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CURRENT PAPERS

The Application of Jet Propulsion to Helicopters

By

Wm. Stewart, B.Sc.

and M. F. Burle

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SUMMARY

The various methods of applying jet propulsion to the helicopter are considered, particularly the use of ram jets fitted at the blade tips and the pressure jet (Doblhoff) system where the fuel-air mixture is conducted along the blades to combustion chambers at the blade tips.

The efficiency of these two systems is compared with the conventional reciprocating-engined helicopter in terms of payload and endurance for examples of typical helicopters of 2,500 lb and 10,000 lb gross weight.

The fuel consumption for the jet systems is much higher than for the reciprocating engine but there is a considerable saving in the power plant weight. For flights of very short duration, the ram jet type of helicopter can carry an increased payload. Due to the high fuel consumption the possible endurance is severely restricted. The pressure jet system operates as a compromise between the ram jet and conventional helicopter configurations.

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1 Introduction

There are several obvious advantages in the use of jet propulsion for helicopters. The elimination of torque reaction and the reduction in the complexity of the power plant installation are very desirable features. The extreme simplicity of the ram jet is a particularly attractive possibility. However, the operation of these systems under reasonably suitable propulsive conditions results in a reduction in the aerodynamic efficiency of the rotor.

In considering the application of jet propulsion to the helicopter to replace the reciprocating engine system, there are several methods by which this could be done.

(a) Direct replacement of the reciprocating engine by a gas turbine engine.

This is obviously not a satisfactory method. None of the disadvantages of the reciprocating engine have been eliminated but the comparative simplicity of the gas turbine type should be considered. In addition, the jet engine is working under unsatisfactory operating conditions. Due to the high rotational speed of the gas turbine, considerable gearing would be necessary.

(b) Small gas turbine engines at the blade tips.

These engines would be very small and, although working under reasonable velocity conditions, it is very doubtful if an efficient engine could be developed to work under the high centrifugal accelerations and to give reasonable weight and drag conditions for the required power.

(c) Ram jets at the blade tips.

This is the most attractive system due to its extreme simplicity.

(d) Pressure jet (Doblhoff) system.

A reciprocating engine in the fuselage drives an air compressor. Fuel is added to the air leaving the compressor and the mixture conducted along hollow blades with additional compression from the centrifugal forces. Combustion then takes place at the blade tips.

Methods (a) and (b) are not economic propositions and only methods (c) and (d) are considered in this report.

2 Ram Jet System

2.1 General

The ram jet is the most simple form of combustion engine, consisting essentially of a diffuser, combustion chamber and nozzle. On the helicopter the ram jets would be fitted at the blade tips and the fuel conducted along the blade.

The advantages of the ram jet system compared with the conventional helicopter are:-

(1) simplicity of installation.
(2) extremely low power plant weight.
(3) elimination of transmission, gearing, clutch etc.

(4) elimination of torque reaction, with the consequent saving in weight of tail rotor and tail fuselage.

(5) no moving parts and no lubrication necessary.

The disadvantages of the ram jet system (other than the high fuel consumption, which is dealt with in detail) are:-

(1) difficulty of conducting fuel from the fuselage to the rotating blades.

(2) vibration due to any differences in thrust of the ram jets.

(3) control difficulties due to high inertia of the blades.

(4) poor autorotational characteristics.

(5) difficulty of obtaining satisfactory burning under high centrifugal acceleration conditions.

(6) complications in starting the ram jet units.

(7) high noise level.

2.2 Fuel Consumption

The fuel consumptions for the ram jets are based on unpublished work by Baxter and on American data by Brozowski[1]. The specific fuel consumption is a function of the free stream Mach number, the velocity of the air entering the combustion chamber, the ratio of the burning temperature to the ambient air temperature and the diffuser, nozzle and combustion efficiencies.

The analysis has been made in terms of these variables and the values of fuel consumption for the practical operating conditions on the helicopter were obtained on the following assumptions.

In order to keep to a reasonable length of ram jet, the value of the ratio of burning temperature to ambient air temperature was limited to 6. This corresponds to a burning temperature of the order of 1700°K.

Since the free stream Mach number of the ram jet units will be restricted to about 0.8 from considerations of suitable rotor operating conditions, there is no need to impose any limit on the air velocity at the entry to the combustion chamber and the ram jet can be operated at the optimum thrust coefficient values.

The adiabatic efficiencies of the diffuser and nozzle were taken as 0.8 and 0.95 respectively. The combustion efficiency was assumed to be 0.9, which may be optimistic in view of the short combustion chamber envisaged, but lack of information makes it impossible to predict any more accurate value. The specific fuel consumption is approximately inversely proportional to the combustion efficiency.

