International Atomic Energy Agency
SYMPOSIUM ON THE PRODUCTION OF ELECTRICAL ENERGY BY MEANS OF MHD-GENERATORS
Warsaw, 24-30 July 1968

SM-107/142

THERMODYNAMIC ANALYSIS OF NEW CYCLES FOR LIQUID-METAL MHD GENERATORS *

by

V.M. Boldyrev, A.E. Morozov, P.P. Orlov, Yu. M. Syaskin,
E.E. Shpilrain and K.A. Yakimovich
High Temperature Institute, USSR Academy of Sciences
Moscow, USSR

Properties inherent in MHD power plants using a liquid-metal working medium—the large single-component powers, the possibility of creating reliable completely static plants, the comparatively low temperatures of the working medium in the MHD generator duct—have caused increased interest in this type of plant. However, for the creation of an efficient liquid-metal MHD plant, a series of serious scientific and engineering problems must be solved associated primarily with acceleration devices.

If in this article we disengage ourselves from attempts to create a working medium which simultaneously has adequate compressibility and electrical conductivity (foams, stratified working media, and the like), then the problem of creating an acceleration device can be examined in two variants—separator and injector. The separator variant variant developed in previous papers [ref. #1, 2] suggests that the electrically conducting liquid subject to acceleration is mixed with [added to] a gas or vapor before its expansion in the acceleration nozzle.* Furthermore, in the expansion, a definite velocity is obtained along with a gas (vapor) and a liquid after which the mixture is fed into a separator, whose basic requirements reduce to the fact that it is possible to completely separate the vapor from the liquid, while having preserved the kinetic energy of the liquid. In the injector variant, discussed, e.g., in the papers [ref. #3, 4], the liquid is mixed with the vapor after its expansion in the nozzle; in this case the liquid to be mixed in is not only accelerated by the vapor, but also condenses it making separation unnecessary.

Both the separation and the injector variants are known to be thermodynamically incomplete in the simplest [manner of] execution. By first examining the single-component flow patterns [schemes], i.e., those where liquid and vapor are one and the same substance, we can see their inherent deficiencies. It is known that the optimum (characterized by maximum efficiency) separation cycle has the form depicted in figure 1. In other words, the starting point of the cycle lies very close to the

*A specific case here may be the use, as the initial medium, of a simply sufficiently wet vapor or event a liquid in the saturated state (on the left boundary curve).

Cat 03
Pages – 11
Code – 1

*TRANSLATED FOR THE JET PROPULSION LAB, NAS 7-100; 1968

No. – CR-97885

left boundary curve. But this cycle has a low thermal efficiency due to the fact that it is characterized by the low mean temperature of the heat supply. The displacement of the starting point of the cycle to the right increases the mean temperature of the heat supply, bringing it close to T_1, however here the liquid fraction in the flow drops after expansion and the total efficiency of the cycle is reduced. In addition, the shift of the starting point to the right usually leads to such large liquid velocities that losses in the separator strongly increase.

In the case of the injector variant, the simplest thermodynamic starting cycle can turn out to be fairly efficient, for it essentially coincides with the efficiency of the Rankine cycle at the temperatures selected, figure 2. However, this cycle is characterized by very low internal efficiency due to the large shock losses in the injector. It is impossible to reduce these losses by means of injecting into the mixing chamber a liquid that has the same velocity as the vapor, for the vapor velocity at a fairly high thermal efficiency of the cycle (i.e., in the case when the starting point of the cycle lies close to the right boundary curve) turns out to be extremely high. The optimization of the injector cycle shows that in this case the maximum efficiency will also have a cycle beginning close to the left boundary curve, i.e., a cycle similar to that shown in figure 1.

