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Pulsed Portable Magnetohydrodynamic Power System Program

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A pulsed portable 15-MW_e magnetohydrodynamic (MHD) power system, called the Pamir-3U, was designed, built, and tested. The system is powered by three solid propellant rocket engines that deliver the working fluid to the MHD channels. The magnetic field was provided by four conventional, self-excited ellipsoid copper coils. The power unit is self-contained and operates independently of any external support equipment. The objective of this program was to provide a pulsed power system capable of delivering 15 MW of electrical power to the load for a 6- to 10-s duration with a total system mass of less than 18,000 kg. During the program, five preliminary acceptance tests and eight final acceptance tests were successfully conducted. These tests achieved the performance goals of the program and demonstrated the capability of the Pamir-3U power system in a variety of operating modes.

Nomenclature

A^* = nozzle throat area
$CM1$ = contactor number one
$CM2$ = contactor number two
DA = relative erosion of the throat measured with respect to the initial size
$DC1$ = disconnector number one
$DC2$ = disconnector number two
I_{IES} = initial excitation system current
I_{K1} = MHD channel number one current
I_{K2} = MHD channel number two current
I_L = load current
I_M = magnet current
$K1$ = MHD channel number one
$K2$ = MHD channel number two
$K3$ = MHD channel number three
L = magnet inductance
P_{av} = average plasma generator pressure
P_L = load power
P_{max} = maximal plasma generator pressure
PU = protection unit
P_1 = plasma generator number one pressure
P_2 = plasma generator number two pressure
P_3 = plasma generator number three pressure
Q = switch
R = protection unit resistor
R_B = ballast resistance
R_L = load resistance
R_M = magnet resistance
$R1$ = test hardware article after first refurbishment
$R2$ = test hardware article after second refurbishment
T = plasma generator charge thermal conditioning temperature
TH = load current transducer
THB = initial excitation system current transducer
$TK1$ = MHD channel number one current transducer
$TK2$ = MHD channel number two current transducer
TM = magnet current transducer
V_B = ballast resistor voltage
$V_{K1,K2}$ = MHD channel one and two voltages
V_{K3} = MHD channel three voltage
V_L = load voltage
V_M = magnet voltage
VS = thyristor switches

Introduction

THE Pamir-3U Magnetohydrodynamic (MHD) power system program was successfully completed in 1995. The Pamir-3U MHD system is a self-contained, portable power system that can be transported to various operational locations and does not require extensive support equipment to generate the design power. The objectives of this program were to design, fabricate, test, and deliver a 15-MW_e MHD power system, not to conduct developmental research.

A preliminary acceptance test program, consisting of five power tests and several preliminary tests, was conducted during August 1994 at Geodesiya Research and Development Institute, Krasnoarmejsk, Russia. During this test program, net power levels as high as 15 MW_e were obtained. Operation of the system in various operating modes was demonstrated, and several tests were conducted where the resistance was varied

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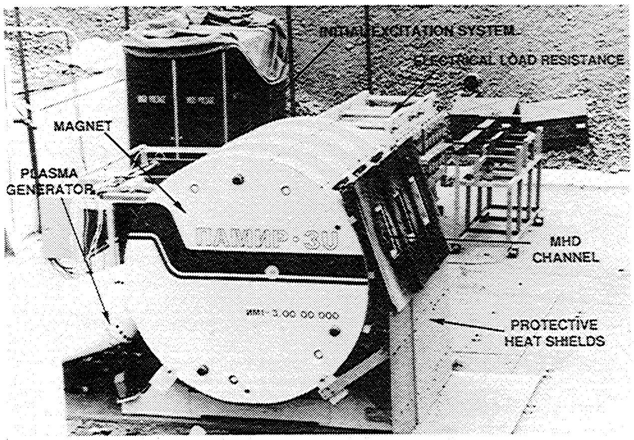

Fig. 1 Pamir-3U MHD power system.

during the hot-fire test run. The final Pamir-3U MHD power system acceptance test program was conducted at Aerojet Corporation, Sacramento, California, and consisted of eight hot-fire tests. The performance levels of the power system were confirmed during these tests. As a result of the experiments performed, the operational ability of the MHD power system to operate in a variety of performance modes and under a variety of operating conditions was confirmed.

The Pamir-3U MHD power system, shown in Fig. 1, is a self-excited pulsed MHD generator driven by three solid propellant plasma generators. The power system consists of three MHD channels designed and built by Nizhny Novgorod, which are placed between the electromagnet coils delivered by Nizhny Novgorod; three plasma generators designed and built by Soyuz; switching and protection equipment and a magnet ballast resistor designed and built by Nizhny Novgorod; and the initial excitation subsystem (IES) and the control, measuring, monitoring, and recording subsystem (CMMRS), designed and built by IVTAN.[1] Textron was the system integrator and importer of the Pamir-3U equipment and overall project manager.

The design requirements for the Pamir-3U MHD generator were established at the beginning of the program. The main system design parameters are listed in Table 1. The system design was based on the previously demonstrated, truck transportable, two-channel IVTAN Pamir-2 MHD power system hardware.[2] Because the specifications of the sponsoring agency required a higher power level, a third MHD channel was necessary.

In the sections that follow, the program highlights from the hardware description to the final acceptance tests are presented. First, the hardware is described. This is followed by a discussion of the system operation. Next, the preliminary acceptance test program and the analysis of the results are presented. Following these sections, a discussion of the acceptance test program and the analysis of the results are shown. The paper concludes with a brief conclusion section.

Hardware Description

The Pamir-3U MHD power system is designed for the conversion of the kinetic and thermal energies of the ionized propellant combustion products flowing through the magnetic field to electrical energy. The main power unit components are shown in Fig. 2. These components are (1) plasma generators with MHD channels and stops; (2) a magnet system; (3) frame, (4), (5) shields; (6) stops; (7) supports; (8) buses; (9) strapping tapes; (10) base plate; and (11) plate. The shields (4) and (5) and the plate (11) are used for protection of the power unit components and the test site from the heating action of the high-temperature flow of combustion products. The material of the shields is a mineral glass-reinforced plastic of 12-mm thickness. The mass of the power unit with the plasma generators is 12,700 kg. The overall dimensions of the unit are a length of 4500 mm, a width of 2000 mm, and a height of 2080 mm.

Table 1 PAMIR-3U system requirements

Parameter	Value
Maximum net electrical power output	15 MW
Nominal net electrical power output	10–15 MW
Maximal pulse duration at the load	8.5–9.5 s
Maximum mass	18,000 kg
Overall dimension:	
Length	10 m
Width	2.4 m
Height	2.4 m
Electrical load	0.015–0.025 Ω
Portability	Transportable by standard flat-bed truck trailer

The magnet system is installed on a frame that is attached to the base plate. The MHD channels are placed between four electrical magnets of the magnet system. The longitudinal axes of the MHD channels are inclined at an angle of 19 deg to the horizontal. The power-producing sections of the MHD channels are contained within the magnet system. The plasma generators rest on supports and are attached to them by a yoke with a metal band.

