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Development of an Air-Driven Alternator for the XM734 Light-Weight Company Mortar Fuze

Air-Driven Alternator for the XM734 Light-Weight Fuze, by Chris E. Spyropoulos

U.S. Army Materiel Development
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Adelphi, Maryland 20783

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Development of a turbine/alternator (T/A) power supply which also provides a second arming signature for the 60-mm Light-Weight Company Mortar Fuze, designated the XM734, has been advanced to include a production-engineered design. The XM734 fuze has undergone extensive advanced development testing, with the T/A having provided highly satisfactory operation. The XM734 T/A, described herein, is a cost-effective version of an earlier development model.

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TABLE

1. INTRODUCTION

An air-driven power supply has been developed for the XM734 Multi-Option Fuze for Mortars that converts the ram-air energy available to a projectile in flight into electrical energy to power the fuze. This power supply also furnishes an arming signature based on projectile velocity.

MIL-STD-I316A specifies requirements of two independent environmental safety signatures to achieve rotor arming. The first arming signature is obtained at launch from acceleration or setback forces, while the second is provided by ram air which rotates the alternator shaft and arms the safety & arming device (S&A) after a predetermined number of shaft rotations have occurred during projectile flight.

Previous reports[1-3] have described the development of the alternator to meet the various fuze requirements. Emphasis has been on the alternator itself, including the production of suitable electrical energy for all mortar trajectories and operation in adverse environments. These efforts have culminated in the alternator shown in figure 1, referred to as engineering development (ED) model 3, which can be produced by high production techniques.

Initial tests of this device with other fuze components showed that rotational speed reduction and proper bearing lubrication were needed in order to achieve successful field-test results. These studies are discussed in this report, which also gives the characteristics of the alternator with these improvements.

To further reduce the cost of the alternator in production, a new design was developed that incorporated cheaper bearings instead of costly miniature precision bearings and eliminated machined parts. This design and its present status in the fuze program are briefly discussed.

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[1] *Carl J. Campagnuolo and Jonathan E. Fine, Development of the HDL Air-Driven Rotary Generator to Power a 60-mm Fuze, Harry Diamond Laboratories TM-72-8, Washington DC (March 1972).*

[2] *Carl J. Campagnuolo and Jonathan E. Fine, Development of an Air-Driven Alternator for 60-mm Mortar Application - Phase II, Harry Diamond Laboratories TM-73-7, Washington, DC (May 1973).*

[3] *Carl J. Campagnuolo and Jonathan E. Fine, Development of an Alternator for the Multi-Option Fuze for Mortars, 27th Annual Proceedings, Power Sources Conference (June 1976).*

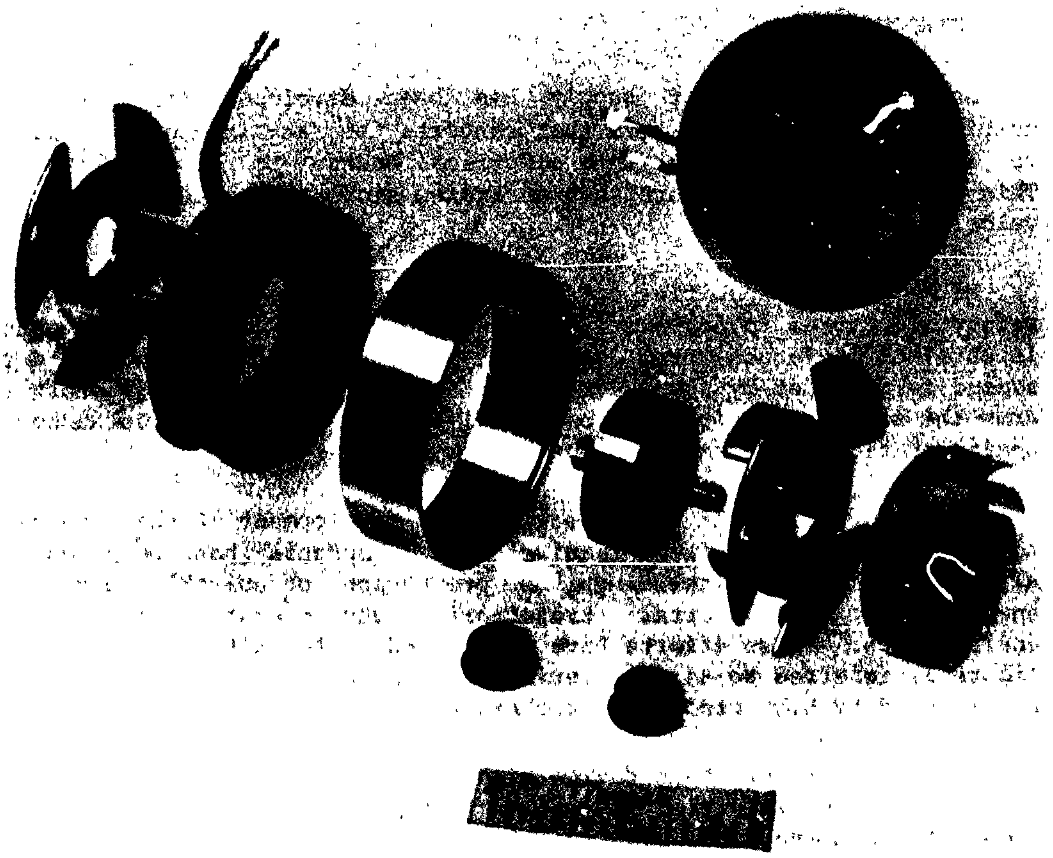

Figure 1. Model 3 turbine/alternator components and assembly.

2. T/A DESCRIPTION

Figure 1 shows the production-engineered model turbine/alternator (T/A) developed at Harry Diamond Laboratories (HDL). This unit can produce the electrical energy required by the XM734 fuze and can also provide the required second S&A signature. During the flight of a mortar projectile, the T/A operates from the ram air it receives through a venturi tube at the nose of the projectile. The air rotates a turbine, which is attached to the shaft of a magnetic rotor. The rotor contains a cylindrical six-pole permanent magnet, which is free to rotate within six stator poles formed by the alternator's end plates. The end plates and a mounting ring enclose a wire-wound bobbin. The rotor assembly is mounted on precision bearings located between the poles of the stator, and the assembly induces an electromotive force (emf) in the bobbin coil. The T/A electrical output is delivered from the bobbin leads. The aft end of the rotor shaft is slotted to mate with the S&A mechanism.

The concentric shaft extends through the rotor and engages a gear-reduction system to arm the S&A. After arming, the gear-reduction system disengages from the alternator, allowing the shaft to spin free of the S&A load. The rotational speed of the shaft under S&A load determines the mechanical arming time, since a specified number of revolutions are required to arm the fuze. The rotational speed is established by the ram air passing through the turbine and varies with the round velocity along the flight trajectory.

Figure 2 shows the location of the T/A within the XM734 fuze. It is located immediately behind the fuze electronics and in front of the S&A. The T/A shown in this figure was produced by the Eastman Kodak Company and is based on the Model 3 design developed at HDL.

