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MEMORANDUM No. M.163

RAM-JET TEST PLANT

by

W.G.E.LEWIS and R.K.P.STEVENS

DECEMBER, 1952

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SUMMARY

This memorandum gives the ram-jet operating conditions over a range of Mach Number and altitude which must be simulated during ground tests. Alternative types of plant for this duty are discussed.

Existing and planned plants in this country and their individual characteristics are described.

The test ranges of these plants are calculated, and typical values are summarised below for a ram jet operating at an effective fuel-air ratio of 0.07 without an exhaust nozzle.

Plant	Free-Jet Tests at 100% Spill			Connected Tests	
	Combustion Chamber Diameter (in.)	Maximum Mach No.	Altitude (ft.)	Combustion Chamber Diameter (in.)	Altitude Range at Flight Condition of M = 2.0
R.A.E.	6.0	2.5	45,000	16	45,000 to 65,000
	7.0	2.2	35,000 to 45,000	14	45,000 to 75,000
	7.75	2.0	30,000 to 40,000		
	8.80	1.8	24,000 to 40,000		
N.G.T.E. (Old Site)	5.4	2.0	20,000	16	47,500
	6.5	1.9	15,500	14	47,500 to 55,000
	7.0	1.8	12,000	17.5	22,000
N.G.T.E. (New Site)	6.0	2.9	40,000	30	47,500
	8.4	2.6	40,000	24	47,500 to 60,000
	11.3	2.2	25,000	31	20,000
	12.8	2.0	25,000		
	17.5	1.75	0		

CONTENTS

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ILLUSTRATIONS (Cont'd)

1.0 Introduction

This memorandum presents a new survey of ram-jet testing plants; it supersedes the previous work by A. Sharpe and R. P. Probert.

Flight conditions dictate the basic requirements, which are summarised in performance curves.

The weight flow and pressure of the air supply, together with suction capacity and other plant characteristics, are given for each plant considered.

Finally, the predicted testing ranges of the various plants are shown in graphical form.

2.0 Ground tests required

Ram-jet propulsion systems must be ground tested before flight tests begin. There are three categories of ground tests:

(a) Combustion chamber tests

(b) Engine tests

(c) Ignition tests

2.1 Combustion chamber tests - connected rig

Figure 1 shows a diagrammatic arrangement of a connected rig. A direct measurement of burner performance is made possible by introducing the air to the burner duct with zero axial momentum. Three characteristics define burner performance:

(a) Air-fuel ratios over which combustion is maintained.

(b) Combustion efficiency. (Defined as the $\frac{\text{actual air-fuel ratio}}{\text{theoretical air-fuel ratio}}$ at the same air specific impulse).

(c) Burner pressure loss factor.

Combustion conditions in flight are simulated by reducing the test cell pressure to just below the choking pressure ($M = 1.0$) at the ram-jet outlet, and not to the corresponding altitude ambient pressure.

2.2 Engine tests - free-jet

Figure 1 shows the free-jet testing layout; the ram-jet intake is immersed in a supersonic airstream corresponding to the flight conditions. The diameter of the airstream must be sufficient to prevent any interference with the internal flow of the intake, which may be set at different angles of yaw.

2.3 Ignition tests

In the flight of interceptor weapon ram jets, ignition occurs at speeds up to a Mach Number of approximately 1.8. During the launching period, flow conditions in the ram jet change rapidly; to simulate these conditions on the test bed requires special equipment which is not yet fully developed.

At present, ignition tests are carried out in two ways:

(a) On a free-jet rig at a series of fixed inlet Mach Number.

(b) On a connected rig at a series of airflows and temperatures.

3.0 Performance requirements

Figures 2, 3, and 4 show the ram-jet requirements as a function of flight Mach Number and altitude in terms of the following parameters:

(a) Combustion chamber air inlet temperature and pressure.

(b) Weight flow in lb. per sec. per square foot of combustion chamber cross sectional area.

(c) Exhaust static pressures and total temperatures under choked conditions. ($M = 1.0$).

3.1 Assumptions made in evaluating performance requirements

3.1.1 Intake

Intake design is developing continuously, and some performance assumption must be made. The intake recovery assumed here is the theoretical maximum for a central body diffuser with a shock system comprising one oblique and one normal shock[2]. For convenience, the values of overall pressure recovery at several inlet Mach Numbers are tabulated in Figure 2.

3.1.2 Combustion chamber

The internal drag loss is taken as five times the dynamic head at inlet to the chamber.

The variation in air mass flow with effective fuel-air ratio ($\eta_c q$) is illustrated by taking two values, namely 0.04 and 0.07.

The curves are presented for parallel sided and nozzle combustion chambers; the nozzle have $\frac{\text{outlet area}}{\text{combustion area}}$ ratios of 0.8 and 0.6. No losses are assumed in the nozzle.

3.2 Additional requirements for free-jet testing

Figure 5 shows the variation in blowing pressure with Mach Number and altitude for a free-jet nozzle. The nozzle inlet temperature is given in Figure 2.

3.2.1 Spill factor

The size of a supersonic airstream required to test a ram jet without interference to the flow pattern is influenced by the inlet Mach Number and the amount of air spilled by the intake. Figure 6 indicates the percentage excess of free-jet air over ram-jet air against Mach Number; Schlieren photographs of the airflow around a centre body intake provided the data on which the values are based[3]. This intake had a semi-cone angle of 30° and a lip position angle of 44°.

The curves show that for a given $\frac{\text{intake flow}}{\text{maximum intake flow}}$, the spill factor rapidly decreases with increasing Mach Number. The percentage spill factor increases as the intake flow is reduced below its maximum.

Note that the curves are given for a lip angle of 44°, and the size of free jet is some function of this angle.

4.0 Influence of ground test requirements on plant specification

4.1 Air supply temperature

All ram-jet testing plant should include air temperature control, to give the range of air temperature variation met in flight.

4.2 Humidity effects in supersonic nozzles

Humidity effects may give rise to condensation shocks in supersonic nozzles[4]; there are two possible solutions to this problem:

(a) To reduce the absolute humidity by drying.

(b) To lower the relative humidity by heating.

The latter solution is the more economic in ram-jet plant.

Figure 7 shows the temperature and Mach Number (M_c) at which condensation shocks will occur when the absolute humidity is 0.006 (average summer conditions in the British Isles). For example, at a supply pressure of six atmospheres and with an isentropic compression efficiency of say 85 per cent the compressor outlet temperature is 498°K. Under these conditions a maximum Mach Number of 2.45 is reached before the onset of condensation shocks.

Table 1 presents the temperature corresponding to M_c, and the flight temperature for various values of nozzle inlet pressure and flight Mach Number.

TABLE I

Nozzle Inlet Pressure (atmospheres)	Flight Mach No.	Flight Temperature °K.	Temperature at M_c °K.
3	2.0	433	410
	2.5	487	486
	3.0	605	578
6	2.0	495	425
	2.5	530	506
	3.0	605	602
12	2.5	602	528
	3.0	647	624

In most cases, if flight conditions are simulated, condensation shocks are avoided.

4.3 Air supply pressure for ignition tests

An important plant demand is the need for ignition tests at speeds up to Mach Number 1.8; to satisfy this requirement, a minimum pressure ratio of six atmospheres is required.

5.0 Alternative types of plant

Ram-jet plant must meet three different test conditions. These are:

(a) Low altitude tests - High pressure air to the intake; atmospheric exhaust.

(b) Medium altitude tests - Intake air pressure above atmospheric; exhaust pressure below.

(c) High altitude tests - Air induced from atmosphere; exhaust at low absolute pressure.

The various types of plant for the above duties are discussed in paragraphs 5.1 and 5.2.

A large supply of water is essential to avoid limitation of plant capacity by inadequate cooling of the exhaust gases.

5.1 Compressed air supply

The high pressure air demand is met by three separate types of plant; they are:

(a) Continuous flow compressors.

(b) Discontinuous systems. (i.e. storage tanks pumped up by small capacity air compressors).

(c) Air bleed gas turbines.

Figure 8 illustrates roughly the power demand for a free-jet test under sea level conditions; for example 30,000 horse power is required to give a Mach Number 1.85 test with a spill factor of 150 per cent for each square foot of combustion chamber area.

Various kinds of prime mover are used to drive continuous flow compressors, the choice is dependent on water, electrical power, and running cost existing on any particular site.

A way of reducing the power demand is to pump up a storage tank over a long period of time, and to let the tank blow down during the test. A disadvantage lies in the very short testing time available.

Plants exist which bleed off air from jet engines. Gas turbines may be used in their existing form or they can be modified to increase the quantity of air bled off at full engine pressure. The two most practicable methods of increasing the airflow are:

(a) Reduction of nozzle guide vane area to lower the turbine throughput.

(b) Reduction of nozzle guide vane area as in (a) together with redesigned turbine assembly to cater more efficiently with the increased expansion ratio of the bleed engine.

Both methods entail structural alterations, the former method is naturally simpler.

Figure 9 shows the air bleed from an unmodified "Nene" engine and one fitted with redesigned nozzle guide vanes as in (a). The latter gives an airflow of 14 lb./sec. at 4 : 1 pressure ratio; the corresponding flow for the unmodified engine is only 4 lb./sec.

Air bleed gas turbine plants are easily and quickly installed, and they provide a flexible system in that any number of engines may be run together. Case (a) has higher running costs than those of electrical plant.

5.2 Exhausting plant

There are two types of exhausting plant, they are:

(a) Suction pumps

(b) Air or steam operated ejectors

For high mass flows suction pumps are usually axial or centrifugal compressors; certain special machines such as the Nash Hytors exist, but these are mainly used for small airflows.

Suction pumps require expensive cooling plant to cool the exhaust gases in order to obtain a reasonable working temperature and a low specific volume.

The compressors used to provide the high pressure air can themselves be used as exhausters, however, this arrangement may present difficulties with the matching of the blowing and exhausting capacities.

A solution to the matching problem is to use the high pressure air as the driving fluid in an air ejector. Preheating, and subsequent cooling of the ejector driving fluid by water injection increases the total output from the ejector.

Because they use an existing supply of air, ejectors have a low capital cost; their running costs however, are much higher than those for suction pumps, especially when preheater fuel charges are included.

Figure 10 shows the relative performance of exhausters and air driven ejectors for both the normal and steam boosted cases. Using a compressor to deliver high pressure air at six atmospheres in an ejector gives a higher airflow throughput over a range of pressures approximately 6.5 - 30 inches Hg. as compared with the same compressor used as an exhauster; below 6.5 inches Hg. the suction pump is the better machine.

Ejectors may be staged in series when it is necessary to operate at very low pressures. Steam can be used to drive an ejector when a large water supply is available; it offers a better driving fluid when the ejectors are staged as the steam can be condensed out between stages. Finally, a combination of air or steam ejectors with suction pumps is possible.

6.0 Existing and planned testing facilities in the Ministry of Supply

6.1 Hercules - Nash Hytors - L.F.A. plant at R.A.E.

The plant at R.A.E. combines earlier existing plant with the Volkenrode (L.F.A.) high altitude plant which was brought from Germany. The main components of this plant are:

(a) Air drying equipment

(1) Butterly air drier (2 machines)

(2) L.F.A. air drier (1 machine)

The whole plant is distinguished by its air drying capabilities which enable a weight flow of 27 lb./sec. to be dried down to a moisture content of 0.0005 lb. per lb. of air.

(b) Compressing equipment

Hercules aero engine superchargers (7 machines)

The blowers are electrically driven; inlet air is drawn either from the driers or from atmosphere. Table 2 gives the performance of one machine, the combined performance of seven machines is not yet available.