The reactive force arising from the operation of the plasma generators is contained by the stops attached to the base plate. For electrical isolation and prevention of current leakage from the electrical circuit, which contains the electrodes of the MHD channel, the front and back ends of the plasma generators, and the propellant combustion products, there are mineral fiberglass-reinforced plastic insulated plates and isolation blocks made from the same material.

The electrical assembly is made of flat copper buses, (8), which are shown in Fig. 2. The bus cross sections are 100 mm × 10 mm and 80 mm × 100 mm. The buses with a direct operating voltage of 2.5 kV are insulated from the power unit components, which are grounded. For the purpose of decreasing the contact resistance, a tin coating with a nickel precoat is applied to the bus contact surfaces. The bus connections are made with standard fasteners.

The plasma generators use a cesium-seeded solid rocket propellant. The BP-10F plasma charge propellant is a double-based compound (nitrocellulose and nitroglycerin) with a 95/5 aluminum/magnesium alloy (~20% by mass) and cesium nitrate (~10% by mass) added to the propellant mixture. The SPK-10M and SPK-14S plasma charge compositions are similar, but use potassium nitrate instead of cesium nitrate. The actual percentages varied slightly from batch to batch. The thermal power released during Pamir-3U operations is approximately 600 MW. Under these operating conditions, the combustor stagnation temperature was estimated to be ~3900 K, and the MHD channel inlet electrical conductivity was estimated to be in the range of 50–60 mho/m. More complete details of the burning rate characteristics of each batch are provided in Ref. 1. The plasma generators were similar in design and performance to those used for the Pamir 2 system.[2]

The variations of the plasma generator parameters—mass flow rate (18.5–26.0 kg/s), operating time (7.4–10.5 s), and combustion pressure (34–52 atm)—are caused by variations of the burning rate of the propellant, as well as by the dependence of the burning rate on the initial charge temperature, which is normally 5–35°C. For operation of the MHD power system in the maximum pulse-duration mode, a special modification of the plasma generator with the initial charge temperature of 0°C and an enlarged throat area of 80 cm^2 was analyzed and approved for use during the acceptance test program. Similarly, a separate analysis was approved for plasma generator charge operation at 40°C for the acceptance tests. This analysis, which results in the approval of only the plasma

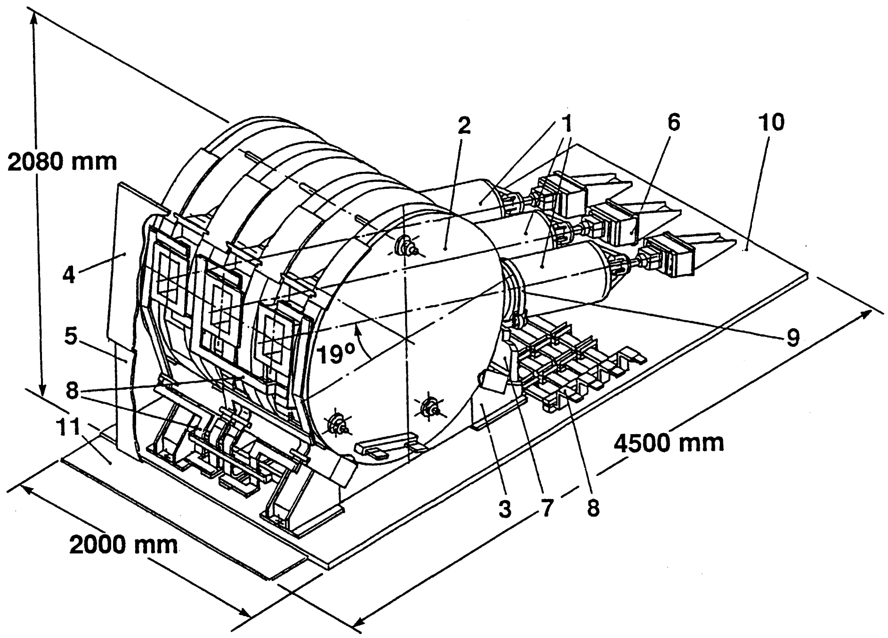

Fig. 2 Pamir-3U system power unit.

charge batch being assessed, is based on archival data of previous batches, mechanical and chemical data of the batch of interest, and actual performance data of the batch during operation. If the appropriate criteria are satisfied, operation at initial charge temperatures outside of the 5–35°C range is possible.

The Pamir-3U MHD generator is a Faraday-type generator with continuous electrodes. The generator operates at a relatively high pressure to keep the Hall parameter relatively low. The MHD channel consists of three areas: inlet, power-producing zone, and outlet. In the inlet area, the combustion products are accelerated up to a Mach number of 2.4. In the power-producing zone, the MHD energy conversion occurs. The outlet area is intended for the exhaust of the combustion products and the protection of the magnet system from the heat load of the gas flow. The MHD channel is a heat-sink unit. The heat protection is achieved through heat absorption by the design components that are made from heat-absorbing materials: ceramics and mineral fiberglass-reinforced plastic. The channel exit temperature was estimated to be ~3000 K.

The power-producing zone of the MHD channel consists of two electrode walls with constant divergence and two parallel insulating walls. The inlet area is 159 mm × 159 mm, and the exit area is 159 mm × 258 mm. The length of the MHD power-producing zone is 1008 mm.

The impact of the high-temperature gas flow and the current density distribution results in a variation of the electrical parameters along the channel length. For the purpose of providing the same resistance of the MHD channel components and for decreasing the MHD channel cost, different materials are used for the interior surfaces of the channel walls. At the MHD channel inlet, where the electric intensity is a minimum and the heat flux is a maximum, the lining is made of a thicker insert of erosion resistant graphite. In the pre-electrode area and at the beginning of the power-producing zone of the insulating walls, where the electric intensity is a maximum and the heat flux is less, the lining is made of modules of a high-temperature, electrically insulating ceramic. These modules are plates with a variety of geometric shapes.

To decrease the erosion at the boundaries of the adjacent modules, the intermodule clearances are located not in parallel, but at an angle of 45 or 90 deg to the gas flow direction. The gas-side lining on the insulating walls of the working zone, excluding the inlet part of the working zone, on the insulating walls of the outlet area, and on the outlet area of the electrode walls is made of panels of a high-temperature, electrically insulating, mineral fiberglass-reinforced plastic.

The MHD generator electrodes are fabricated from dense, arc-resistive graphite. This material provides acceptable near-electrode voltage drops and erosion resistance during the normal operating time of 10 s. The electrodes are made as square plates with dimensions of 83 mm × 83 mm. Each of the 24 electrode plates are attached to the electrode wall at one point. The electrodes are connected by a copper current tap attached to the power takeoff bus.