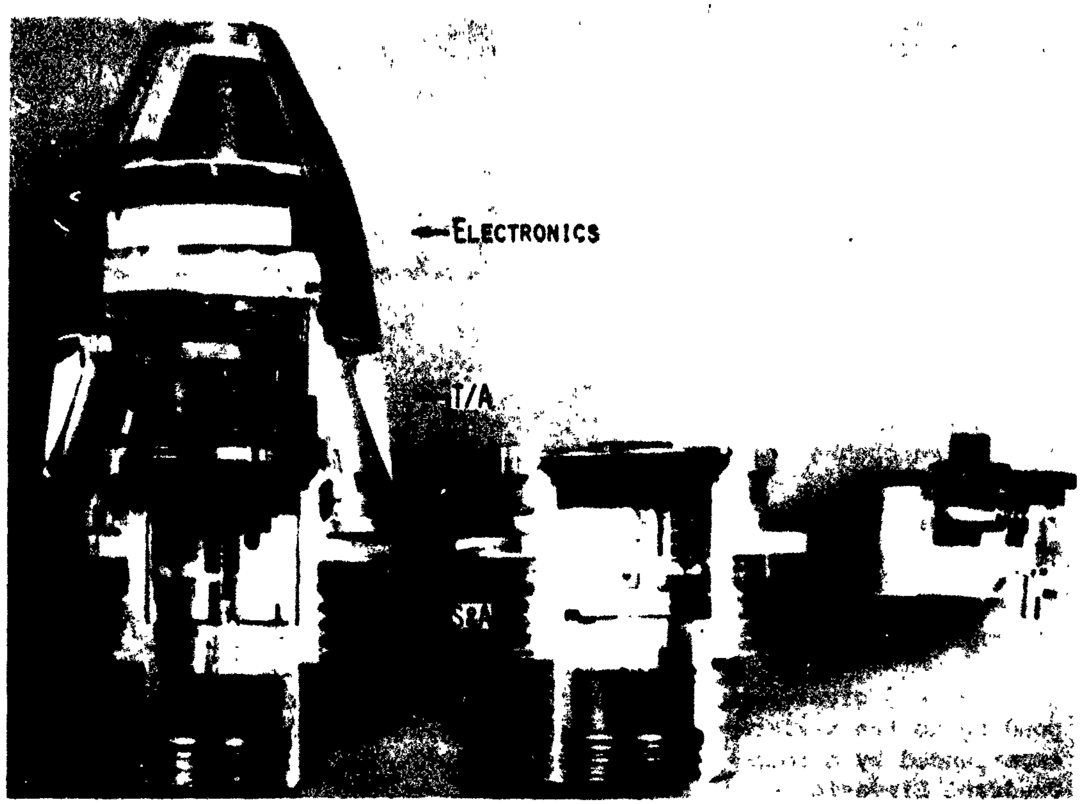

Figure 2. Location of turbine alternator within XM734 fuze.

3. LIMITING ROTATIONAL SPEED

The specified minimum safe arming distance for the fuze is 100 m (about 328 ft) from the gun. Initial tests of the alternator mated with the S&A showed that the alternator rotational speed was too high, which caused the S&A to arm below the required arming distance. This indicated that limitation of the alternator-shaft rotational speed was needed.

To attain speed limitation, the turbine blade tips were undercut (fig. 3) to obtain radial flexure of the tips from centrifugal force, at the higher turbine speeds, thus reducing the turn angle of the air flow through the blades. To determine the optimum speed reduction from blade tip undercut, a series of tests at room temperature (70°F, 21°C) were conducted in the lab. Turbine speed versus input pressure was measured with turbines molded of Type 66 nylon. The turbines were modified by machine-undercutting blade tips to result in test items with base diameters of 0.82 to 0.69 in. (20.83 to 17.53 mm).

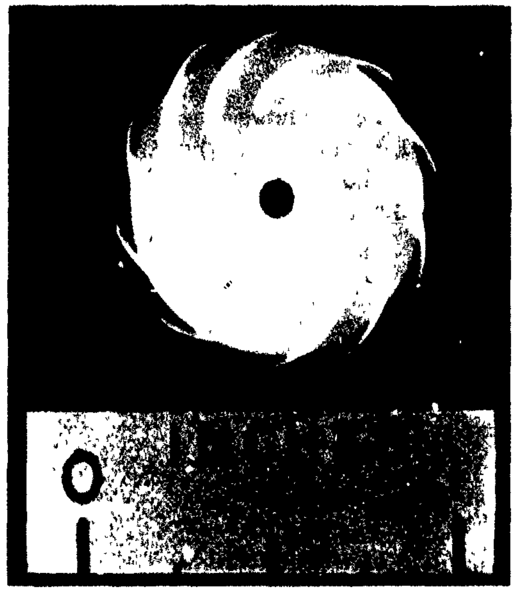

Figure 3. Turbine with undercut blades to limit alternator shaft rotational speed.

The test item with instrumentation for these tests is shown in figure 4. Regulated air from a settling chamber enters directly into the inlet of a fuze ogive, which houses the T/A. The output frequency of the T/A is measured across a 600-ohm resistor. Stagnation pressure in the settling chamber is monitored with a strain-gage pressure transducer. Alternator frequency versus inlet stagnation pressure is then recorded on an X-Y recorder. The turbine rotational speed may be obtained directly from the alternator frequency by multiplying the alternator frequency by 20.

Figure 5 gives resulting turbine speed at an inlet pressure corresponding to the maximum analytically predicted dynamic pressure that is experienced by a round when fired at 70°F (21°C) (sea level) with a Quadrant Elevation of 45 deg, versus the undercut base diameter. From this curve it is seen that maximum shaft speed decreases with decreasing turbine base diameter. The corresponding shaft speed decreases from 140,000 rpm for the nonundercut base (0.850 in., 21.59 mm) to 82,000 rpm

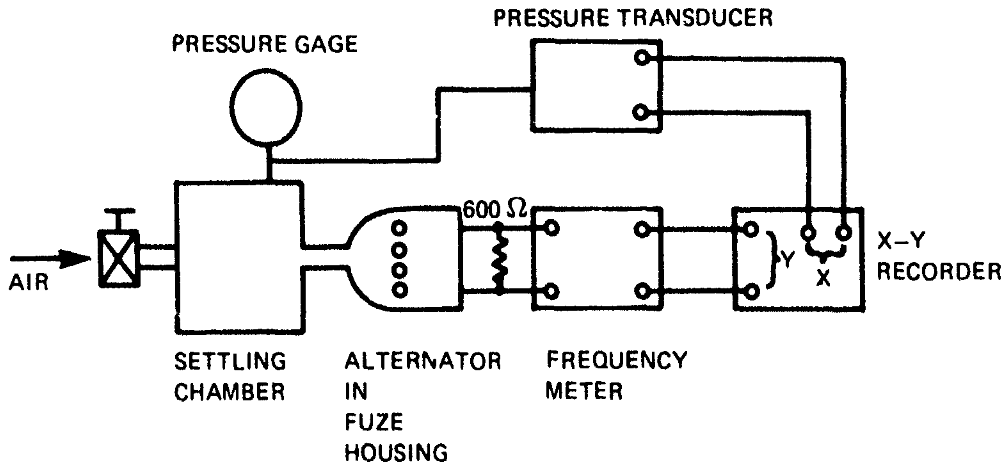

Figure 4. Laboratory test arrangement for measuring operating characteristics of alternator.

for the turbine with a base diameter of approximately 0.73 in. (18.54 mm).

Although speed limiting is desired at the higher flight velocities, the mechanism which produces the limiting should not affect turbine performance at low flight velocities. This means that no significant speed reduction should take place at the minimum fuze operational inlet pressure (0.206 psig) (1.42 kPa). This is the pressure that exists at the minimum flight velocity of 160 ft/s (48.8 m/s). The turbine base diameter that was selected from the tests that meet this criteria was 0.76 in. (19.30 mm) in diameter. This unit, designated A-1, was molded from Type-66 nylon and is shown in fig. 3. In order to evaluate T/A performance at the low speed, with the A1 model, plots were recorded of alternator frequency versus inlet pressure to the alternator with an A1 turbine installed in a fuze ogive. Similar data were obtained with a nonundercut turbine.

Figure 6 presents typical data for each type of turbine. It is seen that there is no degradation of alternator frequency at 0.206 psig (1.42 kPa), with turbine A-1. The degradation of frequency at the inlet pressure at minimum round muzzle velocity, 0.40 psig (2.76 kPa), is 6 percent. This is considered to be an acceptable level, because the power output is sufficient to operate the fuze. The effect of this frequency degradation on fuze arming time is considered to be negligible.

