delta \quad (5)$$

for the velocity distribution [6].

Relations (4) and (5) coincide if  $P = 1$  and  $\delta' = \delta$ .

The quantities  $\delta$  and  $a$  were determined in [6] from experimental data obtained by the measurement of velocities in the layer close to a wall or in tubes. We have good agreement with hydrodynamic experimental results for  $\delta = 7.8$  and  $a = 0.39$ .

If we use (2), we find that (4) implies

$$\frac{\Delta \bar{T}}{\beta} = \frac{1}{a} \ln [1 + P a (\eta - \delta \cdot P^{-1/4})] + \delta \cdot P^{3/4}. \quad (6)$$

This relation yields temperature distributions as functions of  $\eta$  and  $P$ .

For  $a = 0.39$  and  $\delta = 7.8$  (the values derived from hydraulic measurements), temperature profiles were calculated and comparisons were made with the experimental results in [1, 10, 11].

Unfortunately we have at our disposal only velocity-profile measurements for Prandtl numbers close to unity. The temperature profile obtained from (6) gives a good description of the whole range of distances from the wall.

For Prandtl numbers differing considerably from unity, i.e., for  $0.5 < P < 3000$ , the law for heat exchange has been investigated experimentally [1] from the point of view of the dependence of Stanton's number on Prandtl's number.

Stanton's number  $S$  is defined by the equation

$$S^{-1} = \frac{u_{\text{mean}} \bar{T}_{\text{mean}}}{\nu_* \beta} \quad (7)$$

Experimental results are usually processed by taking an average weighted by the flow in a given section, i.e., by using the formula

$$\frac{\Delta \bar{T}_{\text{mean}}}{\beta} = \frac{\int_0^{\eta_0} \frac{\Delta \bar{T}}{\beta} \cdot \frac{u}{\nu_*} (\eta_0 - \eta) d\eta}{\int_0^{\eta_0} \frac{u}{\nu_*} (\eta_0 - \eta) d\eta} \quad (8)$$

which is equivalent to defining  $S$  by the relation

$$S^{-1} = \frac{2}{\eta_0^2} \int_0^{\eta_0} \frac{\Delta \bar{T}}{\beta} \cdot \frac{u}{\nu_*} (\eta_0 - \eta) d\eta,$$

where  $\eta_0 = rv_*/\nu$  and  $r$  is the tube radius.

Relations (5) and (6) can be used explicitly to estimate the difference between the average given by (8) and the simple mean given by the formula

$$\frac{\Delta \bar{T}'_{\text{mean}}}{\beta} = \frac{2}{\eta_0^2} \int_0^{\eta_0} \frac{\Delta \bar{T}}{\beta} (\eta_0 - \eta) d\eta. \quad (9)$$

For  $P = 1$  we have

$$\Delta \bar{T}_{\text{mean}} \approx \Delta \bar{T}'_{\text{mean}} \left[ 1 + \frac{5}{4a^2} \left( \frac{\beta}{\Delta \bar{T}'_{\text{mean}}} \right)^2 \right]. \quad (10)$$

For sufficiently large values of  $\Delta \bar{T}'_{\text{mean}}/\beta$ , the second term in (10) is small and we may take

$$\Delta \bar{T}_{\text{mean}} = \Delta \bar{T}'_{\text{mean}} \quad (11)$$

with a high degree of accuracy.

For large Prandtl numbers, the exact value of  $\Delta \bar{T}_{\text{mean}}$  in the heat-exchange law is of no great importance, and errors in its value may be ignored. Hence in our calculations we may use temperatures given by (9).

On the other hand averages obtained from (8) must be retained in the calculation of the heat balance, since errors in the calculation of the longitudinally transported flow are all retained in the calculations of the thermal balance.

Using the above facts concerning the average, and the relation

$$\frac{u_{\text{mean}}}{\nu_*} = \frac{2}{\eta_0^2} \int_0^{\eta_0} \frac{1}{a} \{ \ln [1 + a(\eta - \delta)] + \delta \} (\eta_0 - \eta) d\eta = \sqrt{\frac{8}{\lambda}}, \quad (12)$$

where  $\lambda$  is the resistance, we have

$$\frac{\Delta \bar{T}'_{\text{mean}}}{\beta P} = \delta_1 - \frac{\delta_1^2}{\eta_0} + \frac{1}{3} \cdot \frac{\delta_1^3}{\eta_0^2} + \frac{2}{a_1^2 \eta_0} \left[ 1 + \frac{a_1 \delta_1 - 1}{a_1 \eta_0} \right] \left[ \alpha (\ln \alpha - 1) + 1 \right] + \frac{2}{a_1^2 \eta_0^2} \left[ \frac{\alpha^2}{2} \left( \ln \alpha - \frac{1}{2} \right) + \frac{1}{4} \right], \quad (13)$$

where  $a_1 = aP$ ,  $\delta_1 = \delta \cdot P^{-1/4}$ ,  $\alpha = 1 + a_1(\eta_0 - \delta_1)$ ,  $\eta_0 = rv_*/\nu$ , and  $r$  is the tube radius, or we can use the approximation

$$\frac{\Delta \bar{T}'_{\text{mean}}}{\beta} = \sqrt{\frac{8}{\lambda}} + (P^{3/4} - 1) \delta + \frac{1}{a} \ln P + \varepsilon, \quad (13')$$

where  $\varepsilon$  is small.

Hence for large Prandtl numbers we have the very accurate relation

$$S^{-1} = \frac{8}{\lambda} \left\{ 1 + \sqrt{\frac{\lambda}{8}} \left[ (P^{3/4} - 1) \delta + \frac{1}{a} \ln P \right] \right\}. \quad (14)$$

It follows that for the Nusselt number  $N = S \cdot R \cdot P$  we have

$$N^{-1} = \frac{8}{\lambda R \cdot P} \left\{ 1 + \sqrt{\frac{\lambda}{8}} \left[ (P^{3/4} - 1) \delta + \frac{1}{a} \ln P \right] \right\}. \quad (15)$$

For Prandtl numbers smaller than unity (in this case  $\delta_0^1 = \delta_0$ ), we have the following accurate relation

$$S^{-1} = \sqrt{\frac{8}{\lambda}} \left\{ \frac{1}{a} \ln [1 + aP(\eta - \delta)] + \delta \right\}. \quad (16)$$

Figures 1-3 show curves obtained from values of  $S$  calculated from (14) for the values  $a = 0.39$  and  $\delta = 7.8$  obtained from hydrodynamic experiments and the corresponding values of  $\lambda$  given in [6].

Conversion of the above results to apply to diffusion problems is carried out by replacing the thermal conductivity  $\chi$  by the diffusion coefficient  $D$  and the temperature  $T$  by the concentration  $C$  of the diffusing material.

The points marked in the diagrams are experimental values concerning heat and mass exchange ( $T$  and  $M$ ) given by Deissler [1].

The accuracy of values of  $S$  and  $N$  obtained from (14), (15), and (16) depends on the accuracy of  $\delta$ , and can be increased by improving the accuracy of determination of  $\delta$  and the accuracy of the thermal measurements.

Calculated and experimental results can be considered to coincide within the contemporary accuracy possible in hydraulic and thermal measurements.

We note in conclusion that, by using the superposition of molecular and turbulent viscosity and the concept of a laminar sublayer whose thickness for hydrodynamic considerations is different from its thickness for heat and mass exchange, we have obtained a description of turbulent heat and mass exchange valid for a wide range of Prandtl numbers. Good quantitative agreement is obtained with experimental data over a wide range of Prandtl numbers without using any constants which must be determined from thermal measurements except the constant  $c = 1$ , used in (1). There is no need to consider the interaction between molecular and turbulent exchange or to use interpolation formulas requiring the determination of extra coefficients by experiment.

The author wishes to thank I. S. Kudryavtseva for her help in connection with the computations.

#### LITERATURE CITED

1. R. Deissler, NACA Report 1210 (1954).
2. V. G. Levich, Physicochemical Hydromechanics [in Russian], Nauka, Moscow (1962).
3. L. G. Loitsyanskii, Proceedings of the All-Union Congress on Theoretical and Applied Mechanics [in Russian], Izd-vo AN SSSR, Moscow-Leningrad (1962).
4. P. L. Kapitsa, "Wave flow of thin layers of a viscous liquid. I. Free flow. II. Flow accompanied by a gas flow and heat flux," *Zh. Eksp. Teor. Fiz.*, 18, No. 1 (1948).
5. P. L. Kapitsa and S. P. Kapitsa, *Zh. Eksp. Teor. Fiz.*, 19, No. 2 (1949).
6. M. D. Millionshchikov, Turbulent Flow in the Boundary Layer and in Tubes [in Russian], Nauka, Moscow (1969).
7. M. D. Millionshchikov, *Atomnaya Énergiya*, 28, 206 (1970).
8. M. D. Millionshchikov, *Atomnaya Énergiya*, 28, 317 (1970).
9. M. D. Millionshchikov, *Atomnaya Énergiya*, 29, 16 (1970).
10. B. Pinkel, *Trans. ASME*, 76, No. 2 (1954).
11. R. Deissler, *Trans. ASME*, 76, No. 1 (1954).

SPECIAL ASPECTS OF THE DEFORMATION OF URANIUM  
SUBJECTED TO TENSILE STRAIN AT A CONSTANT VELOCITY

A. I. Voloshchuk, V. F. Zelenskii,  
Yu. F. Konotop, and Yu. T. Miroshnichenko

UDC 621.039.543.4:621.039.544.57

The accelerated swelling of uranium under the influence of irradiation at 400 to 500°C is associated with the effects of stresses arising from radiation growth. Independently of the actual mechanism responsible for the formation of large pores [1, 2], the swelling is ultimately determined by the manner in which the stresses relax under specific irradiation conditions. The mechanism underlying the deformation of uranium is of particular interest [3-6].

In this paper we shall consider the results of a study of the deformation (strain) characteristics and the structure of deformed uranium samples of reactor purity (~0.3 wt.% of impurities) and also a uranium-base alloy containing an additional 0.5 wt.% of beryllium oxide.

RESULTS

Properties of Samples under Tensile Strain. We studied cylindrical rupture-test samples with a working part 15 mm long and a diameter of 3 mm. The samples were prepared from bars quenched from the  $\beta$ -phase after technological processing.

Judging from the strain curves (Fig. 1) the rate of strain hardening of the uranium alloy was the same as that of the uranium at 360°C, indicating that the conditions governing the blocking of sliding dislocations by tangled dislocations and well-dispersed particles were the same in the two cases. Deformation takes place mainly by way of the transverse slipping of screw dislocations. As the temperature increases, individual dislocations are thermally activated and are able to move by way of diffusion creeping. As a result of this, the system of intersecting dislocations enters into an unstable state, and softening of the material

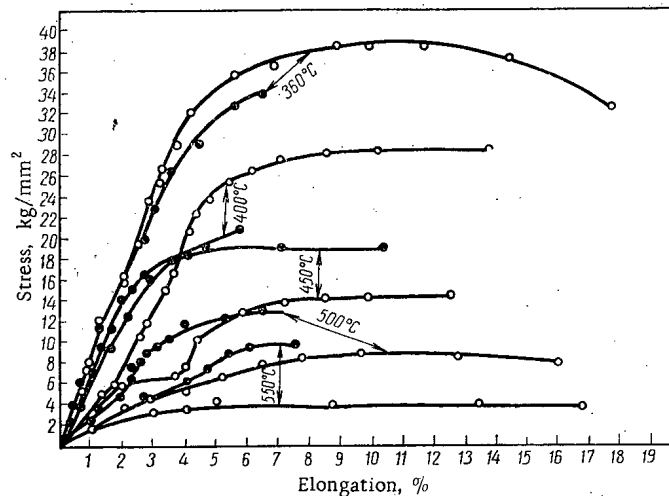


Fig. 1. Strain curves of uranium (O) and the alloy (●). Deformation at various temperatures at a rate of  $6 \cdot 10^{-3} \text{ h}^{-1}$ .

Translated from *Atomnaya Energiya*, Vol. 29, No. 6, pp. 416-422, December, 1970. Original article submitted December 19, 1969; revision submitted May 4, 1970.

© 1971 Consultants Bureau, a division of Plenum Publishing Corporation, 227 West 17th Street, New York, N. Y. 10011. All rights reserved. This article cannot be reproduced for any purpose whatsoever without permission of the publisher. A copy of this article is available from the publisher for \$15.00.

takes place. When the dislocations are blocked by dispersed particles, the creeping of individual dislocations has little effect on the deformation mechanism as a whole, and the softening of the dispersion-hardened materials occurs at higher temperatures. It follows from the strain curves that a considerable reduction in the rate of strain hardening of uranium sets in at temperatures of over 360°C. For the alloy containing

beryllium oxide, raising the temperature from 360 to 450°C has little effect on the rate of strain hardening, the strain mechanism presumably remaining the same. Softening of the alloy occurs at temperatures of over 450°C; the rate of hardening of the alloy at 500 to 550°C is very similar to that of uranium at 450 to 500°C, suggesting that the mechanisms underlying the deformation of uranium and its alloy at the corresponding temperatures are analogous.

These results are in good agreement with earlier conclusions based on a study of the temperature dependence of the activation energy of creep [6], and are also supported by metallographic analysis.

Figure 2 illustrates the temperature dependence of the parameters characterizing some of the mechanical properties of uranium and the uranium alloy containing 0.5% beryllium oxide.

At temperatures of under 400°C, the alloy has lower strength characteristics than the unalloyed uranium. The relative elongation of the uranium has a minimum close to 400°C, coinciding with a region of softening associated with a change in the deformation mechanism. In the case of the alloy, the rise in ductility with temperature becomes less rapid in the neighborhood of these temperatures.

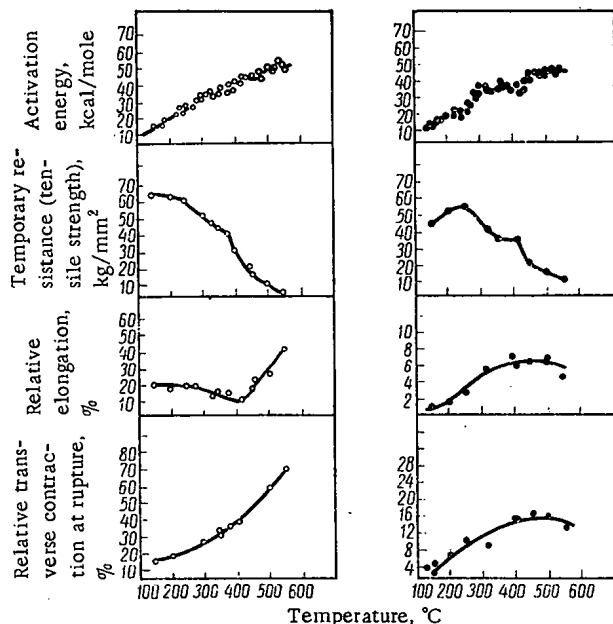


Fig. 2. Temperature dependence of the creep activation energy and the stress/strain characteristics of uranium and the U-BeO alloy (○ and ● respectively).

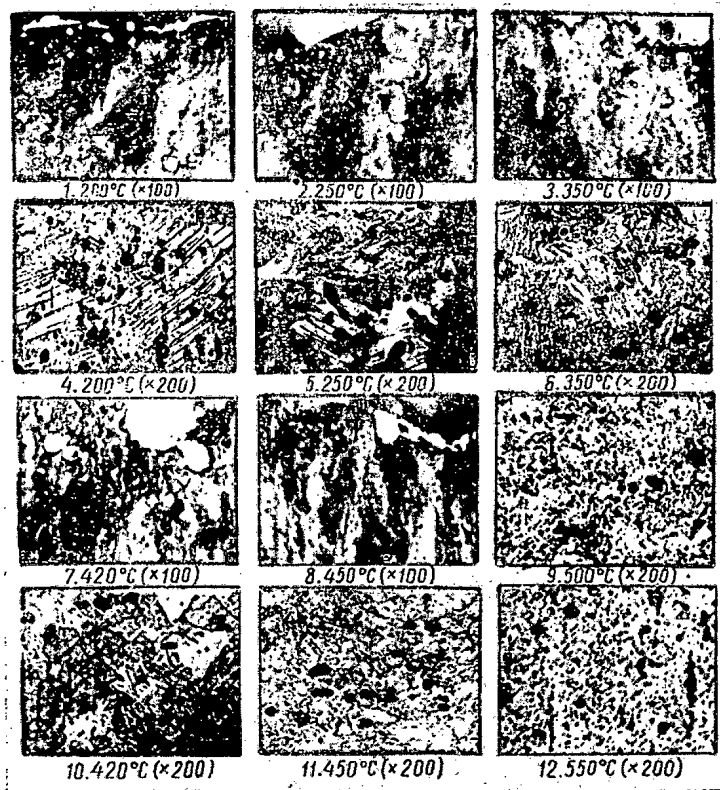


Fig. 3. Structure of ruptured uranium samples in the zone of maximum deformation.

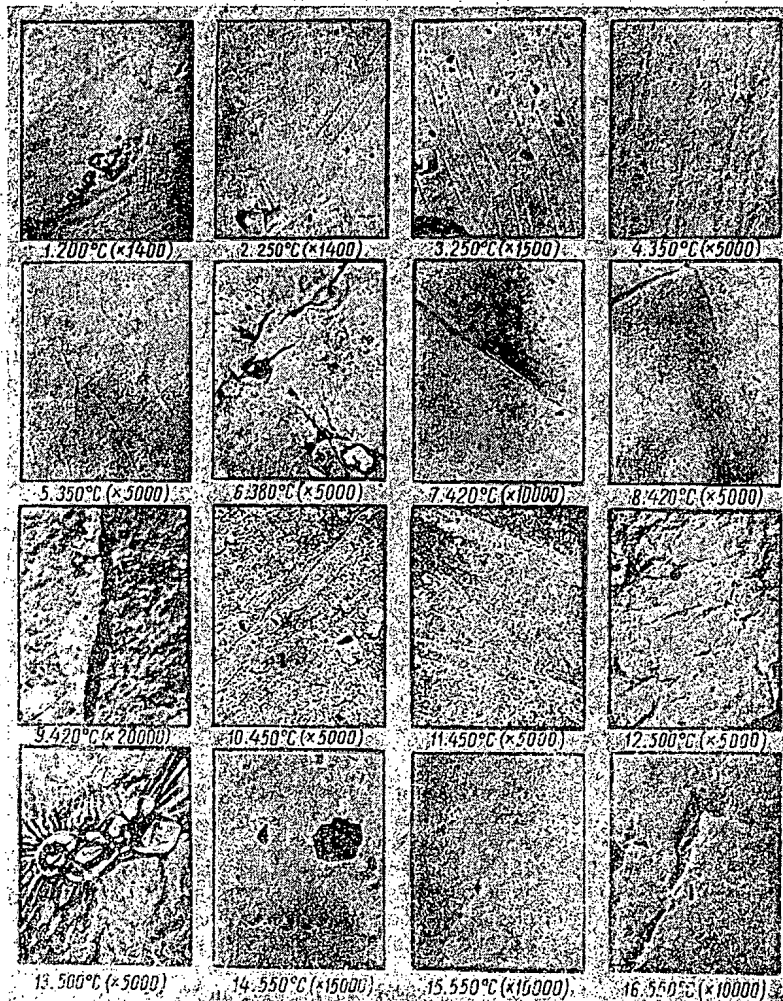


Fig. 4. Development of deformation processes in uranium.

Structure of Deformed Samples. The structure of the materials in question was studied in the zone of maximum deformation of samples ruptured at various temperatures by subjecting to a constant strain rate of  $6 \cdot 10^{-3} \text{ h}^{-1}$ . The plane of the microsection was parallel to the elongation axis.

As the temperature rises, so does the degree of deformation of the grain, this being particularly noticeable at 450°C (Fig. 3, 8). A study of the development of slip lines, the behavior of the grain boundaries, and other structural characteristics yields the following conclusions. Up to temperatures of 400 to 420°C, deformation in the grains is effected by twinning or slipping. Starting from 420°C, in some regions intersecting slip systems appear; these indicate the activation of earlier-blocked slip directions. At 450°C there is a considerable refinement of the structure, and etch pits develop, these constituting the result of polygonization processes. A particularly high etch-pit density occurs in samples deformed at 500°C. At 550°C it would appear that a thermally-activated coarsening of the polygonized structure occurs, and the etch-pit density falls.

Electron-microscope analysis gives a more detailed picture of the mechanism underlying the deformation of the samples.

Deformation by twinning or simple slip takes place mainly between 200 and 250°C (Fig. 4, 1-3). On subjecting to deformation between 320 and 350°C, the samples develop characteristic transverse slip lines (Fig. 4, 4 and 5). At 380 to 420°C (region of minimum elongation) cracks are formed around particles and cavities along the grain boundaries (Fig. 4, 6 to 9). In the temperature range in which the creep activation energy is close to the activation energy of self-diffusion, migration of the grain boundaries and slip lines occurs, confirming the diffusion character of the deformation (see Fig. 4, 10 and 11). Samples ruptured at 500°C have a well-expressed polygonization structure. Considerable stress concentrations occur near the particles during the deformation process, leading, in individual cases, to the formation of cavities (Fig. 4,

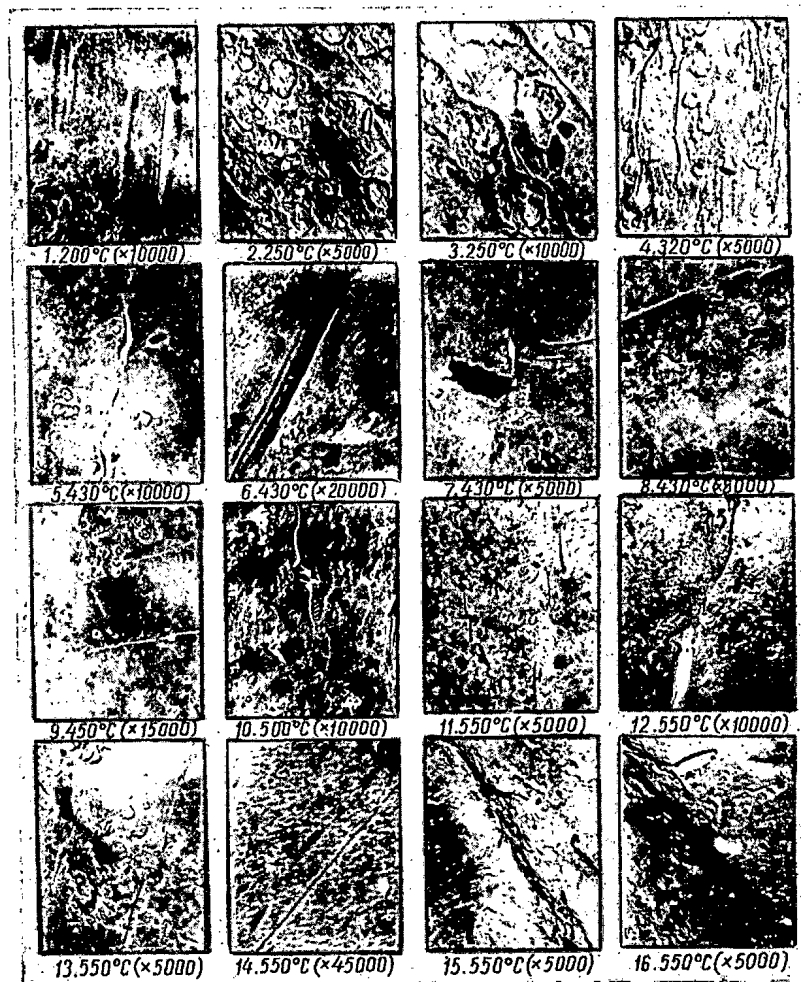


Fig. 5. Development of deformation processes in a U-0.5% BeO alloy.

13). It is interesting to note that the cavities are formed, not exactly on the particle/matrix interface, but at some distance from the particles. In the samples deformed at 550°C, pores of diffusion origin develop (see Fig. 4, 14 and 15). In view of the high mobility of the subsidiary boundaries, the latter may sweep the dislocation tangles along during their motion and carry them toward obstacles of a more stable nature (particles or grain boundaries). As a result of this, pores of diffusion origin are formed at these obstacles; these may later grow as a result of the inflow of vacancies, accelerated by the applied stresses.

Together with the pores of a diffusion character, cavities of a mechanical origin are also found at this temperature (Fig. 4, 16).

In view of the high density of the second-phase particles, a metallographic analysis of the structural details of uranium-beryllium alloys is practically impossible. Structural analysis of deformed samples of the uranium-beryllium oxide alloy was therefore confined to electron-microscope observations (Fig. 5). Twins only appear in the samples ruptured at 200°C. Twinning is retarded by the beryllium oxide particles, and the individual twins are of small dimensions (Fig. 5, 1). Simple slip is retarded close to the particles in the early stages of loading, and the deformation develops principally by way of the "squeezing" of the dislocations between the particles in accordance with the Orowan mechanism (Fig. 5, 2 and 3). Transverse slip is to be seen between 320 and 550°C (see Fig. 5, 4, 8 to 11). Only at 550°C do we find slipping along grain boundaries, and a fan-like propagation of dislocations, constituting a result of creep processes (Fig. 5, 11 and 12). Cracks and cavities of mechanical origin appear at 430°C (Fig. 5, 7); these are usually associated with the grain boundaries and not the particles of beryllium oxide, even in the zones with high stress concentrations (Fig. 5, 15 and 16). Small cavities of mechanical (but not diffusion) origin were observed in the slip lines at 550°C (Fig. 5, 11, 13, and 14).

## DISCUSSION OF RESULTS

The conditions governing the rupture of materials subjected to tensile tests differ considerably from those encountered as a result of the stresses arising from irradiation. In the first case, the deformation takes place as a result of the action of a concentrated load applied to the sample as a whole; in the second case, sources of stress are distributed uniformly throughout the whole sample. In tensile tests, the stress in the sample increases until the yield stress in the weakest section is exceeded. Subsequently the principal deformation (strain) occurs solely in the zone associated with this section, and in a low-ductility material rupture follows rapidly. In materials of high ductility, having the capacity to heal the defects arising under the influence of the load, higher strength characteristics may be achieved under these conditions.

In the case of a uniform distribution of stress sources, local cracks have a less severe effect on the deformation of the sample as a whole, and the character of sample rupture differs considerably from that associated with tensile tests. It is thus essential to be very cautious in drawing analogies between the results of strength and radiation tests. In interpreting the results of strength (tensile) tests, the main factor to be considered is not that of comparing the absolute values of the temporary resistance or time to rupture (failure), but that of considering the mechanisms of deformation under various conditions more deeply.

The results here obtained confirm the existence of at least three mechanisms of uranium deformation at high temperatures: transverse slip, creeping, and the migration of polygonal boundaries. This agrees with Holmes investigation [5] based on the analysis of published uranium creep data. It is also interesting to note that the observed temperature ranges, corresponding to the various mechanisms of uranium deformation, coincide with the stages of the temperature dependence of radiation growth established by Buckley [7]. This may be regarded as a confirmation of the generality of the mechanisms underlying the phenomena of radiation growth and the conditions of stress relaxation in uranium.

The activation of the diffusion processes in uranium (starting from temperatures of 380 to 400°C) leads to a change in the deformation mechanism, a certain reduction in the relative elongation, and a considerable softening of the samples on subjecting to tensile strain at low deformation rates. The latter fact is associated with the formation of a considerable number of cracks along the grain boundaries and around included particles. Although the mechanism of deformation by transverse slip remains operative to higher temperatures in the alloy containing beryllium oxide (440°C, see Fig. 1), the cavities at the grain boundaries, the reduction in the rate of increase of ductility with temperature, and the reduction in the temporary resistance (tensile strength) occur at practically the same temperatures, 420 to 430°C. Evidently the main reason for the formation of cavities in this temperature range is associated with special aspects of the development of the diffusion processes.

It is well known that diffusion occurs more intensively along grain boundaries, dislocations, and other structural disruptions. It may reasonably be considered that the cavities are formed at a stage of thermal activation at which a considerable softening takes place close to the grain boundaries or other surfaces of phase separation, as a result of a substantial acceleration of the diffusion processes. The supply of material through the grain to heal the damaged regions, however, is insufficiently rapid. At higher temperatures the diffusion contribution increases, and no cavities appear at the grain boundaries, or else they only appear rarely at points of maximum stress concentration. The hardening of the grain boundaries by well-dispersed particles slightly retards the onset of cavity formation; however, since the diffusion parameters remain practically unaltered, the effect of the hardening phase is comparatively slight.

At 550°C a new form of porosity appears, due to the intensive activation of three-dimensional diffusion. Whereas the dispersed particles have only a slight effect on the temperature of formation of mechanical cavities, they greatly retard the onset of the development of diffusion-type porosity. All the particles, and not simply those lying along the grain boundaries, have an effect on the pore growth. The mechanism of this effect may be twofold: the blocking of moving dislocations and subsidiary boundaries, and a redistribution in the flow of individual vacancies. In the latter case the vacancies may condense in a large number of dispersed particles, without the creation of appreciable porosity.

One further interesting fact should be emphasized. Cracks appear around included particles in uranium samples containing only a small number of inclusions. Yet in an alloy with a very high density of beryllium oxide particles no such cracks are to be found, even in places with considerable stress concentrations. For a low density of comparatively large particles, each such particle constitutes a barrier against a large number of moving dislocations. Since the stresses arising at the surface of a particle are proportional to



the number of dislocations present, their magnitude may prove sufficient for the formation of considerable cracks. In the case of a high density of particles and comparable degrees of deformation, the latter may become distributed among the particles in such a manner that individual disruptions in each particle will not necessarily lead to crack formation.

We may thus express the following views as to the possible mechanism underlying the swelling of uranium. The rupture of uranium as a result of the formation of cracks of mechanical origin under irradiation may occur in a narrow temperature range around 400°C. By hardening the grain boundaries, this range may be shifted in the high-temperature direction. In view of the activation of diffusion mobility within the grain, the conditions for the formation of cracks will then be less favorable, and the accelerated swelling associated with crack formation may cease. For high rates of irradiation, when the radiation-growth stresses remain operative up to temperatures of 450 to 550°C, another form of accelerated uranium swelling should appear; this is the formation of spherical pores of diffusion origin at the grain boundaries and other surfaces of phase separation at temperatures above 500°C. It follows from the foregoing analysis that dispersed particles may substantially reduce the rate of formation of such pores.

#### LITERATURE CITED

1. M. Speight and G. Greenwood, *J. Nucl. Materials*, 16, 327 (1965).
2. J. Harrison, *J. Nucl. Materials*, 23, 139-153 (1967).
3. D. Taplin, *J. Austral. Inst. Metals*, 12, 32-44 (1967).
4. P. Grenier and P. Lacombe, *J. Nucl. Materials*, 22, No. 3, 241-256 (1967).
5. J. Holmes, *Trans. Amer. Soc. Metals*, 59, No. T-1 (1966).
6. V. E. Ivanov, *Atomnaya Énergiya*, 29, 178 (1970).
7. S. Buckley, *AERE-R*, 5262 (1966).

SUBBARRIER NEUTRON FISSION OF  $\text{Pu}^{238}$  (E/T)

S. B. Ermagambetov and G. N. Smirenkin

UDC 539.173.4

As with most even-even nuclei, the cross section  $\sigma_f$  for fast-neutron fission of  $\text{Pu}^{238}$  has a "threshold" nature, and, as shown in [1], it is in rather good agreement with the monotonic exponential dependence of the fission width at a few hundred kiloelectron volts:

$$\Gamma_f(E_n) \sim P(E_n) = \left[ 1 + \exp\left(2\pi \frac{E_f - B_n - E_n}{\hbar\omega}\right) \right]^{-1},$$

where  $P$ ,  $E_f$ , and  $\hbar\omega$  are the penetrability, height, and buckling parameter of the fission barrier. However, the magnitude of  $\Gamma_f(0) \approx 30\text{--}50$  MeV, obtained in that study by extrapolating the fission width to  $E_n = 0$ , is somewhat larger than the thermal value  $\Gamma_f^T$ , which is about 1 MeV, which is easily estimated from the radiation width  $\Gamma_\gamma \approx 30$  MeV and the fission and absorption cross sections (which are 18 and 615 barns respectively [2]). In 1965 data was published [3] for the experimental upper estimates of the fission widths  $\Gamma_{fr}$  for the first three resonances of the reaction  $\text{Pu}^{238} + n$ ; these are shown in Table 1. They indicated a further strong difference between  $\Gamma_{fr}$  and  $\Gamma_f(0)$ . Some more recent measurements [4], also shown in Table 1, indicate a rather large fissility of  $\text{Pu}^{238}$  by  $s$ -neutrons. The average fission width  $\bar{\Gamma}_{fr}$  determined from the first ten resonances was about 5 MeV, which is much larger than the value obtained by James [3], but as usual, much smaller than the value of  $\Gamma_f(0)$  found in [1].

The ratio  $\Gamma_{fr}/\Gamma_f(0) \ll 1$  is realized in many nuclei and has been interpreted in terms of the two-humped fission barrier picture [5] as a consequence of the intermediate structure in the cross sections in the resonance region of the neutron energies [6]. The origin of this structure lies in the presence of quasistationary levels in the second well (between the humps). This interpretation permits significant deviations of  $\Gamma_{fr}$  from the average value in the interval between the levels, without the total suppression of the  $s$ -waves as is often assumed when discussing the large difference between  $\Gamma_{fr}$  and  $\Gamma_f(0)$ . These consequences of the two-humped barrier model are underscored by the results for the distribution of the fission widths in  $(n, f)$  reactions in  $\text{Pu}^{240}$  and  $\text{Np}^{237}$  [6], for which the ratio  $\Gamma_{fr}/\bar{\Gamma}_{fr}$  varies over a rather large range.

The available information concerning resonance neutron fission of  $\text{Pu}^{238}$  is insufficient and, as the above shows, very contradictory. However, the question of the role of  $s$ -waves in the fission of  $\text{Pu}^{238}$  can be solved in another way: one can study  $\sigma_f$  in the high energy region where the individual resonances are not resolved, but where the  $s$ -wave makes the dominant contribution to the cross section for forming a compound nucleus. We have made such measurements on an electrostatic generator using  $\text{Pu}^{238}$  as a target. The preliminary results of that study have been published elsewhere [7]. This paper will present some more accurate data and the results of a more detailed analysis.

TABLE 1. Fission Widths (MeV) for  $\text{Pu}^{238}$  in the Epithermal Energy Range of the Neutrons

Neutron resonance energy, eV	Data and reference	
	[3]	[4]
2,9	0,083	1,2
10,1	0,196	6,8
18,7	0,202	1,6

The measurements were performed using the comparative method.  $\text{U}^{235}$  was used as a standard. Glass detectors were used to record the fission fragments. The neutron source was the reaction  $\text{T}(p, n)$ . As a rule, a number of pairs of fissionable layers and detectors were irradiated at once. The detectors were situated at various angles ranging from 0 to 150° with respect to the proton beam. The  $\text{Pu}^{238}$  used was practically isotopically pure (99.8%), so that the fission of impurities was not included. The relative behavior of  $\sigma_f$  for  $\text{Pu}^{238}$ , as corrected for the background of spontaneous fission and

Translated from *Atomnaya Énergiya*, Vol. 29, No. 6, pp. 422-424, December, 1970. Original article submitted May 11, 1970.

© 1971 Consultants Bureau, a division of Plenum Publishing Corporation, 227 West 17th Street, New York, N. Y. 10011. All rights reserved. This article cannot be reproduced for any purpose whatsoever without permission of the publisher. A copy of this article is available from the publisher for \$15.00.

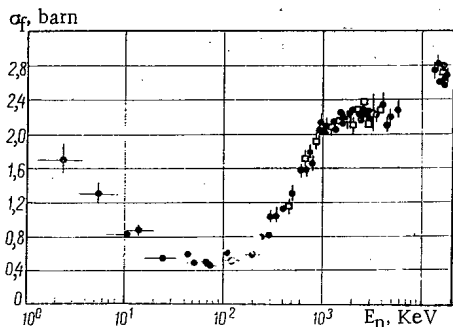


Fig. 1

Fig. 1.  $Pu^{238}$  fission cross section  $\sigma_f$  as a function of the neutron energy  $E_n$ :  $\square$  [9];  $\blacktriangle$  [10];  $\bullet$  present work and [8].

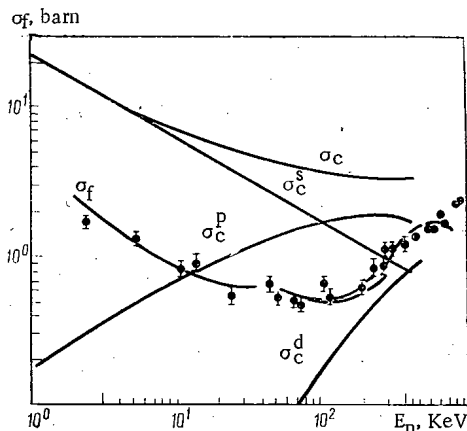


Fig. 2

Fig. 2. Comparison of the experimental and calculated results:  $\sigma_c$  and  $\sigma_c^{(l)}$  are respectively the cross sections for forming a compound nucleus and its partial components for s-, p-, and d-neutrons. The solid curve for  $\sigma_f$  is computed from Eqs. (1-3); the dotted line is calculated with all the allowed states  $K \leq 7/2$  included.

TABLE 2. Measured Cross Sections  $\sigma_f$  for Fission of  $Pu^{238}$

$E_n$ , KeV	$\sigma_f$ ( $Pu^{238}$ ), barn	$E_n$ , KeV	$\sigma_f$ ( $Pu^{238}$ ), barn
2.4±1.3	1.70±0.18	420±15	1.14±0.05
5.5±2.5	1.30±0.12	635±25	1.60±0.06
11.3±6.0	0.83±0.06	680±25	1.60±0.06
14.4±5.0	0.88±0.07	770±25	1.67±0.07
25.5±10	0.55±0.04	910±10	2.06±0.08
46.4±20	0.62±0.04	1080±20	2.11±0.08
53±6	0.52±0.03	1210±20	2.13±0.08
70±7	0.50±0.03	1330±20	2.08±0.08
78±10	0.47±0.02	1430±25	2.20±0.10
110±7	0.62±0.03	1500±20	2.15±0.07
120±10	0.53±0.03	1650±20	2.20±0.10
200±20	0.60±0.03	1800±20	2.18±0.10
250±5	0.80±0.04	2000±20	2.30±0.10
290±20	0.84±0.04	2260±20	2.25±0.09
305±10	1.05±0.05	2400±20	2.22±0.09
350±8	1.06±0.04		

the fission due to epithermal neutrons and the neutrons scattered in the target, was normalized to the values which we obtained earlier [8]. The measured values of  $\sigma_f$  for  $Pu^{238}$  are shown in Table 2 and the reference values of  $\sigma_f$  for  $U^{235}$  were taken from [9]. Figure 1 shows the good agreement between the data for  $\sigma_f$  for  $Pu^{238}$  from our work and the values in [8-10]. The data in the range  $0.1 \lesssim E_n \lesssim 1.5$  MeV from [1, 2] is 20-30% higher on the average, but the relative behavior of  $\sigma_f$  is very close to that shown in Fig. 1.

We have recently become aware of a work [11] which is an experimental study in the 1-10 keV energy range which used a nuclear explosion as a source of neutrons [12]. The results of these measurements revealed a resonant structure with resonance widths of about 0.1-0.2 keV and separations averaging about 1 keV. In [11] this structure was related to the quasistationary states in the second well of the

fissile nucleus  $Pu^{239}$ . The energy resolution of our measurements has nearly smoothed out this structure, but the data from both experiments agree quite satisfactorily (if the values in [12] are averaged over the interval  $2\Delta E_n$  shown in Table 1).

In addition to the experimental data for  $\sigma_f$  of  $Pu^{238}$ , Fig. 2 shows the cross section  $\sigma_c$  for forming a compound nucleus, together with its partial components  $\sigma_c^{(l)}$  for s-, p-, and d-neutrons. Even without a detailed analysis it can be seen by comparing the characteristics shown that the s-neutron fission of  $Pu^{238}$  plays an important role. The energy dependence of the fission cross section for  $Pu^{238}$  for neutron energies less than 50 keV does not differ qualitatively from the behavior of  $\sigma_f(E)$  for  $U^{233}$ ,  $U^{235}$ , and  $Pu^{239}$ , and other isotopes which are easily split by slow neutrons [2].

In order to obtain a qualitative comparison of the probability of splitting  $Pu^{238}$  by s- and p-neutrons, we have calculated the fission cross sections using the static theory of Hauser and Feshbach

$$\sigma_f = \frac{\pi k^2}{2} \sum_{J, K, \pi} (2J+1) T_l^J \frac{P_{K\pi}}{\sum_{K' \leq J} P_{K'\pi} + \sum_{l', j', \nu} T_{l'}^{j'}(E_n - E_\nu) + \frac{2\pi}{D_J} \Gamma_\nu} \quad (2)$$

under the assumption that the penetrability is the same for s- and p-neutrons; i.e.,

$$P_{JK\pi} = P_{K\pi} = P_{1/2^+} = P_{1/2^-} = P_{3/2^-}, \quad (3)$$

$K$  is the projection of the angular momentum  $J$  of the compound nucleus on the symmetry axis,  $\lambda$  is the neutron wavelength,  $T_l^J$  are the penetrability coefficients for neutrons with orbital momenta  $l$  [13],  $\pi = (-1)^l$ ,  $j' = l' \pm 1/2$ ,  $E_{\nu}$  are the levels of the target nucleus,  $D_J = (2D_{1/2})/2J + 1$  is the distance between levels of the compound nucleus with spin  $J$  ( $D_{1/2} = 10$  eV),  $\Gamma_{\gamma} = 30$  MeV is the radiation width. The solid line for  $\sigma_f(E_n)$  in Fig. 2 was computed using Eqs. (1-3) and these parameters:  $E_f = 0.5$  MeV,  $h\omega/2\pi = 0.115$  MeV,  $P(0) = 10^{-2}$ ,  $\Gamma_f(0) = 15$  MeV. This last quantity is only three times greater than the estimate of  $\bar{\Gamma}_{fr}$  in [13]. The dotted line shows the results of a calculation in which the assumption of Eq. (3) is extended to the allowable angular momentum state  $K \leq 7/2$  of both parities.

Keeping in mind the narrow interval over which the widths of the separate resonances  $\Gamma_{fr}$  were averaged in [4], the complicated structure in  $\sigma_f(E_n)$  due to the quasistationary states in the second well, and the approximate nature of our original premises in this analysis, one cannot take the difference between  $\bar{\Gamma}_{fr}$  and  $\Gamma_f(0)$  too seriously. The results of this experiment do not indicate any kind of prohibition on the  $s$ -neutron fission of  $\text{Pu}^{238}$ . This conclusion is also confirmed by an analysis of the cross sections and angular anisotropies in the reactions  $\text{Pu}^{238}(\gamma, f)$  and  $\text{Pu}^{238}(n, f)$  in [14].

We wish to thank M. K. Golubeva for scanning the glass detectors.

#### LITERATURE CITED

1. P. E. Vorotnikov et al., *Yadernaya Fizika*, **3**, 479 (1966).
2. Neutron Cross Sections. BNL-325, 2nd Ed. Suppl. No. 2, Vol. III (1965).
3. G. James, Proc. Symp. on Phys. and Chem. of Fission (Salzburg, 1965), Vol. 1, Vienna, IAEA (1965), p. 235.
4. C. Bowman et al., *Phys. Rev. Letters*, **18**, 15 (1967).
5. E. V. Gaii et al., *Yadernaya Fizika*, **10**, 542 (1969).
6. E. Migneco and G. Theobald, *Nucl. Phys.*, **A112**, 603 (1968); A. Fubini et al., *Phys. Rev. Letters*, **20**, 1373 (1968).
7. S. B. Ermagambetov and G. N. Smirenkin, *Pis'ma Zh. Éksp. Teor. Fiz.*, **9**, 510 (1969).
8. S. B. Ermagambetov and G. N. Smirenkin, *Atomnaya Énergiya*, **25**, 527 (1968).
9. Neutron Cross Section, BNL-325, Suppl. No. 2, Vol. III (1965); W. Davey, *Nucl. Sci. Engng.*, **26**, 149 (1966).
10. D. Barton and P. Koontz, *Phys. Rev.*, **162**, 1070 (1967).
11. J. Lynn, Proc. Symp. on Phys. and Chem. of Fission, Vienna, IAEA (1969), p. 249.
12. M. Silbert, Report LA-4108-MS (1969).
13. S. B. Ermagambetov et al., *Yadernaya Fizika*, **8**, 704 (1968).
14. A. S. Soldatov, Yu. M. Tsipenoyuk, and G. N. Smirenkin, *Yadernaya Fizika*, **11**, 992 (1970).

## DESIGN OF CASCADES FOR SEPARATING ISOTOPE MIXTURES

N. A. Kolokol'tsov, V. P. Minenko,  
B. I. Nikolaev, G. A. Sulaberidze,  
and S. A. Tret'yak

UDC 621.039.3

Interest is growing in the separation of isotope mixtures, and thus in the theory of the design of separation cascades, primarily because of the requirements of nuclear power. Not only the isotopes at the extreme ends of the mass scale must be separated, but also the intermediate isotopes or groups of intermediate isotopes. One problem in the design of such cascades is that the concentration of the intermediate-mass isotopes tends toward a maximum within the cascade [1, 2].

In this paper, we discuss continuous-profile cascades for separating intermediate isotopes and a method for modeling these cascades by real ones consisting of sections with constant fluxes. We will call these cascades "rectangular-stepped" cascades. To simplify the calculations, we will consider only symmetrical cascades, in which the fluxes having been separated in a step are sent to the following and preceding steps.

The system of transport equations for an  $m$ -component isotope mixture, for sampling part of the cascade with an arbitrary distribution of interstep fluxes  $L$ , can be written

$$\left. \begin{aligned} \frac{dN_i}{ds} &= N_i \sum_{j=1}^m \varepsilon_{ij} N_j - \frac{P}{L(s)} (N_i^P - N_i), \\ i &= 1, 2, \dots, m-1; \\ \sum_{j=1}^m N_j &= 1, \end{aligned} \right\} \quad (1)$$

where  $N_i$  is the molar concentration of the  $i$ -th component in the  $s$ -th step;  $P$  is the flux in the cascade sample;  $N_i^P$  is the concentration in this sample; and  $\varepsilon_{ij}$  are the enrichment factors for the isotope pair  $i, j$ ; these factors are additive,

$$\varepsilon_{ij} = \varepsilon_{ir} + \varepsilon_{rj}$$

and antisymmetric,

$$\varepsilon_{ij} = -\varepsilon_{ji}.$$

Below we assume that the isotopes are numbered in order of increasing mass.

Kucherov and Minenko [3] replaced the concentrations  $N_i(s)$  by the functions  $\varphi_i(s)$ , and reduced system (1) with a continuous function  $L(s)$  to a single Volterra equation for one of these functions:

$$\varphi_i(s) + \sum_{j=1}^m \frac{PN_j^P}{L(s)} \int_0^s \varphi_j(t) e^{\varepsilon_{ji}(s-t)} dt = \sum_{j=1}^m \frac{N_i^P L^j}{L(s)} e^{\varepsilon_{ji}s} \quad (2)$$

and to the  $(m-1)$ -th relation of the form

$$\varphi_j(s) = \varphi_i(s) e^{\varepsilon_{ij}s}, \quad (3)$$

Translated from *Atomnaya Énergiya*, Vol. 29, No. 6, pp. 425-429, December, 1970. Original article submitted July 6, 1970.

© 1971 Consultants Bureau, a division of Plenum Publishing Corporation, 227 West 17th Street, New York, N. Y. 10011. All rights reserved. This article cannot be reproduced for any purpose whatsoever without permission of the publisher. A copy of this article is available from the publisher for \$15.00.

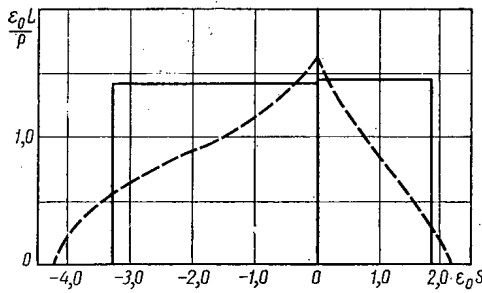


Fig. 1

Fig. 1. Two-section rectangular-stepped cascade with  $\eta = 78.5\%$  for separating tungsten isotopes.

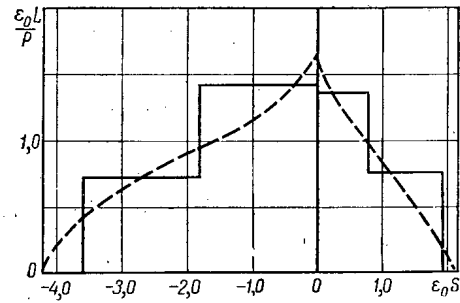


Fig. 2

Fig. 2. Four-section rectangular-stepped cascade with  $\eta = 91\%$  for separating tungsten isotopes.

where  $L^f$  and  $N_j^f$  are the flux and concentration at the supply point with  $s = 1$ ; it is convenient to use the substitution  $s = s^P - l$ , where  $s^P$  is the number of steps in the sampling part. Then Eqs. (2) and (3) are rewritten

$$\varphi_i(l) = \sum_{j=1}^m \frac{PN_j^P}{L(l)} \int_0^l \varphi_i(t) e^{\varepsilon_{ji}(t-l)} dt = \sum_{j=1}^m \frac{N_j^P L(0)}{L(l)} e^{-\varepsilon_{ji}l}; \quad (4)$$

$$\varphi_j(l) = \varphi_i(l) e^{\varepsilon_{ji}l}, \quad (5)$$

where  $L(0)$  is the flux at  $l = 0$ , i.e., at the end of the sampling.

The functions  $\varphi_i(l)$  are related to the concentrations and flux in the cascade by

$$N_i(l) L(l) = \frac{N_i^P L(0) + N_i^P P \int_0^l \varphi_i(t) dt}{\varphi_i(l)}. \quad (6)$$

Introducing the notation  $N_i L = \chi_i$ , we find

$$\sum_{j=1}^m \chi_j(l) = L(l) \quad (7)$$

and thus

$$N_i(l) = \frac{\chi_i(l)}{\sum_{j=1}^m \chi_j(l)}. \quad (8)$$

For each given flux distribution  $L(l)$  in the cascade, the functions  $\varphi_i(l)$  and thus  $N_i(l)$  are determined unambiguously.

We consider continuous-profile cascades which satisfy the condition

$$\varphi_i(l) = e^{Q_i l}, \quad (9)$$

where  $Q_i$  are some constants which, according to (5), should be related by

$$Q_i - Q_j = \varepsilon_{ij}. \quad (10)$$

Thus only one of the quantities  $Q_i$  can be chosen arbitrarily. For brevity, we will call those continuous-profile cascades which satisfy (9) "Q-cascades."

In minimizing the total flux of the cascade, it is natural to assume that the flux at the end is zero:

$$L(0) = 0. \quad (11)$$

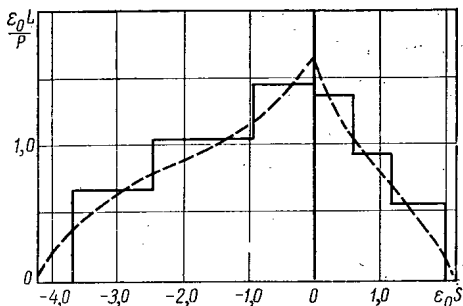


Fig. 3. Six-section rectangular-stepped cascade with  $\eta = 94.6\%$  for separating tungsten isotopes.