The electrical insulation of the electrodes located on opposite walls along the hot gas surfaces is made in the pre-electrode area and at the beginning of the working area by the application of a high-temperature, electrically insulating mineral fiberglass-reinforced plastic. Electrical insulation is achieved by mounting the electrode and insulating walls on plates of mineral fiberglass-reinforced plastic, and by using a load-bearing shell made from a winding of fiberglass braid.

The Pamir-3U magnet system principal views are shown in Fig. 3. The magnet system consists of four round electromagnets: (1) one left electromagnet; (2), (3) two middle electromagnets; (4) and one right electromagnet; (5), (6) which are separated by glass-reinforced plastic inserts; and (7) tightened by three studs; (8) commutating buses; and (9) protected from the exhaust gases by shields. The right and the left electromagnets each consist of a single electromagnet and cover, and the middle electromagnets, which differ from each other by the commutation of the current buses, consist of two single electromagnets.

For the convenience of the MHD channel installations, the upper inserts (6), shown in Fig. 3, are removable, and the lower inserts are fixed to the middle electromagnets (2 and 3), and the right electromagnet (4). Commutating buses (8) are mounted in the lower part of the magnet system and brought out through the insert windows of the single electromagnet.

The magnet coils are made of copper and are wound in an ellipsoid shape. There are 64 turns per coil. Each coil is insulated through the application of case insulation and its impregnation with an epoxy compound, followed by pressure and temperature polymerization of the insulation. The magnetic field in the magnet central region is 0.247 and 0.204 T/kA for the two side magnets. The magnet temperature at the end of a

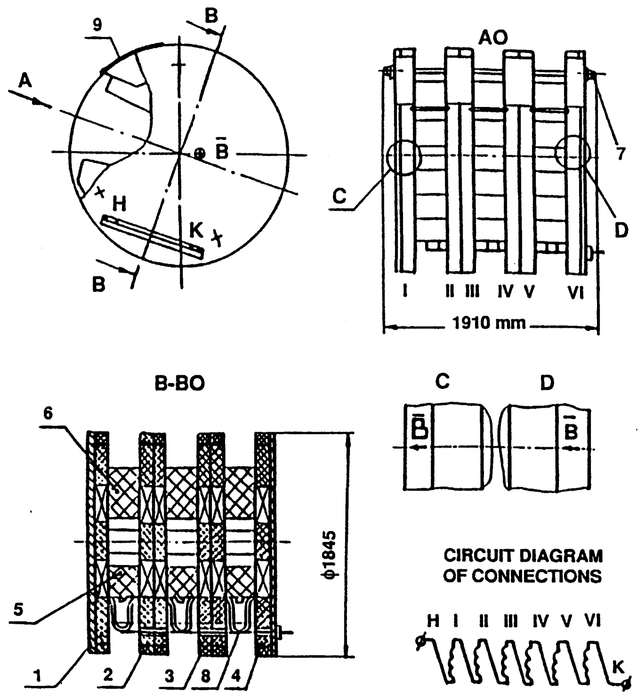

Fig. 3 **Pamir-3U magnet system.**

test run is less than 100°C, and the magnet cooldown time for the next test is less than 24 h.

The IES, which is based on the use of a battery bank, is used to provide the electrical energy necessary for the initial magnetic field over the MHD channel working volume. The system includes a current source, charger, switching, protection and interlock devices, and transducers and measuring instrumentation.

The CMMRS includes the computer for control and recording of the test parameters, the ignition unit used for plasma generator initiation, the control board, the primary electric power supply system, and the connecting cables and fiber-optic lines. The number of channels for measurement and recording is 16, which includes six electrical current measurements, four voltage measurements, four pressure measurements, and two spare channels.

System Operation

The MHD generators are connected in a series/parallel arrangement. During the initial stage of self-excitation, all three of the MHD generator channels supply power to the electromagnet. During nominal steady-state operating conditions, all three MHD channels operate in the circuit with the electromagnet, but two of them, connected in parallel circuits, also supply power to the load. Figure 4 shows a circuit diagram of the power unit, load circuit, initial excitation system, and the magnet circuit. The detailed description of the Pamir-3U pulsed portable MHD power system and its parameters has been presented in Ref. 1.

The MHD power system operates in the following manner. For the initial state of the MHD power system, all components and subsystems are in the ready mode and available for service. At the very beginning of the operating process, the thyristor switches, VS, are closed (switch Q is closed) by a command from the CMMRS that initiates a discharge from the IES for 1.5–1.6 s. Based on the analysis of the operation of the IES, approximately 0.5 s before the magnet current is expected to achieve 3 kA, the CMMRS generates a command to start the plasma generators. This process initiates the MHD channel electrode warm-up, which results in a decrease of the electrode voltage drop. When the magnet current reaches 3 kA, the CMMRS generates a command to the contactor, CM1, and

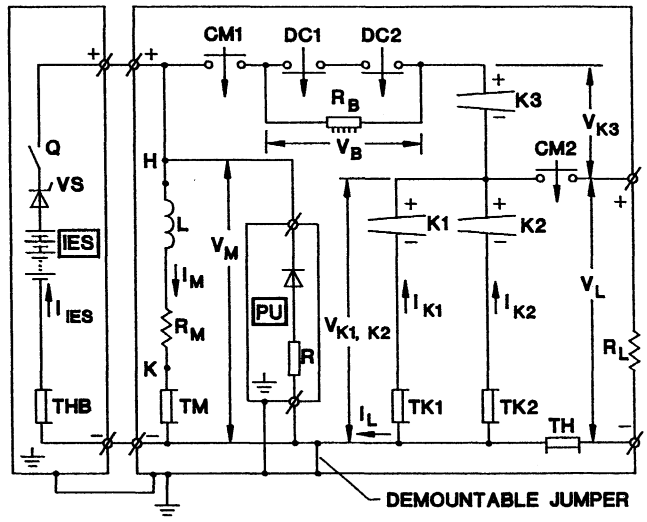

Fig. 4 **Pamir-3U MHD power system electrical circuit.**

connects the MHD generators to the magnet system, and the MHD power system self-excitation process begins. When the voltage of the MHD generators exceeds the voltage of the storage battery, the thyristor switches, VS, disconnect the IES from the magnet system automatically. Then, the switch Q is opened by a command from the CMMRS, and the IES current is switched off. For current limitation and in case of excess magnet current over the maximum allowable value, the disconnectors DC1 and DC2 switch a ballast resistor into the circuit by a command from the CMMRS. During the self-excitation process, when the magnet current increases up to the specified value, but not more than 16 kA, the CMMRS generates a command to connector CM2 that switches the load into the circuit. After the operation ends, the energy stored in the magnet system is dissipated in the resistances of the magnet system and of the protection unit, PU.

Preliminary Acceptance Test Program

The preliminary acceptance tests of the Pamir-3U pulsed portable MHD power system were performed in Russia during July and August of 1994 at a test site of the Geodesiya Research Center, Krasnoarmejsk, Russia. The tests were performed for the final adjustment and check-out of all subsystems of the MHD power system in the operational mode. In addition, the tests were used for a demonstration of the MHD power system output parameters and their agreement with the requirements of the technical assignment document.