Taking these conditions into consideration, reasons have been expressed in the literature concerning the fact that the efficiency of the injector cycle can be increased by utilizing a multistage injector, in each stage of which the velocities are small, which makes it possible to sharply reduce or even completely eliminate shock losses [ref. #5, 6, 7]. However, the calculations performed (see, e.g., [ref. #8]) showed that an increase in the efficiency due to the use of a multistage injector turns out to be extremely minute. At first glance, this strange result can be given a fairly simple explanation. The point is that in examining a single-stage injector, whose temperature T_2 can be considered a given temperature, it can usually be considered that a liquid with the temperature of the surrounding medium T_0 can be understood as the condensing liquid to be mixed in [added]. The fact that here two flows with essentially different temperatures T_2 and T_0 are mixed does not affect the efficiency of the cycle, for this mixing takes place beyond the limits of the cycle itself. Moreover, since the shock losses are basic losses in a very simple injector, it is convenient that the temperature T_0 be lower than T_2 as much as possible, here the amount of liquid to be mixed [added], and consequently the shock losses, are reduced.

In a previous paper [ref. #8] it was tacitly allowed that even in the case of the multistage cycle, a liquid with a temperature of T_0 can be added in each stage, and that just as in the single-stage cycle the mixing of the flows with different temperatures will turn out to be insignificant here. However, in reality this is not so. Even in the intermediate stage of the multistage injector, the mixing of the cold liquid having a temperature T_0 and the vapor having a temperature $T_i > T_2$ takes place within the temperature range of the cycle, unavoidable losses, which also lead to the fact that in spite of the decrease in the shock losses the efficiency of the multistage cycle turns out to be practically the same as the single-stage, are connected with this irreversible mixing.

From the analysis presented, the natural conclusion follows—a multistage injector cycle will be more efficient only when not just shock losses are eliminated, but also the losses due to the irreversible mixing of flows with substantially different temperatures. In other words, if in the intermediate stages of the injector a liquid is added having a temperature at the limit, [i.e.,] equal to the temperature of the vapor in these stages. Of course, in this case condensation of the vapor will not occur in the intermediate stages. Condensation here will rest on the final stage with the vapor temperature T_2, to which, according to the previously expressed reasons, a liquid at temperature T_0 can be added.

A liquid having the necessary temperature for mixing in the intermediate stages could be obtained by heating it in the heat source. However, in this case the mean temperature of the heat supply would be reduced and the cycle would essentially become equivalent to the cycle shown in figure 1. The sole possibility* of assuring high thermal efficiency of the cycle is included in the use for heating the regeneration liquid. Regeneration in the cases that we examined encounters known difficulties connected with the fact that in its use possible losses of kinetic energy should be considered.

Our suggestions for the improvement of thermodynamic multistage cycles with regeneration are basically related to the following three variants:

1. A multistage separator plant with regenerative [pre]heaters;

2. A multistage injector plant with condensation of the vapor phase at optimum velocities of the vapor and liquid;

3. A multistage injector-separator plant using wet metal vapor.

Figure 3 shows a flow pattern [diagram] of a four-stage separator plant with heat regeneration. It is assumed that at the output of the heat source there is 1 kg of the liquid metal in a saturated state. At the nozzle of the first stage *N'* this liquid expands to a pressure corresponding to the initial pressure in the second stage. The very wet vapor formed enters the separator of the first stage *S'* with a definite (given by the conditions of optimization of the entire flow pattern) velocity, where x_1 kg of the dry saturated vapor is separated and sent to the regenerative preheater *Pr'*, and $(1 - x_1)$ kg of the liquid enters the generator of the first stage *G'* where it releases its kinetic energy. It is most convenient in the generator not to trigger all the kinetic energy of the liquid, but rather a part of it, to restore in exit cone *E* the pressure equal, with a certain excess, to the initial pressure at the input into nozzle *N'*. In this case pumps are not needed to close [complete] the cycle.

*Here we do not examine any non-equilibrium conditions, when the cold liquid is in the vapor for a short time, is accelerated by it, but does not exchange heat with it.

