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TECHNICAL REPORT NO. LWL-CR-07M67

WATERJET PROPULSION KIT

FOR

M-113 ARMORED PERSONNEL VEHICLE

Final Report
Contract No. DAAD05-67-C-0625

By
H. C. Schlappi
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Sacramento, California

April 1968

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U. S. ARMY LIMITED WAR LABORATORY

Aberdeen Proving Ground, Maryland 21005

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ABSTRACT

This program consisted of the design and installation of an Experimental Waterjet Propulsion Kit on a Government-owned M-113 Vehicle, Serial No. F13127,USA12CK01. Two Aerojet-General Type A Waterjet pumps were equipped with special inlets, discharge nozzles, and maneuvering gates designed to provide optimum propulsion of the vehicle. The waterjets were driven from the vehicle transfer case by use of a special power transmission system. The complete water propulsion system which is suitable for field retrofit on existing vehicles, was installed and tested prior to delivery at Aberdeen Proving Ground, Maryland, where further evaluation is planned.

FOREWORD

This is the Final Report submitted under Contract DAAD05-67-C-0625 on the Experimental Waterjet Propulsion Kit for the M-113 Armored Personnel Carrier. In accordance with Exhibit "B" of the Contract, this report presents a summary of the design, test, and evaluation work performed during the contract. A brief description and preliminary specifications for a production waterjet propulsion kit for the vehicle are presented.

Distribution of this report is limited to the Aerojet-General Corporation and to the United States Army. No copies shall be distributed to contractors or other Government agencies without the specific approval of the sponsoring agency.

The program is sponsored and directed by the Limited Warfare Laboratory, Aberdeen Proving Ground, Maryland, and is under the technical cognizance of Mr. Robert McGowan, Army Program Manager.

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I. INTRODUCTION

A. GENERAL

The M-113 Armored Personnel Vehicle, currently in production and widely deployed by the Army, is a lightweight, air droppable, tracked amphibian used primarily for the transporting of troops. The vehicle has limited water mobility, since propulsion is provided by the tracks and track braking is employed for steering.

Aerojet-General Corporation was awarded Contract DAAD05-67-C-0625 by the Department of the Army, Limited Warfare Laboratory, to design and install an experimental waterjet propulsion kit suitable for a test program, on an M-113 vehicle. The purpose of the program was to determine the feasibility of retrofitting vehicles now in the field with a water propulsion system capable of providing significantly better water mobility. Preliminary characteristics and performance objectives for the system were as follows:

Width	Vehicle width unchanged
Angle of Departure	Unchanged
Static Thrust	3150 lb total both pumps
Power Absorption	150 bhp total both pumps
Reverse Thrust	2500 Δ total both pumps
Static Turning Moment	16,500 lb ft

The waterjet pump (impeller and stator) proposed for use on the M-113 vehicle is a proprietary design previously designed and demonstrated by Aerojet-General Corporation. Hence, design of the pump was not a contractual requirement; the pumps installed in the demonstration vehicle are owned by Aerojet-General and were loaned to the Government at no cost.

B. BACKGROUND

Most amphibious vehicles use tracks or tires for propulsion in water. Because of the simplicity of this means of propulsion, considerable effort has been expended in developing track and tire designs which will improve water performance; however, water speeds are low (typically 1 to 3 mph). In general, the vehicle changes required to provide higher water speeds with tracks or tires tend to degrade performance reliability or versatility in other areas.

Propellers have been tried on several vehicles with limited success. While a propeller drive system is simple and relatively inexpensive, serious limitations were experienced. On low-speed (under 10 mph) vehicles a large diameter propeller located in the free stream (underneath or on the side of the vehicle) is required to obtain propulsion significantly better than that provided by tracks or tires. Location of the propeller in these areas increases width or reduces ground clearance unless a retractable system is used. The propeller is highly susceptible to damage both on land and when operating in shallow water. A propeller rudder system is limited in its ability to provide high maneuverability at low speed, particularly in limited space with adverse current or weather conditions.

Waterjets have been used for water propulsion of low-speed vehicles with varying degrees of success. Like the propeller, a waterjet must use a large rotor to obtain optimum propulsion efficiency. However, unlike the propeller, a waterjet is not restricted to location in the free stream and the pumping unit can be placed within the vehicle or in an area where it is not subject to damage. On several vehicles less than optimum waterjet propulsion has resulted from use of a pump not suited for the application. In general, low flow rate pumps with excessive jet velocity have been employed. While having the advantage of small size, such pumps produce low thrust on low-speed vehicles and tend to de-emphasize the advantages of waterjet propulsion. The use of high flow rate, low head pumps is particularly important on high drag, low horsepower vehicles like the M-113 where optimum use of power is required.

Maneuverability provided by a waterjet system is far superior to that of a propeller. Unlike the propeller, a waterjet can direct high thrust in any direction at any speed by means of ducts and gates. Aerojet-General has demonstrated the advantages of high flow rate waterjets on two Army vehicles, both of which had previously tried other type waterjets or propellers in addition to the normal track or tire propulsion.

The M-113 vehicle currently uses tracks for water propulsion; thus, it has low speed and very poor maneuverability in water.

II. DESCRIPTION

A. GENERAL

The experimental waterjet propulsion kit installed on the M-113 vehicle by Aerojet-General Corporation is shown by Figure 1 and 2. The kit consists of two standard Aerojet Type A150D75 RH waterjet pumps equipped with special 90-degree discharge housings, driven by a power train from the vehicle transfer case power take-off (PTO). The power train uses four right-angle gearboxes, a hydraulic clutch and three interconnecting drive shafts with covers. Equipment installed in the crew's compartment for transmission of power to the waterjets is shown in Figures 3 and 4.

B. POWER TRANSMISSION

Power for driving the waterjet system is taken from the PTO on the transfer case. The power is transmitted to the dual waterjets mounted on the rear of the vehicle through a series of shrouded drive shafts, right angle gearboxes and a clutch. The PTO drives directly into the first gearbox through a flexible coupling. A hydraulically operated clutch mounted directly on the first gearbox transmits power to a second gearbox mounted on the roof of the vehicle as shown in Figure 5. The connecting drive shaft uses flexible couplings on both ends to eliminate misalignment problems. A second drive shaft, also utilizing flexible couplings, transmits power along the top of the vehicle to a third gearbox mounted on top of the right-hand waterjet. This gearbox, equipped with three shafts, drives the vertical pump shaft in the right-hand pump and also transmits power across the back of the vehicle to the fourth gearbox on top of the left waterjet (see Figure 6). All gearboxes utilize the same housings, shafts and gears, and are identical except that the third gearbox is equipped with a second pinion shaft. The housing assembly for the second pinion is interchangeable with the covers used on the other gearboxes.

C. WATERJET CLUTCH SYSTEM

A hydraulically actuated clutch mounted on the first gearbox in the power train is used to disengage the propulsion kit from the transfer case when not in use. Oil for lubrication and cooling of the clutch is taken from the engine oil distribution system. A metering valve in the feed line is used to reduce the pressure from 40 to 10 psi. Oil is returned to the oil pan of the engine by a line attached to the top of the clutch housing.

An auxiliary oil pump, also using oil from the engine oil system is mounted on the rear of the transfer case to provide oil at 250 psi for clutch actuation. This pump, mounted on the transfer case, is driven by a double groove pulley in contact with the V-belts driving the engine blower and generator as shown in Figure 4. High-pressure oil from the pump is routed to the waterjet clutch control valve located on the bulkhead in front of the operator. This two-position valve incorporates a relief valve for setting the system pressure at 250 psi. Placing the valve in the waterjet position (up) directs oil to the clutch, engaging the waterjets.

D. WATERJET

The waterjet pumps installed on the M-113 vehicle are high flow rate, low head axial flow units specifically designed to provide

provide maximum thrust on low-speed vehicles. A vertical pump shaft design was selected to place the inlet low in the water, reduce length and simplify the power transmission. The vertical impeller shaft is supported by grease-packed tapered roller bearings in a 90-degree elbow shaped housing. This housing, which forms the mail structural part of the waterjet, is vaned to provide efficient flow from the pump to the rectangular discharge nozzle. The rectangular shaped nozzle was used to permit use of a maneuvering gate for steering and reverse. For forward thrust, the gate is open as seen in Figure 1 and the water is discharged straight aft. Closing the gate uncovers tne reverse nozzle located on the side of the forward nozzle and the water is discharged forward alongside of the vehicle to provide reverse thrust. When placed in an intermediate position, the forward and reverse components cancel, providing a neutral thrust condition for normal turning. The lower end of the pump housing is fitted with a bell shaped inlet equipped with a conical debris screen and zinc anode for galvanic protection where operation in salt water is required. The inlet is bolted to the pump housing on the prototype. A production design would use a V-band clamp, to permit rapid removal for maintenance or cleaning of debris from the pump. The impeller and stator are readily removable. The pump impeller and stator used in the M-113 prototype waterjet is a design proprietary to Aerojet-General Corporation (on loan to the Government at no cost), hence design details are not given in this report. With the exception of a bronze impeller, 4130 pump shaft and the miscellaneous bolts, nuts and pins, aluminum is used exclusively in the waterjet to reduce weight and provide corrosion resistance.

E. HYDRAULIC CONTROL SYSTEM

Hydraulic power for operation of the maneuvering gates is obtained from the vehicle system provided for operating the ramp. A hydraulic valve, hooked in tandem with the valve for clutch actuation, is used to divert hydraulic power from the ramp system to the waterjet system. The maneuvering gates are individually operated by four-way, open-center hydraulic valves.

The vehicle hydraulic system is set at 1600 psi. A relief valve located in the bottom of the right steering valve is used to limit the pressure in the waterjet portion of the system to 1000 psi.

Copper tubing (0.375 in. OD) is used for lines located under the floor of the cargo space and in the operator's compartment. Flexible hose is used for all lines routed through the engine compartment and for connecting the gate hydraulic cylinders to the fittings on the rear of the vehicle.

F. WATERJET CONTROLS AND INSTRUMENTS

The waterjet system requires no additional instruments for operating in water. As previously described, the waterjet clutch utilizes oil from the engine lube system; hence, the oil temperature and pressure warning light for the engine also serve the clutch. The normal operating temperature of the clutch is the same as the engine oil temperature (approximately 275°F). Therefore, heat from the clutch housing and gearbox located in the crew's compartment should not be interpreted as a sign of system malfunction.

The waterjet propulsion system uses two controls located on the bulkhead in front of the driver as shown in Figure 10. The waterjet clutch control lever serves two functions. When placed in the down position marked RAMP, the vehicle's hydraulic system is connected to the ramp and the normal control for raising and lowering the ramp is effective. Placing the lever in the up position marked WATERJET connects the hydraulic system to the waterjet steering controls and simultaneously engages the waterjet clutch. The ramp can be lowered when the waterjet control lever is up; however, it cannot be raised unless the lever is placed in the down (RAMP) position.

The dual waterjet steering control levers located directly in front of the operator use the same control philosophy as the steering levers for land operation. The left lever controls the left waterjet and the right lever the right waterjet. Momentarily pushing both levers forward and downward produces forward thrust in both waterjets. When released, the levers return to neutral; however, the waterjet gates stay in the open forward thrust position. Pulling the levers back and upward closes the waterjet gates providing reverse thrust for backing the vehicle. A left turn is made by momentarily pulling back the left lever. To stop the turn the lever is pushed forward to again place the left control gate in the forward position. A right turn is made in a similar manner using the right steering control lever.

G. GENERAL SPECIFICATIONS

1. Waterjet

Pump rotor and stator. . . . . .Model A' 150-D-75RH

Rotor diameter. . . . . 15 in.

Pump design speed. . . . . .1140 rpm

Flow rate at design speed (each unit).11,100 gpm

Jet velocity. . . . . 30 ft/sec

Nozzle area (each unit). . . . . 122 sq.in.

Weight (each unit). . . . . 160 lb

Design HP (input to each unit). . . . . 75 bhp

Forward static thrust at design speed (total)*. . . . . 3000 lb

Reverse static thrust at design speed (total)*. . . . . 1300 lb

Pump efficiency at design speed. 75

2. <u>Power Transmission</u>

Gearbox ratio (input/output).	1.5
Gears.	Stock spiral bevel, hardened & lapped
Bearings.	Tapered roller (class IV)
Seals.	Lip type oil seals
System ratio (engine speed/pump speed). .	3.47
Drive shafts.	Tube type
Flexible couplings.	Gear type, 1¼ in. bore (grease packed & sealed)
Hydraulic clutch.	Twin disc, Model BC 605.5, 10 psi lube pressure, 250 psi actuation pressure
Total weight of components.	280 lb

III. DESIGN AND FABRICATION

A. DESIGN CONSIDERATIONS

The M-113 is a high-production, low-cost vehicle widely deployed in the field. Therefore, it was considered mandatory that the waterjet propulsion kit be designed in a manner to minimize cost and installation time, and that changes to the vehicle which would affect its basic mission be avoided. The vehicle is basically a box with tracks; hence, locating

* Predicted from tests concluded at 4500 ft altitude with 52 bhp input to each pump.

the waterjets on the sides or underneath the vehicle in a fixed position would violate the requirement that width and ground clearance not be affected. Retractable waterjets were considered impractical for field retrofit since it would be necessary to cut large holes in the armored sides, weakening the hull and reducing payload space in the vehicle.

