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EXPERIMENTAL STATIONARY MHD-INSTALLATION, OPERATING ON RANKINE --ETC(U)
JAN 78   Y P VALIKHOV, V T KARPUKHIN
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FOREIGN TECHNOLOGY DIVISION

EXPERIMENTAL STATIONARY MHD-INSTALLATION, OPERATING ON RANKINE CYCLE

by

Ye. P. Valikhov, Yu. A. Kareyev, et al.

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EDITED TRANSLATION

FTD-ID(RS)T-2264-77 12 January 1978

MICROFICHE NR: FTD-78-C-000123

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English pages: 30

Source: Ordena Lenina Institut Atomnoy Energii im. I. V. Kurchatov, IAE-2087, Moscow, 1971, pp. 1-28.

Country of origin: USSR
Translated by: Robert Allen Potts
Requester: FTD/PDBA
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PREPARED BY:

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Block	Italic	Transliteration	Block	Italic	Transliteration
А а	*А а*	A, a	Р р	*Р р*	R, r
Б б	*Б б*	B, b	С с	*С с*	S, s
В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
Ж ж	*Ж ж*	Zh, zh	Ц ц	*Ц ц*	Ts, ts
З з	*З з*	Z, z	Ч ч	*Ч ч*	Ch, ch
И и	*И и*	I, i	Ш ш	*Ш ш*	Sh, sh
Й й	*Й й*	Y, y	Щ щ	*Щ щ*	Shch, shch
К к	*К к*	K, k	Ъ ъ	*Ъ ъ*	"
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М м	*М м*	M, m	Ь ь	*Ь ь*	'
Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

*ye initially, after vowels, and after ъ, ь; e elsewhere.
When written as ё in Russian, transliterate as yё or ё.

RUSSIAN AND ENGLISH TRIGONOMETRIC FUNCTIONS

Russian	English	Russian	English	Russian	English
sin	sin	sh	sinh	arc sh	$\sinh^{-1}$
cos	cos	ch	cosh	arc ch	$\cosh^{-1}$
tg	tan	th	tanh	arc th	$\tanh^{-1}$
ctg	cot	cth	coth	arc cth	$\coth^{-1}$
sec	sec	sch	sech	arc sch	sech^{-1}
cosec	csc	csch	csch	arc csch	csch^{-1}

Russian	English
rot	curl
lg	log

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Experimental Stationary MHD-installation, Operating On Rankine Cycle (Construction and technological problems)

ANNOTATION

In the work is given a description of the elements and units of thermophysical circuit, MHD-generator unit, magnetic system of the experimental installation, operating on Rankine cycle on a mixture of

mercury and cesium. There is examined a number of technological problems, connected with the selection of construction materials, preparation of the circuit for operation.

II. CONSTRUCTION AND CHARACTERISTICS OF THE UNITS OF INSTALLATION* M-30.

II-1. Block-diagram of the installation. The diagram of the thermophysical circuit of the installation M-30 and its overall view are presented in Figs. 1 and 2. The heating and evaporation of the amalgam occur in the evaporator (1), then the temperature of vapor is raised to 900°C in the steam superheater (2). Through a high-temperature steam pipe the vapor enters the unit of the experimental MHD-generator, placed in the gap between coils of a solenoid (4). In the nozzle part of the unit the flow velocity of the gas increases to supersonic. The kinetic energy of the flow is converted into electrical in the channel of MHD-generator (3). In water-coolable condenser (5) the steam is condensed, liquid amalgam of cesium is passed through a settling tank with cermet filters (6) for purification from solid slags and through a pipeline by gravity flow is returned to the evaporator.

The preparation of cesium amalgam is accomplished in an amalgam tank (8), to which is connected the mercury and cesium distillers. The amalgam is poured off into this same tank during reassembly of the installation and in emergency conditions. The composition of the amalgam in the circuit is changed either by reloading of components (roughly), or, more precisely, by admission of cesium vapor (9) from the system of admission of cesium into high-temperature steam pipe before the channel of the MHD-generator. The removal of foreign bodies, located in the circuit in gaseous phase, is provided by the vacuum system of the circuit (10). The thermophysical parameters of the installation and the elements of the circuit are controlled from a central panel.

1. INTRODUCTION

In the I. V. Kurchatov Institute of Atomic Energy for a number of years work has been performed on the study of the problem of the MHD conversion of thermal energy into electrical with the use of the nonequilibrium conductivity of plasma. The program of work includes the investigation of questions connected with the physics of motion of nonequilibrium plasma in a magnetic field, the effectiveness of energy conversion, technology of MHD-generators etc. In accordance with this program there was designed and constructed the experimental stationary MHD-generator M-30, operating on Rankine cycle on a mixture of mercury and cesium. As an experimental installation it has a number of advantages in comparison with installations operating on the Brighton cycle: simplicity of completion of cycle, absence of the problem of introduction and removal of easily ionizable additive. The selection of mercury with the addition of cesium (cesium amalgam) was determined by its more favorable thermophysical characteristics with respect to other metals (thallium, zinc etc.).