The pressure loss, due to aerodynamic losses, in the combustion chamber was assumed equal to the dynamic head at the combustion chamber entry.

On the above assumptions, the specific fuel consumption for the ram jet operating under the required helicopter conditions was obtained in terms of free stream (blade tip) Mach number as given in fig.1.

2.3 Application to helicopter

In applying the ram jets to the helicopter, a three bladed rotor configuration has been assumed. The rotor performance for the helicopter is calculated and the thrust required from each ram jet evaluated.

The size of the ram jet is then found from the flow conditions in terms of the thrust and Mach number and can be evaluated (sea level conditions) in the form

$$T = 2.2 M^2 D^2$$

where T is the thrust in lbs

D is the jet diameter in inches.

Having found the size of the ram jet, the drag can be evaluated from available wind tunnel data on bodies of revolution and drag tests of a faired ram jet. The value used was 0.009 lb per sq.in. frontal area at 100 ft/sec.

Adding the thrust and drag, the gross thrust required from the ram jet is obtained. The drag must then be re-evaluated for the increased ram jet size and the final thrust and size of ram jet required is obtained by successive approximation.

The weight of the ram jet units is very small but can be evaluated, assuming reasonable values for the length/diameter ratio and for the wall thickness. The total weight of ram jet power system (excluding any starting systems) may be taken as $0.25 D^2$.

3 Pressure Jet (Doblhoff) System

3.1 General

In the pressure jet system, an air compressor, located in the fuselage, is driven by an ordinary reciprocating engine. Fuel is added to the compressed air and the mixture conducted through glands in the rotor head and along the blades. Further compression is obtained from the centrifugal force action. Combustion takes place in combustion chambers at the blade tips, producing the required jet thrust. Considerable work on the development of this scheme was done by Doblhoff in Germany.

The advantages of this system compared with the conventional helicopter are:-

(1) elimination of torque reaction and consequent saving in weight of tail rotor and tail fuselage.

(2) elimination of transmission, gearing, clutch etc.

(3) ability to operate the rotor at any rotational speed independently of the compressor engine speed.

The disadvantages are:-

(1) difficulty of producing gas-tight glands to conduct the air-fuel mixture into the rotating blades.

(2) necessity for vapourising the fuel and maintaining a reasonable fuel distribution throughout the mixture, under high centrifugal accelerations, if reasonable combustion efficiency is to be attained.

(3) vibration due to any differences in the thrust of the jet units.

(4) control difficulties due to the high inertia of the blades.

3.2 Fuel Consumption

The fuel consumption and optimum operating conditions for the pressure jet system were estimated by the following method.

The jet velocity is given by

$$V_J = \sqrt{2 g J K_p \Delta T}$$

where K_p is specific heat at constant pressure

and $$\Delta T = \eta_e T_3 \left[1 - \left(\frac{P_o}{P_2}\right)^{0.29}\right]$$

where η_e is the expansion efficiency

T_3 is the maximum combustion temperature

P_o is the inlet pressure at the compressor

P_2 is the combustion chamber pressure.

The pressure in the combustion chamber is determined from the pressure rise in the air compressor, the pressure rise due to centrifugal action in the blades, the pressure loss due to friction in the blade and the pressure loss at the combustion chamber. The pressure rises in the air compressor and due to centrifugal action in the blade can be evaluated simply. The pressure loss in the flow through the blade is estimated from Blasius equation for loss in pipes and is a function of the geometry of the pipe, the mass flow and the air viscosity. The combustion chamber pressure loss is small and is taken empirically as equal to the dynamic head at entry to the chamber.

Assuming $\eta_e = 0.9$ and $T_3 = 1000^\circ C$ the jet velocity can be evaluated in terms of $\frac{P_o}{P_2}$ (i.e. the overall compression ratio). The mass flow can then be determined in terms of the jet velocity and the rotor tip speed for a given jet thrust.

The temperature at the inlet to the combustion chamber is obtained from the temperature rise in the compressor and the temperature rise due to centrifugal compression, the latter being small in comparison with the former. Hence, the temperature rise in the combustion chamber can be obtained and the fuel/air ratio found from combustion charts for the appropriate fuel.

The fuel consumption of the jet unit is then obtained from the mass flow and the fuel/air ratio for the corresponding compression ratio.