To obtain test data for the MHD power system operation at loads of 15, 20, and 25 mΩ in one hot-fire test, two additional connectors were inserted into the load circuit. The generation of the commands for the connectors was provided by the CMMRS. Before the firing run, the initial load resistance of 25 mΩ was set. After operation of the contactors, the relevant section of the load was shunted, and the load resistance was sequentially reduced to values of 20 and 15 mΩ.

The ability to change the ballast resistance by external commutation is also available. The duration of time delays for the control command signal may also be adjusted. These adjustments were performed during the process of the power system preparation for the firing run, and they depend on the operational mode and on the predicted plasma generator parameters.

Two types of the plasma generators were used for acceptance tests. Both types are described in Table 2. Technical data and operating parameters of the MHD channels, plasma generators, and propellant charges used for the preliminary acceptance tests conducted in Russia of the Pamir-3U MHD system are listed in Table 3.

The preliminary acceptance test program included five tests. During the test program, the three test objectives, maximum

Table 2 Parameters of plasma generators

Plasma generator type	Propellant[a] type	Chamber[b] pressure, atm	Pressure dependence on time	Operation time, s
GP-77	BP-10F	29–51	Approximately constant	7–12
	SPK-10M	25–45	——	8–13
GP-86	BP-10F	25–51	Rising	4–6
	SPK-14S	20–45	~1.3–1.5 times the initial value	4.5–6.5

[a]BP-10F-plasma-generating propellant with ~10% cesium nitrate; SPK-10M, SPK-14S-plasma-generating propellants with ~10% potassium nitrate.
[b]Chamber pressure for the range of the propellant grain temperatures of 5–35°C.

Table 3 Equipment used and operating conditions for the preliminary acceptance tests

Test no.	Plasma generator				Operating time, s	MHD[b] channel	Ballast resistor, mΩ	Load resistor, mΩ
	Type	Propellant type[a]	T, °C	P_{av}, atm				
1	GP-86	OI-304	20	——	2.6	1, 2, 3	20	15
2	GP-86	OI-304	20	28–39	5.6	1R1, 2R1, 3R1	10[c]	25, 20, 15
3	GP-86	OI-304	20	36–50	5.1	4, 7, 8	20	25, 20, 15
4	GP-77	OI-72	20	39, 41, 40	9.0	4R1, 7R1, 8R1	20	20
5	GP-77	OI-72	35	46, 46.8, 46	8.3	5, 6, 9	24	16

[a]OI-304, 6-s duration operation.
[b]OI-72, nominal 10-s duration operation.
[c]Ballast resistance was connected before the test was started.

Table 4 Summary of the preliminary acceptance test results[a]

Test no.	Current pulse duration, s	Load resistance, mΩ	Average electrical output power,[b] MW	Average magnet current, kA	Average plasma generator pressure, atm	Plasma generator duration, s
1	2.35	15	11.0	15.8	——	5.5
2	2.43	25	10.8	17.0	33.5	5.6
		20	11.7	16.5		
		15	12.1	16.5		
3	3.15	25	12.8 (11.9)	15.8	43.0	5.07
		20	14.6 (12.6)	16.6		
		15	15 (13.6)	16.6		
4	7.13	20	12.9 (11.4)	14.1	41.0	9.01
5	6.36	16	15.1 (14.0)	14.0	46.3	8.3

[a]Conducted during July and August 1994.
[b]The power is based on V_L^2/R_L. The values in parenthesis are based on $V_L I_L$.

power mode, nominal power mode, and maximum load pulse duration, were demonstrated along with load switching during a test run. Table 3 lists the preassigned data for each test.

The operating parameters of the MHD power system obtained in the acceptance tests are listed in Table 4. The values of parameters given in the tables, except where noted, are the maximal values obtained in the firing runs. Table 5 provides the values for various operating parameters for preliminary acceptance test no. 3, which was a nominal power mode, load-switching test. In this test, an operation duration of just over 3 s was achieved, which provided approximately 1 s of operation at each load resistance. An electrical power output of 12–15 MW was achieved for the various operating conditions during the test run. The Pamir-3U power system load voltage and current are shown in Fig. 5.

Table 6 lists the values for the various operating parameters for preliminary acceptance test no. 5. In this test, the maximum power levels were achieved and proper operation of the system was demonstrated. Figure 6 shows a plot of some of the data from this test. Shown in the figures are the electrical load current and voltage and the magnet current as a function of time. Reference 1 contains a complete presentation of each of the tests conducted during the preliminary acceptance test program.

Analysis of the Preliminary Acceptance Test Results

The purpose of the preliminary acceptance tests was to provide a verification that the Pamir-3U MHD power system could achieve the performance specifications and operate in the various power-producing modes as designed. These tests were conducted in Russia before the system was shipped to the U.S., so that if any equipment modifications or adjustments were necessary, these changes could be performed before shipment was made. After performing the preliminary acceptance test program, no modifications or adjustments were required before shipment to the U.S.

The MHD power system control and recording of the test parameters during the first three hot-fire tests were performed with a CMMRS. The reserve CMMRS used light tracing oscilloscopes with an accuracy of 5%. In addition, the most important parameters were recorded by a Hewlett–Packard digital recording system with a random error of measurement of 0.2%. For preliminary acceptance tests no. 4 and 5, the standard CMMRS was used. The test parameters were recorded using a multichannel digital voltmeter. The standard CMMRS measurement accuracy is as follows: the load voltage = 1%; plasma generator pressure = 3%; and other electric measurements = 3%.

Table 5 Pamir-3U variable load preliminary acceptance test results

	Value for load resistance, R_L			
Parameter, Fig. 4	25 mΩ	20 mΩ	15 mΩ	Calculated/measured
Load voltage, V_L, V	565	540	475	M[a]
Ballast resistance voltage, V_B, V	296	318	318	C[b]
Magnet voltage, V_M, V	964	962	932	C
K3 channel voltage, V_{K3}, V	695	740	775	C
K2 channel voltage, V_{K2}, V	565	540	475	M
K1 channel voltage, V_{K1}, V	565	540	475	M
Load current, I_L, kA	21.0	23.4	28.7	M
K1 channel current, I_{K1}, kA	16.4	18.5	19.5	M
K2 channel current, I_{K2}, kA	16.4	18.5	19.5	M
Magnet current, I_M, kA	15.8	16.6	16.6	M
Initial excitation current, I_{IES}, kA	2.46	2.46	2.46	M
PG1 pressure, P_1, atm	36–38	——	49–50	M
PG2 pressure, P_2, atm	36–38	——	49–50	M
PG3 pressure, P_3, atm	36–38	——	49–50	M
Load power, $P_L = V_L^2/R_L$, MW_e	12.8	14.6	15.0	C[a]
Load power, $P_L = V_L I_L$, MW_e	11.9	12.6	13.6	C[a]
Excitation time, t_E, s	1.18	1.18	1.18	M
Total pulse duration in the load, t_L, s	3.15	3.15	3.15	M
Total PG burning duration, t_{PG}, s	5.07	5.07	5.07	M
Test conditions:				
Fuel type = BP-10F				
Charge type = OI-304				
Fuel temperature = 20°C				
Ballast resistance = 20 mΩ				

[a]Without accounting for the load resistance increase caused by heating.
[b]Without accounting for the ballast resistance increase caused by heating.