Locating the waterjets externally on the rear of the vehicle was considered a practical location. Use of a pump with a vertical shaft has several advantages. It places the inlets low in the water for good suction performance, simplifies the problem of transmitting power, and minimizes the overall length of the vehicle with the propulsion system installed.

The vertical shaft arrangement places the discharge nozzle above the waterline. This produces slightly more thrust than if placed below the waterline where mixing losses are present without decreasing the vehicle departure angle.

The external location of the power drive train was selected to minimize vehicle modifications and to avoid reducing the internal cargo and crew space.

The requirement that the vehicle width not be increased restricted the diameter of the pump impeller to 15-in. A larger unit would either interfere with the ramp or project beyond the side of the vehicle. Fortunately, the 15-in.-dia was very close to the optimum size for maximum thrust at 6 mph and also permitted use of a pump design previously tested by Aerojet-General.

B. SYSTEM DESIGN AND FABRICATION

1. Waterjet

The waterjet pump was designed to utilize a 15-in.-dia Aerojet Model A150D75RH impeller and stator previously designed. Similar 18-in.-dia waterjet pumps were previously tested with excellent results on an Army vehicle. The major design effort involved the design of the discharge nozzle housing. Although optimum flow efficiency around the 90-degree turn from pump to nozzle requires more complex vanes than the one utilized, the design using only two turning vanes was selected because of reduced pattern costs and more rugged construction. The nozzle housing was designed to obtain a smooth area transition from the pump to the required nozzle area. The forward nozzle was designed to accept inserts for varying the operating point of the pump during test. This feature was felt necessary because of uncertainties regarding system hydraulic losses and power input at the pump shaft. Each waterjet was designed to absorb 75 bhp at 1140 rpm and produce 1575 lb of static thrust.

The maneuvering gate was designed to provide lateral rather than pure reverse thrust when in the partially open position. This feature has the advantage of not significantly reducing forward thrust when a slight turning force is applied.

The system as originally proposed used a side inlet rather than a bottom inlet. Use of this design on the M-113 would have required modification of the fender covering the track. This would weaken the fender and be difficult to accomplish in the field. The bottom inlet selected has lower losses, is in a protected location, and is inexpensive to fabricate.

The inlet bell, bearing housing, discharge nozzle, maneuvering gate, and seal housing were all cast from Al 356 heat treated to the T-6 condition. This material combines good castability and machinability with high strength and corrosion resistance. The stator was fabricated from aluminum casting and plate. The blades and outer ring were formed from Al 6160 and the hub was cast in Al 356. The cost of tooling for a one-piece casting was prohibitive for fabrication of the two experimental units. The impeller blades and hub were cast from manganese bronze having a yield strength of 90,000 psi. This excellent impeller material combines high strength and elongation with high corrosive resistance in salt water. The galvanic corrosion problem associated with the use of bronze and aluminum when used in salt water was solved by use of a zinc anode on the inlet grill. Unless continued operation in salt water is a requirement, the anode would be unnecessary.

2. Power Transmission

The power transmission system was designed to utilize high production stock gears, bearings, seals, couplings, and a new lightweight hydraulic clutch recently put on the market. Use of these components, which have established industrial ratings, greatly reduced the design analysis required and ensured the immediate availability of spare parts and production quantities if needed. The gear ratio selected for the gearboxes was dictated by the desire to use the same gears in all four boxes. Fortunately, a stock ratio of 2 to 3 resulted in the desired pump shaft speed of 1140 rpm. Analysis was restricted to the determination of gear tooth and bearing loads, stress analysis of shafts and keys, and critical speed calculations on the drive shafts. Gears, bearings, and couplings were selected on the basis of industrial torque speed and load ratings. The spiral bevel gears are hardened and lapped for quiet operation and are conservatively rated for 1000 hr of operation in the M-113 application. The tapered roller bearings are Class IV (industrial quality) normally used in nonprecision gearboxes and have a B-10 life in excess of 1000 hr under load at design power. All shafts with the exception of the drive shaft tubes are made of 4130 steel and have a minimum factor of safety of 2, based on yield strength. All gearbox and clutch housing castings were conservatively designed for the experimental waterjet kit to remove the need for detailed stress and deflection analysis. If put into production, these castings should be refined to remove metal in low stress areas. All castings were made from Al 356 heat treated to the T-6 condition for maximum strength and stability.

All gears and bearings are lubricated by the splash system with special passages provided to ensure adequate oil flow to bearings in all four gearbox applications. The hydraulic clutch unit, Twin Disc Model 605.5, has a torque rating approximately twixe that required for the application. This unit was selected on the basis of immediate availability. A smaller unit would be considered for production to reduce size and cost.

IV. DEMONSTRATION PROGRAM

A. INSTALLATION

1. General

The prototype waterjet propulsion kit was installed on Government-furnished M-113, SN F13127, USA 12CK01, at the Nevada Automotive Test Center, Carson City, Nevada. To demonstrate the field retrofit feature of the propulsion kit, all work was performed by automotive mechanics using normally available hand tools working under the direction of the Aerojet Project Engineer. A 1/2-in. capacity electric drill and a portable grinder of the type normally found in automotive body repair shops, were the only hand power tools used during the installation.

2. Waterjet

Removal of brackets, tie-downs and guards welded on the rear of the vehicle was accomplished with an abrasive cutoff wheel. All welds were ground flush with the surface, primed and repainted. The holes for attaching the waterjet support brackets were drilled and tapped on the rear of the vehicle in the locations shown on the installation drawings. The plates which support the upper end of the waterjet units were clamped under the existing lifting eyes on the rear corners of the roof as shown by Figures 7 and 8. With the support plates and brackets in place, the waterjet units were lifted in place by two men (approximate weight 150 lb) and the four attaching bolts on each unit were installed (Figure 9). The approximate time required for the above installation including preparation of the vehicle was 8 manhours.

3. Power Transmission

The gearbox, which mounts on the roof of the vehicle, is shown installed in Figure 6. The drilled and tapped holes for securing the gearbox support in place and the elongated hole for passing the vertical drive shaft through the roof were laid out using the dimensions shown on the installation drawing. The large hole for the drive shaft was cut out by drilling a circle of holes and removing a plug. This operation required approximately 3 hr. However, the time could be shortened by use of a portable machine attached to the vehicle roof using the gearbox mounting holes.

The guard rail in the vicinity of the gearbox interfered and was cut off, as shown in Figure 6. A 0.25-in.-thick rubber pad was installed under the gearbox support to reduce noise transmission to the vehicle roof. This pad appeared unnecessary during testing and could be eliminated on future installations. A fitting resembling a roof jack was installed to seal the large hole through the roof. The location of the holes for attaching this fitting was determined at assembly by using the fitting for a template. The cover plate on the gearbox was removed and replaced by the support bracket, Item 14 on the installation drawing, prior to mounting on the vehicle. Alignment of the gearbox is not critical because of the flexible coupling used in all drive shafts.

The gearbox clutch assembly, located in the crew's compartment, was mounted on the gearbox support, Item 20, as seen in Figures 4 and 5, using the bolts which retained the cover plate. The modified bearing retainer, Item 6, was installed on the transfer case using the original shims. The holes for securing the gearbox support to the floor of the vehicle were located at assembly using the support as a template. When properly located, the PTO shaft and gearbox pinion shaft are in line. The double flexible coupling between these shafts permits movement of the transfer case on its rubber mounts and eliminates the need for precise alignment when installing the gearbox.

The gearbox mounted on top of each waterjet is held in place by four bolts. Two of the bolts are accessible on the outside of the waterjet; the other two are installed by opening the maneuvering gate and reaching inside of the nozzle. The flexible coupling hubs are positioned on the drive shafts and gearbox shafts so that there is 1/8-in. clearance between the faces of the gears in each coupling. The hubs with crowned gear teeth are installed on the gearbox shafts, and those with straight teeth on the drive shafts. The shaft covers are placed over the shafts prior to installation. With the covers telescoped together on both ends the couplings are assembled and greased. The movable sleeves on the covers are held in place by a lock screw. The hole for the screw on one end of the cover was located and drilled on assembly to obtain a tight axial fit. The total time required for installation of the power transmission system in the demonstration vehicle was approximately 16 manhours.

4. Hydraulic System

The hydraulic steering system and engine oil system for clutch lubrication and control were installed using the schematic diagram of the installation drawing. The steering and clutch control valves are shown installed in the driver's compartment in Figure 10. The holes for bulkhead fitting were drilled with a 1/2-in. portable drill. All hoses and lines were cut to length and end fittings installed during installation. This operation was time consuming and would be eliminated on a retrofit program by use of prefabricated lines of proper length. All connections to the existing hydraulic system were made at the ramp control valve. The pressure line to the ramp valve was rerouted to the waterjet control valve used to select either ramp or waterjet operation. Fluid return from the waterjet control system was routed to a tee placed in the ramp valve return line. The bypass valve located in the right steering valve was set by use of a gage at the desired 1000 psi required by the waterjet system.

The bracket supporting the clutch oil pump was attached to the transfer case using existing bolts. Oil for the clutch system was taken from the engine at the distribution manifold located directly under the hydraulic reservoir. Oil returning from the clutch was returned to the engine pan through an existing unused plug on the left side of the engine. The clutch actuation pressure was set at 250 psi using the bypass valve in the clutch control valve. A gage placed in the oil lube line at the clutch housing connection was used to adjust the lube oil metering valve to the required 10 psi. During initial checkout of the clutch system, oil leakage occurred at fittings which carry the oil through the housing wall to the clutch unit. Intermittent leakage occurred throughout the test program but was later remedied by fabricating and installing a new fitting. The leakage problem was partially attributable to a defective hydraulic clutch unit which permitted excessive piston leakage. This problem is discussed further in the following section on testing.

B. TESTING

1. General

Testing of the M-113 Armored Personnel Carrier equipped with the experimental waterjet propulsion kit was conducted at Lake Lahontan, Nevada, by personnel of Hodges Transportation Inc. of Carson City, Nevada and Aerojet-General Corporation. The pump design used in the waterjets was previously tested by Aerojet; hence, tests to obtain detail pump performance data were not necessary and testing was restricted to determining overall system performance and vehicle characteristics. Static thrust and water speed were measured for both forward and reverse operation and the maneuvering characteristics of the vehicle were established.

2. Instrumentation

Power input to the waterjet system was measured by use of a Lebow, Model 1105, torque sensor and a Weston DC Generator rpm sensor. The torque sensor was incorporated in a special drive shaft, which replaced the shaft connecting the waterjet clutch to the gearbox mounted on the roof of the vehicle. In this location, losses in the first gearbox and clutch could not be measured and a correction was applied to obtain actual power input to the system. RPM was measured on the transfer case power take-off of the engine blower and a correction was applied for the difference in gearing between this shaft and the torque sensor shaft. Static thrust of the waterjets was measured by an A.H. Emery load cell mounted on a vehicle located at the water's edge. Two cables were used to transmit thrust from the vehicle to the load cell. Data from all three instruments were recorded by a two-channel X-Y blotter. Two curves were plotted, speed versus torque and static thrust versus torque. These data are sufficient for determining input horsepower, jet horsepower, propulsion efficiency, pump flow rate, jet velocity and head at the nozzle. By estimating nozzle and duct losses, pump efficiency, can also be determined.