TABLE II

Hercules Compressor Performance

Delivery Pressure (lb./in.^{2} abs.)	Weight Flow (lb./sec.)	Delivery Temp. °K.
19.5	2.5	325
26.4	3.5	360
29.4	4.0	375
36.3	5.1	400

(c) Suction equipment

(1) Nash Hytors suction pumps. (14 machines)

(2) L.F.A. suction pumps. (3 machines)

The L.F.A. plant, consists of three pumps each having four stages; two machines can be run independently or in parallel with each other, while the third is run in series with the first two in order to reach the lowest suction pressures. Table III presents the performance of the combined Nash Hytor and L.F.A. plants.

TABLE III

Performance of the combined Nash Hytor and L.F.A. Suction Plants at R.A.E.

Suction Pressure (Inches Hg. abs.)	Dry Weight Flow (lb./sec.)	Saturated Weight Flow (lb./sec.)	Inlet Temp. °K.
20	38.0	33.75	313
10	22.4	17.25	313
8	18.5	13.9	303
6	14.5	11.2	303
4	10.5	6.7	303
2	4.25	1.5	303

Note that the inlet temperature is controlled by cooling the exhaust gas; at high weight flow there is only sufficient water to cool down to 40°C., while it is possible to reach 30°C. at low flow.

At the moment the plant is used to run six inch connected tests under altitude conditions. By the middle of 1953 two further test cells will be available, mainly for free-jet testing.

6.2 Old Site test plant at N.G.T.E.

(a) Compressing plant

(1) B.T.H. compressor (1 machine)

(2) "Nene" air bleed gas turbines (5 machines)

The British Thomson Houston compressor is a 4,000 H.P. electrically driven four stage centrifugal machine; it has a wide range of speed control through a Ward-Leonard set.

An aftercooler controls the temperature between 50° - 190°C. Table IV presents the performance details for two rotor speeds:

TABLE IV

Performance of B.T.H. Compressor at N.G.T.E.

Rotor Speed R.P.M.	Delivery Pressure Ratio	Weight Flow (lb./sec.)	Delivery Temp. °K. (without cooler)
800 (Max.)	4.3	23.5	190
	4.0	25.3	190
	3.5	28.0	190
	3.0	29.7	190
700	3.3	18.2	160
	3.0	21.2	160
	2.5	24.2	160

The air bleed gas turbines have redesigned nozzle guide vanes as discussed in Section 5.1. The characteristics are shown in Figure 9.

Five air bleed engines are installed, it is usual to run three machines leaving the others as spares.

(b) Suction plant

The suction plant consists of two air ejectors; one is used for six inch diameter connected tests only and is not fitted with a preheater, the larger ejector is fitted with a preheater to boost the driving flow. Design details of the large ejector are based on the results of experiments on a model[5].

Table V presents the performance:

TABLE V

Performance of the Old Site Ejector at N.G.T.E.

Suction Pressure (Inches Hg.)	Weight Flow (lb./sec.)	Inlet Temp. °K.
25	42.0	373
20	33.0	373
15	21.0	373
12	10.0	373

Note that the weight flow includes water vapour left in the exhaust by the cooling process.

The above plant can be used to run five test rigs, they are:

(a) Up to 16 inch diameter ram-jets, sea-level connected rig tests.

(b) Up to 16 inch diameter ram-jets, sea-level free-jet tests. ($M = 1.45$).

(c) Up to 16 inch diameter ram-jets, altitude connected rig tests.

(d) Free-jet tests on small diameter high speed intakes. ($M = 2.0$).

(e) Up to 6 inch diameter ram-jets, sea-level and altitude connected rig tests.

6.3 Proposed new plant at N.G.T.E.

A new ram-jet test plant is now almost completely designed. This plant is to be sited near the new gas turbine laboratories at N.G.T.E. where it can take advantage of a 14,000 H.P. steam turbine power supply.

The plant is to have an airflow capacity of 200 lb./sec. at 6 : 1 compression ratio. It is intended that this air should be supplied from two similar Metropolitan Vickers axial flow compressors of 60 lb./sec. capacity each, and from an aircraft compressor driven by a 14,000 H.P. steam turbine.

Figure 11 shows the plant layout. It will consist of four air ducts from the compressors which are to feed either of two twelve foot diameter metal test cells; one for free-jet, the other for connected rig testing. Under sea-level conditions, the cells will exhaust direct to atmosphere through silencers; when altitude tests are required large doors will close the exhaust ends and the cells will be exhausted by the suction plant.

The suction plant will consist of four similar ejectors fitted with preheaters. The choice of four instead of one ejector should give a flexible arrangement; under reduced airflow conditions a saving in running cost is possible because the number of ejectors can be arranged to match the test conditions, alternatively the air preheaters may not be used.

The temperature of the incoming air is to be controlled by coolers fitted in the delivery lines of the two axial compressors and by a 3,000 K.W. heater which will give inlet air heating up to 350°C.

The plant will include certain new features and use new techniques, these are discussed in an Appendix.

7.0 Test plants in industry

7.1 The Bristol Aeroplane Co.

Compressing plant

"Proteus" aero engine compressors (3 machines).

The compressors are electrically driven; they give a total flow of 120 lb./sec. at 6 : 1 compression ratio. This air supply feeds four test beds, one of these is to be fitted with an air ejector.

The ram-jet airflow can be boosted by an inducing nozzle for medium altitude connected tests; normally 12 lb./sec. at 6 : 1 pressure air is used to induce extra air from the atmosphere. The pressure and temperature of the resultant mixture depends upon the amount of air that is induced.

7.2 D. Napier & Son Ltd.

At Liverpool, there is a steam turbine power supply of 10,000 H.P. which could be used to run suitable compressor equipment.

The existing plant is:

(a) Reavell compressors

Two machines supply a total flow of 33 lb./sec. at a 7 : 1 pressure ratio and 478°K.

(b) Reavell exhausters

Three machines can suck 33 lb./sec. down to a pressure of 8 inches Hg. abs. at an inlet temperature of 367°K.

(c) Cooling plant

Exhaust coolers are fitted which can cool 33 lb./sec. from 1200° to 373°K. with 1 lb./in.^{2} pressure drop.

At the moment this plant is not used for ram-jet testing.

8.0 Estimated range of tests

The curves of the free-jet test range are given in all cases for a six inch diameter ram-jet operating at an effective fuel : air ratio of 0.07 without an exhaust nozzle. An estimate of the individual test plant capacities is therefore possible.

A spill factor of 100 per cent is taken in determining the ejector performance in the free-jet case; this performance is taken from model test results[6].

No pressure recovery is assumed at the ram-jet exhaust in the determination of suction plant capacity; the range of tests presented can therefore be regarded as a minimum. However, if some pressure recovery is achieved by means of diffusers, the pumping pressure ratio required of the plant is reduced for given ram-jet exhaust conditions.

In the case of the ejector plant, the ram-jet exhaust is assumed to be cooled down to 100°C. by water injection; in the curves the airflow capacity is reduced by the quantity injected, for example, when the ram-jet is operating at the effective fuel-air ratio of 0.07 the mixture pumped by the ejector consists of 47 per cent dry steam and 53 per cent air.

8.1 R.A.E. plant

8.1.1 Free-jet tests

Figure 12 shows the range of tests; the variation of airflow requirement with altitude for the six inch ram-jet under zero spill conditions is drawn for a series of Mach Numbers. The inlet air supply pressure determines the altitude at which a given Mach Number is obtained, hence a limiting pressure line is superimposed on the Mach Number curves. Above this line a ram-jet cannot be tested as there is insufficient pressure ratio available. Also shown is the limiting line fixed by the exhaustor capacity. For the six inch ram jet considered the exhaustor airflow line lies above the driving pressure limitation line. The difference in airflow between the exhauster limit and the working point determines the spill factor. There is no effective limit on the high pressure airflow.

Example

Mach Number 2.2, altitude 40,000 ft.

From curve: Airflow required = 3.6 lb./sec.

Exhauster limit = 10.4 lb./sec.

Spill factor available is 190 per cent.

It can be seen that reasonable spill factors can be maintained for Mach Numbers up to 2.4. When exhaust nozzles are used the air demand is less and the spill factor is increased.

8.1.2 Connected tests

Figure 12 also shows the range of connected rig tests at three equivalent flight speeds, namely M = 1.5, 2.0 and 2.5.

At a given Mach Number, the range of altitude is governed, on the one hand, by suction plant capacity at the ram-jet exit throat pressure corresponding to the simulated altitude, (see Figure 4), and on the other by the compressing plant supply pressure. The Mach Number determines the altitude at which a given exhaust pressure is attained. For this plant there is also a cooling water limitation which limits the airflow to approximately 20 lb./sec. for an effective fuel/air ratio of 0.07.

The size of ram-jet that can be tested is determined with the aid of Figure 3.

Example

Mach Number 2.0, altitude 70,000 ft.

Figure 12 gives an approximate available flow = 4.5 lb./sec.

Figure 3 gives a required airflow of 3.6 lb./sec. per square foot.

Diameter = 15.0 inches.

8.2 N.G.T.E. Old Site plant

8.2.1 Free-jet tests

Figure 13 shows the range of tests, which is presented in a similar manner to that of Figure 12 and described in paragraph 8.1.1. The air pressure available enables a Mach Number of 1.5 to be attained under sea-level conditions; to obtain a Mach Number of 2.0 it is necessary to reduce the ambient pressure to that corresponding to an altitude of 20,000 ft. Under the latter conditions the spill factor is approximately 65 per cent using a 6 inch diameter ram-jet.

8.2.2 Connected tests

The plant provides the following test conditions:

(a) Combustion chamber exhaust at atmospheric pressure or above.

(b) Combustion chamber pressure below atmospheric.

For (a) the available weight flow is sufficient to test 16 inch diameter chambers, the range of testing can be determined from Figures 2 and 4.

The test range for condition (b) is shown in Figure 13 for three flight speeds. Typically, a 14 inch diameter chamber can be tested at a simulated flight condition of $M = 2.0$ and an altitude of 55,000 ft.

8.3 N.G.T.E. New Site plant

8.3.1 Free-jet tests

The main features of the planned new site plant will be the higher Mach Number and greater mass flows at similar Mach Numbers compared with the plants previously described. A Mach Number of approximately 2.9 will be possible at a spill factor of 100 per cent. At lower Mach Numbers it will be possible to test larger ram-jets. Figure 14 shows that a spill factor of 490 per cent will be available for a six inch ram-jet operating at $M = 2.2$ at 30,000 ft.; more realistically, by reducing this factor to say 100 per cent the ram-jet diameter could be increased to ten inches. With a further reduction in spill factor to 50 per cent a thirteen inch diameter ram-jet could be tested at flight conditions corresponding to $M = 2.2$ at 25,000 ft.

Similarly with a reduction in spill factor to 25 per cent a 15.65 inch diameter ram-jet with a 20 per cent exit restrictor could be tested at the same flight condition.

8.3.2 Connected tests

Figures 14 and 15 show the range of tests for combustion chamber inlet pressures above and below atmospheric respectively.

When the exhaust pressure is atmospheric or above, a total airflow of 200 lb./sec. will be available; this will test thirty inch diameter combustion chambers. For convenience, the duct size that can be tested at $M = 2.0$ is given in Table VI.

TABLE VI

Duct Diameter (Inches)	Altitude (Feet)	Remarks
24	60,000	Inlet and exhaust pressure below atmospheric
29	50,000	Inlet and exhaust pressure below atmospheric
24	40,000	Inlet pressure above, exhaust pressure below atmospheric
26.5	30,000	Inlet pressure above, exhaust pressure below atmospheric

8.4 Bristol plant

The 6 : 1 pressure ratio air supply allows free-jet tests to be carried out up to Mach Numbers of approximately 1.7 at sea-level conditions.

Combustion chambers of up to 22 inch diameter can be tested with the maximum flow capacity of 120 lb./sec.

No estimate can be made at present of the altitude test range owing to the uncertainties in design of the proposed suction plant, but the potential of the plant is everywhere three-fifths of the figures quoted for the N.G.T.E. New Site plant as this is the ratio of the air flows.