This turbine was tested over the required operating temperature range (-60° to 160°F, -51 to 71°C). Figure 7 shows the instrumentation

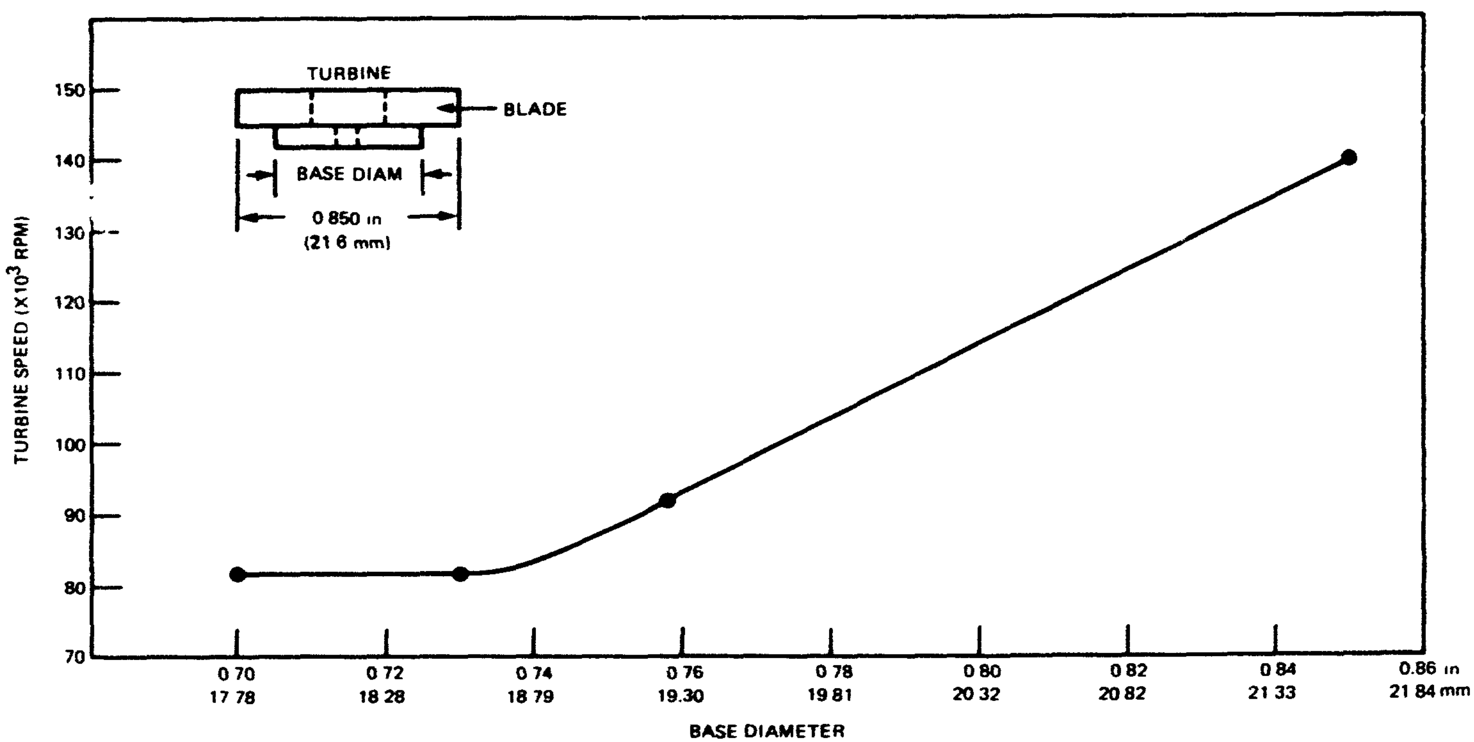

Figure 5. Turbine speed at maximum simulated projectile velocity versus undercut of base diameter.

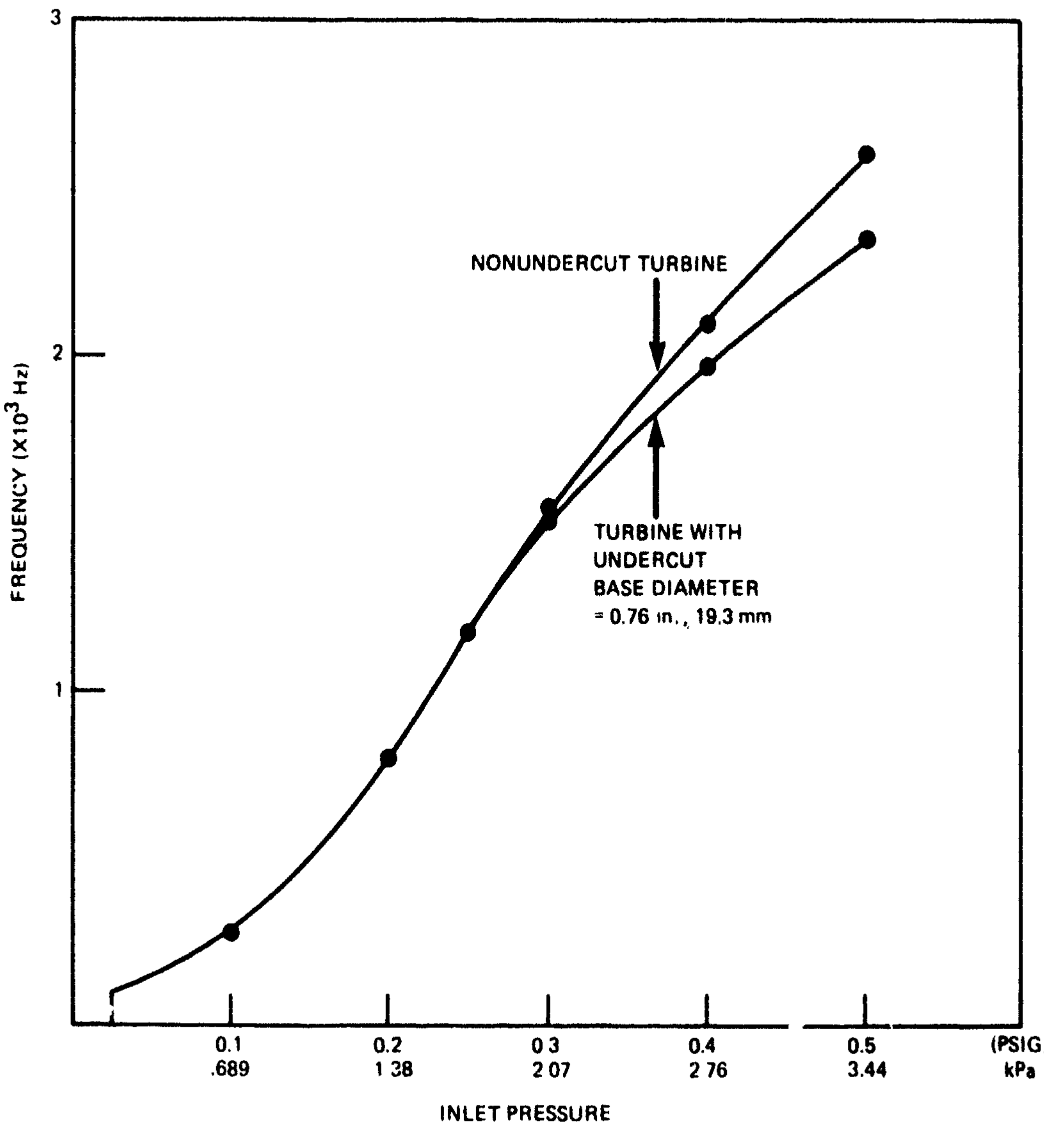

Figure 6. Effect of diameter of turbine undercut on alternator frequency versus inlet supply pressure.

