DRIVING PARALLEL FLASHLAMPS WITH A COMPENSATED PULSED ALTERNATOR

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Abstract

Test results are given for a prototype Compensated Pulsed Alternator that was operated up to its 5400 RPM design speed. The machine has delivered approximately 140 kilojoules of energy in a single 1.3 millisecond pulse into a load comprising sixteen parallel flashlamps. The energy delivered to the lamps follows a $W = (RPM/225)^4$ scaling law to about 4200 RPM. Beyond that speed, eddy current losses become significant with the present design. New codes are able to model the machine parameters, and the prototype is presently being rebuilt to reduce the high speed losses predicted by the codes and verified by experiment.

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Summary

A prototype Compensated Pulsed Alternator, or "Compulsator" has been given its first proof of principle demonstration tests. It has been run to full speed -- 5400 RPM -- and it has been repeatedly discharged into a parallel flashlamp load, delivering up to 140 kilojoules of energy in a 1300 microsecond pulse. The purpose of the test was to measure the factors that determine the energy delivered by the Compulsator into a representative flashlamp load. The ultimate goal is to replace a capacitive energy store with a very large inertial energy store of the Compulsator type for new large lasers.

The test results indicate that the energy delivered to flashlamps follows a fourth-power scaling law with machine speed up to about 4250 RPM. At the optimum firing angle of about 45^{o} before minimum inductance, the prototype delivered a net energy of $(RPM/225)^{4}$ joules to a 16-parallel lamp load, or 127 kJ at 4250 RPM.

At 4800 RPM, the energy delivered was 139 kJ, or only 67% of the fourth-power prediction. Computer circuit modeling indicated that this deficit is due to a probable eddy-current loss that becomes significant at the higher speeds.

New codes to model the Compulsator have now been developed that are being used to treat this problem quantitatively. A physical mockup of

the machine windings has also been made, and tests are underway to determine the optimum design for rewinding the prototype machine, including the use of eddy-current shields.

A new series of dynamic tests of the prototype Compulsator will be undertaken after the machine is reassembled. The results of this work will be used for the design of a large inertial-store pulse generator for application in very large future laser systems. It is anticipated that the next generation machine will deliver the order of 10 megajoules of energy to flashlamps in less than one millisecond.

Prototype Description

A picture of the prototype Compulsator is given in Fig. 1. It is surrounded by a steel torque frame and housed in a six-foot deep pit. It is driven by a timing belt and a 125 HP DC motor.

An outline drawing of the machine is given in Fig. 2. It has a vertical shaft and a 15-inch diameter by four-foot long laminated steel rotor. The torque frame is about five feet square and six feet high overall. The complete machine, including rotor, poles, backiron, bearings, and torque frame weighs 22,000 lb.

Electrical Test Circuit

The output of the prototype Compulsator was designed to drive sixteen parallel Shiva laser flashlamps. Each lamp is a 15-mm i.d. quartz tube, filled with 300 Torr xenon, and each lamp has a 44-inch arc length. The simplified test circuit that drives these lamps is given in Fig. 3.

Flashlamp balancing is achieved by use of the parallel inductors shown in each lamp circuit.[1] The fuses protect against faults in these circuits. The diodes in the Compulsator circuit are used to help the ignitron switch extinguish, preventing follow-on pulses. In addition, a vacuum relay that opens in about 11 milliseconds is located in the Compulsator circuit. This relay is timed to open soon after the first zero crossing of the output current pulse.

The startup capacitor serves the dual function of providing flashlamp trigger energy and initial current flow through the Compulsator. At the proper machine angle, the machine's computer sends a trigger pulse to a master timing unit. This unit then provides triggers to the vacuum relay and to the pulse transformer that bumps the flashlamp reflector, causing the lamps to break down. The timing unit also fires the output ignitron switch.

The initial current in the flashlamps is in the negative direction, driven by the startup capacitor. Current also flows in the Compulsator circuit, and the voltage across the capacitor quickly reverses direction until it reaches the output voltage level of the machine. Current then flows in the positive direction through the flashlamps as energy is delivered by the Compulsator. The initial energy stored in the startup capacitor need only be 5% or 10% of the energy delivered by the machine. With a large Compulsator, this energy will probably be 2% or less.