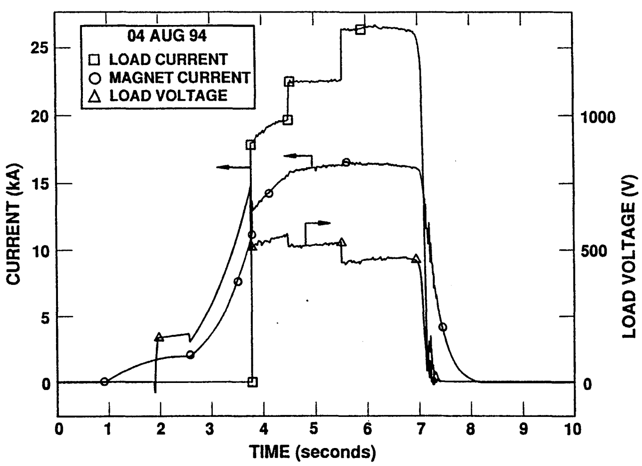

Fig. 5 Performance results from the variable load preliminary acceptance test.

Table 6 Pamir-3U maximum power preliminary acceptance test results

Parameter, Fig. 4	Value	Calculated/measured
Load resistance, R_L	16 mΩ	M[a]
Load voltage, V_L	492 V	M
Ballast resistance voltage, V_B	336 V	C[b]
Magnet voltage, V_M	998 V	M
K3 channel voltage, V_{K3}	830 V	C
K2 channel voltage, V_{K2}	504 V	M
K1 channel voltage, V_{K1}	504 V	M
Load current, I_L	28.5 kA	M
K1 channel current, I_{K1}	20.8 kA	M
K2 channel current, I_{K2}	21.4 kA	M
Magnet current, I_M	14.0 kA	M
Initial excitation current, I_{IES}	2.6 kA	M
PG1 pressure, P_1	46 atm	M
PG2 pressure, P_2	46.8 atm	M
PG3 pressure, P_3	46 atm	M
Load power, $P_L = (V_L^2/R_L)$	15.1 MW_e	C
Load power, $P_L = (V_L I_L)$	14.0 MW_e	C
Excitation time, t_E	1.395 s	M
Pulse duration in the load, t_L	6.36 s	M
PG burning duration, t_{PG}	8.3 s	M
Test condition:		
Fuel type = BP-10F		
Charge type = OI-72		
Fuel temperature = 35°C		
Ballast resistance = 24 mΩ		

[a]Without accounting for the load resistance increase caused by heating.
[b]Without accounting for the ballast resistance increase caused by heating.

The acceptance tests in Russia were conducted using plasma charges whose rated service life had been exceeded. Thus, the prediction of the operating parameters of the plasma charge combustion products was very difficult. Because of this circumstance, the initial test preparation posed some uncertainties. In particular, the selection of the timing of the connection of the load and the ballast resistance to the MHD power system circuit, as well as the ballast resistance value, presented some difficulties.

In test no. 1, the limiting value of magnet current of 20 kA was reached. The magnet current time dependence shows that even before the load and the ballast resistance connection, the magnet current began to stabilize near the level reached. Another anomaly of the first experiment was a premature operation of the dummy load commutators before the planned connection to the channels. Thus, the dummy load resistance value did not change and was equal to 15 mΩ during the entire run.

For test no. 2, the ballast resistance was connected to the magnet circuit from the very beginning. Thus, the self-excitation process was prolonged by artificial means. The dummy load was commutated in this experiment, as well as in the third one, and its value was equal to 25, 20, and 15 mΩ. The load current step change corresponds to the recommutation of a dummy load from 25 to 15 mΩ. At these load resistances the maximum output power values of 10.8, 11.7, and 12.1 MW_e, respectively, were reached.

The third test was performed using the standard BP-10F propellant. The facility operated in the standard mode. The maximum output power reached was equal to 12.8/11.9, 14.6/12.6, and 15/13.6 MW_e, corresponding to load resistances 25, 20, and 15 mΩ, respectively.

In the fourth test, the dummy load value was not changed. Its nominal value was set equal to 20 mΩ. The current pulse

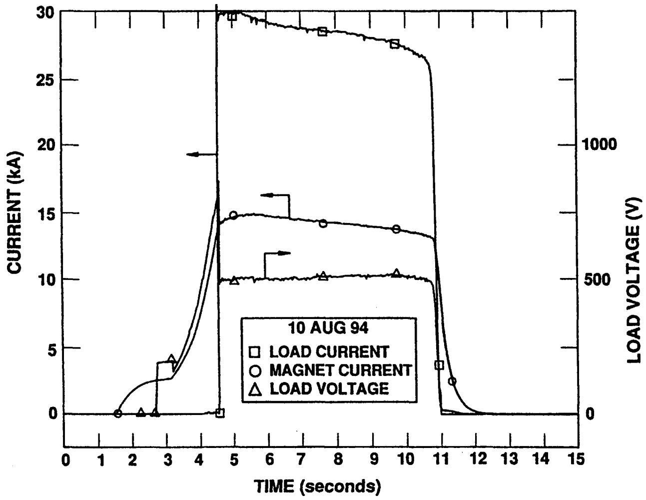

Fig. 6 Performance results from the maximum power preliminary acceptance test.

duration in the load was 7.25 s. The maximum output power in the load was equal to 12.9/11.4 MW_e. Although the load pulse duration obtained was less than that specified by the design requirements, these test results permitted certain conclusions to be made. For fuel lots with similar burning rates operating at a plasma charge conditioning temperature of 0°C with a nozzle throat section area of 80 cm^2, the extended plasma generator operation time will be about 10 s, and the load pulse duration will be about 8.5 s, which matches the design requirements. This conclusion was later confirmed by the results of the acceptance tests conducted in the U.S.

In the fifth preliminary acceptance test, the plasma generator pressure was less than predicted: 46 atm vs 56 atm. The effect may be explained by the fact that the process of thermally conditioning the charges wasn't properly conducted. The time from the removal of the charges from the thermal conditioning facility until hot-firing exceeded the 3-h time specification. Thus, the effective thermal conditioning temperature may have differed from the 35°C that was specified. In comparing the test no. 5 results with previous data where the thermal conditioning temperature was known, the performance results from this test could be interpreted to indicate that the effective thermal conditioning temperature was closer to 20°C.

The self-excitation process was extended and interrupted by the CMMRS. For redundancy, the CMMRS has an algorithm for issuing the command for *CM*2 operation, not only after reaching the specified current value in magnet system, but also after reaching the specified time of excitation process. Therefore, the magnet current value was equal to 14.4 kA compared to the 16 kA that was calculated. Nevertheless, the maximum output power reached in this experiment was as high as 15.1/14 MW_e. The pulse duration was equal to 6.36 s.