The vapor drawn off into preheater Pr' is condensed giving off the heat of the liquid entering the second stage, the amount of this liquid α_2 is selected from the equation of heat balance so that the liquid is heated to a saturated state at its pressure. The condensate of the vapor x_1 together with the liquid $(1 - x_1)$ is returned to the heat source HS_1. Figure 3a depicts the [pre]heater Pr' as a surface heater for a better understanding of the flow pattern. Actually, since the pressure of the vapor after the preceding stage is equal to the pressure of the liquid in front of the second stage, this preheater is conveniently made as a mixing [pre]heater.

The operation ofthe last stages is the same as the first. In the last stage expansion in the nozzle takes place prior to the final pressure (temperature) of the cycle which is selected for reasons of construction and economy. The vapor to be separated from this stage is condensed in a condenser HS_2 giving off heat Q_2 to the surrounding medium. In principle, the vapor of the last stage can be removed not by means of separation, but by condensing it in the injector.

The operation of the multistage separator MHD plant becomes clearer from the analysis of the *T-S* diagrams presented in figure 3b.

The liquid metal on the left boundary curve (point 1) at a pressure p_{01} is expanded in the nozzle to state 2. After the separator, the parameters of complete retardation [braking] of the liquid without taking into account losses in the separator is defined by point 4. If pumps are not provided in the MHD-plant flow pattern, the the assumed gradient of temperatures in the MHD generator is equal to segment 4-5.

The vapor after separation at a static pressure p_1 (this same pressure is the pressure of complete retardation p_{02} for the second stage) heats the liquid in the amount of α_2 having state [condition] 9 after the generator of the second stage. After the preheater the liquid reaches the saturation state (point 3) and is fed into the nozzle of the second stage. The work produced in the generator of the second stage is presented by segment 8-9. Thus, all subsequent stages beginning with the second obtain heat in the regenerative heaters from the vapor separated out in the preceding stage. Consequently, the advantages of the suggested flow pattern consist of the following: first, heat from the external source is supplied at a quantity of Q_1 only to the first stage, i.e., at a high mean integral temperature. Simultaneously, heat to the cold source is removed only from the last stage at the same temperature as in the one-stage cycle. All this leads to an increase in the efficiency of the cycle. Secondly, in the suggested MHD plant the heat source will give out a liquid, and not a vapor, which in a number of cases can turn out to be quite substantial.

As an example, a calculation of the multistage regenerative flow pattern was made for Hg, Cs, and K. The upper temperature was assumed equal to $T_1 = 1200°K$; the temperature corresponding to pressure $p_2 = 0.5$ abs atm was assumed to be the lower temperature T_2. The number of stages n varied within the limits from 2 to 8. The temperature gradient in one stage was defined as $(T_1 - T_2)/n$. The thermodynamic efficiency of the cycle without taking into account the losses in the two-phase nozzles, separators, and MHD generators is equal to: approximately 19% for potassium, approximately 23% for cesium, and approximately 34% for mercury. An estimate of the efficiency η_{eff} was made for potassium at $\eta_{nozzle} = 0.9$, $\eta_{separator} = 0.85$, and $\eta_{MHD} = 0.7$. For the four-stage plant $\eta_{eff} = 12\%$.

The flow pattern of the four-stage injector plant is shown in figure 4a, and its cycle is drawn in the T-S diagram in figure 4b. Here it is also assumed in the separator flow pattern that 1 kg of the liquid metal in a saturated state (point 1) comes from the heat source HS_1. The metal is expanded in the nozzle of the injector of the first stage In', here its static parameters are characterized by point 2. Liquid in the amount of m' drawn off from the generator of the second stage G'' and having parameters of complete retardation characterized by point 9, and static paramters by point 7 are mixed in the mixing chamber of the injector. Point 9 is selected so that the liquid that enters the mixing chamber would have an optimum velocity. After the injector of the first stage the liquid metal in a quantity of $(1 + m')$ kg, having parameters of complete retardation characterized by point 4 is taken into the generator of the first stage G'. After the parameters of complete retardation are reduced in the generator to point 5, 1 kg of the liquid is drawn off and returned to the heat source HS_1. The remaining m' kg continue operation in the generator G', while the parameters of complete retardation and the static parameters corresponding to point 3 whihc is the initial state for the second stage at the input into the injector In'' are attained. Subsequent stages operate similarly. In the last stage the flow m^{IV}, having left generator G^{IV} with parameters of retardation and static parameters corresponding to point 14 are cooled in the condenser HS_2 to point 15 giving up the heat Q_2 to the surrounding medium. At a temperature corresponding to point 15, this flow is taken into the mixing chamber of the injector of the last stage, having as before an optimum velocity.