3. Waterjet System Checkout and Demonstration

The vehicle with waterjets installed was put in the water for initial checkout and familiarization during the week of 4 September. As previously mentioned, oil leakage problems with the clutch had previously been encountered during checkout in the shop. This problem had then been attributed to leakage of seals on oil lines passing through the clutch housing and had been corrected. Failure of the clutch occurred on 7 September during maneuvering trials. Disassembly of the clutch disclosed that the hydraulic clutch unit, a commercial item received completely assembled, had been delivered improperly assembled. The ring-shaped hydraulic piston was inserted in the cylinder backwards, allowing the thrust bearing to run on the face of the piston rather than on the bearing race. The bearings and seals were seriously damaged. With the piston installed improperly, the seals were ineffective; hence, the excessive oil leakage previously experienced. The clutch was repaired and testing continued during the week of 11 September. One of the waterjet maneuvering gates was cracked on 13 September due to improper adjustment of the hydraulic steering cylinder which allowed the gate to jam in the housing. The crack was welded and both gates were reinforced the following morning. The system was reassembled and run during a demonstration on 14 September for Army, Aerojet, and FMC personnel. Overheating of the clutch occurred during maneuvering tests after the demonstration. Disassembly indicated that insufficient lube oil was being supplied to the unit. The complete clutch was replaced and the clutch lube system was reworked to ensure adequate oil flow. No futher troubles were experienced with the clutch system during the following two weeks of testing. The clutch is considerably overdesigned for the application. This fact plus planned changes in the clutch lubrication system will ensure a highly reliable and trouble-free clutch system for any future applications.

4. Static Thrust Tests

Static thrust tests using the instrumentation previously described were conducted on 22 September. Analysis indicated some discrepancies in data; therefore, the tests were rerun on 26 September for verification and check. Tests were run using three nozzle discharge areas, obtained by the use of tapered inserts placed on each side of the nozzle. Changes in nozzle area varies the flow rate of the pump and indicates the points of maximum thrust and system efficiency. Tests were run using areas of 105, 112, and 122 sq in. A test run consisted of slowly increasing the engine speed to a maximum and then slowly reducing it back to idle, while continuously recording the curves of speed versus torque and thrust versus torque on the two-channel X-Y plotter. The maximum power delivered to the waterjet system at the test altitude of 4500 ft was 108 bhp. It should be noted that the waterjet pumps were designed for 75 bhp input at each pump shaft, the power expected at sea level. Because of the reduced power during testing, the pumps could not be brought up to the design speed of 1140 rpm and the static thrust was proportionately lower. The nozzle area had no significant effect on static thrust speed or input power as shown by the following table:

Nozzle Area, sq in.	Thrust, lb	Pump Torque, lb/ft	Pump Speed, rpm	Input, bhp	Pounds Thrust per HP
105	2300	594	925	105	21.9
112	2350	615	935	108	21.7
122	2300	565	970	104	22.1

The data show a slightly higher overall system efficiency and higher thrust per horsepower for the larger nozzle; hence, the vehicle was delivered in that configuration. Because of the higher pump flow rate associated with the large discharge nozzle it is important that the vehicle be loaded in a manner to keep the pump inlets well below the waterline to prevent taking in air which reduces thrust. From the above data, assuming the same system efficiency, a static thrust of 3000 lb is predicted for the design horsepower of 150 expected at sea level.

Static thrust in reverse was measured at 1000 lb during test. At sea level, a reverse thrust of 1300 lb is predicted.

As a comparison, static thrust using only track propulsion was measured. A thrust of 825 lb was produced, approximately one third of that obtained with the waterjet system. Static thrust was also measured using track and waterjet propulsion simultaneously. Because of the inefficiency of the tracks when compared with the waterjets, static thrust was reduced to 1650 lb.

5. Vehicle Speed Tests

Vehicle speed was measured along a straight course 440 ft long. Two stakes, placed 100 ft apart permitted the start and finish of the course to be determined from the vehicle. Time for the run was measured with a stop watch. Two runs in each direction were made on 26 September and four additional runs in each direction were made on 28 September, when wind conditions were more favorable. These runs resulted in quite consistent times giving an average speed of 5.55 mph, with a measured power input of 112 bhp to the waterjet system. It should be noted that the higher power input resulted from engine tuneup performed after static testing. Views of the vehicle traveling full speed forward, full speed in reverse and making a high speed turn are shown in Figures 11, 12, and 13, respectively. Performance of the vehicle during test and as predicted for sea level conditions is shown by Figure 14. The dynamic thrust curves are derived from static thrust measurements using the relationship

$$\text{Dynamic Thrust} = \text{Static Thrust} \left(\frac{V_j - V_v}{V_j}\right)$$

where V_j and V_v are jet velocity and vehicle velocity, respectively. The vehicle drag curve established during test was lower than the drag curve used during design of the system. As shown by Figures 1 and 2, a larger moldboard (4 ft x 8 ft) was used during speed and maneuvering tests to prevent water from breaking over the vehicle. It is assumed that lower drag resulted from this change, which provides smoother flow around the vehicle than when the smaller board is used. It should be noted that even though the static thrust is lower than predicted, the desired speed of 6 mph should be obtained at sea level because of lower drag.

Reverse speed of the vehicle over the measured course was clocked at 3.65 mph and a sea level speed of 4 mph is predicted. Vehicle speed for forward and reverse operation as a function of engine rpm is shown by Figure 15.

For comparison, speed using track propulsion only was measured. The 3.55 mph obtained agreed with published data.

A speed of 5.17 mph was recorded using track and waterjet propulsion simultaneously. This test was conducted with the tracks in the highest speed range. While not checked it is probable that a slightly higher speed would be obtained with the tracks in the low speed range, where a greater share of the power would go to the waterjet system. In shallow water where occasional contact with the bottom is expected, operation of the vehicle in this manner should prove highly satisfactory.

6. Maneuverability

During the initial familiarization phase, demonstration and speed testing with the waterjet system, hundreds of turning and reversing maneuvers were performed. Other than cracking of one maneuvering gate because of faulty adjustment early in the test program, no significant problems were encountered with the steering and reversing system. Slight corrections in heading were smoothly accomplished using short bursts of reverse thrust on the side toward which steering was desired. While traveling forward, the vehicle is basically unstable in yaw due to the lack of a sharp bow, keel, or rudder. Hence, periodic corrections are needed to keep the vehicle traveling in a straight line. This fault, which is particularly noticeable at maximum speed, is not a serious problem with an experienced operator.

Pivot turns, during which the vehicle essentially turns about its c.g., were safely made at all speeds with the vehicle heavily loaded (approximately 12 in. freeboard). The vehicle can be stopped in approximately one vehicle length while traveling full speed forward by simultaneously reversing both waterjets. When left in this position, the vehicle rapidly accelerates to full speed in reverse. While traveling in reverse, the vehicle is stable and little correction in heading is required to maintain a straight course.

Maneuvers using only track propulsion, and track and waterjet propulsion simultaneously were also conducted to obtain a comparison. The improvement in maneuverability provided by the waterjet system over the tracks is much more impressive than the like improvements in thrust and speed. The ability of the vehicle to almost instantaneously change direction and speed should prove to be highly beneficial in combat situations or when operating in swift streams.

7. Bank Egress Tests

The banks of Lake Lahontan are made up of very hard-packed sand clay and shale which afford excellent traction for the tracks. Considerable effort was spent in trying to locate a bank which could not be climbed using only track power, but which could be climbed when assisted by the waterjets. Banks were located which could not be mounted; however, in all cases, traction was sufficient to stall the vehicle without slippage of the tracks. In such a situation the waterjets obviously offered little help since the tracks absorbed practically all the available power. On banks having a gentle slope, the waterjets were capable of pushing the vehicle up the slope without the use of track power until the pump inlets left the water. Assuming no rolling friction, the 3000 lb thrust available at sea level would push the vehicle up a grade of approximately 14%.

Testing on banks affording poor traction, where track slippage occurs with little absorption of power, should demonstrate considerable help from the waterjet system. In such situations most of the engine power will be available to the waterjets and the forward thrust will cause the tracks to dig in until traction is improved to the point where the waterjets are not needed. During such an operation, a smooth transfer of the power from the waterjets to the tracks should automatically occur. The waterjet system should provide the additional benefit of being able to counteract the current in a swift moving stream while trying to egress from the water. The ability to rapidly reverse and to accurately maneuver to the desired location on the bank with the waterjets even under adverse water conditions should in itself be very helpful in crossing streams and climbing a bank. It cannot be too highly stressed that there is not a conflict between the division of power between the tracks and waterjet system. The tracks can make the most efficient use of power when good traction conditions exist and the waterjet system can most efficiently provide forward thrust under poor traction conditions. The proper division of power to the two systems is completely automatic.

C. PERFORMANCE SUMMARY

All significant vehicle performance data and system characteristics established during the test program are summarized below:

1. Waterjet Propulsion

Forward speed at sea level (75 bhp pump)	6.00 mph
Forward speed measured at 4500 ft altitude (52 bhp pump)	5.55 mph
Reverse speed at sea level*	4.00 mph
Reverse speed at 4500 ft altitude	3.65 mph
Turn radius at 5.55 mph	10 ft
Turn radius at zero speed	pivot on c.g.
Forward static thrust at sea level	3000 lb
Forward static thrust at 4500 ft altitude	2300 lb
Reverse static thrust at sea level	1300 lb
Reverse static thrust at 4500 ft altitude	1000 lb
Flow rate at design speed (each pump)	11,100 gpm
Jet velocity	30 fps
Pump efficiency	75%
Propulsion efficiency	21.5%
Maneuverability	Excellent

2. Track Propulsion

Forward speed at 4500 ft altitude	3.55 mph
Static thrust at 4500 ft altitude	825 lb
Turn radius (estimated)	75 ft
Maneuverability	Poor

3. Track and Waterjet Propulsion

Forward speed at 4500 ft altitude	5.17 mph
Forward static thrust at 4500 ft altitude	1650 lb
Maneuverability	Good

* Predicted from tests conducted at 4500 ft altitude with reduced power.

V. PRODUCTION DESIGN

A. GENERAL

The experimental waterjet propulsion kit installed on the M-113 vehicle for demonstration purposes was designed with simplicity, ease of installation and low production cost as objectives. However, components such as the impeller, stator and discharge nozzle require expensive tooling for low-cost production which could not be justified during the experimental program.

Testing to date with the experimental system has shown excellent performance and the mechanical integrity and reliability appear satisfactory, with the exception of the problems discussed previously. Some minor design changes are being made to reduce the number of parts, fabrication time, material costs, and installation time. In general, these improvements will reduce maintenance requirements, improve reliability, reduce cost and provide increased system cost effectiveness. Changes planned for each major part of the system are discussed below.

B. WATERJET

The impeller used in the experimental system was fabricated by brazing sand cast blades to a cast hub. This required complex machining and tooling not suitable for production. The impeller has been redesigned for casting in one piece and is adaptable to either the investment or permanent mold process. The impeller material has been changed from bronze to 17-4 stainless steel. This material has greatly improved mechanical properties (150,000-psi yield strength) and will result in a more reliable impeller less subject to damage.

The stator used in the experimental waterjet was fabricated in aluminum from stamped blades, a cast hub and a rolled and welded outer ring. In production, this component will be cast in one piece from stainless steel or aluminum. The number of blades in the stator has been reduced to provide increased clearance for passage of debris and a thicker blade for greater strength. It should be noted that the blade design and, hence, pump performance will not be affected by the planned changes in fabrication technique.

The internal vanes were fabricated from sheet material and welded to the cast discharge nozzle housing for the demonstration hardware. For production, the vanes would be cast integral with the housing. Also, the two brackets which bolt to the rear of the vehicle for supporting the lower end of the waterjet have been incorporated on the discharge nozzle housing. The bearing housing, which now bolts inside the nozzle, has been redesigned and would be cast integral with the stator. The vane enclosing the pump shaft has been eliminated by use of water-lubricated bearings and a stainless steel shaft. Use of water-lubricated sleeve bearings in place of the grease-packed tapered rollers used on the experimental pump will reduce maintenance, eliminate the seal housing and seals, and provide improved reliability. Pump thrust will be carried by a grease-packed bearing external to the pump, where leakage is not a problem.

The inlet grill has been redesigned for rapid removal and lower cost. Expanded metal would replace the existing bars used for the grill. The grill is a separate part which, if damaged, can be replaced without replacing the complete inlet section. The bolted flange joint between the inlet housing and discharge nozzle has been replaced by a V-band clamp for rapid removal when cleaning or inspection of the pump is required. The maneuvering gate has been redesigned for greater strength at reduced weight, and the pivot pins and bearings have been changed for improved reliability. The inserts used on the experimental nozzle to vary discharge area are not required on a production model and have been eliminated. Also, the zinc anode galvanic protection is deleted since continuous exposure to salt water is not anticipated.

None of the planned changes affect the hydraulic efficiency or performance of the waterjet pump.

It should be noted that the total number of parts has been significantly reduced from 44 on the experimental design to 32 on the production version.

C. POWER TRANSMISSION

The three drive shafts interconnecting the four gearboxes have been redesigned to reduce fabrication time. A coupling with a flanged hub, which can be welded directly to the drive shaft tube, is utilized. Reliability will be improved by the elimination of the keyed joint on each end of the shaft and weight is reduced.