TABLE 1. External Parameters of a Continuous-Profile Cascade for Separating Tungsten Isotopes [4]

$i$	$M_i$	$N_i^F$	$N_i^P$	$N_i^W$
1	180	0,0014	$10^{-9}$	0,0028
2	182	0,2646	0,0009	0,5363
3	183	0,1440	0,0238	0,2678
4	184	0,3060	0,4180	0,1906
5	186	0,2840	0,5573	0,0025

Substituting (9) into (6) and (7), and taking (11) into account, we find

$$\chi_i(l) = \frac{PN_i^P}{Q_i} (1 - e^{-Q_i l}); \tag{12}$$

$$L(l) = P \sum_{j=1}^m \frac{N_j^P}{Q_j} (1 - e^{-Q_j l}). \tag{13}$$

Equations (12) and (13) give the distribution of concentrations and flux in the sampling part of the Q-cascade.

Analogous equations can be written down for the dumping part:

$$\chi_i(l) = \frac{WN_i^W}{Q_i} (e^{Q_i l} - 1); \tag{14}$$

$$L(l) = W \sum_{j=1}^m \frac{N_j^W}{Q_j} (e^{Q_j l} - 1), \tag{15}$$

where W is the flux at the dumping part;  $N_i^W$  is the concentration of the i-th isotope there, and  $l = s^W - s$ .

We can use Eqs. (12)-(15) and (8) to express the concentrations  $N_i^P$  and  $N_i^W$  at the sampling and dumping points, respectively, in terms of the concentration  $N_i^f$  at the supply point:

$$N_i^P = \frac{Q_i N_i^f}{1 - e^{-Q_i s^P}} \left/ \sum_{j=1}^m \frac{Q_j N_j^f}{1 - e^{-Q_j s^P}} \right.; \tag{16}$$

$$N_i^W = \frac{Q_i N_i^f}{e^{Q_i s^W} - 1} \left/ \sum_{j=1}^m \frac{Q_j N_j^f}{e^{Q_j s^W} - 1} \right. \tag{17}$$

It should be emphasized that the concentrations  $N_i^f$  at the supply point are in general not equal to the concentrations  $N_i^F$  in the supply flux. This equality can hold only if there is no mixing of concentrations in the supply.

Using the mass-balance equations

$$\left. \begin{aligned} PN_i^P + WN_i^W &= FN_i^F; \\ P + W &= F, \end{aligned} \right\} \tag{18}$$

we can eliminate  $N_i^f$  from Eqs. (16) and (17) and express  $N_i^P$  and  $N_i^W$  in terms of the concentrations  $N_i^F$  in the supply flux:

$$N_i^P = \frac{1 - e^{-Q_i s^W}}{e^{-Q_i s^P} - e^{-Q_i s^W}} N_i^F \left/ \sum_{j=1}^m \frac{1 - e^{-Q_j s^W}}{e^{-Q_j s^P} - e^{-Q_j s^W}} N_j^F \right.; \tag{19}$$

$$N_i^W = \frac{e^{-Q_i s^P} - 1}{e^{-Q_i s^P} - e^{-Q_i s^W}} N_i^F \left/ \sum_{j=1}^m \frac{e^{-Q_j s^P} - 1}{e^{-Q_j s^P} - e^{-Q_j s^W}} N_j^F \right. \tag{20}$$

Equations (19) and (20) show that Q-cascades can concentrate isotopes of a certain part of the isotope spectrum with suitable choice of  $Q_i$ . This follows from the following arguments. We assume for definiteness that  $Q_i > 0$  for the i-th isotope. In addition, it is natural to assume that we are dealing with long cascades,

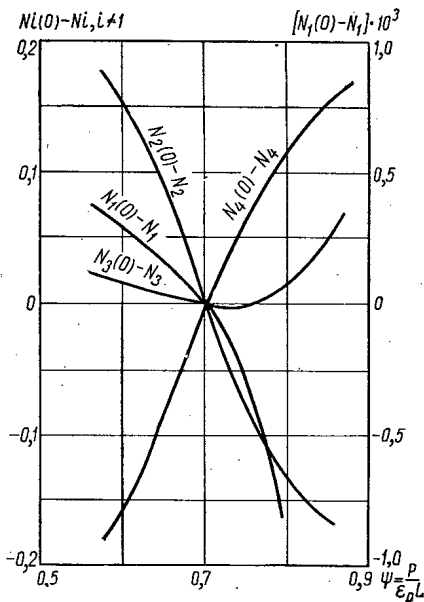


Fig. 4. Dependence of the boundary concentration  $N_i$  in the section of a rectangular-stepped cascade as a function of  $P/\varepsilon_0 L$  [ $N_i(0)$  is the concentration of the  $i$ -th component at a suitable point in the continuous-profile cascade].

increase during the separation in the same ratio as the concentration of the  $i$ -th isotope. The concentrations of all isotopes with  $j > i$  will decrease sharply.

It should be noted that the  $Q$ -cascades can separate all isotopes of a given element into two groups; in the first group the concentrations of all the isotopes increase simultaneously, while in the second group they all decrease sharply.

Design of cascades of this type has shown that  $k$  should be chosen equal to one-half for the least net flux  $\Sigma L$ .

It immediately follows that the concentration of an intermediate isotope at a sampling point cannot be increased without limit in a single  $Q$ -cascade, since the net concentration of the enriched isotopes must not exceed unity.

Two cascades can be used to solve the problem of producing an intermediate isotope of any practical purity. The first cascade would separate the group of isotopes in which the desired intermediate component is an extreme member, while the second cascade would eliminate the other members of this group.

It should be noted that the use of the so-called  $M^*$ -cascades, found on the basis of slightly different arguments but leading to analogous results, was proposed in [4] to separate the intermediate isotopes. It should again be emphasized that  $Q$ -cascades are not ideal cascades, since the concentrations are mixed in them at the input; therefore, their efficiency should be compared with a certain "standard" cascade without such mixing. The introduction of a standard cascade was discussed in [5].

In this paper we consider another problem of practical importance: is it possible, having a continuous-profile cascade, in particular a  $Q$ -cascade, designed for given parameters, to replace it by a cascade consisting of rectangular sections, i.e., a rectangular-stepped cascade in such a manner that the output concentrations are the same? The possibility of this replacement is not obvious, since the effect of a disruption of the theoretical profile on the various components of the mixture is generally not the same. System (1) was solved analytically for the sections of a rectangular-stepped cascade with  $L = \text{const}$  in [3, 6]. For the computer design of a real cascade, however, it would be better to carry out a direct numerical integration of system (1).

for which  $s^P$  and  $s^W$  are large. In evaluating the separation effect, we make a sharp distinction between the isotopes for which  $Q_j$  is greater and less than zero.

For  $Q_j > 0$ , and assuming that the denominators in these equations are the same, we find from (19) without difficulty the following estimates:

$$\frac{N_i^P}{N_j^P} \approx \frac{N_i^F}{N_j^F}. \quad (21)$$

Analogously, if  $Q_i < 0$ , we find from (19) that

$$\frac{N_i^P}{N_j^P} \gg \frac{N_i^F}{N_j^F}. \quad (22)$$

For the depleted part of the cascade, analogous estimates are found for  $Q_i < 0$ .

If it is required that a certain intermediate isotope with a given number  $i$  is to be separated at the sampling point, we assume  $Q_i$  is given by

$$Q_i = k\varepsilon_{i, i+1} \approx k\varepsilon_0 (M_{i+1} - M_i), \quad (23)$$

where  $k$  is some quantity whose value is arbitrarily assumed, for the time being, to lie in the interval  $0 < k < 1$ ;  $\varepsilon_0$  is the enrichment factor for a pair of isotopes differing by unit mass; and  $M_i$  is the molecular weight of the  $i$ -th component. Then, according to (21) and (10), the concentrations of all isotopes for which  $j < i$  will in-



Let us formulate the problem of designing a rectangular-stepped cascade in the following manner: we are to find the parameters of the cascade corresponding to a Q-cascade in output concentrations and having a specified efficiency.\* The unknown parameters of the cascade are the number of sections, the flux L, and the number of steps in each section.

In contrast with the case of a two-component rectangular-stepped cascade, in which the specified concentration at the sampling point can always be arranged, when one changes the flux (i.e., one parameter) in a multicomponent cascade, one must find  $m - 1$  specified concentrations. However, analysis of the design of several rectangular-stepped cascades has shown that any part of a continuous-profile cascade can be replaced by a section of constant width with properly chosen flux, while all the component concentrations at the ends of the sections are held constant.

According to this result, the problem posed – the replacement of a continuous-profile cascade by a rectangular-stepped cascade with the same output parameters – can always be solved, and the specified efficiency can be achieved with a suitable choice of the number of sections.

The calculation is carried out in the following order.

1. A continuous-profile cascade is designed for the given parameters. This could be, in particular, a Q-cascade, but it could be any other type of continuous-profile cascade.

2. The number of sections is estimated on the basis of the required efficiency, and the continuous-profile cascade is broken up into parts. To fix the boundary of the section at this boundary, the concentration of one of the isotopes is set equal to the corresponding concentration in the continuous-profile cascade. That isotope whose concentration changes monotonically along the cascade is recommended for use to fix the boundary.

3. A certain initial flux is specified in each section in correspondence with the flux distribution in the continuous-profile cascade, and the concentrations of the other mixture components at the junctions are found. By varying the flux in each section, all the concentrations at the junction are made equal to the concentrations in the continuous-profile cascade, and the corresponding number of steps in each section is found.

4. Then the efficiency is determined:

$$\eta = \frac{\sum_{\text{RSC}} L}{\sum_{\text{CPC}} L}$$

5. If the efficiency is not equal to the specified efficiency, the calculation is repeated with a corrected number of sections.

The use of this design procedure has been checked for several isotope mixtures. The calculations were carried out on an M-20 computer by a standard program for solving a system of differential equations by the Runge-Kutta method with automatic choice of step.

As an example, we show here the results of the design of a rectangular-stepped cascade modeling a continuous-profile cascade for separating tungsten isotopes (in the form of the gaseous compound  $WF_6$ ); the external parameters of the continuous-profile cascade are shown in Table 1. The design of this cascade was described in [4]. Figures 1-3 show designs for modeling rectangular-stepped cascades with two, four, and six sections of constant width (the dashed lines in the figures show the flux distribution in the corresponding continuous-profile cascade). The output concentrations in all three cases are essentially equal to those at the output of the continuous-profile cascade.

Figure 4 illustrates the possibility of replacing a part of a continuous-profile cascade by sections of a rectangular-stepped cascade. The differences between the boundary concentrations of the isotopes in this part of the continuous-profile cascade are seen to simultaneously tend toward zero at the same L value (the quantity  $P/\epsilon_0 L$  is plotted in this figure).

It has thus been shown that by choosing the number sections properly, one can obtain practically any efficiency.

\*By "efficiency" here we mean the ratio of the total flux of the Q-cascade (continuous-profile cascade) to the total flux of the corresponding rectangular-stepped cascade.

LITERATURE CITED

1. E. Schumacher and L. Clusius, *Helv. Chim. Acta.*, 36, 949 (1953).
2. J. Meinrenken, *Z. Naturforsch.*, A, 23, No. 2 (1963).
3. R. Ya. Kucherov and V. P. Minenko, *Atomnaya Énergiya*, 19, 360 (1965).
4. S. Levin, *J. Chim. Phys. et Phys. Chim. Biol.*, 60, Nos. 1-2 (1963).
5. N. A. Kolokol'tsov et al., *Atomnaya Énergiya*, 29, 128 (1970).
6. A. Narten, *Z. Naturforsch. A.*, 20a, No. 5 (1965).

## STORAGE OF MULTIPLY-CHARGED IONS IN A RELATIVISTIC ELECTRON BUNCH

M. L. Iovnovich and M.M. Fiks

UDC 622.039.521:621.039.55

The method of collective ion acceleration proposed in [1] is being intensively developed at the present time. The possibility of obtaining stable electron-ion bunches is the basis for this method. Under certain conditions, the lifetime of the bunch is sufficient for effective acceleration of the bunch as a unit. During production of a bunch and during acceleration, the ions are confined within the bunch by the electron space charge. Since the translational velocity of the ions and electrons is identical, the ion energy is greater than the electron energy by a factor  $MA/m\gamma$ , where  $m$  and  $M$  are respectively the rest masses of the electron and nucleon;  $A$  is the ion mass number, and  $\gamma$  is the electron relativistic factor in the bunch at rest. The acceleration of ionized heavy atoms to high energies is therefore possible [2, 3].

The production of a two-component bunch takes place in the following manner. A thin ring of relativistic electrons is first formed in an external magnetic field. At this stage, there are practically no ions in the bunch; their storage occurs after the electron ring is essentially formed. Ion storage has been discussed previously [2, 3]. This paper considers the storage of multiply-charged ions of heavy atoms in a thin electron ring with major radius  $R$  and minor radius  $a$ .

### Storage of Ions of a Monatomic Gas in a Relativistic Electron Bunch

Let neutral atoms with sufficiently small kinetic energy enter a bunch of relativistic electrons; as a result of collisions with the latter, the atoms become ionized.

At the same time, a change takes place in the potential energy of an ion which is within the field of the electronic space charge. This change in potential energy, which arises from the increased charge of the heavy particle, is much larger on the average than the kinetic energy transferred to the particle by collision. Therefore the majority of ions formed will be captured in the potential well of the electron ring.

During subsequent collisions with electrons, the charge of ions confined within the ring will increase. The probability of multiple ionization, where the charge of particles is increased by more than unity in a single interaction, is considerably less than that for single ionization. We shall therefore consider ionization to be a stepwise process, namely: particles with charge  $Z$  are formed from ions with charge  $Z - 1$ . In addition, it is reasonable to neglect recombination between relativistic electrons and ions of all charge states.

The variation of the concentration  $n_0$  of neutral atoms averaged over the bunch per unit time is given by the expression [4]

$$\begin{aligned} \dot{n}_0 &= -\lambda_i n_0 + \lambda_a (n_a - n_0); \\ \lambda_i &= n_e c \sigma_0; \quad \lambda_a = \frac{S \bar{v}}{V}, \end{aligned} \quad (1)$$

where  $n_a$  is the neutral atom concentration in the neighborhood of the bunch;  $n_e$  and  $c$  are respectively the concentration and velocity of the electrons in the ring;  $\sigma_0$  is the cross section for ionization of a neutral atom by an electron;  $S$  is the area of the surface through which the atoms penetrate into the bunch;  $\bar{v}$  is the average value of the neutral atom velocity component normal to the bunch surface, and  $V$  is the bunch volume.

Translated from *Atomnaya Énergiya*, Vol. 29, No. 6, pp. 429-433, December, 1970. Original article submitted January 4, 1970.

© 1971 Consultants Bureau, a division of Plenum Publishing Corporation, 227 West 17th Street, New York, N. Y. 10011. All rights reserved. This article cannot be reproduced for any purpose whatsoever without permission of the publisher. A copy of this article is available from the publisher for \$15.00.

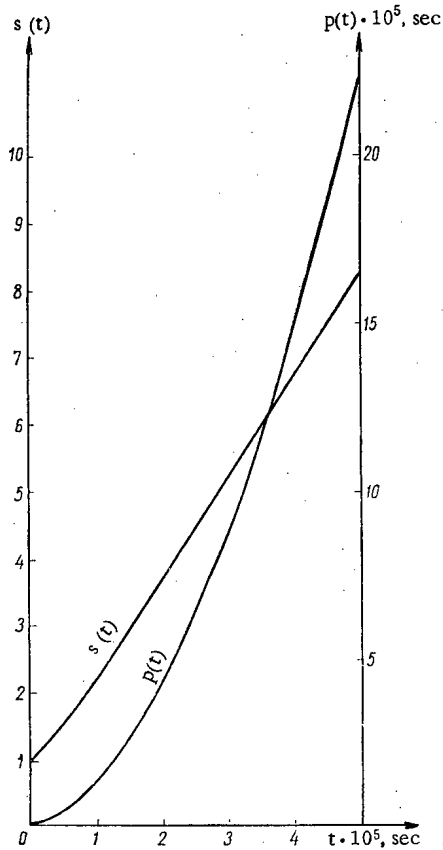


Fig. 1. Xenon storage in an electron bunch (atomic beam with  $v_a = 4.76 \cdot 10^4$  cm/sec,  $n_e = 10^{14}$  cm $^{-3}$ ,  $a = 0.1$  cm, and  $N_e = 10^{14}$ ).

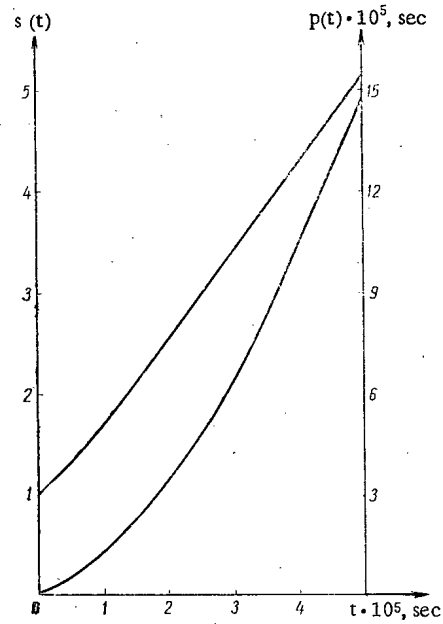


Fig. 2.  $Xe_{54}^{131}$  storage in an electron bunch (residual gas with  $I = 300^\circ K$ ,  $v_T = 2.38 \cdot 10^4$  cm/sec,  $n_e = 10^{14}$  cm $^{-3}$ ,  $a = 0.1$  cm, and  $N_e = 10^{14}$ ).

According to Eq. (1), the variation of neutral particle concentration in the bunch results from ionization by electrons and from the difference in the fluxes associated with difference in atom concentrations inside and outside the bunch. Depending on the method chosen for feeding atoms into the vacuum chamber in which the electron ring is formed, the concentration of neutral particles in the neighborhood of the bunch is given either by the density of the flux incident on the surface of the ring or by the partial pressure of the corresponding gas in the vacuum chamber. Let a thin ring of electrons intersect a flux of atoms at a velocity  $v_a$  directed along the axis of the ring. The average value of the velocity component normal to the surface of the bunch is then  $\bar{v} = (2/\pi)v_a$ , the area  $S = 2\pi^2 Ra$ , and hence  $\lambda_a = (2/\pi)(v_a/a)$ . If atoms of residual gas enter the ring and their thermal velocity is  $v_T$ , then [4]  $\bar{v} = v_T/4$  and  $\lambda_a = (v_T/a)/2$ .

We write Eq. (1) in the following form:

$$\begin{aligned} \dot{n}_0 + \lambda_0 n_0 &= \lambda_a n_a; \\ \lambda_0 &= \lambda_i + \lambda_a. \end{aligned} \quad (1a)$$

The time variation of the mean concentration  $n_1$  of singly ionized atoms is described by the equation

$$\dot{n}_1 + \lambda_1 n_1 = \lambda_i n_0; \quad (2)$$

the equation for the concentration  $n_Z$  of ions with charge  $Z > 1$  is

$$\begin{aligned} \dot{n}_Z + \lambda_Z n_Z &= \lambda_{Z-1} n_{Z-1}; \\ \lambda_Z &= n_e \sigma_Z, \end{aligned} \quad (3)$$

where  $\sigma_Z$  is the ionization cross section for an ion with charge  $Z$  in a collision with an electron where  $\lambda_{Z_0} = 0$  ( $Z_0$  is the atomic number). Hence

$$\dot{n}_{Z_0} = \lambda_{Z_0-1} n_{Z_0-1}. \quad (4)$$

In the system of Eqs. (1a)-(4), no consideration is given to collisions between heavy particles which lead in particular, to ionization and charge exchange. The ion contribution in these processes is determined by the ratio of the characteristic collision times, which is  $n_1 \sigma_i v_i / n_e \sigma_e c$ . The average velocity of an ion with

mass number  $A$  and charge  $Z$  undergoing oscillations in the potential well created by the electron space charge is  $v_i = (Z/A)^{1/2} v_p$ ; the collision cross section [5]  $\sigma_z = Z^2 \sigma_p$ , where  $v_p$  and  $\sigma_p$  are respectively the average velocity and cross section for a proton. The proton velocity  $v_p$  in a bunch is  $\approx 10^{-2}c$ , and the cross section  $\sigma_p \approx 10^3 \sigma_e$ . Consequently, if the ratio of the number of electrons and ions is

$$\frac{n_i}{n_e} \ll \frac{A^{1/2}}{10Z^{5/2}}, \quad (5)$$

the ion contribution can be neglected.

Assume that at  $t = 0$ , there are in the bunch only neutral atoms,  $n_Z(0) = n_a \delta_0 Z$ . We shall write the solution of the equation system (1a)-(4) as the sum of a particular solution of the inhomogeneous system and the general solution of the homogeneous system:

$$\begin{aligned} n_0 &= n_a \left( \frac{\lambda_a}{\lambda_0} + y_0 \right); \\ n_Z &= n_a \frac{\lambda_i}{\lambda_a} \left( \frac{\lambda_a}{\lambda_Z} + y_Z \right), \quad 1 \ll Z \ll Z_0 - 1; \\ n_{Z_0} &= n_a \frac{\lambda_i}{\lambda_0} (\lambda_a t + y_{Z_0}), \end{aligned} \quad (6)$$

where the particular solution is represented by the first terms and the function  $y_Z$  is determined by the homogeneous system

$$\begin{aligned} \dot{y}_0 + \lambda_0 y_0 &= 0; \\ \dot{y}_Z + \lambda_Z y_Z &= \lambda_{Z-1} y_{Z-1}; \\ \dot{y}_{Z_0} &= \lambda_{Z_0-1} y_{Z_0-1} \end{aligned} \quad (7)$$

with the initial conditions  $y_0(0) = \lambda_i/\lambda_0$ ;  $y_Z(0) = -(\lambda_a/\lambda_Z)$ ;  $y_{Z_0}(0) = 0$ .

An equation system similar to (7) describes decay in a family of radioactive elements [6]. Using the known solutions, we obtain expressions for the concentration of ions with a charge  $Z$  varying from one to  $Z_0 - 1$ :

$$n_Z = n_a \frac{\lambda_i}{\lambda_0} \left[ \lambda_a \left( \frac{1}{\lambda_Z} - \sum_{h=1}^Z \frac{S_{Zh}}{\lambda_h} \right) + \frac{\lambda_i}{\lambda_0} S_{Z_0} \right] \quad (8)$$

and the concentration of completely ionized atoms

$$n_{Z_0} = n_a \frac{\lambda_i}{\lambda_0} \left[ \lambda_a \left( t - \sum_{k=1}^{Z_0-1} \frac{S_{Z_0k}}{\lambda_k} \right) + \frac{\lambda_i}{\lambda_0} S_{Z_0} \right]. \quad (9)$$

Here, for  $Z \ll Z_0 - 1$

$$\begin{aligned} S_{Zh} &= \prod_{m=h}^{Z-1} \lambda_m \sum_{s=h}^Z \frac{e^{-\lambda_s t}}{Z} \prod_{n=h}^s \lambda_{ns}; \quad S_{ZZ} = e^{-\lambda_Z t}, \\ 0 &\ll k \ll Z - 1; \end{aligned} \quad (10a)$$

and for  $Z = Z_0$

$$\begin{aligned} S_{Z_0k} &= 1 - \prod_{m=k}^{Z_0-1} \lambda_m \sum_{s=k}^{Z_0-1} \frac{e^{-\lambda_s t}}{Z_0-1} \prod_{n=k}^s \lambda_{ns}, \quad 0 \ll k \ll Z_0 - 1; \\ \lambda_{ns} &= \lambda_n - \lambda_s; \quad \lambda_{ss} = 1. \end{aligned} \quad (10b)$$

The concentrations of neutral and singly ionized atoms are respectively:

$$n_0 = n_a \left( \frac{\lambda_a}{\lambda_0} + \frac{\lambda_i}{\lambda_0} e^{-\lambda_0 t} \right); \quad (11a)$$

$$n_1 = n_a \frac{\lambda_i}{\lambda_0} \left[ \frac{\lambda_a}{\lambda_1} - \frac{\lambda_i}{\lambda_{01}} e^{-\lambda_0 t} - \frac{\lambda_0 (\lambda_a - \lambda_1)}{\lambda_1 \lambda_{01}} e^{-\lambda_1 t} \right]. \quad (11b)$$

Summing the system (1a)-(4), we obtain an equation which the concentration of all heavy particles (atoms and ions),  $n = \sum_{z=0}^{Z_0} n_z$ , satisfies:

$$\dot{n} = \lambda_a (n_a - n). \quad (12)$$

In the case  $n(0) = n_a$ , its solution takes the form

$$s(t) = \frac{n}{n_0} = 1 + \frac{\lambda_a \lambda_i}{\lambda_0} t - \frac{\lambda_a \lambda_i}{\lambda_0^2} (1 - e^{-\lambda_0 t}). \quad (13)$$

We also give the value of the quantity  $p = 1/n_a \int_0^t n(t') dt'$ :

$$p(t) = \left(1 - \frac{\lambda_a \lambda_i}{\lambda_0^2}\right) t + \frac{\lambda_a \lambda_i}{2\lambda_0} t^2 + \frac{\lambda_a \lambda_i}{\lambda_0^3} (1 - e^{-\lambda_0 t}). \quad (14)$$

If the ion storage time satisfies the condition  $\lambda_0 t \gg 1$ ,  $\lambda_1 t \gg 1$ , . . . ,  $\lambda_Z t \gg 1$ , the concentration of ions with the corresponding charge tends toward a limiting equilibrium value

$$n_z = n_a \frac{\lambda_a}{\lambda_0} \cdot \frac{\sigma_0}{\sigma_Z}; \quad 0 \ll Z \ll Z_0 - 1, \quad (15)$$

which, like the time to reach this value, increases with an increase in ion charge. At the same time, the total concentration  $n$  of the heavy particles rises in proportion to the storage time.

The storage of xenon is shown in Figs. 1 and 2 (function  $s(t)$ ). In one case (see Fig. 1), the neutral atoms reach the bunch from a directed flow with a velocity  $\sim 1.4$  M, i.e.,  $v_a \approx 4.8 \cdot 10^4$  cm/sec; in the other case (see Fig. 2), xenon storage is accomplished from the residual gas in the vacuum chamber at a temperature  $T = 300^\circ\text{K}$ , i.e.,  $v_T = 2.4 \cdot 10^4$  cm/sec. The final concentration of heavy particles can be increased by decreasing the time for filling the volume of the ring with neutral atoms. If  $\lambda_a \gg \lambda_i$ , the quantity  $\lambda_a/\lambda_0$  should be replaced everywhere by its maximum value, which is unity.

#### Electron Loss during Ion Storage

The probability of electron scattering by atoms and ions increases as the concentration of heavy particles increases, leading to a limitation on the final value of the heavy particle concentration  $n$ . Since the amplitude of electron betatron oscillations is increased by scattering, one can assume that the electron will escape from the boundary of the circular beam if the square of this amplitude becomes larger than the square of the minor radius of the ring  $a^2$ . The average value over a betatron oscillation period of the square of the amplitude in the case of elastic scattering at a small angle  $\vartheta$  is determined by the expression [7]

$$\overline{u^2} = u_0^2 + \frac{\vartheta^2 R^2}{2n_B}, \quad (16)$$

where  $u_0^2$  is the square of the amplitude immediately before scattering and  $n_B$  is the magnetic field index.

An electron can be knocked out of the beam both by single collisions with heavy nuclei (large-angle scattering; bremsstrahlung emission in an atomic nucleus) and by small, frequently repeated changes in its trajectory.

Electron Loss through Single Collisions. Equation (16) indicates that an electron is removed from the beam as the result of a single scattering at an angle

$$\vartheta \gg \vartheta_0 = \sqrt{2n_B \frac{(a^2 - u_0^2)}{R^2}}. \quad (17)$$

Since scattering at an angle  $\vartheta > \vartheta_0$  corresponds to impact parameters less than the atomic radius, it can be assumed that the scattering occurs in the atomic nucleus with a cross section which is given by the Rutherford scattering law. In this case, the electron scattering probability per unit time for an angle  $\vartheta \geq \vartheta_0$  is

$$P(u_0^2, t) = cn(t) \int_{\vartheta_0}^{\pi} \sigma(\vartheta) d\vartheta = 2\pi \frac{Z_0^2}{v^2} \cdot \frac{1}{n_B} r_e^2 cn(t) \frac{R^2}{a^2 - u_0^2}, \quad (18)$$

where  $r_e = e^2/mc^2$  is the classical radius of the electron.

The relative electron loss because of single scattering is given by [7]

$$q_0 = 1 - \int_0^{a^2} du_0^2 F(u_0^2) \exp \left[ - \int_0^t P(u_0^2, t') dt' \right], \quad (19)$$

where  $F(u_0^2)$  is the electron distribution function at time  $t = 0$  normalized to unity.

If  $F = \delta(u_0^2)$ , the relative loss can be expressed as

$$q_0 = 1 - \exp \left[ -2\pi \frac{Z_0^2}{\gamma^2} \cdot \frac{1}{n_B} \cdot \frac{R^2}{a^2} r_e^2 c n_a p \right]. \quad (20)$$

Inelastic electron scattering can be taken into account if  $Z_0^2$  in Eq. (20) is replaced by the number of electrons in the ionized atom, which is  $Z_0 - Z$ . It is obvious that the contribution from inelastic collisions of heavy atoms to the amount of loss will be insignificant.

A three-body interaction occurs during bremsstrahlung emission. Furthermore, electron losses from the ring occur even with the emission of soft  $\gamma$ -rays since the transfer of a large amount of momentum to the nucleus is possible. The amount of relative electron loss  $q_r$  can be estimated by means of the expression for the total cross section for bremsstrahlung emission, which is, for heavy atoms and for  $1 \ll \gamma < 137Z_0^{-1/3}$  [5],

$$\sigma_r = \frac{4Z_0^2}{137} r_e^2 (\ln 2\gamma - 1/3). \quad (21)$$

Hence

$$q_r = 1 - \exp [-\sigma_r c n_a p]. \quad (22)$$

Electron Loss through Multiple Scattering. From theoretical considerations of particle loss in accelerators [7], it follows that the relative electron loss produced by multiple scattering in atoms is determined by

$$\tau = \frac{c}{2} \int_0^t \frac{R^2}{n_B a^2} \cdot \frac{d\bar{\vartheta}^2}{dx} dt', \quad (23)$$

where the mean value of the square of the scattering angle per unit path length for an ultrarelativistic electron is [5]:

$$\frac{d\bar{\vartheta}^2}{dx} = \frac{8\pi}{\gamma^2} r_e^2 \sum_{Z=0}^{Z_0} Z^2 n_Z \ln \frac{\vartheta_{\max}}{\vartheta_{\min}}. \quad (24)$$

Equation (24) was obtained under the assumption the impact parameter in multiple scattering is considerably greater than atomic dimensions and the scattering occurs in ions with charge  $Z$ . We shall assume the maximum angle for multiple scattering is equal to the minimum angle for single scattering:

$$\vartheta_{\max} = \sqrt{2n_B} \frac{a}{R}. \quad (25)$$

The minimum scattering angle is determined by the maximum impact parameter which corresponds to the minor radius of the ring since the Debye screening radius is considerably greater than the minor radius of the ring in that case:

$$\vartheta_{\min} \approx \frac{2Z}{\gamma} \cdot \frac{r_e}{a}. \quad (26)$$

As a result, we obtain

$$\tau = \frac{4\pi}{\gamma^2} \cdot \frac{1}{n_B} \cdot \frac{R^2}{a^2} r_e^2 c \sum_{Z=0}^{Z_0} Z^2 + \int_0^t n_Z(t') dt' \ln \sqrt{\frac{n_B}{2}} \cdot \frac{\gamma}{Z} \cdot \frac{a^2}{R r_e}. \quad (27)$$

To estimate the loss, one can make use of the fact that  $\tau$  is always less than

$$4\pi \frac{Z_0^2}{\gamma^2} \cdot \frac{1}{n_B} \cdot \frac{R^2}{a^2} r_e^2 c n_a p L, \quad (28)$$

where  $L$  is the average value of the logarithm in Eq. (27).

By determining the value of  $\tau$  and knowing the initial electron distribution with respect to betatron oscillation amplitudes, one can find the electron loss produced by multiple scattering [7]. A comparison of the loss equations shows that bremsstrahlung emission leads to considerably smaller losses than scattering. Obviously, the main source of loss is multiple elastic scattering of electrons at small angles. If an acceptable value for electron loss during the storage period is assumed to be 5-10%, the total concentration  $n$  of stored heavy particles (xenon) is bounded by the value  $n/n_e \approx 10^{-3}$ .

## LITERATURE CITED

1. V. I. Veksler et al., *Atomnaya Énergiya*, 24, 317 (1968).
2. M. L. Iovnovich et al., JINR Preprint P9-4257, Dubna (1969).
3. Symposium on Electron Ring Accelerators, UCRL-18103, Berkeley (1968).
4. A. Simon, *Phys. Fluids*, 1, 495, (1958).
5. *Experimental Nuclear Physics* (E. Segre, editor) [Russian translation], Vol. 1, IL, Moscow (1955).
6. S. E. Bresler, *Radioactive Elements* [in Russian], Gostekhteorizdat, Moscow (1957).
7. A. A. Kolomenskii and A. N. Lebedev, *Theory of Cyclic Accelerators* [in Russian], Fizmatgiz, Moscow (1962).



ENERGY BALANCE IN THE PLASMA IN APPARATUSES  
OF THE "TOKAMAK" TYPE

Yu. N. Dnestrovskii and D. P. Kostomarov

UDC 621.039.626

In recent years a large number of theoretical papers has appeared on calculating the transport coefficients in toroidal systems on the basis of the classical mechanism of Coulomb collisions [1-4]. At the same time numerous experiments on "Tokamak" apparatuses indicate the absence of large-scale turbulent oscillations of the plasma under conditions for which hydrodynamic instabilities are suppressed [5, 6]. In this connection it is of great interest to calculate the energy balance of the plasma in such apparatuses on the assumption that the losses are of a classical character, and to compare the results of this calculation with experimental data. In the present paper results are given of a numerical solution of the thermal conductivity equations for ions and electrons, and the equations for the magnetic field of the current in a plasma pinch with allowance for the classical transport coefficients. These calculations allow the dependence of the ion and electron temperatures and the energy lifetime on the geometric dimensions of the plasma pinch, the plasma density, the longitudinal magnetic field intensity, and the magnitude of the discharge current to be investigated within the framework of the assumption made concerning the character of the losses. The results obtained are in good agreement with available experimental data [5-8]. This indicates the possibility of explaining the energy balance of the plasma in specified operating modes within the framework of classical concepts, and substantiates the conclusion of the theory to the effect that the confined particles play a special role in the transport processes.

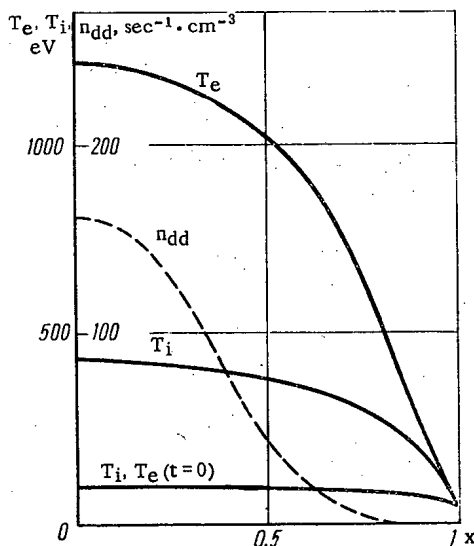


Fig. 1

Fig. 1. The dependence of  $T_e$ ,  $T_i$ , and  $n_{dd}$  on the space coordinate  $x = r/a$  for  $t = 0$  and  $t = 18$  msec ( $R = 100$ ,  $a = 12$ ,  $H = 38$ ,  $I = 110$ ,  $N = 4$ ,  $\xi_p = 0.3$ ,  $\xi_d = 0.7$ ,  $\gamma = 1$ ).

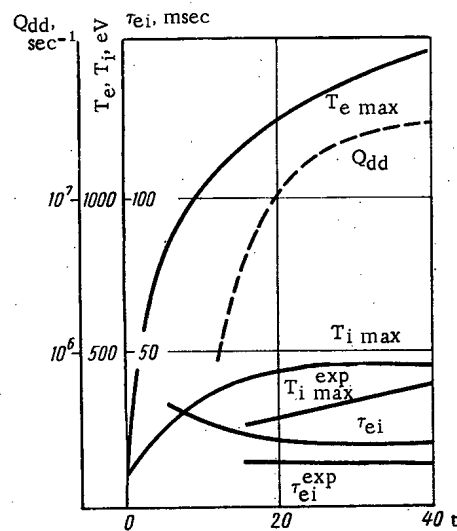


Fig. 2

Fig. 2. The dependence of  $T_{e \max}$ ,  $T_{i \max}$ ,  $\tau_{ei}$ , and  $Q_{dd}$  on the times ( $R = 100$ ,  $a = 12$ ,  $H = 38$ ,  $I = 110$ ,  $N = 4$ ,  $\xi_p = 0.3$ ,  $\xi_d = 0.7$ ,  $\gamma = 1$ ).

Translated from *Atomnaya Énergiya*, Vol. 29, No. 6, pp.434-438, December, 1970. Original article submitted April 2, 1970.

© 1971 Consultants Bureau, a division of Plenum Publishing Corporation, 227 West 17th Street, New York, N. Y. 10011. All rights reserved. This article cannot be reproduced for any purpose whatsoever without permission of the publisher. A copy of this article is available from the publisher for \$15.00.

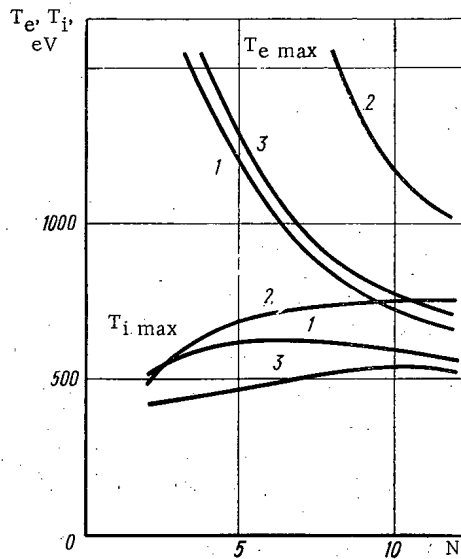


Fig. 3

Fig. 3. Dependence of the steady-state values of  $T_e \max$  and  $T_i \max$  on the density  $N$  for three versions ( $R = 100$ ,  $a = 12$ ,  $H = 38$ ,  $I = 110$ ). 1)  $\xi_p = 1$ ,  $\gamma = 1$ ; 2)  $\xi_p = 1$ ,  $\gamma = 3$ ; 3)  $\xi_p = 0.3$ ,  $\xi_d = 0.7$ ,  $\gamma = 1$ .

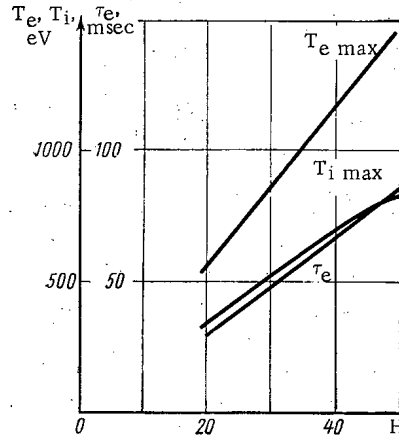


Fig. 4

Fig. 4. Dependence of the steady-state values of  $T_e \max$ ,  $T_i \max$ , and  $\tau_e$  on the longitudinal magnetic field  $H[q(1, t) = 2.2 = \text{const}$ ,  $R = 100$ ,  $a = 12$ ,  $N = 6$ ,  $\gamma = 1$ , and  $I = 3.28H$ ].

### The Basic Equations

In formulating the equations which describe the energy balance of a toroidal plasma pinch in systems of the "Tokamak" type in the case of classical losses, we shall consider the fact that for such systems the diffusion lifetime is much longer than the energy lifetime [1-4]. This allows a) neglect of plasma diffusion in comparison with thermal conductivity, and b) the assumption that the plasma density is independent of time. As a result the system of equations describing the variation of the magnetic field of the current and the energy of the plasma [9] takes the form:

$$\frac{\partial \mu}{\partial t} = A\gamma \frac{1}{x} \cdot \frac{\partial}{\partial x} \left[ \frac{1}{T_e^{3/2}} \cdot \frac{1}{x} \cdot \frac{\partial}{\partial x} (x^2 \mu) \right]; \quad (1)$$

$$\frac{\partial T_e}{\partial t} = \frac{1}{nx} \cdot \frac{\partial}{\partial x} (xn\chi_e \frac{\partial T_e}{\partial x}) - C \frac{n}{T_e^{3/2}} (T_e - T_i) + B\gamma \frac{1}{nT_e^{3/2}} \left[ \frac{1}{x} \cdot \frac{\partial}{\partial x} (x^2 \mu) \right]^2 - Q_r; \quad (2)$$

$$\left. \begin{aligned} \frac{\partial T_i}{\partial t} &= \frac{1}{nx} \cdot \frac{\partial}{\partial x} (xn\chi_i \frac{\partial T_i}{\partial x}) \\ &+ C \frac{n}{T_e^{3/2}} (T_e - T_i). \end{aligned} \right\} \quad (3)$$

Here  $\mu(x, t) = 1/q = RH_V/rH$  is a function which is proportional to the magnetic field  $H_V$  of the current;  $H$  is the longitudinal magnetic field  $T_e(x, t)$  and  $T_i(x, t)$  are the electron and ion temperatures;  $n(x)$  is the density of the plasma;  $x = r/a$ ;  $r$  is the radial space coordinate;  $R$  and  $a$  are the large and small radii of the plasma torus;

$$\begin{aligned} A &= \frac{6.1 \cdot 10^8}{a^2}; \\ B &= \frac{2 \cdot 10^7 H^2}{R^2}; \quad C = \frac{470}{p}; \end{aligned} \quad (4)$$

$p$  is the ratio of the reduced mass of the ions in the mixture of hydrogen, deuterium, and tritium to the proton mass. The quantity  $Q_r$  in Eq. (2) denotes the possible additional energy losses by electrons. In the calculations the bremsstrahlung losses  $Q_r = 7.2 \cdot 10^{-4} n \sqrt{T_e}$  were considered. In Eqs. (1)-(3) and in the subsequent equations the time is measured in milliseconds, the temperature in electron-volts, the density in  $10^{13} \text{ cm}^{-3}$ ;  $R$  and  $a$  in centimeters, and  $H$  in kilooersted.

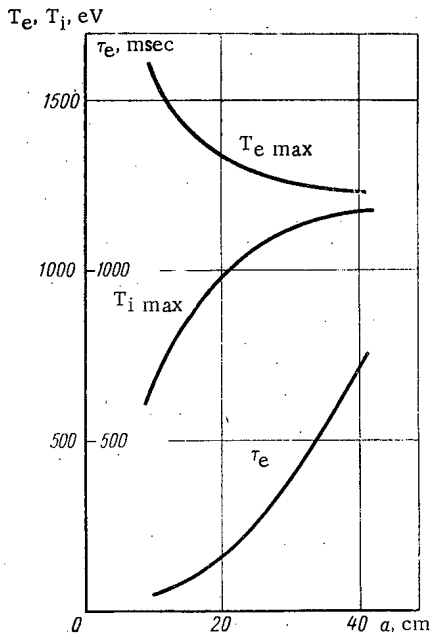


Fig. 5

Fig. 5. Dependence of the steady-state values of  $T_e \max$ ,  $T_i \max$ , and  $\tau_e$  on the radius  $a$  of the plasma [ $q(1, t) = 2.2 = \text{const}$ ,  $H = 40$ ,  $N = 6$ ,  $R = 7a$ ,  $I = 12.6a$ , and  $\gamma = 1$ ].

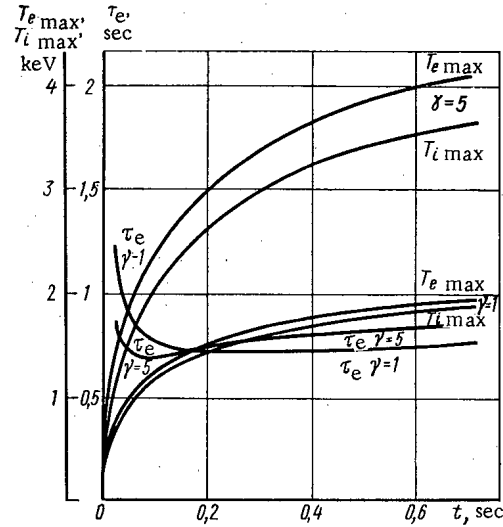


Fig. 6

Fig. 6. The dependence of  $T_e \max$ ,  $T_i \max$ , and  $\tau_e$  on time for a hypothetical apparatus for  $\gamma = 1$  and  $\gamma = 5$  ( $R = 150$ ,  $a = 40$ ,  $H = 50$ ,  $I = 1000$ ,  $N = 10$ , and  $\xi_p = 1$ ).

The coefficients of thermal conductivity  $\chi_e$  and  $\chi_i$  of electrons and ions depend in a very complex way on the collision frequency  $\nu$  and on the other parameters of the plasma in accordance with [2-4]. In the range of low collision frequencies the equations of [3, 4] are valid. If the explicit expressions for the collision frequencies are used and all of the quantities are written in the units given above, then the corresponding equations take the form

$$\chi_j = 300 \frac{F_j n q^2}{a^2 H^2 \sqrt{T_j}} \left( \frac{R}{ax} \right)^{3/2} J(\alpha_j) \quad (\alpha_j \leq \alpha_0), \quad (5)$$

where

$$J(\alpha) = 0.3 \int_0^\infty \frac{e^{-z^2} dz}{\sqrt{z^2 + \alpha}} \quad (J(0) = 1); \quad (6)$$

$$\alpha_j = 420 f_j \frac{R^5 n^2 q^2}{T_j^4 (ax)^3};$$

$$\alpha_0 = 1.25 \left( \frac{q^2}{1+q^2} \right)^2 \left( \frac{R}{ax} \right)^3 \gg 1;$$

$$F_j = \begin{cases} \sqrt{p} & j = i \\ \frac{5}{43} & j = e \end{cases}; \quad f_j = \begin{cases} 1 & j = i \\ 4 & j = e \end{cases}. \quad (7)$$

For  $\alpha_j \ll 1$  and  $1 \ll \alpha_j < \alpha_0$  one can derive the following asymptotic equations from Eq. (5):

$$\chi_j = 300 \frac{F_j n q^2}{a^2 H^2 \sqrt{T_j}} \left( \frac{R}{ax} \right)^{3/2} \quad (\alpha_j \ll 1); \quad (8)$$

$$\chi_j = 26 \frac{F_j T_j^{3/2} q}{\sqrt{f_j} a^2 H^2 R} \quad (1 \ll \alpha_j \ll \alpha_0). \quad (9)$$

Finally, for  $\alpha_j > \alpha_0$  the following equations in [2] are valid in the range of comparatively high frequencies:

$$\chi_j = 480 \frac{F_j n (1+q^2)}{a^2 H^2 \sqrt{T_j}} \quad (\alpha_j \gg \alpha_0). \quad (10)$$

The limits of applicability of the equations given above are very sensitive to the parameters of the plasma. Usually, Eqs. (10) are valid for the thermal conductivity coefficients at the initial stage of the discharge while the temperature of the plasma is low. However, as the internal portion of the plasma pinch is heated up, the collision frequencies begin to decrease, and we go over to Eqs. (9); after that we may even reach the range of validity of Eqs. (8). The transition from one branch to the other does not occur simultaneously for the entire pinch. Therefore, in order to calculate the coefficients of thermal conductivity at different points it is necessary to use different equations. All this greatly complicates the problem, making its qualitative investigation difficult and allowing reliable quantitative results to be obtained only by means of numerical methods.

The factor  $\gamma$  is included in the terms of Eqs. (1) and (2), which are connected with the current. This factor allows a phenomenological description to be given of the resistance observed in the experiment. The case  $\gamma = 1$  corresponds to the classical plasma resistance given by the Spitzer formula.

The initial and boundary conditions were chosen in the form

$$\mu(x, 0) = \mu_0(2 - x^2); \quad T_j(x, 0) = T_{j0}(2 - x^2) \quad (j = i, e); \quad (11)$$

$$\mu(1, t) = \mu_0 = 0.2 \frac{RI}{a^2 H}; \quad T_j(1, t) = T_{j0} \quad (j = i, e), \quad (12)$$

where  $I$  is the total current in the plasma in kiloamperes. The radial density distribution of the plasma was assumed to be parabolic:  $n(x) = N(1 - (1/2)x^2)$ .

Equations (1)-(3) with the complementary conditions (11), (12) were integrated on an electronic computer. The time evolution of the electron and ion temperatures were investigated, as well as the dependence of the steady-state values of these temperatures on plasma density, longitudinal magnetic field, total current, and the dimensions of the plasma pinch. The results of the corresponding calculations are described below. In these calculations it was assumed that the total current  $I$  was independent of time and was distributed over the pinch cross section according to the parabolic law  $f(x, 0) = 2I(1 - x^2)\pi$  at the initial time in accordance with the conditions (11). Thus, in the given series of calculations the problem of current penetration into the plasma during the initial stage of the process corresponding to an increase of the total current with time was not considered. Under these assumptions the function  $\mu(x, t)$  and the current density  $f(x, t)$  remain practically constant with time. A change in the electron and ion temperatures  $T_{0e}$  and  $T_{0i}$  on the boundary over fairly wide limits (10 to 100 eV) had a very slight effect on the solution of the problem. As far as the initial temperatures were concerned, they ceased to affect the solution after a time had elapsed which was 4-5 times as short as the energy lifetime.

### The Results of the Calculations

As an example, Figs. 1 and 2 show the results of the numerical solution of the problem formulated above for parameter values corresponding to the parameters of the T-3 apparatus at the I. V. Kurchatov Atomic Energy Institute [5-7]. In the calculations it was assumed that

$$R = 100, \quad a = 12, \quad H = 38, \quad I = 110, \quad (13)$$

$$T_{j0} = 50 \quad (j = i, e).$$

Since the characteristic time of the process in this case is of the order of several tens of milliseconds, the integration of the system (1)-(3) was carried out till  $t = 40$  msec. During this time  $T_e$ ,  $T_i$ , and  $\tau_e$  practically reach their steady-state values. The calculations were carried out for purely hydrogen plasma and for a mixture of hydrogen and deuterium having relative concentrations  $\xi_p$  and  $\xi_d$  ( $\xi_p + \xi_d = 1$ ). In the latter case the yield of neutrons accompanying the d-d reaction was determined.

The energy lifetime  $\tau_e$  was found according to the equation

$$\tau_e = E \left( Q - \frac{\partial E}{\partial t} \right)^{-1}, \quad (14)$$

where  $E$  is the thermal energy of the plasma;  $Q$  is the Joule heat released by the current. For purposes of comparison with experiment the energy lifetime  $\tau_{ei} = E_i Q_i^{-1}$  of the ions was likewise calculated, where  $E_i$  is the energy in the ions, and  $Q_i$  is the heat flux from the ions to the wall. The density  $n_{dd}$  of the neutron yield and the total flux  $Q_{dd}$  of neutrons from the plasma were determined from the equations [10]:

$$n_{dd} = \xi_0^2 n^2 T_i^{-2/3} \exp(32 - 188 \cdot T_i^{-1/3}); \quad (15)$$

$$Q_{dd} = 4\pi^2 R a^2 \int_0^1 n_{dd} x dx.$$

Figure 1 shows the dependences of the ion and electron temperatures of the space coordinate  $x = r/a$ . The dashed line shows the density  $n_{dd}$  of the neutron yield resulting from the d-d reaction. For the chosen value of plasma density the heat exchange between electrons and ions is relatively small, and therefore the "detachment" of the electron temperature from the ion temperature takes place during the heating process.