The advantage of the examined flow pattern in comparison to the previous one is that the use of the injector with the optimum flow velocities makes it possible to increase the efficiency of the plant due to the absence of shock losses. In addition, the kinetic energy of the liquid drawn off from the last stage is used beneficially in the injector flow pattern.

A real calculation was made for K, Hg, and Cs for the same operating temperatures and pressures and in the separator flow pattern. Here the overall efficiency of the cycle was 14% ($\eta_{MHD} = 0.7$, $\eta_{nozzle} = 0.9$, and $\eta_{exit\ cone} = 0.85$) for the four-stage plant using potassium.

The multistage injector flow pattern examined in figures 4a and 4b is not regenerative in the complete sense of the word. Its peculiarity [distinguishing feature] consists of the fact that not cold liquid, but liquid that comes from the last stage is delivered to the mixing chamber of the injectors of all stages with the exception of the last one. Here the kinetic energy of the liquid flows introduced into the mixing chamber are used beneficially. But in this flow pattern, complete condensation occurs in each injector, and each stage beginning with the second is obliged to operate from the left boundary curve.

Figures 5a and 5b show a flow pattern and cycle of a multistage injector plant constructed on another principle. Here regeneration is clearly used, the injectors of the intermediate stages are only mixers, and only the last stage is a condensing stage. In this case, vapor with any initial degree of dryness including dry saturated vapor can be used in the cycle. In accordance with figures 5a and 5b, 1 kg of wet vapor (point 1) comes from the heat source HS_1. This vapor is expanded in the injector nozzle of the first stage In' to a state with static parameters at point 2. Some m_1' kg of liquid at the same temperature T_1' is fed into the mixing chamber of the injector; the static parameters of this liquid correspond to point 3, and its parameters of complete retardation—[point] 3. The pressure at point 3 created by pump Pu' is selected so that the liquid reaches the mixing chamber with optimum velocity. The quantity of liquid m' should also be optimized. Due to the mixing [adding] of liquid m', the vapor flow is humidified somewhat and retarded, accelerating the admixed liquid. The static parameters of the flow at the output from the injector In' correspond to point 4. Furthermore, from this vapor flow α' kg dry saturated vapor is drawn off with static parameters at point 5. This vapor is used in the mixing [pre]heater Pr' for heating the liquid to the temperature T'_1. The quantity α_i is found from equations of heat balance. The kinetic energy of the vapor to be drawn off in the flow pattern under study is not used. In order to draw off the vapor, a very coarse separator (s', s'', s''' in figure 5a) can be used, for its task does not consist of complete separation of the vapor from the liquid, but only of drawing off a certain quantity of vapor. After drawing off the vapor, the flow acquires static parameters at point 6 with which they also enter [sic! it also enters] the injector of the second stage. The last stages operate similarly. In order to obtain applied pressures in the mixing heaters, pumps Pu_1, Pu_2, Pu_3, Pu_4 are used. Liquid cooled to the lowest possible temperature in the condenser HS_2 due to the giving up of heat Q_2 to the surrounding medium is sprayed into the injector of the last stage. Thus, the last stage of the injector is the condensing stage. After it, the flow with static parameters at point 8 and parameters of complete retardation at point 9 enters the generator. Thus, in the flow pattern under study, shock losses as well as losses connected with irreversible heat exchange in the intermediate stages can be omitted. Naturally, a certain irreversibility remains in the mixing heaters.