From the corresponding air compressor conditions, the power required to operate the compressor can be obtained. Using a reciproacting engine to supply this power and assuming the appropriate specific fuel consumption, the fuel rate to drive the compressor can be calculated. Hence the total fuel consumption for the pressure jet helicopter can be obtained.

The fuel consumption for the pressure jet helicopter is given against compression ratio in fig. 2 and the component consumptions by the jet units and by the compressor unit are shown.

3.3 Application to helicopter

Considering the effect of compression ratio on the fuel consumption, fig. 2, the fuel consumption for the jet units falls off rapidly with increase in compression ratio but the corresponding increase in compressor size necessitates a greater fuel consumption for this unit. Thus, the total fuel rate for the helicopter shows a minimum value at a compression ratio of about 3, with very little increase over the range 2 to 4.

However, considering the installation, the size of the compressor engine is increasing rapidly with compression ratio and its weight soon exceeds the weight of the reciprocating engine, which it is to replace. Thus it is found that, from weight considerations, the compression ratio must not exceed 2. The value for the optimum configuration may be slightly below the compression ratio 2 but lack of knowledge on the rate at which the fuel consumption increases at the low compression ratios does not allow any more accurate estimate to be made. Hence, the value of 2 is used in this report.

These conclusions are in good agreement with the two practical examples available, the German Doblhoff[3] and the American Marquardt[4] jet helicopters, which both operate at a compression ratio of 2. In the case of the Doblhoff, the compressor data is available and the power to drive the compressor per lb of jet thrust is also in agreement with the present calculations.

The fuel consumption for the Doblhoff was higher than the present estimate but the recent Marquardt claims are in good agreement with the present calculations.

4 Performance

4.1 General Considerations

In order to compare the jet driven helicopters with the conventional type some form of performance parameters must be used. The most suitable forms for this work would appear to be the payload and endurance for given flight conditions. In this report, power conditions to give hovering are considered as representative.

For hovering conditions, it can be shown that the theoretical induced power, assuming constant induced velocity over the rotor disc, is given by

$$W \sqrt{\frac{W}{2 \rho \pi R^2}}$$

where W is the weight of the helicopter

and R is the rotor radius.

Flight tests[5] have shown that in the practical case, the divergence of the induced velocity distribution from constant and the tip loss necessitate an increase in power of 15%. The induced power is therefore taken as $1.15\,W\sqrt{\dfrac{W}{2\rho\pi R^2}}$.

The profile drag power for the blades is given by

$$\sigma\pi R^2 \rho\,(\Omega R)^3\,\frac{\delta}{8}$$

where σ is the rotor solidity

ΩR is the rotor tip speed

and δ is the blade profile drag coefficient (assumed constant at 0.012).

The rotor power is then given by

$$1.15W\sqrt{\frac{W}{2\rho\pi R^2}} + \sigma\pi R^2\rho(\Omega R)^3\frac{\delta}{8}.$$

For the purpose of the present comparisons two examples have been taken:-

(a) a single rotor helicopter with a gross weight of 2,500 lbs.

(b) a helicopter with a gross weight of 10,000 lbs.

For the conventional helicopter at the larger weight there are many advantages in having a twin-rotor layout and this configuration has been assumed. On the ram jet helicopter there is less to chose between the two configurations and both single and twin-rotor layouts are considered.

The comparisons are based on operating the different types from the same gross weight and giving the same performance condition. An analysis of the weight distributions of existing conventional helicopters has been made in order to find the fuel capacity and payload, and also to obtain the weight of engine, transmission etc. replaceable by fuel and/or payload in the jet helicopters. This provides the basis on which the practicable conventional helicopter is obtained and the application of jet propulsion considered. There are very few helicopters in the 10,000 lb class and the data is therefore more reliable for the case of the small helicopter. However, it will be seen later that the comparative performance does not depend critically on this assessment.

4.2 Conventional Helicopter

The disc loading was assumed to be 2.5 lb per sq.ft and the rotor power to hover evaluated. It was assumed, as from Ref.5, that the transmission, tail rotor and cooling losses amounted to 17% of the total power required on the single-rotor helicopter. For the twin-rotor helicopter, with counter-rotation of the rotors, no torque reaction loss (equivalent to tail rotor power on the single rotor helicopter) is considered. Hence, the engine power and fuel consumption for the conventional helicopter can be obtained.

It is well known that optimum hovering performance on the conventional helicopter is obtained at low tip speed, the lower limit being determined to give satisfactory forward flight conditions. Fig.3 gives the payload-endurance curves for the 2,500 lb helicopter in terms of tip Mach number and for two values of rotor solidity.