Figure 2 shows the dependence of  $T_{e \max}$ ,  $T_{i \max}$ , and  $\tau_{ei}$  on time for the same plasma parameters. The experimental curves for  $T_{i \max}$  and  $\tau_{ei}$  were obtained on the T-3 apparatus. Good agreement between the results of the theory and experimental data indicates a possible explanation of the energy balance of the plasma in this case within the framework of classical concepts of heat exchange and losses, and substantiates the conclusion of the theory concerning the necessity of considering confined particles in the transport processes. Analogous calculations were carried out for the T-3 apparatus in other operating modes with modified values of the longitudinal magnetic field and total current. The results obtained under these conditions are in good agreement with experimental data.

The curves in Fig. 2 indicate a comparatively rapid establishment of the steady state in apparatuses of this type. In order to clarify the possibilities of ohmic heating of the plasma in such apparatuses the investigation of the dependence of the limiting steady-state values of the quantities  $T_{e \max}$ ,  $T_{i \max}$ , and  $\tau_e$  on the geometric dimensions of the plasma pinch and such parameters as the plasma density, the magnitude of the longitudinal fields, and the magnitude of the current is of great interest. Certain results of the investigation of these dependences have been presented in Figs. 3-5.

Figure 3 shows the dependence of the steady-state values  $T_{e \max}$  and  $T_{i \max}$  on density for hydrogen plasma and for a mixture of hydrogen and deuterium. The shape of the curves may be interpreted as follows. With increasing plasma density the heat exchange between electrons and ions improves, and due to the fixed total current the fraction of energy released per particle decreases. Both of these factors lead to an abrupt decrease in  $T_e$  with increasing  $N$ . The ion temperature first increases due to the improvement of heat exchange, and then begins to decrease. This is clearly evident for curves 1 and 3, while for curve 2 the corresponding value of density lies beyond the limits of the diagram. Note that as a whole the ion temperature is very "inert" to a change in the plasma parameters. Whereas the electron temperature in Fig. 3 differs by a factor of 2-3 in different operating modes, the change in ion temperature is 20 to 30%.

Figures 4 and 5 show the dependences of the steady-state values of  $T_{e \max}$ ,  $T_{i \max}$ , and  $\tau_e$  on the longitudinal magnetic field and the dimensions of the plasma pinch for hydrogen plasma at a constant value of density  $N = 6$  and a value of the quantity  $q(1, t) = 2.2$ . In plotting Fig. 4 the values of the geometric parameters were chosen in accordance with Eq. (13), while the current varied with the magnetic field in accordance with the boundary conditions (12):  $I = 3.28H$ . Calculations show that in this case  $T_{e \max}$ ,  $T_{i \max}$ , and  $\tau_e$  increase with increasing  $H$  and  $I$  according to a practically linear law.

In calculating the curves in Fig. 5 the magnetic field was fixed ( $H = 40$ ), while the current and the large radius  $R$  of the torus were varied along with the radius  $a$  of the plasma pinch:  $I = 12.6a$ ,  $R = 7a$ . The shape of the curves in Fig. 5 may be qualitatively interpreted as follows. The linear dependence of  $I$  on  $a$  is connected with the decrease in current density with increasing  $a$ , which leads to a decrease of  $T_{e \max}$ . However, since with increasing  $a$  the losses via thermal conductivity decrease, it follows that  $T_{i \max}$  (and especially  $\tau_e$ ) increases under these conditions.

Figure 6 is similar to Fig. 2. This figure shows the calculations for a hypothetical large apparatus. The time variations of the quantities  $T_{e \max}$ ,  $T_{i \max}$ , and  $\tau_e$  are shown for hydrogen plasma ( $\xi_p = 1$ ) having a normal resistance ( $\gamma = 1$ ) and an anomalous resistance ( $\gamma = 5$ ). The characteristic time of the process is equal to 800 msec in this case. The high plasma density provides for good heat exchange between electrons and ions, and as a result the differences in their temperatures are insignificant. The temperature of the ions in the central portion of the plasma pinch reaches 1800 eV  $\gamma = 1$ , while for  $\gamma = 5$  it reaches 3000 eV.

The authors express their deep thanks to Academician L. A. Artsimovich for stating the problem and discussing the results.

#### LITERATURE CITED

1. D. Pfirsch and A. Schüter, Max Planck Institute, Rep. MPI/Pa/7/62 (1962).
2. V. D. Shafranov, *Atomnaya Energiya*, **19**, 120 (1965).
3. A. A. Galeev and R. Z. Sagdeev, *Zh. Éksperim. i Teor. Fiz.*, **53**, 348 (1967).

4. L. M. Kovryzhnykh, Zh. Eksperim. i Teor. Fiz., 56, 877 (1969).
5. L. A. Artsimovich et al., Report CN-24/B-1 at the Third Conference on Research in the Field of Plasma Physics and Controlled Fusion Reactions [in Russian], Novosibirsk (1968).
6. L. A. Artsimovich et al., Report to the International Conference on Plasma Confinement in Closed Systems [in Russian], Dubna (1959).
7. H. Peacock et al., *ibid.* [Russian translation].
8. Yu. N. Dnestrovskii and D. P. Kostomarov, *ibid.* [in Russian].
9. B. B. Kadomtsev, in: Problems of Plasma Theory [in Russian], No. 5, Atomizdat, Moscow, p. 209.
10. L. A. Artsimovich, Controlled Fusion Reactions [in Russian], Fizmatgiz, Moscow (1961).

## REVIEWS

THERMODYNAMICS OF THE URANIUM - CARBON,  
URANIUM - NITROGEN, AND PLUTONIUM - CARBON SYSTEMS

V. V. Akhachinskii and S. N. Bashlykov

UDC 621.039.542.3:541.11

The Uranium - Carbon System

Heat Capacity at Low Temperature. Certain results of recent measurements of the low-temperature heat capacity of uranium carbides are presented in Table 1.

The data for  $U_2C_3$  and  $UC_2$  are in very good agreement, but for UC there is a certain difference, evidently caused by the different composition of the samples. In [1, 2], in a measurements of the heat capacity of UC, pieces of cast carbide were used, the carbon content in which only slightly exceeded the stoichiometric; moreover, in [1] the measurements were performed on a well characterized sample, and no correction was introduced for the small excess of bound carbon. In [2], however, a correction was made for the presence of  $UC_2$ , but the influence of oxygen, the amount of which in the carbide was rather high (1.9 mole %), was not taken into consideration.

The authors of [4] recommend that the average value from [1, 2] be used for the heat capacity of UC.

The results of a measurement of the heat capacity of UC,  $U_2C_3$ , and  $UC_{1.94}$  in the interval 5-350°K [1, 4] are presented graphically in Fig. 1 [5].

Heat Capacity and Heat Content at High Temperature. Measurements of the true heat capacity of UC and  $UC_2$ , performed in [6] in an adiabatic calorimeter in the interval 373-473°K and in [7] on the determination of  $C_p$  of uranium monocarbide in the interval 300-900°K by the nonstationary system method with pulsed heating of the sample with a laser beam, should be considered insufficiently accurate.

The new technique, using pulsed heating (details unknown), was used in [8] to measure the heat capacity of a homogeneous sample of UC in the interval 600-2700°K. The systematic error of the method did not exceed 3-5%.

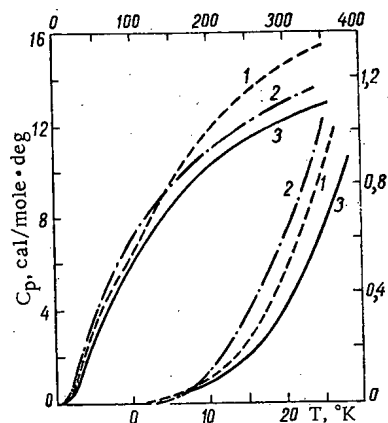


Fig. 1

Fig. 1. Heat capacity of  $U_2C_3$  (1),  $UC_{1.94}$  (2), and UC (3) at low temperature.

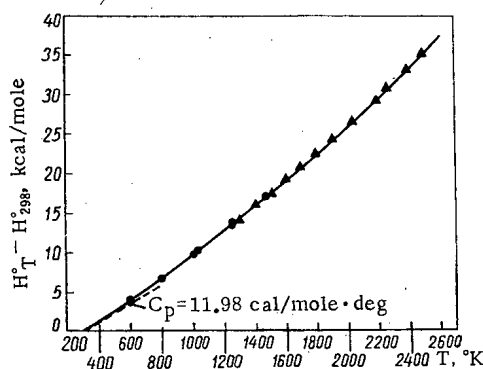


Fig. 2

Fig. 2. Heat content of  $UC_{1.0}$  at high temperature: ● [9]; ▲ [10].

Translated from *Atomnaya Energiya*, Vol. 29, No. 6, pp. 439-447, December, 1970. Original article submitted March 6, 1970.

© 1971 Consultants Bureau, a division of Plenum Publishing Corporation, 227 West 17th Street, New York, N. Y. 10011. All rights reserved. This article cannot be reproduced for any purpose whatsoever without permission of the publisher. A copy of this article is available from the publisher for \$15.00.

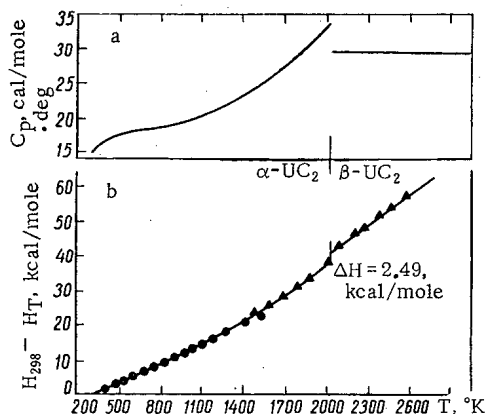


Fig. 3. Heat capacity (a) and heat content (b) of  $UC_{1.9}$ :  $\blacktriangle$  [12];  $\bullet$  [13].

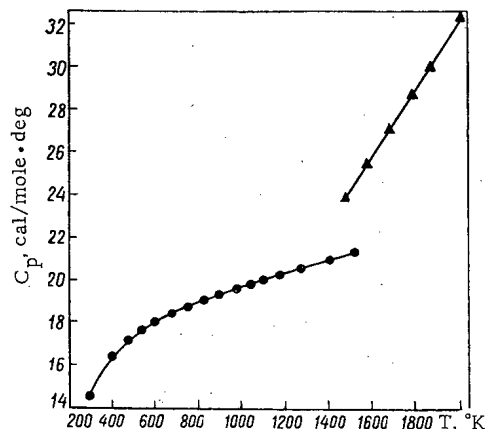


Fig. 4. Heat capacity of  $UC_2$ :  $\bullet$  [13];  $\blacktriangle$  [12].

TABLE 1. Thermal Functions of UC,  $U_2C_3$ , and  $UC_2$  at 298°K

Carbide	$C_p^0$ , cal/mole·deg	$S^0$ , cal/mole·deg	$H_{298.15}^0 - H_0^0$ , cal/mole	Presumed composition, mole %	Literature cited
UC	12,11	14,28	2193	$UC_{1.02 \pm 0.01}$	[1]
	11,84	14,03	2159	97,5 UC + 2,5 $UC_{1.9}$	[2]
$U_2C_3$	25,66	32,93	4829	$U_2C_3$	[3]
	25,55	32,91	4836	75,3 $U_2C_3$ + 10,6 UC + 4,1 $UC_{1.9}$ + 9,9 C	[2]
$\alpha$ - $UC_2$	14,46	16,30*	2513	72,05 $UC_{2.0}$ + 10,03 UC + 17,9 C	[1]
	14,52	16,33*	2521	$UC_{1.94}$	[3]
	14,50	16,31*	2522	95,3 $UC_{1.91}$ + 4,7 UC	[2]

\* The entropy of mixing, characterizing the randomness in the arrangement of the  $C_1$  and  $C_2$  groups, is not included.

TABLE 2. Heat Capacity (in cal/mole·deg K) of UC at High Temperature

T, °K	Data of [8]	Data of [10]	T, °K	Data of [8]	Data of [10]
300	—	12,00	900	14,30	14,64
500	—	13,59	1100	14,85	15,08
700	13,80	14,19			

The heat capacity of the monocarbide can be calculated according to the results of measurements of the heat content in the intervals 300–1500°K [9] and 1287–2481°K [10], presented in Fig. 2, by the method of calorimetry of mixing. The data of these studies are in good agreement with the overlapping temperature interval and fit into the general curve expressed by equation [11] of the type

$$H_T - H_{298} = a + bT + cT^2 + dT^3 + \frac{e}{T} \quad (1)$$

Table 2 presents for comparison the values of the heat capacity of UC, obtained in [8] and calculated in [11] according to the data of [10]. Table 3 presents the thermal functions of UC, calculated in [11].

Variation of the heat content of  $UC_{1.93}$  in the interval 1484–2851°K and  $UC_{1.90}$  in the interval 400–1500°K was determined in [12] and [13], respectively, by the method of calorimetry of mixing (Fig. 3). In the overlapping temperature interval, the values found for the change in the enthalpy coincide within the limits of the experimental errors, but the values of the heat capacity differ substantially. Thus, according to the data of [12], at 1490°K the heat capacity of  $UC_{1.93} = 23.8$  cal/mole·deg, while according to the data of [13] it is equal to 21.2 cal/mole·deg. Moreover, as can be seen from Fig. 4, the nature of the change in the heat capacity also differs. In [11] the data of the two investigations are compared and presented in the form of an equation of the type of (1). In Fig. 3 the sharp increase in the heat capacity of  $\alpha$ - $UC_2$  close to the point of the  $\alpha$ - $\beta$  conversion is clearly visible.

The substantial increase in the heat capacity of  $UC_2$  (and UC) in the region of high temperatures, which follows from the results of the measurements of [12], was the cause of the lack of confidence in these data. However, the author of [11] believes that there is no basis for doubt, since the heat content of other carbides was also measured, and in the case of TiC, ZrC, and TaC, an increase in the heat capacity was found, while in the case of HfC, NbC, and WC, it was not. Nonetheless, the results of measurements of the content of  $UC_2$  above 1650°K should be treated with caution, since when  $UC_2$  is cooled in the interval 2038–1650°K, there is frequently a precipitation of UC. Such precipitation probably occurred during the measurements in [12], which was noted by the authors of [20], who recalculated the data of [12] on the assumption that they pertain to a mixture of 0.055 UC + 0.945  $UC_{1.91}$  + 0.07 C. This theoretically correct correction somewhat lowers the value of the heat capacity of  $UC_2$  but has little effect on the value of the free



TABLE 3. Thermal Functions of UC<sub>1.0</sub>\*

Temperature, °K	H <sub>T</sub> <sup>o</sup> - H <sub>298</sub> <sup>o</sup> , cal/mole	C <sub>p</sub> <sup>o</sup> , cal/mole ·deg	S <sub>T</sub> <sup>o</sup> , cal/mole ·deg	-(F <sub>T</sub> <sup>o</sup> - H <sub>298</sub> <sup>o</sup> )/T, cal/mole·deg
298,15	0,0	11,98	14,15	14,15
500	2 618	13,59	20,82	15,58
700	5 402	14,19	25,50	17,78
900	8 285	14,64	29,12	19,91
1100	11 260	15,08	32,10	21,87
1300	14 320	15,58	34,66	23,64
1500	17 490	16,13	36,92	25,26
1700	20 780	16,77	38,98	26,76
1900	24 200	17,48	40,88	28,15
2100	27 780	18,27	42,67	29,45
2300	31 520	19,14	44,37	30,67
2500	35 440	20,10	46,01	31,83
2700	39 560	21,13	47,59	32,94
2823	42 200	21,81	48,55	33,60

\* H<sub>T</sub><sup>o</sup> - H<sub>298,15</sub><sup>o</sup> = -4,9624 · 10<sup>3</sup> + 14,315 T - 1,5130 · 10<sup>-4</sup> T<sup>2</sup> + 3,5038 · 10<sup>-7</sup> T<sup>3</sup> + 2,0828 · 10<sup>5</sup>/T cal/mole (298° - 2,823°K) ± 0,4%.

TABLE 4. Thermal Functions of UC<sub>1.90</sub>\*

Temperature, °K	H <sub>T</sub> <sup>o</sup> - H <sub>298</sub> <sup>o</sup> , cal/mole	C <sub>p</sub> <sup>o</sup> , cal/mole ·deg	S <sub>T</sub> <sup>o</sup> , cal/mole ·deg	-(F <sub>T</sub> <sup>o</sup> - H <sub>298</sub> <sup>o</sup> )/T, cal/mole·deg
α - 298,15	0,00	14,52	16,33	16,33
500	3 321,3	17,49	24,77	18,13
700	6 900,9	18,23	30,79	20,93
900	10 618	18,99	35,46	23,66
1100	14 527	20,187	39,37	26,17
1300	18 730	21,94	42,88	28,47
1500	23 344	24,30	46,18	30,62
1700	28 493	27,29	49,40	32,64
1900	34 304	30,92	52,62	34,57
2038	38 766	33,80	54,89	35,87
β - 2038	41 264	29,44	56,12	35,87
2100	43 089	29,44	57,00	36,48
2300	48 976	29,44	59,64	38,39
2500	54 864	29,44	62,14	40,19
2800	63 695	29,44	65,47	42,72
α - UC <sub>2</sub>	H <sub>T</sub> <sup>o</sup> - H <sub>298</sub> <sup>o</sup> = 8,377 · 10 <sup>3</sup> + 23,40 T - 5,752 × 10 <sup>-3</sup> T <sup>2</sup> + 2,727 · 10 <sup>-6</sup> T <sup>3</sup> + 5,487 · 10 <sup>6</sup> /T			
β - UC <sub>2</sub>	H <sub>T</sub> <sup>o</sup> - H <sub>298</sub> <sup>o</sup> = -1,873 · 10 <sup>4</sup> + 29,44 T			

\* The entropy of ordering is not included.

energy function  $F_T^o - H_{298}^o/T$ . Moreover, the correction cannot be accurate, since it cannot be established how much UC was precipitated during cooling in the calorimeter [12]. Taking the aforementioned into consideration, the author of [11] did not introduce any corrections into the data of [12] in the calculation of the thermal functions of UC (see Table 3) and UC<sub>2</sub> (Table 4). However, the thermal functions of UC<sub>2</sub> should evidently be corrected by adding the configurational entropy of ordering, calculated in [20] and equal to 0.60 cal/mole · deg, to the experimentally found entropy of UC<sub>2</sub>.

There is no information on the high-temperature heat capacity of U<sub>2</sub>C<sub>3</sub>. Considering the unusual behavior of UC and UC<sub>2</sub>, all attempts to estimate it will be extremely doubtful.

**Enthalpy of Formation.** The standard enthalpy of formation ( $\Delta H_{f298}^o$ ) of uranium carbides was determined most accurately by the method of calorimetry of combustion. On the basis of mass spectrometric measurements [14], we detected a pronounced dependence of the enthalpy of formation of substoichiometric uranium monocarbide on the composition [21]. Therefore, samples with the composition UC<sub>0.996</sub> and UC<sub>1.032</sub> were taken for combustion, i.e., close to the stoichiometric. The enthalpies of formation were found equal to  $-23.3 \pm 0.9$  and  $-28.0 \pm 1.0$  kcal/mole, respectively [14]. Considering the results of our measurements [22] of the heats of formation of U<sub>3</sub>O<sub>8</sub> and UO<sub>2</sub>, these quantities should be approximately 0.8 kcal more negative, i.e.,  $\Delta H_{f298}^o$  for UC<sub>1.00</sub> =  $-24.0 \pm 0.7$  kcal/mole. The value of the enthalpy of formation of UC<sub>2</sub> should also be corrected according to the same principle. Evidently, the most reliable value if  $\Delta H_{f298}^o$  for UC<sub>1.90</sub> =  $-21.6 \pm 1.4$  kcal/mole. In [22] the enthalpy of formation of U<sub>2</sub>C<sub>3</sub> was found equal to  $-44.0 \pm 2$  kcal/mole.

**Free Energy of Formation.** Figures 5-7 present the results of high-temperature measurements of the free energy of uranium carbides, obtained by different researchers, treated in [4]. The solid lines in Figs. 5 and 7 were constructed on the basis of the thermal function of UC<sub>1.0</sub> and UC<sub>1.9</sub> (see Tables 3 and 4) in such a way that they passed through the most reliable values obtained by the calorimetric method at the temperature 298°K.

The performance of measurements in different and frequently very limited temperature intervals and the substantial discrepancies between the results of different authors hinder a comparison of the data and do not give sufficiently reliable values of the free energy of uranium carbides within a broad temperature range. Noteworthy is the discrepancy in the values of the free energy, calculated from the purely calorimetric data and obtained by other methods. Analyzing the causes of this discrepancy, the authors of [4] hypothesized that the entropy of uranium ( $S_{298}^o$ ) may be equal not to 12, but to 14 cal/mole · deg. One of the causes of the discrepancy of the results of measurements of the vapor pressure may be an impurity of oxygen, especially when the investigated material is taken in the form of a powder or pulverized between individual experiments. Evidently a great role in the measurements is played by kinetic factors, since the processes of diffusion determine the concentration gradient.

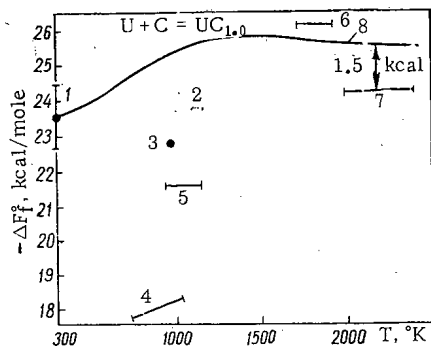


Fig. 5

Fig. 5. Free energy of formation of UC: 1) purely calorimetric method ( $\Delta H_{298} = -23.3$  kcal/mole) [14]; 2) equilibrium of UC + UC<sub>2</sub> and UC<sub>2</sub> + C with liquid bismuth [15]; 3) equilibrium of UC with liquid zinc [16]; 4) measurement of the emf [16]; 5) the same [17]; 6) equilibrium UO<sub>2</sub> + 4C = UC<sub>2</sub> + 2CO [18]; 7) vapor pressure of uranium in the system U - C ( $\Delta H_V = 128$  kcal/mole) [19]; 8) see text.

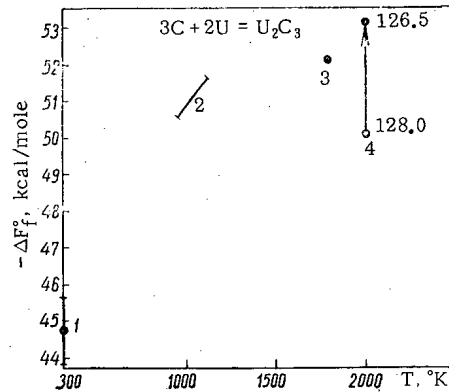


Fig. 6

Fig. 6. Free energy of formation of U<sub>2</sub>C<sub>3</sub>: 1) purely calorimetric data ( $\Delta H_{298} = -43.3$  kcal/mole) [19]; 2) measurement of emf [23]; 3 and 4) see text.

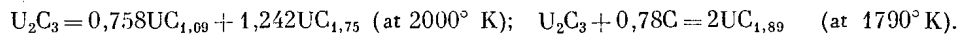
TABLE 5. Thermal Functions of UN

T, °K	C <sub>p</sub> , cal/mole·deg	H <sub>T</sub> <sup>o</sup> - H <sub>298</sub> <sup>o</sup> , cal/mole	S <sup>o</sup> , cal/mole·deg	(F <sub>T</sub> <sup>o</sup> - H <sub>298</sub> <sup>o</sup> )/T, cal/mole·deg
298	11,43	0	14,97	14,97
500	13,07	2 512	21,37	16,35
700	13,65	5 190	25,87	18,46
900	14,06	7 961	29,35	20,50
1100	14,45	10 811	32,21	22,38
1300	14,88	13 743	34,66	24,09
1500	15,36	16 767	36,82	25,64
1700	15,91	19 893	38,77	27,07
1900	16,52	23 125	40,57	28,41
2100	17,20	26 506	42,26	29,62
2300	17,95	30 021	43,86	30,81
2500	18,77	33 692	45,39	31,92
2700	19,66	37 534	46,87	32,97
2900	20,63	41 562	48,31	33,98
3125	21,79	46 333	49,94	35,12

method):

$$\Delta F_f U_2C_3 = -43860 - 7T \text{ kcal/mole.}$$

The value of  $\Delta F_f$  for U<sub>2</sub>C<sub>3</sub> can be calculated, using data for UC and UC<sub>2</sub>, from the equilibria



The corresponding values of  $\Delta F_f$  for U<sub>2</sub>C<sub>3</sub> are equal to -49.96 kcal/mole (at  $\Delta H_V^o = 128$  kcal/mole) and -52.0 kcal/mole [4]. On account of the absence of certain necessary thermal data for U<sub>2</sub>C<sub>3</sub>, it is not known whether there is agreement between the values obtained. However, it is clear that when  $\Delta H_V = 128$  kcal/mole is used, the value of  $\Delta F_f$  for U<sub>2</sub>C<sub>3</sub> is too small, but it becomes more suitable if the calculation is performed at  $\Delta H_V^o = 126.5$  kcal/mole.

### The Uranium - Nitrogen System

In this article we shall discuss only the thermodynamic properties of uranium mononitride, UN, on the basis of the data of [26].

The heat capacity and heat content of UN were determined experimentally at low temperatures in [27, 28] and at high temperatures in [29, 30] (Fig. 8).

The results of both low-temperature measurements [27, 28] are in good agreement in most of the temperature region, but in the interval 250-350°K there is a slight discrepancy. The values of C<sub>p</sub> obtained in

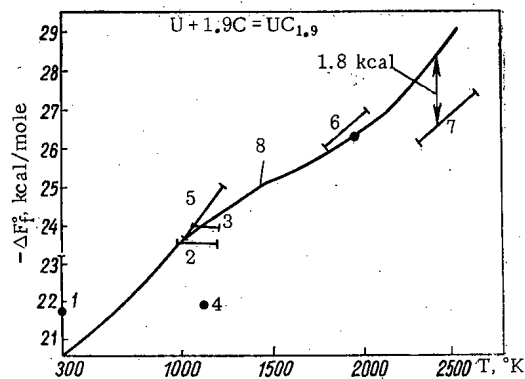


Fig. 7

Fig. 7. Free energy of formation of  $UC_2$ : 1) purely calorimetric data [24]; 2) measurement of emf [17]; 3) equilibrium of  $UC_2 + C$  with liquid bismuth [15]; 4) the same [25]; 5) measurement of emf [23]; 6) equilibrium  $UO_2 + UC_2 = 4UC + 2CO$  [18]; 7) vapor pressure of uranium in the system  $U - C$  ( $\Delta H_v = 128$  kcal/mole) [19]; 8) see text (entropy of randomization taken into consideration).

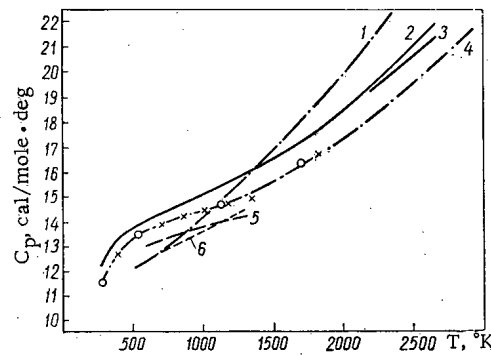


Fig. 8

Fig. 8. Heat capacity of UN: 1) data of [31]; 2) [11]; 3) [31], [29]; 4(O) [26]; 4(x) [29]; 5) [32]; 6) [30].

[28] are somewhat higher and in better agreement with the high-temperature measurements of [29], and for this reason are preferable.

Of the high-temperature measurements [29, 30], the data of [29] are better, since they were performed in a broader temperature interval. The calculated curves obtained [31, 32] were constructed as a result of a mathematical treatment of the experimental data [29, 30]. However, these curves do not coincide with the latter.

The author of [26], using the equation recommended [11] for the calculation of the temperature dependence of refractory compounds of the type of carbides, of the form

$$C_p = c_1 + c_2T + c_3T^2 + c_4T^{-2} \quad (2)$$

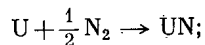
and the experimental data of [29], also constructed the curves cited in Fig. 8. It is in good agreement with experimental data of [29] and almost parallel to the curve expressing the heat capacity of uranium monocarbide UC, cited in Fig. 8 for comparison.

Considering the similarity of the chemical bonds and the monotypic nature of the crystal lattices of UN and UC, such parallelism of the curves of  $C_p$  for UN and UC seems logical and is an additional confirmation of the curve constructed in [26].

The thermal functions of UN, calculated by the author of [26] using the formula that he obtained, as well as the values of the heat capacity  $C$  and the entropy  $S$  at 298°K, determined in [28], are cited in Table 5 and are recommended.

The heat of formation of UN was determined by two methods:

1) by measurement of the heat liberated in the reaction

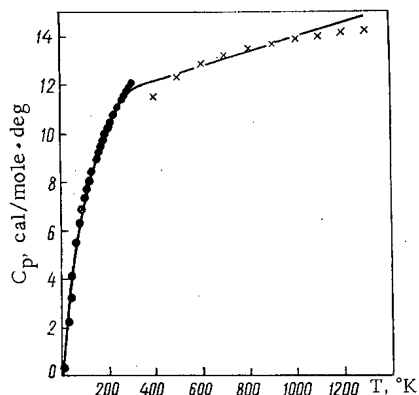


2) by the calorimetric method of combustion in fluorine or oxygen. The values of the heat of formation, measured by the second method, are more negative. The cause of this discrepancy is not known.

Evidently the data obtained by the first method are preferable [35, 36], since they were measured under conditions that better correspond to the practical conditions and are close to the heat of formation of UN, measured by the method of combustion in oxygen [37]. The average of the data of these three studies [35-37] is equal to  $-70.4 \pm 0.7$  kcal/mole and is recommended for the heat of formation of UN.

TABLE 6. Heat Capacity of PuC<sub>0.87</sub> at Low Temperature

T, °K	C <sub>p</sub> <sup>o</sup> , cal/mole · deg	S <sub>T</sub> <sup>o</sup> , cal/mole · deg	H <sub>T</sub> <sup>o</sup> - H <sub>0</sub> <sup>o</sup> , cal/mole
10	0,33	0,15	1,07
30	2,22	1,29	25,09
50	4,10	2,88	89,05
100	7,35	6,84	384,4
150	8,95	10,14	794,3
200	10,20	12,90	1274,1
250	11,21	15,29	1810,3
298,15	12,03	17,33	2370,4

Fig. 9. Heat capacity of PuC<sub>0.9</sub>: ×) data of [33]; ●) [34].TABLE 7. Thermal Functions of PuC<sub>0.87</sub> \*

T, °K	C <sub>p</sub> cal /mole · deg	S <sub>T</sub> <sup>o</sup> , cal /mole · deg	H <sub>T</sub> <sup>o</sup> - H <sub>298</sub> <sup>o</sup> , cal/mole	-(F <sub>T</sub> <sup>o</sup> - H <sub>298</sub> <sup>o</sup> )/T, cal/mole · deg
298	11,794	17,300	0,0	17,300
500	12,413	23,543	2 443	18,657
700	13,040	27,819	4 988	20,693
900	13,671	31,172	7 659	22,662
1100	14,303	33,976	10 456	24,471
1300	14,935	36,417	13 380	26,125
1500	15,567	38,598	16 430	27,645
1700	16,200	40,585	19 607	29,052
1927	16,918	42,660	23 366	30,535

\* The entropy of ordering is not included.

### The Plutonium - Carbon System

**Low-Temperature Heat Capacity.** According to the communication [34], the heat capacity of plutonium monocarbide with the composition PuC<sub>0.95</sub> (49 atomic % carbon) was measured at Harwell. By metallographic analysis, 6.3 mole % Pu<sub>2</sub>C<sub>3</sub> was detected in it, so that the "monocarbide" had a composition of PuC<sub>0.86</sub>. The smoothed out results of the measurements are presented in Table 6. There are no other data on the low-temperature heat capacity of plutonium carbides.

**High-Temperature Heat Capacity.** There is information only on the heat capacity of PuC<sub>0.87</sub>, measured by the method of calorimetry of mixing in the interval 425-1295°K [33]. The thermal functions of PuC<sub>0.9</sub> obtained are cited in Table 7.

It is scarcely possible to evaluate the heat capacity of Pu<sub>2</sub>C<sub>3</sub> sufficiently reliably, since there are no data for compounds with such a structure.

**Enthalpy of Formation.** It should be considered that the values of ΔH<sub>f298</sub><sup>o</sup> for PuC<sub>0.77</sub> and Pu<sub>2</sub>C<sub>3</sub>, obtained by the method of calorimetry of combustion [38], were erroneous on account of the insufficiently accurate characterization of the combustible substances.

V. V. Akhachinskii has proposed a new method of evaluating the heats of formation of plutonium carbides [39]. He has noted that if in carbides formed by chemically similar metals (for example, TiC, ZrC, HfC) the values of the parameter ΔH<sub>subl,Me</sub>/T<sub>m,Me</sub> = K<sub>1</sub> are close, then the values of ΔH<sub>f298</sub>MeC/ΔH<sub>subl,Me</sub> = K<sub>2</sub> and ΔH<sub>f298</sub>MeC/T<sub>m,Me</sub> are also close where ΔH<sub>subl,Me</sub> and T<sub>m,Me</sub> are the heat of sublimation (at 298°K) and the melting point of the metal forming the carbide, while ΔH<sub>f298</sub>MeC is the heat of formation of the carbide per g-atom of the metal. In the case of carbides of variable composition, ΔH<sub>f298</sub> pertains to the carbide with maximum carbon content. As a result of the enthalpy of formation, the value of ΔH<sub>f298</sub><sup>o</sup> for PuC<sub>0.87</sub>, Pu<sub>2</sub>C<sub>3</sub>, and PuC<sub>2</sub> was estimated at -14.5 ± 1.4, -29.0 ± 2.9, and 14.5 ± 1.4 kcal/mole.

**Free Energy of Formation.** Recently the pressure of plutonium above two-phase systems "PuC" + Pu<sub>2</sub>C<sub>3</sub> and PuC<sub>2</sub> + C was measured by the vapor transfer method [40]. The Knudsen method has been used [41] to investigate two-phase regions "PuC" + Pu<sub>2</sub>C<sub>3</sub> and Pu<sub>2</sub>C<sub>3</sub> + C. The results of the measurements, performed by two groups of researchers in overlapping composition regions, differed by no more than 10%. The vapor pressure of plutonium above two-phase regions was expressed by the following equations:

$$\text{«PuC»} + \text{Pu}_2\text{C}_3 \quad \lg P_{\text{atm}} = 5.116 - \frac{18853}{T} \quad (1325 - 1907^\circ \text{K}); \quad (3)$$

$$\text{Pu}_2\text{C}_3 + \text{C} \quad \lg P_{\text{atm}} = 4.39 - \frac{20330}{T} \quad (1366 - 1835^\circ \text{K}); \quad (4)$$

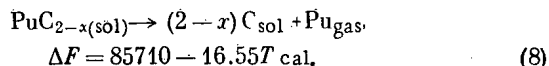
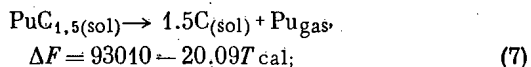
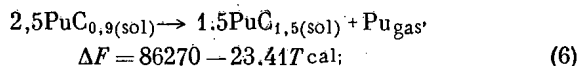
$$\text{PuC}_{2-x} + \text{C} \quad \lg P_{\text{atm}} = 3.618 - \frac{18723}{T} \quad (2017 - 2472^\circ \text{K}), \quad (5)$$

where the first equation is the result of a treatment of the experimental studies [40, 41] by the method of least squares. From these equations we can obtain expressions for the change in the free energy of the

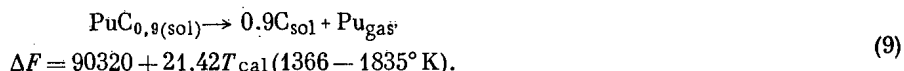
TABLE 8. Thermodynamic Functions of  $\text{PuC}_{0.87}$ 

T, °K	$\Delta H_f^\circ$ , cal/mole	$\Delta S_f^\circ$ , cal/mole · deg	$\Delta F_f$ , cal/mole
300	-10 400	2,89	-11 260
500	-11 110	1,19	-11 700
700	-11 220	1,01	-11 930
900	-11 540	0,56	-12 050
1100	-12 000	0,04	-12 040
1300	-11 700	0,29	-12 080
1500	-11 330	0,55	-12 160
1700	-10 870	0,84	-12 300
1927	-10 240	1,19	-12 530

following reactions, on the assumption that the carbon-rich boundary of the monocarbide phase corresponds to  $\text{PuC}_{0.9}$ , while  $\text{Pu}_2\text{C}_3$  is a stoichiometric phase with a very low concentration interval:



From Eqs. (6) and (7) it follows that



Calculations using the second law of thermodynamics give a value of  $\Delta H_{f298}^\circ = 93.0$  kcal for reaction (9), which is in good agreement with the value calculated according to the third law of thermodynamics and is equal to 93.4 kcal. Combining this value with the standard heat of sublimation of plutonium ( $83.0 \pm 1.0$  kcal), we can find that the standard enthalpy of formation of plutonium monocarbide  $\Delta H_{f298}^\circ$  for  $\text{PuC}_{0.9(\text{sol})} = -10.4$  kcal/mole.

In [42] the activity of plutonium in the two-phase regions  $\text{PuC} + \text{Pu}_2\text{C}_3$  ( $971-1060^\circ\text{K}$ ) and  $\text{Pu}_2\text{C}_3 + \text{C}$  ( $974-1091^\circ\text{K}$ ) was measured by the emf method. Analyzing the results obtained, the author of [34] obtained for the reaction



the equation

$$\Delta F_T^\circ = -15450 + 1,30T \text{ cal.} (970 - 1060^\circ \text{K}), \quad (11)$$

which differs somewhat from that cited in [42]. Evidently the slope of the line  $\Delta F = f(T)$  according to the data of [42] is erroneous, since the value of  $\Delta S$  of the reaction could not be determined accurately on account of the small temperature interval of the measurements. Calculations according to the third law, if  $\Delta F_{1000}$ , calculated according Eq. (11), is taken as the basis, give a value of  $\Delta H_{f298}^\circ$  for  $\text{PuC}_{0.9} = 12.5$  kcal, which is close to the value obtained by V. V. Akhachinskii [39] as a result of an estimate.

For the reaction



the following function was found in [42]

$$\Delta F_T^\circ = -52500 + 14,7T \text{ cal.} (974 - 1091^\circ \text{K}). \quad (13)$$

At the present time, the results of measurements of the vapor pressure are preferable to the data obtained by the emf method on account of the good agreement of the results of various investigators and the good agreement with the theoretical data. Combining the latter with the calculated standard heat of formation of  $\text{PuC}_{0.9}$  ( $-10.4$  kcal/mole), we can obtain the thermodynamic functions cited in Table 8.

The free energy of formation can be represented by two equations:

$$\text{Pu}_{\text{sol}} + 0,9\text{C}_{\text{sol}} = \text{PuC}_{0,9(\text{sol})},$$

$$\Delta F^\circ = -11060 - 1,16T (298 - 913^\circ \text{K});$$

$$\text{Pu}_{\text{liq}} + 0,9\text{C}_{\text{sol}} = \text{PuC}_{\text{sol}},$$

$$\Delta F^\circ = -11510 - 0,48T (913 - 1927^\circ \text{K}).$$

The tables of thermodynamic functions for  $\text{Pu}_2\text{C}_3$  and  $\text{PuC}_2$  cannot be compared on account of the absence of thermal data. However, using the data of [43] on the evaporation of pure plutonium and the thermal data, cited in [44], we can find the values of  $\Delta F^\circ$  in the high-temperature region.

For the process



$$\Delta F^\circ = 79570 - 22.39T \text{ cal} \quad (1366 - 1835^\circ \text{K}); \quad (15)$$

$$\Delta F^\circ = 81360 - 23.32T \text{ cal} \quad (2017 - 2472^\circ \text{K}). \quad (16)$$

From these equations and Eqs. (7) and (8), we find for



$$\Delta F = -13440 - 2.3T \text{ cal} \quad (1366 - 1835^\circ \text{K}) \quad (18)$$

and for



$$\Delta F = -4350 - 6.77 \text{ cal} \quad (2017 - 2472^\circ \text{K}). \quad (20)$$

To eliminate certain contradictions, the author of [44] proposes that Eq. (20) be changed, and reduces it to the form

$$\Delta F = -7580 - 5.33T \text{ cal} \quad (1933 - 2495^\circ \text{K}). \quad (21)$$

There are no data on the thermodynamics of  $\text{Pu}_3\text{C}_2$  (the  $\zeta$ -phase).

Entropy. It may be assumed that the entropy of  $\text{PuC}_{0.87}$  at  $0^\circ\text{K}$  is equal to  $R(0.13 \ln 0.13 + 0.87 \ln 0.87) = 0.77 \text{ cal/mole} \cdot \text{deg}$ . This value should be added to that found experimentally (see Table 7), and then  $S_{298}^\circ$  for  $\text{PuC}_{0.87} = 18.1 \text{ cal/mole} \cdot \text{deg}$ , which agrees with the value proposed in [39]. Evidently the thermal functions of  $\text{PuC}_{0.9}$  cited in Table 7 should be recalculated, considering the new value of the entropy, increasing the absolute values of  $S_T^\circ$  and  $F_T^\circ - H_{298}^\circ/T$  by  $0.77 \text{ cal/mole} \cdot \text{deg}$ . Correspondingly, the enthalpy of formation for  $\text{PuC}_{0.9}$ , calculated according to the evaporation data, using the third law of thermodynamics, proves equal to  $-9.0 \text{ kcal/mole}$ .

In the report [39], the following values of the entropy are recommended for  $\text{Pu}_2\text{C}_3$  and  $\text{PuC}_2$ :  $41.6 \pm 3$  and  $22.5 \pm 2 \text{ cal/mole} \cdot \text{deg}$ , respectively.

#### LITERATURE CITED

1. E. Westrum, E. Suite, and H. Lonsdale, *Advances in Thermophysical Properties at Extreme Temperatures and Pressures*, S. Gratch (editor), ASME (1965), p. 156.
2. R. Andon et al., *Trans. Farad. Soc.*, **60**, 1030 (1964).
3. J. Farr, See [1], p. 162.
4. E. Storms, *The Uranium-Carbon and Plutonium-Carbon Systems*. Report at the Conference of Experts on the Thermodynamics of Uranium and Plutonium Carbides, IAEA, Vienna (September, 1968).
5. E. Westrum, Jr., *Notes on the Thermodynamic Properties of Carbides of Actinides (Preliminary survey)*. See [4].
6. T. Mukaibo et al., *Thermodynamics of Nuclear Materials*, IAEA, Vienna (1962), p. 645.
7. J. Moser and O. Kruger, *J. Appl. Phys.*, **38**, 3215 (1967).
8. C. Affortit, Personal communication, made by R. Lalleman. See [4].
9. L. Harrington and G. Rowe, *Carbides in Nuclear Energy*, L. Russel (editor), Vol. 1 (1964), p. 342.
10. L. Levinson, *ibid.*, p. 429.
11. E. Storms, *The Refractory Carbides*, Academic Press, New York-London (1967).
12. L. Levinson, *J. Chem. Phys.*, **38**, 2105 (1963).
13. A. Macleod and S. Hopkins, *Proc. Brit. Ceramic. Soc.*, **8**, 15 (1967).
14. E. Storms and E. Huber, *J. Nucl. Mater.*, **23**, 19 (1967).
15. I. Craig, Cited according to [4].
16. W. Robinson and P. Chiofti, Report JS-1061 (1966). Cited according to [4].
17. E. McIver, AERE-R 4983, Harwell (1966). Cited according to [4].
18. I. Piazza and M. Sinnot, *J. Chem. Engng. Data*, **1**, 451 (1962).
19. E. Huber and C. Holley, Cited according to [4].
20. L. Leithaker and T. Godfrey, *J. Nucl. Mat.*, **21**, 175 (1967).
21. E. Storms, *Thermodynamics*, Vol. 1, IAEA, Vienna (1966), p. 309.
22. C. Holley, Letter to the Conference of Experts on the Thermodynamics of Uranium and Plutonium Carbides (August, 1968).

23. W. Behl and J. Egan, *J. Electrochem. Soc.*, **113**, 376 (1966).
24. E. Huber, E. Head, and C. Holley, *J. Phys. Chem.*, **67**, 1730 (1963).
25. P. Rice, R. Bajzhiser, and D. Ragone, *Thermodynamics of Nuclear Materials*, IAEA, Vienna (1966), p. 331.
26. H. Blank, *The Ternary System U-C-N. Some Conclusions on the Behavior of Solid Solutions of UC-UN*. See [4].
27. J. Counsell, R. Dell, and J. Martin, *Trans. Farad. Soc.*, **62**, 1736 (1966).
28. E. Westrum and C. Barber, *J. Chem. Phys.*, **45**, 635 (1966).
29. E. Speidel and D. Keller, *BMJ* 1633 (1963). Cited according to [26].
30. L. Harrington, *CN-LM-4461* (1963). Cited according to [26].
31. T. Godfrey, J. Wolley, and J. Leitnaker, *ORNL-TM-1596 (Rev. 1, 1966)*. Cited according to [26].
32. K. Spear and J. Leitnaker, *ORNL-TM-2106* (1968).
33. O. Kruger and H. Savage, *J. Chem. Phys.*, **40**, 3924 (1964).
34. M. Rand, *Thermodynamic Evaluation of the Plutonium-Carbon System*. See [4].
35. P. Gross, C. Hayman, and H. Clayton, *Thermodynamics of Nuclear Materials*, IAEA, Vienna (1962), p. 653.
36. W. Hubbard, *T. J. D. ANL-15554* (1962). Cited according to [26].
37. F. Feder, See [35], p. 665.
38. E. Huber and C. Holley, *Thermodynamics of Nuclear Materials*, IAEA, Vienna (1962), p. 581.
39. V. V. Akhachinskii, *The Heat and Entropy of Formation of Plutonium Carbides*. See [4].
40. F. Harris et al., Cited according to [34].
41. W. Olson and R. Mulford, *Thermodynamics of Nuclear Materials*, IAEA, Vienna (1968), p. 467.
42. G. Campbell, L. Mullins, and J. Leary, *ibid.*, p. 75.
43. Mulford, *RNL, Thermodynamics*, Vol. 1, IAEA, Vienna (1966), p. 231.
44. M. Rand, *Atomic Energy Review*, **4**, Special Issue 1, IAEA, Vienna (1966), p. 7.

## ABSTRACTS

SLOWING DOWN OF RESONANCE NEUTRONS IN MATTER  
COMMUNICATION 4

D. A. Kozhevnikov and V. S. Khavkin

UDC 621.039.512.4

The time dependence of the neutron age  $\tau_S(u, t)$  is examined. In the simplest (Wigner) spectral approximation, for isotropic scattering and constant mean free path

$$\tau_S(u, t) = \tau_S(u) + \frac{\lambda^2}{3} \left[ x^2 - 1 + \frac{2h}{\xi} (x + \ln x - 1) \right]. \quad (1)$$

Here  $\tau_S(u)$  is the total steady-state neutron age,  $h$  the total scattering probability, and  $x = t/\langle t(u) \rangle$ , where  $\langle t(u) \rangle$  is the average slowing-down time.

The analytic features of the complete formal solution of the steady-state slowing-down problem are studied. The spatial, angular, and energy distributions of neutrons close to the source are obtained in explicit form. This result does not depend on the order of the  $B_N$ -approximation ( $N \geq 1$ ) and has the same form for all spectral approximations:

$$\Psi(z, u, \mu) = \chi(z, u, \mu) \Psi_0(z, u); \quad (2)$$

$$\chi(z, u, \mu) = \frac{1}{2} \left\{ 1 + \frac{zZ(u, \mu)}{2\tau_0(u)} + \frac{z^2}{4\tau_0^2(u)} [\tau_S(u, \mu) - \tau_S(u)] + \dots \right\}; \quad (3)$$

$$\Psi_0(z, u) = \frac{\Psi_0(u) e^{-z^2/4\tau_0(u)}}{\sqrt{4\pi\tau_0(u)}} \left\{ 1 + \frac{z^2}{4\tau_0^2(u)} [\tau_S(u) - \tau_0(u)] + \dots \right\} \quad (4)$$

The neutron spectrum  $\Psi_0(u)$ , the total age  $\tau_S(u)$ , the Fermi age  $\tau_0(u)$ , and the second spatial-angular moment  $\tau_S(u, \mu)$  were calculated previously [1, 2] in four spectral approximations (Wigner, Weinberg-Wigner, and the generalized and standard Greuling-Goertzel approximations). The quantities  $\tau_S(u, \mu)$  and  $Z(u, \mu)$  (the first spatial-angular moment) depend on the angular distribution of the source neutrons. The condition for the applicability of (3) and (4) is formulated as the inequality

$$z \ll \frac{2\tau_0(u)}{\lambda_{\max}}, \quad (5)$$

where  $\lambda_{\max}$  is the maximum slowing-down length in the interval. If condition (5) is satisfied the classical age approximation is valid for media with any hydrogen content but is not applicable to an absorbing moderator. The results (3)-(5) are valid for an arbitrary energy dependence of the reaction cross sections and, as is true of the more general formal solution, are easily generalized to take account of inelastic scattering and diffraction anisotropy.

At large distances from the source the spatial and energy neutron distributions are determined by the character of the energy dependence of the total interaction cross section. To explain the principal properties of the distribution function, determined by the resonance character of the  $\Sigma(u)$  dependence, a single negative resonance (interference minimum) of the cross section is considered in the Wigner approximation for isotropic scattering.

In this case

$$\Psi_0(z, u) = B(u) F(z), \quad (6)$$

where the buildup factor  $B(u)$  describes the neutron spectrum, and  $F(z)$  is independent of energy and is

Translated from *Atomnaya Energiya*, Vol. 29, No. 6, p. 448, December, 1970. Original article submitted May 20, 1970.

© 1971 Consultants Bureau, a division of Plenum Publishing Corporation, 227 West 17th Street, New York, N. Y. 10011. All rights reserved. This article cannot be reproduced for any purpose whatsoever without permission of the publisher. A copy of this article is available from the publisher for \$15.00.



determined only by the width of the resonance  $\Gamma$  and the characteristics of the interaction  $h$  and  $\xi$  at the resonance energy:

$$F(z) = \frac{E_1(z/\lambda)}{\lambda \Gamma(\beta)} \left(\frac{2z}{\lambda}\right)^\beta \left\{1 + 0 \left[\frac{1}{z} \ln \frac{z}{\lambda}\right]\right\}, \quad (7)$$

where  $E_1(x)$  is the exponential integral,  $\lambda = \Sigma_{\min}^{-1}$ , and  $\beta = h\Gamma/2\xi$ . This same result holds for two and more negative resonances having the same values of  $\Sigma_{\min}$ . In the latter case  $\beta \rightarrow \beta^* = \beta_1 + \beta_2 + \dots$

#### LITERATURE CITED

1. D. A. Kozhevnikov and V. S. Khavkin, *Atomnaya Énergiya*, 27, 143 (1969).
2. D. A. Kozhevnikov and V. S. Khavkin, *ibid.*, 29, 365 (1970).