In the single-component flow pattern with injector, contradictory requirements are presented to the thermal capacity of the liquid. It should be minimum for obtaining high thermal efficiency of the cycle and maximum for obtaining minimum shock losses in mixing. This condition has led to the idea of using, in the injector flow patterns, different substances in the loops of the hot and cold sources [ref.#9]. In all these flow patterns the division of the working mixture into components for the subsequent closing of the cycle is accomplished in the single-phase separator when both components are in the liquid state. When these flow patterns were analyzed, a satisfactory division of components was suggested, however, the losses associated with them were not taken into account. A more detailed analysis of these flow patterns has shown that taking these losses into account leads to a decrease in the efficiency of the plant by 30 to 35 percent.

In connection with this a new flow pattern of a liquid-metal MHD plant with a two-component injector has been suggested by us that makes it possible to carry out highly efficient division of components with a significant lowering of the total efficiency of the plant, figure 6a.

The vapor of metal I is expanded in nozzle 1 and sent to mixing chamber 2 of the injector. The cold liquid of metal II which completely condenses the vapor of metal I and is simultaneously accelerated by it is also fed into the mixing chamber by means of an electromagnetic pump 3. The liquid mix of the two metals exiting from the mixing chamber is directed into the duct of the MHD generator 4. Furthermore, the flow is directed into exit cone 5 where part of the remaining kinetic energy of the liquid flow is used to increase the pressure necessary for completing [closing] the cycle of metal I. After the exit cone the mixture of liquid metals I and II is fed to the steam generator 6, first being heated in the regenerator 7 nad humidifier 8. Heating of the mixture of liquid metal I and II takes place in the steam generator, then there is complete vaporization of metal I while keeping metal II fundamentally in a liquid state, which assures the selection of the corresponding vapor of the metals. The vapor-liquid flow of metals I and II from the steam generator is sent to the separator of a cyclone type (9), where the liquid of metal II is separated from the vapor of metal I, as a result of which there is practically a complete separation of the components. The flow of liquid metal II after the cyclone is cooled in the regenerator by a flow of the mixture of liquid metals I and II from the MHD generator and is sent to the condenser (10). From the condenser the liquid of metal II is fed to the mixing chamber by means of an electromagnetic pump. The dry saturated vapor of metal I exiting from the separator is partially condensed in the humidifier by the mixture of liquid metals I and II exiting from the regenerator and is sent to the input into the vapor nozzle.

Figure 6b shows in a *T-S* diagram the cycles of metals I and II: (metal I is Cs, metal II is Li).

1-2 - expansion of cesium vapor in the vapor nozzle of the injector;
2-3 - condensation of cesium vapor in the mixing chamber of the injector;
3-4 - compression in the exit cone of the generator of the cesium + lithium mix;
4-5 - heating of the cesium + lithium mix in the regenerator and humidifier;
5-6 - preheating of the cesium + lithium mix in the steam generator;
6-1 - vaporization of the mix in the steam generator;
1-1 - condensation of cesium in the humidifier;
6-7 - cooling of lithium in the regenerator;
7-8 - cooling of lithium in the condenser;
8-9 - compression of lithium in the pump;
9-0 - acceleration of lithium in the liquid nozzle;
0-3 - heating of lithium in the mixing chamber.

In analyzing the suggested flow pattern of the MHD generator, the following simplifying assumptions are understood:

1. The efficiency of the vapor nozzle, MHD generator, electromagnetic pump, and velocity coefficient of the mixing chamber is not a function of the parameters of the cycle.

2. The pressure of retardation of the flow at the output from the MHD generator is negligibly small and is not taken into consideration in the analysis.

3. We disregard the increase in temperature of the liquid in the MHD generator and electromagnetic pump.

4. Losses in the liquid nozzle at the input of the liquid metal II into the mixing chamber are formally taken into consideration by the value η_{Pu}.

5. The quantity of cold liquid metal II introduced into the mixing chamber is defined from the conditions of complete condensation of the vapor of metal I disregarding the irreversible losses in the vapor nozzle and the mixing chamber.