Electrical Monitors

The current in each flashlamp circuit was monitored with current transformers, or "bugs" designed for LLL. With these bugs, we determined that lamp balancing was achieved in all sixteen circuits to within a few percent. The current from four of the sixteen circuits was also monitored with a Pearson 50 kA current transformer. The voltage across the lamps was monitored with a differential pair of Tektronix high voltage probes. The calibrated accuracy of these monitors was measured to 2% or better. Tektronix storage scopes were used to record the data.

Measurements and Data Analyses

The flashlamp current was monitored on thirteen discharges of the prototype machine at nominal operational speeds from 2400 to 4800 RPM. A premature fault occurred inside the machine on a 5400 RPM shot that caused damage to the windings. As a result, this series of tests was terminated without obtaining the maximum speed, 5400 RPM data.

Flashlamp voltage was obtained on a few shots late in the series. Earlier measurements were invalid due to faulty calibration and noise in the voltage probes. The voltage and current traces from a 4800 RPM shot are presented in Fig. 4.

Because flashlamp current measurements were made on all shots that were set up to provide an electrical output, the data can be compared by use of the relationship,[2]

$$W_T = fki_p^{3/2}\Delta t \qquad (1)$$

This formula states that the total energy W_T delivered to the flashlamps is proportional to the peak current i_p to the three-halves power times the current pulse halfwidth Δt. Two constants of proportionality are used: k is the flashlamp constant and f is a waveshape form factor.[1,2] In the present experiment, k = 21.6 for the sixteen parallel flashlamps.

The form factor f varied between 0.8 and about 1.0 on the series of shots. For simple triangular waveshapes, f = 0.8. With more complicated waveshapes, f was obtained by graphical integration via the formula.

$$f = (\int i^{3/2} dt)/i_p^{3/2}\Delta t \qquad (2)$$

In reducing the data, the net energy W delivered to the flashlamps by the Compulsator was obtained by subtracting the energy stored in the startup capacitor from W_T, the total energy received by the lamps. This total energy, obtained by use of Equations (1) and (2), included the energy delivered to the lamps in the negative current pulse from the startup capacitor.

Test Results

Data from all of the runs that were set up to provide electrical pulses to the flashlamps are summarized in Table 1. In Fig. 5, the net energy delivered by the Compulsator to the lamps is plotted versus machine RPM. (Run number 120 is not included because of low field current on this shot.)

The curve $W = (RPM/225)^4$ is also plotted in Fig. 5. The delivered energy from the Compulsator appears to follow this fourth power curve rather closely. We therefore determined a figure of merit F from the formula,

$$F = W/(RPM/225)^4 \qquad (3)$$

that quantitizes the deviation from this fourth power relationship. This number is given in Table 1 for each run.

In order to assess the possible validity of a fourth power law; we plotted the figure of merit against the mechanical firing angle θ in Fig. 6. Here, θ is the mechanical position of the rotor when the switch triggers are fired. Zero degrees occurs at the position of minimum machine inductance. From the two sets of data, W versus RPM and F versus θ, we ascertain that the delivered energy is rather uniquely determined by the RPM of the machine and by the firing angle θ. This relationship holds up to 4255 RPM, provided the field is held constant. It can be summarized by the equation:

$$W = (m\theta + b)\ (\mathrm{RPM}/225)^4 \tag{4}$$

Here, m = -0.0160 and b = 0.286 when the machine is fired after about minus 45^o and m = 0.0128 and b = 1.57 if the machine fires earlier than this optimum 45^o negative angle.

The percent deviation of the measured value of delivered energy versus the calculated value from Equation (4) is given in the last column of Table 1. Note that all measurements up through 4255 RPM fall within about 3% of the calculated value, or well within the errors introduced in data acquisition and reduction.

In two runs, numbers 84 and 85, the energy in the startup capacitor was increased significantly (to 31.5 kJ from 12.6 kJ). We had expected the net delivered output of the Compulsator to likewise increase. But this did not appear to happen, since the reduced data do not show any measurable difference in net energy. Because of this, it may be feasible to reduce the startup capacitor to well below the 12 kJ level without affecting the delivered output energy.

Three runs above 4255 RPM were made. Two were nominally 4800 RPM. The first of these, run number 120, was triggered when the field current was only 74.8% of full value. The second, run number 121, was a normal shot as far as we could determine. The delivered energy, however, only reached 67% of the value predicted by Equation (4) for the RPM and firing angle chosen. The last shot, run number 122, was an attempt to determine the output energy at full rated machine speed. An internal fault caused damage to the machine windings, however, terminating this series of tests.