### INVESTIGATION OF THE CALIBRATION CHARACTERISTICS OF A RADIATION THERMODIVERTER IN HIGH-INTENSITY FIELDS OF IONIZING RADIATIONS

V. S. Karasev, S. S. Ogorodnik,  
and Yu. L. Tsoglin

UDC 621.039.564

An integrated heat flux calorimeter, known as a radiation thermodiverter (RTD), has been proposed for measuring heat generated by radiation; this device features high accuracy, high sensitivity, quick response, and arbitrary shape and size.

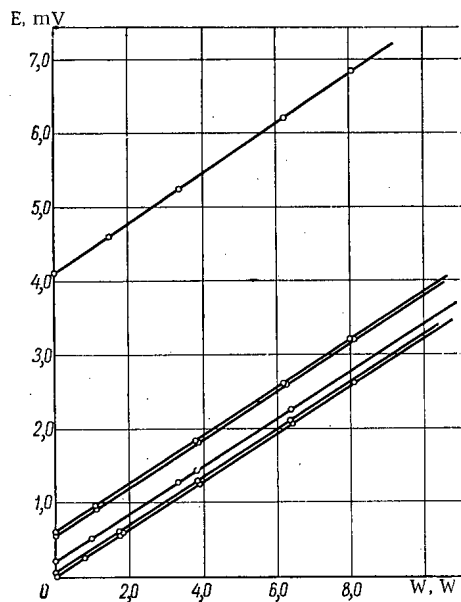


Fig. 1. Calibration curves of RTD (radiation thermodiverter) exposed to pile radiations of different intensity.

The behavior of the calibration curves of the RTD in response to irradiation were studied experimentally in this article, and the results of long-term radiation stability tests directly in the core of the nuclear reactor are reported.

The experimental procedure is designed to take separate account of the effects of intensity, integrated fast flux, and  $\gamma$ -radiation. The transport channel in a reflector at the interface with the reactor core, and an experimental channel in a spent-fuel storage pool, were selected as the exposure zones in the experiment. An RTD with a cylindrical cavity 20 mm in diameter, 20 mm in height, 0.30 mV/W sensitivity, was tested in the reactor channel, and another RTD with an inner cavity 9 mm in diameter and 12 mm in height, with a sensitivity of 66.6 mV/W, was tested in the pool channel.

Results of the RTD calibrations at different positions in the height of the reactor channel, at different stages in the exposure, are plotted in Fig. 1.

The integrated fast (sulfur) flux amounted to  $1.2 \cdot 10^{19}$  neutrons/cm<sup>2</sup> by the time the experiment was over.

For long-term testing for radiation stability, a thermodiverter unit made up of copper-constantan thermopiles with mica interlayers sandwiched between them as electrical insulation, was placed in a hermetically sealed capsule which was

Translated from *Atomnaya Énergiya*, Vol. 29, No. 6, p. 449, December, 1970. Original article submitted March 26, 1970.

inserted into a reactor core cell, replacing one fuel element. The capsule was exposed to irradiation rated at 10 MW for over three months, and received over that time span an integrated fast flux (sulfur) of  $4.3 \cdot 10^{20}$  neutrons/cm<sup>2</sup>, and an integrated thermal flux (gold) of  $6.7 \cdot 10^{20}$  neutrons/cm<sup>2</sup>, with an integrated  $\gamma$ -radiation dose (lead) of  $2.7 \cdot 10^6$  Mrad. A monotonic decline in the dose rate in lead, referred to 1 MW, was observed, ending up at 4.65% by the end of the exposure, and this was accounted for by a decrease in the intensity of the soft component of the  $\gamma$ -radiation stemming from fuel burnup in neighboring fuel elements in the core.

These experiments demonstrated that the calibration curves of the thermodiverter retain their linearity and stability in high-intensity fields of ionizing radiations. The practical feasibility of long-term service of the thermodiverter for in-pile measurements was thereby demonstrated.

## CALCULATION OF PHOTONEUTRON DISTRIBUTION BY MONTE CARLO METHOD

A. A. Morozov and A. I. Khisamutdinov

UDC 539.125.5.348:546:45

The conditions of the problem are as follows. A pulsed source of  $\gamma$ -rays placed at a height  $h$  above the surface of the earth emits 1.667-2.2 MeV photons in a cone of a given angle. The photons fall on beryllium-bearing rock and initiate photonuclear reactions in beryllium, producing neutrons which pass through the air. The beryllium is assumed to be uniformly spread through the rock.

The quantities investigated are the integrated neutron fluxes in given time and energy intervals at various distances from the source. The neutron flux depends on the parameters of the beryllium-containing rock as well as on height, time, energy, and distance from the source.

Plane symmetry in the neutron part of the problem and the uniformity of time were used in finding the required integrated fluxes by a specially developed modification of the Monte Carlo method. Local flux calculations were thus avoided. In the process of solving the problem the neutron trajectory was displaced to the proper point in phase space and then the corresponding "importance of production" was calculated at the point of actual production.

Time histograms were obtained and interpreted for beryllium-bearing granite with porosities of 0, 3, and 6%, energy intervals of 0-0.4 and 0.4-400 eV, heights  $h$  of 20, 45, and 100 m, and distances from the source  $r$  of 0 and 10 m. The time axis of the histograms contains the time intervals  $10^{-5}$ - $10^{-3}$ ;  $10^{-3}$ - $5 \cdot 10^{-3}$ ;  $5 \cdot 10^{-3}$ - $10^{-2}$ ;  $10^{-2}$ - $5 \cdot 10^{-2}$ ; and  $5 \cdot 10^{-2}$ - $10^{-1}$  sec.

The results of the calculations confirm the possibility of air prospecting for beryllium from a height of 45-60 m with a  $\gamma$ -source  $\sim 5 \cdot 10^{12}$  photons/sec for a beryllium density of  $\sim 10^{-5}$  g/cm<sup>3</sup>, and can contribute to the choice of optimum instrument characteristics.

---

Translated from *Atomnaya Energiya*, Vol. 29, No. 6, pp. 449-450, December, 1970. Original article submitted November 11, 1969; revision submitted February 26, 1970; abstract submitted June 23, 1970.

PRECISION SYSTEM FOR THE DETERMINATION OF  
OXYGEN BY FAST NEUTRON ACTIVATION

I. P. Lisovskii and L. A. Smakhtin\*

UDC 621.039.564

A method for determining oxygen from the reaction  $O^{16}(n, p)N^{16}$  is suggested. The samples are irradiated in stainless steel ampoules in an NG-160 neutron generator which is provided with a device for interrupting the deuteron beam (diameter of the ampoules 15 mm, length 20 mm, and internal volume 1.6 cm<sup>3</sup>). The maximum flux at the point of irradiation amounts to  $5 \cdot 10^8$  neutrons/cm<sup>2</sup>·sec. The integral neutron flux through the internal volume of an ampoule (sample) is directly proportional to the flux through the ampoule walls. This makes it possible to use the induced activity of the ampoule (reaction  $Fe^{56}(n, p) \cdot Mn^{56}$ ) as the flux monitor. The sample position during the irradiation need not be exactly determined.

The  $\gamma$ -emission of the samples and of standards was measured with a detector (NaI(Tl) crystal with a size of 150 mm  $\times$  100 mm and with a hole of 20 mm diameter and 50 mm depth) and an LP4050 512-channel analyzer.

The  $N^{16}$  activity was measured in the range 4.8 to 8 MeV. Lucite (C<sub>5</sub>H<sub>8</sub>O<sub>2</sub>) was used as an oxygen standard. The ampoules were transported in an automated pneumatic shuttle. The irradiation time was 30 sec, the delay time 0.9 sec, and the exposure time 30 sec. The background generated by the ampoule was taken into account. The accuracy of the determinations amounted to 1-2.5 relative percent, depending upon the oxygen concentration. The sensitivity was  $10^{-4}$  g O<sub>2</sub>.

VVR REACTOR SEMIAUTOMATIC ACTIVATION  
ANALYSIS SYSTEMI. P. Lisovskii, L. A. Smakhtin,  
N. V. Filippova, and V. I. Volgin†

UDC 621.039.56

A semiautomatic pneumatic shuttle system for a nuclear reactor is described. The specimens were irradiated in hermetically sealed polyethylene capsules which were placed in the shuttle rabbit. After ten rabbits with specimens have been placed in the loader, all further operations (irradiation exposure, extraction of capsule with specimen from the rabbit and delivery of specimen to the laboratory for measurements) are handled automatically. The total time elapsed from the end of the irradiation exposure to the beginning of measurements is 10 to 20 sec (depending on the size of the capsules).

Work done in activation analysis with the aid of this semiautomatic shuttle and irradiation system is reviewed. Operating experience with this pneumatic shuttle, over a four-year period, has demonstrated the versatility, reliability, and ease of operation of the system.

---

\*Translated from Atomnaya Énergiya, Vol. 29, No. 6, p. 450, December, 1970. Original article submitted March 20, 1970.

†Translated from Atomnaya Énergiya, Vol. 29, No. 6, p. 450, December, 1970. Original article submitted March 20, 1970.

METHOD OF ATTENUATING RADIAL BETATRON  
OSCILLATIONS IN CYCLIC ACCELERATORS

L. A. Roginskii and G. F. Senatorov

UDC 621.384.6.07

Systems for the attenuation of betatron oscillations are of great importance for the development and use of cyclic accelerators designed for high intensities and energies. The conventional attenuation systems [1-4] comprise pickup electrodes, which measure the deviation of the beam from the chamber axis (sensors), and electrostatic deflectors (correctors), which adjust the transverse momentum of the particles. The present article is a theoretical consideration of an attenuation method slightly different from the conventional method. The principle of the present method, which was suggested by the author of the article and by Yu. S. Ivanov in the Radiotechnical Institute of the Academy of Sciences USSR, is based on the fact that the voltage of several accelerating sections is modulated by a signal proportional to the signal of a sensor measuring the beam shift. The momentum change which is induced in the particle's momentum by the modulation of the longitudinal accelerating field causes a shifting of the particles in radial direction. The system parameters can be selected so that the radial force attenuates the betatron oscillations.

Compared with the conventional methods, the present method is characterized by the advantage that the existing accelerating sections can be used as correctors (without affecting their actual purpose); thus, special deflectors, which would occupy additional space, are unnecessary. The relatively low efficiency is the principal disadvantage of the method. The low efficiency results from the fact that the indirect effect upon the radial motion (by modifications of the longitudinal momentum) is small. Nevertheless, one can accomplish in such a system a constant attenuation which is equal to several ten revolutions, and this suffices for suppressing certain transverse beam instabilities (e.g., drag instabilities).

The article describes in detail one of the versions of the proposed attenuation system consisting of a sensor and two accelerating sections used as correctors. The voltage of the first section (first section, as far as the motion of the particles is concerned) is modulated with a signal which is proportional to the sensor signal. Therefore, after passage through the resonator, the particles which arrive in the equilibrium phase acquire a momentum different from the equilibrium momentum. A radial force proportional to the relative momentum deviation caused by the modulation of the accelerating voltage acts upon the particles. The phase of the voltage applied to the second resonator is opposite to the modulation of the first resonator, and therefore, the momentum deviation of the particles vanishes after the passage of the particles through the resonator, and the particle motion is not affected by a radial force.

The system was described with a matrix method. The attenuation decrement and the stability regions were determined. It could be shown that the distance between the sensor and the first section must be equal to an integer of the wavelength of the betatron oscillations in order to obtain the highest efficiency; the distance between the sections must be equal to a half integer of the betatron oscillation wavelength.

## LITERATURE CITED

1. C. Pruett, Fifth International Conference on High Energy Accelerators, Frascati (1965), p. 363.
2. J. Martin, Fifth International Conference on High Energy Accelerators, Frascati (1965), p. 347.
3. H. Barton, A Summary of the Cosmotron Experiments on the Coherent Vertical Instability, MOB-7 (November 27, 1963).
4. P. R. Zenkevich, Thesis, Moscow (1965).

---

Translated from *Atomnaya Energiya*, Vol. 29, No. 6, pp. 450-451, December, 1970. Original article submitted November 20, 1969; abstract submitted June 17, 1970; revision submitted June 17, 1970.

PERMANENT ELECTROMAGNET WITH BUILT-IN  
RADIOISOTOPE THERMOELECTRIC DIRECT CONVERTER

A. Kh. Cherkasskii and V. S. Makarov

UDC 621.362

An independently functioning electromagnet with a built-in thermoelectric direct converter for direct conversion of the heat energy of radioactive decay into electrical energy, and combining the positive features of a permanent magnet (continuous and independent operation without the aid of external power supplies) with the advantages of an electromagnet (high field strength, high flux density, linearity of  $B-H$  characteristics, stability to effects exerted by strong externally applied magnetic fields, capability of service at temperatures well above the Curie point of ferromagnetic materials), is proposed by the authors and examined.

This "quasipermanent" magnet (see Fig. 1) consists of the thermopiles 1 and 2 placed on the surface of the fuel slug 3 and the electrically closed winding 4, which envelops the ferromagnetic core 5. A part of the core is cut off to form a working gap. The fuel slug consists of several capsules with radioactive isotope 6 placed within a current-conducting casing 7. The heat energy of radioactive decay is converted by the thermoelectric cells into electrical energy, so that a short-circuit current appears in the magnet winding, and a magnetic field is established in the working gap.

The current in question depends on the parameter  $Y \equiv \alpha\sigma/\kappa$  of the thermoelectric material, which is expressed in A/W units:

$$I = \frac{q_0 b l_{Fe}}{(1+m+zT)} Y A, \quad (1)$$

where  $\alpha, \sigma, \kappa$  are the thermal emf, electrical conductivity, and thermal conductivity of the thermoelectric cell;  $q_0$  is the density of the heat flux flowing through the thermoelectric cell;  $b l_{Fe}$  is the heat contact surface;  $m$  is the ratio of the winding resistance to the resistance of the pn pair;  $zT$  is the Ioffe criterion. When the number of turns  $\omega_{opt} = [(1+zT)/m]^{1/2}$  has been optimized, the field intensity in the working gap will be

$$H_\delta = \frac{q_0 b l_{Fe}}{2 k m_0 \sqrt{1+zT} l_\delta} Y A/m; \quad (2)$$

and the magnetic flux density in the working gap will be:

$$B_\delta = \frac{\mu_0 q_0 b l_{Fe}}{2 k m_0 \sqrt{1+zT} l_\delta} Y m l, \quad (3)$$

while the volume density of electromagnetic energy in the working gap will be:

$$W_\delta = \frac{H_\delta B_\delta}{2} = \frac{\mu_0}{4} \left[ \frac{q_0 b l_{Fe}}{k m_0 \sqrt{1+zT} l_\delta} Y \right]^2 J/m^3, \quad (4)$$

and the specific electromagnetic energy referred to the weight of the core will be:

$$W_{Fe} = \frac{H_\delta B_\delta S_{Fe} l_\delta}{\gamma_{Fe} S_{Fe} l_{Fe}} = \frac{\mu_0}{4} \left[ \frac{q_0 b Y}{k m_0 \sqrt{1+zT}} \right]^2 \frac{l_{Fe}}{l_\delta} \cdot \frac{1}{\gamma_{Fe}} J/kg, \quad (5)$$

where  $m_0 = m/\omega^2$ ;  $l_\delta, S_\delta$  are the length and area of the working gap;  $l_{Fe}, S_{Fe}, \gamma_{Fe}$  are the length, cross-sectional area, and specific weight of the core;  $\mu_0$  is the magnetic permeability constant;  $k$  is a multiplicative factor characterizing the contribution made by the core resistance to the total circuit resistance.

Calculations for basic parameters of this autonomous electromagnet made from thermopiles of silicon-germanium alloy for various types of

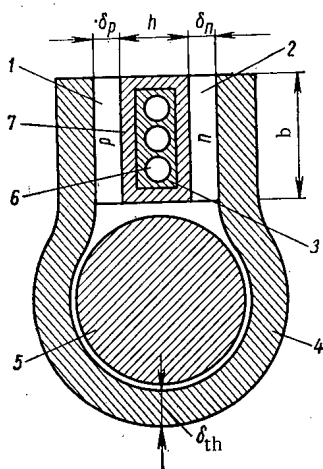


Fig. 1. Layout of permanent electromagnet.

Translated from Atomnaya Énergiya, Vol. 29, No. 6, pp. 451-452, December, 1970. Original article submitted March 3, 1970.

radioactive fuel, including: Sr<sup>90</sup>, Pu<sup>238</sup>, Cm<sup>244</sup>, U<sup>232</sup>, Ce<sup>144</sup>, Po<sup>210</sup>, and Th<sup>228</sup>, are cited. It is shown that other types of built-in director converters can be used along with the thermoelectric converter, e.g., thermionic converters or thermophotovoltaic converters.

## LETTERS TO THE EDITOR

EXPERIMENTAL STUDY OF THE CHARACTERISTICS  
OF THE IR-100 RESEARCH REACTOR

L. V. Konstantinov, I. N. Martem'yanov,  
V. A. Nikolaev, A. A. Sarkisov,  
V. F. Sachkov, A. V. Sobolev,  
S. V. Chernyaev, and I. S. Chesnokov

UDC 621.039.521;621.039.55

The water-cooled, water-moderated IR-100 teaching and research reactor was commissioned in 1967; it was designed for a thermal power of 100 kW and used uranium dioxide (10% enriched) as nuclear fuel. Sheathless fuel cassettes were used for the first time in the IR-100, in conjunction with small graphite displacers and a demountable graphite reflector; these enabled a variety of critical-composition configurations to be created.

The release of heat from the active zone of the reactor is effected by the natural directional circulation of water. The water is cooled in a heat exchanger built into the vessel of the reactor. In order to improve the natural circulation of the water, the reactor vessel contains a concentric cylindrical barrier situated below the active zone. The barrier separates the active zone and the space above it filled with hot water from the water cooled in the heat exchanger.

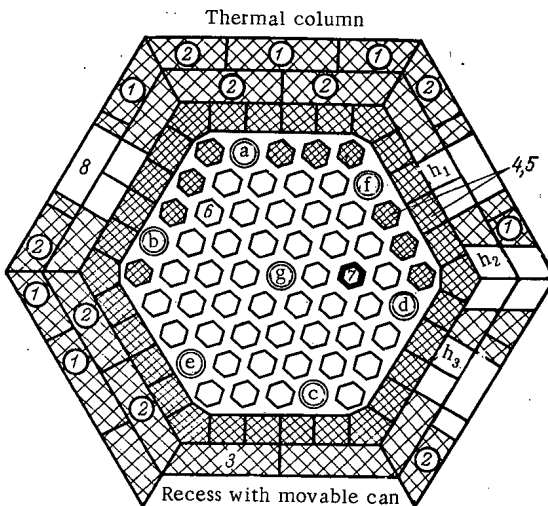


Fig. 1. Schematic chart indicating the loading of the active zone and the arrangement of the experimental sections in the IR-100 reactor: 1) ionization-chamber channels; 2) vertical experimental channels (VEC); 3) graphite reflector; 4, 5) graphite displacers; 6) fuel cassette; 7) photoneutron source; 8) shuttle channel; a) automatic-control rods; b, c, d) scram rods; e, f) manual-control rods; g) CEC;  $h_1$ - $h_3$  HEC.

A description of the construction of the IR-100 and its rated physical and technological parameters was given earlier [1, 2].

In this paper we shall present the results of some measurements carried out during the introductory period and the subsequent running of the reactor, characterizing its experimental potentialities.

A schematic chart representing the loading of the active zone and the arrangement of the experimental sections of the reactor are presented in Fig. 1. The working load (charge) of the active zone comprises 43 fuel cassettes (2.4 kg  $U^{235}$ ), 40 graphite displacers, and one beryllium photoneutron source.

The reactivity reserve of the reactor with the experimental sections empty is 0.58%. The total compensating capacity of the control rods is 4.7%.

The reactivity introduced by the mobile can [1] is 0.06% on filling it with graphite and 0.05% on filling it with water. Filling the central experimental channel (CEC) with water increases the reactivity of the reactor by 0.48%. Filling the other experimental regions with water has no effect on the reactivity of the system.

Table 1 presents the thermal-neutron fluxes and the dose rate of  $\gamma$ -radiation in the vertical experimental

Translated from *Atomnaya Énergiya*, Vol. 29, No. 6, pp. 453-454, December, 1970. Original article submitted January 23, 1970.

© 1971 Consultants Bureau, a division of Plenum Publishing Corporation, 227 West 17th Street, New York, N. Y. 10011. All rights reserved. This article cannot be reproduced for any purpose whatsoever without permission of the publisher. A copy of this article is available from the publisher for \$15.00.

TABLE 1. Thermal-Neutron Fluxes and Dose Rate of  $\gamma$ -Radiation in the Experimental Systems

Experimental system	Thermal-neutron flux, $\cdot 10^{12}$ neutrons/cm <sup>2</sup> · sec	Dose rate of $\gamma$ -radiation, $\cdot 10^6$ R/h	Experimental system	Thermal-neutron flux, $\cdot 10^{12}$ neutrons/cm <sup>2</sup> · sec	Dose rate of $\gamma$ -radiation, $\cdot 10^6$ R/h
CEC	2,75	22	VEC-5	0,99	1,9
VEC-1	1,12	2,1	VEC-6	0,97	1,9
VEC-2	1,11	2,2	VEC-7	0,3	0,71
VEC-3	0,34	0,72	VEC-8	0,22	0,70
VEC-4	0,24	0,68	Can	0,1	0,36

TABLE 2. Characteristics of the Horizontal Experimental Channels

Experimental system	Dose rate of $\gamma$ -radiation, R/h	Thermal-neutron flux, neutrons/cm <sup>2</sup> · sec	Fast-neutron flux, neutrons/cm <sup>2</sup> · sec
HEC-1 (h <sub>1</sub> )	6,8 · 10 <sup>5</sup>	1,43 · 10 <sup>8</sup>	2,86 · 10 <sup>7</sup>
HEC-2 (h <sub>2</sub> )	5,5 · 10 <sup>5</sup>	2,53 · 10 <sup>7</sup>	1,65 · 10 <sup>7</sup>
HEC-3 (h <sub>3</sub> )	7,7 · 10 <sup>5</sup>	1,54 · 10 <sup>8</sup>	3,52 · 10 <sup>7</sup>

channels (VEC) and on the front wall of the unloaded "draw-bridge" can at the level of the center of the active zone, referred to the nominal reactor power of 100 kW.

The thermal-neutron fluxes were determined by reference to the absolute activity of a set of gold indicators, using the method of ( $\beta, \gamma$ )-coincidences (maximum error 7%). The dose rate of  $\gamma$ -radiation was measured with small-scale  $\gamma$ -chambers (maximum error 20%).

Table 2 gives the thermal and fast-neutron fluxes and the dose rate of  $\gamma$ -radiation at the exit from the horizontal experimental channels (HEC) for the case of open gates (valves), measured with a universal radiometer of the RUS-7 type and referred to the nominal reactor power of 100 kW.

Practical experience showed that the cooling system employed in the IR-100 reactor had a considerable reserve factor, enabling the reactor power to be raised to between 200 and 300 kW without seriously changing the loading of the active zone.

## LITERATURE CITED

1. Yu. M. Bulkin et al., *Atomnaya Energiya*, **21**, 363 (1966).
2. Yu. M. Bulkin et al., *Byull. Izobret.*, No. 30, 184 (1968).



EFFECT OF THE FLOW VELOCITY OF A VAPOR - LIQUID MIXTURE OF COOLANT, AND OF VAPOR CONTENT, ON SURFACE HEAT-TRANSFER COEFFICIENT IN BOILING OF WATER INSIDE TUBES

F. F. Bogdanov

UDC 621.039.534.44

The literature contains surprisingly little data on the effect of steam content and the flow velocity of a coolant vapor-liquid mixture on surface heat-transfer coefficients in the case of boiling in channels and tubes. This appears to stem from the fact that many investigators have failed to detect any such effects in their experiments at all. One of the reasons for this would be insufficient attention on the part of investigators to keeping the heating surface sufficiently clean. Experience has shown that the presence of a 0.02-0.03 mm thick oxide film on the heating surface will result in an appreciably steep rise in thermal resistance over the path of the heat flux in boiling, offsetting any comparable drop in steam content or in the flow-speed of the vapor-liquid mixture. Hence, only those investigators who stage their experiments on sufficiently clean heating surfaces will have any success in detecting the influence exerted by the above factors on surface heat transfer when water is boiled in channels.

Generalizations about boiling heat transfer within tubes consequently either fail to take account of the effect of vapor content and of the flowspeed of the vapor-liquid coolant mixture at all, or else take account of the effect of vapor content alone, and that in at best a highly approximate manner.

These circumstances render it more convenient to seek out some new form for making generalizations on experimental data, one which would take into account the effect on surface heat-transfer coefficients of changes in the relative steam content by weight, and in the flowspeed of the vapor-liquid coolant mixture.

At the basis of these generalizations, we placed our improved formula from reference [1], with thermodynamic similitude criteria brought into the picture, and proposed for the purpose of determining the surface heat-transfer coefficients in boiling of water on clean heating surfaces when steam content is either positive or negative, as well as the recommendations in reference [2] on treating the effect exerted on heat-transfer coefficients in boiling of a liquid phase in tubes where the flowspeed of the liquid phase is linear, and laminar flow goes over into turbulent flow.

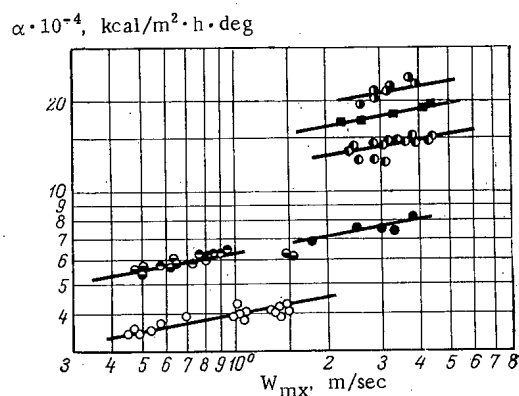


Fig. 1. Dependence of surface heat-transfer coefficients for boiling in tubes on flowspeed of vapor-liquid mixture: ○) author's data for boiling in slightly oxidized tubes (pressure  $p = 55$  atm, heat flux  $q = 2.6 \cdot 10^5$  kcal/m<sup>2</sup>·h, liquid-phase flow-speed  $w_0 = 0.4$  m/sec); ●) same, at  $p = 125$  atm,  $q = 4 \cdot 10^5$  kcal/m<sup>2</sup>·h,  $w_0 = 0.35$  m/sec; ○) same, for  $p = 140$  atm,  $q = 3.7 \cdot 10^5$  kcal/m<sup>2</sup>·h,  $w_0 = 0.4$  m/sec; ●) data borrowed from reference [1], for boiling of water in tubes ( $p = 170$  atm,  $q = 2 \cdot 10^5$  kcal/m<sup>2</sup>·h,  $w_\gamma = 1245$  kg/m<sup>2</sup>·sec); ●) same for  $q = 4.5 \cdot 10^5$  kcal/m<sup>2</sup>·h; ■) same, for  $q = 6 \cdot 10^5$  kcal/m<sup>2</sup>·h; ○) same, at  $q = 8 \cdot 10^5$  kcal/m<sup>2</sup>·h.

Translated from *Atomnaya Énergiya*, Vol. 29, No. 6, pp. 454-456, December, 1970. Original article submitted June 3, 1969; revision submitted November 13, 1969.

© 1971 Consultants Bureau, a division of Plenum Publishing Corporation, 227 West 17th Street, New York, N. Y. 10011. All rights reserved. This article cannot be reproduced for any purpose whatsoever without permission of the publisher. A copy of this article is available from the publisher for \$15.00.

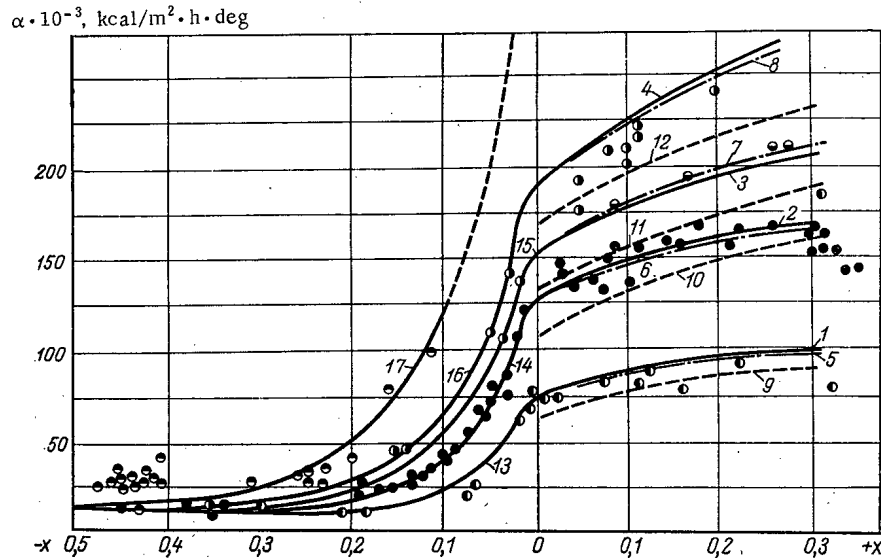


Fig. 2. Dependence of the surface heat-transfer coefficients on the total effect exerted by vapor void content and vapor-liquid mixture flowspeed:  $\odot$ ) data borrowed from reference [1] for a vapor-liquid mixture at  $p = 170$  atm and  $q = 2 \cdot 10^5$  kcal/m<sup>2</sup>·h;  $\bullet$ ) same, at  $q = 4.5 \cdot 10^5$  kcal/m<sup>2</sup>·h;  $\ominus$ ) same, at  $q = 6 \cdot 10^5$  kcal/m<sup>2</sup>·h;  $\oplus$ ) same, at  $q = 8 \cdot 10^5$  kcal/m<sup>2</sup>·h. Curves 1, 2, 3, 4 are theoretical curves plotted on the basis of formula (3) for  $q$  values of  $2 \cdot 10^5$ ,  $4.5 \cdot 10^5$ ,  $6 \cdot 10^5$ , and  $8 \cdot 10^5$  kcal/m<sup>2</sup>·h, respectively; curves 5, 6, 7, 8 are curves plotted on the basis of the formula recommended by the authors of reference [1] for the same heat fluxes, respectively; curves 9, 10, 11, 12 are curves plotted on the basis of formula (3), for  $p = 100$  atm and the same respective heat fluxes; curves 13-16 are plotted on the basis of formula (4), for  $p = 170$  atm and the same respective heat fluxes; curve 17 is plotted on the same basis, but for concentric slit orifices, at  $q = 1.2 \cdot 10^6$  kcal/m<sup>2</sup>·h.

Experimental data borrowed from references [1, 3], and taken from our own experiments, were used in processing the experimental results: 1) on surface heat transfer when subcooled water is boiled on the practically clean heating surfaces of narrow annular channels, and obtained at very high heat flux levels [ $q = 10^6$  to  $3 \cdot 10^6$  kcal/m<sup>2</sup>·h] and at pressure  $p = 175$  atm; 2) on surface heat transfer in the case of boiling in oxide-coated tubes, and obtained at pressures of 50, 120, and 140 atm.

The experiments were carried out by a procedure described in the literature [2], but the arrangement was modified slightly.

A tube of 1Kh18N9T steel with an outer diameter of 23.5 mm and wall thickness of 1.25 mm, total length  $l = 3290$  comprising two sections to be heated:  $l_1 = 345$  mm, and  $l_2 = 1020$  mm, and with a stabilized section left unheated, of length  $l_0 = 805$  mm, was used as the working section in the experiments.

Four Chromel-Alumel thermocouples 0.2 mm in diameter were used on each of two cross sections on the  $l_2$  interval of tubing, and four thermocouples were used in one cross section on the  $l_1$  interval. The thermocouples measured the temperature of the external surface of the experimental tube; the temperature of the tube inner surface was determined by calculations based on K. D. Voskresenskii's formula.\*

The experiments were carried out under rigorously stationary conditions. Only the heat load on the economizer lengths of tubing was varied before each series of experiments. As a rule, the maximum heat load was established in the first experiments in each series, and was found to decrease from one experiment to the next. When the heat load on the economizer tube lengths remained unaltered, five to six experiments each lasting 30 min were carried out.

\*This formula was derived by K. D. Voskresenskii upon the present author's request back in 1949, but has unfortunately remained unpublished. The formula is as follows:

$$\Delta t_w = \frac{q_l}{2\pi\lambda l} \left[ \left( \frac{\ln d_2/d_1}{1-d_2^2/d_1^2} - 0.5 \right) - \ln \frac{d_2}{d_1} q_h \right]^0 C,$$

where  $q_h$  accounts for heat losses to the surroundings.

The steam content by weight of the coolant varied only insignificantly (by a few percent), making it possible to discern the effect exerted by the flowspeed of the vapor-liquid mixture on the surface heat-transfer coefficients, independently of the vapor content, since the direct effect exerted by the vapor phase on the heat-transfer process remains practically unaffected. At the same time, the vapor content by volume varied appreciably from one experiment to the next, and the flowspeed of the vapor-liquid mixture also underwent appreciable changes.

Data from these experiments are plotted in Fig. 1 in the form of the dependence  $\alpha = f(w_{mx})$ . The experimental data points plot out with a modest spread (relative to the skewed straight lines giving the slope  $n = 0.16$  at all the heat fluxes and pressures measured). This means that the change in heat flux and pressure over the range investigated will have no effect on the way heat transfer accompanying boiling of water in tubes is affected by the flowspeed of the vapor-liquid mixture. But the diagram also shows experimental data from reference [1] on heat transfer when water boils in tubes. A correction intended to eliminate any direct effect of the vapor content by weight was introduced into the values of the surface heat-transfer coefficients in this case. The experimental data from [1] corrected in this manner fit with very little spread about the skewed straight lines representing the slopes  $n = 0.16$ . Accordingly, the effect of the flowspeed of the vapor-liquid coolant mixture on the surface heat-transfer coefficients in boiling in tubes and channels can be taken into account by means of the power-law multiplier  $w^{0.16}$  at those parameters, or by the simplex  $(w_{mx}/w_{cr})^{0.16}$  in generalized formulas, at any pressures of the vapor-liquid coolant mixture. This dimensionless criterion links the rate of surface heat transfer, in boiling in channels, with the hydrodynamics of two-phase flow. When we also take into account the recommendations put forth in reference [1] on handling the effect exerted on heat transfer by the steam content by weight in boiling, the total effect of the flowspeed of the vapor-liquid coolant mixture and of the vapor content by weight in this mixture on heat transfer when the coolant boils in the channels in forced flow, can be treated properly by using the dimensionless complex:

$$x^{0.4} \left( \frac{w_{mx}}{w_{cr}} \right)^{0.16} \quad (1)$$

The magnitude of the component of the surface heat-transfer coefficient ascribed to boiling can be determined with sufficient accuracy by using the formula

$$\alpha_b = C \left( \frac{p_{cr}}{p_1} \right)^{0.12} \left( \frac{T_s}{T_{cr} - T_s} \right)^{2/3} q^{0.7} \frac{\text{kcal}}{\text{m}^2 \cdot \text{h} \cdot \text{deg}} \quad (2)$$

Hence, the convective component will be determined from Eq. (2) multiplied by the complex (1). The total heat-transfer coefficient in boiling in tubes is given by the formula

$$\alpha = C \left( \frac{p_{cr}}{p_1} \right)^{0.12} \left( \frac{T_s}{T_{cr} - T_s} \right)^{2/3} q^{0.7} \left[ 1 + x \left( \frac{w_{mx}}{w_{cr}} \right)^{0.4} \right]^{0.4} \frac{\text{kcal}}{\text{m}^2 \cdot \text{h} \cdot \text{deg}} \quad (3)$$

Figure 2 shows experimental data from reference [1] on heat transfer in boiling of water in tubes and when the vapor content is positive, as approximated by formula (3). The free proportionality factor in this formula was adopted in accordance with our recommendations for a weakly oxidized surface, with the assigned value 0.8. The broken curves on this graph are averaging curves [1] plotted for the corresponding heat flux levels.

The theoretical curves based on formula (3) describe the experimental data in [1] quite closely, and almost coincide with the averaging curves based on those data. Figure 3 also shows the theoretical curves based on formula (3) for the pressure  $p = 100$  atm. It is clear from the diagram that these curves are equidistant from the theoretical curves plotted for  $p = 170$  atm.

Here we also have the experimental data from [1] relating the same heat flux levels at negative vapor content (subcooled liquid), at the pressure 170 atm. The experimental data are approximated by the theoretical curves plotted on the basis of a formula in which the multiplicative factor taking the convective component into account is raised to the negative power recommended by the authors of reference [1]. In that case, the computational formula becomes

$$\alpha = C \left( \frac{p_{cr}}{p_1} \right)^{0.12} \left( \frac{T_s}{T_{cr} - T_s} \right)^{2/3} q^{0.7} \left[ 1 + x \left( \frac{w_{mx}}{w_{cr}} \right)^{0.16} \right]^{-2.8} \frac{\text{kcal}}{\text{m}^2 \cdot \text{h} \cdot \text{deg}} \quad (4)$$

The coefficient C is assigned the value 0.8 in this case.

It is clear from the diagram that the experimental data in reference [1] referring to the case of negative vapor void content are described quite closely by formula (4). Our experimental data on surface heat transfer in boiling of subcooled water at the pressure  $p = 170$  atm on a practically clean heating surface of annular channels, with forced flow (indicated by circles blackened in top half), also plotted in that diagram, are again approximated closely by formula (4). The free proportionality factor is assigned the values of 1 and 2 in that case, depending on how clean the heating surface is. These experimentally derived data points fit the approximating curve with a very small spread.

## LITERATURE CITED

1. N. V. Tarasova, A. A. Armand, and A. S. Kon'kov, in: Heat Transfer at High Heat Flux Levels, and Other Special Conditions [in Russian], A. A. Armand (editor), Gosénergoizdat, Moscow (1959), p. 6.
2. F. F. Bogdanov, Izv. Akad. Nauk SSSR, Otd. Tekh. Nauk, No. 4, 136 (1955).
3. W. Elrod et al., Trans. ASME, 89, No. 3 (1967).

NEUTRON YIELD FROM THICK TARGETS BOMBARDED  
WITH 11.5 AND 23.5 MeV PROTONS

V. K. Daruga and E. S. Matusевич

UDC 621.384.633

The measurements were performed at the FEI cyclotron. The energy of the proton beam was determined by the range in aluminum foils and by a semiconductor detector. At the time of the measurements the energy was  $11.5 \pm 0.5$  MeV (molecular hydrogen) and  $23.5 \pm 0.7$  MeV (atomic hydrogen).

The targets of Li, Be, C, Mg, Al, Ti, Fe, Co, Ni, Cu, Zn, Nb, Cd, Ta, W, Pb, Bi, and U had their natural isotopic compositions, and thicknesses equal to the range of the bombarding protons.

The experimental procedure and technique were described earlier [1].

Absolute measurements were made with a  $\text{BF}_3$  long counter. The angular distributions of neutrons from the targets were measured with a  $\text{ZnS(Ag)}$  scintillator in Plexiglas and a  $\text{B}^{10} + \text{ZnS(Ag)}$  scintillator with a polyethylene neutron moderator 5 cm thick. Backgrounds were determined with a shadow cone. The total yields were obtained by integrating the areas under the angular distribution curves, taking account of the neutron spectra and the detector characteristics. The shape of the angular distribution in the  $\theta > 140^\circ$  region was obtained by extrapolation. The angular distributions for all targets except carbon fall smoothly from  $\theta_{\text{lab}} = 0$  to  $\theta_{\text{lab}} = 180^\circ$ . The neutron yield from carbon increases in both the forward and backward directions.

Table 1 shows the absolute neutron yields in  $4\pi$  and in the  $\theta_{\text{lab}} = 0^\circ$  direction. Table 2 gives the characteristics of the neutron spectra in the range  $E_n = 1-6$  MeV for  $E_p = 23.5$  MeV, listing values of the parameters  $T_W$  and  $T_L$  for describing the spectra in the form  $\sim E_n \exp(-E_n/T_W)$  and  $\sim E_n^{5/11} \exp(-E_n/T_L)$  respectively. The spectra of neutrons emitted in the  $\theta_{\text{lab}} = 0^\circ$  direction from light targets (Li, Be, C) are very different from spectra of evaporated neutrons. All spectra have different values of  $T$  in the ranges  $E_n < 3$  MeV and  $3 < E_n < 6$  MeV. The data on neutron spectra for  $E_p = 11.5$  MeV are given in [2].

TABLE 1. Absolute Neutron Yields from Thick Targets

Target	$E_p = 11.5$ MeV		$E_p = 23.5$ MeV	
	Y ( $0^\circ$ ), neutrons/sr $\cdot \mu\text{Ci}$	$Y_{4\pi}$ , neutrons/ $\mu\text{Ci}$	Y ( $0^\circ$ ), neutrons/sr $\cdot \mu\text{Ci}$	$Y_{4\pi}$ , neutrons/ $\mu\text{Ci}$
Li	—	—	$9.5 \cdot 10^9 \pm 13\%$	$5.5 \cdot 10^{10} \pm 16\%$
Be	$6.3 \cdot 10^9 \pm 10\%$	$3.9 \cdot 10^{10} \pm 15\%$	$2.2 \cdot 10^{10} \pm 10\%$	$1.1 \cdot 10^{11} \pm 14\%$
C	$1.75 \cdot 10^7 \pm 6\%$	$1.1 \cdot 10^8 \pm 27\%$	$1.3 \cdot 10^8 \pm 9\%$	$8.0 \cdot 10^8 \pm 25\%$
Mg	—	$6.1 \cdot 10^8 \pm 17\%$	$1.0 \cdot 10^9 \pm 8\%$	$7.5 \cdot 10^9 \pm 15\%$
Al	$1.7 \cdot 10^8 \pm 10\%$	$1.35 \cdot 10^9 \pm 18.5\%$	$1.5 \cdot 10^9 \pm 8\%$	$1.15 \cdot 10^{10} \pm 13\%$
Ti	—	$4.8 \cdot 10^8 \pm 23\%$	$3.95 \cdot 10^9 \pm 10\%$	$3.6 \cdot 10^{10} \pm 14\%$
Fe	—	—	$2.8 \cdot 10^9 \pm 10\%$	$2.5 \cdot 10^{10} \pm 16\%$
Co	—	$5.0 \cdot 10^9 \pm 16\%$	$4.35 \cdot 10^9 \pm 10\%$	$3.7 \cdot 10^{10} \pm 14\%$
Ni	—	$4.6 \cdot 10^8 \pm 18\%$	$1.35 \cdot 10^9 \pm 8\%$	$1.0 \cdot 10^{10} \pm 16\%$
Cu	—	—	$4.1 \cdot 10^9 \pm 8\%$	$3.9 \cdot 10^{10} \pm 15\%$
Zn	—	$2.6 \cdot 10^9 \pm 23\%$	$3.3 \cdot 10^9 \pm 11\%$	$3.0 \cdot 10^{10} \pm 17\%$
Nb	$4.1 \cdot 10^8 \pm 7\%$	$4.6 \cdot 10^9 \pm 15\%$	$5.0 \cdot 10^9 \pm 8\%$	$5.0 \cdot 10^{10} \pm 12\%$
Cd	—	$3.7 \cdot 10^9 \pm 19\%$	$5.0 \cdot 10^9 \pm 8\%$	$5.2 \cdot 10^{10} \pm 14\%$
Ta	—	$1.2 \cdot 10^9 \pm 16\%$	$3.95 \cdot 10^9 \pm 10\%$	$5.0 \cdot 10^{10} \pm 14\%$
W	$9.5 \cdot 10^7 \pm 10\%$	$1.05 \cdot 10^9 \pm 19\%$	—	—
Pb	$5.0 \cdot 10^7 \pm 10\%$	—	$2.95 \cdot 10^9 \pm 11\%$	$3.5 \cdot 10^{10} \pm 18\%$
Bi	—	$5.6 \cdot 10^8 \pm 18\%$	—	—
U	$7.4 \cdot 10^7 \pm 7\%$	$9.0 \cdot 10^8 \pm 17\%$	$5.7 \cdot 10^9 \pm 11\%$	$7.0 \cdot 10^{10} \pm 14\%$

Translated from Atomnaya Energiya, Vol. 29, No. 6, pp. 456-458, December, 1970. Original article submitted June 30, 1970.

© 1971 Consultants Bureau, a division of Plenum Publishing Corporation, 227 West 17th Street, New York, N. Y. 10011. All rights reserved. This article cannot be reproduced for any purpose whatsoever without permission of the publisher. A copy of this article is available from the publisher for \$15.00.

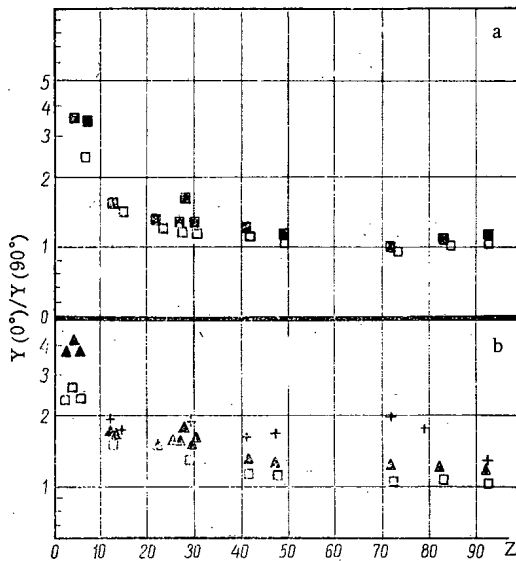


Fig. 1. Ratio of neutron yields  $Y(0^\circ)/Y(90^\circ)$  from thick targets bombarded with protons. a)  $E_p = 11.5$  MeV, mean square error  $\pm\delta = 5-10\%$ ; b)  $E_p = 23.5$  MeV,  $\pm\delta = 10-15\%$ ;  $\square$ )  $E_n > 0$ ;  $\blacksquare$ )  $E_n > 1.6$  MeV;  $\blacktriangle$ )  $E_n > 1.8$  MeV;  $+$ )  $E_n \geq 8$  MeV from [3].

TABLE 2. Parameters for the Analytic Description of Spectra

Target	$\theta = 0^\circ$		$\theta = 90^\circ$	
	$T_W$ , MeV	$T_L$ , MeV	$T_W$ , MeV	$T_L$ , MeV
Li	0,7-1,2	0,8-1,4	0,7-1,0	0,8-1,1
Be	0,9-2,3	1,1-2,9	0,80-2,1	0,95-2,6
Al	1,0-2,7	1,2-3,9	0,9-2,2	1,1-2,6
Cu	0,95-1,55	1,2-1,8	0,8-1,2	0,95-1,4
Cd	0,85-1,15	1,0-1,3	0,75-1,1	0,95-1,25
Pb	0,85-1,1	1,1-1,25	0,8-0,9	1,0-1,1
U	1,0-1,27	1,25-1,45	0,95-1,25	1,25-1,4

Figure 1 shows the ratio of the yields  $Y(0^\circ)/Y(90^\circ)$  as a function of the Z of the target nuclei.

The authors thank V. A. Dulin and N. N. Pal'chikov for help with the measurements, and A. A. Ognev for measuring the proton energy.

#### LITERATURE CITED

1. V. K. Daruga et al., Preprint FEI [in Russian] (1970).
2. V. K. Daruga et al., Bulletin of the Nuclear Data Information Center [in Russian], No. 6, Atomizdat, Moscow (1970).
3. B. Cohen, Phys. Rev., 98, 49 (1955).

## A METHOD OF DETERMINING THE IRON CONTENT OF CORROSION PRODUCT DEPOSITS

B. A. Alekseev, N. N. Kozhenkov,  
and G. A. Kotel'nikov

UDC 621.039.553.36

The current method of analyzing the amount of accumulated corrosion product deposits in nuclear reactor circuits, using specimens of zirconium alloys, is based on boiling the deposits in 6N HCl. However, solution is very slow and systematic errors may be incurred owing to incomplete solution of these products (chiefly iron oxides). These difficulties can be eliminated by determining the content of the corrosion product deposits from their  $\gamma$ -radiation.

Study of the deposits was performed on specimens from outside the active zone – in the heat-transfer agent of the forced-circulation loop of the MR reactor of the I. V. Kurchatov Institute of Atomic Energy. The specimens were prepared from zirconium alloys. The spectrum of the  $\gamma$ -quanta, measured by means of a Ge(Li) detector, clearly displayed  $\text{Co}^{60}$  and  $\text{Cr}^{51}$  isotopes. The iron content was determined by means of o-phenanthroline. The error of the iron determination was assessed by the accuracy of the spectrophotometric method. Thus, during the experiment we determined how the activity of  $\text{Co}^{60}$  in the sweeping-out liquor depends on its iron content.

Analysis of the experimental data revealed that in the corrosion product deposits, the activity of  $\text{Co}^{60}$  is proportional to the iron content to within  $\sim 10\%$  (see Table 1). This fact may be used for rapid and remote-controlled determinations of accumulated iron concentration of specimens, and also in pipelines (for studying the kinetics of sweeping away of deposits), and other similar problems.

We thank V. F. Kozlova for helping with the assembly of the spectrometer, V. A. Ermakov for his useful advice, and V. F. Leonov for operating the apparatus.

TABLE 1. Activity of  $\text{Co}^{60}$  versus Concentration of Accumulated Iron

Fe, mg/liter ( $\cdot 10^3$ )	11	12	18	19	22	27	29	32	34	42	44	54	57	58	69
$\text{Co}^{60}$ , counts /sec	4,0	6,5	8,5	8,0	10,0	12,0	13,0	10,5	14,5	19,0	16,5	21,0	17,0	23,0	27,0

Translated from *Atomnaya Énergiya*, Vol. 29, No. 6, p. 458, December, 1970. Original article submitted July 17, 1969; revision submitted June 1, 1970.

© 1971 Consultants Bureau, a division of Plenum Publishing Corporation, 227 West 17th Street, New York, N. Y. 10011. All rights reserved. This article cannot be reproduced for any purpose whatsoever without permission of the publisher. A copy of this article is available from the publisher for \$15.00.

## GROUP SEPARATION OF FISSION PRODUCTS BY THE CHROMATOGRAPHIC METHOD

L. N. Moskvina and N. N. Kalinin

UDC 543.544.6

Analysis of radioactive elements in the water of the reactor primary loop is protracted and complicated, no matter whether the methods of analysis used are sedimentation techniques, extractive techniques, or chromatographic techniques [1-3]. The appearance of Ge(Li)-detectors in  $\gamma$ -ray spectroscopy has made the job of identifying radioactive elements a much simpler one. It has become possible to estimate the content of individual isotopes directly from the  $\gamma$ -ray spectrum of the primary loop water in the reactor system [4]. But because of the different yields in fission, different activation cross sections for impurities, and peculiar spectral features, some of the radioactive isotopes may escape detection directly against the  $\gamma$ -ray spectrum background of the total sum of active products present in the coolant stream.