The basic parameters of the installation are the following:

1. Flow rate of vapor - up to 100 g/s.
2. Stagnation temperature - 900°C.
3. Stagnation pressure - up to 0.6 atm (abs).
4. Mach number at channel inlet ≈ 1.8.
5. Magnetic field - 4 T.

II-2. Cesium amalgam evaporator. As the working mixture of the M-30 installation there is used cesium amalgam (35 at. o/o cesium and

65 at. o/o mercury). This composition of amalgam made it possible to obtain the necessary ratio between the basic gas and the easily ionizable addition, in order with reasonable energy expenditures to provide nonequilibrium conductivity of plasma, on the order of several tens of mho/m in the channel of the MHD-generator. The diagram of partial pressures of components, constructed on the basis of analysis of experimental [1] and calculation [2, 3] data, is presented in Fig. 3. The amalgam evaporator (Fig. 4) was rated, proceeding from the conditions that the vapor flow rate should be approximately 100 g/s at temperature 700°C. It is manufactured from steel EI-695R, having satisfactory strength characteristics in the indicated temperature range. The diameter of the bottom of the evaporator is 800 mm. The usable electric power is 30.5 kW. Into the evaporator is loaded 115 kg of cesium amalgam (71.4 kg mercury and 43.6 kg cesium). To the housing of the evaporator are mounted level gauge, thermocouple sensors and a pressure sensor.

II-3. Steam superheater. Further increase of the gas temperature from 700 to 900°C is accomplished in the steam superheater. The steam superheater is made in the form of lyre-shape bended tube 50 mm in diameter from steel EI-652 (GOST 5632-61), heated by electric current (12 V x 1500 A) to temperature 1100°C (Fig. 5). Length of the tube is 9m. The usable electric power is 18 kW. The steam superheater is placed in a thermostat. As heat-insulation material of the thermostat there is used silica fiber. At the entrance and exit of the steam superheater there are pressure indicators and thermocouples.

II-4. Unit of experimental MHD-generator. This unit consists of a high-temperature steam line, located in the gap between the solenoid coils, acceleration device (nozzle), channel of MHD-generator and a diffuser. This part of the installation is replaceable, the construction of separate elements can be changed depending on the type of investigated MHD-generator. As one of the versions for experiment there was manufactured a Faraday type linear MHD-generator. The thermodynamic parameters of flow, the geometry of the channel and the electrical parameters of the generator were examined by quasi-unidimensional theory taking into account the turbulent conductivity of plasma [4, 5]. During the calculation of the experimental characteristics of MHDG we used data of specially conducted experiments on the study of nonequilibrium conductivity of mercury-cesium plasma [5, 6]. The construction of the channel unit, as the entire installation on the whole, should be accomplished taking into account the inadmissibility of depressurization of the circuit. Because of this, there was proposed a version of placement of the container of the channel inside a vacuum-tight housing. The inside of this housing has a pressure control system. The container of the generator is manufactured from ceramic (pure aluminum oxide) and can be assembled from separate plates or all-soldered. As the electrode material is used tungsten-rhenium alloy (cathodes) and niobium (anodes). For optical measurements in the walls of the channel and housing are mounted sapphire disks. The leads of the electsodes, thermocouple sensors and tubes for the measurement of pressure outside are accomplished through sealed leads of the outer housing.

The diffuser of the linear version of the channel is represented by a rectangular container, assembled from ceramic plates.

The view of the steel sides of the outer body with sealed leads and ceramic channel is presented in Figs. 6 and 7.

II-5. Condenser. From the unit of the experimental MHD-generator through a compensation bellows unit the mercury-cesium vapor enters the condenser at temperature 600-700°C (Fig. 8). The cooled cesium amalgam through the pipe line is returned to the evaporator. The condenser is made in the "pipe in a pipe" scheme and is designed for the removal of heat load up to 50 kW. The condenser is made from steel Kh18N10T (GOST 5949-61). The diameter of the body of the condenser is 325 mm, inner pipe is 267 mm. The height of the condenser is 1495 mm. The condenser is cooled with desalinized water. For measurement of the water temperature at the entrance and exit, and also for measurement of the flow rate there are installed resistance thermometers and differential manometers. From the top part of the cavity of the condenser through a pipe line with diameter 100 mm and length 2 mm the gaseous impurities are pumped out by a mercury diffusion apparatus RVA-05-2.

Introduction of cesium. The content of addition in the steam can be changed quite rapidly (toward increase) by the injection of cesium vapor into the supply pipeline before the nozzle of the MHD-generator. The system for additional introduction of cesium consists of an evaporator and high-temperature pipeline (Fig. 9). The flow rate of cesium is monitored by readings of the level gauge in the cesium evaporator. The temperature of cesium vapor at the inlet to the main steam line is 900°C.

