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ANALOG STUDY OF FACTORS AFFECTING INJECTION STARTS OF A CLOSED-LOOP SINGLE-SHAFT BRAYTON POWER PLANT

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ABSTRACT

The starting performance of a Brayton cycle test loop was simulated with an analog computer. The test loop turbomachinery consisted of a turbine, compressor and alternator mounted on a single shaft. The design working fluid was a helium-xenon mixture with a molecular weight of 83.8. The results of actual and simulated test runs are compared. The variation of rotative speed with time during injection starts is shown as a function of injection rate, turbine inlet temperature, and initial test loop pressure.

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SUMMARY

An analog computer program was used to simulate closed loop injection starts of a Brayton cycle test loop. The test loop turbomachinery consisted of a turbine, compressor and alternator mounted on a single shaft and has been designated the Brayton Rotating Unit or BRU. At the design conditions for the turbomachinery, the net electrical output was 6 kW using a helium-xenon mixture with a molecular weight of 83.8 as the working fluid. The validity of the simulation was established by comparison with actual operating results. The simulation was then used to study the effect of loop operating conditions on injection starts.

Closed loop injection was indicated to be a practical method of accelerating the rotor to self-sustaining speed. For a given injection rate, turbine inlet temperature and injection period, rotative speed increased as the loop initial pressure was decreased. For a given injection period and turbine inlet temperature, rotative speed increased with injection rate. For a given time and turbine inlet temperature, rotative speed was almost linear with injection rate. The highest rotative speed for a given amount of inventory injected was not necessarily obtained with the highest injection rate. For turbine inlet temperatures of 1400° R (777° K) and higher, starts could be obtained by injecting less than 2.5 pounds (1.1 kg) of working fluid.

INTRODUCTION

The NASA-Lewis Research Center is currently conducting an investigation to determine the potential of the Brayton cycle for space power generation. As part of this program, a test loop was built to test both single-shaft and two-shaft systems. Recently, a single-shaft system was tested in this loop. The rotating equipment consisted of a turbine, compressor, and alternator mounted on a single shaft, and has been designated the Brayton Rotating Unit or BRU. This power package was designed and built under contract by the AiResearch Manufacturing Company. The design working fluid is a mixture of helium and xenon with an average molecular weight of 83.8. Krypton, which has the same molecular weight, was used for the initial tests.

One proposed method for starting the system is to preheat the heater, preevacuate the system and then inject gas at the heater inlet. A valve at the compressor discharge prevents back flow of injected gas through the compressor and ensures that all flow is toward the turbine inlet. The hot gas leaving the heater passes through the turbine and spins the package shaft to self-sustaining speed. Because of the high costs of krypton and of the helium-xenon mixture, it is desirable to use closed-loop starts in which none of the injected gas is vented to atmosphere.

An analog simulation was devised to simulate the startup characteristics of the single-shaft system in this test loop. A previous simulation of a system containing a turbocompressor is described in reference 2. The simulation was required for several reasons: (1) It is important to determine if closed-loop injection starts can be obtained with the loop design configuration. If not, the loop must be altered or another startup system used. (2) During startup, the shaft passes through several critical speed regions. At these speeds, shaft orbits are much larger than at design speed. The risk of bearing failure can be reduced by exploring startup characteristics with an analog simulation rather than making a large number of experimental starts. (3) A simulation can be used to estimate startup characteristics for operating conditions which cannot be obtained experimentally. For example, design turbine inlet temperature of 2060° R (1144° K) cannot be obtained in actual test loop starts. This is because the loop was designed primarily to investigate steady state operation. The heat transfer rates between the heaters and the working fluid are not high enough to reach design temperature during startup.

The objectives of the study presented in this report were therefore to determine if closed loop injection starts are practical for this single-shaft system, to estimate the effects of varying loop operating conditions, and to establish the validity of the simulation by comparing actual startups with simulated startups. In accomplishing these objectives the report presents the following information: a comparison of actual startups with simulated startups; the variation of rotative speed with time as a function of system operating variables including flow rate, turbine inlet temperature and initial loop pressure.

SYMBOLS

p	absolute pressure, psia; N/cm^2 abs
T	absolute temperature, ^{o}R; K
W	weight flow, lb/sec; kg/sec
Γ	torque, in-lb; cm-N

Subscripts:

in	conditions at inlet
out	conditions at outlet

Superscript:

'	absolute total state

TEST LOOP AND PACKAGE DESCRIPTION

A schematic drawing of the experimental test loop is shown in figure 1. The BRU package was designed for use in space. The heaters and the cooler, however, are workhorse components intended for ground use only. The design working fluid is a helium-xenon mixture with a molecular weight of 83.8. A sectional drawing of the BRU package is shown in figure 2. The package rotor is mounted on self-acting gas lubricated bearings. There are two journal bearings and a double-acting thrust bearing, all lubricated with the working fluid. A description of the package is given in reference 1.

The test loop was designed for closed loop injection starts. In this start method, part of the system inventory is injected into the inlet of the first heater. The hot gas leaving the second heater expands through the turbine and accelerates the rotor to self-sustaining speed. A check valve at the compressor outlet prevents back flow through the compressor and ensures that all flow is toward the turbine inlet. Injection is accomplished by controlling the pressure upstream from the injection valve at a constant value and opening the injection valve sufficiently to obtain the desired constant flow rate. During injection, the check valve is in the closed position and the compressor bypass valve is open to prevent compressor surge. Gas is injected until a preset compressor inlet pressure is obtained. When this set point is reached, pressure switches close the injection and compressor bypass valves and open the check valves. Since the alternator field is not energized during the start, there is no electrical load.

SIMULATION METHOD AND ASSUMPTIONS

The analog computer program was intended to provide a simulation of loop performance only during the injection period. The simulated injection procedure was the same as for the actual loop, with the check valve closed and the compressor bypass valve open. It was assumed that the compressor bypass valve is opened far enough to allow open throttle compressor operation (see figs. 3(c) and (d)). Initial loop pressure was assumed to be 6.0 psia (4.1 N/cm^2 abs) for those simulations used for experimental comparison. This is because a diaphragm compressor is actually used to evacuate the test loop, and 5 to 6 psia (3.4 to 4.1 N/cm^2 abs) is approximately the lowest suction pressure that can be obtained.

The analog computer program is similar in general to the program described in reference 2. Since the turbine and compressor for the subject turbine-compressor-alternator package are not the same as for the reference 2 package, new turbine and compressor maps were required. The turbine and compressor maps used for the simulation are shown in figure 3. These maps were drawn from unpublished data at the Lewis Research Center. The simulation extrapolates the experimental data to cover all conditions that occur during injection starts.

Reference 2 contains a discussion of the simplifying assumptions which were made to reduce problem complexity and conserve computer equipment in a previous analog study. These assumptions, which were also made for the subject study, are as follows:

1. Constant heater and cooler discharge temperatures.
2. The neglecting of small volumes such as the turbine, compressor, injection line, etc.
3. Instantaneous operation of the injection valve.
4. Isothermal flow in the line between the heater and the turbine inlet.
5. A mean gas temperature of 600° R (333 K) in the cooler inlet line.