8.5 Comparison of plant utility in different types of tests

Figure 16 illustrates the size of ram jet which can be tested under various conditions assuming an air supply at 6 : 1 pressure ratio. The diagram assumes the use of preheated air ejectors for producing vacuum conditions where necessary.

Acknowledgment

The authors wish to acknowledge the contributions of Mr. A. Sharpe and Mr. R.P. Probert to the subject matter of this memorandum.

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6	-	Unpublished Work at N.G.T.E.

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APPENDIX I

Special Features of Planned New Site Plant at N.G.T.E

(A) Speed of operation

Because the running costs of the plant are high, the design aims especially at rapid operation. For example, a change in angle of free-jet nozzle (angle of yaw) can be made without shutting down the plant. Photographic recording of all instruments is to be used.

The doors of the test cells are to be operated by remote control to allow a quick changeover from sea-level to altitude exhaust conditions. The ejector starting cycle will be semi-automatic, and full load conditions should be reached in approximately three minutes.

(B) Thrust installation

The range of thrust measurement is from 1,000 to 30,000 lb. It is desirable to use the same equipment to test over the whole range; consequently the friction loss must not exceed ten pounds (1 per cent of 1,000 lb.). A final choice of suspension arrangement is not yet made.

Thrust will be measured hydraulically by three instruments of different range and interchangeable during running.

(C) Ignition test equipment

Realistic ignition trials demand that the velocity of the inlet air to the ram-jet increases rapidly with time. To fulfil this duty, two 48 inch diameter butterfly valves are to be installed in the inlet pipes to the test cells. (Figure 11). The valves will be interconnected to work simultaneously; one valve will open as the other closes. In this way the air can be switched at a controlled rate from a bypass circuit to the test cell. The rate of opening of the valve determines the weight-flow against time relationship.

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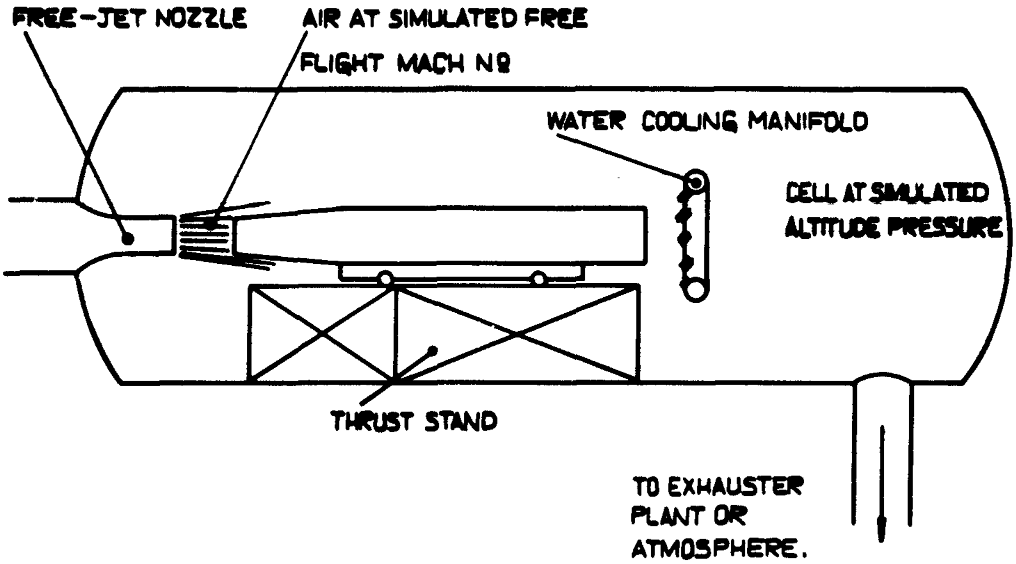
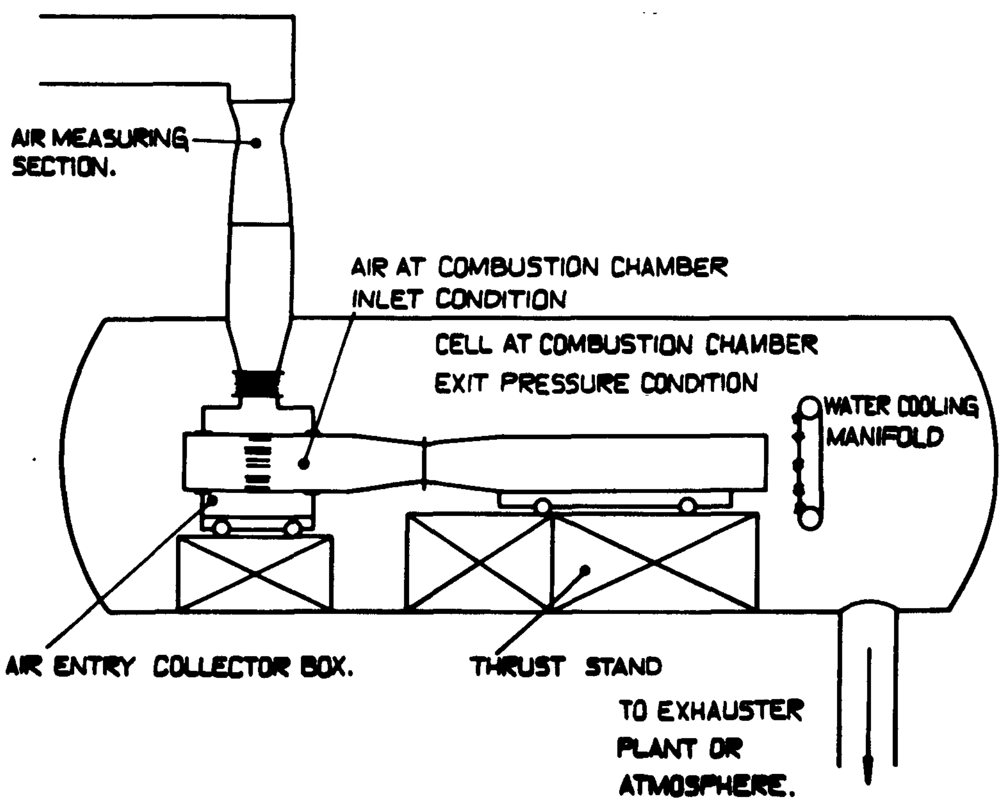
FIG. I

FREE-JET TEST ARRANGEMENT



CONNECTED COMBUSTION CHAMBER TEST ARRANGEMENT.



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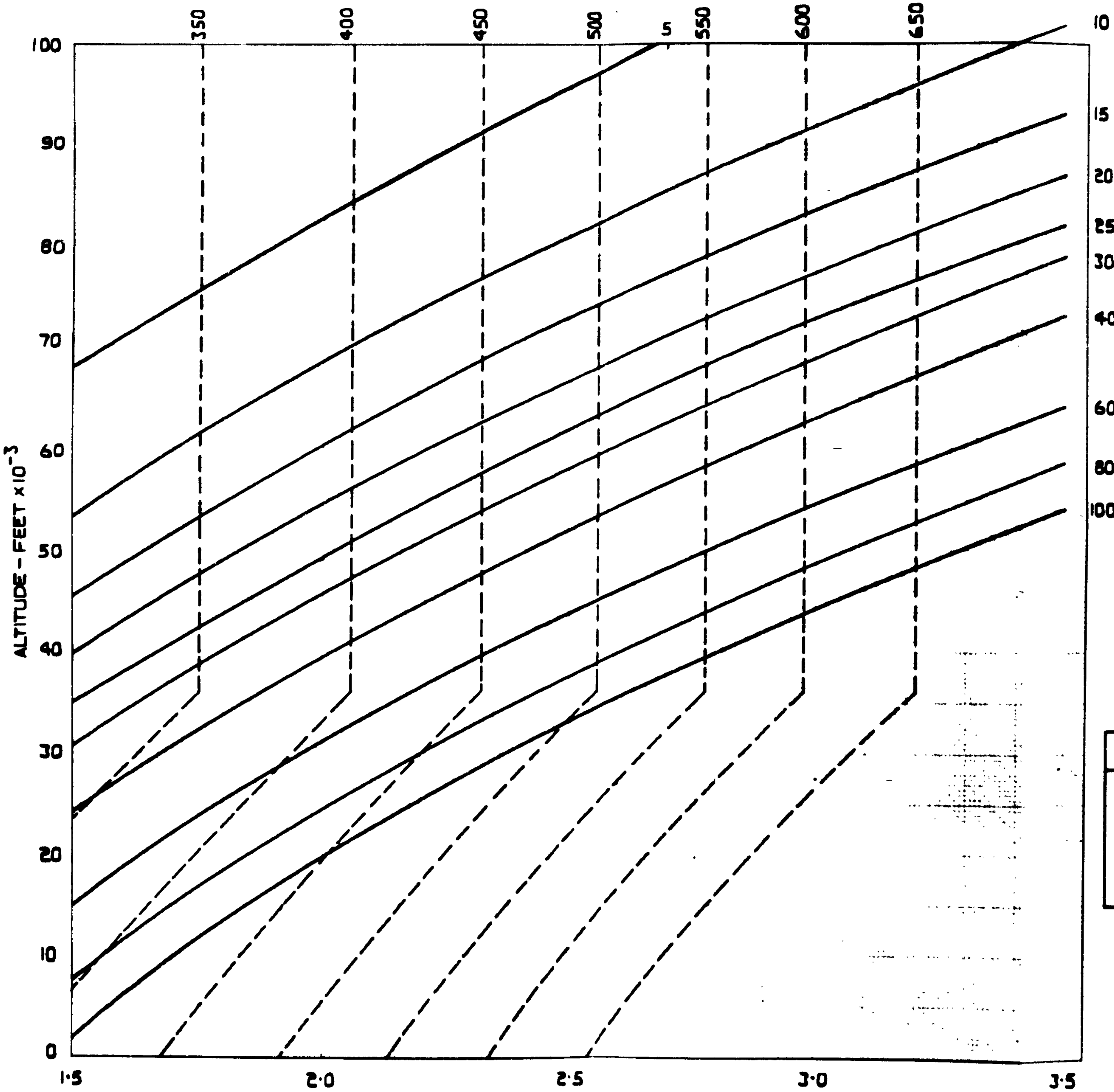
VARIATION OF COMBUSTION CHAMBER INLET CONDITIONS WITH ALTITUDE AND MACH. NUMBER.