A computer model of the complete test circuit was made in order to describe the data of the 4840 RPM shot number 121. This model provides the best fit to the data when a resistive loss term is introduced that is a $(1-\cos\theta)$ function of the machine angle. From these results, it is apparent that eddy current losses become significant in this prototype machine at the higher speeds.

A new space harmonic model for the calculation of inductances and eddy currents in machines of this type has now been developed.[3] Predictions with this model are presently being calibrated and verified by physical measurements, using a mock-up of the prototype Compulsator windings. The results of this work will be integrated into the rebuilding of the prototype machine. We expect thereby to extend the fourth-power scaling to higher speeds, and to deliver up to 200 kilojoules of energy into the flashlamps at the 5400 RPM design speed.

References

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3. W. L. Bird and H. H. Woodson, "Detailed Design, Fabrication and Testing of an Engineering Prototype Compensated Pulsed Alternator", Final Report, UCRL-15213, March 1980.

Figure Captions

Figure 1. Prototype Compulsator Installation.

Figure 2. Components of the Prototype Compulsator.

Figure 3. Simplified Test Circuit.

Figure 4. Run number 121, 4840 RPM. Top Trace: Flashlamp Voltage, 5 kV/division. Bottom Trace: Flashlamp Current, 16 kA/division.

Figure 5. Plot of net energy (W) delivered to flashlamps versus compulsator speed (RPM).

Figure 6. Figure of merit, F, versus firing angle for compulsator runs up to 4255 RPM.

Table 1. Prototype Compulsator Electrical Test Summary

RUN NUMBER	RPM	FIRING ANGLE (DEGREES)	STARTUP CAPACITOR ENERGY (JOULES)	PEAK CURRENT i_p (AMPS)	CURRENT PULSE HALF-WIDTH Δt (μsec)	NET ENERGY DELIVERED TO FLASH-LAMPS W (kJ)	FIGURE OF MERIT F	DEVIATION OF NET ENERGY FROM FOURTH POWER LAW (%)
69	2450	49	10976	8000	1420	13.1	0.935	-0.8
76	3280	20	10976	14300	1100	27.4	0.607	0.2
78	3200	28	10976	12900	1400	30.1	0.736	0.3
79	3640	30	10976	18500	1300	51.6	0.757	-1.1
80	3680	31	10976	18600	1520	57.2	0.798	2.1
81	3730	43	10976	18200	1820	71.0	0.943	-3.2
82	3640	41	12600	17400	1700	64.5	0.946	1.2
84	3700	38	31500	23800	1290	67.0	0.921	3.0
85	3700	45	31500	19200	1880	73.1	1.000	0.2
94	3750	52	12600	17500	1540	69.8	0.904	0.0
119	4255	48	12600	25300	1610	122.7	0.959	-0.4
120	4800	50	12600	20500	1290	69.6	0.336	-63.9
				LOW FIELD (74.8% OF NORMAL)				
121	4840	47	12600	30200	1300	139.3	0.589	-32.7
122	5360	-	12600	EARLY FAULT		-	-	-