II-6. Magnetic system. For excitation of the magnetic field in the channel of MHD-generator there is used a water-coolable battery type solenoids (Fig. 10), manufactured in the D. V. Yefremov NIIEFA. The solenoid consists of two cylindrical coils with external diameter 1280 mm and internal diameter 420 mm. The minimum clearance between coils, in which the experimental channel unit is placed, is 50 mm.

The magnitude of magnetic induction in the clearance is 4 T. Fig. 11 shows curves of propagation of the magnetic field along the axis of the solenoid and along the radius. It is possible to see that the heterogeneity of the magnetic field in the region of location of the channel of MHD-generator does not exceed 0.5 o/o.

Each solenoid coil has a supporting housing of Kh18N10T stainless steel and copper winding. The winding is made from 78 copper disks 5 mm thick, butt welded. As interloop insulation there is used Lavsan 0.2 mm thick. The coil has 128 radial-axial holes 35 mm in diameter for the passage of cooling water. The weight of the coil is 5 t.

The power use of the solenoid is 3.25 MW (25000 A x 130 V). The power supply system includes a powerful silicon rectifier of type VAK-160-25000. For cooling the solenoid winding there is used desalinized water. The flow rate of water through the solenoid is ≈200 m^3/h. Purification of the water up to resistance ≈ 2 MΩ/cm is accomplished with the aid of ion-exchange resins.

II-7. System of automatics and KIP. The indicated system is designed for automatic control of the temperature conditions of the circuit, the pressure, level and flow rate of the working medium, flow rate of cooling water, and also for giving warning, emergency signals and shutting off separate elements and the installation on the whole. It consists of thermocouple sensors with secondary instruments of type PSR, differential manometers DM, level gauges PUZhM with secondary instruments EPV. Schematic diagram of measurements of the thermophysical parameters of the circuit is given in Fig. 12. Secondary instruments of various sensors, monitoring and control instruments of the electrical parameters, signal armature are placed in the panel installation.

System of measurement of pressure of the working medium.

The pressure measuring system consists of:

a) compensation type sensors, contact;

b) electromagnetic valves, providing change of the compensation pressure of argon;

c) differential manometer "DM" in a set with secondary instruments DSR-1, designed for measurement of the compensation pressure;

d) control circuit of operation of electromagnetic valves.

Measurement occurs in the following manner. The contact of the sensor through an intermediate relay controls the operation of the electromagnetic valves so that in the cavity above the measuring bellows (Fig. 18) there is established argon pressure, equal to the measured pressure of the vapors of working medium.

The compensation pressure is measured by differential manometer "DM" and is recorded on secondary instrument DSR.

III. TECHNOLOGICAL PROBLEMS OF INSTALLATION M-30.

With the creation of closed circuit of MHD-generator, using nonequilibrium conductivity of working medium, there appears a consideral quantity of complicated technological questions, such as the selection of structural materials taking into account their interaction at high temperature with aggressive working medium, which is the mixture of cesium and mercury, welding of units, the provision of very high (10^{-2} - 10^{-3} o/o) purity of working medium, high mechanical and electrical strength of the construction of experimental channel of MHD-generator etc. Below in more detail will be covered the basic technological problems, which we encountered during the designing, manufacture and the first operation of the M-30 circuit.

III-1. Structural materials. One of the most important technological problems during the creation of MHD-generators is the problem of the stability of materials in aggressive media at high temperatures. At the time of designing the circuit of the installation M-30 in literature there was available data on the interaction of various steels with mercury and its vapors mainly at temperatures up to 700-800°C. At higher temperatures (900-1100°C) there was no information about the interaction of metal and electric insulating materials with cesium amalgam. Therefore a cycle of relatively short-duration tests was conducted on various heat-resistant steels, alloys, welding samples, and also ceramics in a mercury-cesium medium for the purpose of their selection for use in constructions of the installation. The materials were tested on I. V. Kurchatov IAE stands, and analysis of interaction - in A. A. Baykov IMET and other organizations. The methods of testing involved holding the samples in cesium amalgam vapors at temperatures 900-1100°C in vacuum chambers. The chambers preliminarily undergo many days of vacuum conditioning at temperature 600°C. Remaining rarefaction was always better than 1.10^{-6} torr. After preliminary outgassing the samples were heated to the needed temperature either by direct passage of current or in special thermostats. The appropriate measures were taken for preventing the samples from getting dusty from the material of the walls of the chambers. The temperature was monitored through sapphire windows by an optical pyrometer. Vapor pressure of amalgam was created by heating the tap, in which the cesium amalgam of 50 o/o composition (50 at. o/o Hg and 50 at. o/o Cs) was distilled. Holding at assigned pressure (~ 45 torr of mercury and ~1.1 torr of cesium) was conducted for 50 hours. The following steels and alloys were tested: VZh-100, V-2, EI-559A, EI-652, Kh18N10T, alloy 0Kh15 N10M2. During investigation of the samples after tests the following characteristics were determined:

1. State of the surface.

2. Change of weight.

3. Plasticity during bending.

4. Microstructure.

Tests showed that at temperature 1000°C the best characteristics show steel EI-652. On the sample were observed the least losses of weight, it did not have a noticeable change of state of the surface and possessed the greatest plasticity. Therefore as structural material for elements of the circuit, operating at wall temperature 1000°C (steam superheater, unit of experimental MHD-channel), steel EI-652 was selected. From it the corresponding tubes and forgings were manufactured. Welding tests of this steel also gave satisfactory results. For amalgam evaporator (t_{max} = 800°C) steel EI-695R was selected, and the remaining parts of the circuit were manufactured from steel Kh18N10T.

Electric insulation materials (EIM) are used for the creation of the channel of MHD-generator. During its operation depending on the mode there can appear electrical voltages up to 1000 V (≈ 100 V/cm). This requires the application of good insulation of electrodes, current leads and diagnostic sensors from the body of the channel.

Analysis of data on the compatibility of various ceramics with mercury, cesium and various electrode materials, and also the conducted tests showed that ceramic on an aluminum oxide base (pure or with the addition of yttrium) is suited as a structural material. From this ceramic were manufactured shaped containers for MHDG, electrode plates and leads.

Electrode materials. The selection of electrode materials is determined, besides the satisfaction of requirements for compatibility, by the degree of their emissivity. According to calculations the current density from one electrode in the MHDG channel of the M-30 installation was ≈5 A/cm². Consequently, it was necessary to have electrodes, providing the prescribed density of emission uniformly over the entire surface, without the formation of cathode spots, or the heterogeneities of current in the MHDG channel with nonequalibrium conductivity strongly affect the efficiency of conversion. Special experiments were conducted in discharge tubes with electrodes, manufactured from various materials [7]. Primarily were investigated metals and alloys, in a vacuum having the most work function of electrons, since the film of cesium is held the strongest on their surface. They include: W, Ta, Pt, Mo-Re, W-Re. Results showed that the best material for cathodes working in mercury-cesium vapor at t = 900°C is alloy WRe-27. Further investigations of this alloy confirmed the high value of thermoelectrode emission, reaching up to 20 A/cm² at t of cathode ≈900°C without the appearance of cathode spots.

Thus, as cathode material was selected alloy WRe-27, and for anodes is used niobium, having satisfactory stability in mercury and cesium vapors at high temperature and coefficient of linear expansion close to the coefficient of expansion of the applied aluminum oxide. From this material were manufactured the current leads, passing through the ceramic.

III-2. System of purification of the working medium from impurities. As shown by the experience of the study of discharges in A + Cs, He + Cs, Hg + Cs mixtures, the nonequalibrium conductivity in discharge, sufficient for use in MHD-generator, takes place with concentration of impurities (O_2, N_2 etc.) on the order of 10^{-2} - 10^{-3} o/o [6, 8], i.e., with pressure of mercury 50 torr and cesium 10^{-1} torr, pressure of the remaining gases should be less than 10^{-4} - 10^{-5} torr. This superposes the determination of the condition not only on the selection of materials of the circuit of the installation, but also on the development of a complex system of maintaining the indicated level of impurities in the operating mode of the installation. This complex of measures is put together from the preliminary technological preparation of the elements of the vacuum circuit of the installation (all possible methods of cleaning the parts from oil and other contaminants), subsequent vacuum conditioning in hot state, evacuation in operating mode, purification of the cesium amalgam from slags in cermet filters and purification of gases, admitted into the circuit of the installation.

Vacuuming of circuit. Pressure of the remaining gases in the installation on the order of 10^{-5} torr in the operating mode is provided by the system of oil-free evacuation of the circuit. It consists of a mercury-jet diffusion unit of type RVA-05-2 with capacity 200 l/s with pressure 10^{-6} torr and two zeolite forevacuum units of type TsVA-1-1. Evacuation of the circuit in the operating mode is accomplished from the cavity of the condenser. With preliminary (until filling with working medium) vacuuming of the circuit additionally to the RVA-05-2 is connected a DRN-50 type mercury pump, placed in the region of the amalgam tank. For the creation of preliminary rarefaction in the circuit after admission of inert gas into the circuit in emergency conditions or with the replacement of some elements of the circuit there is used a forevacuum pump with zeolite trap (silica gel + activated carbon), hot trap (copper at t = 400°C) and water-cooled trap.

Fig. 14 shows the dependence of the pressure of remaining gases in the installation on the time of evacuation with warming up without filling with working medium. The magnitude of pressure of remaining gases in the condenser is $5 \cdot 10^{-7}$ torr, in the evaporator $5 \cdot 10^{-6}$ torr. As can be seen from the provided data, the system of evacuation with the appropriate mode of vacuum conditioning can provide the indicated percentage of impurities of foreign gases in the circuit of the installation.