The coupling between the vehicle transfer case and waterjet gearbox was fabricated from a PTO shaft and two standard couplings. One special coupling incorporating the shaft has been designed for a production application.

No significant change in gearbox design is required for production. All four boxes now utilize the same parts which can be assembled differently to obtain the two types required. Some simplification in design is possible without this interchangeable feature, and would be considered for production when quantities and spares philosophy were known. The gearbox supports have been re-designed to utilize casting rather than welded construction. Hold-down bolts have been increased to 0.5-in.-dia, and the number reduced to simplify installation. No change in clutch design is planned; however, the clutch actuation and lubrication system has been changed as discussed below.

D. HYDRAULIC CONTROL SYSTEM

The hydraulic clutch used on the experimental system utilizes vehicle engine oil for lubrication and actuation. A separate oil pump is used to boast the 40-psi engine pressure to the 250 psi required for clutch operation. The production design shown schematically by Figure 16 will utilize the vehicle hydraulic system for clutch lubrication and actuation. This change eliminates the oil pump, an oil valve and several lines and bulkhead fittings. The possibility of imparing engine lubrication is also removed, and the 275°F clutch and gearbox temperature produced by the circulating hot engine oil is also eliminated.

The clutch generates very little heat because of infrequent clutching. Normally, the clutch would be engaged and disengaged only once during a water operation; hence, the only heat generated is produced by the thrust bearing. Transfer through the clutch housing will easily dissipate this heat and circulation of clutch lubricant would be only that due to piston ring leakage. A return line is provided to return this leakage to the hydraulic reservoir. The hydraulic system which would be used for a production waterjet propulsion system is shown by Figure 16. The steering valves, waterjet control valve, pressure regulator, and their interconnecting lines would be assembled as a unit for mounting in the driver's compartment. The hydraulic system would consist of the following items:

1 Control Unit

14 Hydraulic Lines (cut to length with fittings)

18 Bulkhead Connectors

2 Tees

The hydraulic cylinders are part of the waterjet assembly.

E. INSTALLATION

Installation of the waterjets on the rear of the vehicle consists of the following steps:

1. Remove interfering brackets and handles on rear of vehicle.
2. Drill and tap 0.500-13 UNC four holes on rear of vehicle.
3. Remove two rear lifting eyes on roof of vehicle.
4. Lift waterjets in position, replace lifting eyes and install two bolts attaching each pump to vehicle.

5. Install gearbox on top of each waterjet.

Installation of the gearbox and clutch in the crew's compartment requires the following steps:

1. Remove floor plate and saw hole for fitting around gearbox support.

2. Drill and tap 0.500-13 UNC four holes in vehicle floor for attaching gearbox.

3. Modify engine compartment cover to accomodate drive coupling.

4. Install modified bearing retainer on transfer case. Place gearbox clutch assembly in position with coupling engaging PTO and bolt gearbox to floor.

Installation of the gearbox on roof of vehicle involves the following steps:

1. Cut clearance hole drive shaft using special hole cutting tool.

2. Drill and tap 0.500-13 UNC four holes in vehicle roof.

3. Bolt gearbox in position.

The three drive shafts are installed as follows:

1. Place shaft inside of cover.

2. Place assembly in position and slide coupling sleeves and seals in position.

3. Insert snap rings.

4. Extend telescoped covers and install lock bolt on each end.

Installation of the hydraulic system requires the following steps:

1. Drill 18 holes and install bulkhead fittings.

2. Drill and tap 0.250-20 UNC four holes for mounting control unit in driver's compartment.

3. Install pre-assembled control unit and attach lines to bulkhead fittings.

4. Install 14 additional lines and two tees interconnecting bulkhead fittings, clutch, and existing ramp control valve.

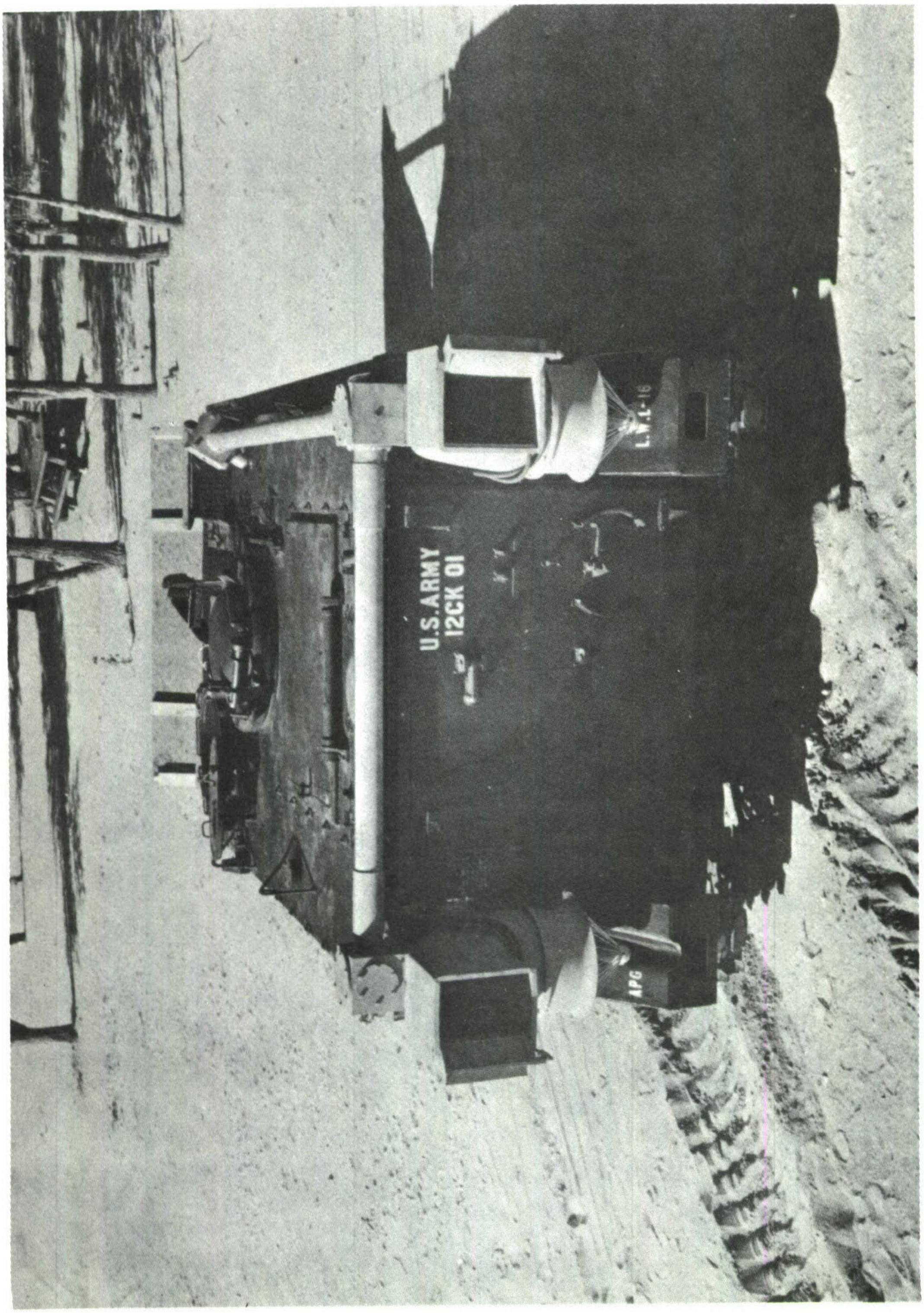
5. Connect hydraulic lines from control cylinders on waterjet to fittings on rear of vehicle.

6. Bleed air from system.

On the basis of experience gained during installation of the experimental waterjet propulsion system on an M-113 vehicle, it is estimated that the production waterjet system would require 24 manhours for installation and checkout in a field maintenance shop.

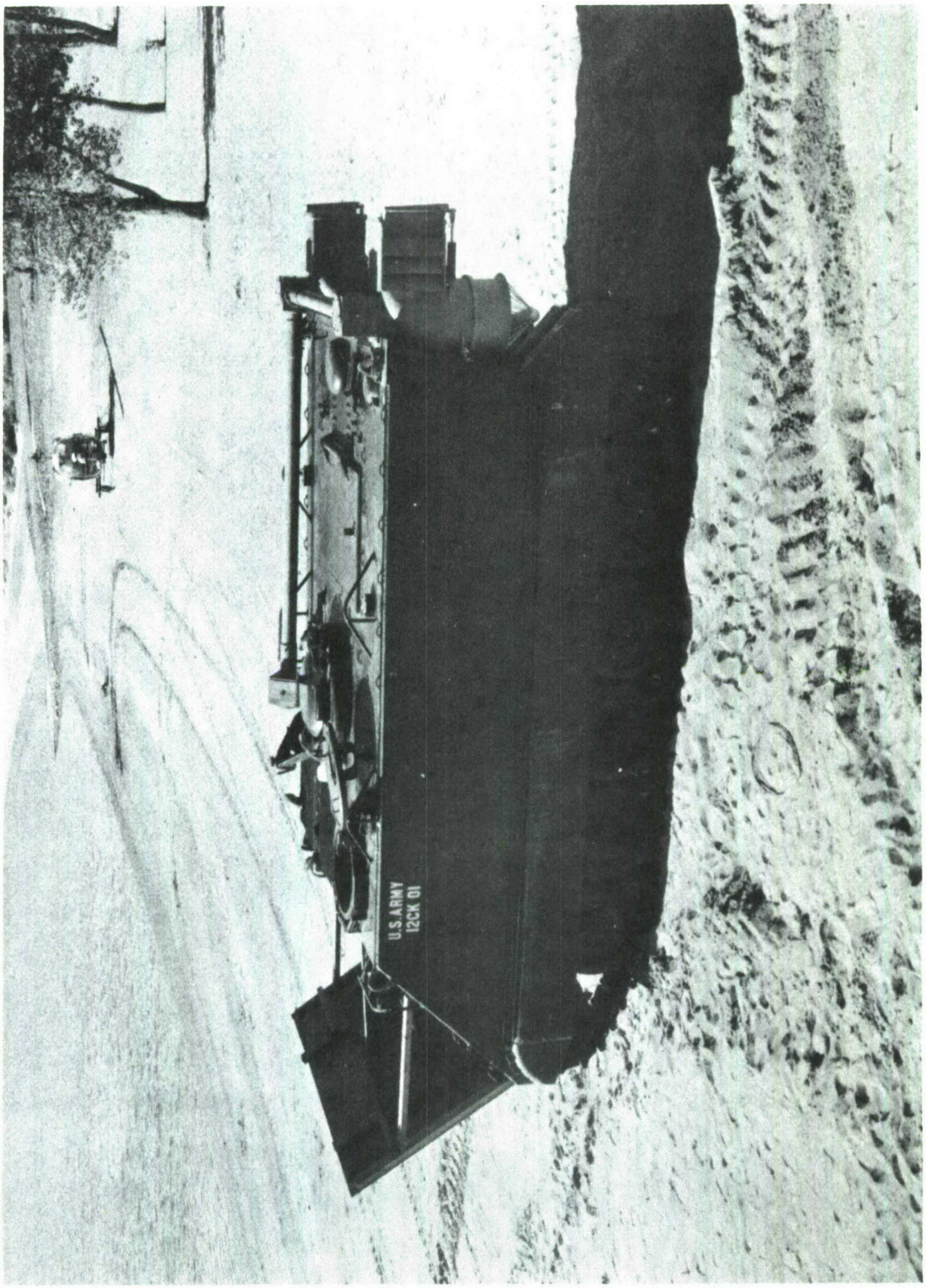
F. SPECIFICATIONS

Preliminary specifications and performance requirements for a production waterjet propulsion kit for the M-113 Armored Personnel Carrier are as listed in Section II,G and Section IV,C of this report.