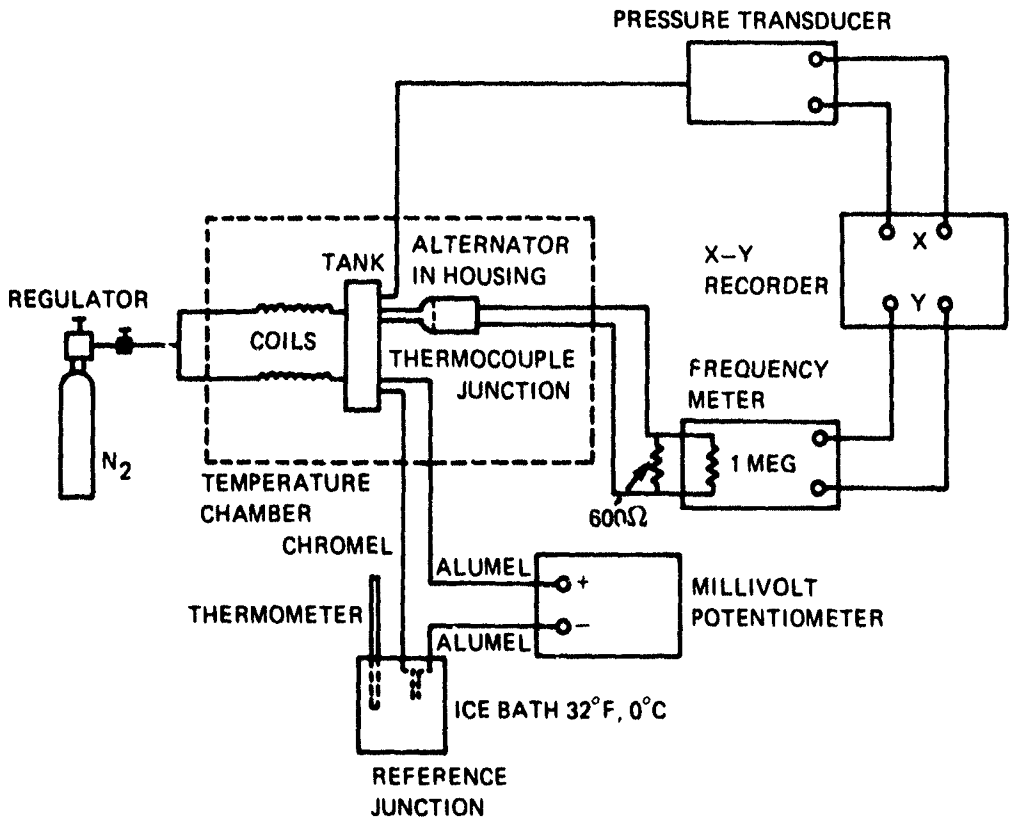

Figure 7. Experimental arrangement for studying effect of temperature on alternator output.

for these tests. The alternator housing, settling chamber, and preconditioning coils were located within a temperature conditioning chamber. For these tests, dry nitrogen was used as the working fluid. The nitrogen is temperature conditioned as it passes through the copper coils to the T/A, so that its temperature is nearly identical to the conditioning chamber temperature when it enters the T/A inlet.

When conducting these tests, the test unit is temperature conditioned for a minimum of two hours; then the inlet pressure to the T/A is set to correspond to the expected maximum flight velocity. The unit is then operated at this pressure for 60 s, and its frequency is recorded as a function of inlet pressure. Each unit is tested at temperatures of -60, 70, and 160°F (-51, 21, and 71°C). Typical data from these tests are shown in figure 8. Although turbine speed at a given inlet pressure varies with temperature, the power delivered at the temperature extremes is sufficient to operate the XM734 fuze. The five A-1 turbines, subjected to this test procedure, performed satisfactorily.

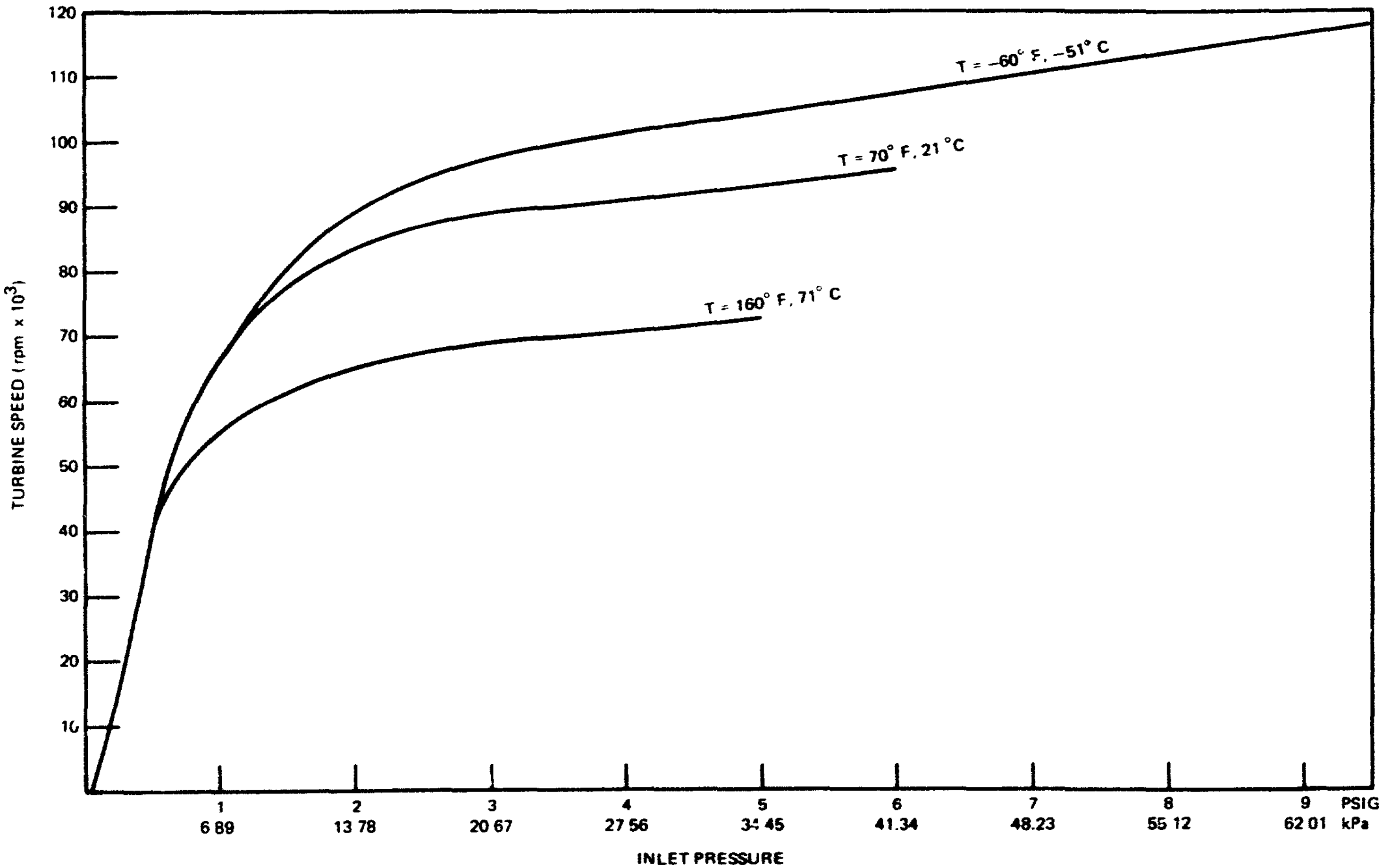

Figure 8. Shaft speed versus inlet stagnation pressure for three conditioning temperatures.