Purification of inert gases. (argon, nitrogen etc.) from moisture and oxygen, intended for admission into the circuit of the installation, is accomplished by passing first through a silica gel filter, then melted alkali metal and a trap cooled with nitrogen.

Preliminary purification of mercury and cesium from gases dissolved in them before pouring into the circuit of the installation is accomplished by repeated distillation under evacuation in the appropriate distillers.

The ceramic parts of the channel also undergo complex purification from contaminations by chemical agents, ultrasound and subsequent vacuum annealing at temperature 1300-1500°C. The assembled model of the channel before installation in the circuit undergoes tests for airtightness, electrical strength and heat-resistance on a special stand.

Fig. 1. Block diagram of installation M-30.

1. Cesium amalgam evaporator. 2. Steam superheater. 3. Unit of experimental MHDG. 4. Solenoid. 5. Condenser. 6. Settling tank with filter. 7. Level stabilizer. 8. Amalgam tank. 9. Cesium evaporator. 10. Mercury diffusion and zeolite vacuum units.

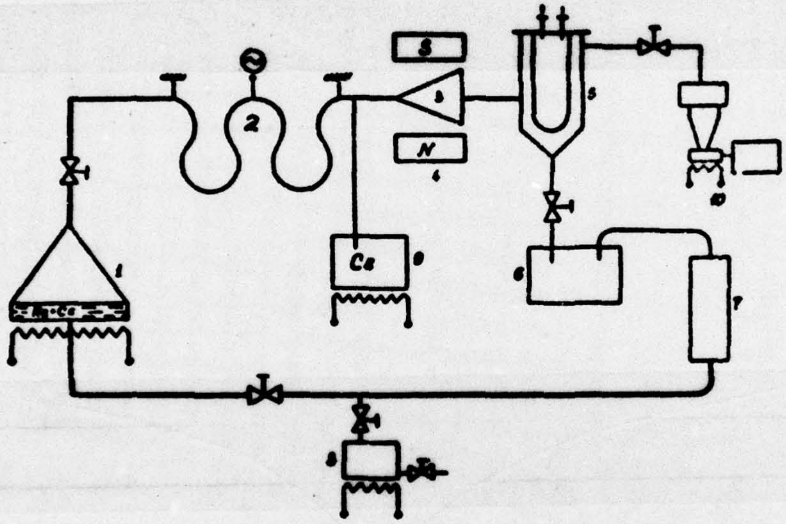


Fig. 2. Installation M-30.

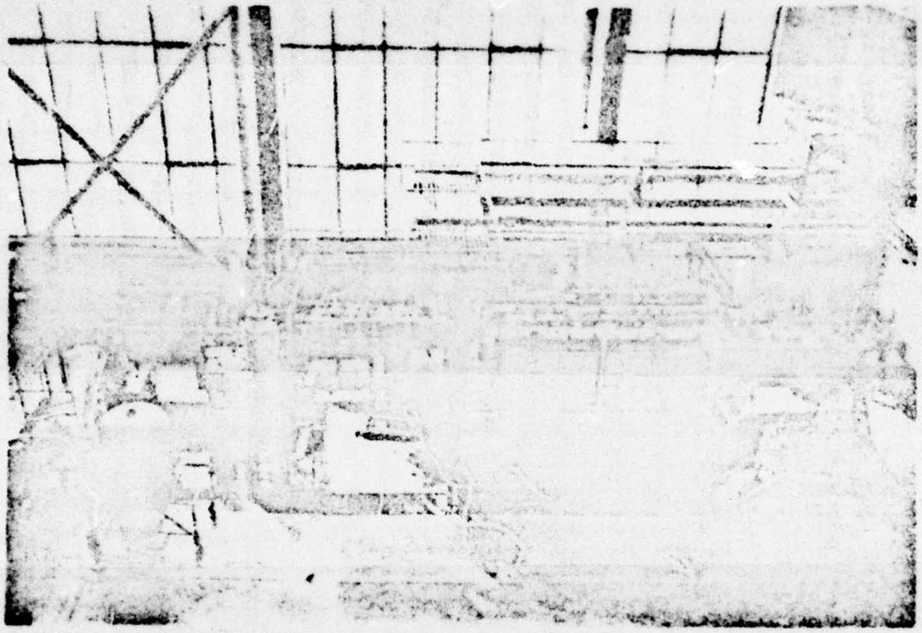


Fig. 3. Dependence of partial pressures of components of mercury-cesium vapor on the composition of amalgam and its temperature.

Key: (1) torr.