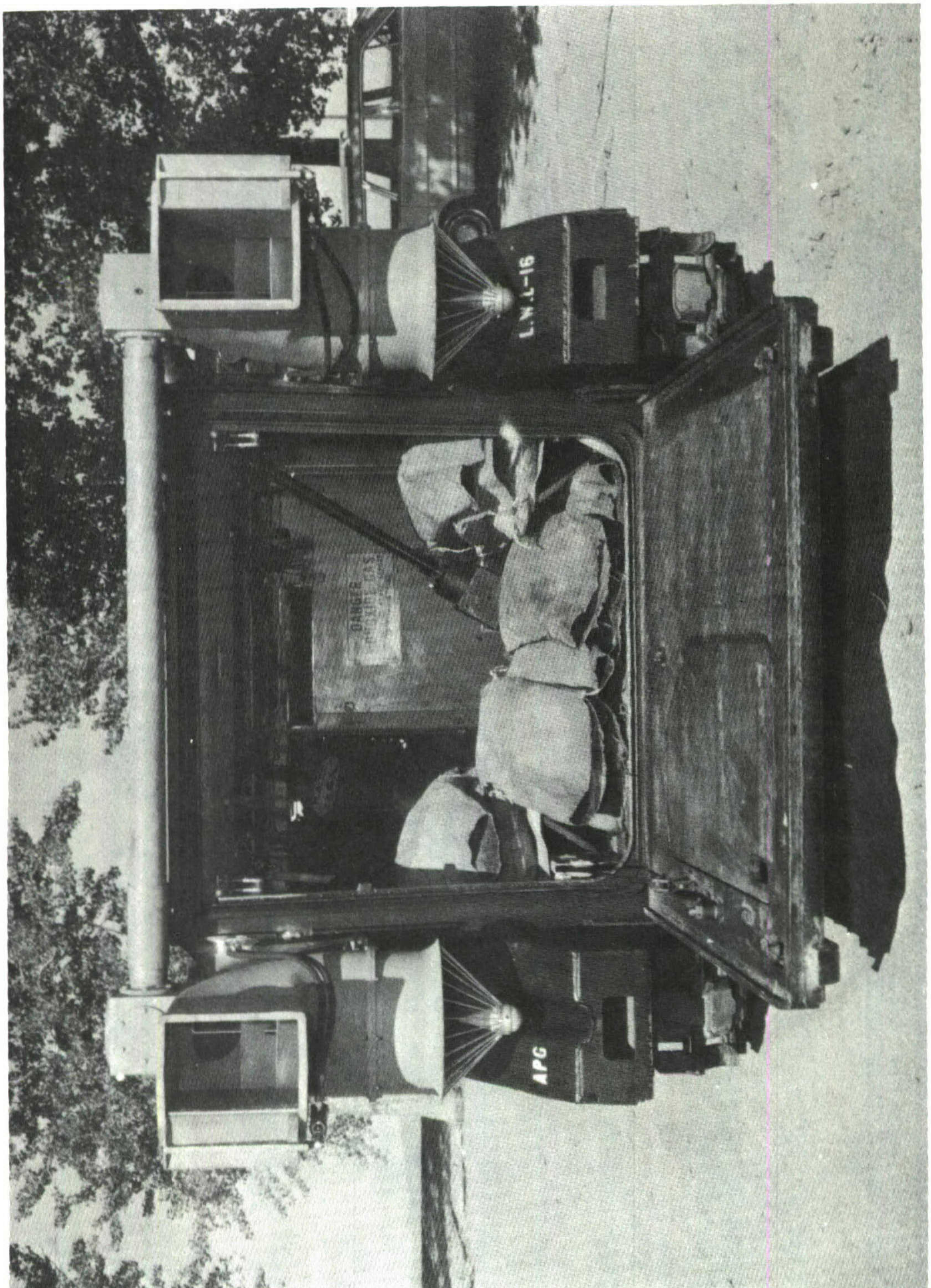
Rear View of M-113 Vehicle with Prototype Waterjet
Propulsion Kit Installed

Figure 1



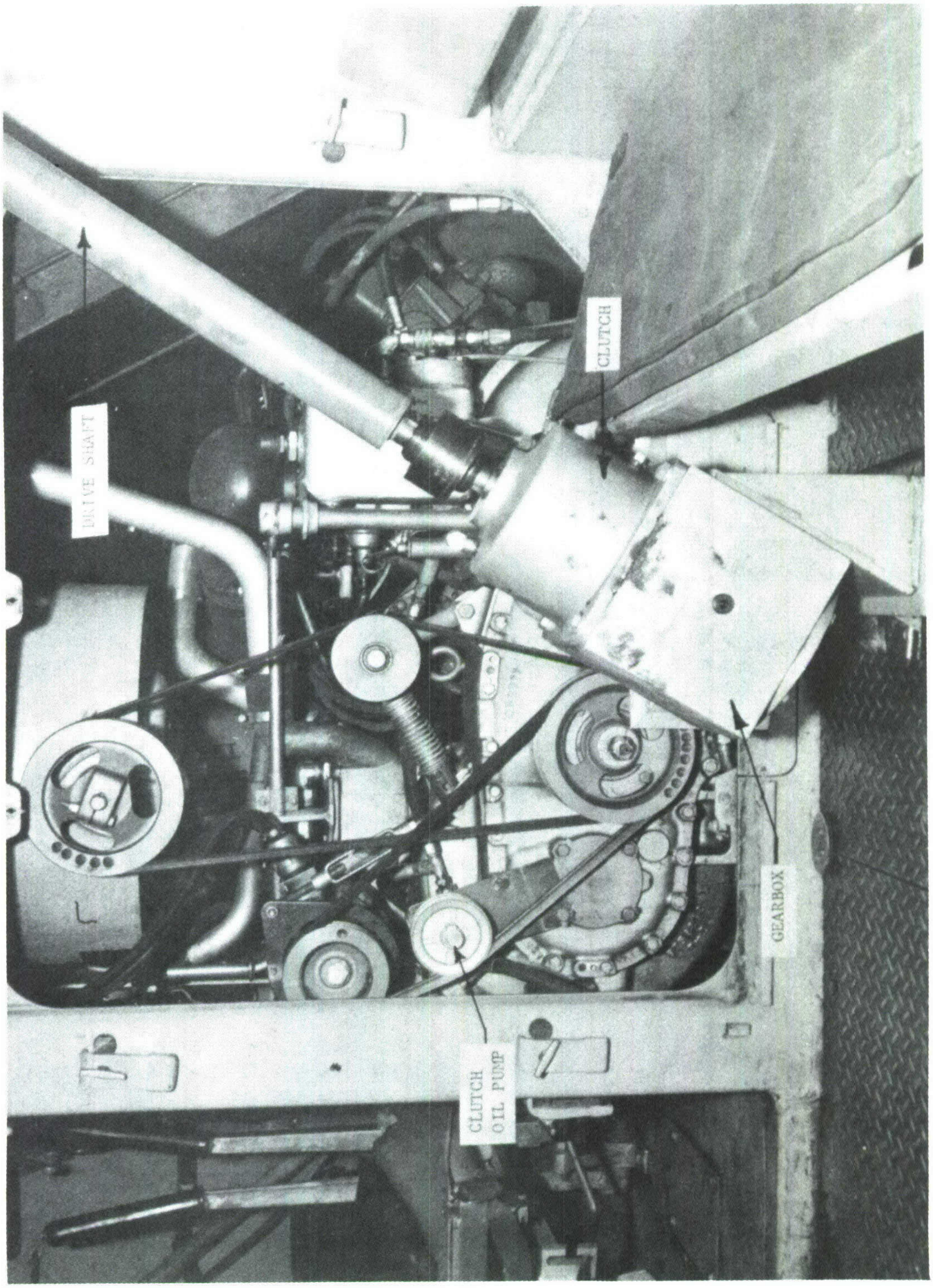
Side View of M-113 Armored Personnel Carrier Equipped with Prototype Waterjet Propulsion Kit

Figure 2



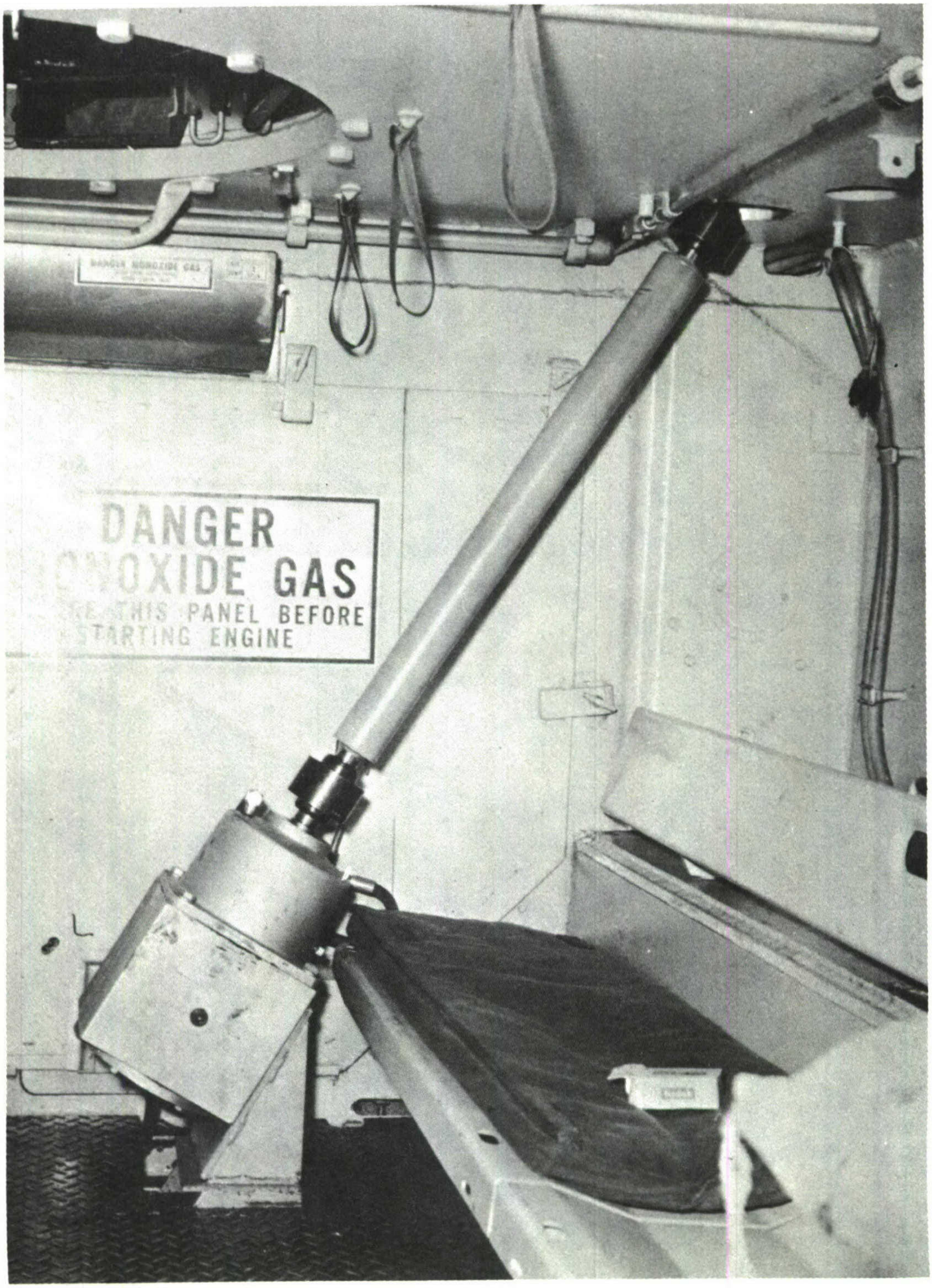
M-113 Vehicle with 1,800 lb Load for Demonstration of Waterjet System