FIG. 2



M	P_{t2}/P_{t0}
1·5	0·97
2·0	0·90
2·5	0·75
3·0	0·59
3·5	0·44

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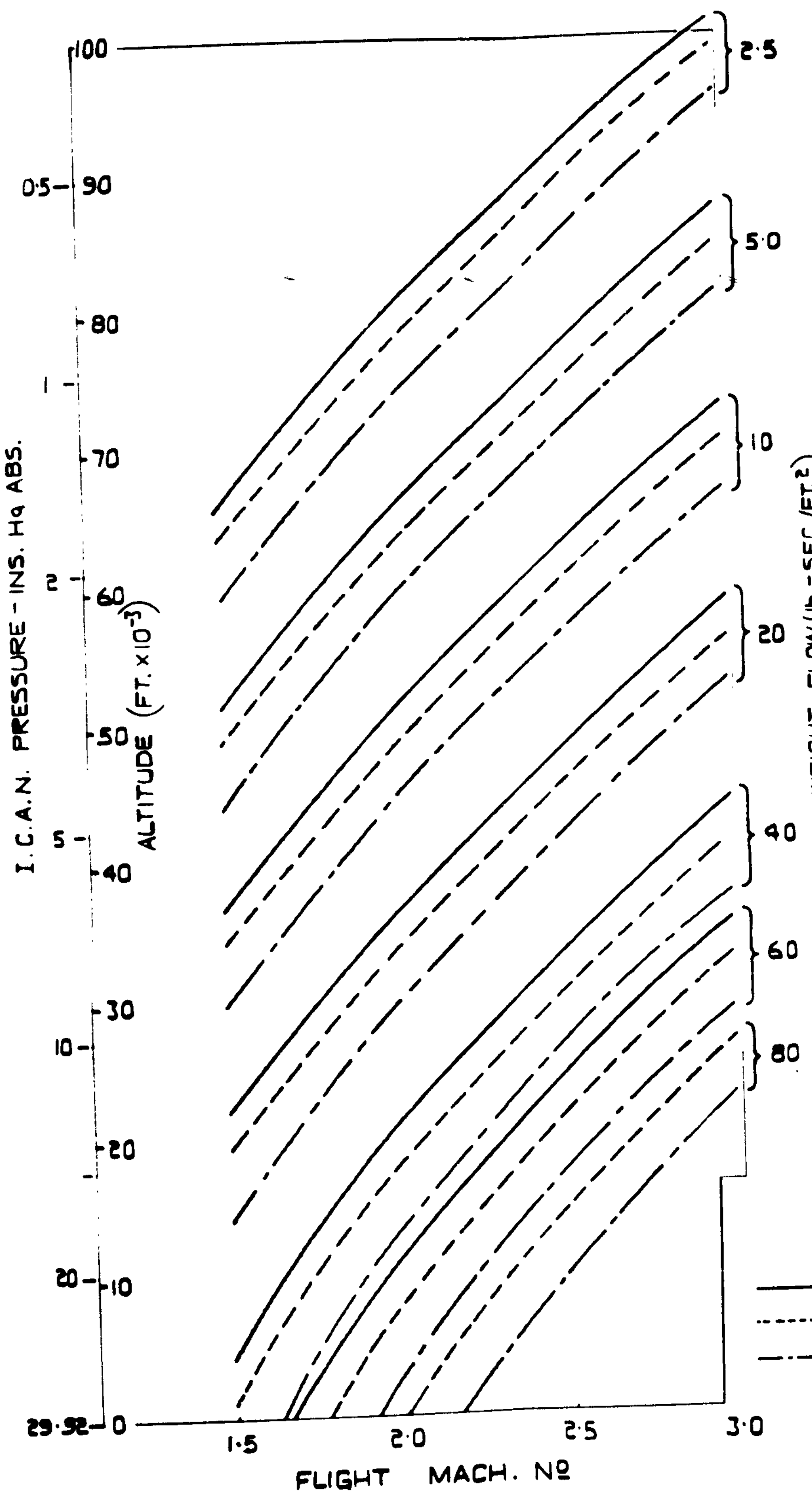
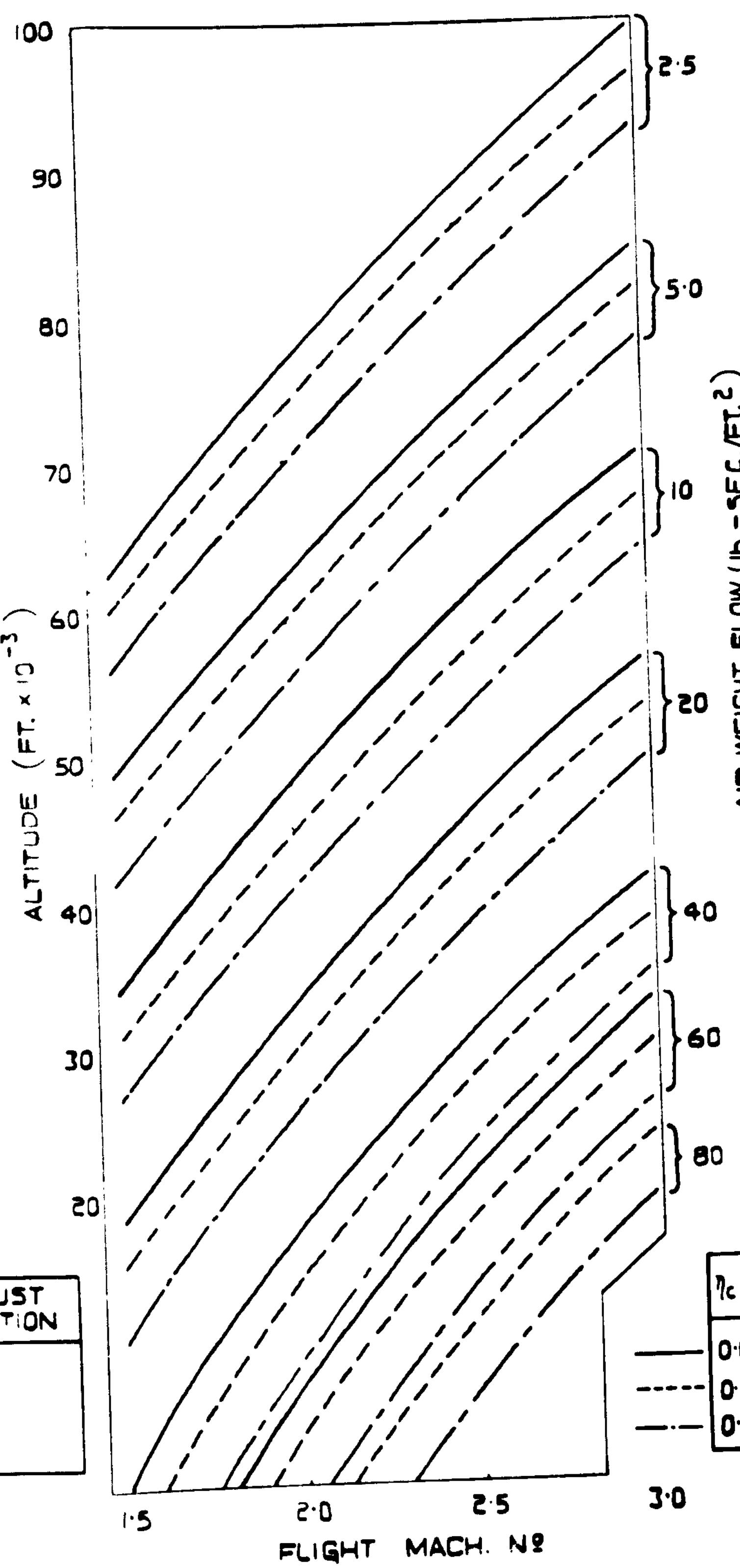
FIG. 3

VARIATION OF AIR WEIGHT FLOW PER. SQ. FT. OF DUCT WITH ALTITUDE AND MACH. NUMBER.



	$\eta_c q$	% EXHAUST RESTRICTION
———	0·04	0
- - - -	0·04	20
—·—	0·04	40



	$\eta_c q$	% EXHAUST RESTRICTION
———	0·07	0
- - - -	0·07	20
—·—	0·07	40

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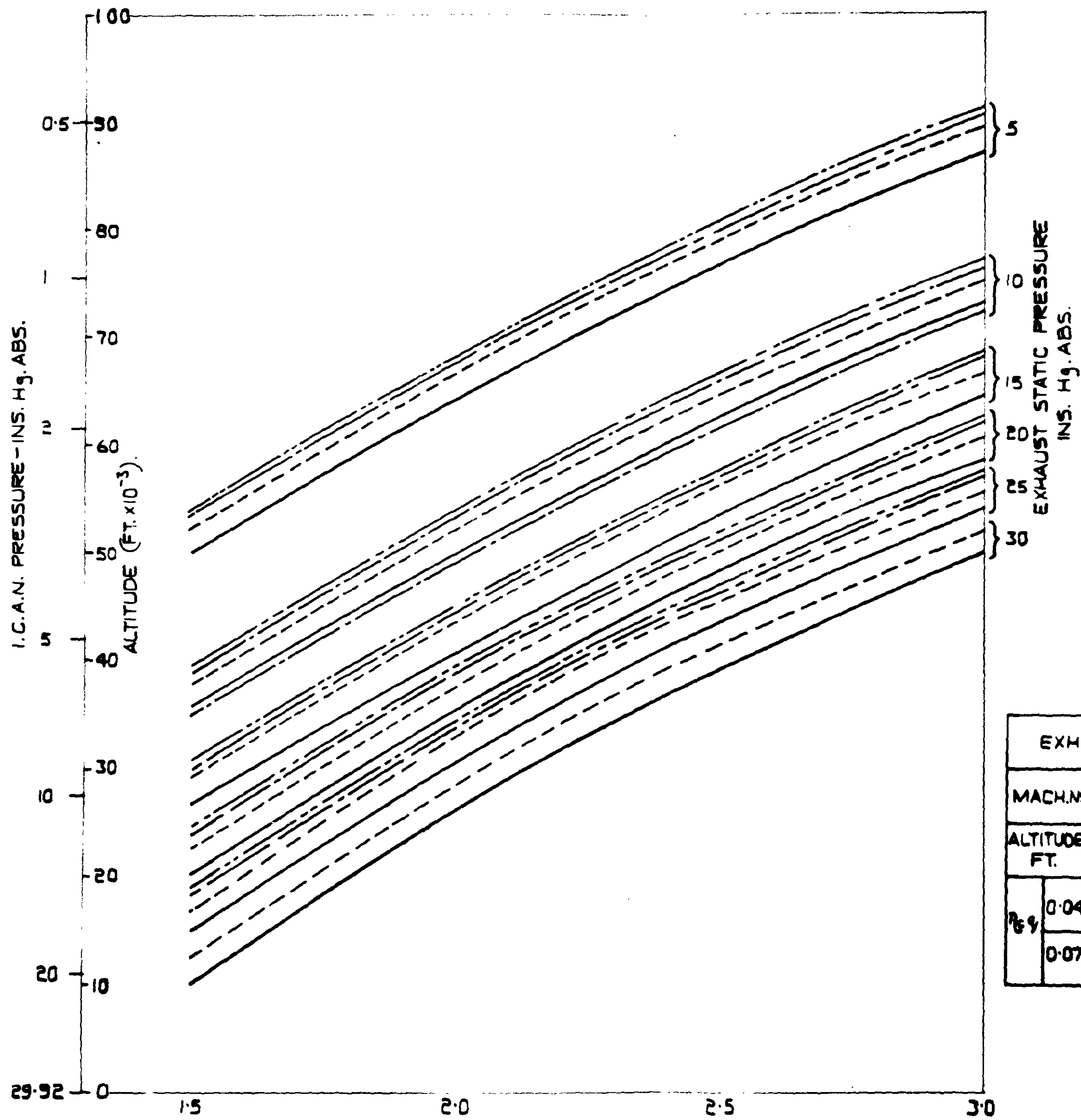
FIG. 4

VARIATION OF EXHAUST CHOKING PRESSURE WITH ALTITUDE AND MACH. NUMBER.



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	$\eta_{c}\varphi$	% EXHAUST RESTRICTION
	0·07	0
	0·07	20
	0·07	40
	0·04	0
	0·04	40

EXHAUST TEMPERATURE °K					
MACH. Nº		1·5		3·0	
ALTITUDE FT.		0	36000	0	36000
$\eta_{c}\varphi$	0·04	1760	1680	1930	1890
	0·07	2360	2300	2540	2450

VARIATION OF INLET PRESSURE TO FREE-JET RIG WITH MACH NUMBER AND ALTITUDE.