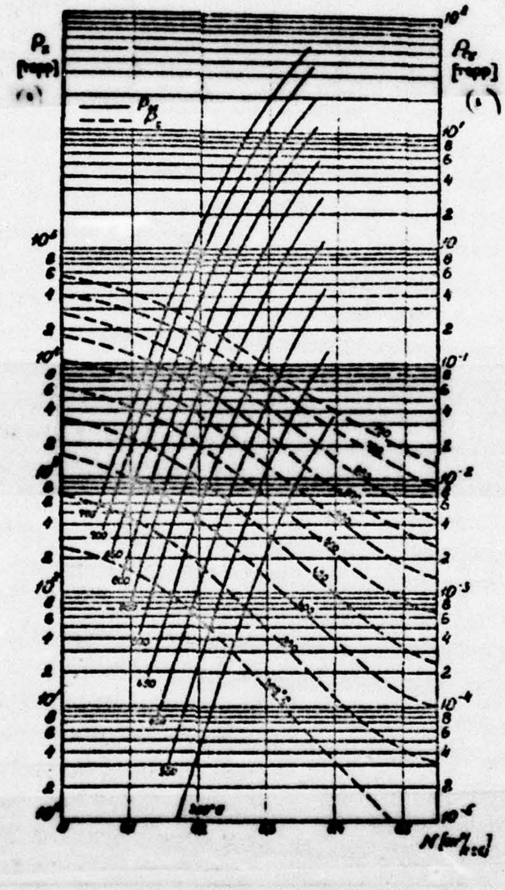


Fig. 4. Evaporator.

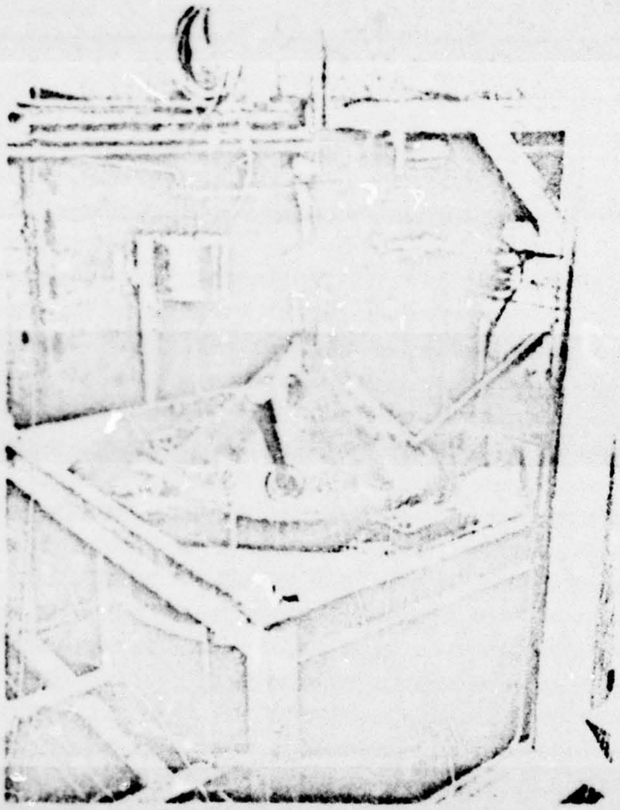


Fig. 5. Steam superheater.

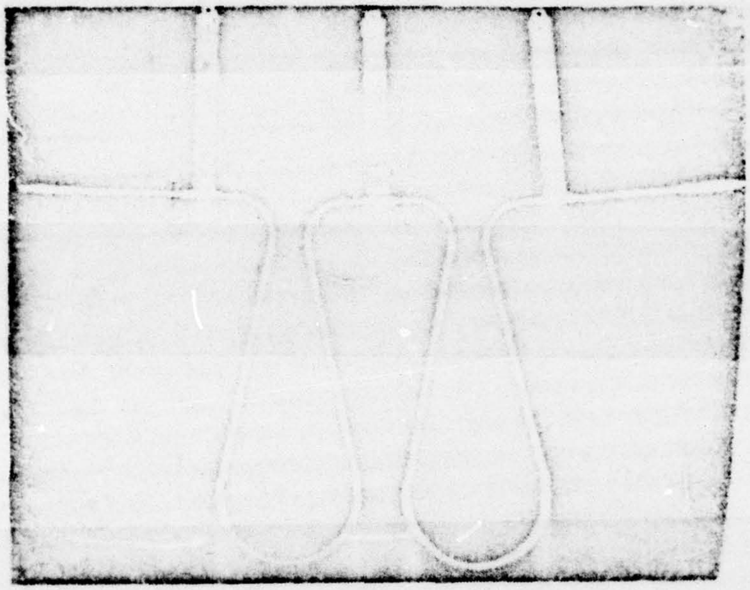


Fig. 5. Channel of MHD-generator. Sides of outer housing.