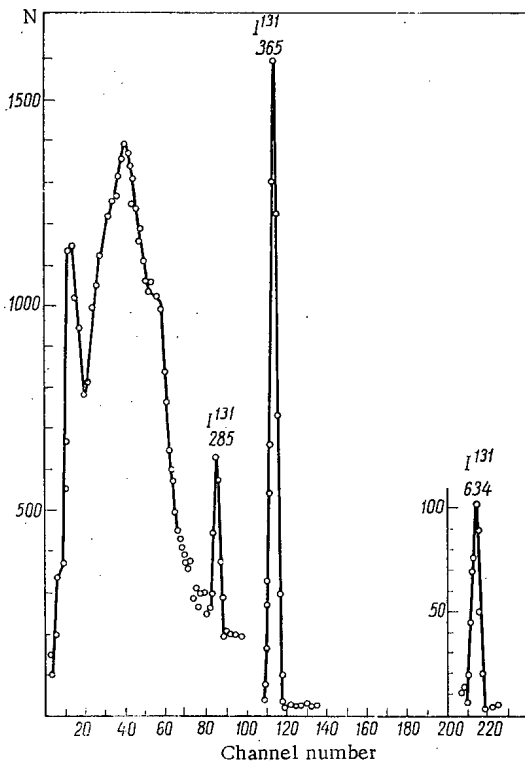


Fig. 1.  $\gamma$ -Ray spectrum of fraction separated out on column packed with AB-17 anion-exchange resin.

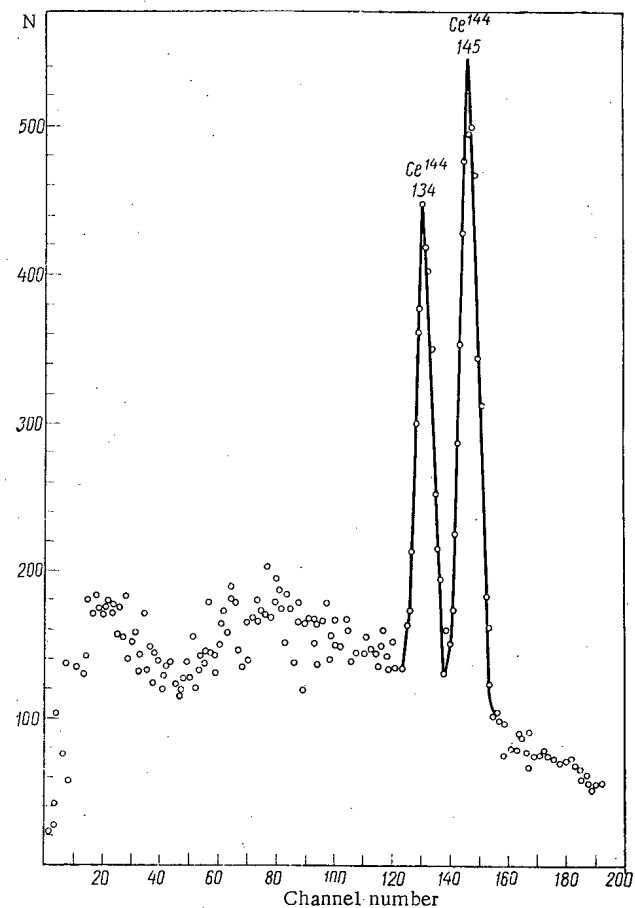


Fig. 2.  $\gamma$ -Ray spectrum of fraction separated out on column with di-2-ethylhexylphosphoric acid.

Translated from *Atomnaya Énergiya*, Vol. 29, No. 6, pp. 458-461, December, 1970. Original article submitted January 4, 1970; revision submitted April 2, 1970.

© 1971 Consultants Bureau, a division of Plenum Publishing Corporation, 227 West 17th Street, New York, N. Y. 10011. All rights reserved. This article cannot be reproduced for any purpose whatsoever without permission of the publisher. A copy of this article is available from the publisher for \$15.00.



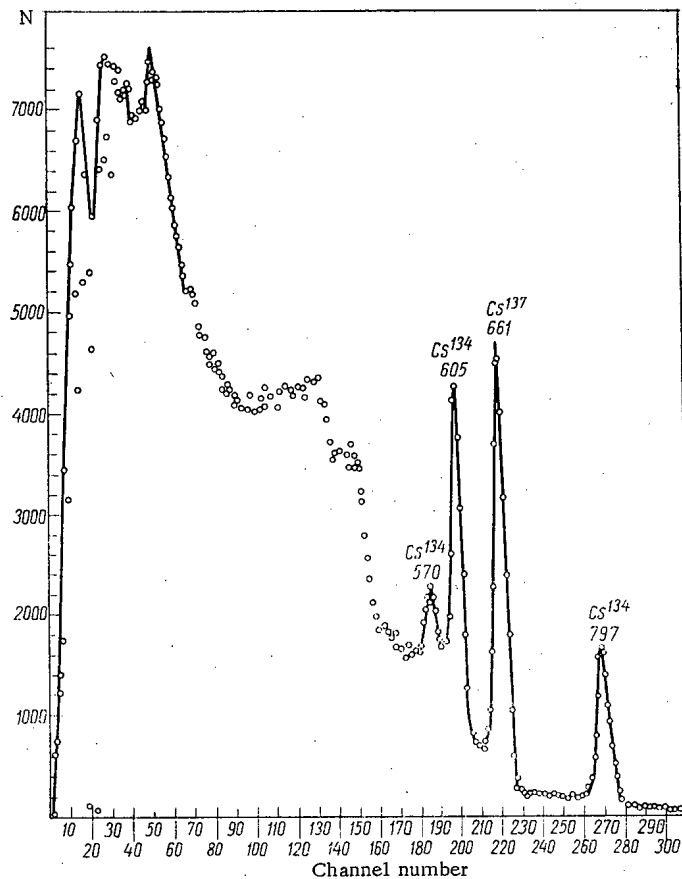


Fig. 3.  $\gamma$ -Ray spectrum of fraction separated out on third column in first two free volumes of eluate.

The authors of the present article made some attempts to combine group express chromatographic separation of fission products with subsequent identification on a Ge(Li)-spectrometer, an approach which makes provisions for singling out the most highly active impurities in the reactor loop water (viz., iodine and alkali metals) and considering them in separate groups.

Radioactive elements have to be stabilized in a single chemical form in order to isolate them in quantitative work. The introduction of formic acid is important in setting up conditions favorable to chromatographic separation of fission fragments. As a strong reducing agent, formic acid contributes to the conversion of different forms of iodine and bromine to a single reduced form,  $I^-$  or  $Br^-$ , which then makes it possible to isolate these elements quantitatively on a column with a strongly basic anion-exchange resin (AB-17 in our case) in the formate form. The acidity of the solution needed in order to separate out the rare earths from the alkali and alkali earth metal on a chromatographic partition column of Teflon coated with di-2-ethylhexylorthophosphoric acid as the stationary organic phase is achieved at the same time, and with ease.

A system of columns made of glass, all of the same dimensions (100 mm in height, 12.5 mm in diameter) and connected in series, was utilized in the chromatographic separation. The first column was filled with AB-17 anion-exchange resin with grain sizes from 100 to 250  $\mu$ , in the formate form ( $HCO_2^-$ ). The second column consisted of Teflon in pellet form, coated with di-2-ethylhexylorthophosphoric acid. The preparation of this type of column has been described in detail in the literature [5]. The third column was filled with Dowex-50X8 cation-exchange resin, grain sizes 100 to 250  $\mu$ , in the  $H^+$ -form. Cation-exchange resin KU-2 lends itself equally well to this application.

The aqueous solution to be analyzed (100 to 250 ml in volume), containing traces of iodine, cesium, barium, lanthanum, and cerium, was acidified to pH = 2 with formic acid, and was passed under pressure, at a flowspeed of 8 to 10 ml/min, through the array of columns. The eluate was collected in a receptacle and checked for activity. All the activity contained in the solution under analysis was retained in the system of columns after the solution had made one traversal of the system.

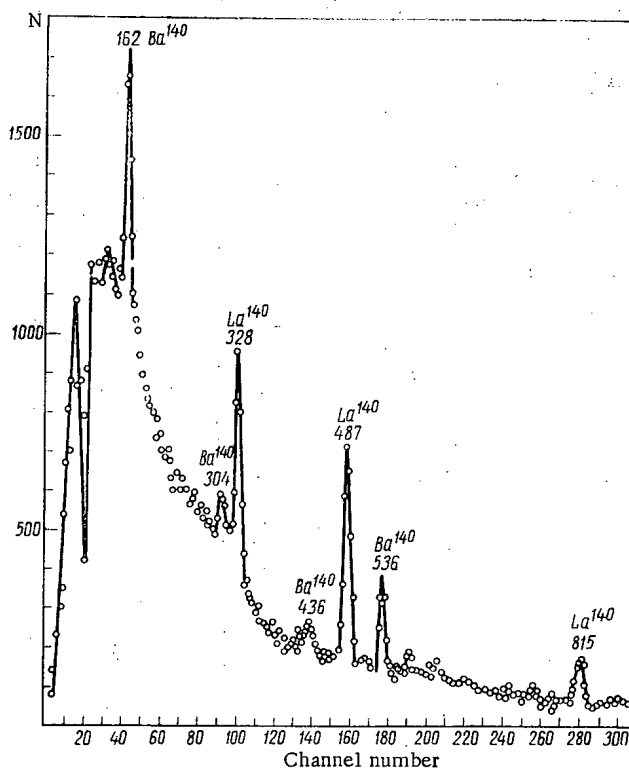


Fig. 4.  $\gamma$ -Ray spectrum of fraction separated out on third column.

The columns, together with the vessel for the original working solution, were washed with 10 to 20 ml 0.01 M solution of formic acid. No activity was detected in the wash effluent. The coating and washing operations take 15 to 20 min. After washing, the system was analyzed. The third column was washed with 10 ml 6 N hydrochloric acid (1.5 to 2 free volumes). Each column and the test tube with the eluate from the third column were covered with stoppers and measured on a  $\gamma$ -ray spectrometer with a 512-channel analyzer.

As was to be expected, quantitative absorption of iodine takes place in the first column: the  $\gamma$ -ray spectrum (Fig. 1) indicates the presence of the isotope  $I^{131}$ . No other elements were detected in the first column. The  $\gamma$ -ray spectrum of the second column (Fig. 2) is indicative of the presence of isotopes  $Ce^{141}$  and  $Ce^{144}$ , i.e., absorption of rare earths is observed in the second column. No isotopes of other elements were detected. The isotope  $La^{140}$  is lacking, since the measurements were taken 19 days after the chemical separation had been effected. Isotopes  $Cs^{137}$  and  $Cs^{134}$  (see Fig. 3) were detected in the eluate from the third column.  $Ba^{140}$  and its daughter  $La^{140}$  remained in the column (Fig. 4). The extent to which the separation of each group of elements in the respective fraction went to completion is confirmed by the absence of activity in the filtrate taken from the system of columns, and by the absence of mutual contamination of the distinct fractions.

The scheme of express chromatographic groupwise separation of fission products contained in the reactor loop waters, with subsequent identification of the isotope composition on a semiconductor  $\gamma$ -ray spectrometer as described, is thus proposed as a regular technique.

The authors take this opportunity to express their deep thanks to Yu. E. Loginov for having made it possible to use the Ge(Li)- $\gamma$ -ray spectrometer for the measurements, and for the assistance which he kindly rendered in the work.

#### LITERATURE CITED

1. Radiochemical Studies of Fission Products, Vol. I-III, New York (1951).
2. Radiochemical Analysis of Fission Products [in Russian], Yu. M. Tolmachev (editor), Izd-vo AN SSSR, Leningrad (1960).

3. Yu. P. Saikov, *Atomnaya Énergiya*, 20, 123 (1966).
4. O. A. Miller et al., *Atomnaya Énergiya*, 25, 524 (1968).
5. B. K. Preobrazhenskii et al., *Radiokhimiya*, 10, 377 (1968).

## EXPERIMENTAL VERIFICATION OF THE RADIATION-CHEMICAL METHOD FOR PRODUCING TETRACHLOROALKANES

A. A. Beér, P. A. Zagorets,  
V. F. Inozemtsev, L. A. Maiorov,  
V. I. Slavyanov, G. A. Artyushov,  
I. F. Strygaev, and V. A. Novozhilov

UDC 541.15

A pilot plant designed to produce new products, tetrachloroalkanes, by radiation-chemical methods was put on stream in late 1967 at the Grozny chemical combine. At the present time, the experimental operations have been pretty much completed, and current plans envisage expanding the facility to full industrial scale.

The tetrachloroalkanes are of great interest to the chemical processing industry, as semifinished products useful in the synthesis of polymeric materials, additives, lubricants, pesticides, stabilizers, plasticizers, etc., [1]. Tetrachloropropane and tetrachloropentane are acquiring special importance.

The tetrachloroalkanes are obtained by a reaction of telomerization from ethylene and carbon tetrachloride:

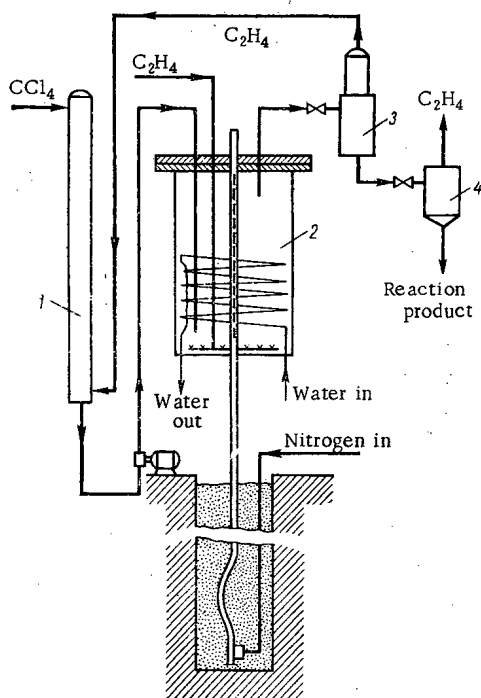
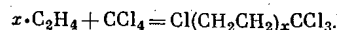


Fig. 1. Basic layout and flowsheet of facility designed for radiation telomerization between CCl<sub>4</sub> and C<sub>2</sub>H<sub>4</sub> (reaction unit).

This reaction is usually initiated by free radicals obtained via thermal decomposition of peroxides or azo-compounds. It has been shown [2-4] that this reaction is initiated by  $\gamma$ -emission from Co<sup>60</sup>, and the radiation method of initiation has certain advantages here. Subsequently, the radiation-chemical process has been described in the literature by other investigators as well [5, 6].

On the basis of their research findings, the present authors designed and built a pilot plant with two divisions, one for telomerization, the other for rectification, of the tetrachloroalkanes. The basic layout of the telomerization division is shown in Fig. 1.

Carbon tetrachloride is supplied by the pump to the absorber tower 1 for absorption of unreacted ethylene. The solution enters the reactor 2, into which compressed ethylene is bubbled. The sources (total activity ~18 kg-equivalents radium) are raised up from their storage pool into the central irradiation tube of the reactor under pressure from compressed nitrogen [7]. The irradiated mixture from the reactor is then throttled to 3-5 atm in the separator 3. The unreacted ethylene from the separator is directed to the absorber tower 1, where it is dissolved in carbon tetrachloride and recycled to the process. Liquid reaction products leaving the separator 3 are throttled to atmospheric pressure in the separator 4, and pass

Translated from *Atomnaya Énergiya*, Vol. 29, No. 6, pp. 461-463, December, 1970. Original article submitted June 10, 1970.

© 1971 Consultants Bureau, a division of Plenum Publishing Corporation, 227 West 17th Street, New York, N. Y. 10011. All rights reserved. This article cannot be reproduced for any purpose whatsoever without permission of the publisher. A copy of this article is available from the publisher for \$15.00.

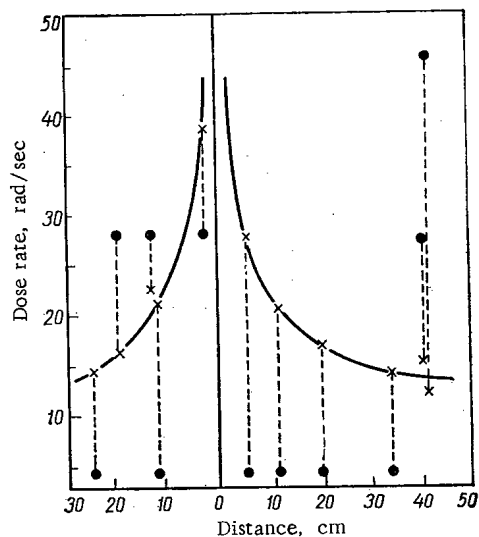


Fig. 2. Dose field of reactor (according to data provided by ferrosulfate dosimeters): ●) location of dosimetric capsule; x) dose rate.

from there to the rectification step so that the unreacted carbon tetrachloride can be driven off (and recycled to the process), and the pure tetrachloroalkanes can be isolated.

All of the process equipment was made of Kh18N10T steel. The absorber tower was packed with porcelain rings. The reactor, 550 liters in volume and 800 mm in diameter, was equipped with a coil for heating or cooling, and a bubbler for feeding the ethylene stream.

The process is carried out at 15-20 atm and 100°C, for 6 h, and the resulting reaction mixture contains ~80% unreacted carbon tetrachloride and approximately equal quantities of tetrachloropropane and tetrachloropentane. The impurity content remains the same, to within a fraction of a percent.

The assigned process parameters correspond to the molar composition of the irradiated mixture  $R = [CCl_4]/[C_2H_4] = 5 \sim 10$ . Any change in this composition will mean a change in the content of the distinct tetrachloroalkanes in the mixture, as described by the equations

$$F_1 = \frac{C_1 R}{(C_1 R + 1)}; \quad F_2 = \frac{C_2 R}{(C_1 R + 1)(C_2 R + 1)};$$

$$F_3 = \frac{C_3 R}{(C_1 R + 1)(C_2 R + 1)(C_3 R + 1)} \text{ etc.}$$

where  $F_i$  is the molar fraction of the telomer in the mixture;  $R$  is the molar ratio  $[CCl_4]/[C_2H_4]$ ;  $C_i$  is the transfer constant.

The transfer constants, according to the data collected by the present authors, have the following values:

Temperature, °C	$C_1$	$C_2$	$C_3$
0	0.045	3	10
20	0.059	2.9	9
50	0.89	2.8	7
100	0.155	2.7	5
140	0.218	2.6	4.7

A drop in the reaction temperature will depress the content of tetrachloroalkanes in the reaction mixture slightly, since the energy of activation of the reaction is 5.5 kcal/mole.

Dosimetric monitoring of the reactor (with the aid of a methylene blue solution) showed the average absorbed dose rate to be 10 rad/sec. The dose field in the interior of the reaction, taken from readings of ferrosulfate dosimeters, is given by the curve plotted in Fig. 2.

The radiation-chemical yield (converted to the dose rate 1 rad/sec) is 22,000 to 27,000 molecules of tetrachloroalkanes per 100 eV of radiation absorbed. According to laboratory data, the yield is inversely proportional to the dose rate, with the exponent 0.73, and is equal to 30,000 molecules per 100 eV at a dose rate of 1 rad/sec.

The radiation efficiency is 0.23, which is below the rating (0.38).

The formula

$$P = 3.7 \cdot 10^{-9} M_{av} g' (\eta A)^{0.27} (V\rho)^{0.73},$$

where  $P$  is the reactor throughput, in kg/h;  $g'$  is the radiation-chemical yield at a dose rate of 1 rad/sec,  $M_{av}$  is the average molecular weight of the tetrachloroalkanes,  $\eta$  is the radiation efficiency;  $A$  is the source

activity [gram-equivalents radium];  $V$  is the reactor effective volume [liters];  $\rho$  is the specific weight of the irradiated mixtures [ $\text{g}/\text{cm}^3$ ], was proposed for large-scale simulation of the process, and was checked for experimental verification.

The experimental verification revealed that the process takes place in a stable manner, responds amenable to control measures, and ceases immediately after the sources are removed from the reactor core. A slight induction period was discovered. The process parameters and the composition of the resulting mixture were found to be in close agreement with laboratory data.

The discharge coefficient of the carbon tetrachloride at the telomerization step is 0.8 to 0.9 (the theoretically predicted discharge coefficient is 0.78). Ethylene losses are negligible.

The tetrachloroalkanes obtained after rectification exhibit the required degree of purity.

This flowsheet is a reliable one, but could be improved. The process equipment should be made of titanium, since stainless steel is still subject to corrosive attack.

Optimization calculations were performed, on the basis of prevailing prices, with due attention to the basic features of the process, on reactor dimensions and activity of radiation sources for different levels of productivity. It was found economically feasible to utilize a reactor of fairly large volume with low-level irradiators. For example, the optimum reactor volume for a throughput of 200 kg/h was found to be  $\sim 5 \text{ m}^3$ , with the activity of the sources set at 55 to 60 kg-equivalents radium.

Engineering cost calculations showed that the net cost of tetrachloroalkanes in full-scale industrial production is 600 to 700 rubles/ton. Compared to the process achieved with azo-bis-isobutyronitrile, the radiation-chemical method requires much less initiator (the amount required is cut by 10 to 20 times).

#### LITERATURE CITED

1. R. Kh. Freidlina and Sh. A. Karapetyan, *Telomerization and New Synthetic Materials* [in Russian], Izd-vo AN SSSR, Moscow (1961).
2. M. A. Besprozvannyi, A. A. Beér, and G. B. Ovakimyan, *Inventors' Certificate No. 106988, Byull. Izobret.*, No. 14 (1957).
3. A. A. Beér et al., in: *Radioactive Isotopes and Nuclear Radiations in the National Economy of the USSR* [in Russian], Gostoptekhizdat, Moscow (1961), p. 211.
4. A. A. Beér et al., *Neftekhimiya*, 2, 617 (1962).
5. C. David and P. Gosselian, *Tetrahedron*, 18, 369 (1962).
6. M. Takehisa, M. Yasumoto, and J. Hosaka, *Kogyo Kagaku Zasshi*, 65, 531 (1962); *ibid.*, 66, 259 (1963).
7. V. A. Dobrovol'skii, B. I. Ryabov, and Yu. V. Kastrup, *Inventors' Certificate No. 166975, Byull. Izobret.*, No. 24 (1961).

USE OF XENON PROPORTIONAL COUNTER ESCAPE  
PEAKS FOR X-RAY RADIOMETRIC ANALYSIS OF  
TUNGSTEN IN ORES

N. G. Bolotova, V. V. Kotel'nikov,  
and E. P. Leman

UDC 550.835

The use of proportional counters significantly expands the technical capabilities of x-ray radiometric ore analysis and increases the number of elements which can be determined by this method. For example, the high accuracy and sensitivity of x-ray radiometric analysis in the determination of elements with atomic numbers  $Z \leq 30$  by means of the characteristic radiation of the K series can only be achieved with the help of proportional counters [1]. An increase in dimensions and an increase in filling-gas pressure to atmospheric makes it possible to increase the efficiency of xenon proportional counters to the extent that elements with a  $Z$  of 40-55 are determined from the K series with satisfactory accuracy and sensitivity [2, 3]. For elements with  $Z > 60$ , the analysis can be made on the basis of the characteristic radiations of the L series [4] since the detection efficiency for 60-100 keV photons is very small in proportional counters. Use of the K series of these elements for proportional counter analysis is only possible in practice by recording the escape peaks [5].

The escape peaks of xenon counters are of particular interest in the determination of heavy elements (with  $Z \geq 70$ ) in ores, and particularly tungsten. Tungsten determination by means of the L series is complicated by the fact that it is close in energy (8.5 keV) to the K lines of iron (6.5 keV), copper (8.0 keV), and zinc (8.6 keV), which are often present in ores along with the tungsten, and the counter resolution in

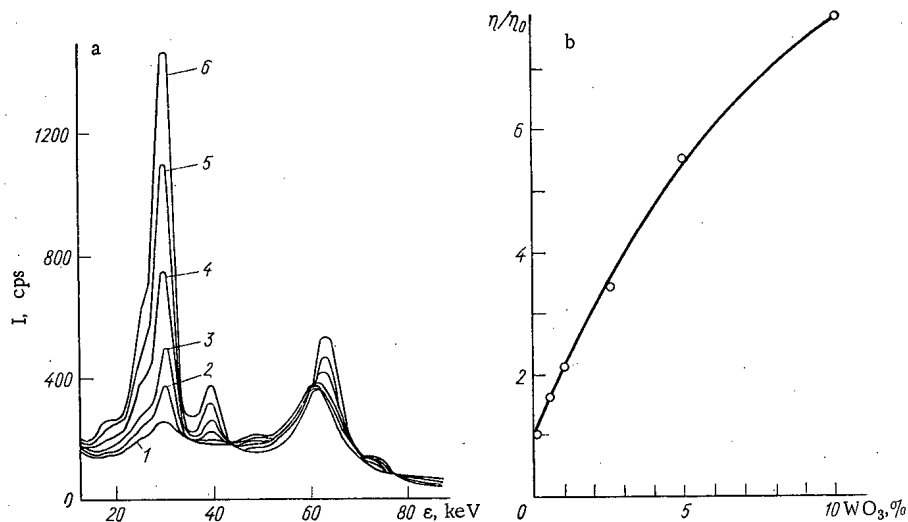


Fig. 1. Example of the use of escape peaks in an SRPO-12 xenon proportional counter for determination of tungsten content in ores by means of the K-series characteristic x-ray radiation ( $\text{Co}^{57}$  source): a) secondary  $\gamma$ -spectra obtained from simulated samples with varying content of tungsten trioxide; 1) 0%; 2) 0.5%; 3) 1%; 4) 2.5%; 5) 5%; 6) 10%; b) dependence of spectral ratios on tungsten trioxide content in simulated samples.

Translated from *Atomnaya Energiya*, Vol. 29, No. 6, pp. 463-465, December, 1970. Original article submitted May 14, 1970.

© 1971 Consultants Bureau, a division of Plenum Publishing Corporation, 227 West 17th Street, New York, N. Y. 10011. All rights reserved. This article cannot be reproduced for any purpose whatsoever without permission of the publisher. A copy of this article is available from the publisher for \$15.00.

this energy region, which is 18-20%, is insufficient for complete separation. The tungsten K lines (57-59 keV) efficiently excite the characteristic radiation of the xenon filling in a proportional counter. The xenon is practically transparent to its own characteristic x radiation, and the radiation consequently leaves the counter or is absorbed in the counter walls producing clearly defined escape peaks. The intensity of an escape peak is determined by the photon flux in the characteristic K radiation from tungsten and the position of the peak in the secondary spectrum - the energy difference between the K radiations of xenon and tungsten (see Fig. 1a).

An SRPO-12 xenon proportional counter was used as the detector. The characteristic tungsten x radiation was excited with a  $\text{Co}^{57}$  source (123 keV). Measurements were made with an AI-8 spectrometer on simulated samples of tungsten ores (a mixture of quartz sand and gypsum was used as filler) over a large solid angle without collimation of the radiation. A maximum was observed in the 60 keV region of the secondary instrumental spectra which resulted from the superposition of the tungsten K lines (57-59 keV) and the xenon K-series escape peak for singly scattered radiation (~90 keV) from the  $\text{Co}^{57}$  source. This situation, along with the low detection efficiency for photons with energies above 50 keV, prevents the use of xenon counters for the determination of tungsten in ores by means of the characteristic K radiation.

A different picture was observed in the spectral region 20-40 keV where one finds the xenon escape peaks associated with the tungsten K series. Three peaks were very clearly distinguished: the first (in the 25 keV region) corresponds to the energy difference between the tungsten  $K_{\alpha}$  lines and the xenon  $K_{\beta}$  lines; the second (in the 29 keV region) is equal to the difference between the energies of the xenon and tungsten  $K_{\alpha}$  lines; the third (with energies of 37-38 keV) results from the difference between the energies of the  $K_{\beta}$  line of tungsten and the  $K_{\alpha}$  line of xenon. The intensity of the escape peaks increases with an increase in tungsten concentration. The most intense peak is the second one, which can be used as an analytic line for spectral ratio techniques.

Figure 1b gives the curve for the dependence of spectral ratios on tungsten trioxide content in simulated samples. Scattered radiation at 46 keV was chosen as the internal standard for background. The spectral ratios  $\eta$  were normalized to the value  $\eta_0$  in the ore-free sample. The  $\eta/\eta_0$  curve is close to linear in the tungsten trioxide concentration range 0-5%. The sensitivity of the analysis can be increased by using collimation of the radiation and by reducing the scattered radiation background in the region of the escape peaks. Thus x-ray radiometric analysis of some heavy elements, and of tungsten in particular, by means of characteristic K-series x radiation can be performed with the help of the escape peaks from xenon proportional counters when direct recording of the K radiations of these elements proves to be impossible or inefficient. Such a method can be used for the determination of tungsten in tungsten and molybdenum-tungsten ores. In the analysis of antimony-tungsten or tin-tungsten ores, the use of this technique is complicated by the fact that the xenon escape peaks resulting from the presence of tungsten coincide in energy with the analytic K lines of antimony and tin.

#### LITERATURE CITED

1. R. I. Plotnikov et al., Instruments and Methods in X-Ray Analysis [in Russian], No. 2, Izd. SKBRA, Leningrad (1967), p. 126.
2. E. P. Leman et al., Development of Geology and Mine-Survey Services in Nonferrous Metallurgical Enterprises (Mining Industry Series) [in Russian], Izd. TsNIItsvetmetinformatsiya, Moscow (1970), p. 31.
3. A. L. Yakubovich, E. I. Zaitsev, and S. M. Przhiyalgovskii, Nuclear Physics Methods for the Analysis of Minerals [in Russian], Atomizdat, Moscow (1969).
4. I. V. Tomskii, V. N. Mitov, et al., Instruments and Methods in X-Ray Analysis [in Russian], No. 5, Izd. SKBRA, Leningrad (1969), p. 111.
5. R. I. Plotnikov et al., Instruments and Methods in X-Ray Analysis [in Russian], No. 2, Izd. SKBRA, Leningrad (1967), p. 121.



# DIAGNOSTICS OF AN ELECTRON - ION BUNCH USING BREMSSTRAHLUNG

M. L. Iovnovich, V. P. Sarantsev,  
and M. M. Fiks

UDC 533.95:621.039.61

A new method has been proposed [1] for the collective acceleration of ions. The method is based on the possibility of creating electron-ion bunches which are accelerated as a unit in external electromagnetic fields. The creation of a bunch begins with the formation in an external magnetic field of a thin ring of relativistic electrons (major radius of the ring is  $R$ , minor radius is  $a$ ) where storage of ionized atoms occurs. The storage process has been discussed [2-4]. During storage, bremsstrahlung from the electrons arises through electron collisions with atoms and ions, and this bremsstrahlung can be used for bunch diagnostics.

The bremsstrahlung from a relativistic electron in an atomic nucleus is essentially anisotropic. For  $\gamma \gg 1$  ( $\gamma$  is the electron relativistic factor in the bunch at rest), almost all the radiation is concentrated in a small solid angle  $\Omega = 4\pi \sin^2(\theta/2)$ , where  $\theta/2 = 1/\gamma$  is the angle between the photon direction of propagation and the tangent to the trajectory at the point of radiation [5].

The average number  $N$  of photons with energies  $\varepsilon = h\nu/mc^2 \geq \varepsilon_0$  emitted by the ring per unit time into an angle  $\Delta$ , within which the "illuminated" portion of the radiation detector is seen, is determined by the expression

$$\frac{dN}{dt} = \sum_{Z_0} \int_{\varepsilon_0}^{\varepsilon} d\varepsilon' \Phi(Z_0, \varepsilon') dQ \sum_{Z=0}^{Z_0} n_{Z_0 Z} j_e R \frac{4\pi}{\Omega_0} \int d\varphi \sin^2 \frac{\Delta}{4}, \quad (1)$$

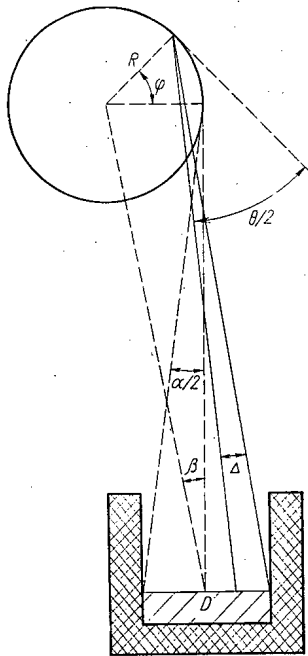


Fig. 1. Diagram of the arrangement of the bremsstrahlung detector D.

where  $\Phi(Z_0, \varepsilon)$  is the cross section for emission of photons with energies in the range  $\varepsilon, \varepsilon + d\varepsilon$  from a nucleus of charge  $Z_0$ ,  $n_{Z_0 Z}$  is the concentration of heavy particles ( $Z_0$  is the nuclear charge and  $Z$  is the ionic charge), and  $j_e$  is the electron current density in the ring.

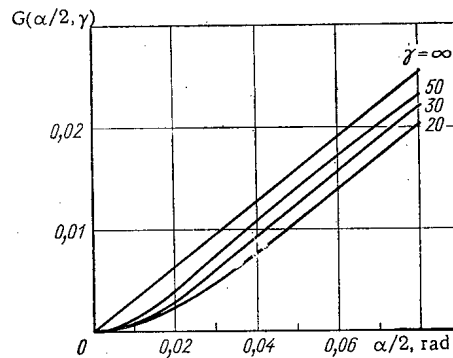


Fig. 2. Ratio of bremsstrahlung intensity incident on the detector to the total intensity from the entire ring.

Translated from *Atomnaya Energiya*, Vol. 29, No. 6, pp. 465-467, December, 1970. Original article submitted January 4, 1970.

© 1971 Consultants Bureau, a division of Plenum Publishing Corporation, 227 West 17th Street, New York, N. Y. 10011. All rights reserved. This article cannot be reproduced for any purpose whatsoever without permission of the publisher. A copy of this article is available from the publisher for \$15.00.

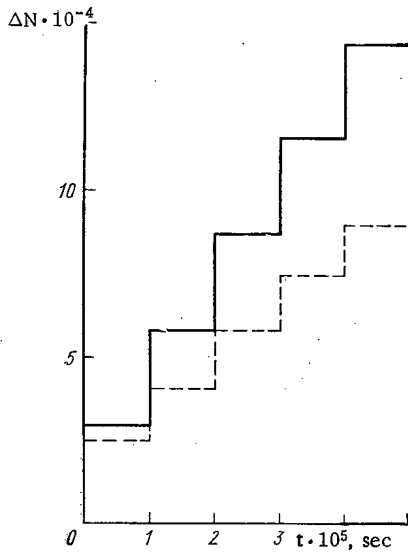


Fig. 3. Number of photons with energies  $0.1 \leq h\nu \leq 1.0$  MeV incident on the detector in an interval  $\Delta t = 10^{-5}$  sec: —) storage from atomic beam; ----) storage from residual gas;  $n_e = 10^{14} \text{ cm}^{-3}$ ,  $a = 0.1 \text{ cm}$ ,  $N_e = 10^{14}$ ,  $\alpha/2 = 0.02$ .

Integration is carried out over the ring cross section  $Q = \pi a^2$ . Equation (1) was obtained under the assumption the electron current was transparent to photons.

If the detector dimension  $d \gg a$  and the electron and heavy particle concentrations are constant over the cross section  $Q$  of the ring, then

$$\frac{dN}{dt} = N_e c \sum_{Z_0} \int_{\varepsilon_0}^{\varepsilon} d\varepsilon' \Phi(Z_0, \varepsilon') \sum_{Z=0}^{Z_0} n_{Z_0 Z} \frac{2}{\pi} \gamma^2 \int d\varphi \sin^2 \frac{\Delta}{4}, \quad (1a)$$

where  $N_e$  is the total number of electrons in the ring.

The function  $\Delta(\varphi)$  and the equations which determine the limits of integration over  $\varphi$  are found from simple geometric considerations (see Fig. 1). In the case where not only  $1/\gamma \ll 1$  but also  $\alpha/2 \ll 1$ ,  $\beta < 1$ , one can obtain an approximate evaluation of the geometric factor  $G(\alpha/2, \beta, \gamma) = (2/\pi)\gamma^2 \int d\varphi \sin^2(\Delta/4)$  in analytic form:

$$G\left(\frac{\alpha}{2}, \gamma\right) \approx \begin{cases} \frac{1}{3\pi} \left(3\frac{\alpha}{2} - \frac{1}{\gamma}\right) & \frac{\alpha}{2} \geq \frac{1}{\gamma} \\ \frac{1}{3\pi} \gamma^2 \left(\frac{\alpha}{2}\right)^2 \left(3\frac{1}{\gamma} - \frac{\alpha}{2}\right) & \frac{\alpha}{2} \leq \frac{1}{\gamma} \end{cases} \quad (2)$$

The family of curves  $G(\alpha/2, \beta, \gamma) \Big|_{\gamma=\text{const}}$  is shown in Fig. 2.

During storage of a single type of ion of a monatomic gas, the radiation intensity and the number of photons incident on the detector in a time  $t$  are given by

$$\frac{dN}{dt} = \left(\frac{dN}{dt}\right)_0 G\left(\frac{\alpha}{2}, \beta, \gamma\right) s(t); \quad (3)$$

$$N(t) = \left(\frac{dN}{dt}\right)_0 G\left(\frac{\alpha}{2}, \beta, \gamma\right) p(t), \quad (4)$$

where

$$\left(\frac{dN}{dt}\right)_0 = N_e c n_a \int_{\varepsilon_0}^{\varepsilon} d\varepsilon' \Phi(Z_0, \varepsilon') \quad (5)$$

is the radiation intensity of the entire bunch at the initial time  $t = 0$ ;  $n_a$  is the neutral atom concentration near the bunch, and the functions  $s(t) = \sum_{Z=0}^{Z_0} n_{Z_0 Z} / n_a$  and  $p(t) = \int_0^t s(t') dt'$  are defined in [4].

Small values of  $\varepsilon$  make the main contribution to the integral in Eq. (5). For reason of computational convenience, we therefore use an expression for  $\Phi(Z_0, \varepsilon)$  which is valid for the case of small energies (complete screening) [5]:

$$\Phi(Z_0, \varepsilon) = \frac{4Z_0^2}{137} r_e^2 \frac{1}{\varepsilon} \left\{ \left[ 1 + \left(1 - \frac{\varepsilon}{\gamma}\right)^2 - \frac{2}{3} \left(1 - \frac{\varepsilon}{\gamma}\right) \right] \ln(183Z_0^{-1/3}) + \frac{1}{9} \left(1 - \frac{\varepsilon}{\gamma}\right) \right\}, \quad (6)$$

where  $r_e = e^2/mc^2$  is the classical radius of the electron. Equation (6) is applicable for photon energies up to the value  $\varepsilon_{\text{max}} \approx \gamma^2/137 + \gamma$ . Following integration, we obtain

$$\left(\frac{dN}{dt}\right)_0 = \frac{4Z_0^2}{137} N_e c n_a r_e^2 \left\{ \left[ \frac{4}{3} \ln 183Z_0^{-1/3} + 1/9 \right] \left[ \ln \frac{\varepsilon}{\varepsilon_0} + \frac{\varepsilon - \varepsilon_0}{\gamma} \right] + \frac{\varepsilon^2 - \varepsilon_0^2}{2\gamma^2} \ln 183Z_0^{-1/3} \right\}. \quad (7)$$

The limits of integration,  $\varepsilon_0$  and  $\varepsilon$  are determined by the spectral sensitivity of the detector. The number of photons detected during the time of storage depends on the spectral sensitivity of the detector and the detection efficiency. For bunch diagnostics, one can use a germanium-lithium detector, for which the maximum spectral sensitivity is in the photon energy range 0.1-1.0 MeV, and the detection efficiency is a few tens of percent with an energy resolution of  $\sim 2\%$ . The frequency of electron synchrotron radiation, which forms the background in these measurements, is many orders of magnitude less than that of the radiation detected. By measuring the radiation intensity, one can determine the total concentration of heavy particles in the ring with an accuracy of a few percent.

Figure 3 shows the number of photons in the energy range mentioned reaching the detector during storage of xenon ( $Z_0 = 54$ ) (broken down into intervals  $\Delta t = 10^{-5}$  sec). This data indicates that one can study the process of xenon storage in bunches having electron numbers  $N_e \cong 3 \cdot 10^{12}$ .

The study of ions formed from diatomic gases, particularly protons, requires special consideration. Nevertheless, one can assume that in a bunch with  $N_e = 10^{14}$ , the observation of proton storage is feasible if the concentration of hydrogen molecules in the region of the bunch is roughly two orders of magnitude greater than the concentration of residual gas molecules.

We note in conclusion that the proposed diagnostic technique also allows one to determine the total number of electrons in a ring since the initial concentration of heavy particles is known.

The authors thank A. B. Kuznetsov, Yu. Ts. Oganessian, and N. V. Rubin for discussions of the problems involved.

#### LITERATURE CITED

1. V. I. Veksler et al., *Atomnaya Énergiya*, 24, 317 (1968).
2. M. L. Iovnovich, N. B. Rubin, and V. P. Sarantsev, JINR Preprint, P9-4257, Dubna (1969).
3. Symposium on Electron Ring Accelerators, UCRL-18103, Berkeley (1968).
4. M. L. Iovnovich and M. M. Fiks, this issue p. 1199.
5. *Experimental Nuclear Physics* [Russian translation], E. Segre (editor), Vol. 1, Izd-vo IL, Moscow (1955).

## EXCITATION OF RADIAL BETATRON OSCILLATIONS BY A LONGITUDINAL ACCELERATING FIELD

Yu. S. Ivanov, A. A. Kuz'min,  
and G. F. Senatorov

UDC 621.384.6

In the adjustment and use of proton synchrotrons it is essential to be in possession of adequate information regarding the frequency of the betatron oscillations during the whole cycle of acceleration.

Usually at the beginning of the cycle one encounters intrinsic coherent oscillations of the center of gravity of the beam of accelerated protons, due to the nonzero initial conditions prevailing on injection; however, the period of their "coherence," which is mainly determined by the distribution function of the particles in the beam with respect to the betatron-oscillation frequencies, is not very long. For example, in the case of the 70 GeV accelerator of the Institute of High-Energy Physics, under normal operating conditions the period of coherence is no longer than 3 to 5  $\mu\text{sec}$ .

In order to measure the frequencies of the betatron oscillations throughout the whole acceleration cycle, the oscillations must first be excited [1].

In this paper we shall consider one of the methods of exciting coherent radial betatron oscillations. The method is of the resonance type; however, in contrast to the method described earlier [2], the periodic stimulating force varies the longitudinal rather than the transverse momentum of the center of gravity of the beam.

It is well known [3] that the radial betatron oscillations of a particle with a momentum differing from the equilibrium value are described by the equation

$$\frac{d^2x}{dt^2} + Q^2\omega^2x = \omega^2r_0 \frac{\delta p}{p}, \quad (1)$$

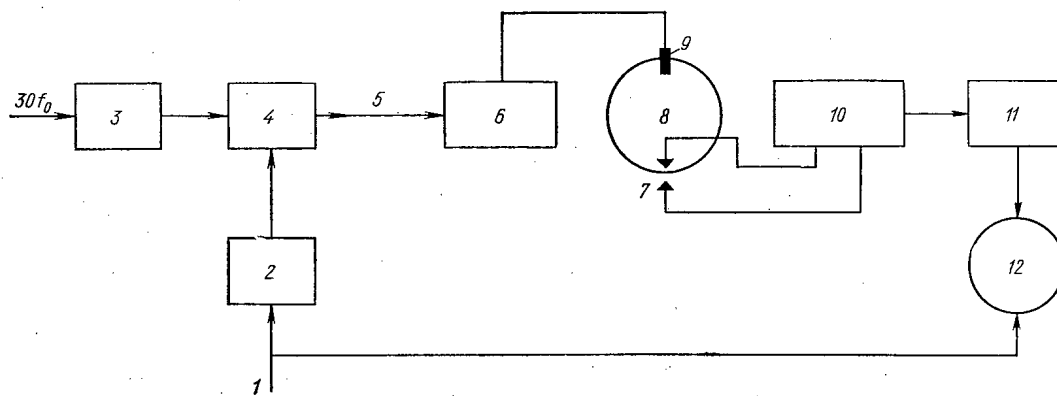


Fig. 1. Arrangement for the excitation and observation of betatron oscillations: 1) pulse initiating the excitation; 2) control system; 3) frequency divider; 4) key; 5) modulating voltage; 6) accelerating stage; 7) signal electrodes; 8) ring; 9) resonator; 10) differential amplifier; 11) low-frequency filter; 12) oscilloscope.

Translated from *Atomnaya Énergiya*, Vol. 29, No. 6, pp. 467-469, December, 1970. Original article submitted December 17, 1969.

© 1971 Consultants Bureau, a division of Plenum Publishing Corporation, 227 West 17th Street, New York, N. Y. 10011. All rights reserved. This article cannot be reproduced for any purpose whatsoever without permission of the publisher. A copy of this article is available from the publisher for \$15.00.

where  $x$  is the radial deviation of the particle from the equilibrium value;  $\omega$  is the frequency of revolution;  $t$  is the time;  $Q$  is the frequency of the betatron oscillations;  $\delta_p$  is the deviation of the longitudinal momentum from equilibrium;  $p$  is the total momentum of the particle; and  $r_0$  is the average radius of the accelerator.

If the voltage on one of the accelerating stages is modulated in accordance with a law of the  $f(t)$  type, then

$$\frac{d^2x}{dt^2} + Q^2\omega^2x = r_0\omega^2 \sum_{n=0}^{N-1} \frac{\Delta p_0}{p} f(t) H(t - n\tau_0), \quad (2)$$

where  $\Delta p_0$  is the maximum possible difference of the momentum from equilibrium;  $H$  is a unitary function;  $\tau_0$  is the period of rotation of the particle; and  $N$  is the number of turns.

Let us consider simply the forced solution of (2):

$$x = \omega r_0 \Delta p_0 / p Q \int_0^t \sum_{n=0}^{N-1} f(t) H(t - n\tau_0) \sin Q\omega(t - \tau) d\tau. \quad (3)$$

If  $f(t) = \sin q\omega t$  (where  $q$  is an arbitrary number), then expression (3) takes the form

$$x = \omega r_0 \Delta p_0 / p Q \sum_{n=0}^{N-1} \sin q\omega n\tau_0 \int_{n\tau_0}^t \sin Q\omega(t - \tau) d\tau, \quad (4)$$

or finally

$$x = r_0 \Delta p_0 / 2p Q^2 \left\{ 2 \sum_{n=0}^N \sin 2\pi n q + \cos Q\vartheta \sum_{n=0}^N [\sin 2\pi n (q+Q) + \sin 2\pi n (q-Q)] + \sin Q\vartheta \sum_{n=0}^N [\cos 2\pi n (q-Q) - \cos 2\pi n (q+Q)] \right\}, \quad (5)$$

where  $\vartheta = \omega t$ .

When

$$Q \pm q = m$$

(where  $m = 0, \pm 1, \pm 2, \dots$ ), solution (5) assumes the resonance form.

The most interesting case is that in which  $m$  is the closest whole number to the frequency of the betatron oscillations  $Q$ . This corresponds to the lowest modulation frequency, and it constitutes an important factor, since the accelerating stages are quite narrow-banded (the band width of the accelerating stages in the Institute's synchrotron is of the order of 80 to 100 kc/sec).

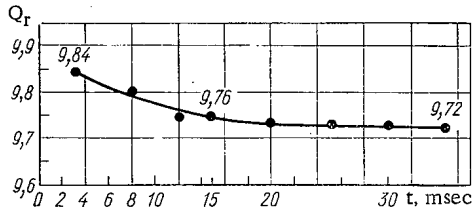


Fig. 2. Time dependence of the betatron-oscillation frequency.

The frequencies of the phase oscillations differ considerably from the frequencies  $q\omega$ , and the mutual influence of the radial and phase oscillations may be neglected [2]. In order to confirm the theoretical results we carried out some experiments on the excitation of radial oscillations in the Institute's proton synchrotron.

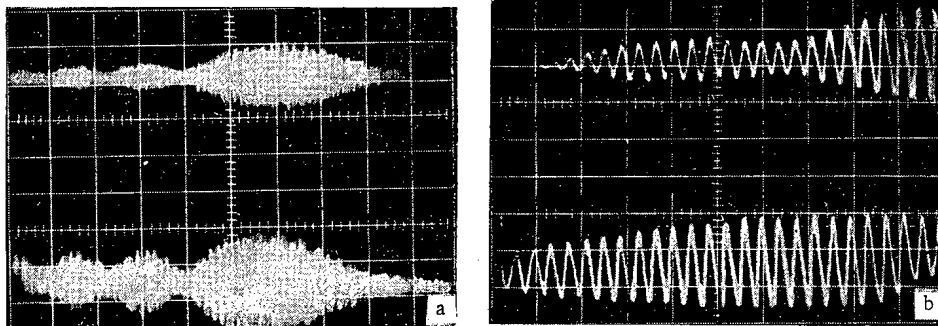


Fig. 3. Oscillograms of the build-up of radial and vertical betatron oscillations: a) sweep 200  $\mu\text{sec}/\text{cm}$ ; b) sweep 70  $\mu\text{sec}/\text{cm}$ .

A block diagram of the arrangements for exciting and observing the betatron oscillations is presented in Fig. 1. The voltage from a master generator with a frequency of  $30f_0$  ( $f_0$  being the frequency of rotation of the particles) is fed to a frequency divider, which divides this frequency by a whole number  $n$  ( $n$  may vary in unit steps from 67 to 300). The signal at a frequency of  $30f_0/n$  is amplified, passes through a timer-controlled key, and is applied to the grid of the output tube of the accelerating stage, as a result of which the amplitude of the accelerating voltage is modulated.

The measuring system is also controlled by a timer and contains low-frequency filters considerably increasing its sensitivity.

An oscillograph incorporating a memory enables information relating to the betatron oscillations to be analyzed directly from the screen; alternatively, the processes may be photographed and analyzed later.

Our experiments enabled us to measure the frequency of the radial betatron oscillations and also to establish the relationship between the radial and vertical oscillations at individual points of the cycle up to energies of the order of 2 GeV. For energies greater than 2 GeV the betatron oscillations of the beam could not be increased to amplitudes sufficient to allow accurate measurement ( $\sim 0.5$  mm) using only one accelerating stage.

Figure 2 shows the experimental time dependence of the betatron-oscillation frequency in the accelerating cycle. This relationship may be varied by adjusting the accelerator.

Figures 3a and b present photographs of two oscillograms obtained when studying the development of betatron oscillations. The upper oscillograph beam represents the excitation of the radial oscillations and the lower beam represents that of the vertical oscillations arising from the coupling between the radial and vertical oscillations of the beam. The processes give the appearance of passing through resonance, and in Fig. 3b (corresponding to a faster sweep) we see how the energy is transferred from one form of oscillation to the other.

These results demonstrate the efficiency of the proposed method of exciting radial betatron oscillations at low energies. The use of this method requires no special excitation apparatus and hence demands no space for locating such apparatus in the accelerator ring.

In conclusion, the authors wish to thank V. E. Pisarevskii, A. M. Gudkov, and V. P. Ustinov for help in the experiments.

#### LITERATURE CITED

1. V. A. Uvarov and G. F. Senatorov, *Pribory i Tekh. Éksperim.*, No. 6, 20 (1968).
2. A. A. Kolomenskii and A. N. Lebedev, *Theory of Cyclical Accelerators* [in Russian], Fizmatgiz, Moscow (1962).
3. A. Shoch, *Theory of Linear and Nonlinear Perturbations of Betatron Oscillations in Alternating-Gradient Synchrotrons*, CERN, Geneva (1958).