Figure 3



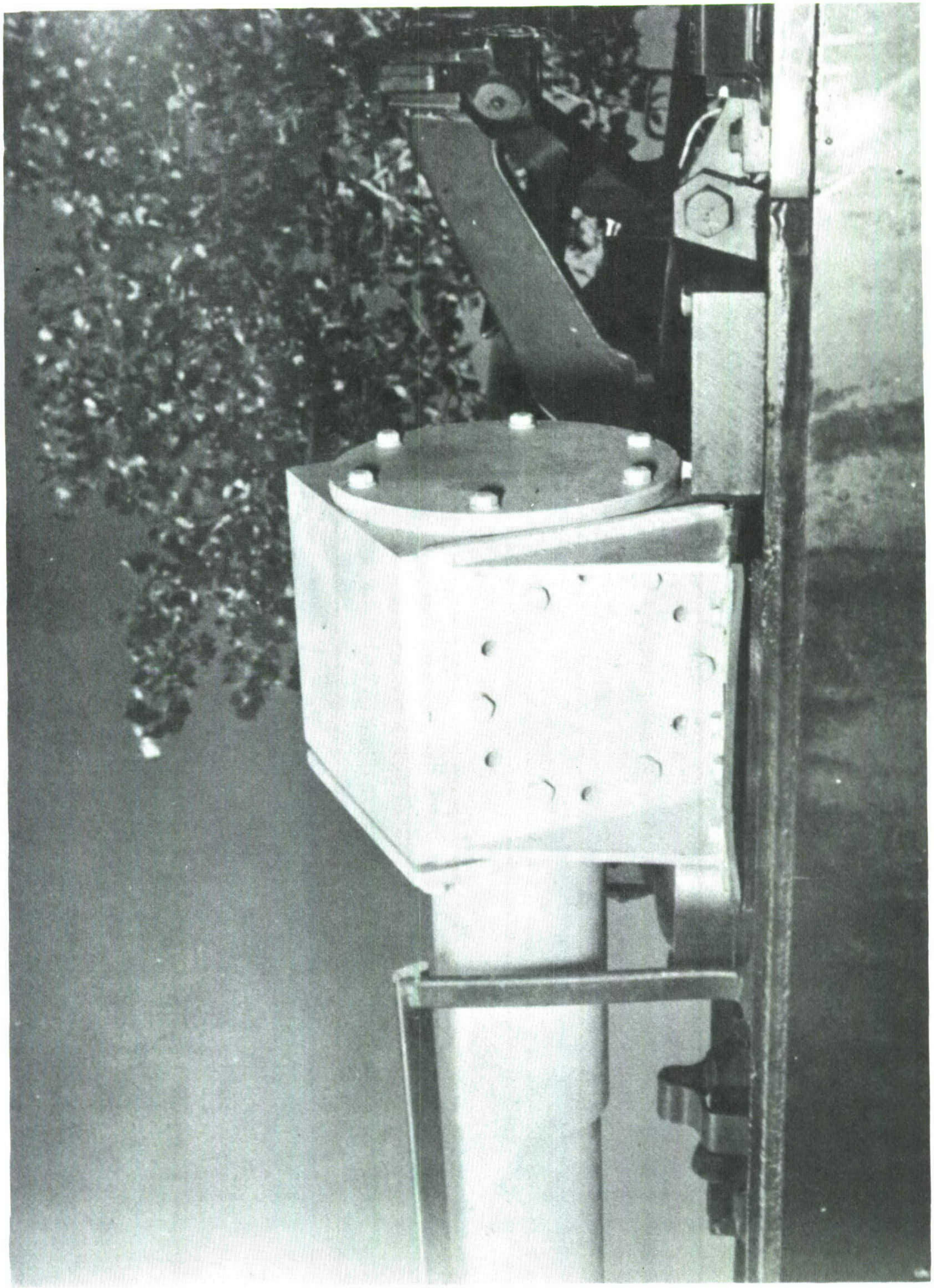
Waterjet Power Transmission System Installed in Crew's Compartment of M-113 Vehicle

Figure 4



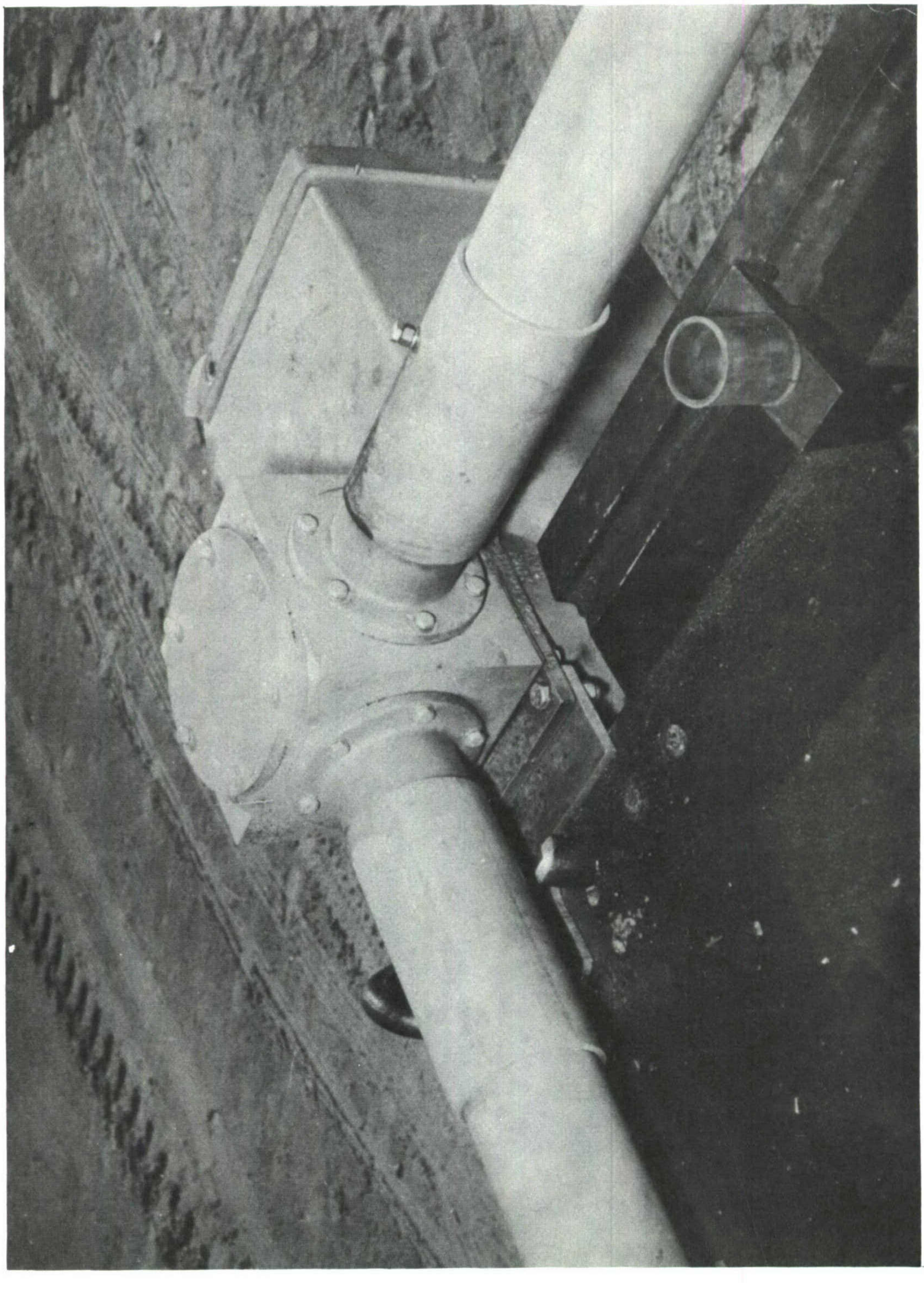
Gear Box in Crew's Compartment of M-113 Vehicle

Figure 5



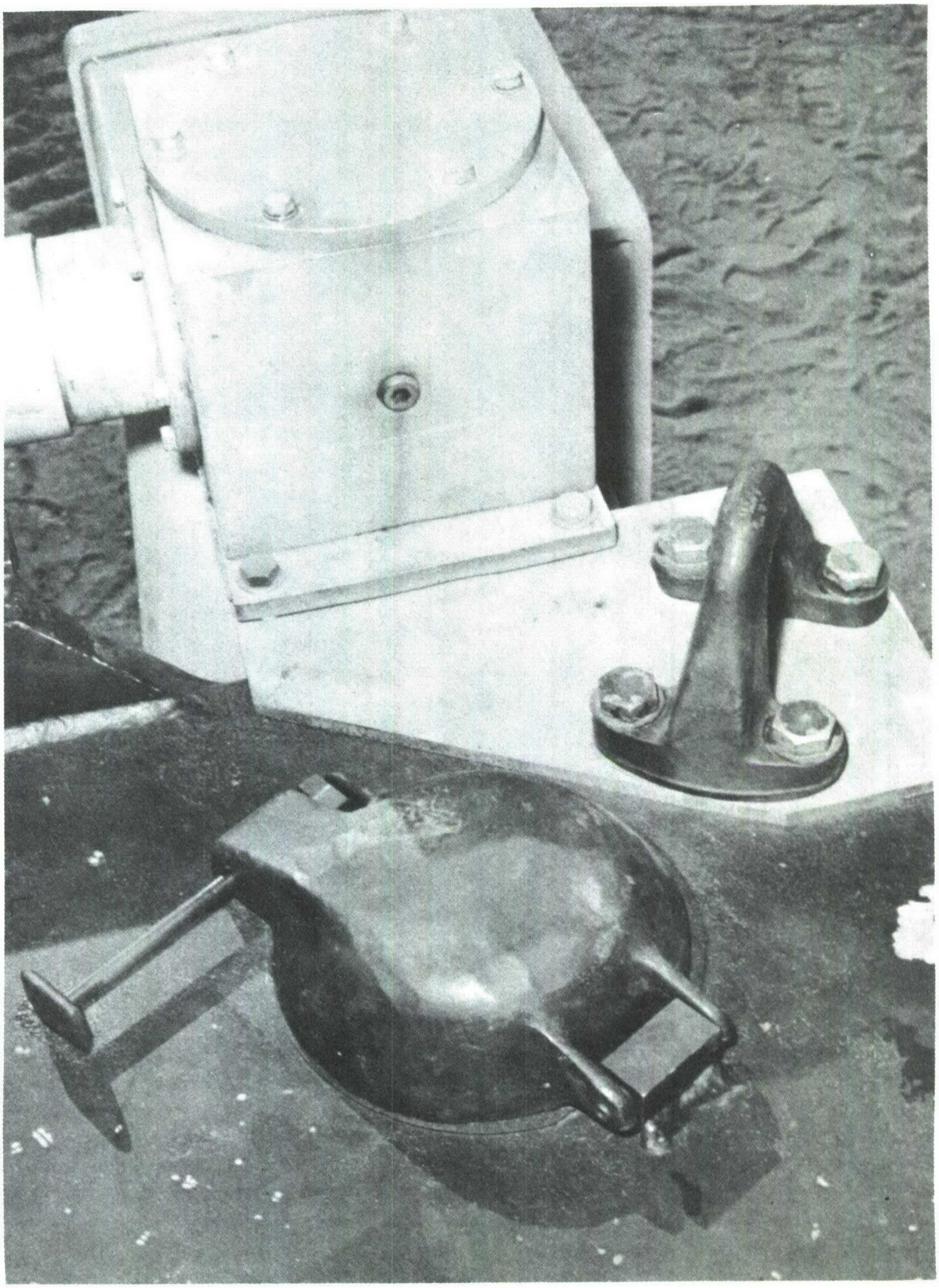
Gear Mounted on Roof of M-113 Vehicle

Figure 6



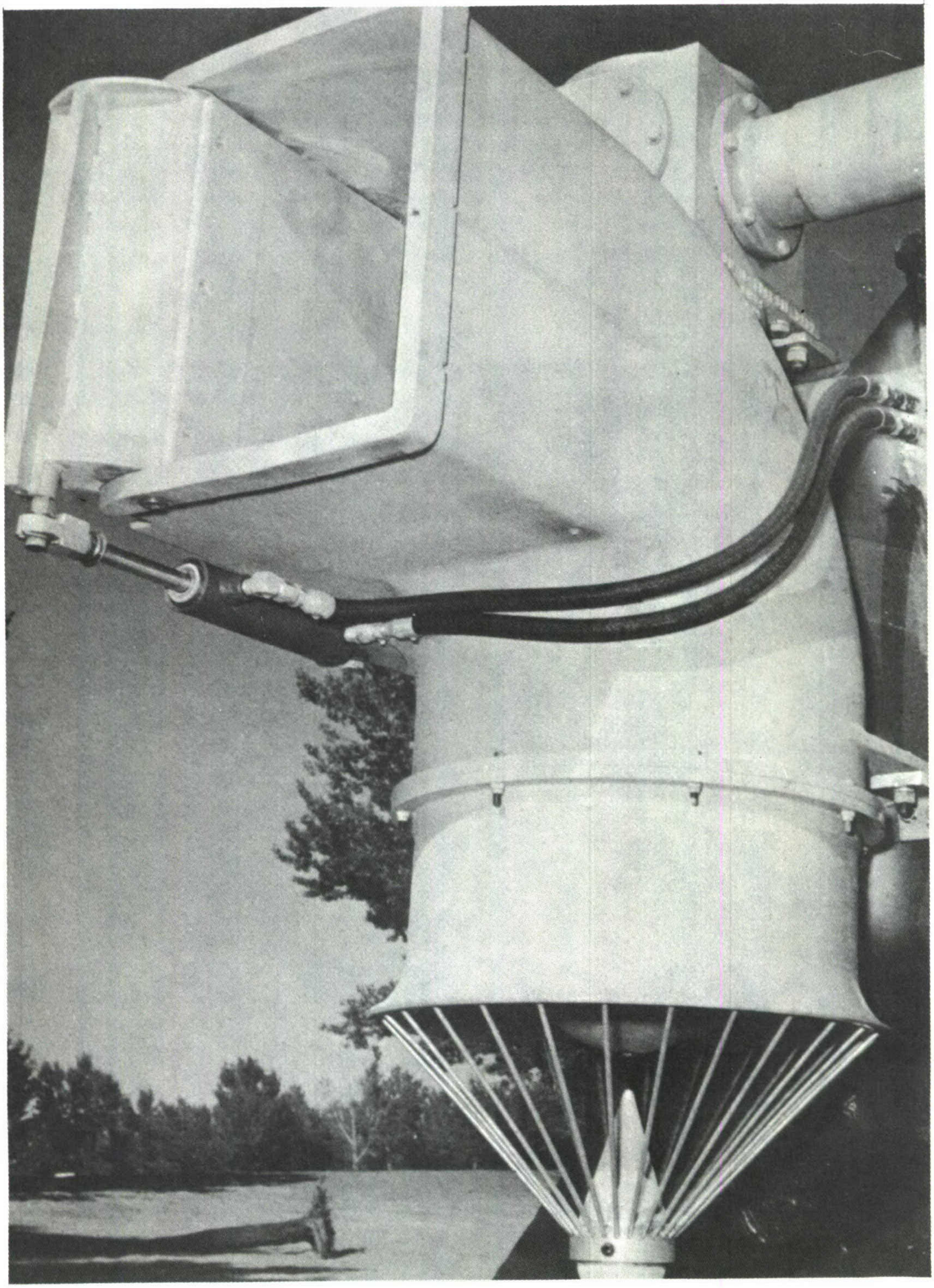
Gear Box Mounted on Top of Right Waterjet