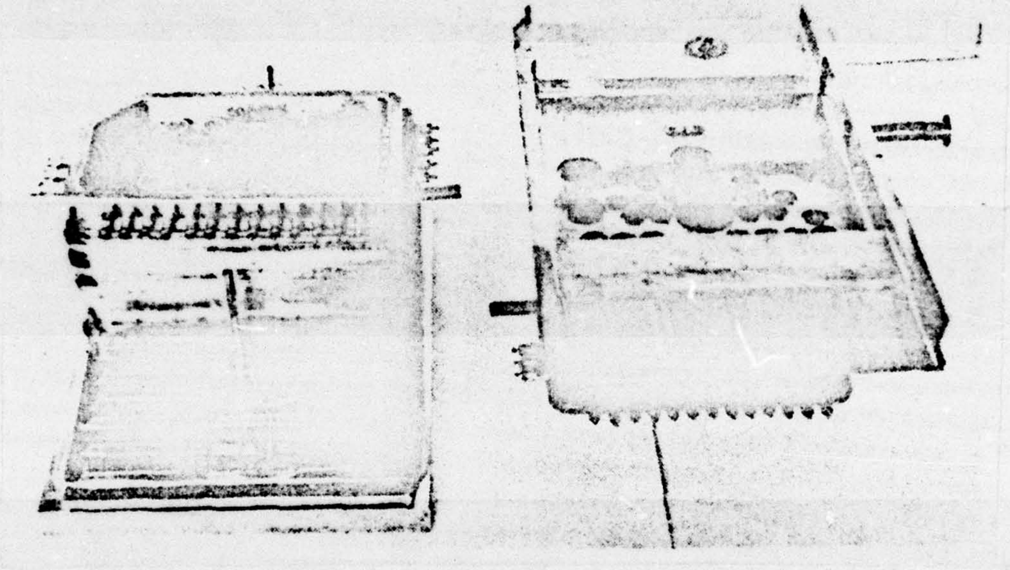


Fig. 7. Channel of MHD-generator. Ceramic container. Heat shields. Sealed leads.

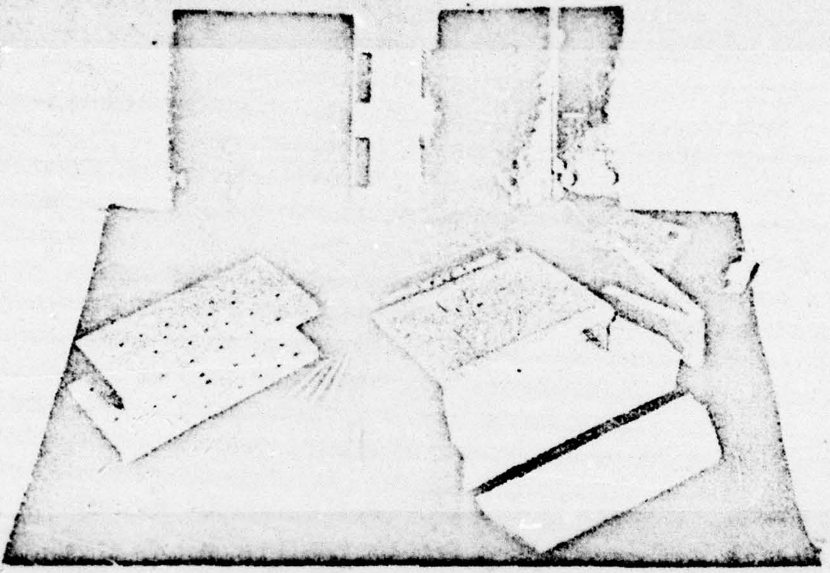


Fig. 8. Condenser.

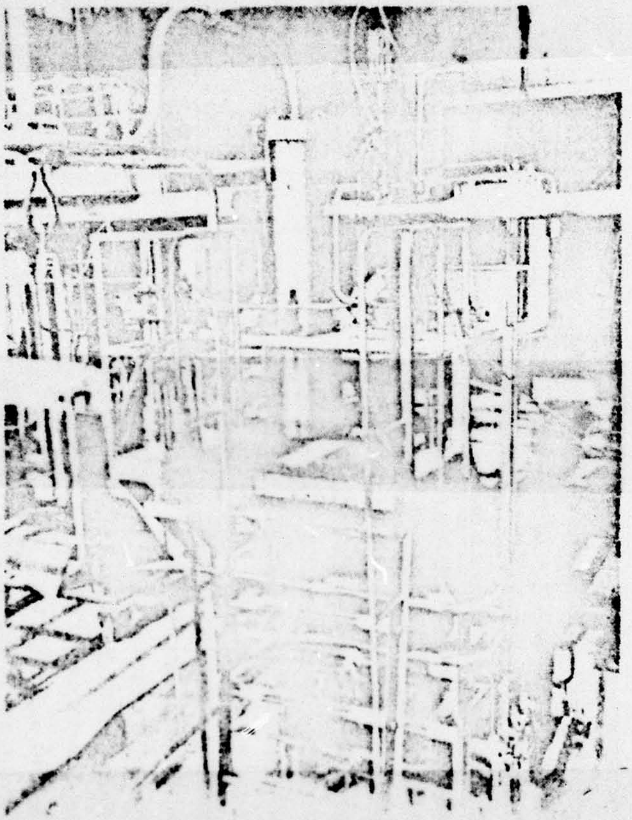


Fig. 9. System of introduction of cesium.