The results achieved during the Preliminary Acceptance Test Program conducted in Russia demonstrated that the performance objectives of the Pamir-3U MHD power system could be achieved. The facility was operated over the full range of specific load resistances, power-production modes, and facility operating schemes. Satisfactory test results were obtained for the test objectives. A maximum peak power of 15.1 MW_e and a maximum average power of 14.4 MW_e were obtained.

During the acceptance test program, all elements of the Pamir-3U facility performed as expected. Except for a few minor anomalies that were easily corrected, the entire test operation proceeded without any flaws or test delays caused by the equipment. All Pamir-3U MHD power system and facility components were undamaged during the testing and were ready for the subsequent tests to be performed. All consumable items performed according to their specifications and lifetime requirements. The MHD channels and plasma generator cases are considered consumables, and each component was only used for three tests. The overall results of the test program demonstrated that the Pamir-3U could perform according to specification, that a test rate of three tests per week can be achieved, and that maintenance and supporting operations can be adequately performed during the nontest periods.

Acceptance Test Program

The acceptance tests of the Pamir-3U MHD power system were performed at the Aerojet test facilities, Sacramento, California, during February 1995. The tests were performed to demonstrate the capability of the MHD system to achieve the requirements of the technical assignment document and to provide confirmation of the system's operability and reliability.

The GP77 plasma generator is designed for operation as a part of the MHD system. Technical data for the plasma generator are given next: combustion products mass flow = 18.5 to 26.0 kg/s, operation time = 7.4 to 10.5 s, plasma generator pressure = 34 to 52 atm, time from grain ignition to achievement of operating conditions = <0.1 s, plasma-generating propellant mass = 200 kg, and charge temperature operating range = 0 to 40°C. Technical data and operating parameters of the MHD generator channels, plasma generators, and propellant charges used for the Pamir-3U MHD facility acceptance tests in the U.S. are listed in Table 7. In addition, the firing conditions of the plasma generators are also included in the table.

The acceptance test program included eight tests. The ninth and tenth tests were considered as a reserve. During this time, the three test objectives, 1) maximum power mode, 2) nominal power mode, and 3) maximum load pulse duration mode, were demonstrated. Table 7 lists preassigned data for each test.

A summary of the results from each of the eight tests that were performed is provided in Table 8. Table 9 provides the values for various operating parameters for a long-duration test. In this test, an operation duration of approximately 9.5 s was achieved with an output power level greater than 10 MW_e. For this test, the electrical power delivered to the load was nearly constant over the entire duration of the test. This result along with the plasma generator pressures and the MHD channel, load, and magnet currents and voltages are shown in Fig. 7.

Table 10 lists the values for the operating parameters for a maximum power test. In this test, the maximum power levels were achieved, and proper operation of the system was demonstrated. Figure 8 shows the plots of the test data for this test. The plots show, from top to bottom, the magnet and load voltages; the center channel (magnet), side channels, and load currents; the plasma generator pressures; and the power generated as function of time. Reference 1 contains a discussion of each of the tests conducted during the program.

Analysis of the Test Results

The maximum power mode was demonstrated in test nos. 1, 2, 4, and 8. The BP-10F plasma charges from the 6-94-L batch and new MHD channel hardware and plasma generator cases were used in these tests. In test no. 1, an average output power of 12.8 MW_e, a peak output power of 13.6 MW_e, and a load current pulse duration of 6.72 s were obtained with an initial load resistance of 20 mΩ.

To achieve a greater output power in test no. 2, the magnetic field was increased by decreasing the ballast resistance and increasing the magnet switching current, which is the magnet current at the time that the load and the ballast resistance were switched into the circuit.

As a result, an average generator output power of 13.4 MW_e, a maximum generator output power of 14.0 MW_e, and a load current pulse duration of 6.48 s were achieved in test no. 2 at the same load resistance that was used for test no. 1. The analysis of the current and voltage curves showed that boundary-layer separation appeared to have occurred in generator channel 3, which supplies the magnet current, when the mag-

Table 7 Pamir-3U equipment used and operating conditions

Test no.	GP-77 Case no.	A^*, cm^2	OI-72 Batch	T °C	Plasma generator P_{av}, atm	Plasma generator P_{max}, atm	Oper. time, s	DA, %	MHD channel	Ballast resist, mΩ	Load resist, mΩ	Switching current, kA
1	9401	73.48	6-94-L	35	44.7	47.1	8.5	3.0	1	25	20	16
	9402	73.48	6-94-L	35	45.3	48.8	8.5	2.3	2			
	9403	73.48	6-94-L	35	46.3	49.0	8.5	2.6	3			
2	9404	73.48	6-94-L	35	45.1	48.4	8.5	3.0	4	16	20	18
	9405	73.48	6-94-L	35	46.3	48.7	8.5	3.5	5			
	9406	73.48	6-94-L	35	47.5	49.4	8.4	1.7	6			
3	9403R1	73.48	5-94-L	35	44.6	46.8	8.6	2.8	4R1	18	15	14.5
	9402R1	73.48	5-94-L	35	46.6	48.6	8.5	2.8	5R1			
	9401R1	75.69	5-94-L	35	44.2	46.5	8.6	1.0	6R1			
4	9409	73.48	6-94-L	42	45.6	48.9	8.3	2.6	7	8	15	18
	9407	73.48	6-94-L	42	48.1	50.8	8.3	4.7	8			
	9408	73.48	6-94-L	42	49.3	51.8	8.3	2.7	9			
5	9404R1	80.17	5-94-L	0	31.7	33.0	10.4	0.99	4R2	18	15	12
	9405R1	80.17	5-94-L	0	33.8	35.0	10.4	0.92	5R2			
	9406R1	80.17	5-94-L	0	34.3	35.7	10.4	1.1	6R2			
6	9403R2	75.69	5-94-L	20	37.8	40.3	9.4	1.0	1R1	20	25	14.5
	9401R2	74.7	5-94-L	20	40.1	41.9	9.3	1.7	2R1			
	9402R2	75.38	5-94-L	20	40.0	42.3	9.4	1.7	3R1			
7	9408R1	75.43	5-94-L	0	34.0	34.6	10.2	0.97	7R1	12	15	+
	9407R1	77.58	5-94-L	0	34.0	37.9	10.1	0.79	8R1			
	9409R1	75.39	5-94-L	0	34.9	37.5	10.1	1.38	9R1			
8	9411	73.48	6-94-L	42	46.9	51.3	8.1	3.1	10	14	15	14.5
	9410	73.48	6-94-L	42	46.7	50.2	8.1	2.3	11			
	9412	73.48	6-94-L	42	46.3	49.6	8.1	2.0	12			

Note: + = The load was switched on at the very beginning of the run. Oper. Time = time of the plasma generator operation (time of the OI-72 charge burning)

Table 8 Summary of the U.S. acceptance test results[a]

Test no.	Current pulse length, s	Total load energy, MJ	Average output power, MW_e	Maximum output power, MW_e	Average magnet current, kA	Average plasma generator pressure, atm	Plasma generator duration, s
1	6.72	86.0	12.8	13.6	14.9	45.8	8.28
2	6.48	86.8	13.4	14.0	16.1	46.9	8.26
3	6.70	86.8	13.0	13.3	14.7	45.4	8.32
4	6.20	85.6	13.8	14.9	16.7	48.7	7.92
5	8.96	92.3	10.3	10.6	12.6	34.1	10.32
6	7.48	77.8	10.4	10.9	14.1	40.1	9.27
7	10.4	87.8	10.3[b]	11.0	13.9	34.3	10.20
8	6.43	89.9	14.0	14.9	15.5	46.6	7.97

[a]Conducted during February and March of 1995.
[b]Averaging over the quasi-steady-state portion of the current pulse.