This speed-reduction technique also reduced bearing wear by lowering the maximum rotational speed and paved the way for the low-cost bearings discussed in a later section of the report.

4. BEARING LUBRICATION STUDIES

During cold temperature firing of XM734 fuzes during the engineering development phase of the test program, it was discovered that the S&A's were not arming when they were fired at charge 0. Test units employed for these tests were conditioned at -40°F (-40°C) and then fired at ambient temperature. Because of change in lubricant viscosity with temperature, bearing lubrication was suggested as a possible cause of this problem. A study was undertaken to investigate the effects of bearing lubrication on cold-temperature T/A operation.

Three methods of bearing lubrication were investigated to identify whether or not bearing lubrication contributed to the arming problem, and to select an alternate method of lubricating the bearings if necessary. The three lubrication methods investigated consisted of (1) soaking the bearings in oil (as supplied by the manufacturer), (2) lubricating the bearings with a film of Anderoil 501, obtained by dipping bearings in a 96-percent Freon, 4-percent Anderoil 501 mixture, and (3) removing all lubrication so that the bearings were dry.

Test units were assembled with bearings lubricated as described, and start-up characteristics were obtained, employing the instrumentation shown in figure 9. The inlet pressure to each test T/A for all runs was held at 0.30 psig (2.07 kPA). This pressure was chosen as being

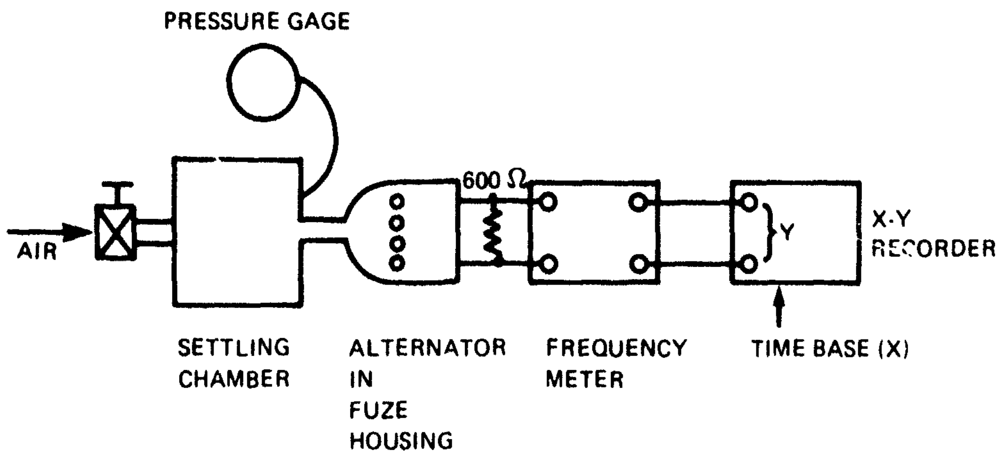

Figure 9. Laboratory test arrangement for measuring alternator start-up characteristics.

representative of the minimum average inlet pressure that would be experienced by a T/A during a mortar firing at charge 0. Starting characteristics of the T/A were generated by first setting the inlet pressure while maintaining the rotor stationary. The rotor was then released and allowed to rotate, and the turbine speed was monitored as a function of time.

Figure 10 gives start-up characteristics at 70°F and -40°F, (21 and -40°C,) of test T/A's with bearings lubricated with the three different methods. Unit No. 447 consisted of bearings soaked in oil, as received from the manufacturer. Unit No. 443 consisted of bearings that were dry, while unit No. 442 had bearings oiled with 96-percent Freon and 4-percent Anderoil 501. Time required for the rotor speed to come up to 30,000 rpm was measured from the graphs for all tests. This information is given in table I for comparison of times.

The effect of cold-temperature conditioning on T/A start-up time is readily obtained from these data. The start-up time to 30,000 rpm of the unit with oil-soaked bearings, unit No. 447, increases by 60 percent when it is conditioned at -40°F (-40°C), while the startup time of the other two units increases by about 7 percent. This was considered to be conclusive evidence that the previous method of lubrication adversely affected arming time, and that an improved lubrication method was needed.

The two alternate lubrication methods were further investigated. This investigation consisted of subjecting four samples of T/A's assembled with bearings lubricated with 4-percent Anderoil 501 and 96-percent Freon, and four test samples of T/A's assembled with dry bearings to the testing procedure specified for turbine validation in section 3.

This test procedure consisted of pretemperature-conditioning each unit at -60, 70, and 160°F (51, 21, and 71°C) and then operating the unit at each conditioned temperature for 60 s. The inlet pressure to the unit for each run was set to correspond to the expected maximum flight velocity at that temperature. Alternator frequency was recorded as a function of inlet pressure for each run. If each unit's performance was not degraded as a result of these tests, then the probability of a similar unit performing adequately during actual flight environments would be very high. All samples exhibited satisfactory performance based on these tests.

Bearing lubrication with 4-percent Anderoil 501 and 96-percent Freon was selected for the XM734 T/A. This light film lubrication is considered sufficient to protect the bearings during storage. The increase in alternator start-up time at -40°F (-40°C) with this method of lubrication was considered acceptable.