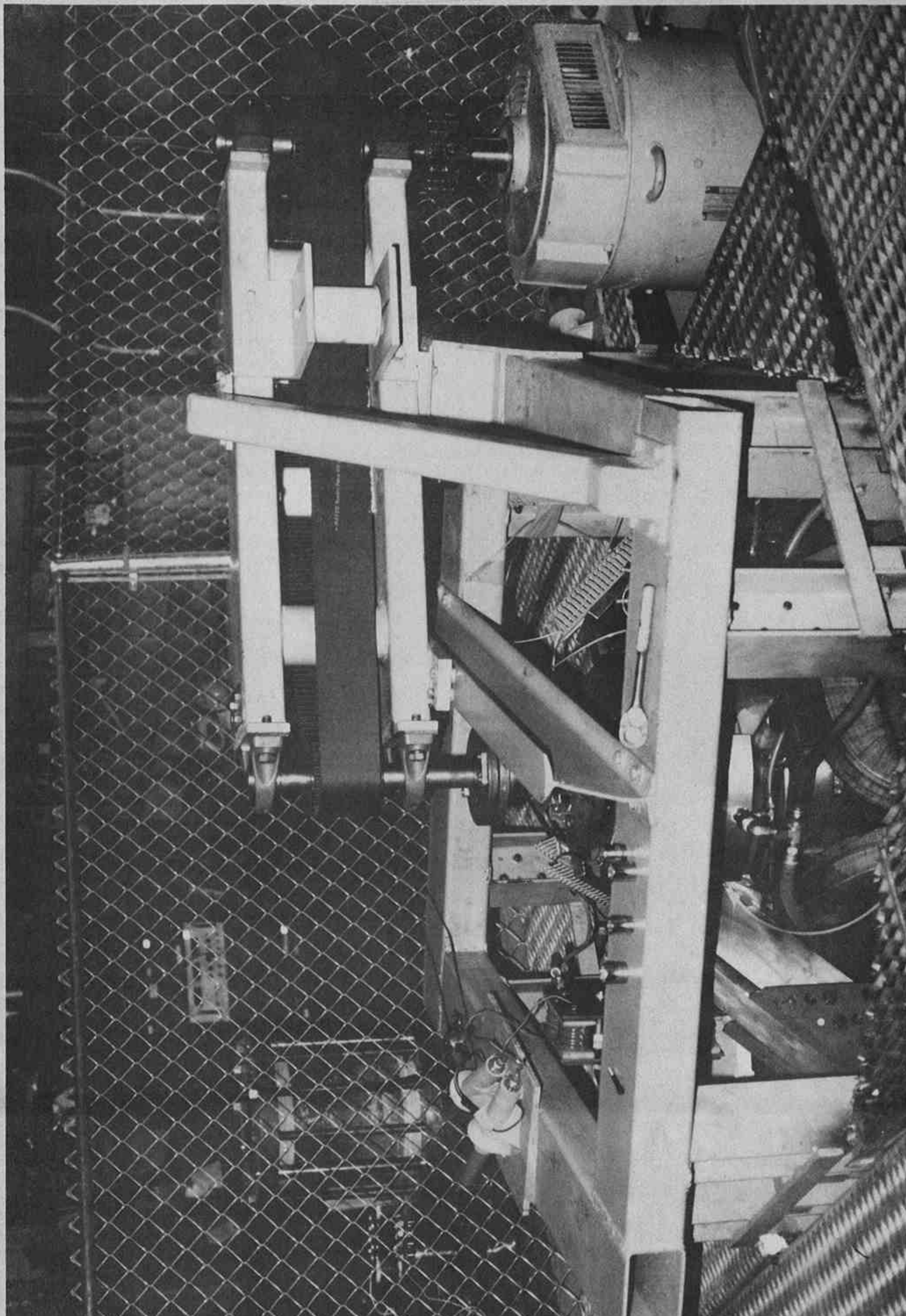

Figure 1

PROTOTYPE COMPULSATOR

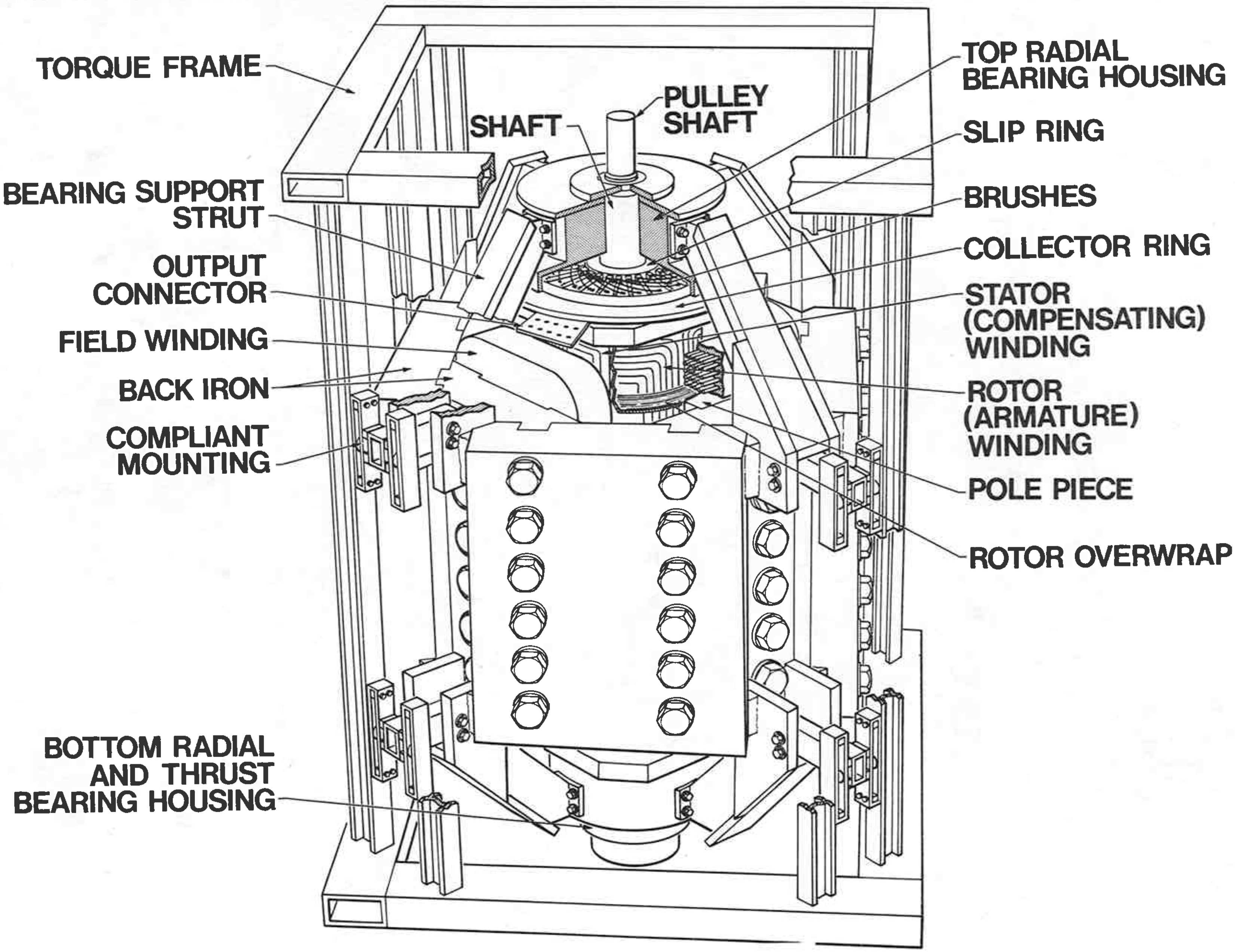

Figure 2