No attempt was made to determine experimentally the threshold of self-sustaining speed. For this study, however, 12, 000 rpm was considered the minimum acceptable speed for injection starts. This value was selected because it is above the bearing critical speeds. There are four critical speeds, all below 11, 000 rpm. In order to minimize the shaft orbits, acceleration through the critical speed range should be rapid. For self-sustaining operation at low aerodynamic speeds, the rotor accelerates very slowly because of the low turbine torque level. If injection is stopped in a critical speed region, large shaft orbits could result. In addition, it was projected from argon test data that, when using krypton, the BRU would be self-sustaining at 12, 000 rpm for the 1400° to 2060° R (778 to 1144 K) temperature range covered in this study. At 1380° R (767 K), the BRU maximum self-sustaining speed in argon was found to be 16, 650 rpm. For krypton operation at 1380° R (767 K), the maximum aerodynamic self-sustaining speed will remain approximately the same. This corresponds to an actual rotative speed of 11, 500 rpm. Since this maximum value is higher than the minimum self-sustaining speed, and since minimum self-sustaining speed decreases with increasing temperature, the BRU should start at 12, 000 rpm for the turbine inlet temperature range of 1400° to 2060° R (778 to 1144 K) covered in this study.

RESULTS AND DISCUSSION

The results obtained from the analog simulation of the single-shaft Brayton cycle test loop are presented in two sections. The first section compares two actual starts with simulated starts. The second section consists only of simulation results and shows the effect of system operating variables on start characteristics. These variables include injection rate, turbine inlet temperature, and loop initial pressure.

Comparison of Actual and Simulated Starts

Comparison of actual and simulated starts are shown in figures 4 and 5. Rotative speed and compressor inlet pressure are shown as functions of time. The figures show that initially, the rotative acceleration is higher for the simulation than for the actual start. This may be due to differences in the time required for the injection valve to open. In the simulation, the injection valve opens instantaneously. In an actual start, about 0.5 second are required to reach the maximum injection flow rate.

A comparison between actual and predicted rotative speeds is given in table I. From this table it is evident that, in these two cases, the simulation predicted the rotative speed within 1500 rpm for a given injection period. The simulation can therefore be used to determine whether a given speed can be obtained by closed loop injection and to estimate the rotative speed at a given time.

TABLE I. - Comparison of Actual and Simulated Test Results

Figure	Time, sec	rpm		Compressor inlet pressure	
		Actual	Predicted	Actual	Predicted
4	3	11,800	13,300	8.9	8.3
	4	16,800	18,300	10.1	9.8
	5	21,100	22,200	11.2	11.4
5	3	12,600	13,100	9.2	8.6
	4	18,300	17,900	10.4	9.9
	5	22,500	21,200	11.3	11.1

Although the differences between actual and simulated rotative speeds and compressor inlet pressures are not large, the simulation cannot be used to predict rotative speed for a given compressor inlet pressure. For the data shown in figures 4 and 5, errors of over 3,000 rpm may result. This is important when considering the rotative speed at which the injection valve is closed since, in actual loop starts, the injection valve is closed and check valve opened when preset values of compressor inlet pressure are reached, to predict rotative speed at the end of the injection period, better accuracy can be obtained by stopping injection at a preset time rather than at a preset pressure.

Simulation Results

Effect of initial loop pressure. - As discussed in the SIMULATION METHOD AND ASSUMPTIONS section, the loop pressure could not be reduced below 5 to 6 psia (3.4 to 4.1 N/cm^2 abs). The effect of this high initial pressure is shown in figure 6. Rotative speed is shown as a function of time for initial pressures of 1.0 and 6.0 psia (0.69 and 4.1 N/cm^2 abs). Turbine inlet temperature is 2060° R (1144 K) and injection rate is 0.4 lb/sec (0.18 kg/sec). Rotative speeds are seen to be considerably higher for the lower pressure because turbine pressure ratios are higher and the compressor torque is lower. At 4 seconds, the rotative speeds are 21,000 rpm for an initial pressure of 1 psia (0.69 N/cm^2 abs) and 12,700 rpm for an initial pressure of 6 psia (4.1 N/cm^2 abs). However, figures 4, 5, and 6 all show that self-sustaining speeds (12,000 rpm or greater) can easily be obtained with an initial pressure of 6.0 psia (4.1 N/cm^2 abs). At a given turbine inlet temperature, the minimum injection rate required to obtain a start will increase with the initial loop pressure.

Effects of injection rate and turbine inlet temperature on starting characteristics. - Figure 7 shows the variation of rotative speed with injection rate and turbine inlet temperature. Rotative speed is plotted against time for various injection rates and turbine inlet temperatures with an initial loop pressure of 6.0 psia (4.1 N/cm^2 abs). At a given time, rotative speed is seen to increase with injection rate over the range of injection rates and temperatures covered in this study. For example, figure 7(a) shows the effect of injection rate at design turbine inlet temperature of 2060° R (1144 K). At

2.0 seconds, rotative speed increases from 2500 rpm to 16,300 rpm as the injection rate increases from 0.2 lb/sec (0.09 kg/sec) to 1.0 lb/sec (0.45 kg/sec). This increase in rotative speed with injection rate occurs because of higher turbine inlet pressures and pressure ratios.

For a given injection rate, rotative speed increases with temperature for the temperatures and injection rates used in this study. At an injection rate of 0.4 lb/sec (0.18 kg/sec) and a time of 5 seconds, rotative speed increases from 11,000 rpm at 1400° R (778 K) (fig. 7(d)) to 15,300 rpm at 2060° R (1144 K) (fig. 7(a)). This increase in rotative speed with temperature occurs because higher turbine inlet temperatures result in lower gas densities upstream from the turbine, higher turbine inlet pressures and higher turbine pressure ratios.

Figure 7 also shows that for the range of temperatures and injection rates covered in this study, below 20,000 rpm rotative speed varies almost linearly with injection rate for a fixed injection period.

Figure 7 indicates that closed loop injection is a practical means of bringing the BRU to self-sustaining speed. The minimum desirable speed of 12,000 rpm can be obtained with injection rates of less than 0.2 lb/sec (0.09 kg/sec) at 2060° R (1144 K) and less than 0.3 lb/sec (0.14 kg/sec) at 1400° R (778 K). Actual starts at higher injection rates have been obtained in this manner (figs. 4 and 5) without danger to the BRU.

Figure 7(b) shows curves of constant inventory for 1.5 lb (0.68 kg), 2.1 lb (0.91 kg), and 2.5 lb (1.13 kg). For a fixed total amount of inventory injected, the highest rotative speed does not necessarily occur at the highest injection rate. As the amount of injected inventory increases, the injection rate at which maximum rotative speed occurs also increases. If 1.5 lb (0.68 kg) of inventory is injected, the maximum rotative speed occurs at an injection rate between 0.4 and 0.6 lb/sec (0.18 and 0.27 kg/sec). When the inventory is increased to 2.5 lb (1.13 kg), the maximum rotative speed occurs at an injection rate greater than 1 lb/sec (0.45 kg/sec).

The total inventory required for a start consists of the initial amount corresponding to the loop initial pressure plus the amount injected. This value becomes significant if it greatly exceeds design inventory. The design of the inventory control system and the amount of expensive helium-xenon mixture which must be purchased will both be affected. To start the

BRU in this particular test loop, it is not necessary to exceed the design inventory of 6.3 lb (2.9 kg) for a 6.0 kW alternator output. The initial amount, corresponding to 6.0 psia (4.1 N/cm^2 abs) is less than 4 lb (1.8 kg). For the temperature range of 1400° to 2060° R (778 to 1144 K) starts can be obtained by injecting amounts of less than 2.5 lb (1.13 kg) or less (note curve on fig. 7(d)).

SUMMARY OF RESULTS

An analog computer program was used to simulate closed loop injection starts of a Brayton cycle test loop. The test loop turbomachinery consisted of a turbine, compressor, and alternator mounted on a single shaft and designated as the Brayton Rotating Unit or BRU. The design electrical output was 6 kW using a helium-xenon mixture with a molecular weight of 83.8 as the working fluid. The validity of the simulation was established by comparison with actual operating results. The simulation was then used to study the effect of various loop operating conditions on injection starts. The following results were obtained from the study:

1. Comparison of simulated injection starts with actual starts indicated that the simulation could be used to predict the variation of rotative speed with time for various injection rates and turbine inlet temperatures.