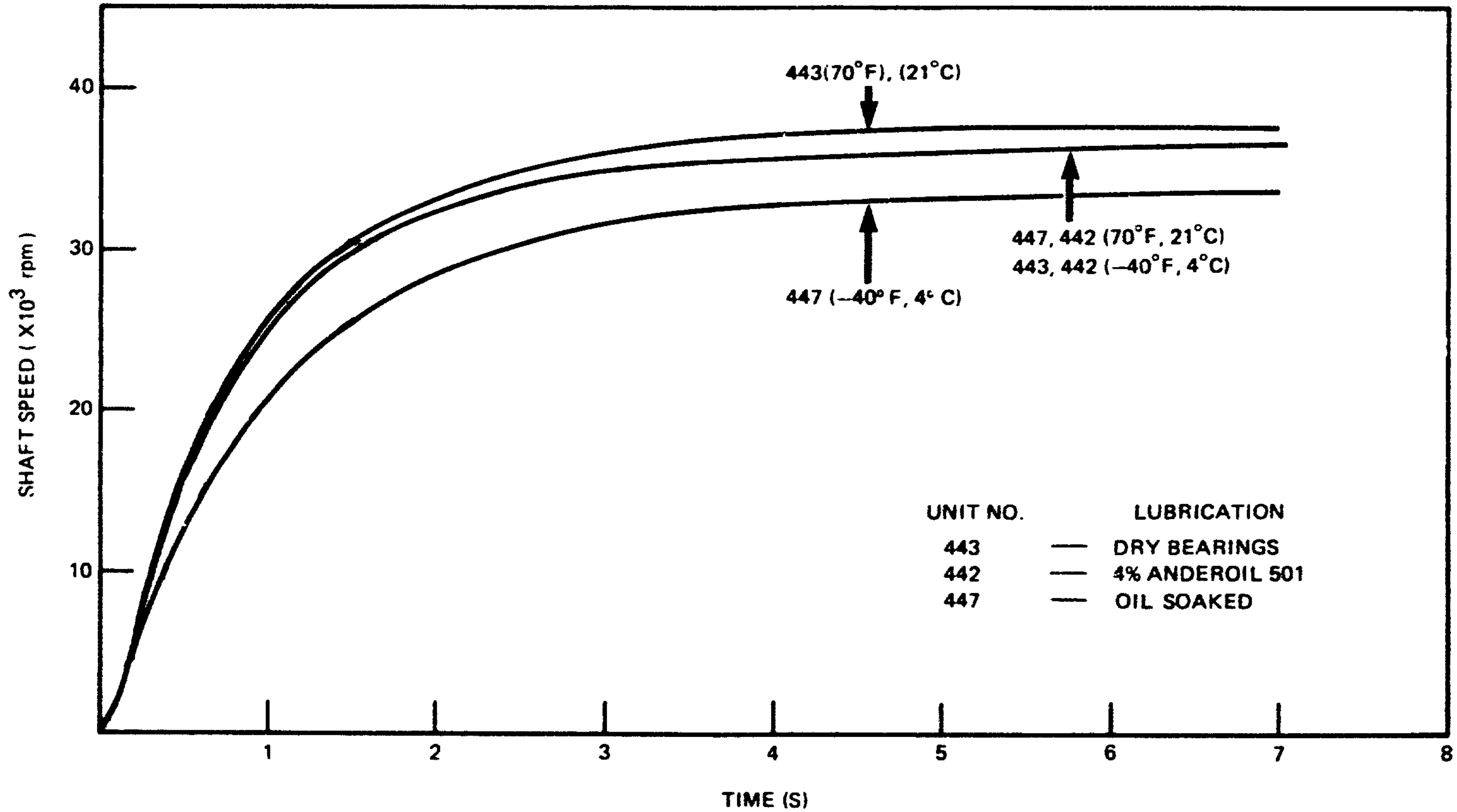

Figure 10. Start-up characteristics of engineering development Model 3 T/A's with three different methods of bearing lubr..ation.

TABLE I. COMPARISON OF START-UP TIMES

Unit No.	Time to Reach 30,000 rpm (s)	
	Unit Conditioned at 70 F (21 C)	Unit Conditioned at -40°F (-40°C)
447	1.5	2.4
442	1.4	1.5
443	1.4	1.5

5. T/A PERFORMANCE

Figure 11 gives performance curves for a typical HDL research and development (R&D) 600-Series T/A. Comparing these curves with similar ones given for the production-engineered version, designated Model 3 (fig. 12), shows that power output of the Model 3 unit is greater at projectile velocities below 212 ft/s (64.6 m/s). This is due to the fact that the Model 3 unit employs a turbine with improved efficiency. Use of this improved turbine yields higher shaft speed for this unit up to approximately 450 ft/s (137 m/s). At higher airspeeds, rotor-speed limiting incorporated in the Model 3 turbine results in lower shaft speeds for this unit. The improvement in power output of Model 3 over the R&D model T/A is approximately 32 percent at the mortar-round minimum terminal velocity (160 ft/s, 48.8 m/s).

A contractor, Eastman Kodak, has produced prototype XM734 fuzes--including T/A's--as part of the fuze engineering development program. Contractor-furnished T/A's have essentially the same characteristics as the Model 3, HDL units.

Extensive environmental safety and field tests have been conducted on the XM734 fuze. The results of these tests will be reported by the XM734 Fuze Project Office as part of its final report. The T/A has passed the required environmental and safety tests. In firings of about 1,000 rounds, the T/A has demonstrated reliable performance.

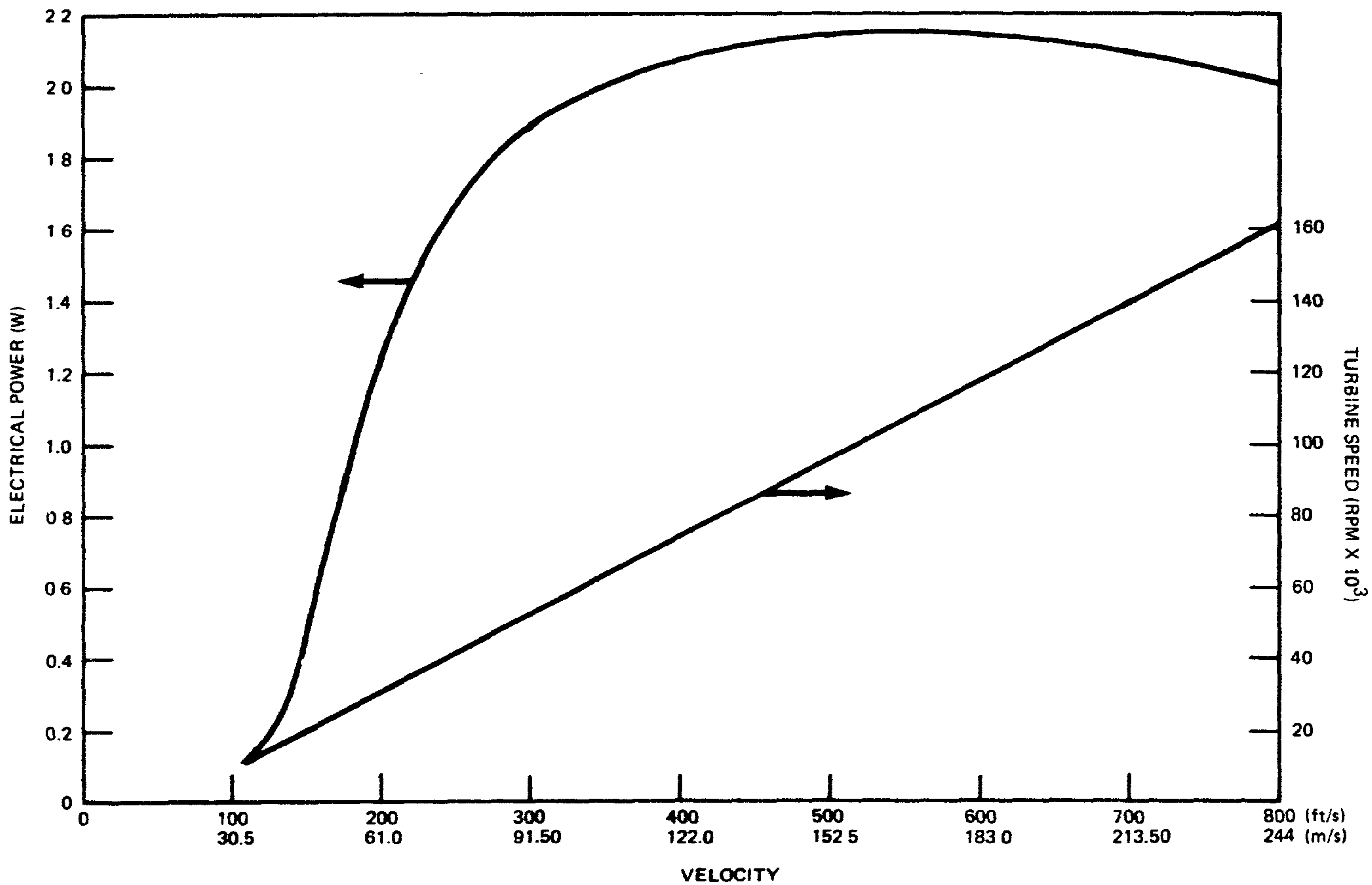

Figure 11. Electrical power output and rotational speed of 600-series alternator over velocity range of Light-Weight Company Mortar System.