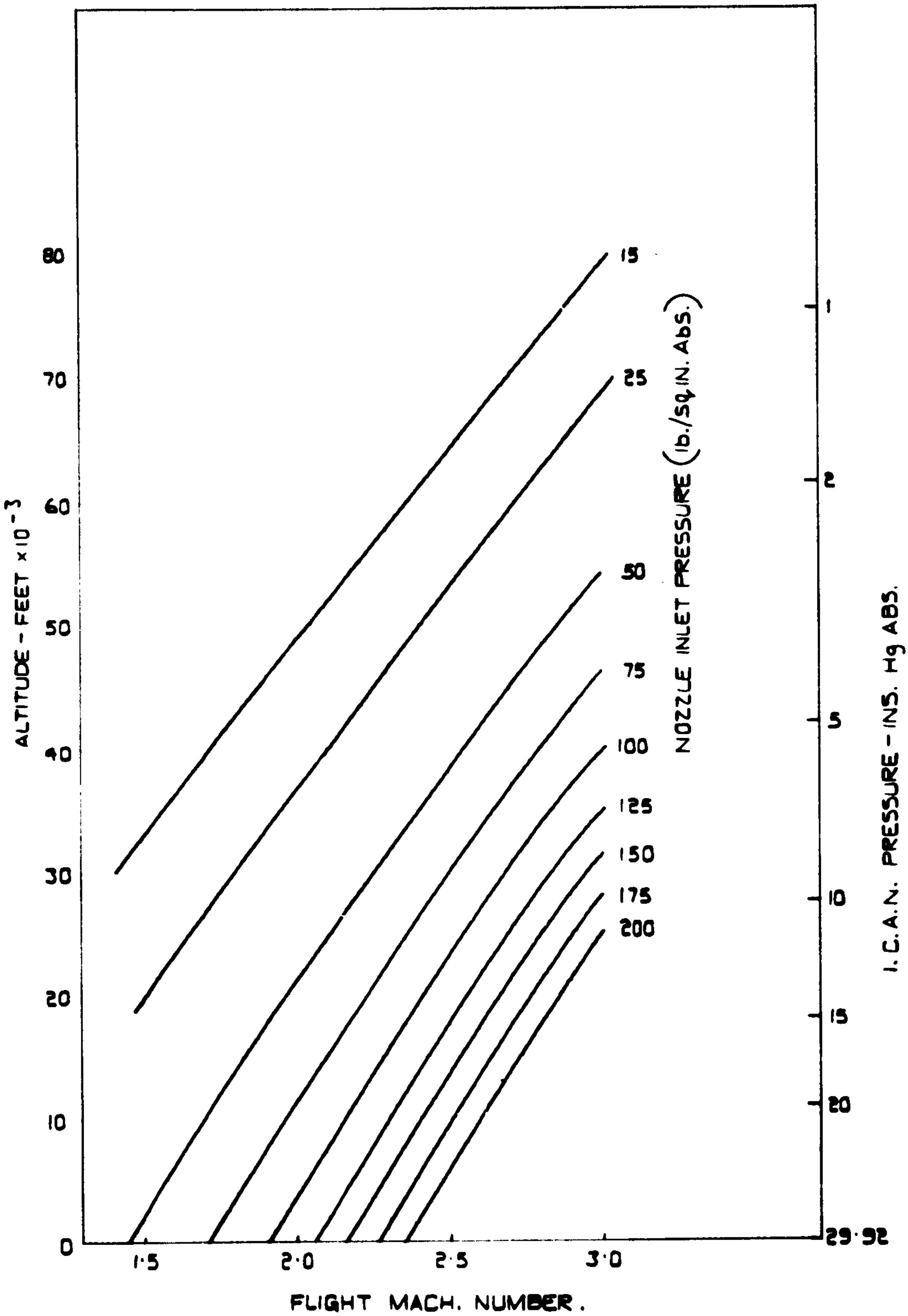

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FIG. 6

SPILL FACTORS FOR CONICAL INTAKE TESTS AT ZERO INCIDENCE.

(REPRODUCED FROM REFERENCE 3)

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SHOCK ON LIP AT M = 2·34
CONICAL INTAKE LIP POSITION ANGLE = 44°
CONE SEMI-ANGLE = 30°
SPILL FACTOR = $\frac{\text{FREE JET NOZZLE FLOW}}{\text{INTAKE FLOW.}} - 1$

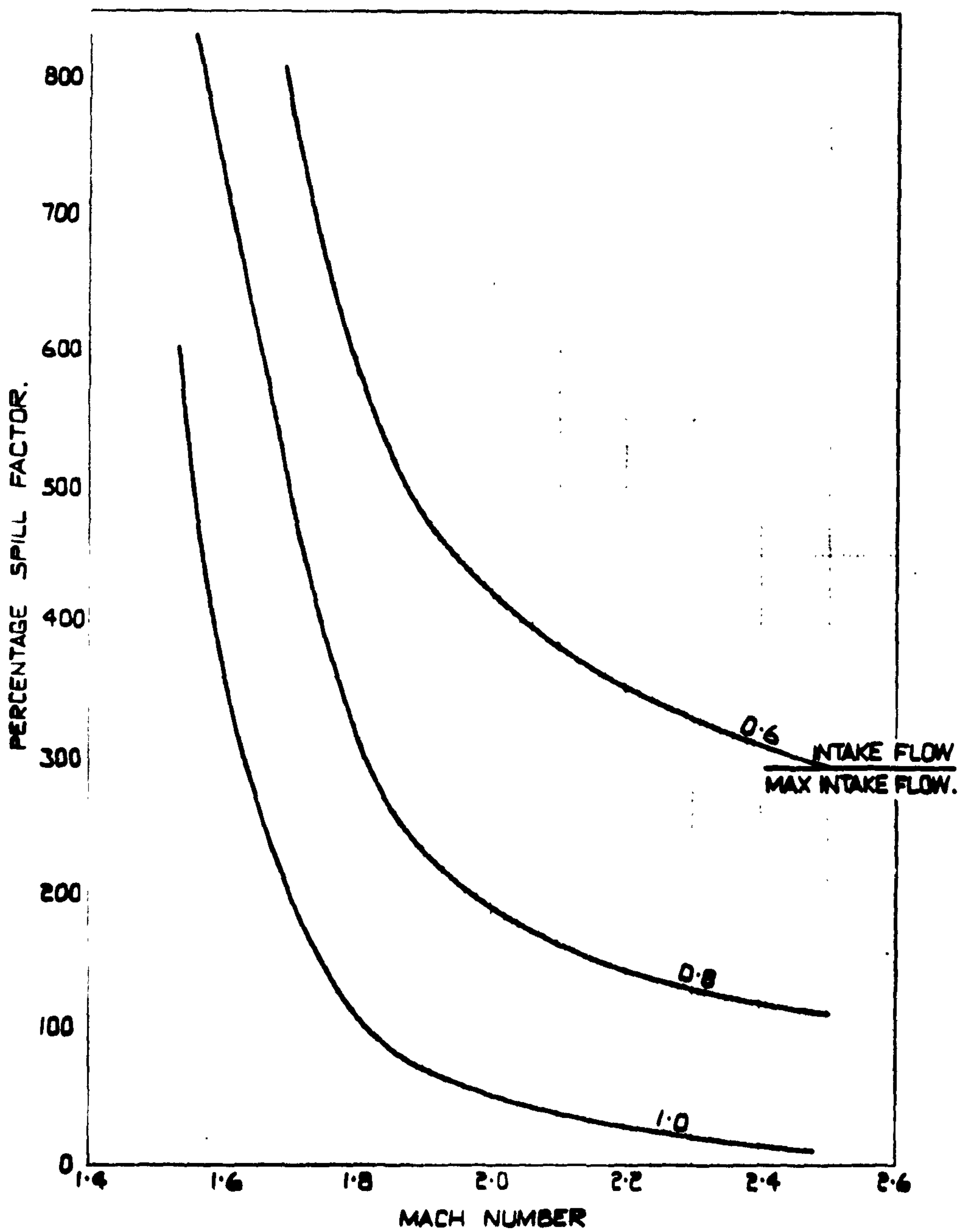

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FIG. 7

EFFECT OF NOZZLE INLET TEMPERATURE ON Mc FOR VARIOUS INLET PRESSURES.

SUMMER CONDITIONS :-

ABSOLUTE HUMIDITY = ·006

ADIABATIC SUPERCOOLING = 50°C

Ms = MACH. NUMBER AT SATURATION

Mc = MACH. NUMBER AT WHICH CONDENSATION SHOCK OCCURS.

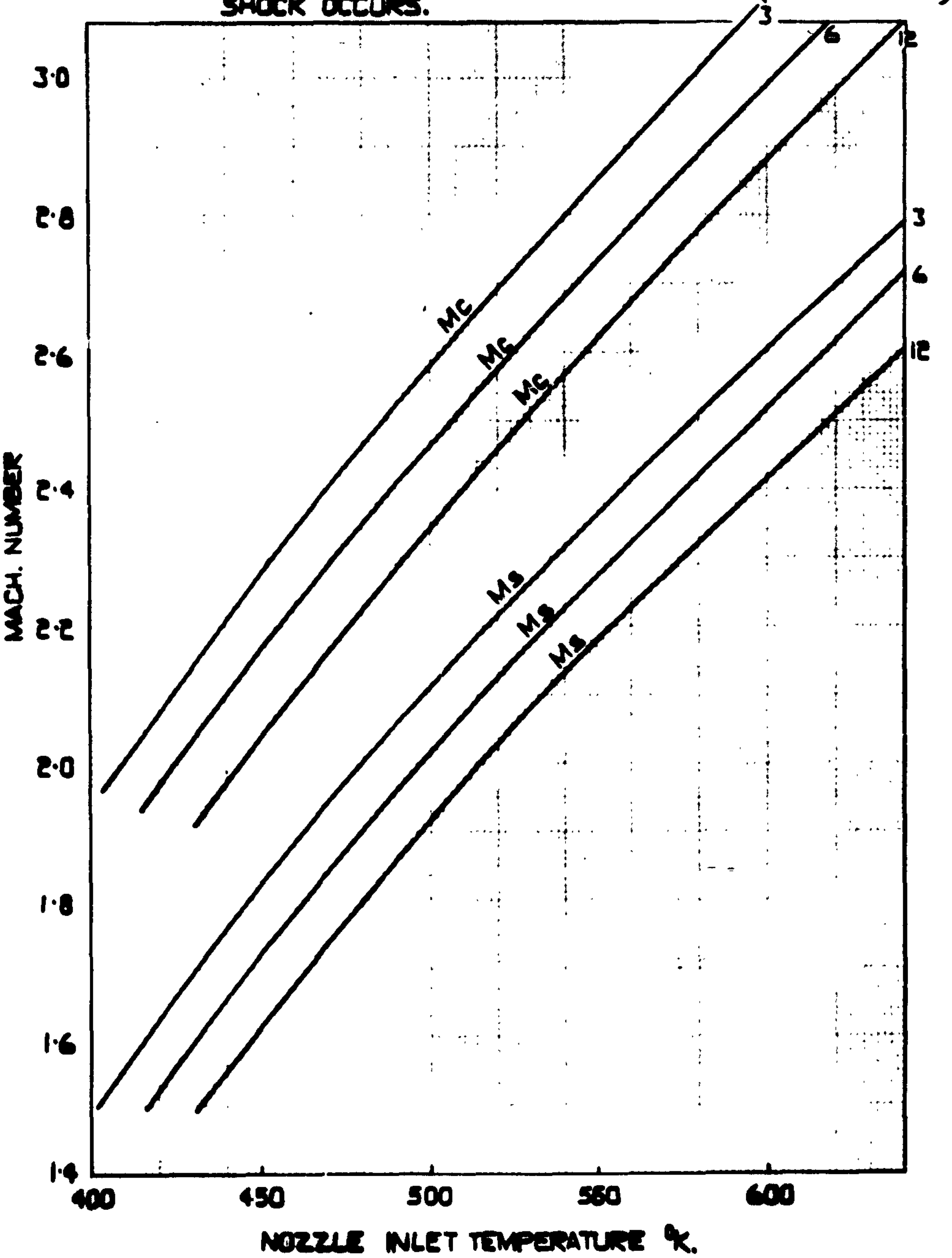

FIG. 8

SK 57035

POWER DEMAND FOR FREE-JET. TEST UNDER SEA-LEVEL CONDITIONS.