2. Closed loop injection was indicated to be a practical method of accelerating the BRU rotor to self-sustaining speed. At a turbine inlet temperature of 1400° R (778 K), starts could be obtained with injection rates of less than 0.3 lb/sec (0.14 kg/sec). At design turbine inlet temperature of 2060° R (1144 K), starts could be obtained with injection rates of less than 0.2 lb/sec (0.09 kg/sec).

3. Actual starts were made with initial pressures between 5 and 6 psia (3.4 and 4.1 N/cm^2 abs) because of a design limitation. Much higher rotative speeds were predicted to be obtained at a given injection rate and turbine inlet temperature if initial pressure would be reduced to 1 psia (0.69 N/cm^2 abs).

4. For a given injection period and turbine inlet temperature, rotative speed increased with injection rate. At a given time, rotative speed was almost linear with injection rate at speeds under 20,000 rpm for injection

rates between 0.2 and 1.0 lb/sec (0.09 and 0.45 kg/sec) and turbine inlet temperatures between 1400° and 2060° R (778 and 1144 K).

5. For a given amount of inventory injected, the highest rotative speed did not necessarily occur at the highest injection rate. As the amount of inventory injected increased, the injection rate for maximum rotative speed also increased. Starts could be obtained by injecting less than 2.5 lb (1.1 kg) at turbine inlet temperatures of 1400° R (778 K) and higher.