Table 9 Pamir-3U maximum duration acceptance test results

Parameter, Fig. 4	Peak	Average	Range	Calculated/measured
Load resistance, R_L, mΩ	17.9	16.7	15.4–17.9	C/M
Magnet resistance, R_M, mΩ	65.3	60.6	56–65.3	C
Load voltage, V_L, V	433	416	363–433	M
Ballast resistance voltage, V_B, V	235	226	194–235	C
Magnet voltage, V_M, V	1257	812	0–1257/784–840	M
K3 channel voltage, V_{K3}, V	626	622	0–609/617–626	M
K2 channel voltage, V_{K2}, V	648	426	0–648/375–443	M
K1 channel voltage, V_{K1}, V	648	426	0–648/375–443	M
Load, current, I_L, kA	25.0	24.0	22.6–25.0	M
K1 channel current, I_{K1}, kA	19.4	18.5	17.4–19.4	M
K2 channel current, I_{K2}, kA	19.2	18.5	17.4–19.2	M
Magnet current, I_M, kA	13.1	12.6	0–13.1	M
PG1 pressure, P_1, atm	32.9	31.7	26.6–32.9	M
PG2 pressure, P_2, atm	35.2	33.8	26.9–35.2	M
PG3 pressure, P_3, atm	36.5	34.3	28.6–36.5	M
Load Power, P_L, MW	10.4	10.0	8.7–10.4	M
Test conditions:				
Fuel type = BP-10F				
Charge type = OI-72, 5-94-L				
Final I_{IES} current = 2.7 kA				
Fuel temperature = 0°C				
Ballast resistance = 19 mΩ				

net current reached 16.2 kA. This phenomenon was exhibited by a magnet voltage decrease. This behavior did not occur in generator channels 1 and 2, which were supplying the load. Thus, output power in the load was rather stable. The boundary-layer separation phenomenon in generator channel 3 primarily impacts the current dynamics in the magnet system, and it can be eliminated by a variation of the ballast resistance.

The analysis of the first two test results showed that a further increase in output power would only be possible by increasing the pressure in the plasma generators or by an increase in the combustion product mass flow rate. Under real test conditions,

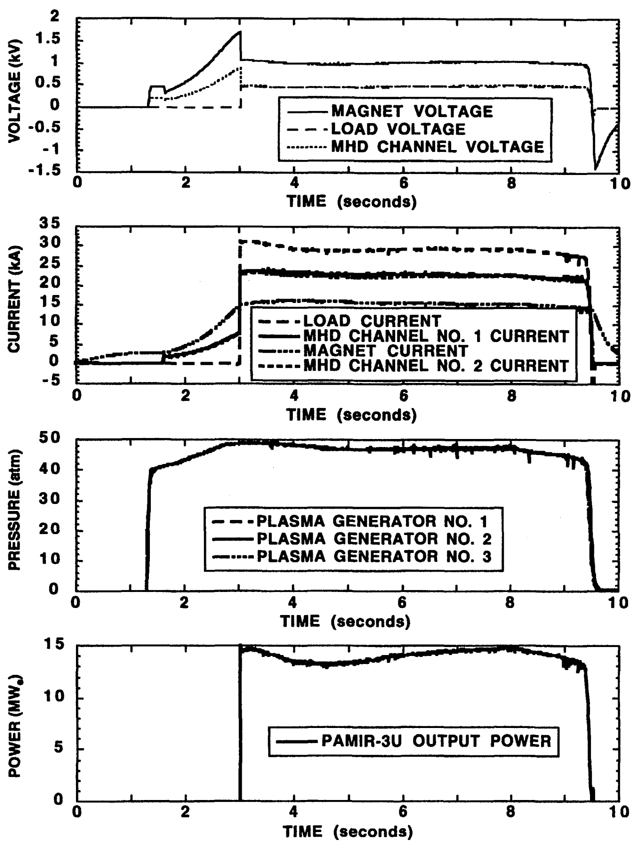

Fig. 7 Performance results from the maximum duration acceptance test.

this goal could be achieved only by an increase in the plasma-charge thermal conditioning temperature.

Thus, the thermal conditioning temperature for test no. 4 was increased to +42°C. Because this temperature is above the upper limit of +35°C given in the technical specification developed by the manufacturer (Soyuz), special approval was requested and received for a thermal conditioning temperature in test no. 4 of 40 ± 2°C. Because the thermal conditioning facility was capable of precise temperature control well within this limit, the temperature could be set to the maximum without exceeding the temperature limit. In this test at a load resistance value of 15 mΩ, an average channel output power of 13.8 MW_e, a peak channel output power of 14.9 MW_e, and a load current pulse duration of 6.2 s were obtained.

Analysis of the current and voltage curves revealed the beginning of boundary-layer separation phenomenon in generator channel 3 at a magnet current of 16.9 kA. A load power decrease within the time interval from 3.2 to 5 s appears to be explained by the onset of this phenomenon in generator channels 1 and 2, which are providing current to the load. This appears to be the case during test no. 4 because these two generator channels were loaded by a lower resistance than in previous tests and their currents were correspondingly more: 15 mΩ compared with 20 mΩ in test no. 2, and 23.8 kA compared with 22.0 kA, respectively.

On the basis of these results, the last test in the maximum power mode (test no. 8) was carried out at a lower magnetic field to avoid the boundary-layer separation. In this test, an average output power of 14.0 MW_e, a maximum output power of 14.9 MW_e, and a load current pulse duration of 6.43 s were achieved under the same test conditions as those in the test no. 4: a thermal conditioning temperature of +42°C and a load resistance of 15 mΩ. Again, special approval was received in advance from Soyuz for the higher thermal conditioning temperature of 40 ± 2°C. However, the increase in the average output power cannot be expected to be substantial. This is probably the result of the fact that boundary-layer separation occurred in generator channels 1 and 2 during test no. 4, but had no drastic effects. In general, the effect of boundary-layer separation on the Pamir-3U output performance requires further study.