## NEWS

LIEGE MAY 1970 INTERNATIONAL SYMPOSIUM ON  
MODERN ELECTRIC POWER GENERATING STATIONS

P. A. Andreev

An international symposium on modern electric power generating stations was held in Liege (Belgium) in May 1970, and attracted over 500 specialists from 22 countries. A total of 52 papers was presented at this symposium, dealing the design, fabrication, investigation, adjustment, and operation of heat process equipment and electromechanical equipment for modern electric power stations. Topics covered in the papers ranged over: nuclear-fueled electric power stations, gas turbine plants and gas turbines, hydroelectric power stations, and electric power generating stations burning fossil fuels.

Attention was centered on nuclear power at this symposium; topics focused upon were equipment and operating experience, in relation to nuclear power stations based on different types of reactors, with a large number of papers taking up these questions and provoking a lively discussion. Equally close attention was given to the urgent problems of reliability and efficient use of the basic power equipment in modern nuclear power stations with water-cooled reactors and above all water-moderated water-cooled reactors (reactors, steam generators, steam turbines, and circulating pumps). The outlook for nuclear power development and forecasts projecting into the future of nuclear power were discussed to a lesser extent.

Awareness of the damage suffered by the thermal shielding in reactors similar in design to the American Westinghouse Corp. reactors (e.g., the damage to the SENA Franco-Belgian power station reactor) lent added interest to a report on experience in the adjustment and startup of the Obrigheim (West Germany) power station.

The first full-scale tests of an unloaded reactor to probe into temperature and fluid dynamic conditions brought on severe vibrations in the thermal shielding because of the impact of the stream of water. These vibrations resulted in severe damage to the surfaces of the reactor pressure vessel, on which the thermal shielding, 28 tons in weight, rested freely. After trying out several variants in fastening the shielding structures which failed to pay off, even after over 1500 h of testing, a reliable design was worked out which was checked out again after fuel had been loaded in. A special feature of this successful design variant is seen in the six support brackets with welded-on retaining vertical backup plates to which the thermal shielding is pinned. This mode of fastening allows free radial and axial temperature expansion of the shielding while holding it rigidly fast against any rotational displacements.

Another source of malfunction and misalignment in the performance of the power station was the excessively high moisture content of the steam feed to the turbine, as a result of the unsuccessful design of the first and second stages of the steam separator. Attempts to cope with this led to working out a new design of the separator first stage on full-scale models, with a horizontal cyclone, and using thin moisture traps manufactured by the Peerless firm as the second separator stage. The separation system thereafter brought about a moisture content of not more than 0.25% in the steam under the entire range of operating conditions of the nuclear power station.

Because of the excessive amount of wear on the seals, malfunctions of the main circulation pumps were also reported; the rapid wear on ring seals made of tungsten carbide is accounted for by the high boron content in the primary coolant. A satisfactory solution was found through the use of ring seals coated with chromium oxide.

It is interesting to note that computer process monitoring of the operation of the Obrigheim nuclear power station, using the Siemens-305 computer, shows much promise, with 450 analog variables monitored and ~2200 binary signals processed.

---

Translated from *Atomnaya Énergiya*, Vol. 29, No. 6, pp. 470-471, December, 1970.

© 1971 Consultants Bureau, a division of Plenum Publishing Corporation, 227 West 17th Street, New York, N. Y. 10011. All rights reserved. This article cannot be reproduced for any purpose whatsoever without permission of the publisher. A copy of this article is available from the publisher for \$15.00.

The symposium discussed cleanup of primary loop water at nuclear power stations. Since the commonly encountered water treatment systems using ion exchange, degassing, and evaporation equipment fail to provide efficient filtration of active corrosion products, it was proposed that the problem be solved through recourse to special mechanical filters.

A report presented by the Belgian concern Cocril-Ugrais-Providence made a convincing demonstration of the advantages of upright steam generators; data on the advantages of inconel as a material in the fabrication of steam generators, instead of the stainless steel AJSJ-316, were also presented.

Some of the reports dealt with improved design of water-cooled water-moderated reactors, and their operation. Most of the authors of reports analyzing reasons for breakdown of heat processing and transfer machinery at nuclear power stations, reach the unanimous conclusion that the overwhelming majority of failures are due to insufficient knowledge of hydrodynamical phenomena, which are responsible for damaging vibrations, generated under certain sets of operating conditions. Work is now underway everywhere on developing means and techniques for keeping a check on vibrations executed by the internal components of reactors and steam generators.

Lowering capital costs and improving the reliability of power station equipment are of vital significance in efforts to achieve economically competitive nuclear power. This explains the very serious attention being given to the building of more powerful high-efficiency and highly reliable steam turbines for nuclear power stations. Many of the papers presented by leading turbomachinery manufacturing concerns in France, West Germany, Czechoslovakia, the USA, and Switzerland dealt with the design and fabrication of low-speed turbines with extremely high specific power ratings, development and improvements in the design and fabrication of blading for the last stages of turbomachinery (TsND blading) of critically extended blade length, general principles in the design of steam turbines for nuclear power stations, designs of last stages, operating experience, and unitization and typization principles in the standardization of turbomachinery.

Most of the firms view the use of low-speed turbines (in the 1800 rpm or 1500 rpm speed range) as correct for nuclear power stations, but justify this solely in terms of cost considerations, without bringing into question the reliability of modern high-speed turbines. Maximum interest was evoked by a report submitted by the Czechoslovak Skoda works, containing extremely valuable information on the characteristics of the exhaust stages of turbines with blades extending to 1000 mm in length, and with turbine runner speeds up to 3000 rpm, depending on the choice of structural material and on the selection of blade fastening arrangement. Results of an investigation of anticorrosion coatings for long blades designed for service in wet steam, and designs of stator guide blading with suction drainage slits, are presented. Methods for eliminating dangerous vibrations of turbine blades are described.

Valuable experience in coping with and overcoming defects in turbomachinery is communicated in a report devoted to a description of startup operations at the Gundremingen nuclear power station (in West Germany) centered around a 237 MW boiling-water reactor. Repeated failures and fractures of turbine blades in the first stages of a cylinder of an AEG turbine at 1500 rpm resulted in repeated breakdown of power station operations, with downtime lasting over nine months. The reason for the damage lay in pulsations of the stream of steam deriving from uneven moisture distribution in the piping leading to the TsND (the existence of zones with moisture content as high as 12% when the average moisture content only reached 1%). The introduction of changes in the design of the feed pipe connection brought about more uniform distribution of steam moisture; the design of the blade shanks in the first stages and runner disks of TsND.

A report on heavy-water power reactors which presented Canadian experience in this area in a systematic manner evoked considerable interest as did a report on high-temperature gas-cooled reactors.

The French EdF concern, in a report shedding light on five years of operating history of basic heat exchangers, drew the inference that the use of heat-transfer surfaces of complex configuration is not justified, because of difficulties in inspection and removal of flaws, and that efforts should rather be directed to the design of simpler heat exchangers (specifically, smooth-tube exchangers are recommended).

The design of a Japanese experimental fast reactor with a power output rating of 50 MW(e) was also of some interest.



JUNE 1970 PRINCETON SYMPOSIUM ON PLASMA STABILIZATION  
BY FEEDBACK AND DYNAMICAL TECHNIQUES

D. A. Panov

The extensive development undergone by research on methods for suppressing plasma instabilities by feedback systems or by dynamic stabilization provided the basis for convening a symposium, organized under the sponsorship of the Plasma Physics Laboratory of Princeton University, at Princeton (USA) in June, 1970. The symposium drew participation from scientists of Britain, Italy, Norway, the Soviet Union, France, and West Germany. Forty-eight papers were presented at the sessions of the symposium.

The work done by V. V. Arsenin and V. A. Chuyanov, and published in 1968 [1], has provided a stimulus for developing research on feedback stabilization of plasma, and has furnished a basis for successful experiments on suppressing flute instabilities in the plasma in the magnetic trap of the OGRA-2 thermonuclear fusion machine [2]. The use of a feedback system to stabilize plasma instabilities was first proposed by A. I. Morozov and L. S. Solov'ev in 1964 [3].

Work on plasma stabilization by feedback systems, as presented and discussed at the symposium, touched on many questions ranging from classification of the stabilization mechanisms to the use of feedback in the study of specific modes of instability.

J. Taylor and C. Lashmore-Davis (Britain) showed that relevant feedback systems can be subdivided into two types, active and reactive, depending on the modes of instability to be suppressed. Instabilities of the interchange type, characterized by negative or positive energy of oscillation, belong to the first category. The signal has to be phase-shifted  $\pm 90^\circ$  in order to suppress such instabilities in a feedback system. The choice of sign depends on the sign of the energy of oscillation. Instabilities of the interchange type characterized by zero energy of oscillation being in the second category. The conclusion is that the allowable phase shift for the stabilization of such instabilities is either  $0^\circ$  or  $180^\circ$ .

Most of the experimental papers presented at the symposium on the subject of feedback dealt with active plasma stabilization techniques. In those cases, it is possible to write out the dispersion equation with the effect of the feedback loop taken into account, and to derive a theoretical dependence of the shift in the real part of the frequency, of the size of the increment, and of the displacement of the instability threshold, on the gain and on the phase shift in the feedback loop. An excellent concordance between measured dependences and theoretically predicted dependences was demonstrated. The most typical results of that sort are to be found in the papers submitted by T. Symonen (USA) and D. Jessby et al. (USA); these experiments were conducted with alkali plasma generated in Q-machines. Similar results were communicated in a report by B. Anker-Johnson et al. (USA).

A paper submitted by V. A. Zhil'tsov et al. (USSR) demonstrated that when a surface of finite conductivity is placed parallel to the boundary of a plasma, energy absorption in that surface due to the flowing of induced currents in the surface will be greater, under optimized conditions, than the rate of increase in the energy associated with unstable ion-cyclotron oscillations. At the same time, attenuation greater than the instability growth rate is introduced into the plasma. The feedback loop will behave, at a certain phase shift, like a surface of finite conductivity. Results of experiments on the suppression of an ion-cyclotron instability in the plasma in the magnetic trap of the OGRA-2 thermonuclear machine were reported.

In most of the earlier experiments on suppression of instabilities by feedback, the control components used were electrodes placed outside the plasma, or Langmuir probes immersed in the plasma. For understandable reasons, neither of these approaches is applicable to the case of a dense high-temperature plasma.

---

Translated from *Atomnaya Energiya*, Vol. 29, No. 6, pp. 471-473, December, 1970.

© 1971 Consultants Bureau, a division of Plenum Publishing Corporation, 227 West 17th Street, New York, N. Y. 10011. All rights reserved. This article cannot be reproduced for any purpose whatsoever without permission of the publisher. A copy of this article is available from the publisher for \$15.00.

On that account, close attention was given in the reports presented at the symposium to techniques involving electrodeless and contactless manipulation of the plasma. Reports by A. Huang et al. (USA) put forth results of successful suppression of a trapping instability in an alkali plasma by microwave radiation at the upper hybrid frequency ( $\sim 10$  GHz) modulated by the feedback loop signal. A report by F. Cheng (USA) drew attention to the fact that direct utilization of microwave radiators to set up a contactless feedback loop is fraught with difficulties in the case of a thermonuclear plasma. To cope with the problem, he suggested recourse to a system of a pair of CO<sub>2</sub> gas lasers situated in a such a way that the nonlinear interaction between the two infrared laser rays would produce a difference frequency equal to the upper hybrid frequency of the plasma. According to the estimates cited in the paper, the laser power output required to seriously affect plasma oscillations is well within reasonable limits.

In the papers referred to above, as well as others submitted at the symposium, it was demonstrated that the mechanism underlying active suppression of plasma instabilities characterized by either positive or negative energy has been given sufficient study, as evidenced by the excellent agreement between theoretical calculations and experimental findings.

The experiments and theory of reactive feedback stabilization of plasma were presented in far less generous volume. Only the reports by V. A. Chuyanov (USSR) and E. Murphy (Britain) gave information on experiments dealing with stabilization of instabilities of that type, specifically flute instability of a plasma in a magnetic field of a simple mirror configuration. A single-electrode feedback loop has been used successfully in stabilizing the first mode of the plasma flute instability. But the suppression of flute instabilities of the first mode is accompanied by a buildup of oscillations at other frequencies determined by the characteristics of the feedback loop. Plasma losses accompanying the activation of the feedback loop are smaller. In a theoretical paper, C. Lashmore-Davis (Britain) posed the question of the optimum frequency response of a feedback loop for stabilizing a flute instability. But no satisfactory solution of this problem meeting practical needs has been found.

Practically all of the work described in the experimental papers was done with the aid of a single feedback loop. A model of homogeneous boundary conditions was used, however, in the theoretical analysis of the problem. The validity of the use of such a model was the subject of a paper by J. Crowley (USA). The example of a six-pole feedback loop designed to suppress plasma flute instabilities was brought up to show that all modes of flute instability below the sixth mode can be suppressed provided the loop gain is above a certain critical value. But flute oscillations with a mode number of seven or higher continue to build up, even if the plasma density has not reached the level at which these oscillations become unstable when the feedback loop is switched off.

Some of the reports presented results of a theoretical analysis of the feasibility of suppressing Kruksal-Shafranov instabilities in Tokamak type systems. A paper by J. Clarke and R. Dorey (USA) solved the problem of stabilizing a corkscrew instability in a pinch, and showed that currents stabilized by a feedback loop in a surface enveloping a plasma are capable of stabilizing unstable modes of oscillation which have no radial modes. Practical realization of a system of that type would require first that some complicated engineering problems be solved. G. Furth (USA) presented a brief review of problems pertaining to the use of feedback loops to stabilize plasma instabilities in Tokamak machines. Among the other problems considered was the possibility of controlling currents in loops replacing the copper liner of Tokamak facilities by a feedback system. The removal of the copper liner would open the way for using magnetic compression in order to heat up the plasma more effectively.

Several theoretical papers dealt with the possible use of feedback where the feedback system is activated only for very brief time intervals, to match signals from transducers recording displacements of the plasma surface. Analysis of systems of the type described revealed that the difficulties attendant upon stabilization of interchange instabilities by a linear feedback loop have been overcome to an appreciable extent. This problem was discussed in greatest detail in application to stabilization of plasma in Tokamak type facilities, in a paper submitted by A. Milner (USA).

The use of high-frequency fields to stabilize plasma instabilities has been the object of research for a fairly protracted period. This problem appears to have been tackled for the first time by S. M. Osovets (USSR) back in 1957 [4]. Further development of this work can be traced in contributions of a theoretical nature by Ya. B. Fainberg, V. D. Shapiro, V. P. Silin, L. I. Rudakov, and A. A. Ivanov (USSR), J. Teichman (Czechoslovakia), and other authors as well.

The problems touched upon in most of the theoretical reports presented at the symposium involve improvements and refinements on work done earlier, or finding stabilization conditions applicable to specific experiments. Of greatest interest in this context was a theoretical report by A. A. Ivanov and V. F. Murav'ev (USSR) which demonstrated that the ordinary wave and the helicon mode are capable of suppressing electrostatic instabilities such that  $k_Z \ll k$ , whenever the frequency of the mode excited is much higher than the frequency of the instability. The example of a cone instability was brought up to show that recourse to a helicon type mode is preferable, since the amplitude of the magnetic field on the wave in this case will have to be lower.

There was great interest shown in a paper by M. Alcock and B. Keen (Britain) citing results on suppression of a drift-dissipative instability in the plasma of the positive column of a discharge in helium and in hydrogen, by means of a high-frequency azimuthal magnetic field. The natural frequency of the unstable oscillations is 4 kHz. The frequency of the azimuthal magnetic field was varied over the range from 8 to 100 kHz. It was shown that the instability became suppressed, in harmony with the theory expounded by A. A. Ivanov and J. Teichman, when the amplitude of the variable field came to  $\sim 1\%$  of the amplitude of the constant longitudinal field.

Suppression of the drift (trapping) instability by means of a high-frequency electric field with a frequency higher than the ion plasma frequency was demonstrated in a report presented by the Japanese scientists Y. Nishida et al. The experiments were carried out using the plasma of a gas discharge struck in helium, at a particle density of  $2 \cdot 10^9$  to  $5 \cdot 10^{10} \text{ cm}^{-3}$ .

Sausage type instabilities and helical instability in the hole plasma of indium-antimony semiconductors placed in a magnetic field were suppressed with the aid of an HF field established by quadrupole conductors such as Ioffe rodlets. The results of this work were presented in a paper by A. Anker-Johnson (USA).

The audience also showed keen interest in a report by G. Wolf (West Germany) which made available the results of work on dynamical stabilization of a Rayleigh-Taylor instability in a heavy fluid above a light fluid. High-frequency mechanical oscillations were impressed on the system in a direction parallel to the interface separating the two liquid phases. While these mechanical vibrations were acting, the time over which equilibrium of the heavy fluid over the lighter fluid was maintained was stretched to  $10^4$  times the length of time in which large-scale instability ensued with the stabilization system deactivated.

The feasibility of stabilizing instabilities by impressing the high-frequency component of a longitudinal magnetic field was studied in experimental papers presented by G. Becker et al. (West Germany) and J. Phillips (USA). The feasibility of stabilizing an instability with the aid of the high-frequency field of a linear quadrupole was also investigated, in the case of a Z-pinch. In both cases particle suppression of the instabilities was achieved.

On the whole, the papers presented at the symposium constitute a valuable contribution to the further development of research on methods for stabilization of plasma by systems using feedback and HF fields. The promising possibilities of these methods were demonstrated in the study of specific instabilities, and avenues open for utilizing these methods in future controlled thermonuclear fusion research were pointed out. The proceedings of the conference are to be published as a separate edition.

#### LITERATURE CITED

1. V. V. Arsenin and V. A. Chuyanov, Dokl. Akad. Nauk SSSR, 180, 5 (1968).
2. V. V. Arsenin, V. A. Zhil'tsov, and V. A. Chuyanov, Plasma Physics and Controlled Nuclear Fusion Research, Vol. 2, IAEA, Vienna (1969), p. 515.
3. A. I. Morozov and L. S. Solov'ev, Zh. Tekh. Fiz., 34, 1566 (1964).
4. S. M. Osovets, Plasma Physics and Controlled Thermonuclear Fusion Studies, Vol. 4, Izd-vo AN SSSR, Moscow (1958), p. 3.

JUNE 1970 ZAKOPANE SYMPOSIUM ON NONDESTRUCTIVE  
MATERIALS TESTING EQUIPMENT AND TECHNIQUES  
USING NUCLEAR RADIATIONS

A. Maiorov

A symposium on nondestructive testing equipment and techniques using nuclear radiations was held at Zakopane (Poland) in June, 1970. Participating in this symposium were specialists from member-nations of COMECON, and 25 reports were presented and discussed.

Z. Pawlowski (Poland) delivered a review report, which pointed out that impressive advances may be expected in the area of automation of radiographic, radiometric, and radio spectroscopic inspection work. Attention was centered on the need to develop a method for determining the critical dimensions of flaws in a variety of structural elements, and studying the effect of critical flaw dimension on the strength of the structure inspected.

E. Becker (East Germany), presenting a historical survey of the development of radiography over the past half-decade, voiced the suggestion that it will be difficult to expect any radical improvements in this method in the immediate future. L. Brunarski et al. (Poland) and A. N. Maiorov (USSR) devoted their reports to optimization of radiographic conditions, which stimulated deep interest in those attending the symposium, who acknowledged the need to develop a unified procedure and unified recommendations in this area of work.

In a joint report by Polish and USSR specialists, L. Brunarski, L. M. Serebrennikov, et al. expounded the fundamentals of supervision of the use of radiographic quality control work applied to concrete and reinforced concrete structures. A list was drawn up of the equipment needed in the radiographic inspection of concrete, the general technical conditions to be observed in testing work, procedures for measuring the thickness of concrete, the diameter of reinforcing rods and wires and the depth to which they are laid in the concrete, detection of internal voids, and basic points in safety practice in the testing of structural members.

V. G. Firstov et al. (USSR) reviewed the present level of work in the area of xeroradiography, and cited data on the PKR-1, ERGA-S, EGU-6m, KS-1 xeroradiographic machines manufactured in the Soviet Union. The characteristics of similar machines manufactured in the USA, Britain, and Japan were surveyed at the same time. E. Gusew (Poland) reported on xeroradiographic equipment manufactured by the Lodz xerography factory. It was reported that the Pyloris (KS-2 and KS-4) xeroradiographic machines developed by the Electrical Engineering Institute, with their stagewise methods of image development, are being used in industrial inspection work in the Polish Peoples Republic. Even today, the level attained in the development of techniques has opened the way clear for the use of xeroradiography in nondestructive testing work.

Z. Godlewski and B. Kaminski (Poland) reported results of work done at the Electrical Engineering Institute; there radiometric flaw detection instruments have been developed for the inspection of active specimens, tungsten nozzles, refractory materials, and carbon blocks. The sources used in these instruments are  $\text{Co}^{60}$ ,  $\text{Cs}^{137}$ ,  $\text{Ir}^{192}$ ,  $\text{Tm}^{170}$ , and  $\text{Am}^{241}$ . Information was cited on the development of radiometric flaw detection instruments in East Germany for inspection of steel plate, and for inspection of tubes and tanks in Japan, as well as instruments for inspection of rolled goods at metallurgical plants in France and in West Germany, and joint development of radiometric flaw detection instrumentation for inspection of steel blooms by Czechoslovak and Polish industry.

Translated from Atomnaya Energiya, Vol. 29, No. 6, pp. 473-474, December, 1970.

© 1971 Consultants Bureau, a division of Plenum Publishing Corporation, 227 West 17th Street, New York, N. Y. 10011. All rights reserved. This article cannot be reproduced for any purpose whatsoever without permission of the publisher. A copy of this article is available from the publisher for \$15.00.

A report by V. G. Firstov et al. analyzed the feasibility of applying radiometric flaw detection techniques to nondestructive testing and inspection of blooms in the rolling process, to centrifugally cast tubing in mass production, and to unreinforced welded seams. Spectrometric, spectrometric-count, and collimation-spectrometric procedures in radiometric flaw detection work were discussed, and a procedure was worked out for calculating sensitivity and productivity in inspection work, illustrated by graphs of the dependence of inspection productivity on the minimum dimensions of flaws to be discerned and on the dimensions of the collimation hole.

Despite the successes attained in experimental and theoretical research on methods of radiometric flaw detection, to date we still lack quantity-produced equipment to carry out this work on a routine scale in industry, and this is accounted for by the lack of highly efficient radiation detectors, a lack of high-speed electronic equipment featuring small instrument fluctuations and excellent sensitivity to insignificant changes in the signal arriving for processing, and a lack of low-energy sharply focused sources of high specific activity which might contribute to improved resolution and greater productivity at the same time.

Visual methods of nondestructive testing and inspection were discussed at the symposium in reports delivered by J. Ginsztler, "Visual methods of inspection in industrial radiography," and J. Sorm (CSSR), "Application of an image brightness intensifier in inspection of castings." The Czechoslovak "Tesla" firm has now achieved industrial-scale production of the 03QA41, 040QA41, and 05QA41 type electronic image converter tubes with tube dimensions ranging from 175 to 289 mm, which can be used profitably in visual monitoring and inspection arrangements. The observed trend of development of visual techniques shows that further improvements in radioscopy (radiographic flaw detection work) will be impossible either in the field of new developments or in the area of incorporating existing advanced equipment in regular inspection practice, without first developing the instruments and equipment needed to eliminate the subjective fact in assessments of flaws, and thereby opening the way to proceed ahead to automatic computing of all the related data. To a lesser extent this will obtain to its application in the location and classification of flaws in parts.

A report by A. Jedziewski (Poland) provided a description of the Polish IP-8, IP-25, CP-1, and CP-10 type hose-attachment  $\gamma$ -ray flaw detection instruments with pneumatic feed of  $\text{IR}^{192}$  and  $\text{Co}^{60}$  radiation sources to the irradiation target up to distances of 30 m. These sets use lead shielding. At the present time, a modified variant of these  $\gamma$ -ray flaw detection instruments using uranium shielding is under development. These sets are intended mainly for use in production shops where assembly and rigging of outside equipment and structures are handled. Four types of Polish flaw-detection equipment were demonstrated at an exhibit set up at the symposium; also demonstrated were two negative viewers for decoding radiographic images with photographic density up to three and up to five. The first type of negative viewer has a rectangular light field controlled by adjusting blinds, and a photocell for excluding light, while the second type of negative viewer has a diaphragm-controlled circular field.

R. Dubenski (CSSR), in his report "Stereoscopic viewer for x-ray plates," discussed a stereoscope for simultaneous viewing of two radiographic images made by the method of lead markers. The prerequisite for working with the stereoscope is unimpaired vision and space perception ability on the part of the operator. The report also provides a description of a stereoscope relying on the principle of polarization of light; the operator dons polarized eyeglasses, and the radiographic images are projected onto a screen with a metallized silver coating. In addition, a stereoscopic negative viewer in which a mirror system is used to combine and transpose the images is described. These instruments were developed at the Higher Technical School in Prague, and are used to pinpoint the location of flaws in radiographed products.

V. N. Khoroshev et al. (USSR) provided information on completed development work on  $\gamma$ -ray nondestructive testing instruments in the COMECON normal classification RID-11, RID-21, RID-22, and (RID-32), on sets of equipment for irradiation of piping and tanks of large diameter (the Gazprom, Trassa, and Neva sets), specialized equipment for frontal transmission (the Stapel'-5 and Stapel'-20), and hose-attachment automated  $\gamma$ -ray nondestructive testing instruments (the Labirint and the Kama).

A report by W. Listwan and M. Dobrowolsk (Poland) presented results of joint research and development work of Polish and Czechoslovak specialists on radiometric equipment for inspecting communications cables and piping while these are in service. The method is based on the introduction of radioactive tracers with a short half-life into the piping, through which various gases of petrochemicals, etc., are pumped, the concentrations of these tracers in the medium surrounding the piping and subsequent detection of the affected portion of piping by means of a radiometric instrument inserted into the piping and moving through the

interior of the piping under the pressure of the gas or liquid being pumped through. The method has been tested and has been accepted on an experimental production basis in the Czechoslovak and Polish sections of the Druzhba international pipeline, as well as on other gas pipelines.

A report by N. D. Tyufyakov et al. (USSR) cited results of research work on neutron radiography, going in particular into a detailed discussion of neutron sources, the dependences of slow-neutron beam characteristics on beam shaping conditions, and production of beams with optimized properties; the paper also covers determinations of neutron scattering factors, inspection sensitivity, nomograms of exposures for use with detectors of neutron images that have been developed, and goes into a discussion of the range of applicability and convenience of the method. A. Petrov (Bulgaria) cited information on the joint development, in the USSR and Bulgaria, of lightweight transportable flaw-detection laboratories designed for mounting on the UAZ microbus, and the medium weight type laboratory designed for mounting on a large panel truck, and equipped with a set of varied flaw detection equipment.

Several of the reports were devoted to the present utilization, and outlook for future utilization, of radioisotope, x-ray, and betatron nondestructive testing equipment and techniques in construction, boiler manufacture, aviation, foundry work, and in other branches of industry in the member-nations of the Council for Mutual Economic Aid (COMECON).

## THE SATURN-1 PLASMA MACHINE

V. A. Suprunenko

The Saturn-1 toroidal triple-loop stellarator for plasma research was commissioned at the Khar'kov Physicotechnical Institute in the first half of 1970. The distinguishing feature of this plasma machine is its capability of operating in two modes: the stellarator mode and the torsatron mode. In the first mode, magnetic surfaces with large and controlled "shear" values ( $\leq 0.15$ ) and a rotational transform angle of the lines of force ( $\leq 1.3 \pi$ ) are established in the effective volume of the machine. In the second mode, surfaces with "shear" ( $\sim 0.1$ ) and with a "magnetic potential well" ( $\sim 10\%$ ) are established. The maximum intensity of the longitudinal magnetic field in the quasistationary mode attains the level of 10 kOe. The inner diameter of the vacuum chamber is  $\sim 170$  mm.

The first results of research on the magnetic surfaces revealed excellent agreement with theoretically predicted parameters, as clear evidence of the high precision with which the magnetic trap was fabricated.

---

Translated from *Atomnaya Energiya*, Vol. 29, No. 6, p. 474, December, 1970.

© 1971 Consultants Bureau, a division of Plenum Publishing Corporation, 227 West 17th Street, New York, N. Y. 10011. All rights reserved. This article cannot be reproduced for any purpose whatsoever without permission of the publisher. A copy of this article is available from the publisher for \$15.00.

## THE ANGLO-SOVIET PLASMA PHYSICS EXPERIMENT

V. V. Sannikov

From February through December 1969, an experiment designed for determining the electron temperature and density of a plasma, and also to determine the radial distribution of the plasma pinch by the method of Thomson scattering of laser emission, has been staged by a team of physicists from Culham Laboratory, including Drs. N. D. Peacock, D. C. Robinson, P. D. Wilcock, and M. D. Forrest, in collaboration with colleagues of the I. V. Kurchatov Institute of Atomic Energy (IAE), at that latter institute. This method, in contrast to those used earlier, made it possible to measure the electron temperature and density of the plasma directly.

British equipment was installed on the Tokamak T-3 plasma machine (large radius 1 m, small radius 25 cm, diaphragm radius 17.5 cm).

With the plasma parameters of this machine  $T_e \sim 10^2$  to  $2 \cdot 10^3$  eV,  $n_e \sim 10^{13}$  to  $5 \cdot 10^{13}$  cm<sup>-3</sup>, the Salpeter coefficient  $\alpha = \lambda_0/4\pi\lambda_D \sin\theta/2 \ll 1$ , where  $\lambda = 6943$  Å;  $\lambda_D$  is the Debye radius;  $\theta$  is the scattering angle ( $\theta = 90^\circ$ ). The case of scattering on free electrons was realized here. The scattered radiation spectrum is described by a Gaussian curve, with a Maxwellian distribution of electron velocities assumed.

A beam of light with a divergence of 2.5 mrad was directed from a ruby laser operated in the giant pulse mode, with radiation energy 5 J and pulse duration 20 to 30 msec, through the plasma pinch diametrically. Radiation scattered at  $90^\circ$  was recorded from a plasma volume of 1 cm<sup>3</sup> by means of collimating optics and a wide-aperture spectrograph with a ten-channel photoelectric system for recording the spectrum. The spectral width of each channel was 78 Å.

Half the Gaussian curve was taken from the shortward end of the spectrum, from the laser emission line 6943 Å. The spectrum was recorded in a single current pulse simultaneously on all the channels. The intensity of the hydrogen line H $\alpha$  was measured in one of the channels.

The electron concentration in the plasma was estimated from the ratio of the absolute values of the energy of the scattered light and the energy of laser emission.

A special periscopic viewing system was set up so as to obtain the radial temperature distribution and radial distribution of electron density in the plasma. The distribution of concentration was recorded at the same time by a multichord two-millimeter interferometer. Data on density obtained with the laser and with the microwave interferometer were in close agreement.

The measured electron temperature of the plasma ranged from 100 to 2000 eV, depending on the discharge conditions. The plasma concentration ranged from  $10^{13}$  to  $4.5 \cdot 10^{13}$  cm<sup>-3</sup>, while the current ranged from 40 to 150 kA, and the intensity of the longitudinal magnetic field from 17 to 38 kOe.

It is to be noted that the experimental data points fit closely to the theoretical Gaussian curve, within the limits of error of the measurements. This might mean that a Maxwellian distribution of electron energies prevails in this instance. The electron temperature increases to a maximum in 12 msec, and remains practically constant until the discharge current has died away completely.

The radial temperature distribution and radial electron density distribution are sufficiently flat near the axis of the pinch, and diminish monotonically toward the periphery of the pinch. The temperature increases as the discharge current, roughly in obedience to the law  $I^2$  (dependences were taken at current pulse widths of 35 and 70 msec), and varies inversely with the plasma density.

---

Translated from *Atomnaya Énergiya*, Vol. 29, No. 6, p. 475, December, 1970.

© 1971 Consultants Bureau, a division of Plenum Publishing Corporation, 227 West 17th Street, New York, N. Y. 10011. All rights reserved. This article cannot be reproduced for any purpose whatsoever without permission of the publisher. A copy of this article is available from the publisher for \$15.00.



The electron temperature of the plasma is virtually independent of the longitudinal magnetic field.

The experiment was performed under conditions featuring high anomalous resistance presented by the plasma. The plasma temperature as calculated on the basis of conductivity in all the sets of conditions investigated is lower than the temperature measured with the laser, and varies slightly over the current pulse. It amounts to 100-200 eV, depending on the operating conditions.

The electron temperature distribution was measured every 4 msec after the onset of current under various sets of conditions, giving some indication of slight "skinning" of the temperature near the edge of the pinch, but no clearcut "skinning" effect was obtained in later experiments, since measurements earlier in time were impossible on account of the high level of the plasma's intrinsic radiation, while measurements taken later than 4 msec yielded a flat distribution near the axis. The rapid levelling off of temperatures is an indication that the electron thermal conductivity of the plasma is well above the classical value.

The particle lifetime found from measurements of the absolute intensity of the  $H_{\alpha}$  line was 15 to 20 msec, and was longer than the energy-derived plasma lifetime of 5 msec.

Data on the radial distribution of the temperature and electron density of the plasma were utilized in computing the transverse energy of the plasma as a function of the time. The transverse component of the energy was determined simultaneously from the diamagnetic effect of the plasma. The energies measured by these two independent techniques were found to be in satisfactorily close agreement.

Note that the data on plasma parameters obtained by the method of laser scattering confirmed the results obtained earlier by Soviet physicists relying on rival methods.

#### LITERATURE CITED

1. Nature, 224, No. 1, 488-490 (1970).

GKIAÉ – JINR AGREEMENT ON SCIENTIFIC AND  
TECHNICAL COLLABORATION

V. Biryukov

An agreement on scientific and technical collaboration was signed at Dubna, in June 1970, between the State Committee on the Peaceful Uses of Atomic Energy [GKIAÉ] and the international physics research center of the socialist countries, the Joint Institute for Nuclear Research [JINR]. The purpose of this agreement is to "contribute to the rounded all-sided development of scientific and technical collaboration between member-states of JINR by combining the efforts of JINR scientists and scientists working in GKIAÉ-supervised institutes. . . ." The two parties signatory to the agreement state that they will "jointly develop scientific and technical collaboration in the field of nuclear physics, for the maximum and most efficacious utilization of accelerators, nuclear research reactors, equipment for experimental data processing, and other experimental and research facilities at their disposal, and will also devise new equipment for those purposes. . . ."

Specific efforts will be undertaken and expedited on the basis of bilateral contracts or protocols concluded between JINR and institutes under GKIAÉ, to determine the scope, times, and conditions of this research. The contracting parties, in attainment of mutual agreement, agree to draw upon national or international research organizations and other bodies in carrying out this joint work, and will observe the principles of reciprocity and take into account the interests of the parties involved. Institutes in member-nations of JINR engaged in collaboration with JINR and drawn into the overall scientific plans approved by JINR may also be included in the work carried out jointly by the two signatories.

The agreement lays down the general obligations of the two contracting parties on establishing the prerequisite conditions for work on accelerators and other research facilities: the operation and servicing of the equipment, providing electric power, liquefied gases, tool shops, computer and data processing operations, making available the necessary scientific and technical information for this joint work, and so forth. GKIAÉ will assist JINR and the institutes preparing this joint research in the development and fabrication of experimental equipment needed.

In line with the agreement signed, the contracting parties will sponsor annual meetings of their respective representatives and experts, for discussion of concrete problems in scientific and technical collaboration.

The agreement extends over a five-year period, and will be automatically extended another term of equal length, if neither of the two signatory parties voices an intention of terminating the agreement.

The international juridical document signed at Dubna flows both in spirit and in content from the famous 1959 Moscow agreement on the organization of the Joint Institute for Nuclear Research, and will serve the cause of further development of scientific and technical collaboration between the socialist countries.

---

Translated from *Atomnaya Énergiya*, Vol. 29, No. 6, pp. 475-476, December, 1970.

© 1971 Consultants Bureau, a division of Plenum Publishing Corporation, 227 West 17th Street, New York, N. Y. 10011. All rights reserved. This article cannot be reproduced for any purpose whatsoever without permission of the publisher. A copy of this article is available from the publisher for \$15.00.

## BRIEF COMMUNICATIONS

An All-Union science and engineering seminar was held at the "Atomic Energy" pavilion of the Exposition of Achievements of the National Economy of the USSR in July 1970, on the topic "Methods and equipment for dosimetric monitoring of radioactive radiations and x-rays," with 66 organizations participating. In a review report, V. V. Matveev discussed general topics concerning the development of complex dosimetric and radiometric systems, design of functional modules with unified dimensions, and characteristics of instruments developed at the All-Union Research Institute for Instrument Design.

The participants at the seminar discussed various methods for calibrating dosimeters and radiometers, requirements applicable to dosimetric inspection and checkout systems, design of dosimeters, whole-body spectrometers, etc.

\* \* \*

An All-Republic seminar of workers in chemical plants was held in Kiev in June 1970 on the topic "Radioisotope techniques and instruments in the chemical industry of the Ukraine."

The seminar participants reported that radioisotope techniques and instrumentation have been making their way in recent years in production use at advanced chemical processing plants such as the Severo-Donets Chemical Combine, and the Kaluga Chemical-Metallurgical Combine, where applications of radioisotope instruments are yielding impressive savings and improving working conditions.

\* \* \*

A seminar was held in Moscow in June 1970 to expedite exchanges of experience in the operation of in-plant and base isotope laboratories, and the implementation and acceptance of new methods and radioisotope techniques and equipment in industrial process monitoring. Participating in the seminar were 84 organizations and industrial plants under various ministries and departments, whose representatives reported that the national economy of the country has already been benefiting from applications of radioisotope techniques in terms of impressive savings, and that both base and in-plant isotope laboratories have had a positive effect on the acceptance of atomic science and engineering in industry.

\* \* \*

A science-familiarization excursion organized for the benefit of specialists from developing countries with membership in IAEA and FAO took place from August 6 through August 31, 1970, under the joint auspices of the State Committee on the Peaceful Uses of Atomic Energy of the USSR [GKIAÉ] and the Ministry of Agriculture of the USSR, affording an opportunity for these specialists to be brought up to date on applications of isotopes and radiations in agriculture in various locations throughout the Soviet Union. The group included scientists from Brazil, Chile, Costa Rica, Ghana, India, Iran, Lebanon, Mexico, Pakistan, Philippines, Sierra Leone, Sudan, Thailand, the United Arab Republic, and Yugoslavia, as well as leading staff-members of both IAEA and FAO.

One-day seminars at which lectures were delivered on applications of heavy water in soil and agrochemical research, applications of techniques and equipment for radiation work in agriculture, the study of the transformation and use by plant life of nitrogenous fertilizers through the use of such isotopes as  $N^{15}$ ,  $P^{32}$ ,  $C^{14}$ , etc., were organized in the course of the trip for the participants.

The program included visits to Moscow-area scientific research institutes such as the V. V. Dokuchaev Soil Science Institute, the isotopes laboratory of the All-Union Scientific Research Institute for Electrification of Agriculture [VNIIESKh], the D. N. Pryanishnikov All-Union Scientific Research Institute for the study of Fertilizers and Agronomical Soil Science, the Institute of Genetics and Plant Selection of the Siberian Division of the USSR Academy of Sciences (in Novosibirsk), the Biology and Soil Science Department of

---

Translated from *Atomnaya Énergiya*, Vol. 29, No. 6, p. 476, December, 1970.

© 1971 Consultants Bureau, a division of Plenum Publishing Corporation, 227 West 17th Street, New York, N. Y. 10011. All rights reserved. This article cannot be reproduced for any purpose whatsoever without permission of the publisher. A copy of this article is available from the publisher for \$15.00.

Moscow State University, the V/O Izotop agency exhibit hall, the Exposition of Achievements of the National Economy of the USSR, and the P. Lumumba University.

A discussion of the organization of scientific research work utilizing isotopes in agriculture was held at the V. I. Lenin All-Union Academy of Agricultural Sciences. [VASKhNIL].

\* \* \*

An agreement between Sweden and the Soviet Union covering a thirty-year period of collaboration in the area of peaceful uses of atomic energy was concluded in September 1970. Agreement on signing this convention was reached in the course of a visit to Sweden by the Chairman of the Council of Ministers of the USSR, A. N. Kosygin, in the summer of 1968.

Agreement envisions the possibility of both parties delivering and obtaining equipment, including nuclear reactors and fuels for nuclear reactors, nuclear materials, nuclear raw materials, and special nuclear materials of commercial interest. The Soviet Union will provide services in enriching Swedish-acquired uranium at plants in the USSR. The practical realization of this collaboration will be spelled out in further agreements, protocols, or contracts.

In accordance with the Treaty on nonproliferation of nuclear weapons, Sweden and the Soviet Union have decided to turn to IAEA with a request to carry out the provisions of the Treaty on inspection and control of the utilization of nuclear materials and equipment delivered under the terms of this agreement.

**INDEX**

**SOVIET ATOMIC ENERGY**

**Volumes 28-29, 1970**

## SOVIET ATOMIC ENERGY

Volumes 28-29, 1970

(A translation of Atomnaya Énergiya)

**A**

Ado, Yu. M.-163  
 Ad'yasevich, I. K.-74  
 Akhachinskii, V. V.-314, 1211  
 Akimov, I. S.-412  
 Akimova, R. I.-727  
 Aleinikov, V. E.-557  
 Aleksandrov, I. A.-712  
 Aleksandrov, L.-914, 1010  
 Alekseev, A. E.-172  
 Alekseev, B. A.-1235  
 Alekseev, V. I.-412, 1067  
 Aleksin, V. F.-25  
 Anan'ev, V. D.-1012  
 Anan'in, V. M.-941  
 Andreev, V. D.-608  
 Andriushchenko, V. I.-818  
 Anikin, G. V.-532  
 Antonov, A. V.-910  
 Arabei, B. G.-1026  
 Arnol'dov, M. N.-20  
 Arsen'ev, Yu. D.-528  
 Arsenin, V. V.-175  
 Arsent'ev, I. N.-210  
 Artyushov, G. A.-1240  
 Aseev, G. G.-654  
 Averkiev, V. P.-708

**B**

Babulevich, E. N.-172  
 Bak, M. A.-297, 460  
 Bakhurov, V. G.-83  
 Bakulevskii, A. A.-14  
 Balandin, G. S.-198  
 Baranov, V. F.-301, 302  
 Baranov, Yu. I.-297  
 Barchugov, V. V.-816  
 Barkov, S. N.-64  
 Basargin, Yu. G.-809  
 Bashlykov, S. N.-1211  
 Bass, L. P.-53  
 Batalov, A. A.-1016  
 Beér, A. A.-1240  
 Belous, V. N.-14  
 Belovintsev, V. Ya.-635, 810

Bel'skaya, E. P.-74  
 Belyaev, A. A.-303  
 Bevz, A. S.-171  
 Bezel'nitsyn, V. N.-86  
 Biryukov, E. I.-457  
 Biryukov, O. V.-25  
 Bobkov, V. G.-1009  
 Bogatyrev, V. K.-140  
 Bogdanov, F. F.-1229  
 Bogdanov, V. G.-462  
 Bogdanova, V. I.-809  
 Bolotova, N. G.-1243  
 Bol'shov, V. I.-497  
 Bondarenko, N. P.-301  
 Borodin, V. E.-643  
 Bortsov, V. G.-531  
 Bosamykin, V. S.-549  
 Bredikhin, M. Yu.-1003  
 Breger, A. Kh.-331, 624  
 Bugorkov, S. S.-462  
 Buleev, N. I.-683  
 Bulgakov, Yu. V.-221  
 Burchenko, P. Ya.-156  
 Burmagin, L. I.-301  
 Bushuev, A. V.-531  
 Bushuev, N. I.-1129  
 Bychkov, V. A.-135  
 Bychkov, N. V.-180, 622

**C**

Chaivanov, B. B.-630  
 Chalupa, B.-523  
 Chapnin, V. A.-641  
 Chavychalova, T. P.-986  
 Chechetkin, Yu. V.-699, 776  
 Chechetkina, Z. I.-882  
 Cherkasskii, A. Kh.-1225  
 Chernobrovkin, V. V.-537, 786  
 Chernyaev, S. V.-1227  
 Chernyaev, V. A.-528  
 Chernyaev, V. B.-205  
 Chesnokov, I. S.-1227  
 Choporov, D. Ya.-71, 189  
 Chuburkova, I. I.-990  
 Chuchalin, I. P.-727, 826  
 Chudinov, É. G.-71, 189

Chudinov, V. G.-537, 786  
 Chukichev, M. V.-641  
 Chultém, D-1035  
 Churakov, G. F.-25  
 Churin, S. A.-54, 913

**D**

Daruga, V. K.-1233  
 Davidenko, V. A.-135, 195, 866  
 Deev, Yu. S.-1037  
 Demidov, A. M.-145  
 Demikhovskii, D. A.-998  
 Demin, V. E.-1121  
 Dem'yanenko, G. K.-847  
 Denisik, S. A.-55  
 Denprovskii, I. S.-210  
 Desyatnik, V. N.-317  
 Dideikin, T. S.-932  
 Didenko, A. N.-339  
 Dimov, G. I.-1100  
 Dmitriev, A. V.-208  
 Dmitriev, P. P.-333, 335, 637, 916  
 Dmitriev, V. M.-497  
 Dmitrieva, Z. P.-333, 335, 637  
 Dmitrievskii, V. P.-858  
 Dnestrovskii, Yu. N.-1205  
 Dobrovol'skii, V. F.-621  
 Dogaev, Yu. D.-51, 52  
 Dolgikh, P. F.-83, 1140  
 Dovbenko, A. G.-532  
 Dovzhenko, A. S.-981  
 Drapchinskii, L. V.-462  
 Dreval, I. D.-536  
 Drozdov, V. E.-625  
 Druin, V. A.-837  
 Dubinin, A. A.-497  
 Jubovskii, B. G.-140  
 Dubrovskii, B. G.-412  
 Dubrovskii, V. B.-336  
 Dudnikov, V. G.-1100  
 Dunaev, L. M.-625  
 Duvanov, V. M.-531  
 Dvinyaninov, B. L.-299  
 Dvornikov, A. F.-304  
 D'yachenko, P. P.-835  
 Dymkov, Yu. M.-539

Dzantiev, B. G.-763  
Dzhelepov, V. P.-858

**E**

Efanov, A. I.-57  
Efimenko, B. A.-1013  
Egorov, Yu. A.-216  
Emel'yanov, I. Ya.-1067  
Ermagambetov, S. B.-1190  
Ermakov, V. I.-918  
Ershov, Yu. I.-534  
Evseev, A. Ya.-412  
Evstyukhin, A. I.-262  
Ezhov, V. K.-629

**F**

Faul'shtikh, Kh.-431  
Fedorenko, A. I.-510  
Fedorov, A. A.-542  
Fedorov, M. I.-1022  
Fedorova, L. A.-491  
Fehér, L.-440  
Feinberg, S. M.-870  
Feofanov, A. P.-312  
Fiks, M. M.-1199, 1245  
Filin, Yu. P.-633  
Filippova, N. V.-1223  
Flerov, G. N.-390, 967  
Fomenko, V. T.-76  
Fominykh, V. I.-201  
Fradkin, G. M.-986  
Fridman, Sh. D.-840  
Frolov, Yu. G.-794  
Frolov, V. V.-140  
Frunze, V. V.-623

**G**

Gabeskiriya, V. Ya.-259  
Gacs, F.-440  
Gadzhokov, V.-914  
Gaidamachenko, G. S.-886  
Ganichev, G. I.-739  
Garber, R. I.-510, 516  
Gavrilov, K. A.-464, 502  
Gavrilov, N. V.-794  
Generozov, V. L.-226  
Georgievskii, A. V.-25  
Gerasimov, A. I.-549  
Gerasimov, V. F.-150  
Gerasimov, V. V.-14, 923  
Gladkov, V. P.-941  
Glushkov, E. S.-64, 1116  
Goganov, D. A.-78  
Gol'danskii, V. I.-858  
Golovchenko, Yu. M.-135, 886  
Gol'tsev, V. P.-882  
Gommershtadt, V. Ya.-55

Gomozov, L. I.-1131  
Goncharev, L. A.-172  
Gorshkov, V. K.-88, 639  
Goryunov, E. F.-539  
Goshchitskii, B. N.-786  
Govor, L. I.-145  
Grachev, M. I.-712  
Granatkin, B. V.-910  
Grinberg, E. M.-829  
Grishaev, I. A.-648, 847  
Gromova, A. I.-14  
Gubrienko, K. I.-712  
Gusev, V. V.-537, 786

**H**

Havkin, V. S.-1111

**I**

Ibragimov, Sh. Sh.-336  
Ignatenko, A. E.-915  
Ignatov, A. A.-689  
Il'chenko, A. M.-1003  
Inozemtsev, V. F.-1240  
Iovnovich, M. L.-1199, 1245  
Isaev, N. V.-689  
Ivannikov, R. I.-91  
Ivanov, L. I.-829  
Ivanov, R. N.-259  
Ivanov, V. A.-145  
Ivanov, V. E.-886  
Ivanov, Yu. S.-1248  
Ivanovskii, M. N.-20  
Ivanovskii, N. N.-925

**K**

Kabanov, G. L.-228  
Kafengauz, N. L.-1022  
Kalashnikov, L. N.-31  
Kalinin, N. N.-1236  
Kaminker, D. M.-454  
Kanashin, Yu. P.-1011  
Kapchigashev, S. P.-497  
Karalova, Z. K.-259  
Karasev, V. S.-510, 516, 1221  
Kargin, A. N.-1129  
Karnaukhov, V. V.-727  
Kashcheev, I. N.-51, 52  
Kasernovich, A. I.-622  
Katrish, M. P.-31  
Katsaurov, V. I.-320  
Katsitadze, Dzd. G.-60  
Kazachkovskii, O. D.-528  
Kazakova, L. Ya.-532  
Kazarnovskii, M. V.-910  
Kazazyan, V. T.-763  
Kazmovskii, S. P.-9  
Kessel'man, V. S.-221

Khaikovich, I. M.-174, 739  
Kharchenko, V. A.-326  
Kharin, V. P.-918  
Kharitonov, N. P.-893  
Kharitonov, Yu. P.-837  
Khavkin, V. S.-1220  
Kherfort, L.-431  
Kheteev, M. V.-1112  
Khisamutdinov, A. I.-1222  
Khiznyak, N. A.-654  
Khmaruk, V. G.-845  
Khmyzov, V. V.-719  
Khokhlov, Yu. A.-938  
Khokhlov, Yu. K.-723  
Khovanovich, A. I.-635, 1113  
Khristov, V.-1010  
Khrudeva, G. A.-88  
Khudyakov, A. V.-198, 1024  
Kimel', L. R.-557, 643, 1115  
Kirichenko, G. S.-845  
Kirillov, E. V.-529  
Kirilyuk, A. L.-186  
Kisil', I. M.-412  
Kitaevskii, L. Kh.-25  
Klement'ev, A. P.-549  
Klimanov, V. A.-1013  
Klimenkov, V. I.-882, 1024  
Klimentov, V. B.-1009  
Klinov, A. V.-623  
Knyazev, V. A.-699  
Kobzar', I. G.-776  
Kogan, R. M.-840  
Kokhlov, V. F.-689  
Kokovikhin, V. F.-635, 816  
Kolesov, B. I.-14  
Kolesov, B. M.-739  
Kolesov, I. V.-502, 967  
Kolesov, V. E.-532  
Kolokol'tsov, N. A.-832, 1032, 1193  
Kolomenskii, A. A.-1095  
Kolyada, V. M.-510, 516  
Kolyadin, V. I.-1016  
Komar, E. G.-25  
Komochkov, M. M.-557  
Kondrat'ev, B. S.-817  
Kondurushkin, N. A.-635, 816  
Konobeevskii, S. T.-418, 773  
Kononenko, S. G.-554  
Konoplev, K. A.-454  
Konotop, Yu. F.-886, 1184  
Konovalov, É. E.-307  
Kon'shin, V. A.-497  
Konstantinov, I. O.-333, 335, 916, 1114  
Konstantinov, L. V.-57, 412, 537, 786, 1067, 1227