REFERENCES

1. Anon.: Design and Fabrication of a High-Performance Brayton Cycle Radial-Flow Gas Generator. NASA CR-706, 1967.

2. Klassen, Hugh: Analog Simulation of a Closed Loop Brayton Cycle Test Facility. NASA TM X-1715, 1968.

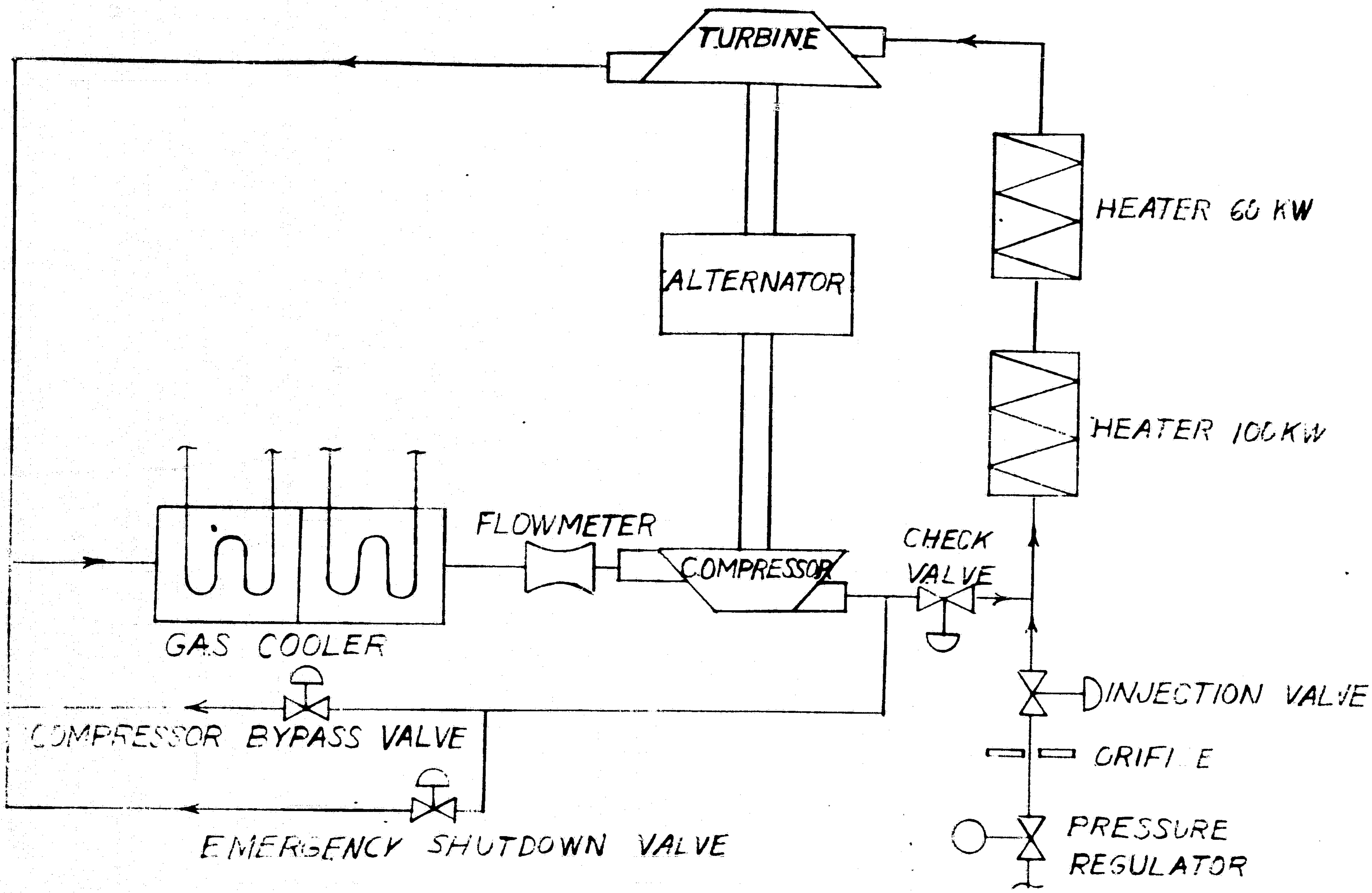

FIGURE 1- TEST LOOP SCHEMATIC

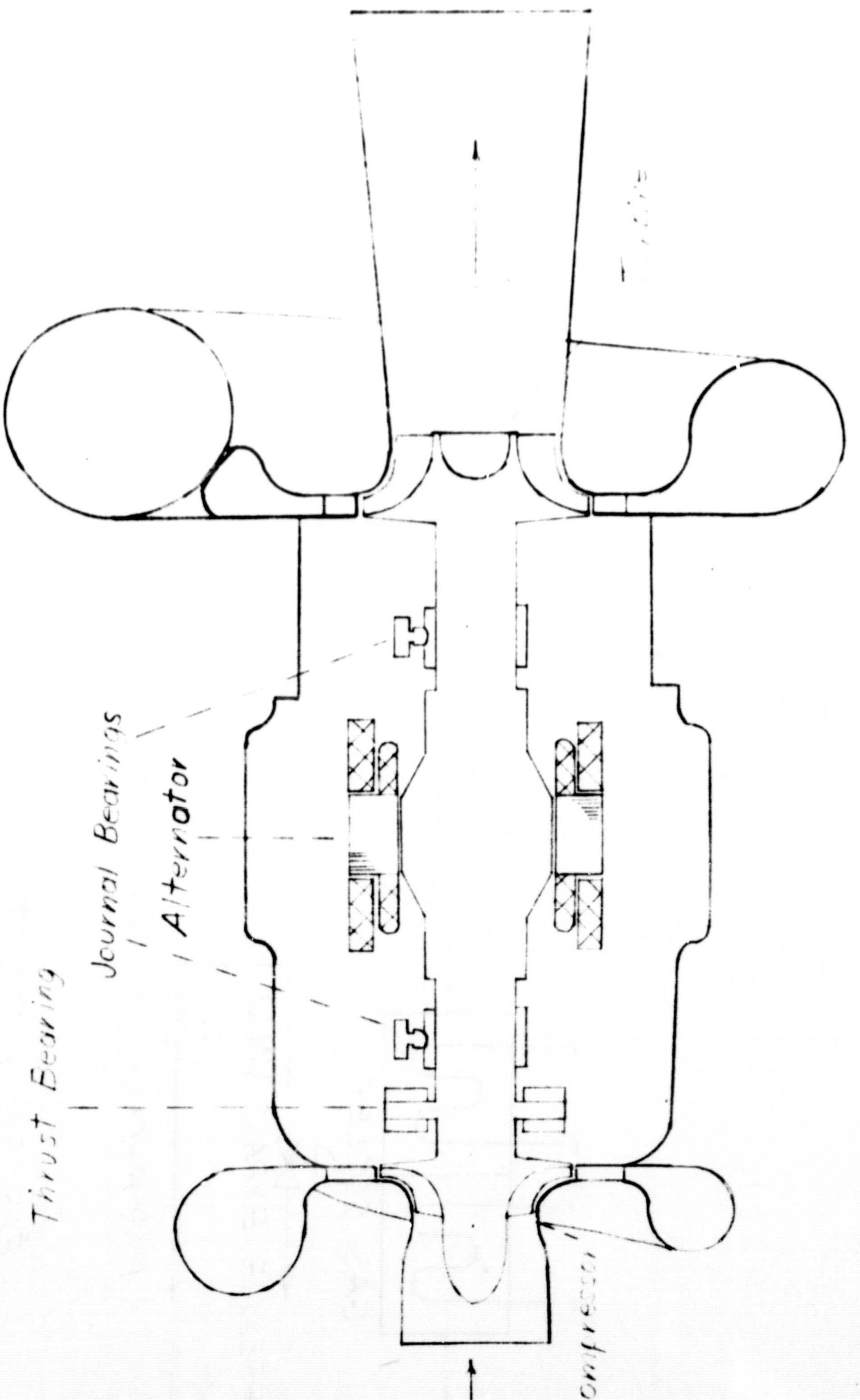