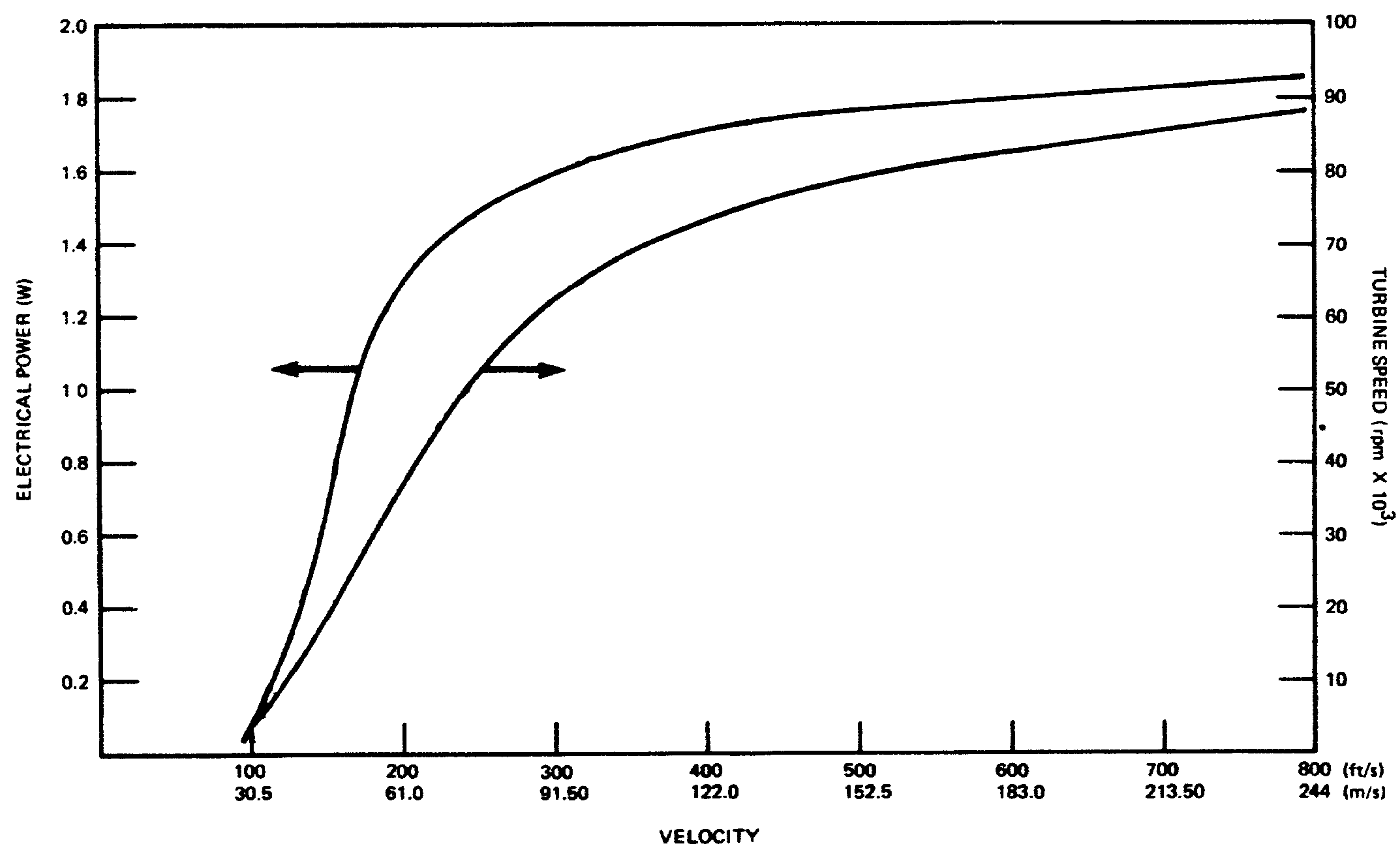

Figure 12. Electrical power output and rotational speed of engineering development Model 3 T/A over the velocity range of the Light Weight Company Mortar System.

6. COST-REDUCTION STUDIES

Cost-reduction studies were performed. The obvious cost saving is the replacement of the precision bearings. Studies were conducted on various types of sleeve bearings. Of those tested, graphite-impregnated carbon bearings were the only types that could survive the high-speed operational requirements. After extensive testing, graphite-impregnated carbon bearings were ruled out, because precise manufacturing tolerances are required between the bearings and the shaft diameter. These bearings also required a run-in for operation at high speed. While lower in cost than precision ball bearings, the graphite-impregnated carbon bearings are still fairly expensive to manufacture.

A contract was awarded to the Alinabal Company, a division of the MPB Corporation, to develop a low-cost stamped bearing, using the same basic dimensions as the bearing in use with the XM734 T/A. However, the low-cost bearing requires the shaft to be the inner race. With the precision-stamping technique, the balls are captured within the retainer, which is also the outer bearing race.

Investigation of the T/A performance with these bearings was initiated. The T/A's, shafts, and end plates were modified. Inner bearing races and curved shoulders for containment of the bearings were machined on the shafts. Bearing retainer cups were attached to front and rear end plates. This design is shown in figure 13.

Test units were assembled and then subjected to maximum mortar set-back forces (charge 4). The bearings were temperature conditioned and subjected to laboratory operation for turbine testing, as described in section 3. This consisted of pretemperature-conditioning each unit at -60, 70, and 160°F (-51, 21, and 71°C) and then operating the unit at each conditioned temperature for 60 s. The inlet pressure to the unit for each run was set to correspond to the expected maximum flight velocity at that temperature. Alternator frequency was recorded as a function of inlet pressure for each run. The results of these tests indicated that these bearings can replace the precision bearings for use with the XM734 fuze.

As a result of these tests, a new T/A was designed and a contract was let with Alinabal to produce parts for qualification of this design. Figure 13 shows the assembly and the components of this new design. This low-cost design differs from previous designs in that: (1) it employs stamped, inexpensive bearings rather than precision, ground bearings, (2) it contains a cold-formed rather than a machined shaft, (3) the magnet is attached to the shaft by inexpensive plastic injection rather than with the more expensive die-cast zinc, which is currently used, and (4) the housing, stamped as part of one end plate, eliminates the requirement for a fairly costly machined mounting ring. The

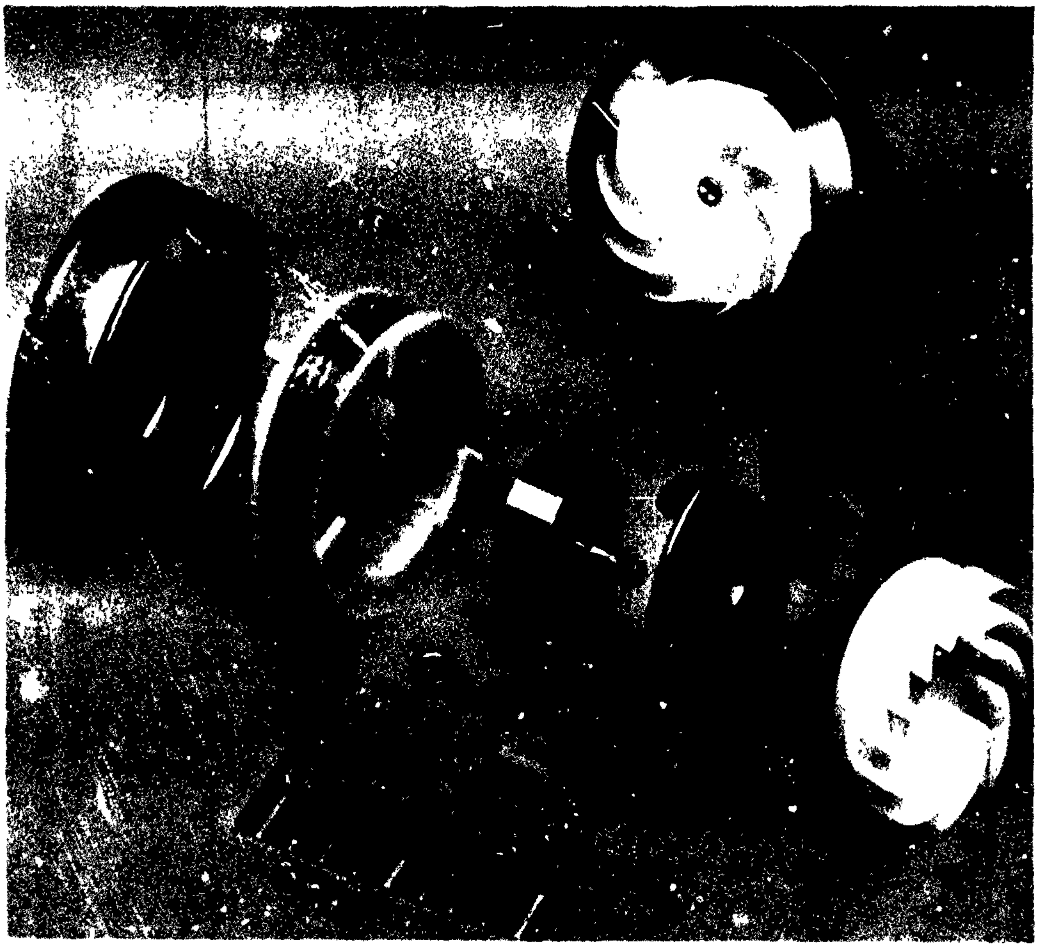

Figure 13. Cost-reduced turbine/alternator components and assembly.

estimated cost of this unit in high production is about $1.50 versus $4.50 in FY77 dollars for the current design. This estimate was developed in the course of a Manufacturing Methods Technology project proposal submitted to the Project Manager for Munitions Production Base Modernization and Expansion.