The nominal power mode was demonstrated in tests no. 3 and 6 using the refurbished MHD channels and plasma generator cases and the 5-94-L charge batch. The thermal conditioning temperature for the plasma generators for test no. 3 was +35°C. Under these conditions, an average generator out-

Table 10 Pamir-3U maximum power acceptance test results

Parameter, Fig. 4	Peak	Average	Range	Calculated/measured
Load resistance, R_L, mΩ	18	16.5	15–18	C
Magnet resistance, R_M, mΩ	65.3	60.6	56–65.3	C
Load voltage, V_L, V	499	472	448–499	M
Ballast resistance voltage, V_B, V	231	217	203–231	C
Magnet voltage, V_M, V	1700	1015	0–1700/956–1064	M
K3 channel voltage, V_{K3}, V	812	764	0–812/722–806	C
K2 channel voltage, V_{K2}, V	885	481	0–885/457–507	M
K1 channel voltage, V_{K1}, V	885	481	0–885/457–507	M
Load, current, I_L, kA	30.0	29.1	27.2–29.97	M
K1 channel current, I_{K1}, kA	23.7	22.8	21.3–23.7	M
K2 channel current, I_{K2}, kA	23.2	21.8	20.8–23.2	M
Magnet current, I_M, kA	16.5	15.5	14.48–16.5	M
PG1 pressure, P_1, atm	51.3	46.9	42.5–51.3	M
PG2 pressure, P_2, atm	50.2	46.7	41.7–50.2	M
PG3 pressure, P_3, atm	49.6	46.3	41.7–49.6	M
Load power, P_L, MW	14.9	14.0	12.5–14.91	C
Test conditions:				
Fuel type = BP-10F				
Charge type = OI-72, 6-94-L				
Final I_{IES} current = 2.7 kA				
Fuel temperature = +42°C				
Ballast resistance = 14 mΩ				

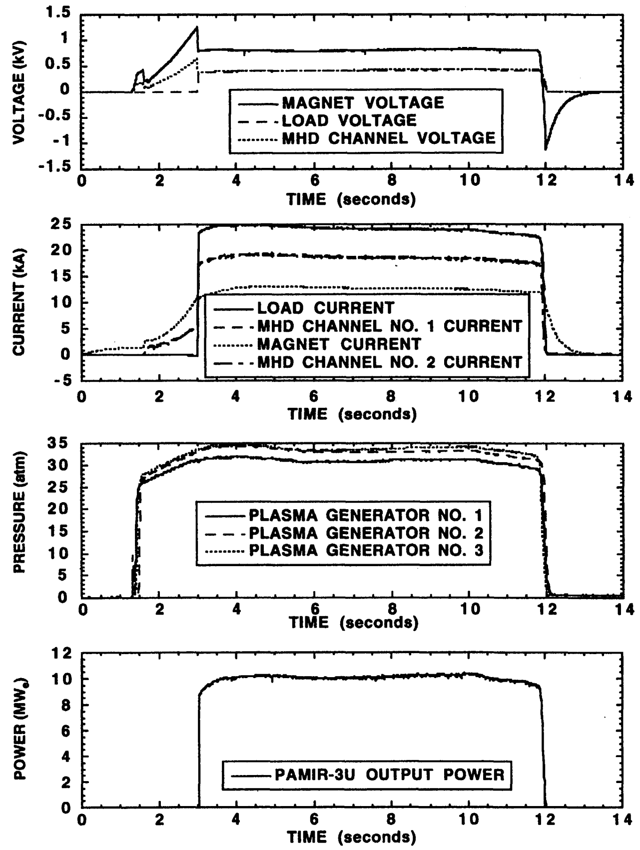

Fig. 8 Performance results from the maximum power accetpance test.

put power of 13.0 MW_e, a peak output power of 13.3 MW_e, and a load current pulse duration of 6.7 s were obtained with a load resistance of 15 mΩ.

The main parameters for test no. 6 were as follows: thermal conditioning temperature of +20°C, load resistance of 20 mΩ, average generator output power of 10.4 MW_e, peak generator output power of 10.9 MW_e, and load current pulse duration of 7.48 s. Estimates showed that the average power would be about 12.5 MW_e at a thermal conditioning temperature of +20°C, when using charges from the 6-94-L batch. Thus, the overall range of the average power in the nominal operation mode appeared to be 10–13 MW_e for the charge batches tested.

The maximum duration mode was demonstrated in two tests: tests no. 5 and 7 using a thermal conditioning of 0°C and plasma charges from batch 5-94-L in both tests. For test no. 5, the nozzle throat area and the inserts in the generator channel acceleration zone were bored out to 80 cm^2. An average channel output power of 10.3 MW_e, a peak generator output power of 10.6 MW_e, and a load current pulse duration of 8.96 s were obtained with a load resistance of 15 mΩ. In this test, a maximum energy release in the load of 92 MJ was achieved. The energy was based on the total integrated net power produced by the system during the time that the electrical load resistance was connected to the MHD power system.

In test no. 7, another approach to the maximum duration mode, which is the use of the plasma generator without boring the nozzle throat area, was undertaken. In this case, the load and ballast resistances were switched into the electrical circuit from the very beginning of the run, rather than at the end of the self-excitation stage. As a result, a load current pulse duration of 10.4 s and a peak output power 11 MW_e were achieved. The average output power within the quasi-steady state portion (6.75 s) of the load current was equal to 10.3 MW_e.

Conclusions

The results achieved during the acceptance test program demonstrated that the performance objectives of the Pamir-3U MHD power system could be achieved. The facility was operated over the full range of specified load resistances, power-production modes, and facility operating schemes. Satisfactory test results were obtained for these test objectives.

A maximum peak power of 14.9 MW_e and a maximum average power of 14.0 MW_e were obtained. While these power levels were slightly below the 15-MW_e goal, these levels were achieved with plasma charges that were slightly below average in performance. Thus, any subsequent tests performed with plasma charges with average or above average performance would be expected to easily achieve the 15-MW_e net output power objective.[1]

The general relationship between temperature conditioning of the plasma charges, burn rate, stagnation pressure, and output produced by the Pamir-3U system was confirmed. Because of the limited amount of test resources available, specific comparisons at identical operating points with different combustion pressures (thermal conditioning temperatures) were not performed. However, the general trend of increased power output for increased operating pressures was consistent with the results that have been obtained previously.

During the acceptance test program, all elements of the Pamir-3U facility performed as expected. Except for a few minor anomalies, the entire test operation proceeded without any flaws or test delays caused by the equipment. All Pamir-3U MHD power system and facility components were undamaged during the testing and are ready for subsequent tests. All consumable items performed according to their specifications and lifetime requirements.

The test program demonstrated that the Pamir-3U performed according to specification, that a test rate of three hot-fire tests per week can be achieved, and that maintenance and supporting operations can be adequately performed during the nontest periods. No damage was incurred by any of the system and subsystem components during the test program. The hardware is ready for subsequent transportable power requirements to support testing at a variety of locations.

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