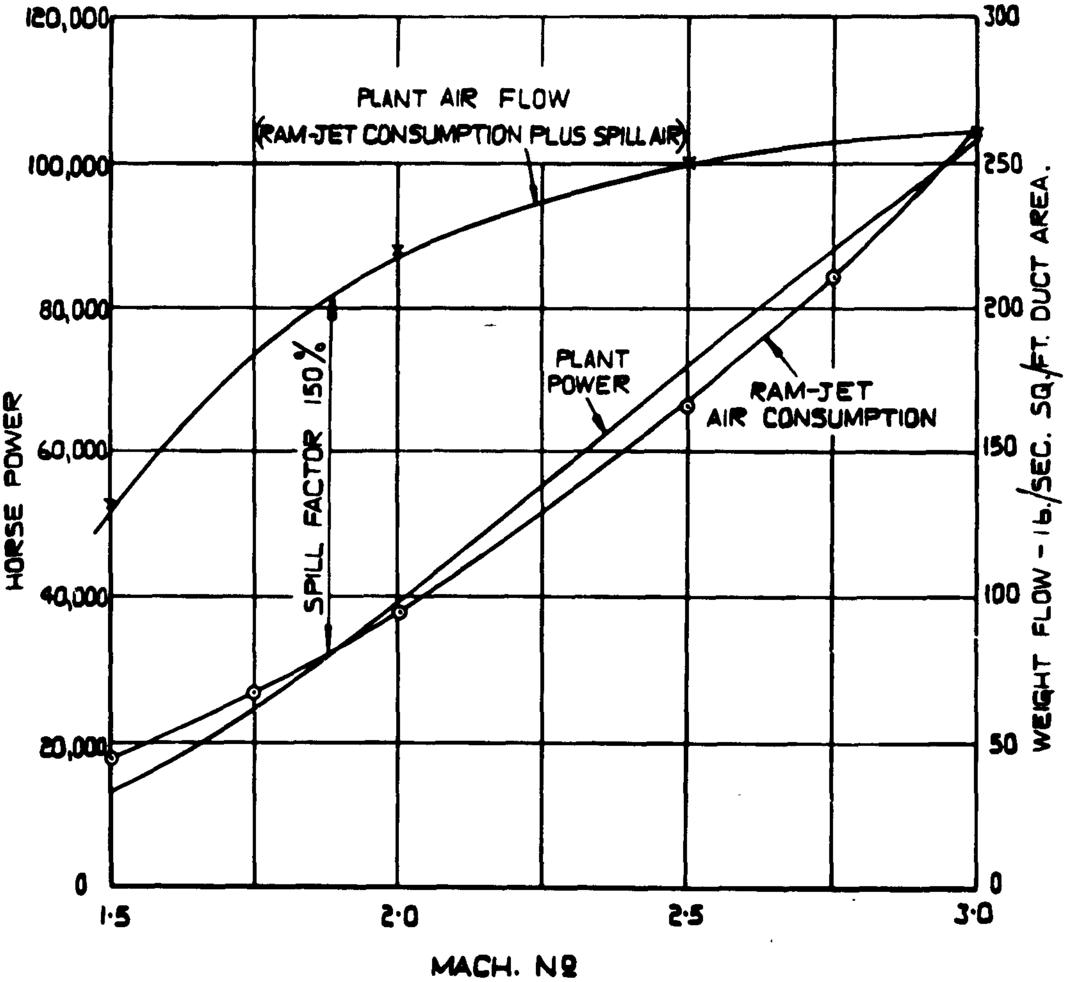

FIG. 9

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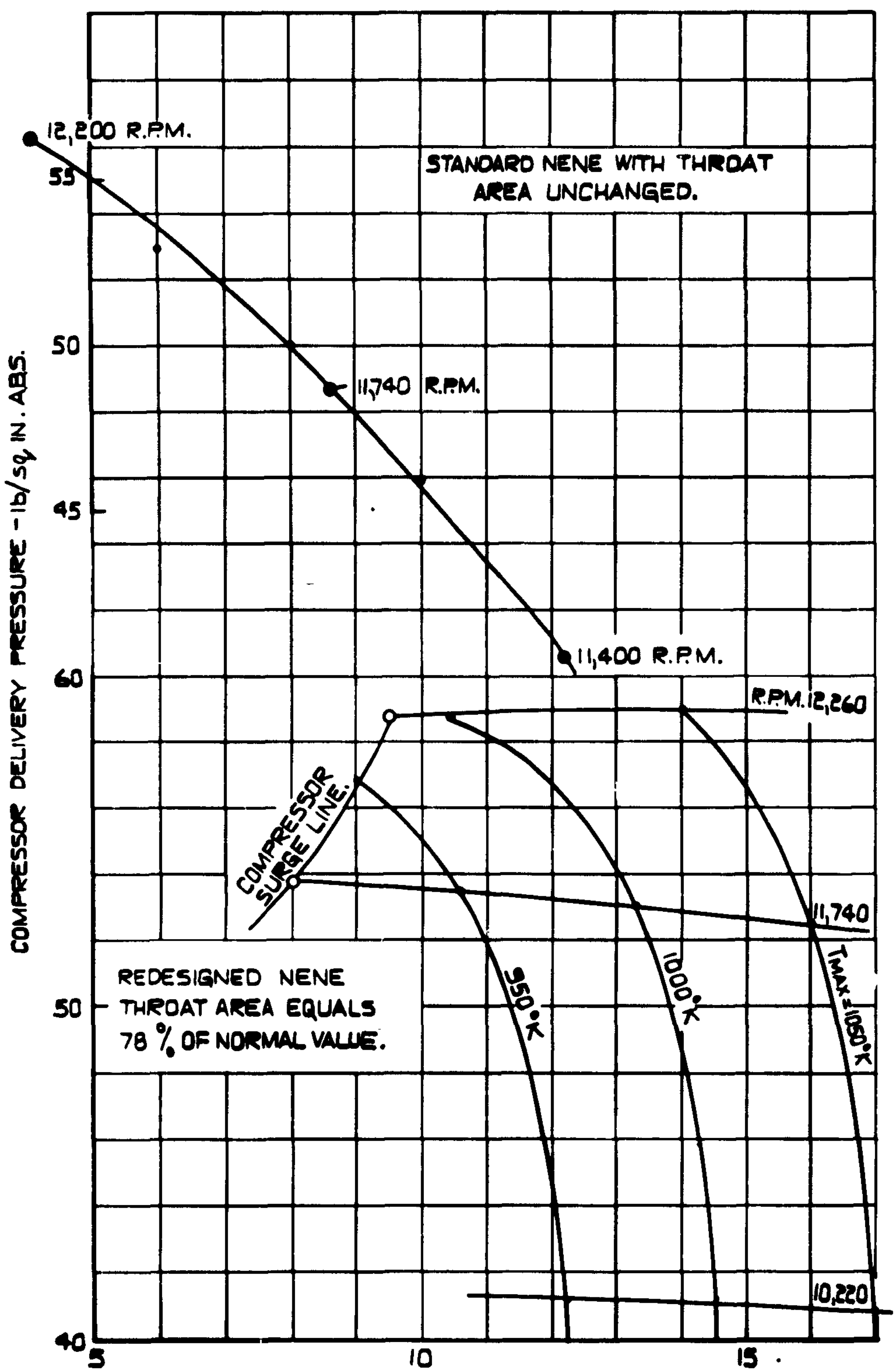
CHARACTERISTICS OF "NENE" AIR BLEED ENGINE.

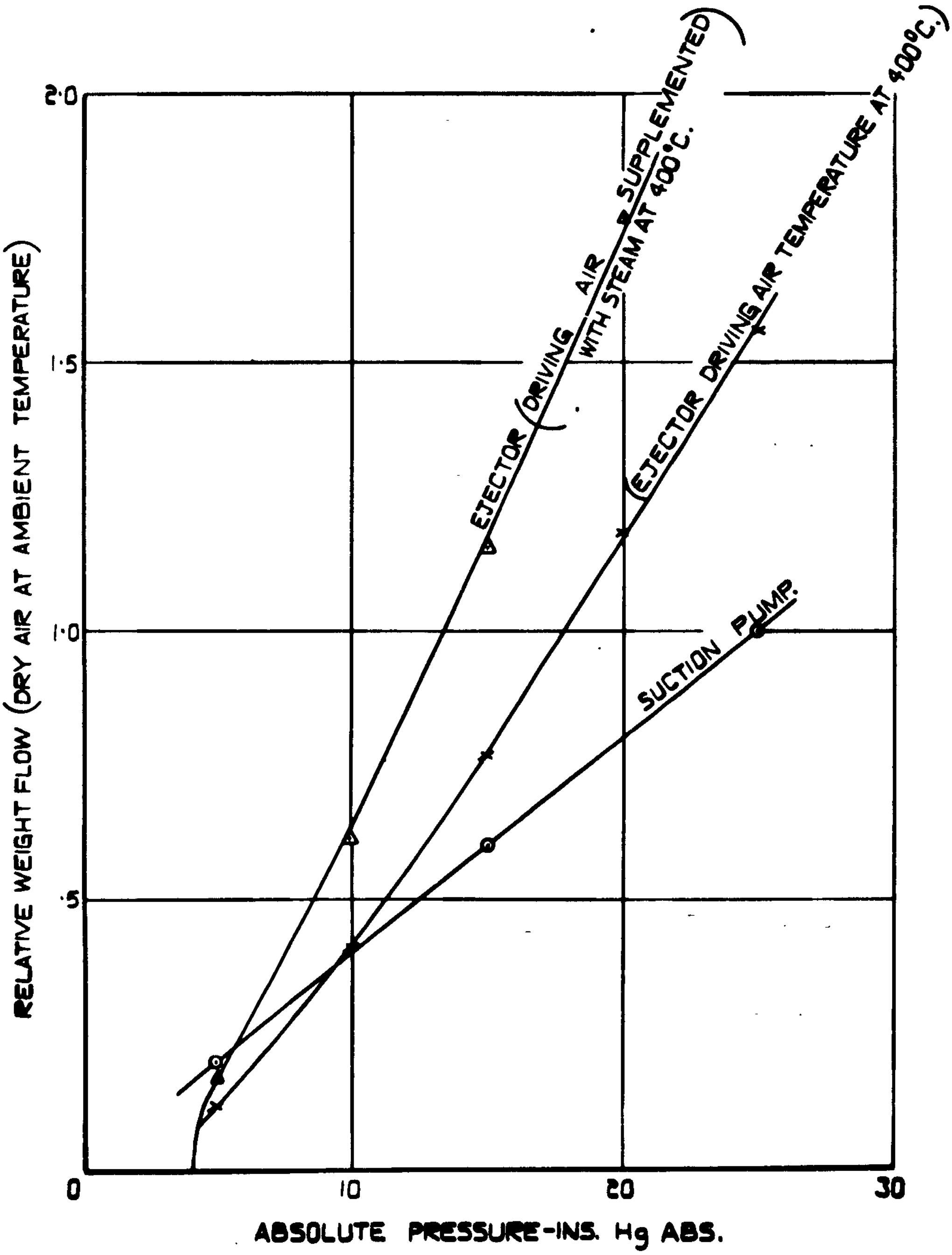


BLEED AIR WEIGHT FLOW - lb/SEC.

FIG. 10

SK 57037

COMPARISON OF EJECTORS AND SUCTION PUMPS AT 6/1 PRESSURE RATIO.