Figure 2- Schematic of BRU

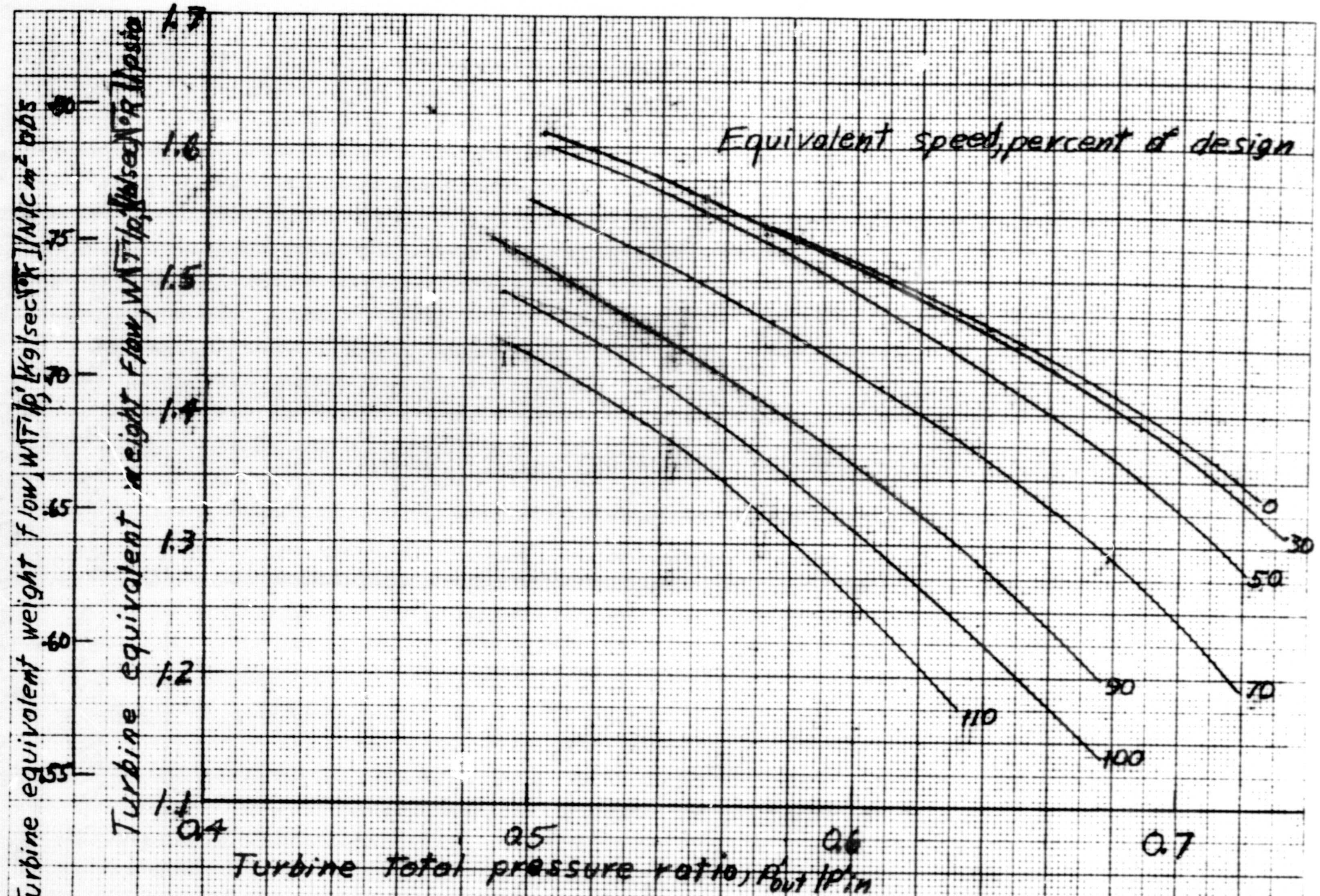

Figure 3a Turbine equivalent weight flow

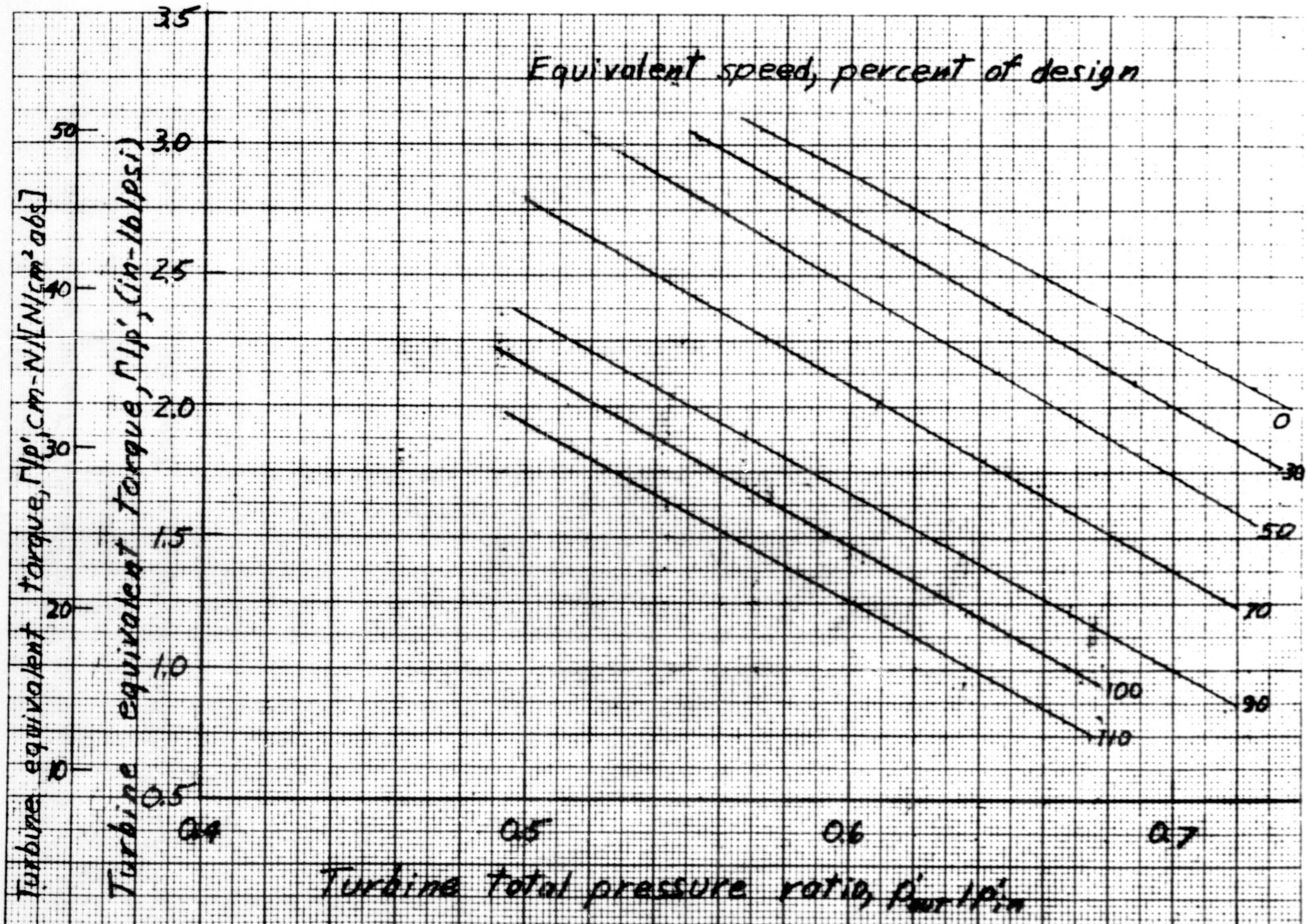

Figure 3b Turbine equivalent torque

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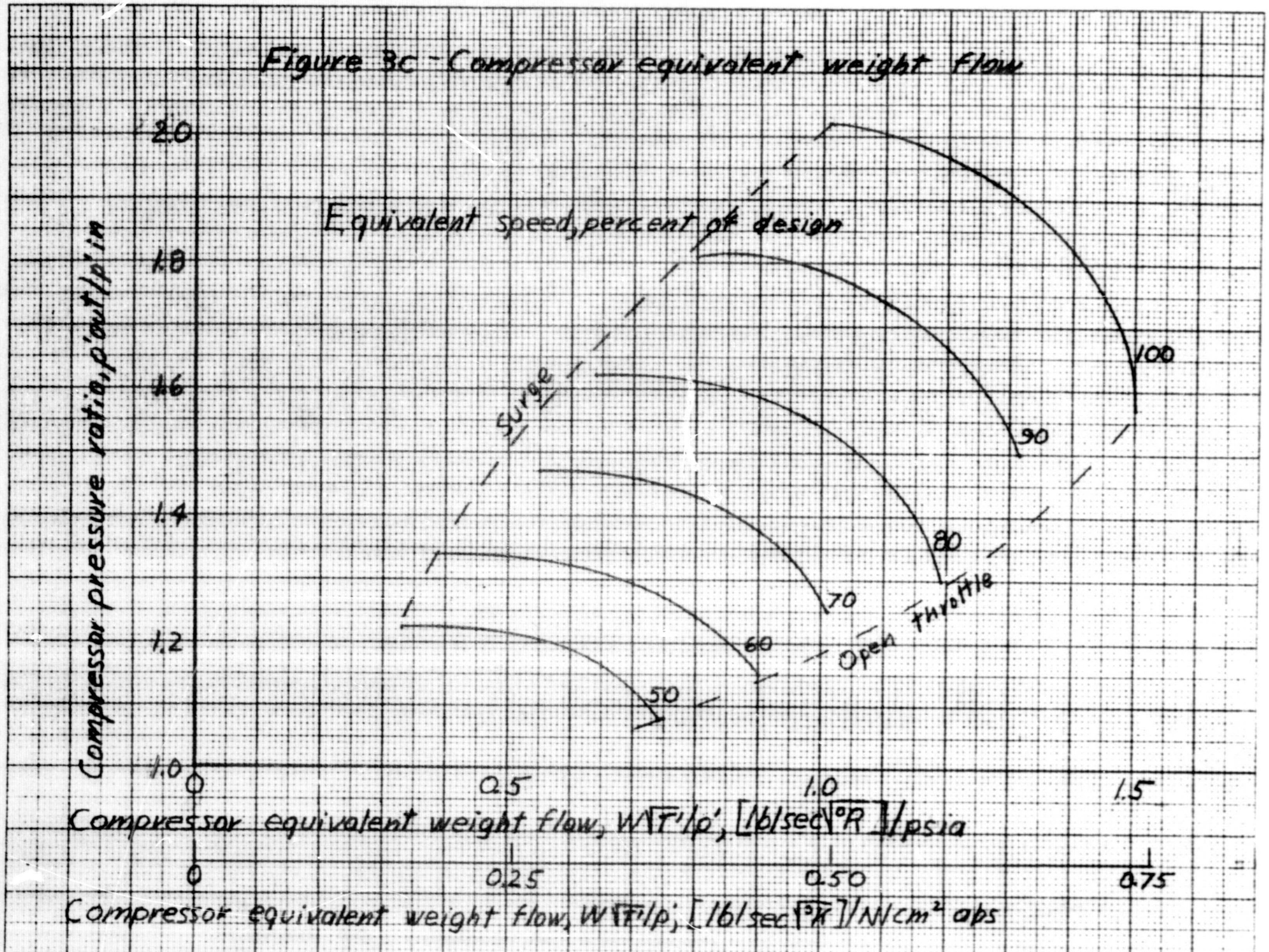
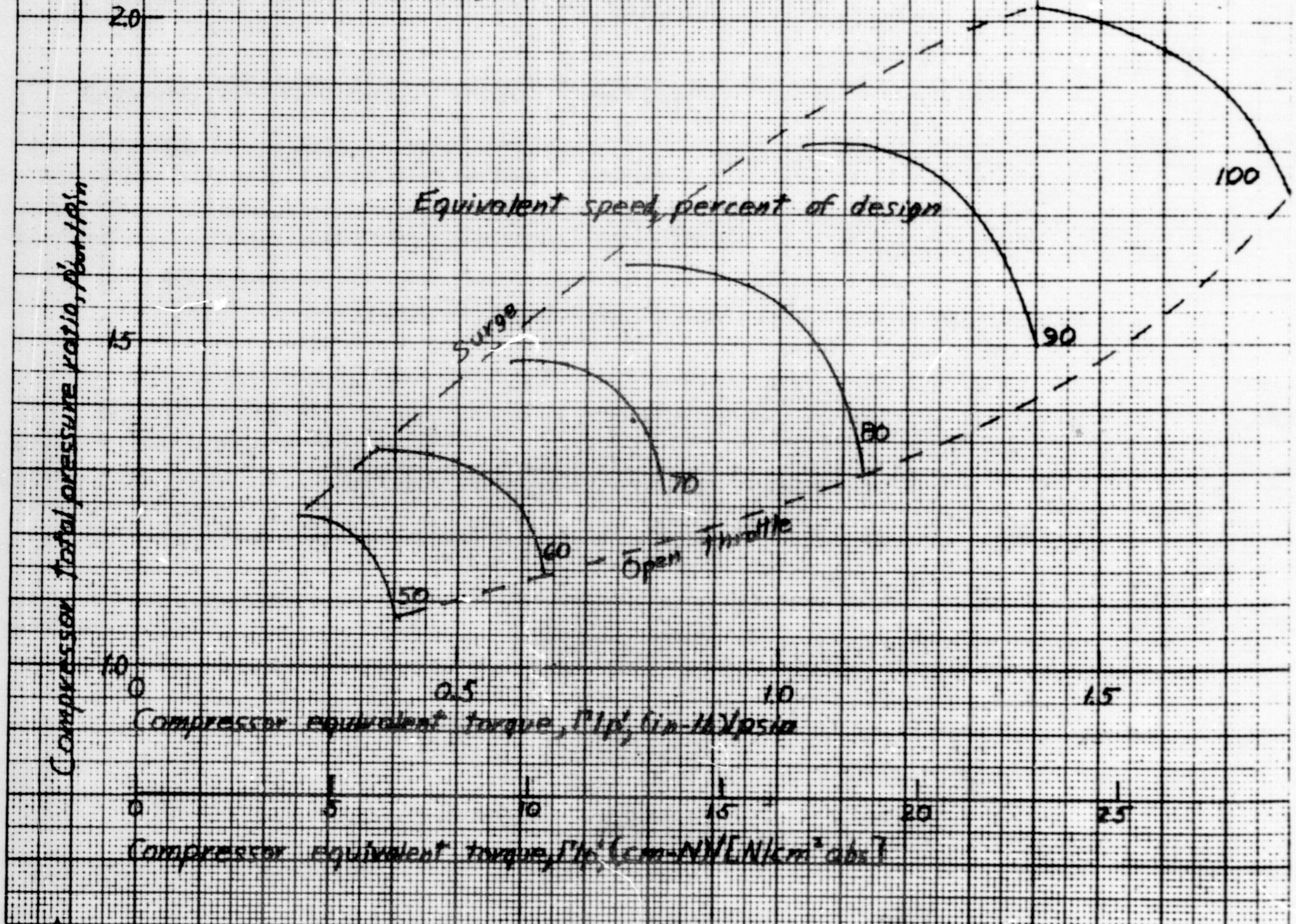