Figure 7



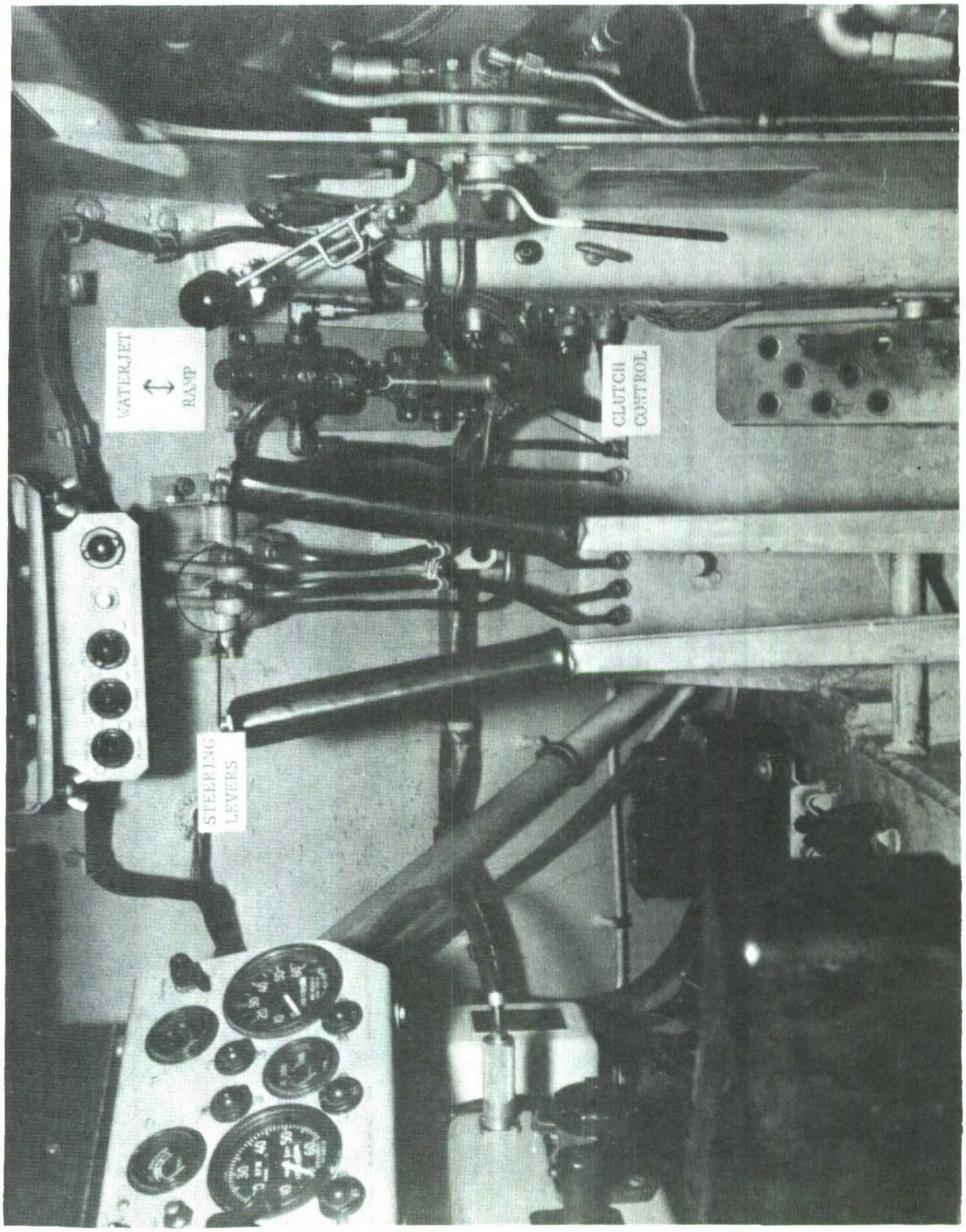
Gearbox Mounted on Left Waterjet Showing Attachment to Vehicle

Figure 8



Prototype Waterjet Mounted on Rear of M-113 Vehicle

Figure 9

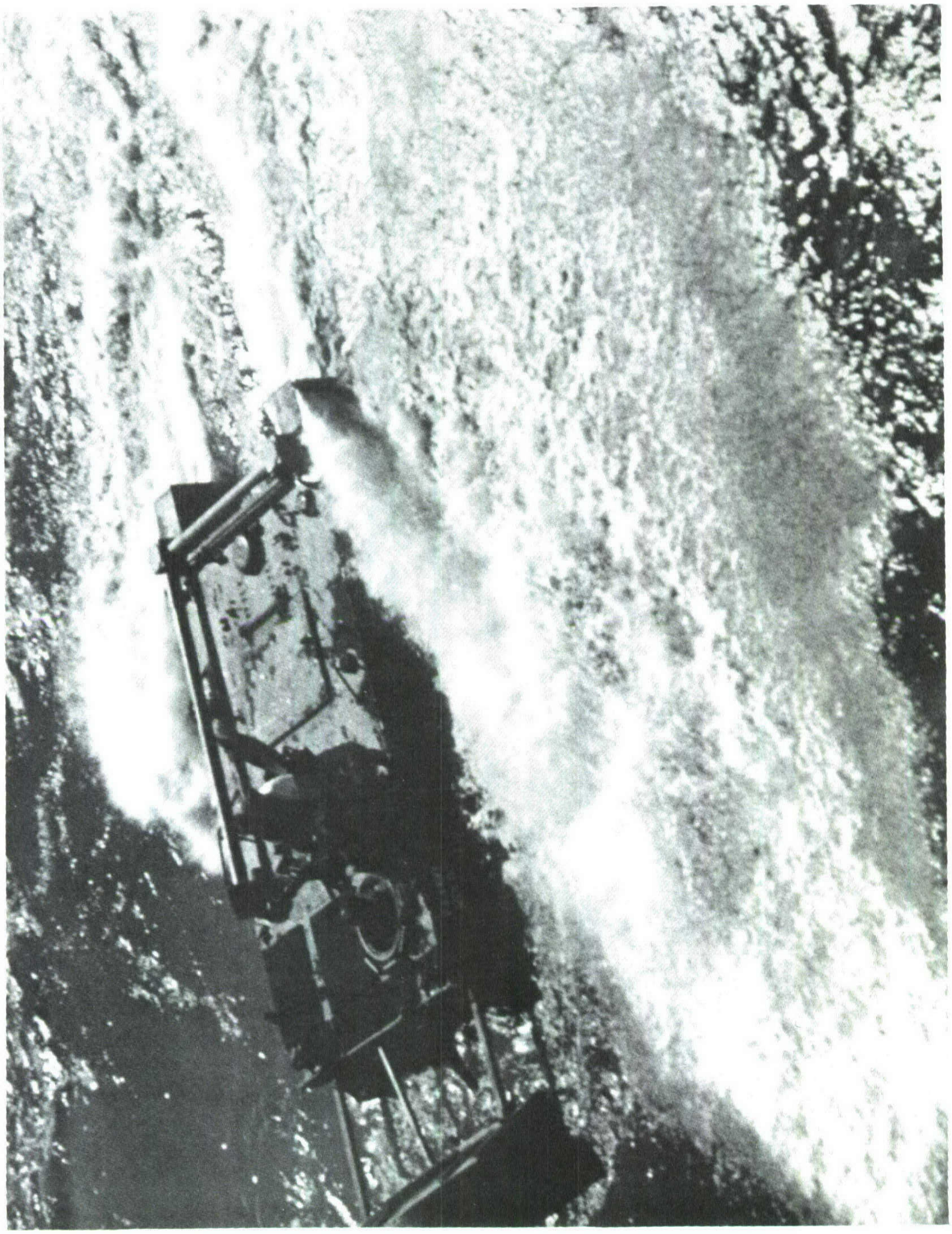


Waterjet Propulsion Kit Controls in Driver's Compartment of M-113 Vehicle

Figure 10

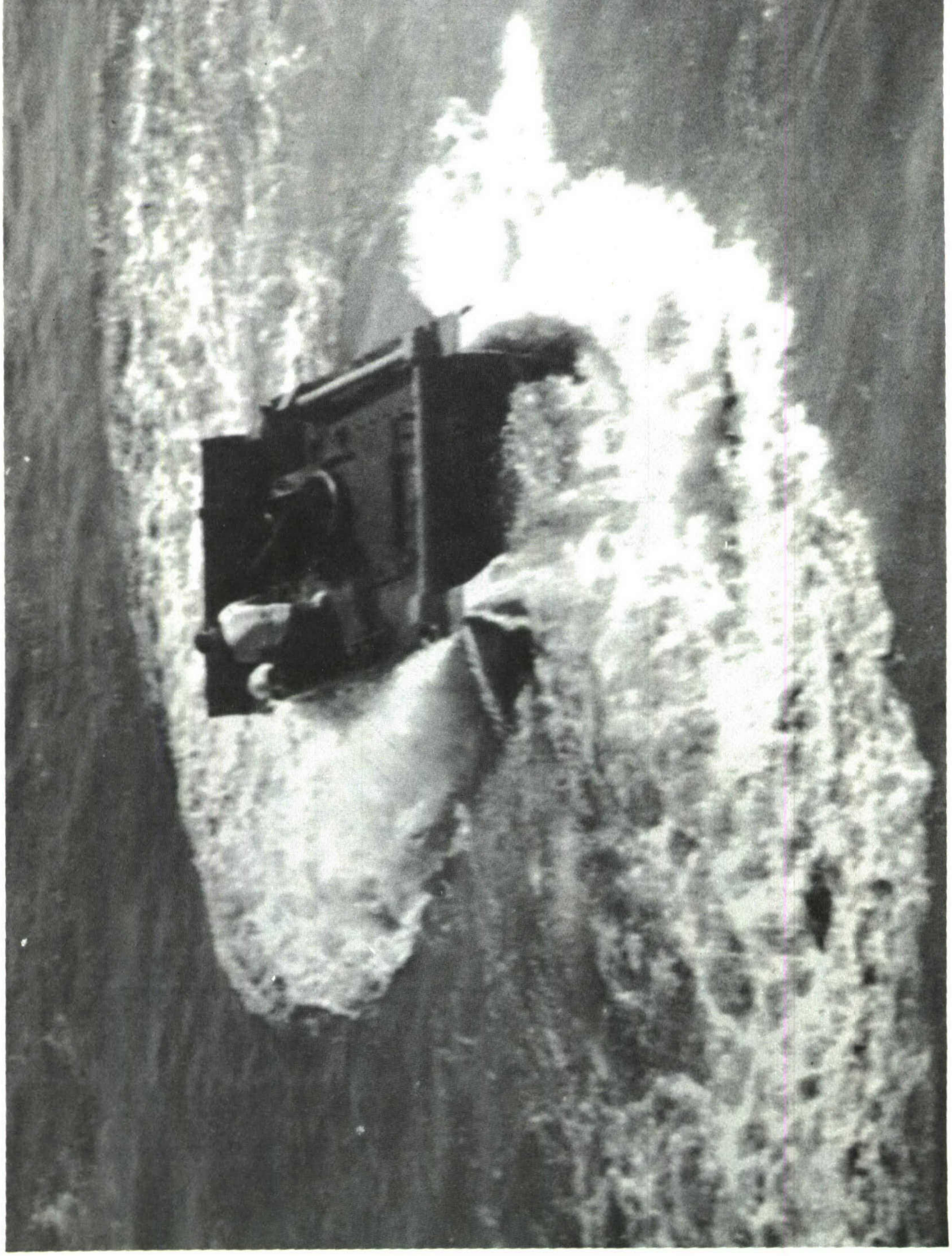
M-113 Armored Personnel Carrier Traveling forward during Waterjet Propulsion Kit Demonstration