Component parts for 2,000 units were received for assembly of test items, and the initial phase of qualification testing was begun. Initial laboratory and set-back testing has demonstrated that the T/A should perform satisfactorily in flight with the XM734 fuze. Figure 14 gives a typical curve of power output and shaft speed as a function of velocity for this unit. Comparing these curves with those for the

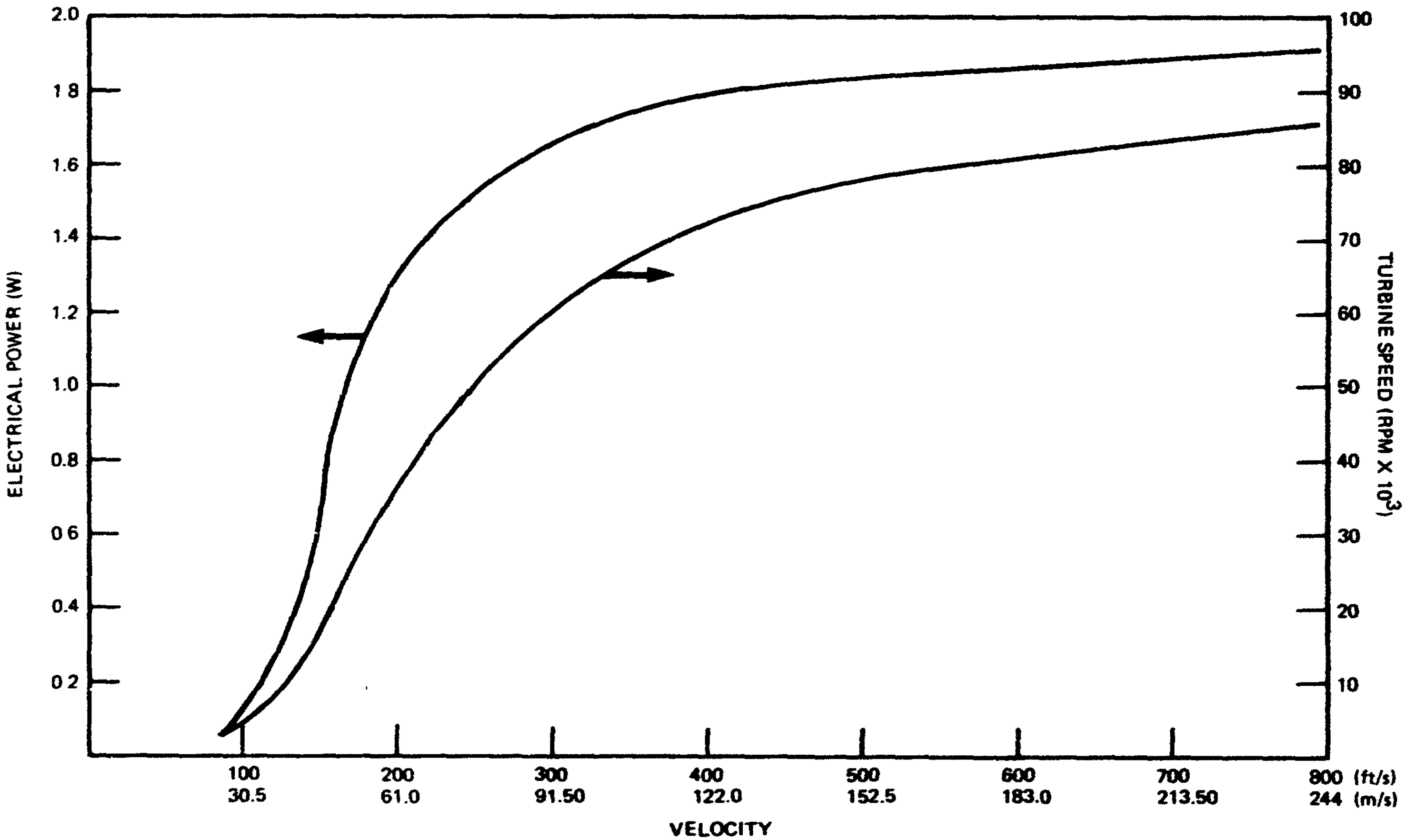

Figure 14. Electrical power output and shaft rotational speed of reduced-cost alternator over velocity range of 60-mm Light-Weight Company Mortar System.

production-engineered version (Mod 3, fig. 12) shows that the performance curves of each are in complete agreement, differing by less than 5 percent over the velocity range. Based on the data for these T/A's, it is expected that the new T/A should be a direct replacement for the existing XM734 fuze T/A. Additional laboratory testing and qualification flight testing is currently being planned.

7. SUMMARY AND CONCLUSIONS

Development of a T/A power supply, which also provides a second arming signature for the 60-mm Light-Weight Company Mortar, has been advanced to include a production-engineered version of an earlier development model. More recently, a reduced-cost production model is undergoing evaluation. Initial development, described by Campagnuolo and Fine[1,2] was concentrated on designing a T/A to meet fuze environmental and functional requirements. The initial model that resulted from this development was redesigned to permit cost-effective, high-volume production, while meeting fuze requirements. The XM734 fuze, including the T/A, has undergone more than 1,000 flight tests with the T/A providing highly satisfactory operation. In addition, the XM734 fuze has been subjected to safety and environmental testing; no failure has been attributed to the T/A.

The current T/A includes an increased efficiency turbine with high-speed limiting characteristics. This results in an increase in alternator power output for projectile velocities up to 225 ft/s (68.6 m/s) and a reduction in shaft speed from a maximum of 140,000 rpm down to 96,000 rpm, based on laboratory tests.

A design for a significantly reduced-cost T/A has been developed. It differs from the previous design in that it employs inexpensive, stamped bearings fit into cups in the end plate and housing, rather than precision, ground race bearings. This new design has a cold-formed shaft and uses molded plastic between the shaft and the magnet, rather than more costly die-cast zinc. It employs a housing stamped as a part of one end plate, thus eliminating the need for a costly machined mounting ring. The estimated cost for this unit in high-volume fuze production is $1.50 versus $4.50 in FY77 dollars for the current T/A. Parts for assembly and test of 2,000 units have been manufactured for qualification tests. Initial laboratory and set-back tests have demonstrated that the T/A should perform satisfactorily in the field.

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[1] *Carl J. Campagnuolo and Jonathan E. Fine, Development of the HDL Air-Driven Rotary Generator to Power a 60-mm Fuze, Harry Diamond Laboratories TM-72-8, Washington, DC (March 1972).*

[2] *Carl J. Campagnuolo and Jonathan E. Fine, Development of an Air-Driven Alternator for 60-mm Mortar Application - Phase II, Harry Diamond Laboratories TM-73-7, Washington, DC (May 1973).*

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