Figure 3c - Compressor equivalent weight flow
Equivalent speed, percent of design
2.0
1.8
1.6
1.4
1.2
1.0
Compressor pressure ratio, p'out/p'in
100
90
80
70
60
50
Surge
Open throttle
0
0.5
1.0
1.5
Compressor equivalent weight flow, W√T'/p', [lb/sec √°R]/psia
0
0.25
0.50
0.75
Compressor equivalent weight flow, W√T'/p', [lb/sec √°K]/N/cm² abs

Figure 3d - Compressor equivalent torque



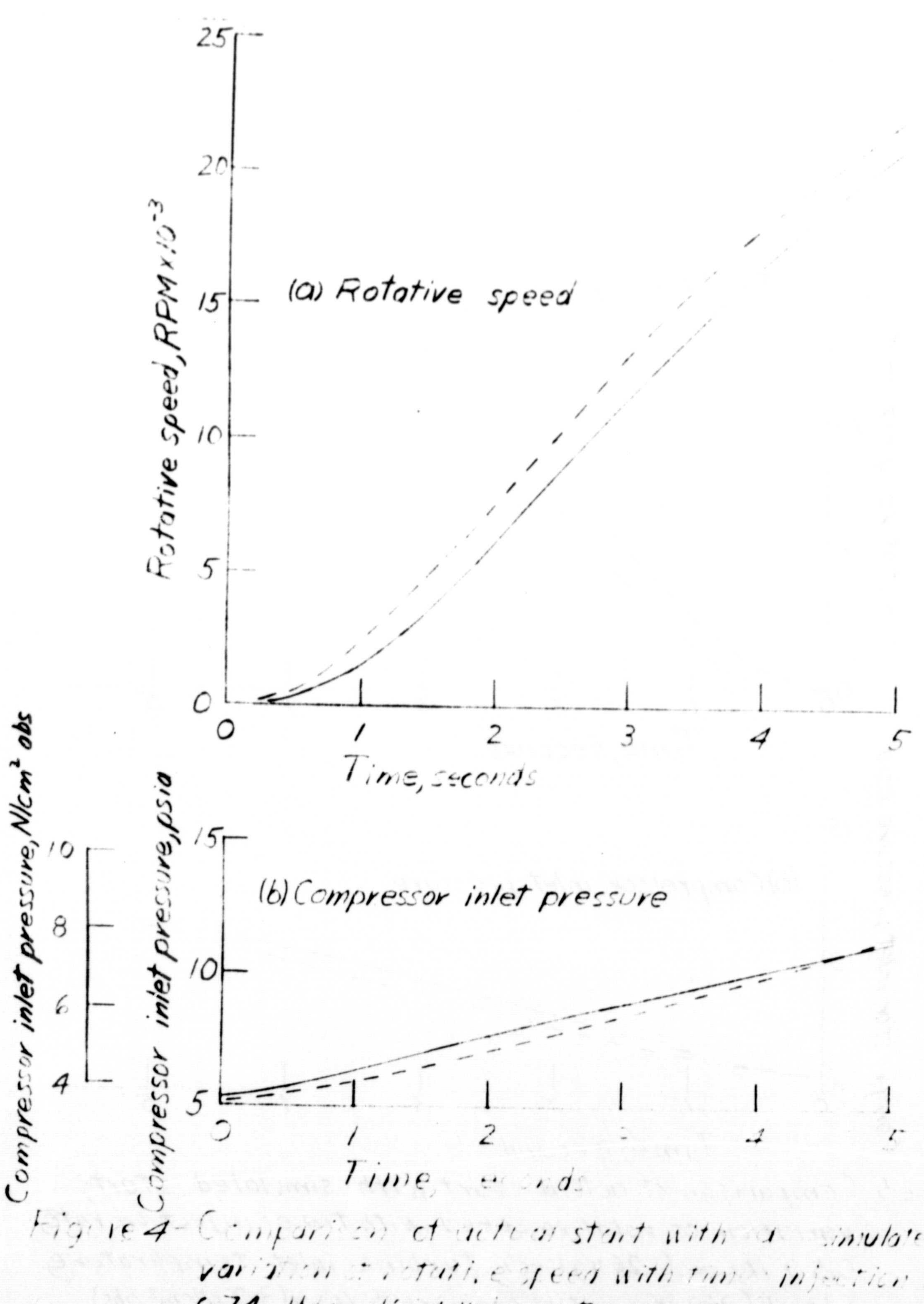


Figure 4 - Comparison of actual start with a simulated start; variation of rotative speed with time; injection rate, 0.74 lb/sec (0.34 kg/sec); turbine inlet temperature, 1470°R (817°K); initial pressure, 5.4 psia (3.7 N/cm²)