6. The process in the mixing chamber is isobaric.

In the understood simplifying assumptions, the optimum ratio of wake velocities of the vapor and cold liquid in the mixing chamber is analytically determined giving a maximum value of the efficiency of the plant:

$$W_*^{opt} = \frac{\psi^2 \eta_G \eta_{Pu}}{1+m(1-\psi^2 \eta_G \eta_{Pu})} W_{vap} \tag{1}$$

where

W_* = the wake velocity of the flow of liquid metal II at the input into the mixing chamber

W_{vap} = the velocity of the vapor of metal I at the output of the vapor nozzle

m = the coefficient of discharge [flow rate] (amount of cold liquid metal II introduced into the mixing chamber per 1 kg of metal I)

η_G = the efficiency of the MHD generator

η_{Pu} = the efficiency of the electromagnetic pump

ψ = the coefficient of velocity taking into consideration the interaction of the vapor-liquid flow with the walls of the mixing chamber

At the optimum ratio of wake velocities of the vapor and cold liquid in the mixing chamber, an analytic dependence of the efficiency of the plant on its thermal parameters is found:

$$\eta_{eff} = \frac{\left(\frac{T_1-T_2}{T_1+T_2} + \frac{\Delta S}{Cp_I}\right)\psi^2 \eta_G \eta_{Pu}}{\left[1+\frac{T_2}{T_2-T_0}\left(2\frac{T_1-T_2}{T_1+T_2}+\frac{\Delta S}{Cp_I}\right)\frac{Cp_I}{Cp_{II}}\left(1-\psi^2 \eta_G \eta_{Pu}\right)\right]\left[1+\frac{\Delta S}{Cp_I}\;\frac{\Delta T p T_2+T_1 T_2-T_1 T_0}{(T_2-T_0)(T_1-T_2)}+\frac{\Delta T p T_2 \cdot 2}{(T_2-T_0)(T_1+T_2)}\right.} \tag{2}$$

[η_{eff} = overal efficiency]

where

T_1 = the temperature of metal vapor I at the input into the vapor nozzle

T_2 = the temperature of the metal vapor I at the input into the mixing chamber

T_0 = the temperature of the cold liquid of metal II at the output from the condenser

ΔTp = the temperature pressure [head] at the output of the liquid metal II from the condenser

ΔS = the difference in entropy of the vapor of metal I at the input into the vapor nozzle and the entropy of the liquid of metal I on the line of saturation at temperature T_1

Cp_I = the heat capacity of the liquid of metal I

Cp_{II} = the heat capacity of the liquid of metal II.

An analysis of expression (2) shows that there exists an optimum value ΔS at which with the other parameters fixed, the overall efficiency of the plant is maximum:

$$\Delta S^{opt} = \frac{T_1-T_2}{T_1+T_2} Cp_I \left[\sqrt{\frac{T_2}{T_1} + \frac{Cp_{II}}{Cp_I} \frac{(T_2-T_0)(T_1+T_2)}{T_1(T_1-T_2)(1-\psi^2\eta_G\eta_{Pu})}} - 1\right] \qquad (3)$$

(here $\Delta Tp = 0$ was used).

An increase in ΔS, on one hand, increases the thermal efficiency in connection with the growth of the mean temperature of the heat supply in the cycle of metal I, and on the other hand, increases the shock losses in the mixing chamber, since here the velocity of the vapor of metal I increases at the input into the mixing chamber and the coefficient of discharge is increased. Such an effect in the change of ΔS also leads to the presence of an optimum. Figure 7 shows the overall efficiency of the plant as a function of the value of ΔS when ΔS varies from 0 to a value corresponding to the dry saturated vapor. The metal Cs was selected as metal I, Li as metal II. The overall efficiency of the plant at the optimum value of ΔS and at a value corresponding to the dry saturation vapor differs little, however, as Δ increases, there is a reduction in the velocity of the liquid at the output from the mixing chamber, which increases the reliability of the plant, but at the same time the change in entropy of the vapor at the input into the adiabatic nozzle is limited by the condensing capability of the liquid of metals I and II exiting from the regenerator, in connection with which the entire sloping section of the efficiency curve in figure 7 cannot be used.