Kopchinskii, G. A.-1009  
 Kopylov, V. S.-307  
 Kopytin, L. M.-314  
 Korenevskii, V. V.-336  
 Kormushkin, Yu. P.-623  
 Kornienko, L. A.-195  
 Korobkov, I. I.-262  
 Korol', K. N.-809  
 Koroleva, V. P.-630  
 Korotaev, S. K.-9  
 Korotaeva, M. N.-307  
 Korotovskikh, P. M.-537, 786  
 Korychanek, J.-1124  
 Korzh, P. D.-76  
 Koshaeva, K. K.-464  
 Kosik, N. A.-31  
 Kostomarov, D. P.-1205  
 Kostritsa, A. A.-454  
 Kostyukov, N. S.-722  
 Kosulin, N. S.-773  
 Kotel'nikov, G. A.-1019, 1235  
 Kotel'nikov, G. N.-1135  
 Kotel'nikov, V. V.-1243  
 Kotikov, P. I.-699  
 Kovalev, V. P.-918  
 Kozhenkov, N. N.-1235  
 Kozhevnikov, D. A.-1111  
 Kozhevnikov, A. V.-339, 1146  
 Kozhevnikov, D. A.-1220  
 Kozlov, F. A.-925  
 Kraitov S. N.-464  
 Kramer-Ageev, E. A.-719  
 Kramerov, A. Ya.-718  
 Kramov, N. N.-457  
 Krasin, A. K.-763  
 Krasnov, N. N.-333, 335, 637, 916, 1114  
 Krasnov, Yu. N.-530  
 Krasovitskii, V. B.-551  
 Krishtal, M. A.-829  
 Krivokhatskii, A. S.-297  
 Kroshkin, N. I.-790  
 Krotikov, V. A.-893  
 Kruglyi, M. S.-1037  
 Krupman, A. I.-303  
 Kryvokrysenko, I. F.-1113  
 Kudinov, V. V.-301  
 Kudryavstsev, A. P.-192, 730  
 Kudyakov, V. Ya.-530  
 Kulikov, I. A.-544  
 Kul'kina, L. P.-534  
 Kul'kov, A. D.-915  
 Kuptsov, V. M.-843  
 Kurilko, V. I.-631  
 Kursakov, V. N.-1144  
 Kushin, V. V.-536, 823  
 Kutner, V. B.-91  
 Kuz'min, A. A.-1248  
 Kuzmin, V. I.-50, 446  
 Kuz'minov, B. D.-835  
 Kuznetsov, É. K.-925  
 Kuznetsov, V. I.-91, 534  
 Kuznetsova, G. G.-654  
**L**  
 Ladygin, A. Ya.-336  
 Lagunstov, N. I.-1032  
 Laletin, N. I.-309  
 Lapiashvili, E. S.-60  
 Laptev, V. G.-699  
 Laskorin, B. N.-491  
 Lavrenikov, V. D.-1010  
 Lazarev, Yu. A.-502, 967  
 Lebedev, I. G.-446  
 Lebedev, V. N.-643  
 Lebedeva, N. S.-398  
 Lebenko, P. I.-708  
 Leipunskii, A. I.-384  
 Leman, E. P.-219, 1243  
 Lenchenko, V. M.-721, 742  
 Leonov, V. F.-1019  
 Levchenko, V. B.-683  
 Levitskii, B. M.-418  
 Levskii, L. K.-443  
 Lezhava, A. N.-60  
 Lipanina, A. A.-923  
 Lisovskii, I. P.-1223, 1223  
 Lobanov, G. P.-876  
 Lobanov, Yu. V.-837, 967  
 Loginov, A. S.-25  
 Logunov, V. N.-298  
 Loktionov, Yu. M.-343  
 Lomakin, S. S.-719  
 Lubanov, Yu. V.-502  
 Lukhminskii, B. E.-55  
 Lunina, L. I.-920  
 Lupakov, I. S.-14  
 L'vov, L. N.-88  
 Lyapidevskii, V. K.-1037  
 Lysikov, B. V.-893  
 Lyubchenko, V. F.-412  
**M**  
 Maier, K.-431  
 Maiorov, L. A.-1240  
 Makarov, V. S.-1225  
 Makhnenko, L. A.-847  
 Makosov, V. V.-317  
 Maksimenko, B. P.-86  
 Mal'kov, V. V.-298, 1129  
 Malyshev, E. K.-208  
 Malyshev, I. F.-25  
 Marenkov, O. S.-627  
 Margulova, T. Kh.-923  
 Martem'yanov, I. N.-1227  
 Martynova, O. I.-776  
 Mashkovich, V. V.-1013  
 Maslov, A. I.-1003  
 Matora, I. M.-1012  
 Matushevich, E. S.-497, 1233  
 Matveenko, V. J.-452  
 Matyukhin, V. V.-925  
 Medvedev, Yu. A.-228  
 Mel'nikov, Yu. T.-317  
 Merkul'ev, Yu. A.-910  
 Merts, V.-431  
 Metelkin, A. I.-708  
 Michalev, R.-523  
 Mikhailov, G. A.-224  
 Millionshchikov, M. D.-268, 406, 696, 1178  
 Milovanov, O. S.-850  
 Minashin, M. E.-412  
 Minenko, V. P.-1193  
 Mirnov, S. V.-160  
 Miroshnichenko, Yu. T.-1184  
 Mitin, A. A.-86  
 Mitov, V. N.-542  
 Mitropolskii, A. N.-1126  
 Mityaev, Yu. I.-412  
 Molin, G. A.-335, 637  
 Monoszon, N. A.-25  
 Mordashev, V. M.-214  
 Mordovskaya, T. S.-719  
 Moroz, E. M.-175, 177  
 Morozov, A. A.-1222  
 Morozov, V. A.-20  
 Morozov, V. M.-398  
 Morozova, I. K.-14  
 Moskalev, S. S.-150  
 Moskalev, Yu. I.-593  
 Moskvina, L. N.-1236  
 Movsisyan, L. M.-651  
 Muminov, M. I.-722  
 Murin, A. N.-443  
 Myae, E. A.-998  
**N**  
 Nalivaev, V. I.-301, 302  
 Naskidashvili, I. A.-60, 418  
 Nasonova, G. I.-794  
 Nazarenko, N. G.-539  
 Nazarov, A. I.-776  
 Nazarov, I. M.-840  
 Nedumova, E. S.-56  
 Nelipovich, E. S.-820  
 Neshkov, D. Z.-228  
 Nesmeyanova, K. A.-781



Nestrel'yev, V. V.-1149  
 Neumann, Jan.-521  
 Nichipor, G. V.-763  
 Nichkov, I. F.-317  
 Nikitin, M. M.-1146  
 Nikolaev, B. I.-1193  
 Nikolaev, N. M.-689  
 Nikolaev, V. A.-57, 1227  
 Nikolaev, V. I.-832  
 Nosov, V. I.-64  
 Novak, V. E.-559  
 Novgorodtsev, R. B.-326  
 Novik-Kachan, V. P.-679  
 Novoselov, G. P.-51, 52  
 Novozhilov, V. A.-1240  
 Nozik, V. Z.-910

**O**

Ochkur, A. P.-78, 542  
 Oganesyanyan, Yu. Ts.-967  
 Ogorodnik, S. S.-1221  
 Orlenko, N. I.-626  
 Orlov, Yu. V.-216  
 Osipov, V. V.-262, 820  
 Organesyan, Yu. Ts.-502  
 Orlov, V. V.-449  
 Ostanin, V. A.-850  
 Ostreikovskii, É. P.-372  
 Otgonsuren, O.-1035  
 Ostrovskaya, G. Ya.-598  
 Ovander, L. N.-1133  
 Ovchinnikov, A. K.-739

**P**

Palei, P. N.-259  
 Panfilov, G. G.-719  
 Panasenkov, A. F.-425  
 Pantelev, L. D.-418  
 Papiro, I. I.-195  
 Paramonova, I. N.-938  
 Pashkin, Yu. G.-184  
 Pasyuk, A. S.-91, 534  
 Pavlichenko, O. S.-156  
 Pavlov, S. Yu.-328  
 Pavlov, Yu. F.-708  
 Pavlovskii, A. I.-549  
 Pavlov-Verevkin, B. S.-81  
 Penionzhkevich, Yu. É.-990  
 Perel'man, A. I.-2  
 Pereygin, V. P.-1035  
 Perevalov, V. G.-336  
 Pergamenschik, V. K.-336  
 Petrenko, A. A.-1126  
 Petros'yants, A. M.-372  
 Petrov, V. I.-719  
 Petrov, Yu. G.-460

Petrov, Yu. N.-547  
 Petrova, T. I.-776  
 Petrzhak, K. A.-460  
 Petushkova, N. A.-1116  
 Pichugin, A. V.-300  
 Pikalov, G. L.-1113  
 Pikel'ner, L. B.-464  
 Pinkhasik, M. S.-1126  
 Piskun, A. S.-446  
 Pletenets, S. S.-20  
 Plis, Yu. A.-822  
 Plotko, V. M.-502, 967  
 Plotnikov, R. I.-78  
 Polivanskii, V. P.-497  
 Polosukhina, K. N.-683  
 Poluboyarinov, Yu. V.-502  
 Polukhin, A. T.-1095  
 Polyani, L. N.-935  
 Ponomarev-Stepnoi, N. N.-64, 1116  
 Popeko, L. A.-210  
 Popkovich, A. V.-25  
 Popov, V. I.-532  
 Posel'skii, N. N.-809  
 Posokhin, Yu. V.-530  
 Postnikov, V. V.-412, 920, 1067  
 Potapenko, V. A.-156  
 Potap'eva, L. E.-819  
 Potetyunko, G. N.-824, 1149  
 Pozdnev, D. B.-300  
 Preobrazhenskaya, L. B.-56  
 Prikot, K. N.-623  
 Primenko, G. I.-320, 323  
 Prisnyakov, V. F.-732  
 Pronman, I. M.-320, 323  
 Prokopchik, V. I.-737  
 Prudnikov, I. A.-918  
 Prusakov, V. N.-629  
 Prutkina, M. I.-724  
 Pshenichnyi, G. A.-78, 627  
 Pupko, V. Ya.-50, 497  
 Pushlenkov, M. F.-312  
 Pyatnov, E. G.-850  
 Pyzhova, Z. I.-259

**R**

Radchenko, S. V.-528  
 Raetskii, V. M.-773, 1131  
 Rambush, K.-431  
 Raspopin, S. P.-317, 1011  
 Ratnikov, E. F.-769  
 Rauzen, F. V.-703, 798  
 Regushevskii, V. I.-497  
 Repalov, N. S.-654  
 Rezanov, R. A.-55  
 Roginskii, L. A.-178, 1224

Romanov, Yu. F.-460  
 Ronzhin, O. B.-181  
 Roslik, S. F.-298  
 Rozhdestvenskii, B. V.-25  
 Rubtsov, K. S.-847  
 Rudakov, V. A.-156  
 Rumyantsev, G. Ya.-69  
 Runov, I. V.-559  
 Rybakova, G. D.-708  
 Ryabka, P. M.-847

**S**

Sabelev, G. I.-533  
 Sabin, M. V.-938  
 Sachkov, V. F.-1227  
 Safronov, B. G.-654  
 Sakharov, E. S.-727, 826  
 Sakhnovskii, É. G.-911  
 Sakovich, V. A.-226  
 Saksaganskii, G. L.-25  
 Samoilov, P. S.-210, 719  
 Samoilov, Yu. F.-776  
 Samsonov, B. V.-876  
 Sarantsev, V. P.-1245  
 Sarkisov, A. A.-1227  
 Sazonova, E. V.-721  
 Sebko, V. P.-343  
 Selivanov, Yu. F.-9  
 Semenov, I. B.-160  
 Senatorov, G. F.-1224, 1248  
 Senin, M. D.-314  
 Serebrennikov, Yu. M.-1029, 1067  
 Serenkov, V. I.-1037  
 Sergachev, A. I.-835  
 Severgin, Yu. P.-809  
 Shabel'nikov, L. A.-25  
 Shafranov, V. D.-801  
 Shamov, V. P.-593  
 Shamovskii, V. G.-1100  
 Shamsutdinov, A. O.-990  
 Sharapov, V. N.-412  
 Shaskin, V. L.-724  
 Shatalov, V. V.-491  
 Shchedrin, I. S.-850  
 Shchepetil'nikov, N. N.-312  
 Shchetinin, O. I.-208  
 Sheglovskii, Z.-990  
 Shembel', B. K.-820  
 Shenderovich, A. M.-554  
 Shifrin, I. G.-708  
 Shikov, S. B.-534  
 Shimanskaya, N. S.-457  
 Shimmel, V. V.-431  
 Shishin, B. P.-932  
 Shlyamin, É. A.-297, 460  
 Sholokhov, A. A.-683

Shol'ts, V.-431  
 Shpirkauskaitė, N. K.-843  
 Shramenko, B. I.-648  
 Shtivel'man, A. Ya.-298  
 Shukeilo, I. A.-559  
 Shulepin, V. S.-67, 69, 452  
 Shulimov, V. N.-876  
 Shuvalov, V. M.-412  
 Sidorin, V. P.-643, 1115  
 Sidorov, S. K.-537, 786  
 Sidorov, V. I.-533  
 Sidorin, V. P.-557  
 Sinel'nikov, K. D.-25  
 Sivintsev, Yu. V.-593  
 Skiba, O. V.-171  
 Skibenko, A. I.-1003  
 Skorikov, A. G.-727  
 Skorov, D. M.-941  
 Skorovarov, D. I.-491  
 Skvortsov, S. A.-380  
 Slavyanov, V. I.-1240  
 Smakhtin, L. A.-1223, 1223  
 Smirenkin, G. N.-532, 1190  
 Smirenkina, L. D.-835  
 Smirnov, I. A.-850  
 Smirnov, M. V.-530  
 Smirnov, O. N.-1121  
 Snitko, É. I.-412, 1067  
 Sobenin, N. P.-850  
 Sobolev, A. V.-1227  
 Sofienko, L. A.-721  
 Sokolov, Yu. A.-25  
 Sokolova, Z. Ya.-205  
 Solov'ev, S. P.-326  
 Solov'eva, Z. I.-462  
 Sorokin, D. N.-192, 603, 730  
 Sorokina, A. V.-462  
 Soroko, L. M.-822  
 Spiridonov, A. I.-1137  
 Sprygaev, I. F.-1240  
 Stanolov, A.-1010  
 Starizhyi, E. S.-331, 624  
 Stavisskii, Yu. Ya.-497  
 Stavitskii, R. V.-1112  
 Stapanov, A. V.-1119  
 Stepanov, B. M.-228  
 Serman, L. S.-1124  
 Stoyanov, Ch.-914  
 Strakhov, I. P.-708  
 Strizhak, V. I.-320, 323  
 Stumbur, É. A.-449, 928  
 Styro, B. I.-843  
 Subbotin, V. I.-9, 20, 192, 603,  
 620, 730, 925  
 Sudakova, N. V.-198  
 Sukhanova, K. A.-299

Sulaberidze, G. A.-832, 1193  
 Sulygin, I. I.-820  
 Suprunenko, V. A.-25  
 Susloparov, M. S.-918  
 Sviridenko, E. Ya.-620  
 Sviridenko, V. E.-9  
 Sychev, B. S.-1129

**T**

Taliev, A. V.-718  
 Talyzin, V. V.-722  
 Tananakin, V. A.-549  
 Tarantin, N. I.-821  
 Tarantin, V. D.-1126  
 Teplyakov, V. A.-645  
 Terent'ev, V. P.-986  
 Tereshchenko, F. F.-156  
 Terman, A. V.-593  
 Tetel'baum, S. D.-976  
 Teverovskii, E. N.-593  
 Tikhinskii, G. F.-195  
 Timchenko, R. A.-876  
 Timofeeva, T. V.-739  
 Tishin, A. S.-532  
 Tolok, V. T.-25, 156  
 Tolstoluzhskii, A. P.-631  
 Tonopetian, S. G.-648  
 Toropov, A. S.-918  
 Tret'yak, S. A.-832, 1193  
 Tret'yakov, Yu. P.-91  
 Tret'yakova, S. P.-502, 967  
 Troshin, V. S.-719  
 Troyanov, E. F.-998  
 Trushkov, N. D.-798  
 Try'yakov, Yu. P.-534  
 Tsoglin, Yu. L.-1221  
 Tsukerman, I. Kh.-1126  
 Tsyganok, A. A.-603  
 Tsykanov, V. A.-623, 876, 882  
 Tustanovskii, V. T.-818  
 Tyminskii, V. G.-1137

**U**

Ushakov, P. A.-620  
 Uspenskii, V. K.-623  
 Ustinov, A. A.-57  
 Usynin, G. B.-935  
 Utkin, V. I.-720

**V**

Vagapov, R. Kh.-641  
 Vagin, Yu. P.-228  
 Val'dner, O. A.-850  
 Vasilenko, B. T.-156  
 Vasil'ev, G. Ya.-454  
 Vasil'ev, S. S.-76

Vasil'kov, V. G.-858  
 Vatulin, V. V.-815  
 Vavilov, V. S.-641  
 Vavra, J.-523  
 Vazinger, V. V.-911  
 Vedishcheva, T. S.-703  
 Velyus, L. M.-76  
 Venikov, N. I.-809  
 Vertebnyi, V. P.-186  
 Vetyukov, V. N.-920  
 Viktorov, A.-1013  
 Vikulov, V. K.-412  
 Viselkina, M. A.-2  
 Vladimirov, L. A.-1140  
 Vladimirova, M. V.-544  
 Vlasov, A. D.-282, 852  
 Voinov, E. M.-976  
 Vol'gemut, A. A.-818  
 Volgin, V. I.-1223  
 Volkov, E. D.-156  
 Volkovich, A. V.-1011  
 Voloshchuk, A. I.-886, 1184  
 Vorobei, M. P.-171  
 Vorob'ev, A. A.-339, 1146  
 Vorob'ev, E. D.-91  
 Vorob'ev, M. A.-135  
 Vorob'ev, V. A.-840  
 Vorob'eva, V. G.-835  
 Vorotnikov, P. E.-735  
 Votinov, S. N.-882  
 Vozzhenikov, G. S.-173

**Y**

Yakovlev, G. N.-312  
 Yanshevskii, Yu. P.-542  
 Yarkovoi, É. A.-1112  
 Yudin, F. P.-1140  
 Yudkevich, M. S.-910  
 Yuferev, V. I.-815  
 Yuferov, V. B.-1003  
 Yurchenko, É. I.-801  
 Yur'ev, Yu. S.-497  
 Yuzgin, V. S.-328

**Z**

Zagorets, P. A.-1240  
 Zaikin, Yu. I.-1016  
 Zaitsev, L. N.-1115  
 Zaitsev, R. Ya.-301, 302  
 Zamyatnin, Yu. S.-790, 938  
 Zaslavskii, V. G.-443  
 Zatserkovskii, R. A.-186  
 Zavgorodnii, A. Ya.-1131  
 Zelenova, O. I.-2  
 Zelenskii, V. F.-886, 1184  
 Zel'venskii, Ya. D.-56

Zenkevich, V.S.-150  
Zenkov, D.I.-549  
Zharkov, G.M.-986  
Zharkov, V.P.-216

Zhukov, A.V.-620  
Zhuravlev, A.A.-163  
Zil'berman, M.I.-722  
Zol'nikov, P.P.-299

Zolotukhin, V.G.-1013  
Zotov, A.V.-643  
Zotov, V.S.-941

## TABLES OF CONTENTS

## SOVIET ATOMIC ENERGY

Volumes 28-29, 1970

(A translation of Atomnaya Énergiya)

Volume 28, Number 1 January, 1970

	Engl./Russ.	
1969 Recipients of USSR State Prizes . . . . .	1	2
Two Classes of Geochemical Reducing Barriers in Exogenous Uranium Deposits – O. I. Zelenova, M. A. Viselkina, and A. I. Perel'man . . . . .	2	3
Investigation of the Dynamics of Vapor Bubbles in Boiling of Water in Thin Shells under Natural Convection – V. I. Subbotin, S. P. Kaznovskii, S. K. Korotaev, V. E. Sviridenko, and Yu. F. Selivanov . . . . .	9	9
Corrosion and Electrochemical Behavior of Carbon Steels in Quasi-Reactor Conditions – V. V. Gerasimov, A. I. Gromova, I. S. Lupakov, I. K. Morozova, A. A. Bakulevskii, V. N. Belous, and B. I. Kolesov . . . . .	14	13
Solubility of Gases in a Eutectic Alloy of Sodium and Potassium – M. N. Arnol'dov, M. N. Ivanovskii, V. A. Morozov, S. S. Pletenets, and V. I. Subbotin . . . . .	20	18
Uragan Experimental Thermonuclear Equipment – V. F. Aleksin, O. V. Biryukov, A. V. Georgievskii, L. Kh. Kitaevskii, E. G. Komar, A. S. Loginov, I. F. Malyshev, N. A. Monoszon, A. V. Popkovich, B. V. Rozhdestvenskii, G. L. Saksaganskii, K. D. Sinel'nikov, Yu. A. Sokolov, V. A. Suprunenko, V. T. Tolok, G. F. Churakov, and L. A. Shabel'nikov . . . . .	25	22
Gas Desorption during Proton Irradiation of Metals and Metal – Metallic Film Systems – M. P. Katrich, L. N. Kalashnikov, and N. A. Kosik . . . . .	31	28
REVIEWS		
Present State and Design Trends of Thermionic Converters – Yu. I. Danilov and D. V. Karetnikov . . . . .	36	33
New Data on Neutron Spectroscopy of Heavy Nuclei – S. I. Sukhoruchkin . . . . .	41	38
ABSTRACTS		
Optimization of Fuel Breeding in Reactors – V. I. Kuz'min and V. Ya. Pupko . . . . .	50	47
Interaction of Uranium and Its Alloys with Alkali Metal Fluorides – G. P. Novoselov, I. N. Kashcheev, and Yu. D. Dogaev . . . . .	51	48
Extraction of Plutonium by Fluoride Melts – G. P. Novoselov, I. N. Kashcheev, and Yu. D. Dogaev . . . . .	52	49
Solution of the Transport Equation by the Method of Characteristics – L. P. Bass . . . . .	53	49
Reconstruction of the Spectral and Angular-Distribution Function of Sources of $\gamma$ -Quantá Radiation – S. A. Churin . . . . .	54	50
Monte Carlo Calculation of Nonstationary Distributions of Neutrons and Capture $\gamma$ -Rays in Nuclear Geophysics Problems – V. Ya. Gommershtadt, S. A. Denisik, B. E. Lukhminskii, and R. A. Rezvanov . . . . .	55	51
Oxygen Isotope Separation Factor at Equilibrium of Water Vapor with Basic Aqueous Solutions – L. B. Preobrazhenskaya, E. S. Nedumova, and Ya. D. Zel'venskii, . . . . .	56	51
LETTERS TO THE EDITOR		
Certain Experimental Neutron – Physical Characteristics of the SO-1 Breeder – L. V. Konstantinov, V. A. Nikolaev, A. I. Efanov, and A. A. Ustinov . . . . .	57	53

Tensile-Testing Device for Micro-Scale Specimens in a Reactor Low-Temperature Channel - I. A. Naskidashvili, É. S. Lapiashvili, A. N. Lezhava, and Dzh. G. Katsitadze. . . . .	60	55
Flux Mapping in Heterogeneous Reactors by Spacing of Blocks - N. N. Ponomarev-Stepnoi, E. S. Glushkov, V. I. Nosov, and S. N. Barkov . . . . .	64	58
Calculation of Reactor Criticality in the Asymptotic Approximation - V. S. Shulepin. . . . .	67	60
Calculation of Reactor Criticality by Solving a System of Nonlinear Equations - V. S. Shulepin and G. Ya. Rummyantsev . . . . .	69	61
Sublimation of Americium Tetrafluoride - É. G. Chudinov and D. Ya. Choporov . . . . .	71	62
Separation and Purification of Gallium Isotopes by an Extraction - Chromatographic Method - I. K. Ad'yasevich and E. P. Bel'skaya. . . . .	74	64
Analysis of Isotopic Composition of Europium and Iridium by Thermal Neutron Absorption - S. S. Vasil'ev, L. M. Velyus, P. D. Korzh, and V. T. Fomenko . . . . .	76	65
Applications of Radioisotope X-Ray Luminescent Analysis to Determination of the Real Composition of Rocks and Ores in Motion - G. A. Pshenichnyi, A. P. Ochkur, R. I. Plotnikov, and D. A. Goganov . . . . .	78	67
Deactivation of Radioactive Waste from Fe <sup>55</sup> Production - B. S. Pavlov-Verevkin. . . . .	81	69
Underground Burial of Harmful Wastes - P. F. Dolgikh and V. G. Bakhurov. . . . .	83	70
Electron Detection by Silicon Surface-Barrier Counters on $\gamma$ -Background of Comparable Energy - B. P. Maksimenko, V. N. Bezmel'nitsyn, and A. A. Mitin . . . . .	86	71
Distribution of Fragments from Spontaneous Fission of Cm <sup>244</sup> , from Track Diameters on the Surface of Silicate Glass - V. K. Gorshkov, L. N. L'vov, and G. A. Khrudeva . . . . .	88	73
Source of Multiply Charged Calcium and Zinc Ions - A. S. Pasyuk, E. D. Vorob'ev, R. I. Ivannikov, V. I. Kuznetsov, V. B. Kutner, and Yu. P. Tret'yakov. . . . .	91	75
<b>CHRONICLES</b>		
Aleksandr L'vovich Mints. On the Occasion of His Seventy-Fifth Birthday . . . . .	95	79
Vladimir Ivanovich Smirnov. On the Occasion of His Sixtieth Birthday. . . . .	98	81
<b>NEWS OF SCIENCE AND TECHNOLOGY</b>		
Symposium on Radiation Damage in Reactor Materials - P. A. Platonov. . . . .	101	83
Conference on Nuclear Reactions Caused by Heavy Ions, Heidelberg, July, 1969. . . . .	104	85
Second Symposium on the Physics and Chemistry of Fission (IAEA, Summer, 1969) - S. A. Karamyan and Yu. V. Ryabov. . . . .	107	87
Conference on the Chemistry of Solvent Extraction - G. A. Yagodin. . . . .	111	89
IAEA Conference on Information on Nuclear Power Facilities - Yu. V. Arkhangel'skii . . . . .	114	90
The Uranium Industry in the Capitalist and Developing Countries in 1968 - V. D. Andreev . . . . .	116	91
Nuclear Research Centers in Belgium and the Netherlands - V. I. Man'ko. . . . .	129	99
<b>BRIEF COMMUNICATIONS</b> . . . . .	132	101

## Volume 28, Number 2 February, 1970

Mechanical Properties of Irradiated Uranium - M. A. Vorob'ev, Yu. M. Golovchenko, A. S. Davydenko and B. A. Bychkov. . . . .	135	107
Neutron-Irradiation Method for Analyzing Fissionable Substances - V. K. Bogatyrev, B. G. Dubovskii, and V. V. Frolov . . . . .	140	111
Use of a Germanium Detector for a Neutron-Radiation Analysis of the Content of Elements and Isotopes - A. M. Demidov, L. I. Govor, and V. A. Ivanov . . . . .	145	115
Neutron Spectrometer for Measuring Scattering Cross Sections by the Time-of-Flight Method - V. F. Gerasimov, V. S. Zenkevich, and S. S. Moskalev . . . . .	150	120

On the Mechanism of Plasma Loss in the Stellarator – P. Ya. Burchenko, B. T. Vasilenko, E. D. Volkov, O. S. Pavlichenko, V. A. Potapenko, V. A. Rudakov, F. F. Tereshchenko, and V. T. Tolok . . . . .	156	126
Measurement of Ion Temperature in the "Tokamak T-3" Facility from Doppler Broadening of Spectral Lines of Neutral Hydrogen and Deuterium – S. V. Mirnov and I. B. Semenov . . . . .	160	129
Some Results of the All-Round Alignment and Startup of the 70 GeV Proton Synchrotron at the Institute of High Energy Physics – Yu. M. Ado, A. A. Zhuravlev, A. A. Logunov, É. A. Myaz, A. A. Naumov, V. E. Pisarevskii, V. G. Rogozinskii, K. Z. Tushabramishvili, I. A. Shukeilo, S. N. Boiko, E. G. Komar, I. F. Malyshev, I. V. Mozin, N. A. Monoszon, I. A. Mozalevskii, F. M. Spevakova, A. M. Stolov, V. A. Titov, F. A. Vodop'yanov, A. A. Kuz'min, V. F. Kuz'min, A. L. Mints, S. M. Rubchinskii, V. A. Uvarov, B. M. Gutner, V. B. Zalmanzon, A. I. Prokop'ev, and A. S. Temkin . . . . .	163	132

## ABSTRACTS

Investigation of Salt Systems Based on LiCl, RbCl, CsCl, and UO <sub>2</sub> Cl <sub>2</sub> – M. P. Vorobei, O. V. Skiba, and A. S. Bevz . . . . .	171	139
Calibration of Direct-Charging Detectors for Measurement of Absolute Thermal-Neutron Flux – A. E. Alekseev, E. N. Babulevich, L. A. Goncharev, V. A. Zagadkin, V. S. Kirsanov, A. A. Kononovich, V. M. Kuznetsov, É. M. Kuznetsov, M. G. Mitel'man, G. P. Pochivalin, and N. D. Rozenblyum . . . . .	172	139
Gamma Intensity of the Induced Activity in Coal Seams of Finite Thickness – G. S. Vozzhenikov . . . . .	173	140
Parameters Determining the Gamma Distribution in a Medium of Arbitrary Elemental Composition – I. M. Khaikovich . . . . .	174	140
On the Possibility of Suppressing Helical Modes of Hydromagnetic Instability of a Plasma Filament with Current by a System of Feed Backs – V. V. Arsenin . . . . .	175	141
Geometry of the Orbits in Sector-Type Cyclotrons – E. M. Moroz . . . . .	175	142
Method of Calculating the Ion Trajectories in a Radial-Sector Step-Field Cyclotron – E. M. Moroz . . . . .	177	143
Stabilization of the Transverse Coherent Resistance Instability by Automatic Correction – L. A. Roginskii . . . . .	178	143

## LETTERS TO THE EDITOR

Gas Evolution in the First Loop of a Water-Cooled, Water-Moderated Reactor with Gas Volume Compensators – N. V. Bychkov and A. I. Kasperovich . . . . .	180	145
Estimate of the Asymptotic Stability Region in Thermal Reactors with Discrete Control Systems – O. B. Ronzhin . . . . .	181	145
Accuracy of the Wigner Approximation – Yu. G. Pashkin . . . . .	184	147
Absolute Measurements of Integrated Dosages of Slow Neutrons in the Active Zone of an Atomic Reactor, Using a Transmission Method – V. P. Vertebnyi, R. A. Zatserkovskii, and A. L. Kirilyuk . . . . .	186	149
Volatility of Plutonium Tetrafluoride – É. G. Chudinov and D. Ya. Choporov . . . . .	189	151
Superheating Values Required for the Boiling of Alkali Metals – V. I. Subbotin, D. N. Sorokin, and A. P. Kudryavtsev . . . . .	192	153
Properties of Irradiated Beryllium – L. A. Kornienko, I. I. Papirova, G. F. Tikhinskii, and A. S. Davidenko . . . . .	195	155
Gaseous Swelling in Irradiated Beryllium Oxide – A. V. Khudyakov, N. V. Sudakova, and G. S. Balandin . . . . .	198	157
Neutrons with Energies Less than 1 MeV in Spectra from Be ( $\alpha$ , N) Sources – V. I. Fominykh . . . . .	201	159
Parameters of ZnS(Ag) Scintillators for Neutron Recording – Z. Ya. Sokolova and V. B. Chernyaev . . . . .	205	162

Three-Component Isotopic Mixture for Neutron Measurements in Fission Chambers – O. I. Shchetinin, A. V. Dmitriev, and E. K. Malyshev . . . . .	208	164
Ge(Li) Spectrometer with Thermoelectric Cooler – I. N. Arsent'ev, I. S. Denprovskii, L. A. Popeko, and P. S. Samoilov. . . . .	210	165
Neutron Scattering in Air – V. M. Mordashev . . . . .	214	168
Back Scattering of Neutrons from Aluminum, Titanium, Graphite, and Polyethylene – Yu. A. Egorov, V. P. Zharkov, and Yu. V. Orlov . . . . .	216	170
Photoabsorption Coefficients and Effective Atomic Number of Elements and Complex Media for Low-Energy Gamma Rays – E. P. Leman . . . . .	219	172
Statistical Spread in Ranges of Heavy Charged Particles – V. S. Kessel'man and Yu. V. Bulgakov . . . . .	221	173
A Method for Simulating the Mean Free Path of a Particle – G. A. Mikhailov . . . . .	224	175
Optimization of the Shape of a Shadow Shield by the Monte – Carlo Method – V. L. Generozov and V. A. Sakovich. . . . .	226	175
Luminescence of Air Bombarded by Fast Electrons – Yu. P. Vagin, G. L. Kabanov, Yu. A. Medvedev, D. Z. Neshkov, and B. M. Stepanov. . . . .	228	177
NEWS		
BOR-60 Reactor now in Operation – E. P. Karelin and B. N. Koverdyaev . . . . .	231	179
Science and Engineering Conference on Nucleonic Instrumentation – N. A. Shekhovtsov . . . . .	234	181
Leaching of Radioactive Isotopes from Solids – V. V. Kulichenko . . . . .	235	182
VIII International Congress and General Assembly of the International Union of Crystallography – M. G. Zemlyanov . . . . .	237	183
III International Conference on Collision of High-Energy Particles, and III International Conference on High-Energy Physics and Structure of the Nucleus – A. A. Kuznetsov . . . . .	239	184
International Conference on the Properties of Nuclear States – V. G. Solov'ev and N. I. Pyatov . . . . .	242	186
International Conference on Interactions of Electrons and Protons at High Energies – L. D. Solov'ev. . . . .	244	187
International School on the Physics of Elementary Particles – V. S. Kaftanov . . . . .	247	189
Symposium on Analytical Chemistry – V. A. Khalkin. . . . .	249	189
Production of Isotopes in the Comecon Countries . . . . .	252	191
BRIEF COMMUNICATIONS. . . . .	254	192
BOOK REVIEWS		
B. N. Sudarikov and E. G. Rakov – Processes and Equipment in Uranium Production – Reviewed by A. Pushkov . . . . .	256	193
Steam Generating and Other Heavy Water Reactors . . . . .	256	193
A. Klusmann and H. Volcker – Nuclear Reactor Fuel Elements . . . . .	258	194

## Volume 28, Number 3 March, 1970

Investigation of the Buildup of Isotopes of Protoactinium and Uranium when $\text{Th}^{230}$ and $\text{Th}^{232}$ Are Irradiated by Thermal Neutrons – Z. K. Karalova, P. N. Palei, R. N. Ivanov, V. Ya. Gabeskiriya, and Z. I. Pyzhova. . . . .	259	199
Intermetallic Compounds of Zirconium and Their Influence on the Corrosion Properties of Zirconium Alloys – A. I. Evstyukhin, I. I. Korobkov, and V. V. Osipov . . . . .	262	201
Turbulent Flow in the Boundary Layer and in Tubes – M. D. Millionshchikov . . . . .	268	207
Limiting Current during Neutral Initial Equilibrium of Clusters in a Linear Accelerator – A. D. Vlasov. . . . .	282	220

## REVIEWS

The Development of Views on Radiation Protection Standards – A. A. Letavet, I. K. Dibobes, E. N. Teverovskii, and A. V. Terman.....	287	225
International Nuclear Information System – I. D. Morokhov, V. F. Semenov, L.L. Isaev, M. V. Ivanov, and I. V. Tikhonov .....	294	231

## ABSTRACTS

Peculiarities of the Production of Th <sup>228</sup> and U <sup>232</sup> by Neutron Irradiation of Pa <sup>231</sup> – M. A. Bak, Yu. I. Baranov, A. S. Krivokhatskii, and É. A. Shlyamin .....	297	234
Calculation of the Yield of Secondary Neutrons in the Interaction of Accelerated Electrons with Matter – V. N. Logunov, V. V. Mal'kov, S. F. Roslik, and A. Ya. Shtivel'man .....	298	235
Albedo of Bremsstrahlung $\gamma$ -Radiation – P. P. Zol'nikov, B. L. Dvinyaninov, and K. A. Sukhanova.....	299	235
Spectral and Angular Distributions of Backscattered Cs <sup>137</sup> $\gamma$ -Rays Emerging from Various Parts of a Reflector – A. V. Pichugin and D. B. Pozdneev .....	300	236
Angular Distribution of Monoenergetic Electrons and Beta Particles Scattered in a Shield – V. F. Baranov, N. P. Bondarenko, L. I. Burmagin, R. Ya. Zaitsev, V. V. Kudinov, and V. I. Nalivaev .....	301	237
An Adsorption Method for Determining the Energy Distribution of Electrons Incident on and Transmitted through a Shield – V. F. Baranov, R. Ya. Zaitsev, and V. I. Nalivaev.....	302	237
Calculation of Self-Absorption in $\beta$ -Sources – A. A. Belyaev and A. I. Krupman .....	303	238

## LETTERS TO THE EDITOR

Effectiveness of Using Steam Power Evaporating Equipment in Atomic Electric Power Plant – A. F. Dvornikov.....	304	239
Detection of Hydrogen in a Sodium Heat Exchanger – V. S. Kopylov, M. N. Korotaeva, and É. E. Konovalov.....	307	241
Distribution of Thermal Neutrons in a Cylindrical Cell – N. I. Laletin .....	309	242
A Miniature Centrifugal Extractor – G. N. Yakovlev, M. F. Pushlenkov, N. N. Shchepetil'nikov, and A. P. Feofanov .....	312	244
Enthalpy of BeH <sub>2</sub> Formation – V. V. Akhachinskii, L. M. Kopytin, and M. D. Senin.....	314	245
The Fusibilities of Salt Systems Containing Uranium Trichloride – V. N. Desyatnik, Yu. T. Mel'nikov, I. F. Nichkov, S. P. Raspopin, and V. V. Makosov.....	317	247
Tritium-Filled Targets of Scandium, Yttrium, Praseodymium, Neodymium, and Erbium – V. I. Strizhak, G. I. Primenko, V. I. Katsaurov, and I. M. Pronman .....	320	249
Preparation and Investigation of Injected Targets for the Reaction T (d, n) – V. I. Strizhak, G. I. Primenko, and I. M. Pronman.....	323	251
Measurement of a Flux of Slow Neutrons by Means of the Hall Effect in Silicon – V. A. Kharchenko, S. P. Solov'ev, and R. B. Novgorodtsev.....	326	253
Efficiency of a Body-Radiation Spectrometer when There is a Nonuniform Isotopic Distribution in the Source – S. Yu. Pavlov and V. S. Yuzgin .....	328	254
Two Methods for Reducing the Nonuniformity of the Dose Field along the Source in a Radiation Loop – E. S. Stariznyi and A. Kh. Breger .....	331	255
Yield of F <sup>18</sup> in the Bombardment of Sodium, Magnesium, and Aluminum by He <sup>3</sup> Ions and Sodium by $\alpha$ -Particles – N. N. Krasnov, P. P. Dmitriev, Z. P. Dmitrieva, I. O. Konstantinov, and G. A. Molin .....	333	257
C <sup>11</sup> Yield in the Reactions Be <sup>9</sup> (He <sup>3</sup> , n)C <sup>11</sup> and Be <sup>9</sup> ( $\alpha$ , 2n)C <sup>11</sup> – N. N. Krasnov, P. P. Dmitriev, Z. P. Dmitrieva, I. O. Konstantinov, and G. A. Molin .....	335	258
Hematite Concrete for Shielding against High Neutron Fluxes – V. B. Dubrovskii, Sh. Sh. Ibragimov, V. V. Korenevskii, A. Ya. Ladygin, V. K. Pergamenshchik, and V. S. Perevalov .....	336	258



Experimental Investigation of the Dynamics of an Electron Beam in a Synchrotron at 1.5 GeV – A. A. Vorob'ev, A. N. Didenko, and A. V. Kozhevnikov.....	339	260
Operation of Stellarator Circularizers in the Presence of an Axial Current – Yu. M. Loktionov and V. P. Sebko .....	343	263
NEWS		
Startup of the Second Reactor Unit in the Novo-Voronezh' Nuclear Power Station – Yu. Arkhangel'skii.....	346	266
First Row of the Belyi Yar Nuclear Power Station Brought up to Design Power .....	347	266
Cost Aspects of Nuclear Power – V. V. Batov.....	349	267
Seminar on Diffusional Saturation and Diffusion Coatings – A. L. Burykina.....	352	269
Isochronous Cyclotrons and Their Applications in Chemistry, Metallurgy, and Biology – N. I. Venikov and B. N. Yablokov .....	354	270
XVIIIth Session of the COMECON Commission on Peaceful Uses of Atomic Energy .....	365	280
International Conference (Kyoto, Japan) on Mass Spectrometry.....	368	282

## Volume 28, Number 4 April, 1970

From the Editor .....	371	286
The Nuclear Research Center at the Birthplace of V. I. Lenin – O. D. Kazachkovskii, N. V. Krasnoyarov, É. P. Ostreikovskii, and A. M. Petros'yants .....	372	287
Special Features of Nuclear Power Stations in Energy Generation – E. P. Anan'ev and G. N. Kruzhilin .....	376	291
Prospects of Water-Moderated Water-Cooled Power Reactors – S. A. Skvortsov .....	380	294
Present State and Future Prospects of Fast Reactions – A. I. Leipunskii .....	384	297
Synthesis and Search for Heavy Transuranium Elements – G. N. Flerov .....	390	302
On the Anomalous Scattering of Neutrons – N. S. Lebedeva and V. M. Morozov .....	398	310
The Basic Laws of Turbulent Flow – M. D. Millionshchikov .....	406	317
Investigation of Critical Assemblies of the Beloyarsk Nuclear Power Station – I. S. Akimov, V. I. Alekseev, V. K. Vikulov, B. G. Dubovskii, A. Ya. Evseev, I. M. Kisil', L. V. Konstantinov, V. F. Lyubchenko, M. E. Minashin, Yu. I. Mityaev, V. V. Postnikov, É. I. Snitko, V. N. Sharapov, and V. M. Shuvalov .....	412	321
Radiative Growth of Uranium at Small Burnups – S. T. Konobeevskii, L. D. Panteleev, B. M. Levitskii, and I. A. Naskidashvili .....	418	326
Fruitful Collaboration for Peace and Progress – A. F. Panasenkov .....	425	332
The Use of Nuclear Energy in the German Democratic Republic – Kh. Faul'shtikh, L. Kherfort, V. Merts, K. Maier, K. Rambush, V. V. Shimmel', and V. Shol'ts ..	431	338

## ARTICLES FROM HUNGARY

The Nuclear Reactor of the Polytechnic Institute in Budapest – D. Csom .....	435	342
Reprocessing of Biological Radioactive Wastes in the Hungarian People's Republic – L. Fehér and F. Gacs .....	440	346

## LETTERS TO THE EDITOR

Isotopic Abundance of Lithium in Uranium Minerals – L. K. Levskii, A. N. Murin, and V. G. Zaslavskii .....	443	349
Swelling of Hot Oxide Fuel – I. G. Lebedev, V. I. Kuz'min, and A. S. Piskun .....	446	351
The Physical Interpretation of the Theorem of the Reactivity Integral – V. V. Orlov and É. A. Stumbur .....	449	353
Determining the Reactivity Margin – V. S. Shulepin and V. I. Matveenko .....	452	355
Entrainment of Neutrons by a Moving Medium – G. Ya. Vasil'ev, D. M. Kaminker, K. A. Konoplev, and A. A. Kostritsa .....	454	356

Measurement of the Parameters of the Neutron Flux in a Reaction by Means of Activation Coincidence Counters – E. I. Biryukov, N. N. Khramov, and N. S. Shimanskaya . . . . .	457	357
Resonance Fission Integrals for Uranium, Plutonium, and Americium Isotopes – M. A. Bak, K. A. Petrzhak, Yu. G. Petrov, Yu. F. Romanov, and É. A. Shlyamin . . . . .	460	359
On the Spontaneous Fission Half-Life of $Cf^{252}$ – B. M. Aleksandrov, M. A. Bak, V. G. Bogdanov, S. S. Bugorkov, L. V. Drapchinskii, Z. I. Solov'eva, and A. V. Sorokina . . . . .	462	361
The Cross Section for Fission of $Np^{237}$ by Slow Neutrons – K. A. Gavrilov, K. K. Koshaeva, S. N. Kraitor, and L. B. Pikel'ner . . . . .	464	362

## NEWS

Truck-Mounted "Kolos" Full-Scale $\gamma$ -Irradiator Facility – D. A. Kaushanskii and B. G. Zhukov . . . . .	468	366
"Éfir" Thermoelectric Radioisotope Facility – G. M. Fradkin, A. I. Ragozinskii, and A. I. Dmitriev . . . . .	470	367
RTR-1 Scintillation Type Radioisotope Relay Device – I. I. Kreindlin and Yu. A. Skoblo . . . . .	472	369
Radioisotope Apparatus for Internal Irradiation – A. G. Sul'kin . . . . .	474	370
Set of Equipment for the Radiological Division of a Hospital – G. I. Lukishov, K. D. Rodionov, and Yu. A. Sokolov . . . . .	475	370
Budapest October, 1969, Symposium on Monitoring and Control of Nuclear Reactions and Power Station Equipment – A. G. Filippov . . . . .	478	372
Radiation Safety in the Design and Use of Hot Laboratories – V. N. Kosyakov . . . . .	482	375
International Conference on Plasma Confinement in Closed Systems – V. S. Strelkov and I. S. Shpigel' . . . . .	485	377
Emission of Radioactive Noble Gases during the Regeneration of Nuclear Fuel – A. D. Turkin . . . . .	489	379

## Volume 28, Number 5      May, 1970

Basic Principles in the Extraction of Uranium by Phosphine Oxide – B. N. Laskorin, D. I. Skorovarov, L. A. Fedorova, and V. V. Shatalov . . . . .	491	383
Physical Investigations of an Electronuclear Neutron-Flux-Generator Target – V. I. Bol'shov, A. A. Dubinin, V. M. Dmitriev, S. P. Kapchigashev, V. A. Kon'shin, E. S. Matusевич, V. P. Polivanskii, V. Ya. Pupko, V. I. Regushevskii, Yu. Ya. Stavisskii, and Yu. S. Yur'ev . . . . .	497	388
Identification of the Elements 102 and 104 by Means of the Collimation Method – Yu. Ts. Organesyan, Yu. V. Lobanov, S. P. Tret'yakova, Yu. A. Lazarev, I. V. Kolesov, K. A. Gavrilov, V. M. Plotko, and Yu. V. Poluboyarinov . . . . .	502	393
Radiation Sputtering and Damage of Certain Metals in the Radiation Field of a Nuclear Reactor. Part I. Sputtering by Fast Neutrons – R. I. Garber, V. S. Karasev, V. M. Kolyada, and A. I. Fedorenko . . . . .	510	400
Radiation Sputtering and Damage to Certain Metals in the Radiation Field of a Nuclear Reactor. Part 2. Sputtering by Fission Fragments from $U^{235}$ and Reactor Neutrons – R. I. Garber, V. S. Karasev, V. M. Kolyada, and A. I. Fedorenko . . . . .	516	406

## ARTICLES FROM CZECHOSLOVAKIA

Collaboration between Czechoslovakia and the USSR in the Peaceful Use of Atomic Energy – Jan Neumann . . . . .	521	411
Study of Neutron Diffraction in the Institute of Nuclear Studies of the Czechoslovakian Academy of Sciences – B. Chalupa, R. Michalec, and J. Vavra . . . . .	523	413

## ABSTRACTS

Multiparameter Optimization of an Atomic Power Plant with Base-Point Distillation of Sea Water – Yu. D. Arsen'ev, S. V. Radchenko, and V. A. Chernyaev.....	528	418
Accumulation of Plutonium for the Development of Fast Reactors – O. D. Kazachkovskii and E. V. Kirillov .....	529	418
Electrochemical Behavior of Thorium in Molten Sodium Chloride and an Equimolar Mixture of Potassium and Sodium Chlorides – M. V. Smirnov, V. Ya. Kudyakov, Yu. V. Posokhin, and Yu. N. Krasnov.....	530	419
Measurement of the Fast Neutron Distribution in a Cell of a Uranium – Graphite Reactor with a Rhodium Threshold Detector – A. V. Bushuev, V. G. Bortsov, and V. M. Duvanov .....	531	420
Optimum Parameters of the U <sup>238</sup> Neutron Optical Potential – G. V. Anikin, A. G. Dovbenko, L. Ya. Kazakova, V. E. Kolesov, V. I. Popov, G. N. G. N. Smirenkin, and A. S. Tishin.....	532	420
Temperature Field in a Nonisothermal Two-Phase Flow – M. Kh. Ibragimov, G. I. Sabelev, and V. I. Sidorov.....	533	421
Role of Energy Dependence in Problems of Transport Theory – Yu. I. Ershov and S. B. Shikhov.....	534	422
Source of Multiply Charged Ions with Cathode Atomization of the Operating Substance – Yu. P. Trt'yakov, A. S. Pasyuk, L. P. Kul'kina, and V. I. Kuznetsov.....	534	423
Conditions for the Existence of Two Stable Equilibrium Phases in Linear Accelerators – I. D. Dreval' and V. V. Kushin.....	536	423

## LETTERS TO THE EDITOR

Characteristics of Spectra of Thermal Neutrons from Straight Tangential Channel of a Reactor – B. I. Goschitskii, V. V. Gusev, L. V. Konstantinov, P. M. Korotovskikh, S. K. Sidorov, V. V. Chernobrovkin, and V. G. Chudinov....	537	425
Reduction of Compact U <sub>3</sub> O <sub>8</sub> by Hydrogen – Yu. M. Dymkov, N. G. Nazarenko, G. A. Dymkova, and E. F. Goryunov.....	539	426
Use of Semiconductor Detectors in Isotopic X-Ray Fluorescence Method – A. A. Fedorov, A. P. Ochkur, V. N. Mitov, and Yu. P. Yanshevskii.....	542	428
New Chemical Method for Determining Dose Rate of Various Forms of Radiation – M. V. Vladimirova and I. A. Kulikov.....	544	429
Observation and Identification of a Radioactive Cloud by a Very Simple Radiometric Method – Yu. N. Petrov.....	547	431
An Iron-Free Linear Induction Accelerator – A. I. Pavlovskii, A. I. Gerasimov, D. I. Zenkov, V. S. Bosamykin, A. P. Klement'ev, and V. A. Tananakin.....	549	432
Resonance Acceleration of a Beam of Oscillators in the Field of a Plane Wave – V. B. Krasovitskii .....	551	434
On the Damping of Nonlinear Synchrotron Oscillations of Two Bunches during the Interaction of a Beam with a Resonator – S. G. Kononenko and A. M. Shenderovich	554	436
Escape of Radiation from the Shield of the Joint Institute for Nuclear Research (JINR) Synchrocyclotron – V. E. Aleinikov, L. R. Kimel', M. M. Komočkov, and V. P. Sidorin .....	557	438
Deformations of the Foundation of the Serpukhov Accelerator and Their Effect on the Shape of the Equilibrium Orbit – V. E. Novak, I. V. Runov, A. E. Khanamiryan, and I. A. Shukeilo .....	559	439