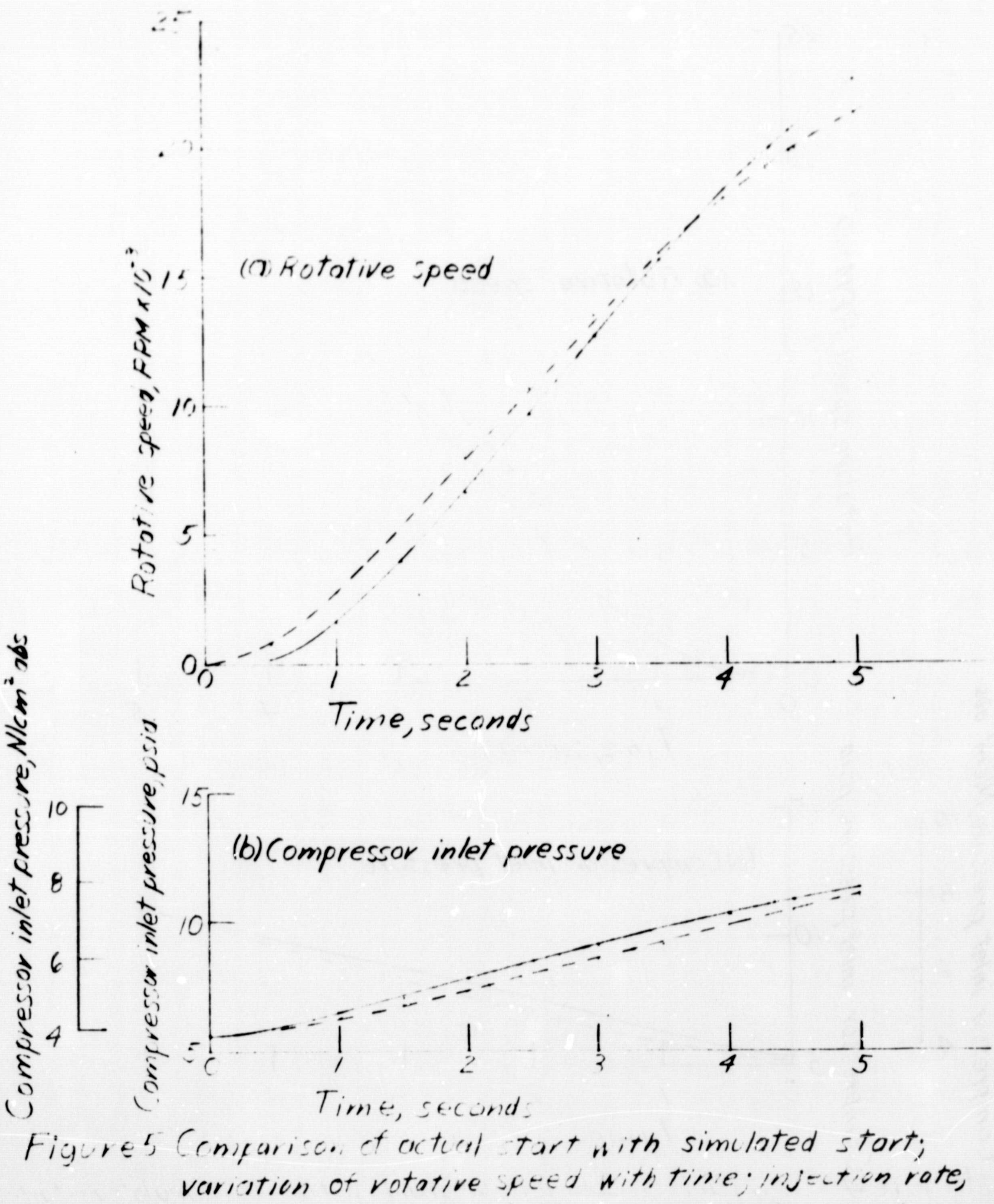


Figure 5 Comparison of actual start with simulated start; variation of rotative speed with time; injection rate, 0.59 lb/sec (0.26 kg/sec); turbine inlet temperature, 1780°R (989 °K); initial pressure 5.7 psia (3.9 N/cm² abs)

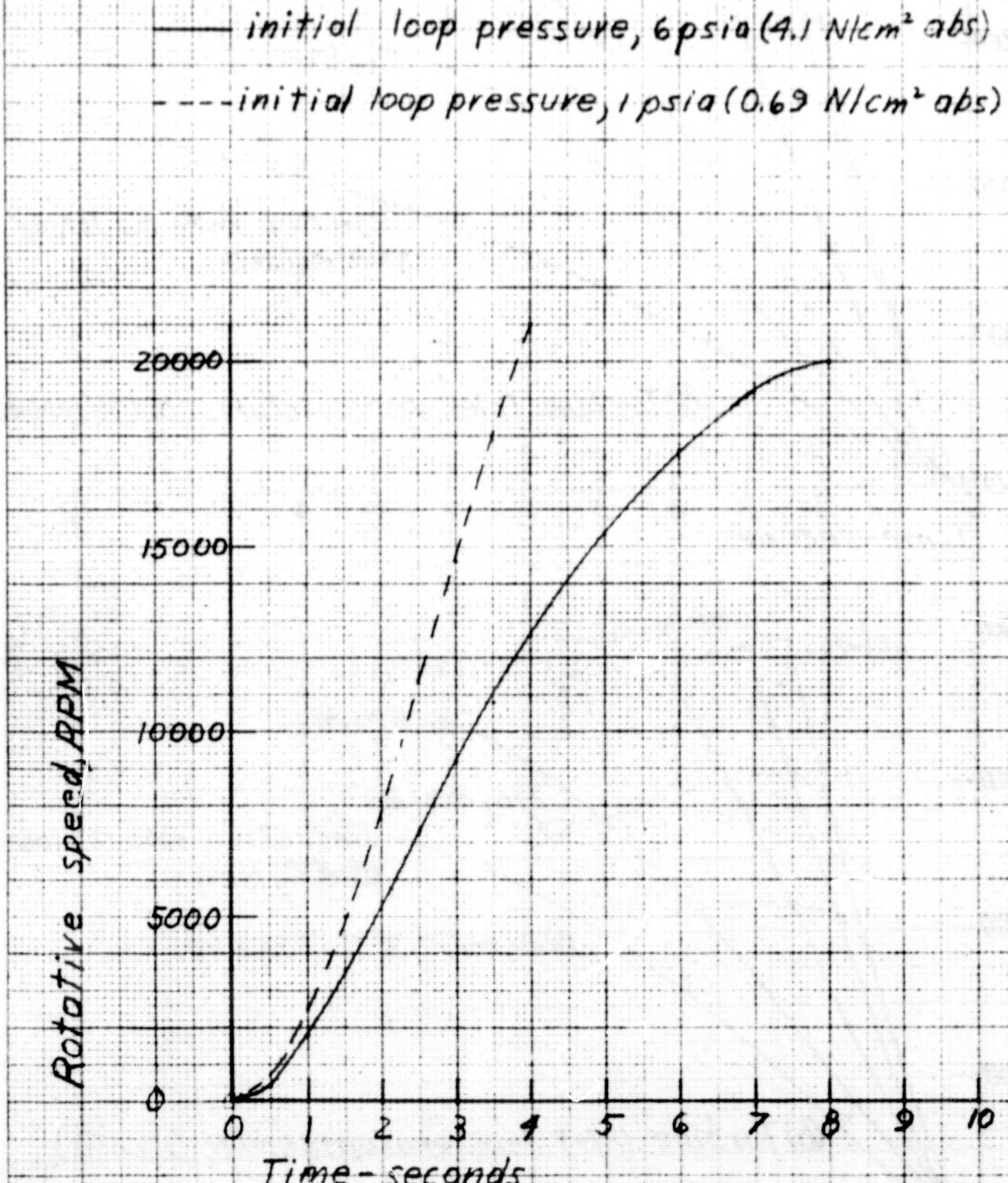


Figure 6 - Variation of rotative speed with time and initial loop pressure; turbine inlet temperature, 2060°R (1144°K); injection rate, 0.4 lb/sec (0.18 Kg/sec)