SIMPLIFIED COMPULSATOR TEST CIRCUIT

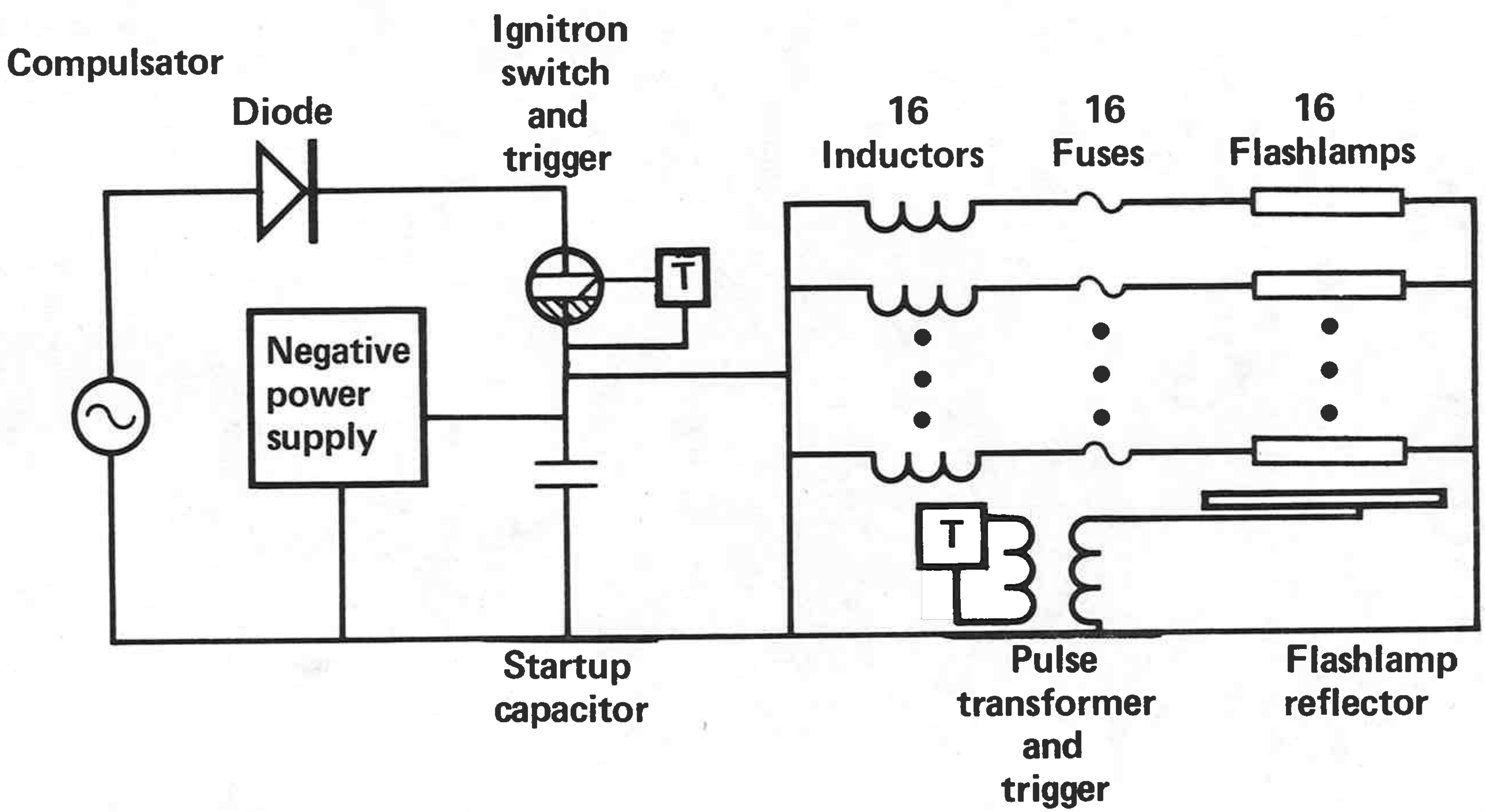

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Figure 3