## NEWS

Scientific and Technical Progress .....	562	442
All-Union Young Scientists' Conference on Radiation Chemistry – I. V. Vershchinskii...	564	443
C <sup>14</sup> Variations in the Earth's Atmosphere – G. E. Kocharov .....	566	444
Anglo-Soviet Seminar at Harwell – E. P. Ryazantsev .....	569	446
Seminar on Nuclear Research Using Low-Energy and Medium-Energy Linear Electron Accelerators – P. V. Sorokin.....	572	448

Conference on Nuclear Data – A. N. Abramov, V. I. Popov, and S. I. Sukhoruchkin.....	575	450
International Congress on Transport of Fission Products – G.I. Pavlov.....	577	451
Nuclear Seminar of Leningrad State University (25th Anniversary) – M. A. Listengarten.	579	451
Research on the Atomic Nucleus and on Cosmic Rays in India – N. A. Burgov.....	581	452
Cost Savings through the Use of "Kolos" $\gamma$ -Ray Production-Model Irradiators – N. S. Prokof'ev, D. A. Kaushanskii, and B. G. Zhukov.....	583	453
"Start" Facility for Measuring and Grading Radioactive Ore – V. P. Bovin, N. K. Dorofeev, and L. N. Posik.....	585	455
BRIEF COMMUNICATIONS		
V. Dolinin.....	586	455
BOOK REVIEWS		
V. V. Batov and Yu. I. Koryakin, Economics of Nuclear Power – Reviewed by E. O. Shteingauz.....	587	456
F. G. Krotov (editor) – Preventive Measures in Dealing with Radiation Sickness and Radiation Injuries as a Public-Health Problem (Scientific Review, No. 1).....	589	456
Neutron Cross Sections for Fast Reactor Materials. Part 1. Evaluation.....	590	457
R. E. Marshak, Riazudin, and C. P. Ryan – Theory of Weak Interactions in Particle Physics.....	591	457
Radiobiology – Medical Radiology Handbook [in German].....	591	458
C. D. Van Cleave – Late Somatic Effects of Ionizing Radiation.....	591	458

## Volume 28, Number 6

Radiation Safety Standards (NRB-69) – I. K. Dibobes, V. A. Knyazev, A. A. Moiseev, Yu. I. Moskalev, Yu. V. Sivintsev, E. N. Teverovskii, A. V. Terman, and V. P. Shamov.....	593	463
Uranium in Carboniferous Rocks – G. Ya. Ostrovskaya.....	598	467
Transfer of Heat with Bubble Boiling in a Large Volume – V. I. Subbotin, D. N. Sorokin, and A. A. Tsyganok.....	603	471

## REVIEWS

The Current State and Development Prospects of Nuclear Power Generation in Industrially Developed Capitalist and Emergent Countries – V. D. Andreev.....	608	477
---	-----	-----

## ABSTRACTS

Temperature Fields of Fuel Elements in the BOR Reactor Core – V. I. Subbotin, P. A. Ushakov, A. V. Zhukov, and E. Ya. Sviridenko.....	620	489
Investigation of Temperature Fields in Fast Reactor Fuel Elements with Variable Power Distribution over Height of Core – V. F. Dobrovol'skii, A. V. Zhukov, E. Ya. Sviridenko, V. I. Subbotin, and P. A. Ushakov.....	621	490
Activation of Corrosion Products in the Primary Loop of a Pressurized-Water Reactor – A. I. Kasperovich and N. V. Bychkov.....	622	490
Optimization of Parameters of Two-Group Approximation of Kinetics Equations by the Method of Logarithmic Frequency Response – K. N. Prikot and V. K. Uspenskii.....	623	491
Measurement of Certain Characteristics of Neutron Fluxes in Experimental Arrangements of the SM-2 Reactor by Reference to Gold Activation – A. V. Klinov, Yu. P. Kormushkin, V. V. Frunze, and V. A. Tsykanov.....	623	491
$\gamma$ -Radiation of Fission Products for a Short Period of Service on the Fuel in a Nuclear Reactor – E. S. Stariznyi and A. Kh. Breger.....	624	492
Calculation of Efficiency of $\gamma$ -Irradiators – V. E. Drozdov and L. M. Dunaev.....	625	492

One-Group Method of Calculating Dose Fields from Sources of $\gamma$ -Radiation with a Complex Spectrum – L. M. Dunaev, V. E. Drozdov, and N. I. Orlenko . . . . .	626	493
Generalization of $\gamma$ -Albedo Calculations on the Basis of Similarity Theory – A. P. Ochkur, G. A. Pshenichnyi, and O. S. Marenkov . . . . .	627	494
Physicochemical Properties of Mixtures of Heavy Metal Fluorides. Communication III. Phase Diagram of the Uranium Hexafluoride – Niobium Pentafluoride System – V. N. Prusakov and V. K. Ezhov . . . . .	629	496
Physicochemical Properties of Mixtures of Heavy-Metal Fluorides. Communication IV. Fusibility Diagram of the Xenon Difluoride – Uranium Hexafluoride System – V. K. Ezhov, V. N. Prusakov, and B. B. Chaivanov . . . . .	630	497
Calculated Isomeric Cross Section Ratios in the Reaction $Se^{80}(n, \gamma)Se^{81m,g}$ – V. P. Koroleva . . . . .	630	497
Contribution of the Theory of Transverse Instability in a Sectional Linear Accelerator – V. I. Kurilko and A. P. Tolstoluzhskii. . . . .	631	498
LETTERS TO THE EDITOR		
Heat Transfer Criterion for Evaluating Quality of Axial Power Distribution in a Reactor – Yu. P. Filin . . . . .	633	500
Neutron Dose from an Isotropic Point Fission Source – A. I. Khovanovich, V. F. Kokovikhin, N. A. Kondurushkin, and V. Ya. Belovintsev. . . . .	635	501
$C^{11}$ , $N^{13}$ , and $F^{18}$ Yields during the Irradiation of Nitrogen by Protons, Deuterons, $He^3$ Ions, and $\alpha$ -Particles – N. N. Krasnov, P. P. Dmitriev, Z. P. Dmitrieva, I. O. Konstantinov, and G. A. Molin . . . . .	637	503
Recording of Fission Fragments by Glass as a Function of the Period between the Irradiation of the Glass and Its Etching – V. K. Gorshkov . . . . .	639	504
Radiation Detectors Using Semi-Insulating Cadmium Telluride – V. S. Vavilov, R. Kh. Vagapov, V. A. Chapnin, and M. V. Chukichev. . . . .	641	505
Measurement of Nucleon Fluxes with Energies Greater than 600 MeV – V. E. Borodin, A. V. Zotov, L. R. Kimel', V. N. Lebedev, and V. P. Sidorin. . . . .	643	506
On a Possible Mechanism for Increasing the Emittance of a Beam – V. A. Teplyakov . . . . .	645	508
The Shaping System and Parameters of the Beam of $\gamma$ -Quanta in an Electron Accelerator Having an Energy of 2 GeV – B. I. Shramenko, S. G. Tonopetian, I. A. Grishaev, N. V. Goncharov, N. I. Lapin, V. I. Nikiforov, G. D. Pugachev, and V. M. Khvorostian. . . . .	648	509
Current Limiting in Linear Accelerators Due to the Longitudinal Space-Charge Forces – G. I. Zhileiko and L. M. Movsisyan . . . . .	651	511
The Instability of an Electron Beam in a Spatially Periodic Electric Field – G. G. Aseev, G. G. Kuznetsova, N. S. Repalov, B. G. Safronov, and N. A. Khizhnyak. . . . .	654	513
NEWS		
Conference on Nuclear Power Station Process Control and Monitoring Instrumentation – V. V. Postnikov. . . . .	657	515
Symposium on Operating Characteristics of Power Reactor Components – B. A. Maslenok . . . . .	660	516
All-Union Conference on the Thermodynamics of Metallic Alloys – G. M. Lukashenko . . . . .	663	518
IV International Congress on Powder Metallurgy – A. F. Islankina . . . . .	664	518
Symposium on New Techniques in Making Radioactive Preparations – V. I. Levin . . . . .	667	520
Soviet Specialists Visiting the USA – V. V. Stekol'nikov. . . . .	669	521
Applications of Electron Irradiation in Potato Growing – N. S. Batsanov . . . . .	671	522
BOOK REVIEWS		
Collections of Standards for a Unified System of Design Engineering Documentation . . . . .	673	524

L. S. Ruzer – Radioactive Aerosols (Measurement of Concentrations and Absorbed Doses]. . . . .	674	524
R. L. Long and P. D. O'Brien (editors) – Fast Burst Reactors (Proceedings of the National Topical Meeting, Jan. 28-30, 1969, Albuquerque, New Mexico). . . . .	675	525
G. L. Shaw and D. Y. Wong (editors) – Pion-Nucleon Scattering. . . . .	676	525

## Volume 29, Number 1 July, 1970

Igor' Evgen'evich Tamm (On His 75th Birthday). . . . .	677	1
Some Features of Uranium Reserve Estimation in Sedimentary Rocks for Underground Leaching – V. P. Novik-Kachan. . . . .	679	3
Determination of Core Temperatures in Liquid-Metal-Cooled Reactors – N. I. Buleev, V. B. Levchenko, K. N. Polosukhina, and A. A. Sholokhov . . . . .	683	6
The Method of Subgroups for Considering the Resonance Structure of the Cross Sections in Neutron Calculations (Part 1) – N. M. Nikolaev, A. A. Ignatov, N. V. Isaev, and V. F. Kokhlov. . . . .	689	11
Turbulent Flow in Pipes of Noncircular Cross Section – M. D. Millionshchikov . . . . .	696	16
Monitoring the Outside Environment of a Nuclear Power Station with a Boiling Water Type Reactor – V. A. Knyazev, P. I. Kotikov, V. G. Laptev, and Yu. V. Chechetkin . . . . .	699	18
Influence of the pH on the Sorption of Radioactive Isotopes by Anion-Exchange Resins – F. V. Rauzen and T. S. Vedishcheva . . . . .	703	21
Change of Properties of Leather Hides when Irradiated with Doses of 1-10 Mrad – I. P. Strakhov, P. I. Lebenko, I. G. Shifrin, A. I. Metelkin, V. P. Averkiev, Yu. F. Pavlov, and G. D. Rybakova. . . . .	708	26
Channel for Negative Particles with Momenta to 60 GeV/c – I. A. Aleksandrov, M. I. Grachev, K. I. Gubrienko, E. V. Eremenko, V. I. Kotov, A. N. Nekrasov, A. A. Prilepin, V. A. Pichugin, R. A. Rzaev, A. V. Samoilov, V. S. Seleznev, B. A. Serebryakov, A. E. Khanamiryan, and Yu. S. Khodyrev . . . . .	712	29

## ABSTRACTS

Application of the Method of Reduced Costs to Estimates of the Effectiveness of Utilization of Nuclear Fuel – A. V. Taliev and A. Ya. Kramerov. . . . .	718	36
Measurement of Effective Neutron Temperature in Uranium-Graphite Reactors – S. S. Lomakin, T. S. Mordovskaya, G. G. Panfilov, V. I. Petrov, P. S. Samoilov, and V. V. Khmyzov. . . . .	719	36
An Express Method for Reconstructing the Spectra of Fast Neutrons in Nuclear-Physics Installations during Measurement by Threshold Detectors – V. S. Troshin and E. A. Kramer-Ageev . . . . .	719	37
The Spectrum of Scattered $\gamma$ -Radiation at Small Distances from the Source – V. I. Utkin . . . . .	721	38
On the Efficiency of Radiators and Absorbers of Charged Particles – V. M. Lenchenko, E. V. Sazonova, and L. A. Sofienko. . . . .	721	38
Electrical Engineering Properties of Porcelain Exposed to $\gamma$ -Radiation – N. S. Kostyukov, V. V. Talyzin, M. I. Muminov, and M. I. Zil'berman . . . . .	722	39
On the Trajectories of Particles in an Isochronous Cyclotron in the Presence of Acceleration – Yu. K. Khokhlov. . . . .	723	39

## LETTERS TO THE EDITOR

Mechanism Underlying the Emanation of Radioactive Ores and Minerals – V. L. Shashkin and M. I. Prutkina. . . . .	724	41
--	-----	----

Radiation Circuit of the IRT Reactor of Tomsk Polytechnic Institute – E. S. Sakharov, I. P. Chuchalin, A. G. Skorikov, R. I. Akimova, and V. V. Karnaukhov . . . . .	727	43
Generalized Relationship for Calculating Heat Transfer in the Developed Boiling of Alkali Metals – V. I. Subbotin, D. N. Sorokin, and A. P. Kudryavtsev . . . . .	730	45
Density of Vapor-Formation Centers during Boiling at a Surface – V. F. Prisyakov . . . . .	732	46
Empirical Transmission Coefficients of Heavy Nuclei for 0.05- to 2-MeV Neutrons – P. E. Vorotnikov . . . . .	735	48
Optimal Conditions for Neutron Activation Analysis for Continuous Determination of Fluorite in a Current of Slurry – V. I. Prokopchik . . . . .	737	50
Thermalization Time of Fast Neutrons in Rocks of Silicate Composition and Different Moisture Content – B. M. Kolesov, G. I. Ganichev, A. K. Ovchinnikov, I. M. Khaikovich, and T. V. Timofeeva . . . . .	739	51
The Electrification of Bodies by $\gamma$ -Radiation – V. M. Lenchenko . . . . .	742	53
NEWS OF SCIENCE AND TECHNOLOGY		
XXVII Session of the Learned Council of the Joint Institute for Nuclear Research [Dubna] – V. A. Biryukov . . . . .	745	56
Twentieth All-Union Conference on Nuclear Spectroscopy and Nuclear Structure – O. E. Kraft and M. A. Listengarten . . . . .	750	58
Soviet Delegation Visits Italy – F. M. Mitenkov . . . . .	753	61
Soviet Solid State Physics Specialists Touring Canada – I. P. Sadikov . . . . .	755	62
The K-200000 General-Purpose Radiation-Chemical Research Facility – V. A. Gol'din . . . . .	759	64
BRIEF COMMUNICATIONS . . . . .	760	64

## Volume 29, Number 2 August, 1970

Calculation of the Channel Rating of a Chemonuclear Reactor under Nonisothermal Flow Conditions of the Gas Undergoing Radiolysis and Variable Dose Intensity – B. G. Dzantiev, V. T. Kazazyan, A. K. Krasin, and G. V. Nichipor . . . . .	763	71
Problems of Constructing Atomic Steam and Gas Plants – E. F. Ratnikov . . . . .	769	77
Resistivity of $\alpha$ -Plutonium Irradiated by Neutrons in Liquid Nitrogen – S. T. Konobeevskii, V. M. Raetskii, and N. S. Kosulin . . . . .	773	80
Transfer of Zinc Corrosion Products from Boiling Water to Steam and Distribution of the Active Component throughout the Circuit of the VK-50 Boiling Water Reactor – O. I. Martynova, A. I. Nazarov, Yu. V. Chechetkin, I. G. Kobzar', Yu. F. Samoilo, and T. I. Petrova . . . . .	776	82
Effect of Oxygen on Steel Corrosion in Steam – Water Flows at a Temperature of 280°C – K. A. Nesmeyanova . . . . .	781	86
Energy Dependence of Neutron Transport Scattering Length in H <sub>2</sub> O, D <sub>2</sub> O, and Graphite – B. N. Goshchitskii, V. V. Gusev, L. V. Konstantinov, P. M. Korotovskikh, S. K. Sidorov, V. V. Chernobrovkin, and V. G. Chudinov . . . . .	786	91
Measurement of Energy Spectrum and Average Number of Prompt Fission Neutrons – N. I. Kroshkin and Yu. S. Zamyatnin . . . . .	790	95
Salting Out in the Extraction of Acids and Certain Radioactive Elements. Communication IV. Salting Out in the Extraction of HNO <sub>3</sub> , UO <sub>2</sub> (NO <sub>3</sub> ) <sub>2</sub> , and Th(NO <sub>3</sub> ) <sub>4</sub> by Amines and Tri-n-Butyl Phosphate – Yu. G. Frolov, G. I. Nasonova, and N. V. Gavrilov . . . . .	794	99
Study of the Sorption of Strontium and Calcium Cations on the Cation-Exchange Resin KU-2 – F. V. Rauzen and N. P. Trushkov . . . . .	798	103
Equilibrium and Stability of Plasma in Closed Traps without Rotational Transformation – V. D. Shafranov and É. I. Yurchenko . . . . .	801	106

System for Monochromatization of the External Beam of a 2.4-Meter Isochronous Cyclotron – Yu. G. Basargin, V. I. Bogdanova, N. I. Venikov, K. N. Korol', N. N. Posel'skii, and Yu. P. Severgin . . . . .	809	112
ABSTRACTS		
Some Problems of Kinetics of Coupled Reactors – V. V. Vatulin and V. I. Yuferev . . .	815	117
Angular Distribution of Neurons Scattered in Air from a Monoenergetic Isotropic Point Source – V. F. Kokovikhin, N. A. Kondurushkin, V. Ya. Belovintsey, and V. V. Barchugov . . . . .	816	118
Angular and Energy Distributions of $\gamma$ -Rays in Lead – B. S. Kondrat'ev . . . . .	817	119
System for Recording the $B^{12}$ Isotope Which Is Formed According to the $C^{12}(n, p)$ Reaction – V. T. Tustanovskii, V. I. Andriushchenko, and A. A. Vol'gemut . . .	818	119
Activation-Analysis Determination of the Silver Content in Microcrystal Centers in a Photographic Emulsion – L. E. Potap'eva and V. I. Kalashnikova . . . . .	819	120
Accelerating System with Parallel Connected Gaps – B. K. Shembel', I. I. Sulygin, E. S. Nelipovich, and V. V. Osipov . . . . .	820	121
A Possible Method of Accelerating Heavy Ions – N. I. Tarantin . . . . .	821	122
Depolarization of Protons in a Phasotron with Spatial Variation of the Magnetic Field – Yu. A. Plis and L. M. Soroko . . . . .	822	122
On Increasing the Efficiency of Alternating-Phase Focusing in Linear Accelerators – V. V. Kushin . . . . .	823	123
Spatial Generalization of Nomographs with an Oriented Transparency Grid, and Their Use in the Kinematics of Nuclear Reactions – G. N. Potetyunko . . . . .	824	124
LETTERS TO THE EDITOR		
Optimum Dimensions of the Working Volumes of Various Units in Radiation Circuits – E. S. Sakharov and I. P. Chuchalin . . . . .	826	125
Track-Delimiting Autoradiography for Studying Microdistributions of Some Elements in Metals – M. A. Krishtal, L. I. Ivanov, and E. M. Grinberg . . . . .	829	127
Value Function in Cascades for the Separation of a Multicomponent Isotope Mixture – I. A. Kolokol'tsov, V. I. Nikolaev, G. A. Sulaberidze, and S. A. Tret'yak . . . . .	832	128
An Analysis of $\bar{\nu}$ as a Function of Neutron Energy Based on the Energy Balance in Nuclear Fission – V. G. Vorob'eva, P. P. D'yachenko, B. D. Kuz'minov, A. I. Sergachev, and L. D. Smirenkina . . . . .	835	130
One Possible Method of Identifying the Products of Nuclear Reactions Taking Place under the Influence of Heavy Ions – V. A. Druin, Yu. V. Lobanov, and Yu. P. Kharitonov . . .	837	132
Method of Separation of Dose Strength of $\gamma$ -Radiation of Artificial and Natural Radioactive Isotopes in Soils – V. A. Vorob'ev, R. M. Kogan, I. M. Nazarov, and Sh. D. Fridman . . . . .	840	133
Altitude Distributions of $U^{238}$ , $Th^{232}$ , and $Pu^{239}$ in Atmospheric Fallout – B. I. Styro, N. K. Shpirkauskaitė, and V. M. Kuptsov . . . . .	843	135
Experimental Study of the Scattering of an Ion Beam in a Plasma with Hot Electrons – G. S. Kirichenko and V. G. Khmaruk . . . . .	845	136
Beam Shaping System and Beam Parameters in Extraction Channels of 360 MeV Linear Electron Accelerator – I. A. Grishaev, G. K. Dem'yanenko, L. A. Makhnenko, K. S. Rubtsov, and P. M. Ryabka . . . . .	847	138
The U-13 10 MeV Linear Electron Accelerator – O. A. Val'dner, O. S. Milovanov, V. A. Ostanin, E. G. Pyatnov, N. P. Sobenin, I. A. Smirnov, and I. S. Shchedrin . . . . .	850	140
Proton Current Attainable in Large Equilibrium Phases in a Linear Accelerator with No Particle Losses – A. D. Vlasov . . . . .	852	141



## Volume 29, Number 3 September, 1970

Electronuclear Generation of Neutrons (Editorial Comment) . . . . .	857	151
The Electronuclear Method of Generating Neutrons and Producing Fissionable Materials - V. G. Vasil'kov, V. I. Gol'danskii, V. P. Dzheleпов, and V. P. Dmitrievskii . . . . .	858	151
On Electronuclear Breeding - V. A. Davidenko . . . . .	866	158
High-Flux Continuous Research Reactors and Their Prospects - S. M. Feinberg. . . . .	870	162
Ampoules for Material Irradiation in the SM-2 High-Flux Reactor - V. A. Tsykanov, B. V. Samsonov, R. A. Timchenko, V. N. Shulimov, and G. P. Lobanov . . . . .	876	169
Behavior of Beryllium Metal in the SM-2 Reactor - Z. I. Chechetkina, V. P. Gol'tsev, V. I. Klimenkov, S. N. Votinov, and V. A. Tsykanov . . . . .	882	174
Uranium Strengthened with Beryllium Oxide Particles - A. I. Voloshchuk, G. S. Gaidamachenko, Yu. M. Golovchenko, V. F. Zelenskii, V. E. Ivanov, and Yu. F. Konotop . . . . .	886	178
Pile Testing of VNPM-1 Organosilicate Molding Compound in Core of IVV-2 Reactor - N. P. Kharitonov, V. A. Krotikov, and B. V. Lysikov . . . . .	893	184
<b>REVIEWS</b>		
Intermediate Structure in Neutron Cross Sections - S. I. Sukhoruchkin . . . . .	896	187
Microdosimetry (Physical Aspects and Basic Problems) - V. I. Ivanov . . . . .	904	195
<b>ABSTRACTS</b>		
Temperature Dependence of Diffusion Parameters of Slow Neutrons in Zirconium Hydride - A. V. Antonov, B. V. Granatkin, M. V. Kazarnovskii, Yu. A. Merkul'ev, V. Z. Nozik, and M. S. Yudkevich. . . . .	910	201
Use of the Method of Lagrange Multipliers for Optimization of Nuclear Reactors - É. G. Sakhnovskii. . . . .	911	201
Determination of Vapor Content by Means of Flow Meters - V. V. Vazinger . . . . .	911	202
Determination of the Spectral and Angular Distribution of $\gamma$ -Quanta in Flat Barriers Containing Radiation Sources - S. A. Churin . . . . .	913	203
Analysis of the Photopeak of Scintillation $\gamma$ -Spectra - Ch. Stoyanov, L. Aleksandrov, and V. Gadzhokov . . . . .	914	203
Stopping Electrons with Matter - V. A. Kononov, K. A. Dergobuzov, and V. M. Zykov Note on Optimized Conditions in X-Ray Absorptiometry - A. E. Ignatenko and A. D. Kul'kov . . . . .	915	204
The Yields of $V^{48}$ in Nuclear Reactions on a Cyclotron - P. P. Dmitriev, I. O. Konstantinov, and N. N. Krasnov . . . . .	916	205
Methods of Obtaining $Cr^{51}$ on a Cyclotron - C. P. Dmitriev, I. O. Konstantinov, and N. N. Krasnov . . . . .	917	206
Measurement of the Energy Spectra of Electrons in the LUÉ-25 Linear Accelerator - V. I. Ermakov, V. P. Kovalev, I. A. Prudnikov, M. S. Susloparov, A. S. Toropov, S. P. Filipenok, and V. P. Kharin. . . . .	918	206
<b>LETTERS TO THE EDITOR</b>		
Reliability of the Evaporation Channels of Reactors of the Beloyarsk Atomic Power Station Type - L. V. Konstantinov, V. V. Postnikov, V. N. Vetyukov, and L. I. Lunina . . . . .	920	208
The Effect of Versene Treatment on the Hydrogenation of Steel - T. Kh. Margulova, V. V. Gerasimov, and A. A. Lipanina . . . . .	923	209
Continuous Diffusion Type Gage Indicating the Hydrogen Present in Sodium - V. I. Subbotin, F. A. Kozlov, É. K. Kuznetsov, N. N. Ivanovskii, and V. V. Matyukhin . . . . .	925	210
Measurements of Reactivity by Pulse Methods - É. A. Stumbur . . . . .	928	212
Determination of the Reactivity Margin by the Method of Double Overcompensation - T. S. Dideikin and B. P. Shishin . . . . .	932	215

The Doppler Effect and Nuclear Safety of a Fast-Neutron Reactor – G. B. Usynin and L. N. Polyaniin . . . . .	935	216
Ratios of Fast Fission Cross Sections of $U^{235}$ , $Pu^{239}$ , and $Pu^{240}$ – M. V. Sabin, Yu. A. Khokhlov, Yu. S. Zamyatnin, and I. N. Paramonova. . . . .	938	218
Diffusion of Nickel in Beryllium – V. M. Anan'in, V. P. Gladkov, V. S. Zotov, D. M. Skorov . . . . .	941	220
NEWS		
Scientific Conference of Moscow Engineering and Physics Institute [MIFI] – V. V. Frolov	944	222
II All-Union Symposium on the Chemistry of Inorganic Fluorides – Yu. A. Buslaev . . . . .	948	224
V Session of the International Communications Group on Thermionic Generation of Electric Power – Yu. I. Danilov and D. V. Karetnikov. . . . .	951	225
Isotopes in Hydrology – Yu. A. Izrael' . . . . .	954	227
Soviet Specialists Visit Denmark – L. Zolinova and V. Khrushchev . . . . .	956	228
A New Show at the "Atomic Energy" Pavilion of the Exposition of Achievements of the National Economy of the USSR – V. M. Kaloshin. . . . .	958	229
BRIEF COMMUNICATIONS. . . . .	964	234

## Volume 29, Number 4      October, 1970

The Synthesis of Element 105 – G. N. Flerov, Yu. Ts. Oganesyanyan, Yu. V. Lobanov, Yu. A. Lazarev, S. P. Tret'yakova, I. V. Kolesov, and V. M. Plotko . . . . .	967	243
Use of Uranium Hexafluoride in Nuclear Power Plants – V. A. Dmitrievskii, E. M. Voinov, and S. D. Tetel'baum. . . . .	976	251
Potential Danger of Embrittlement in Structures Made of Type 22K Steel – A. S. Dovzhenko . . . . .	981	255
Optimum Irradiation Procedure for the Production of Isotopes – V. P. Terent'ev, V. A. Zharkov, G. M. Fradkin, and T. P. Chavychalova. . . . .	986	260
Production of Isotopes in Fission Reactions – Yu. Ts. Oganesyanyan, Yu. É. Penionzhkevich, A. O. Shamsutdinov, N. S. Mal'tseva, I. I. Chuburkova, and Z. Sheglovskii . . . . .	990	264
Transverse Beam Characteristics at the Entrance of the IHEP Proton Synchrotron – D. A. Demikhovskii, E. A. Myae, and E. F. Troyanov. . . . .	998	272
Study of the Conditions of Forming a Dense Plasma on Injecting an Electron Beam into a Magnetic Trap – M. Yu. Bredikhin, A. M. Il'chenko, A. I. Maslov, A. I. Skibenko, E. I. Skibenko, and V. B. Yuferov . . . . .	1003	276

## ABSTRACTS

Microdistribution of Fission Density in VVR-M (Water-Cooled Water-Moderated Reactor) Critical-Assembly Loop Converter Cells – V. B. Klimentov, G. A. Kopchinskii, and V. G. Bobkov . . . . .	1009	283
Some Integral-Reactivity Properties and Their Application to the IGR Reactor – V. D. Lavrenikov . . . . .	1010	283
Note on the Determination of Neutron Diffusion Constants – L. Aleksandrov, A. Stanolov, and V. Khristov. . . . .	1010	283
Precipitation of Uranium from a Melt of Fused Halides with a Molten Zinc Cathode – A. V. Volkovich, I. F. Nichkov, S. P. Raspopin, and Yu. P. Kanashin . . . . .	1011	284
Contribution to the Determination of the Energy Loss of Relativistic Electrons in Thick Lead and Tungsten Targets – V. D. Anan'ev and I. M. Matora . . . . .	1012	285
Distribution of Gamma Radiation at a Shield Boundary from Sources Having Arbitrary Angular Distributions – A. Viktorov, B. A. Efimenko, V. G. Zolotukhin, V. A. Klimanov, and V. V. Mashkovich. . . . .	1013	286

$\gamma$ -Ray Induced Scintillation – A. V. Zhemerev and Yu. A. Medvedev . . . . .	1014	287
Secondary Contamination of the Surface of a Material by Absorbed Radioactive Substances – A. L. Kononovich and E. M. Perfilova . . . . .	1015	287

## LETTERS TO THE EDITOR

Loop for Studying the Electrical Conductivity of Irradiated Materials in a VVR (Water- Cooled Water-Moderated) Reactor – A. G. Kharlamov, N. P. Zakharova, A. A. Batalov, Yu. I. Zaikin, and V. I. Kolyadin . . . . .	1016	289
Study of the Development of Leakages in Fuel Element Cans by Means of $Kr^{88}$ – G. A. Kotel'nikov and V. F. Leonov. . . . .	1019	291
Effect of Fuel Element Dimensions on Heat Emission under Supercritical Pressure – N. L. Kafengauz and M. I. Fedorov. . . . .	1022	293
The Radiation Resistance of Beryllium Oxide at Various Temperatures – V. I. Klimenkov and A. V. Khudyakov . . . . .	1024	294
Rhenium and Its Alloys with Boron – Effective Neutron Absorbers – B. G. Arabei, V. I. Matveev, V. P. Smirnov, and K. I. Frolova . . . . .	1026	295
Inertialess Monitoring of the Reactor Power Level with Respect to the $\gamma$ -Radiation Intensity – I. Ya. Emel'yanov, L. V. Konstantinov, V. V. Postnikov, V. I. Potapkin, and Yu. M. Serebrennikov. . . . .	1029	298
Theory of Asymmetrical Separating Cascades with Arbitrary Degrees of Enrichment in the Separating Unit – N. A. Kolokol'tsov and N. I. Lagunstov. . . . .	1032	300
Deposition of Uranium in the Bones of Animals – O. Otgonsuren, V. P. Perelygin, and D. Chultém . . . . .	1035	301
Mechanism Underlying the Formation of Dendritic or Tree-Like Channels in a Dielectric Irradiated with Charged Particles – Yu. S. Deev, M. S. Kruglyi, V. K. Lyapidevskii, and V. I. Serenkov. . . . .	1037	303
Determination of Radiothorium Content by Means of Delayed Coincidences of Disintegrations of $Tn^{220}$ and $Po^{216}$ – A. A. Pomanskii and S. A. Severnyi. . . . .	1041	305

## NEWS

Second Congress of the International Association of Radiation Protection – O. A. Kochetkov, E. A. Kramer-Ageev, and V. N. Lebedev. . . . .	1044	307
International Conference on the Diagnostics of a Hot Plasma – M. I. Pergament. . . . .	1046	308
International Conference on Microelectronics – A. N. Sinaev. . . . .	1048	309
Fifteenth Yugoslavian Symposium "YuREMA-70" – V. F. Sikolenko . . . . .	1051	310
Regular Session of TC-45 of the IEC – V. V. Matveev and V. S. Zhernov . . . . .	1052	311
Uranium Industry in the Developing Countries and in the Industrially Developed Capitalist Countries in 1969 – V. D. Andreev . . . . .	1054	312
BRIEF COMMUNICATIONS . . . . .	1065	320

## Volume 29, Number 5 November, 1970

Application of $\gamma$ -Chambers for the Power Measurements of Fuel Channels of the Beloyarsk Atomic Electric Power Plant – I. Ya. Emel'yanov, V. I. Alekseev, L. V. Konstantinov, V. V. Postnikov, Yu. M. Serebrennikov, É. I. Snitko, G. A. Shasharin. . . . .	1067	327
Optimization of the Structure of a Developing System of Atomic Power Stations Allowing for Changes in the Load Factor – W. Frankowski . . . . .	1071	330
Cross Sections for the Production of $\gamma$ -Rays as a Result of Inelastic Scattering of Neutrons of a Fission Spectrum – A. T. Bakov, V. G. Dvukhshestnov, and Yu. A. Kazanskii. . . . .	1080	338
Electrolytic Isolation of Plutonium from Solutions of Formic Acid – A. G. Smartseva and Z. A. Zhuravleva. . . . .	1085	342

A High-Current Accelerator that Produces 1.2 MeV Protons – E. A. Abramyan, M. M. Brovin, V. V. Vecheslavov, V. A. Gorbunov, V. I. Kononov, and I. L. Chertok.....	1089	346
Effect of Space Charge on the Stability of Betatron Oscillations in Circular Accelerators – A. A. Kolomenskii and A. T. Polukhin .....	1095	352
Investigation of the Effect of Secondary Charged Particles on a Proton Beam in a Betatron Mode – G. I. Dimov, V. G. Dudnikov, and V. G. Shamovskii .....	1100	356
<b>ABSTRACTS</b>		
A Method for Determining the Coefficients of Reactor Transfer Functions – S. A. Pridatko and A. S. Trofimov.....	1107	362
The Possibility of Variations in Unit Pulses of Radiative Heat – S. S. Ogorodnik and Yu. L. Tsoglin.....	1108	362
Protection against Reactor Emergencies Associated with Reactivity Perturbations – G. G. Grebenyuk, M. Kh. Dorri, and M. M. Solov'ev .....	1109	363
Corrosion and Electrochemical Behavior of a Zirconium Alloy with 2.5% Niobium in Water and Steam at High Temperature – A. I. Gromova, V. V. Gerasimov, N. A. Kabankova, I. G. Shut'ko, and E. V. Volkhonskii .....	1110	364
Resonance Neutron Moderation in Matter (Part Three) – D. A. Kozhevnikov and V. S. Havkin .....	1111	365
Investigation of Buildup Region for $\gamma$ -Radiation from Low-Level Sources – R. V. Stavitskii, É. A. Yarkovoi, and M. V. Kheteev .....	1112	366
Using a Photoelectric Colorimeter for Counting Charged Particle Tracks on the Surface of Glass Detectors – A. I. Khovanovich, G. L. Pikalov, and I. F. Kryvokrysenko..	1113	367
Determination of the Wear of Machine Parts by Charged-Particle Activation – I. O. Konstantinov and N. N. Krasnov.....	1114	367
Activation of the Concrete Shield of the OIYaI Synchrocyclotron by Scattered Radiation – L. N. Zaitsev, L. R. Kimel', and V. P. Sidorin.....	1115	368
<b>LETTERS TO THE EDITOR</b>		
Effective Calculation of One-Dimensional Nuclear Reactors without Using Networks – E. S. Glushkov, N. N. Ponomarev-Stepnoi, and N. A. Petushkova .....	1116	370
Theory of the Method of a Pulsed Neutron Source in Heterogeneous Media – A. V. Stepanov .....	1119	371
Reactivity-Measurement Determination of the Relative Number of Fissions by Epithermal Neutrons – V. E. Demin and O. N. Smirnov.....	1121	372
Critical Heat Fluxes during Boiling of High-Boiling Heat Carriers – L. S. Sterman and J. Korychanek .....	1124	374
Automated System for Indicating Presence of Impurities in Sodium Coolant Stream – A. N. Mitropol'skii, M. S. Pinkhasik, A. A. Petrenko, I. Kh. Tsukerman, and V. D. Tarantin .....	1126	376
Weakening of the Flux of High-Energy Neutrons in a Cylindrical Channel – N. I. Bushuev, A. N. Kargin, V. V. Mal'kov, and B. S. Sychev.....	1129	378
How Irradiation Affects the Electrical Resistance of Alloys of Uranium with Zirconium and Niobium – V. M. Raetskii, A. Ya. Zavgorodnii, and L. I. Gomofov.....	1131	379
On the Theory of the Effect of Neutron Bombardment of Metal Creep – L. N. Ovander ...	1133	381
On the Possible Endogenous Origin of Certain "Secondary" Uranium Minerals – G. N. Kotel'nikov.....	1135	382
Selection of Zones Suitable for Burial of Industrial Waste – V. G. Tyminskii and A. I. Spiridonov.....	1137	383
Estimated Diffusion of Materials through Clayey Soil – P. F. Dolgikh, L. A. Vladimirov, and F. P. Yudin.....	1140	385
Instability Boundary of Trapped Particles in a Finite-Pressure Plasma in Toroidal Systems – V. N. Kursakov .....	1144	388

Engl./Russ.

Experimental Study of the Linear Polarization of Electron Synchrotron Radiation at High Energies – A. A. Vorob'ev, M. M. Nikitin, and A. V. Kozhevnikov.....	1146	389
A Nomogram for Determining the Range of Protons – V. V. Nestrelyaev and G. N. Potetyunko.....	1149	391
<b>NEWS</b>		
VI All-Union Nuclear Physics School – L. N. Sukhotin and K. A. Korotkov.....	1150	392
The Gordon Conference (Seattle, June 1970) on Plasma Physics – V. P. Sarantsev.....	1152	393
Franco-Soviet Seminar on Nuclear Data for Reactor Design Calculations – L. N. Usachev.....	1156	395
I Scientific Practical Workshop Conference on Applications of Isotopes and Ionizing Radiations in Agriculture – D. A. Kaushanskii and B. G. Zhukov.....	1159	397
The RKhM- $\gamma$ -20 Multichamber $\gamma$ -Irradiator for Radiation Research – D. A. Kaushanskii. Operating Experience with the "Beta-S" Radioisotope Thermoelectric Generators – N. P. Korotkov, A. I. Ragozinskii, and G. M. Fradkin.....	1162	398
Has Element 108 Been Discovered? – V. M. Kulakov.....	1165	400
	1166	401
<b>BRIEF COMMUNICATIONS</b> .....	1169	402
<b>BOOK REVIEWS</b>		
A. S. Solovkin and G. A. Yagodin – Extractive Chemistry of Zirconium and Hafnium. Part 1 – Reviewed by V. V. Sergievskii.....	1173	405
F. I. Pavlotskaya, É. B. Tyuryukanova, and V. I. Baranov – Global Propagation of Radioactive Strontium over the Earth's Surface – Reviewed by R. M. Aleksakhin.	1174	405
Atomwirtschaft 1970 Yearbook.....	1174	405
H. Weckesser – Operation of Nuclear Power Plants.....	1175	406
Biological Implications of the Nuclear Age.....	1176	406
Radiation Biology of the Fetal and Juvenile Mammal.....	1176	406

## Volume 29, Number 6 December, 1970

On the Sixtieth Birthday of Boris Sergeevich Dzhel'epov, Corresponding Member of the Academy of Sciences of the USSR.....	1177	
Turbulent Heat and Mass Exchange – M. D. Millionshchikov.....	1178	411
Special Aspects of the Deformation of Uranium Subjected to Tensile Stain at a Constant Velocity – A. I. Voloshchuk, V. F. Zelenskii, Yu. F. Konotop, and Yu. T. Miroshnichenko.....	1184	416
Subbarrier Neutron Fission of Pu <sup>238</sup> (E/T) – S. B. Ermagambetov and G. N. Smirenkin... .	1190	422
Design of Cascades for Separating Isotope Mixtures – N. A. Kolokol'tsov, V. P. Minenko, B. I. Nikolaev, G. A. Sulaberidze, and S. A. Tret'yak.....	1193	425
Storage of Multiply-Charged Ions in a Relativistic Electron Bunch – M. L. Iovnovich and M. M. Fiks.....	1199	429
Energy Balance in the Plasma in Apparatuses of the "Tokamak" Type – Yu. N. Dnestrovskii and D. P. Kostomarov.....	1205	434
<b>REVIEWS</b>		
Thermodynamics of the Uranium-Carbon, Uranium-Nitrogen, and Plutonium-Carbon Systems – V. V. Akhachinskii and S. N. Bashlykov.....	1211	439
<b>ABSTRACTS</b>		
Slowing Down of Resonance Neutrons in Matter. Communication 4 – D. A. Kozhevnikov and V. S. Khavkin.....	1220	448

Investigation of the Calibration Characteristics of a Radiation Thermodiverter in High-Intensity Fields of Ionizing Radiations – V. S. Karasev, S. S. Ogorodnik, and Yu. L. Tsoglin . . . . .	1221 449
Calculation of Photoneutron Distribution by Monte Carlo Method – A. A. Morozov and A. I. Khisamutdinov . . . . .	1222 449
Precision System for the Determination of Oxygen by Fast Neutron Activation – I. P. Lisovskii and L. A. Smakhtin . . . . .	1223 450
VVR Reactor Semiautomatic Activation Analysis System – I. P. Lisovskii, L. A. Smakhtin, N. V. Filippova, and V. I. Volgin . . . . .	1223 450
Method of Attenuating Radial Betatron Oscillations in Cyclic Accelerators – L. A. Roginskii and G. F. Senatorov . . . . .	1224 450
Permanent Electromagnet with Built-in Radioisotope Thermoelectric Direct Converter – A. Kh. Cherkasskii and V. S. Makarov . . . . .	1225 451
<b>LETTERS TO THE EDITOR</b>	
Experimental Study of the Characteristics of the IR-100 Research Reactor – L. V. Konstantinov, I. N. Martem'yanov, V. A. Nikolaev, A. A. Sarkisov, V. F. Sachkov, A. V. Sobolev, S. V. Chernyaev, and I. S. Chesnokov . . . . .	1227 453
Effect of the Flow Velocity of a Vapor-liquid Mixture of Coolant, and of Vapor Content, on Surface Heat-Transfer Coefficient in Boiling of Water Inside Tubes – F. F. Bogdanov . . . . .	1229 454
Neutron Yield from Thick Targets Bombarded with 11.5 and 23.5 MeV Protons – V. K. Daruga and E. S. Matusevich . . . . .	1233 456
A Method of Determining the Iron Content of Corrosion Product Deposits – B. A. Alekseev, N. N. Kozhenkov, and G. A. Kotel'nikov . . . . .	1235 458
Group Separation of Fission Products by the Chromatographic Method – L. N. Moskvina and N. N. Kalinin . . . . .	1236 458
Experimental Verification of the Radiation-Chemical Method for Producing Tetrachloroalkanes – A. A. Beér, P. A. Zagorets, V. F. Inozemtsev, L. S. Maiorov, V. I. Slavyanov, G. A. Artyushov, I. F. Sprygaev, and V. A. Novozhilov . . . . .	1240 461
Use of Xenon Proportional Counter Escape Peaks for X-Ray Radiometric Analysis of Tungsten in Ores – N. G. Bolotova, V. V. Kotel'nikov, and E. P. Leman . . . . .	1243 463
Diagnostics of an Electron-Ion Bunch Using Bremsstrahlung – M. L. Iovnovich, V. P. Sarantsev, and M. M. Fiks . . . . .	1245 465
Excitation of Radial Betatron Oscillations by a Longitudinal Accelerating Field – Yu. S. Ivanov, A. A. Kuz'min, and G. F. Senatorov . . . . .	1248 467
<b>NEWS</b>	
Liege May 1970 International Symposium on Modern Electric Power Generating Stations – P. A. Andreev . . . . .	1251 470
June 1970 Princeton Symposium on Plasma Stabilization by Feedback and Dynamical Techniques – D. A. Panov . . . . .	1253 471
June 1970 Zakopane Symposium on Nondestructive Materials Testing Equipment and Techniques Using Nuclear Radiations – A. Maiorov . . . . .	1256 473
The Saturn-1 Plasma Machine – V. A. Suprunenko . . . . .	1259 474
The Anglo-Soviet Plasma Physics Experiment – V. V. Sannikov . . . . .	1260 475
GKIAÉ-JINR Agreement on Scientific and Technical Collaboration – V. Biryukov . . . . .	1262 475
<b>BRIEF COMMUNICATIONS</b> . . . . .	1263 476
<b>INDEX</b>	
Author Index, Volumes 28-29, 1970 . . . . .	1267
Tables of Contents, Volumes 28-29, 1970 . . . . .	1273

# ALGEBRA AND LOGIC

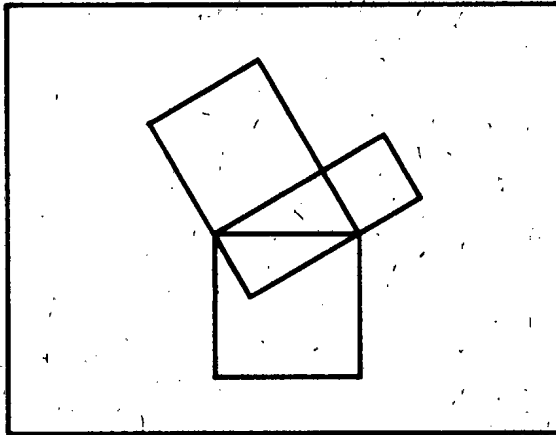
*A cover-to-cover translation of Algebra i logika*

*A publication of the Institute of Mathematics, Siberian  
Section of the Academy of Sciences of the USSR  
Novosibirsk, SSR*

**Editor-in-chief: M. I. Kargapolov**  
*Institute of Mathematics, Siberian Branch  
Academy of Sciences of the USSR*

*Members of the Editorial Board:*  
**Yu. L. Ershov**  
**Yu. I. Merzlyakov**  
**A. I. Shirshov**

Translated from Russian



A new Soviet journal which publishes, at bimonthly intervals, results of the latest research in the areas of modern general algebra and of logic considered primarily from an algebraic viewpoint. The algebraic papers, constituting the major part of the contents, are concerned with studies in such fields as ordered, almost torsion-free, nilpotent, and metabelian groups, isomorphism rings, Lie algebras, Frattini subgroups, and clusters of algebras. In the area of logic, the periodical covers such topics as hierarchical sets, logical automata, and recursive functions.

As is the case with all Consultants Bureau journals, *Algebra and Logic* appears in English translation only about six months after publication of the Russian edition. Translation began with the 1968 issues.

Contents of the first issue (Number 1, 1968):

**A. A. Akataev and D. M. Smirnov**, Lattices of submanifolds of manifolds of algebras • **G. F. Bachurin**, On almost torsion-free nilpotent groups • **L. A. Bokut'**, On the extension of ring isomorphisms • **Yu. L. Ershov**, On one hierarchy of sets, I • **V. V. Koz'minykh**, On one-place primitively-recursive functions • **A. I. Kokorin and G. T. Kozlov**, Extended elementary and universal theories of lattice-ordered Abelian groups with a finite number of threads • **Yu. I. Merzlyakov**, On groups almost approximatable by finite  $p$ -groups • **V. P. Shunkov**, On a periodic group with almost regular involutions.

Contents of the second issue (Number 2, 1968):

**V. N. Agafonov**, The complexity of computing pseudo-random sequences • **V. M. Kopytov and I. I. Mamaev**, Absolute convexity of certain subgroups of an orderable group • **S. P. Kogalovskii**, On compact classes of algebraic systems • **E. N. Kuz'min**, Algebraic sets in Mal'tsev algebras • **I. A. Lavrov**, The answer to a question by P. R. Young • **L. L. Maksimova**, On the strict implication calculus • **E. A. Polyakov**, Certain aspects of the theory of recursive functions • **V. G. Sokolov**, On the Frattini subgroup • **M. A. Taitelin**, On elementary theories of lattices of ideals in polynomial rings.

Annual subscription (6 issues) .....\$85.00\*  
(Add \$5.00 for postage outside the U.S.A. and Canada.)

\*Your Continuation Order authorizes us to ship and bill each volume automatically, immediately upon publication. The Continuation Order will remain in effect until cancelled.

## PLENUM PUBLISHING CORPORATION

Plenum Press • Consultants Bureau • IFI/Plenum Data Corporation  
227 WEST 17th STREET, NEW YORK, N. Y. 10011

In United Kingdom: Plenum Publishing Co. Ltd., Donington House,  
30 Norfolk Street, London, W.C. 2.

**A New Volume in the Highly Acclaimed Series**  
**MONOGRAPHS IN SEMICONDUCTOR PHYSICS\***

Series translated from Russian by Albin Tybulewicz  
 Editor, "Soviet Physics — Semiconductors"

**Volume 3: SWITCHING IN SEMICONDUCTOR DIODES**

By Yurii R. Nosov

A. F. Ioffe Physicotechnical Institute  
 Leningrad, USSR

Covers the physical basis of the operation of a semiconductor diode under pulse conditions and gives, whenever appropriate, quantitative relationships describing transients in diodes. The volume presents the most general mathematical methods for solving the equations of transient processes, enabling the reader to analyze those pulse conditions not directly referred to in the text. In addition, a model of a planar diode with a semi-infinite base is described in detail. Solid state physicists and electrical engineers will find this work invaluable.

**CONTENTS:** List of principle symbols • Basic electronics of the switching processes in semiconductor p-n junctions • Switching in a planar diode • Planar diode with a thin base • Transient processes in a diode with a small-area rectifying contact • Effect of an electric field in a diode base on transient processes • Transient processes in diodes during the passage of a forward current pulse • Transient processes in semiconductor diodes and fundamentals of recombination theory • Literature cited • Index.

Approx. 239 pages PP 1969 \$19.50

Also available:

**Volume 4**  
**SEMICONDUCTING II-VI,**  
**IV-VI, AND V-VI COMPOUNDS**

By N. Kh. Abrikosov, V. F. Bankina,  
 L. V. Poretskaya, L. E. Shelimova,  
 and E. V. Skudnova

A. A. Baikov Institute of Metallurgy  
 Academy of Sciences of the USSR

The first published review of semiconducting chalcogenides of elements in groups II, IV, and V, this monograph presents phase diagrams for binary, ternary, and more complex systems.

234 pages PP 1969 \$19.50

**Volume 2**  
**LIQUID SEMICONDUCTORS**

By V. M. Glazov, S. N. Chizhevskaya,  
 and N. N. Glagoleva

Baikov Institute of Metallurgy  
 Academy of Sciences of the USSR, Moscow

The first to deal with semiconductors in the liquid state, this monograph provides a comprehensive review of the electrical conductivity, thermoelectric power, magnetic susceptibility, thermal conductivity, density, and viscosity of elemental and compound semiconductors just below the melting point, at the melting point, and in the liquid state.

362 pages PP 1969 \$22.50

**Volume 1**  
**HEAVILY DOPED**  
**SEMICONDUCTORS**

By V. I. Fistul'

Institute for Fine Chemical Technology  
 Academy of Sciences of the USSR, Moscow

Deals with the properties of degenerate materials and their applications, including tunnel diodes, lasers, and Hall probes.

418 pages PP 1969 \$25.00

\*Place your continuation order today for books in this series. It will ensure the delivery of new volumes immediately upon publication; you will be billed later. This arrangement is solely for your convenience and may be cancelled by you at any time.

**PLENUM PUBLISHING CORPORATION**  
 Plenum Press • Consultants Bureau • IFI/Plenum Data Corporation  
**227 WEST 17th STREET, NEW YORK, N. Y. 10011**

In United Kingdom: Plenum Publishing Co. Ltd.; Donington House,  
 30 Norfolk Street, London, W.C. 2.