DIAGRAMMATIC LAYOUT OF PLANNED NEW PLANT AT N.G.T.E:

FIG. II

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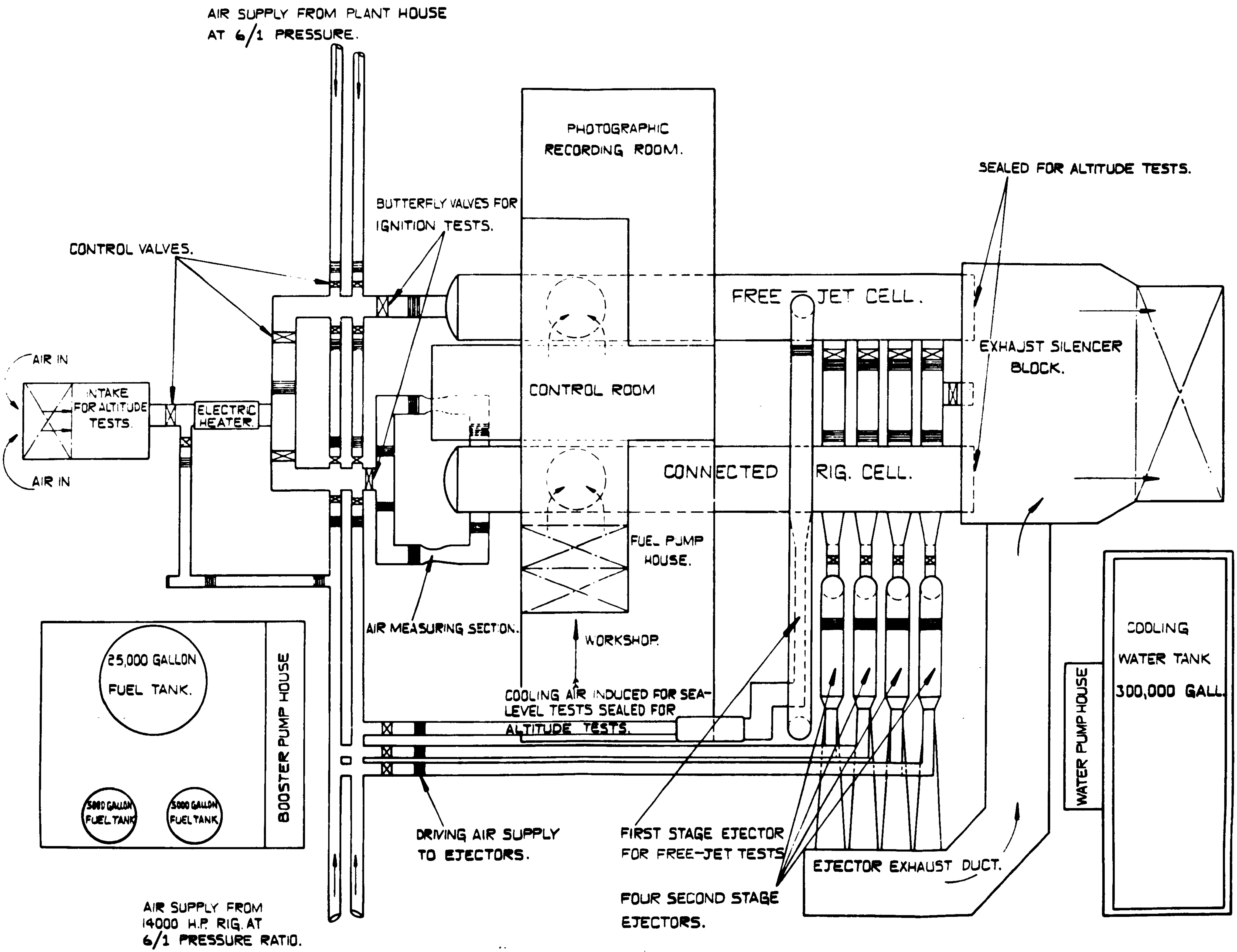

FIG. 12

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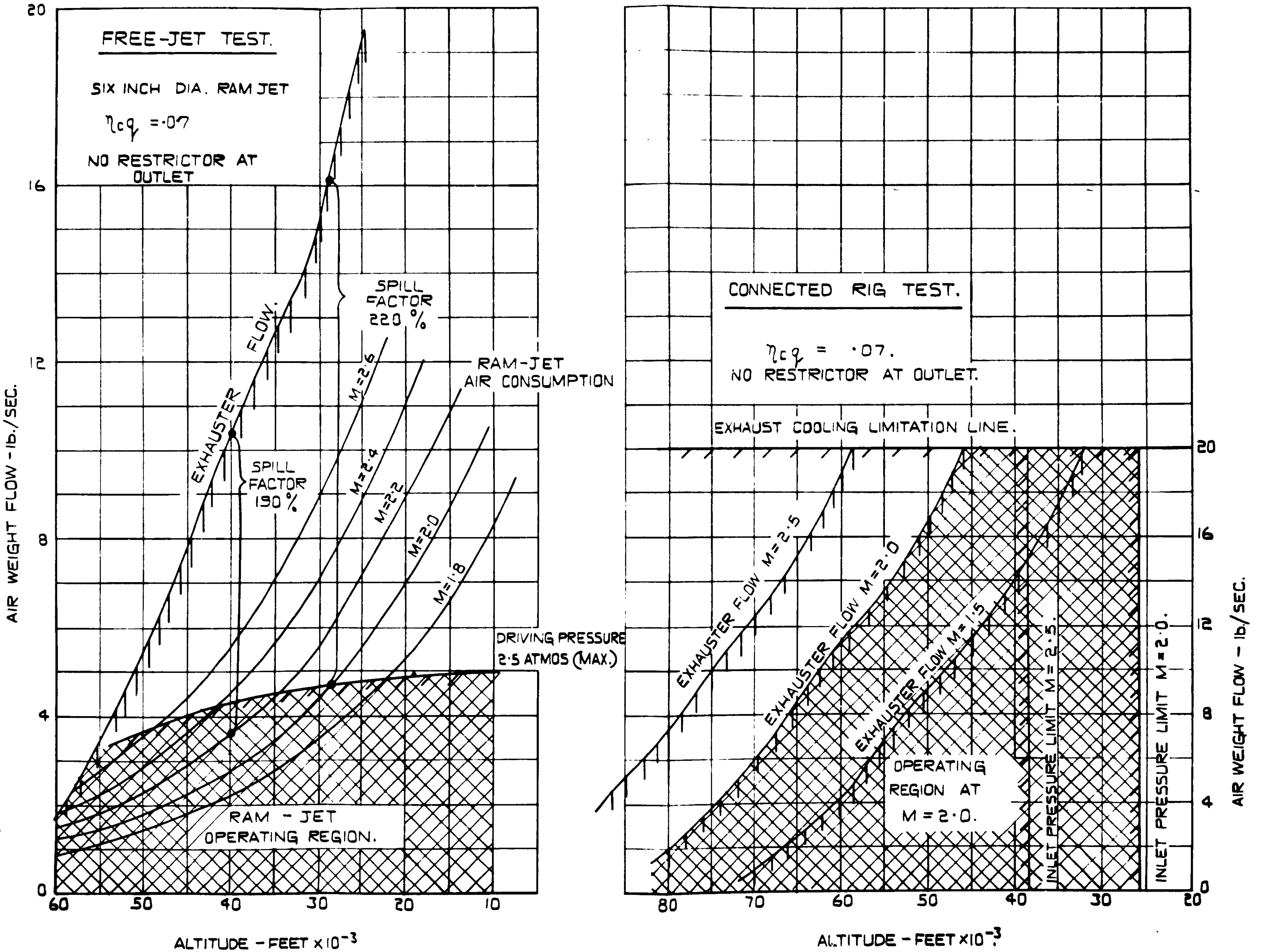
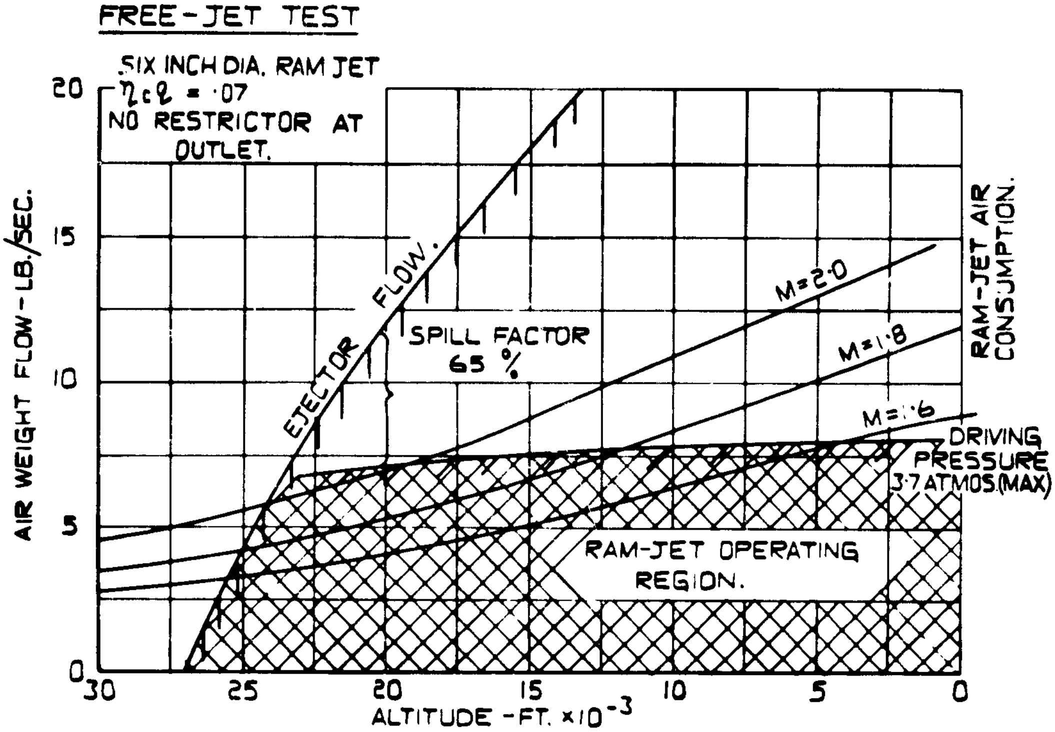
TEST RANGE OF R.A.E. PLANT.



SK 57040

FIG. 13

TEST RANGE OF N.G.T.E. OLD SITE PLANT.



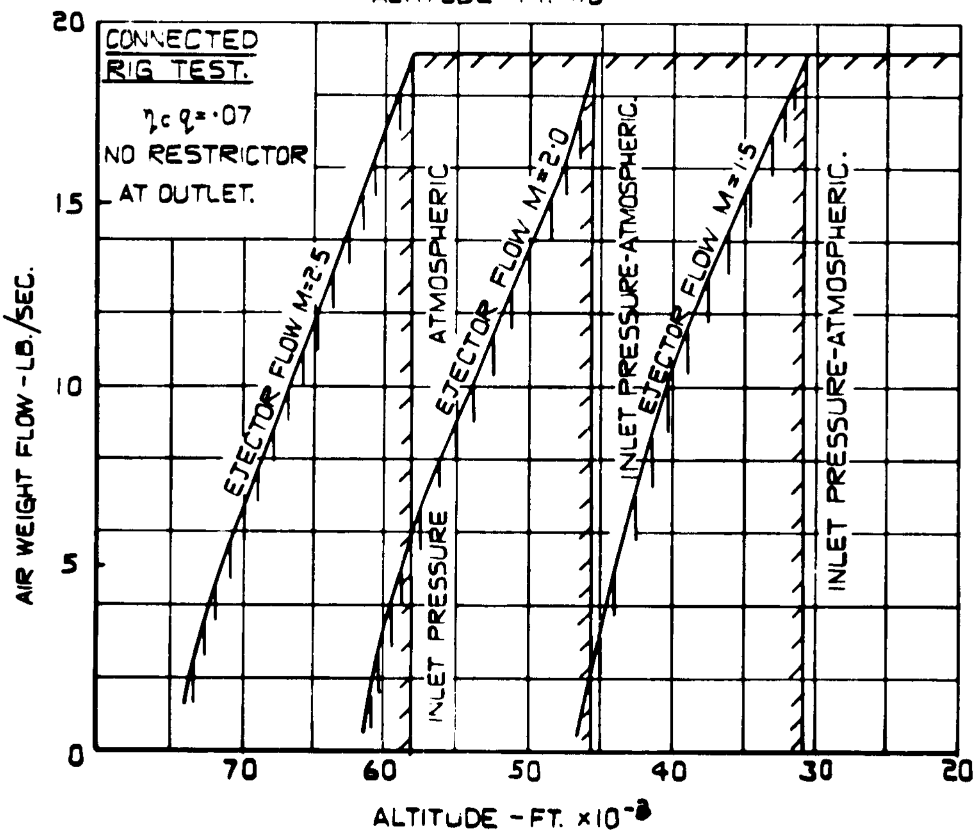


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FIG. 14

TEST RANGE OF N.G.T.E. NEW SITE PLANT.