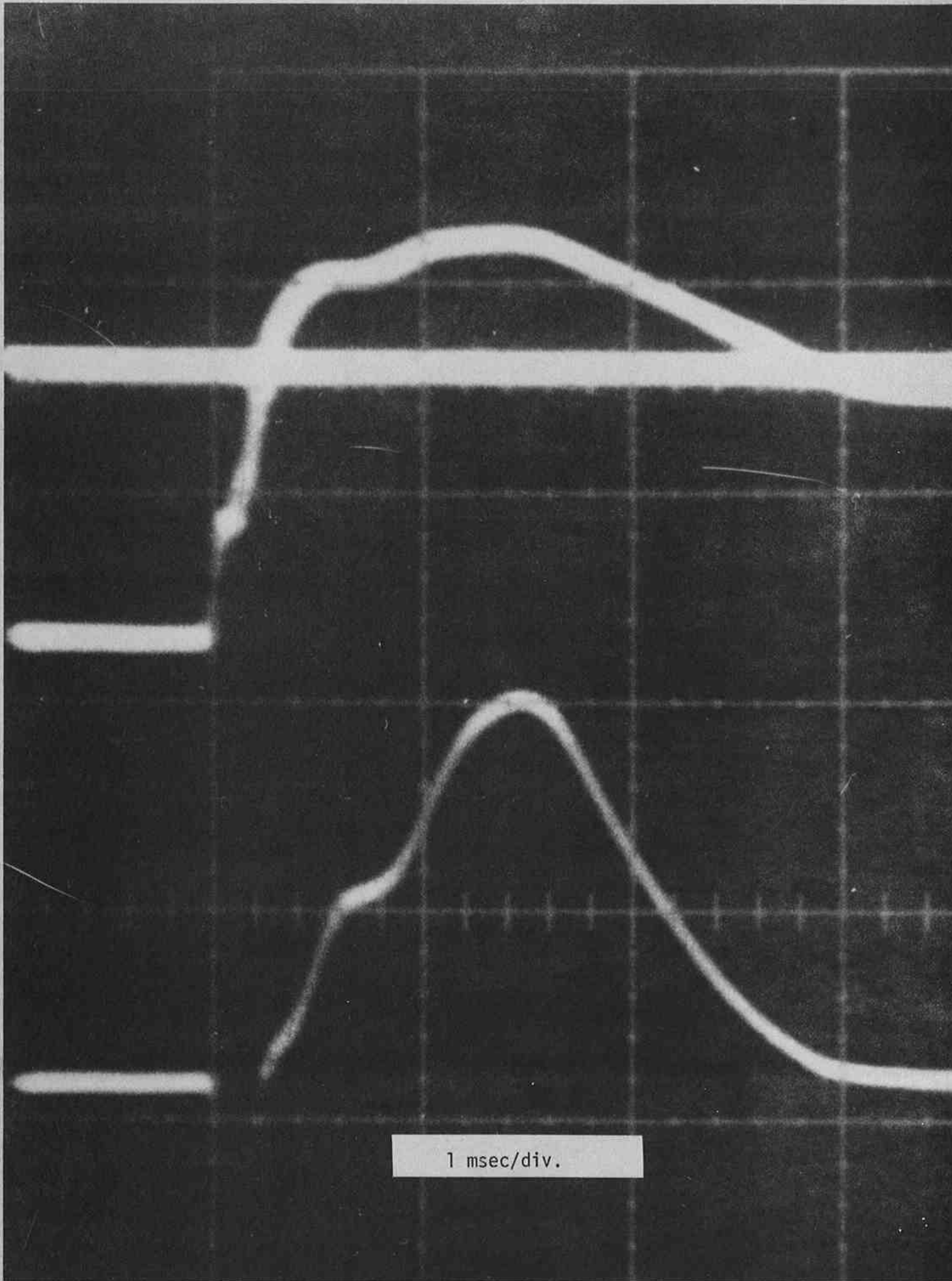

Figure 4

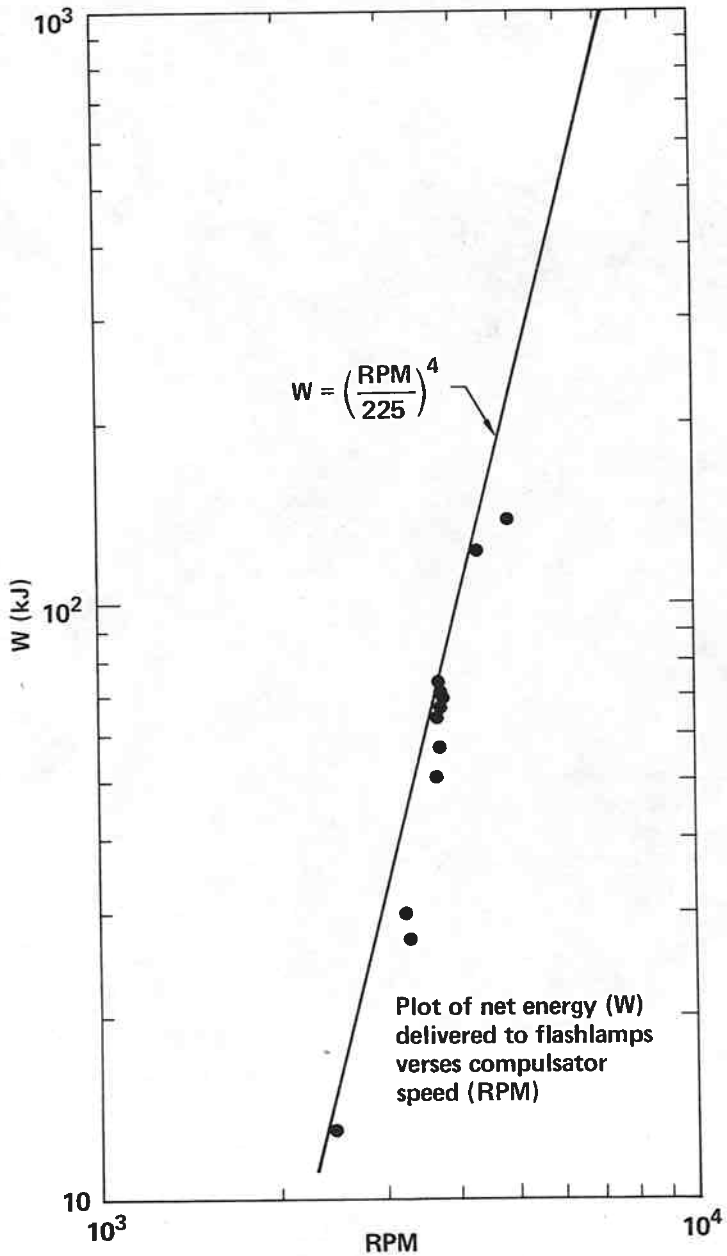

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