The temperature in the mixing chamber T_2 is selected within a range between T_1 and T_0 and in accordance with (2) there exists an optimum value T_2 within this range which yields the greatest efficiency. The presence of an optimum is explained by the fact that as T_2 increases with the other parameters fixed, the thermal efficiency of the plant is reduced, however, the shock losses in the mixing chamber are also reduced in connection with the reduction of the coefficient of discharge.

There is also interest in explaining the effect of the efficiency of the pump η_{Pu} on the overal efficiency of the plant (figure 8). The value of the overall efficiency of the plant at $\eta_{Pu} = 0$ corresponds to the case when the wake velocity of the cold liquid of metal II is equal to 0 and the shock losses in mixing are maximum. From figure 8 it is seen that the acceleration of the injected liquid by the electromagnetic pump does not cause any substantial increase in the overall efficiency of the plant. By way of example, a calculation of the overall efficiency of the plant was performed under the following assumptions:

$T_1 = 1323°K$, $T_2 = 700°K$, $\eta_G = 0.7$, $\eta_{Pu} = 0.5$,

$\eta_N = 0.96$, $\psi = 0.90$, $\Delta Tp = 10°$.

The value ΔS is assumed equal to 0.545 kcal/kg deg, which corresponds to the maximum possible use of the condensing capability of the liquid. With these data, the overall efficiency of the plant turns out to be 19 per cent.

References

1. Elliot, D., *Utilization of MHD-Cycle with Two Liquids for Converting Nuclear Energy to Electric*, Jet Propulsion Lab., Pasadena, California, in *Rocket Engineering*, No.6,23, 1962.

2. Elliot, D., et al., "Investigation of Liquid-Metal MHD Converter. A Direct Conversion of Thermal Energy to Electric and Fuel (Heat) Elements," *Information Bulletin*, Vol. II/40, Nov. 1965.

3. Shpil'rayn, E.E., and Yakimovich, K.A., "Thermodynamic Power MHD Plant with a Liquid-Vapor Injector," *Teplofizika Vysokikh Tyemperatur (Thermal Physics of High Temperatures)*, No. 5, 1965.

4. Kalafati, D.D. and Kozlov, V.B., "The Thermodynamics of Cycles with a Mixture of Liquid Metal Before an MHD Converter," *Teplofizika Vysokikh Tyemperatur*, No. 3, 1966.

5. Dzung, L.S., "Beschleunigung eines Flussigkeitsstroms durch einen Dampfstrahl als Antrieb eines MHD-Generators," Brenustoff Warme-Kraft, 17, Nr.1, 1965, January.

6. Radebold, et al., *The Conversion of Energy in a Liquid-Metal MHD Converter in the Form of a Pressure Shaft Hydromonitor (Hydraulic Excavator)*, in Trudy of the International Symposium in Paris, July 1964., Ch.P., INI Academy of Sciences of the USSR, Moscow, 1966.

7. In English
8. In English
9. In English

Figures

1. Separation cycle in a T-S pattern.
2. Rankine cycle in a T-S pattern.
3. (a) Heat scheme for a four-stage MHD separator plant.
   (b) Cycle for a four-stage separator plant in a T-S pattern.
4. Heat scheme for a four-stage injector MHD plant.
   (b) Cycle for a four-stage injector plant in a T-S pattern.
5. (a) Heat scheme for a four-stage injector-separator plant.
   (b) Cycle for a multi-stage injector-separator MHD plant in a T-S pattern.
6. (a) Heat scheme for an MHD plant with a two-component injector.
   (b) Cycle for an MHD plant with a two-component injector in a T-S pattern.
   ________circuit for meta I
   _ _ _ _ _circuit for metal II
7. Dependence of the effective efficiency of the plant on ΔS.
8. Effect of the pump efficiency on effective plant efficiency.