Figure 11



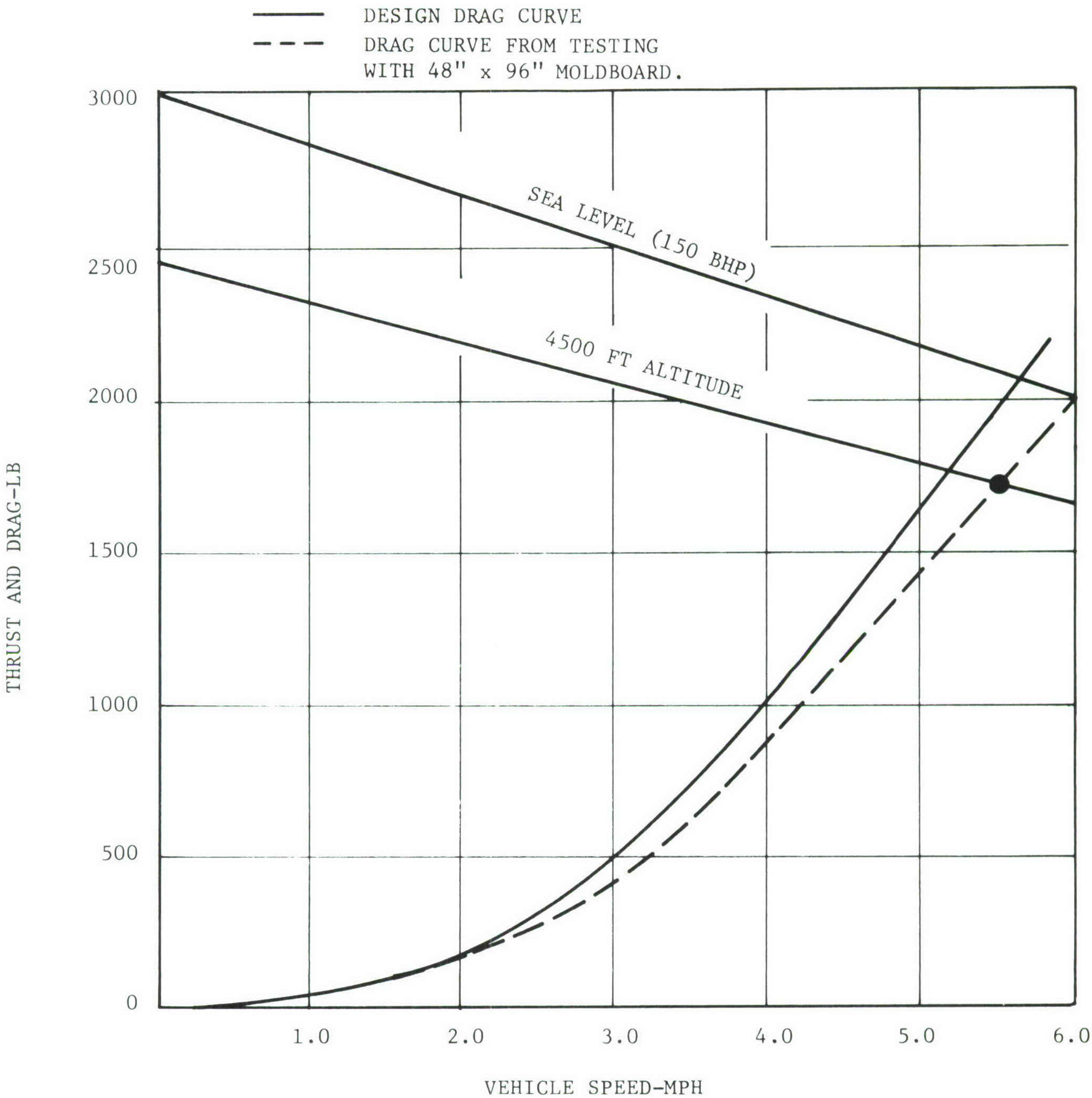
Reverse Operation of M-113 Vehicle with Waterjet Propulsion Kit

Figure 12



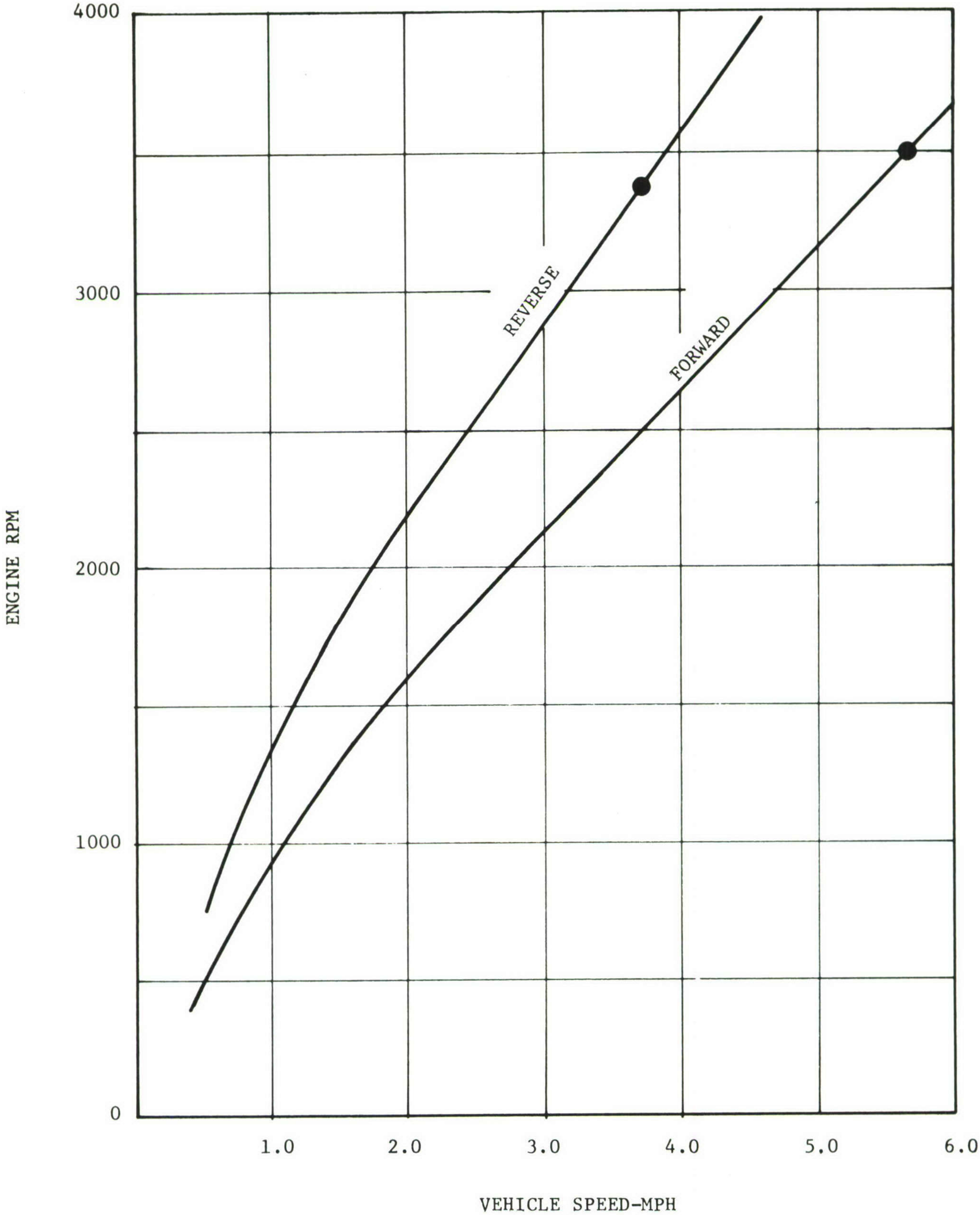
High Speed turn of M-113 Vehicle Equipped with Waterjet Propulsion Kit

Figure 13



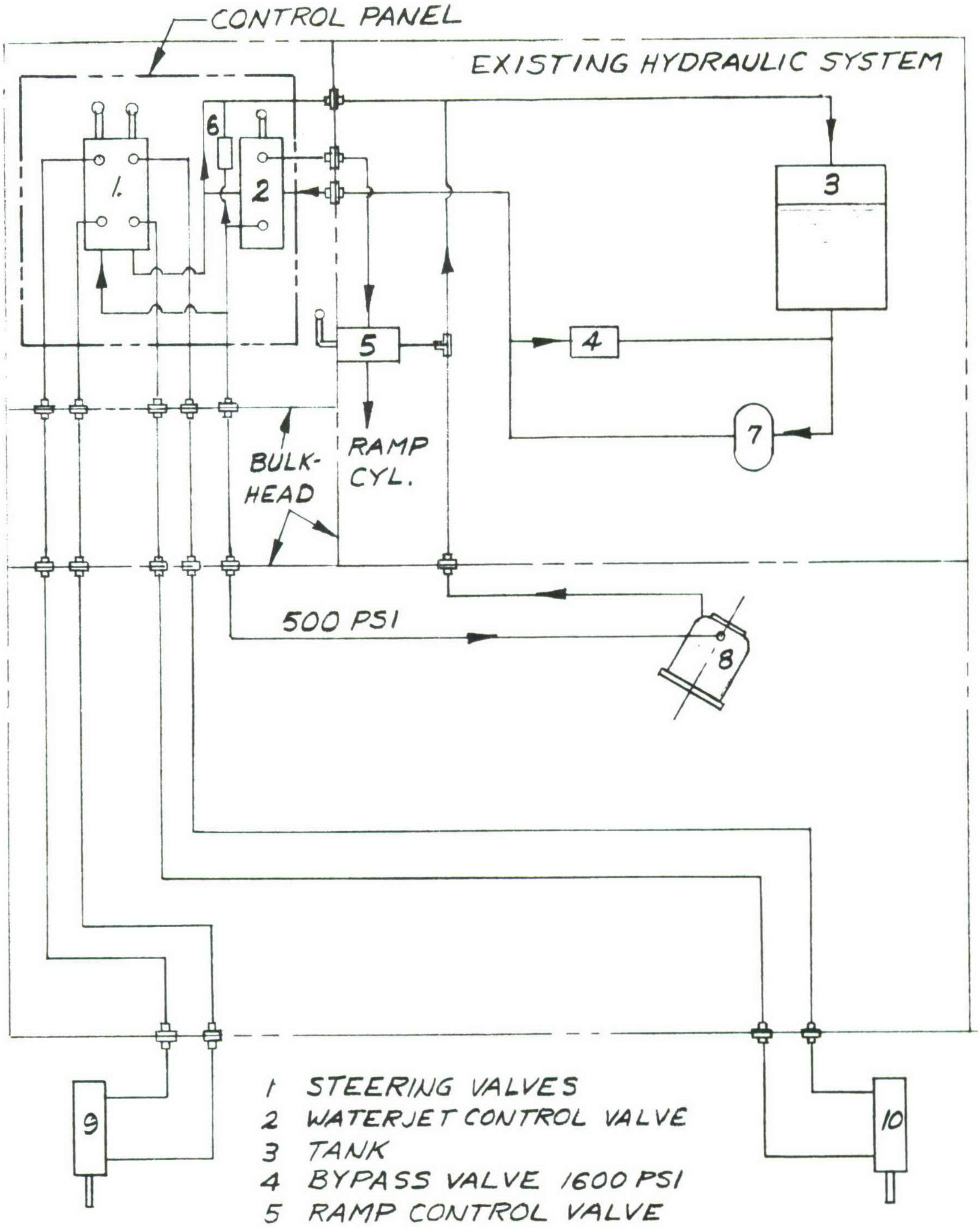
Waterjet Propulsion Kit Performance M-113 Armored Personnel Carrier

Figure 14



Water Speed Versus Engine RPM M-113 Armored Personnel Carrier

Figure 15



1 STEERING VALVES
2 WATERJET CONTROL VALVE
3 TANK
4 BYPASS VALVE 1600 PSI
5 RAMP CONTROL VALVE
6 BYPASS VALVE 500 PSI
7 PUMP
8 WATERJET HYDRAULIC CLUTCH
9 LEFT WATERJET CYLINDER
10 RIGHT WATERJET CYLINDER

WATERJET
HYDRAULIC CONTROL SYSTEM

FIGURE 16

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