Figure 5

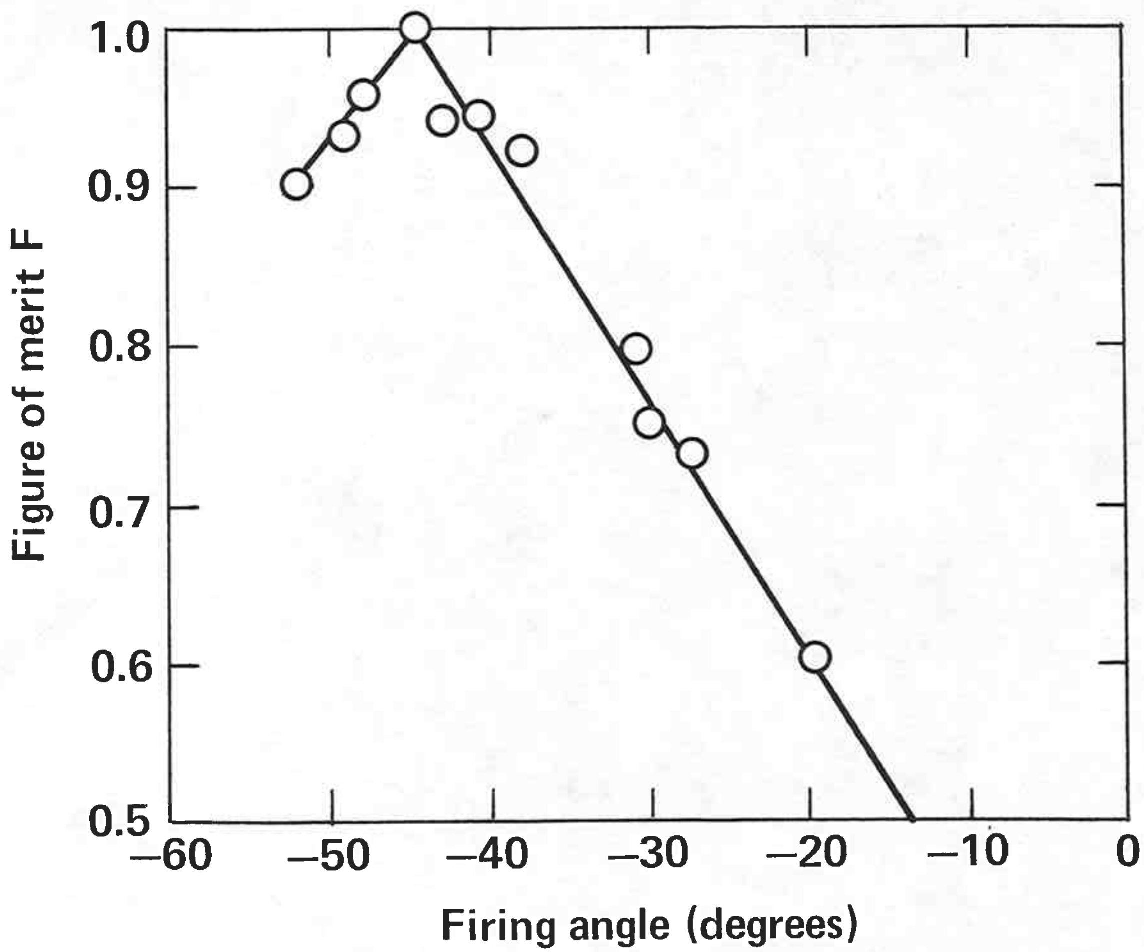

Figure of merit, F, versus firing angle for compulsator runs up to 4255 RPM

$$F = W \Big/ \left(\frac{RPM}{225}\right)^{4}$$

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Figure 6