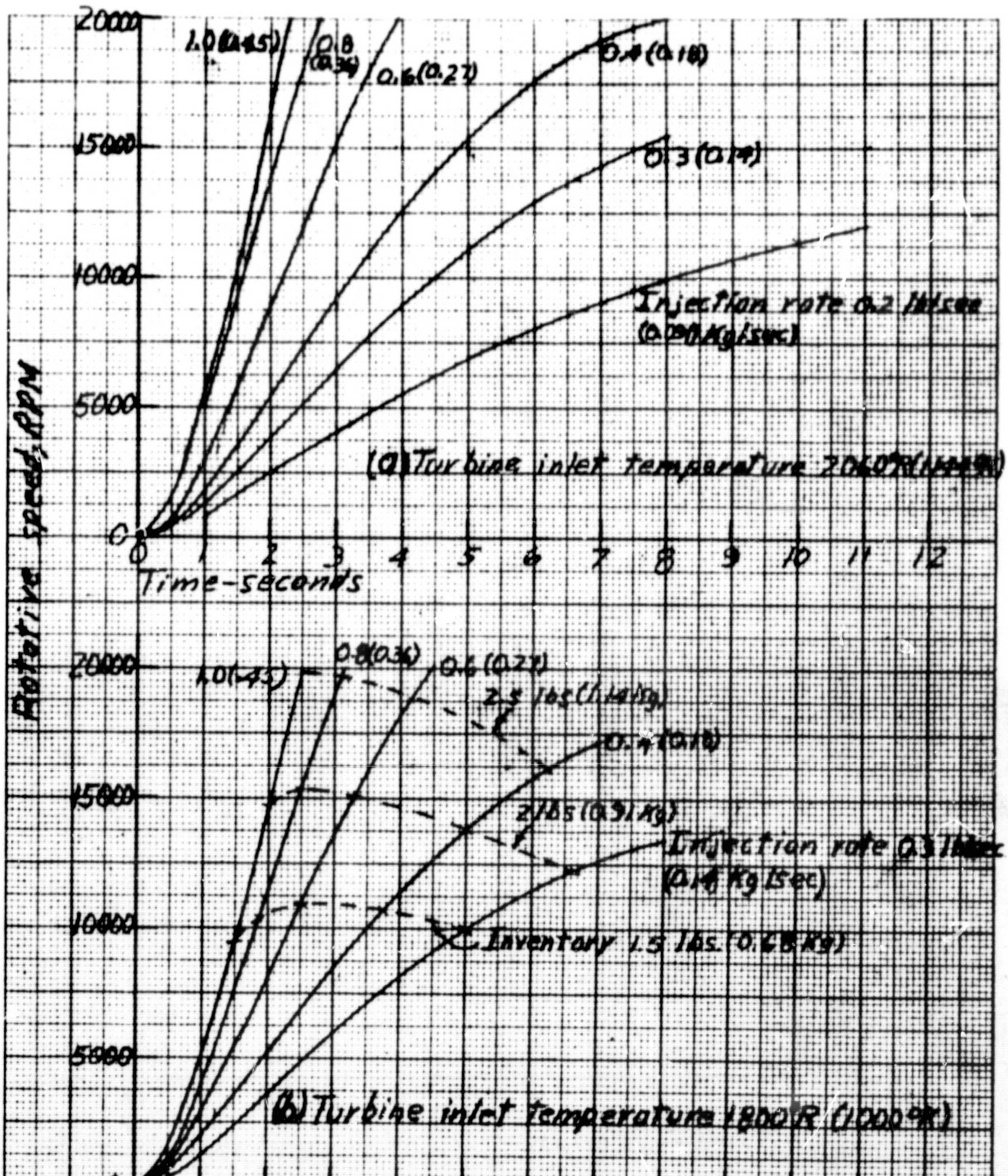


Figure 7 - Variation of rotative speed with time, injection rate, and turbine inlet temperature; initial pressure, 6 psia (4.1 N/cm² abs)

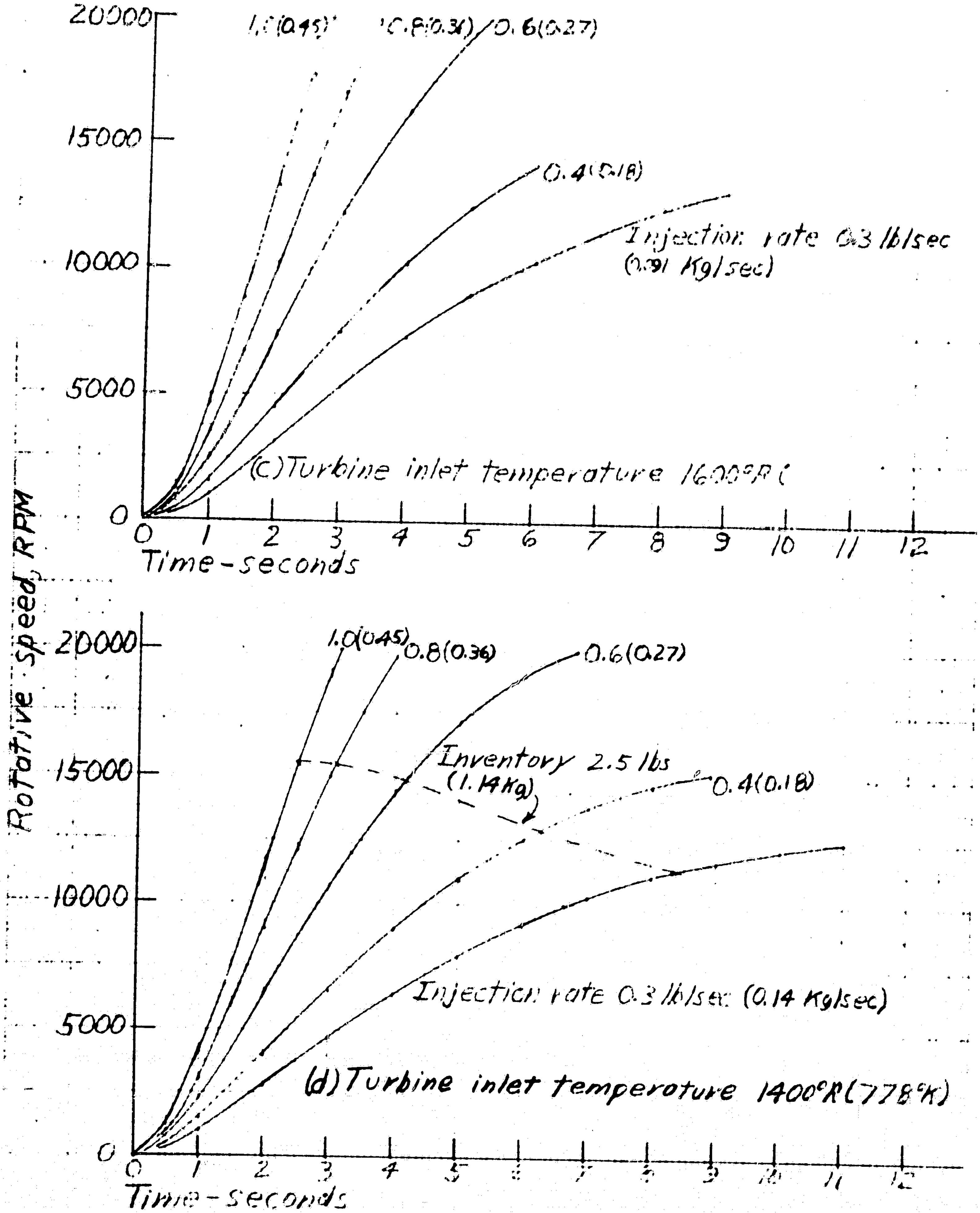


Figure 7 -continued