Fig. 10. Solenoid SO-7.

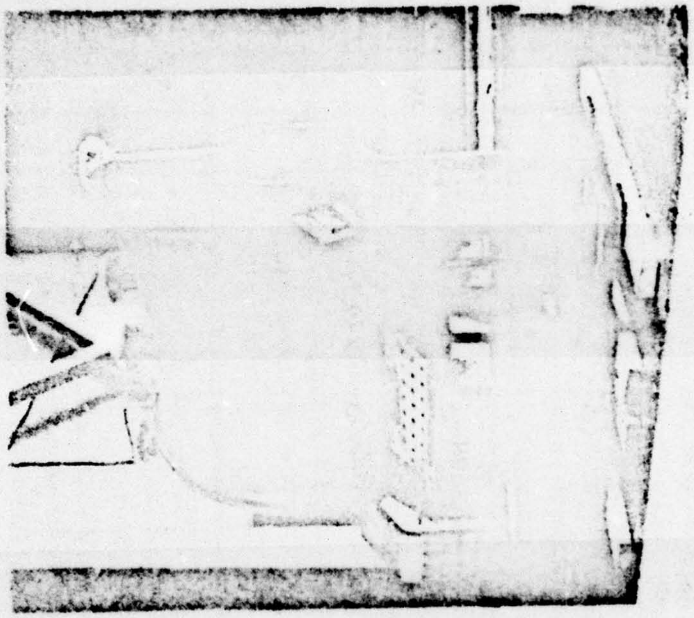


Fig. 11. Curves of distribution of magnetic field along the axis of the solenoid and along the radius.

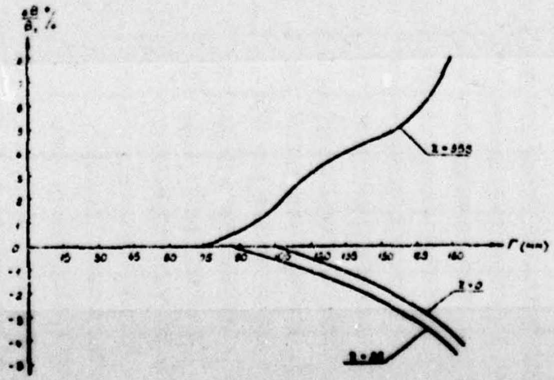
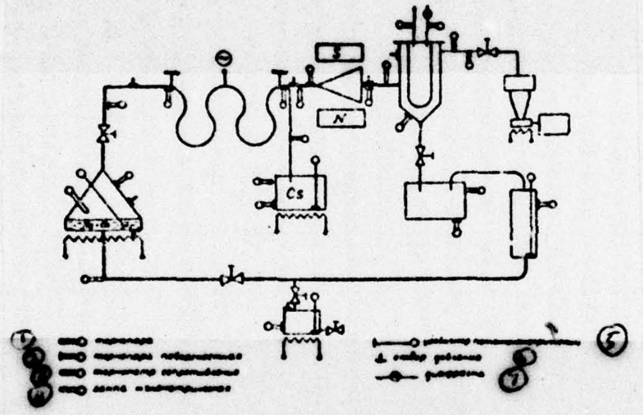


Fig. 12. Schematic diagram of measurements of thermophysical parameters of the circuit.

Key. 1. thermocouple. 2. surface thermocouple. 3. resistance thermometer. 4. manometric lamp. 5. potentiometric level gauge. 6. pressure bleed. 7. diaphragm.



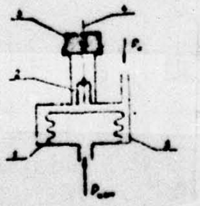
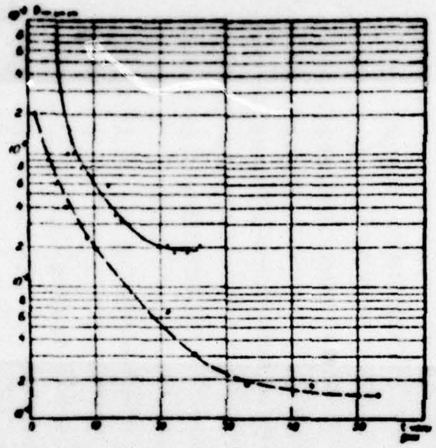


Fig. 13. Pressure sensor.

1. Measuring bellows. 2. Pressurizing bellows. 3. Screw-nut pair. 4. movable contact, isolated from body. 5. Body P - measured pressure. P - compensating pressure.

Fig. 14. Dependence of pressure of remaining gases in the circuit of the installation on time: ● - pressure in condenser (cold circuit); ●-pressure in amalgam evaporator (hot circuit).



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