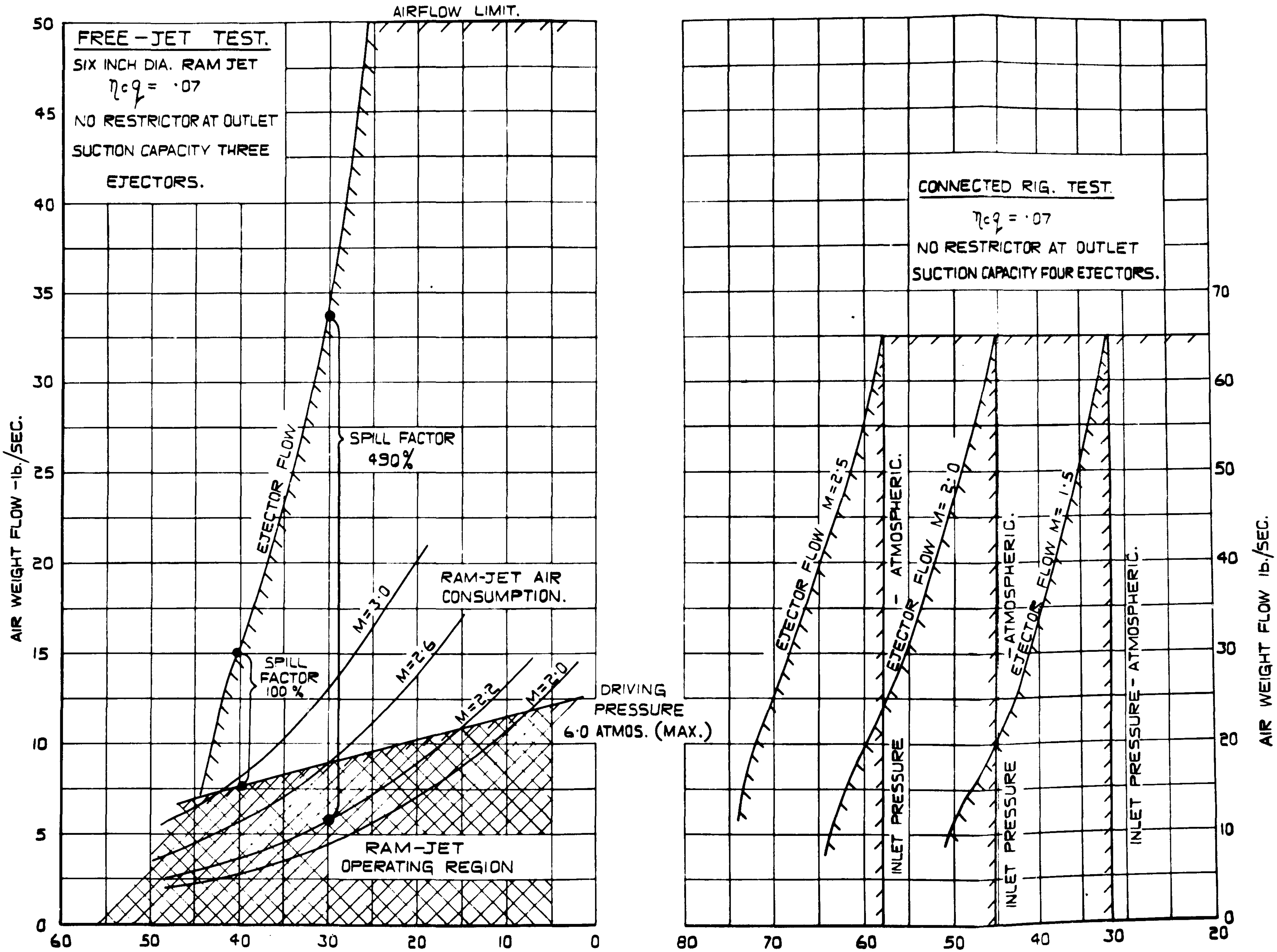


FIG. 15

SK 57042

TEST RANGE OF N.G.T.E. NEW SITE PLANT

CONNECTED RIG. TEST.

$\eta_c q = \cdot 07$

NO RESTRICTOR AT OUTLET.

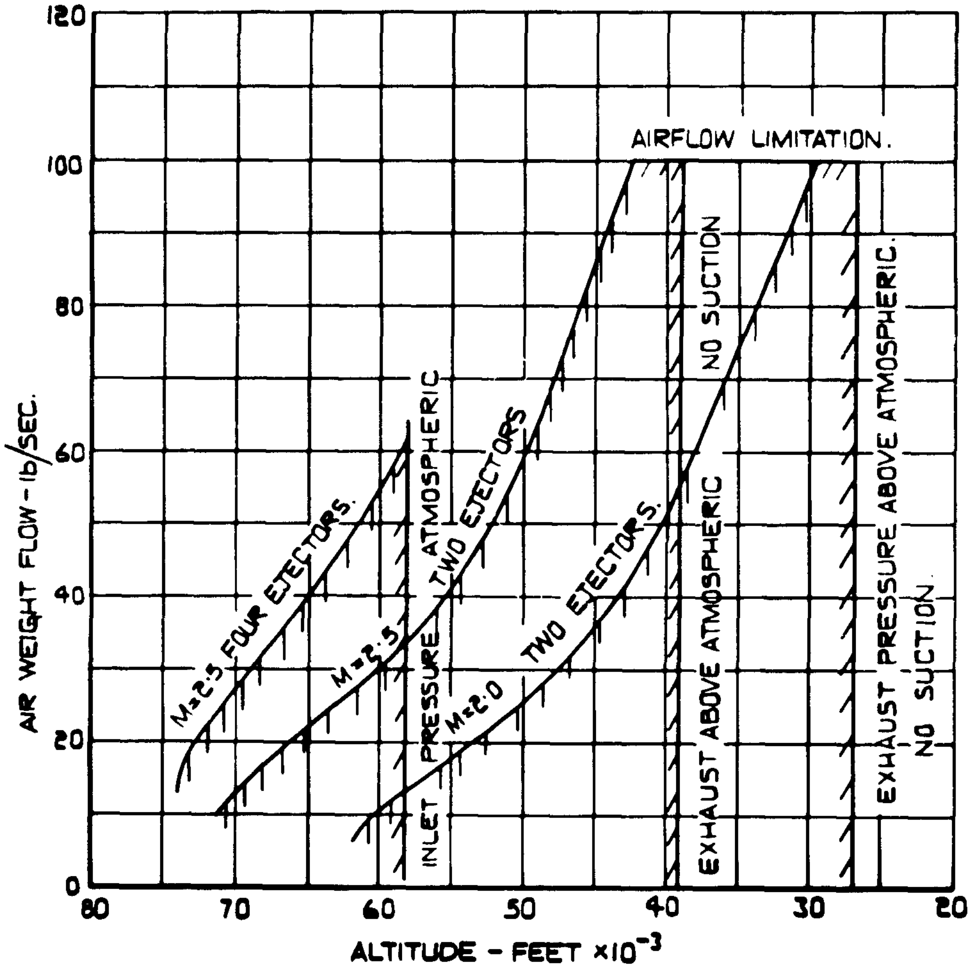
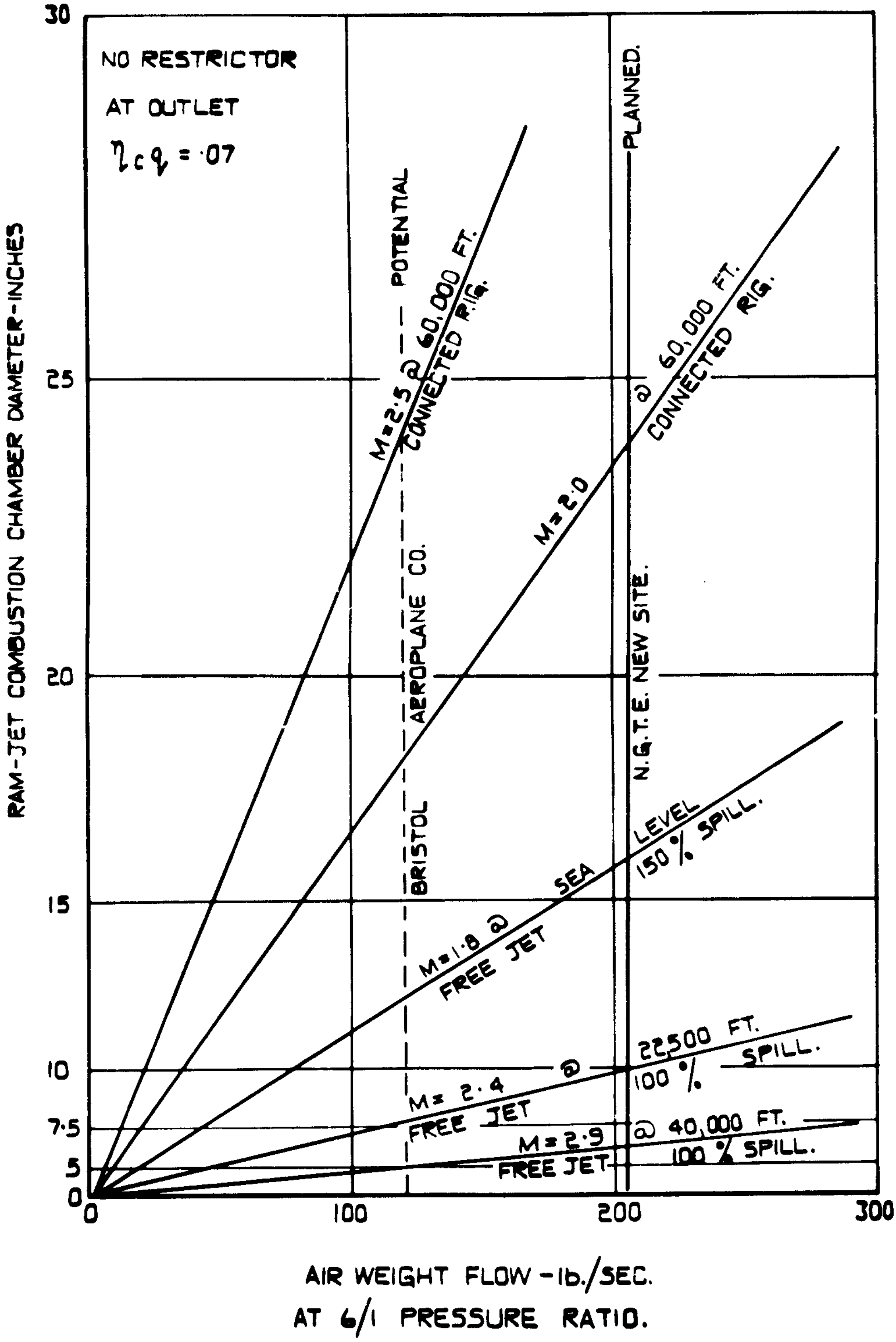


FIG. 16

SK 57043

COMPARISON OF RAM-JET SIZES FOR DIFFERENT TYPES OF TESTS ON COMMON PLANT AIR SUPPLIES.



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