The loss in performance in working to high tip speeds is quite marked and shows the desirability of maintaining low tip speed values. The lower value given in the curves ($M = 0.4$) represents the lowest practical value which would allow reasonable forward flight conditions. The effect of solidity is not important for low tip speeds but has quite a large influence at high tip speed values.

Fig.4 gives the corresponding payload - endurance curves for the 10,000 lb helicopter. The results show similar characteristics to those discussed above for the smaller helicopter.

4.3 Ram Jet Helicopter

The estimation of the fuel consumption for the ram jet helicopter has been dealt with in para. 2.2 and the results given in fig.1. Using the same disc loading as for the conventional helicopter and allowing for the increased fuel capacity and/or payload due to the saving in weight by elimination of the conventional engine, tail rotor etc. the performance for the 2,500 lb ram jet helicopter has been calculated and the results given in fig.5, in terms of tip Mach number and for two values of solidity.

As the tip Mach number is increased, the efficiency of the ram jets is increasing rapidly but this is offset to a large extent by the increased profile drag of the blades. At these high tip speeds, the rotor solidity becomes very important. Thus, at $\sigma = 0.05$ there is an optimum operating condition at $M = 0.7$ but for the lower solidity $= 0.025$ the optimum lies outside the range of the calculations. The range is restricted to $M = 0.8$ to avoid compressibility troubles. Thus, the essential feature for the economic operation of the ram jet helicopter is the attainment of a low rotor solidity.

Turning to the 10,000 lb ram jet helicopter, there are two possibilities. From the point of view of controls etc. the twin-rotor layout is to be preferred. On the other hand, with the elimination of torque reaction a single rotor layout does not incur serious penalties, provided a suitable means of directional control can be devised. A single rotor for a 10,000 lb helicopter is still within any design efficiency limitation.

Assuming that the replaceable weight is the same for both layouts (the single rotor may have to sacrifice some weight for directional control means) the payload - endurance curves for the single and twin-rotor configurations are given in figs.6 and 7 respectively.

Both layouts give curves similar to the small ram jet helicopter but the single rotor shows a better performance. Bearing in mind the above assumptions and the possible difficulty of providing control on the single rotor helicopter, it may well be in practice that this difference in payload-endurance disappears.

4.4 Pressure Jet Helicopter

It has already been shown in para. 3.3 that the optimum operating conditions for the pressure jet system give a compression ratio of 2 and the appropriate fuel consumption curve is given in fig.2. Again, the disc loading used is the same as that for the conventional helicopter. In considering the replaceable weight for the pressure jet helicopter, the weight of the compressor system is taken as the same as a conventional engine of the same power.

The payload-endurance curves for the pressure jet helicopter of 2,500 lb weight are given in fig. 8. For the 10,000 lb helicopter, the two possible configurations, similar to the ram jet helicopter layouts, are considered and the payload-endurance curves given in figs. 9 and 10.

Throughout the investigations it has been found that the pressure jet system operates as a compromise between the reciprocating-engined helicopter and the ram jet helicopter. The use of the compressor and tip jets gives a compromise in the fuel consumption and also in the replaceable weight for the pressure jet system.

At the lower solidity there is an optimum value of tip speed about the centre of the practical Mach number range but the performance characteristics are largely independent of the tip speed. At the higher solidity the increased profile drag of the blades causes a serious deterioration in performance at the higher Mach numbers and results in the optimum configuration occurring at a lower tip speed. Again, the desirability of keeping the solidity low at the higher tip speeds is shown.

5 Results of Comparison

In comparing the payload-endurance characteristics for the different types of helicopter, the optimum condition for each type is considered. Thus, for the conventional helicopter the design would be for the lowest permissible tip Mach number, consistent with satisfactory forward flight conditions. A value of $M = 0.4$ is taken and although this would be optimistic if a high forward flight speed was to be attained, it forms a reasonable basis for comparison with the jet systems.

For the ram jet configurations, the Mach number is taken as 0.8 and the solidity as 0.025. Again, this may give a slightly optimistic value as it is assumed that there are no compressibility effects at 0.8 Mach number and also it may be difficult in practice to achieve a solidity as low as 0.025.

For the pressure jet system a solidity of 0.025 is used, with the same qualification as above, and the optimum Mach number is considered.

The payload-endurance curves for the various configurations of the 2,500 lb helicopter are given in fig. 11 and for the 10,000 lb helicopter in fig. 12. These graphs show immediately the general implications of the jet systems. The ram jet helicopter can carry a considerably greater payload but can only operate for a very short time. The pressure jet is a compromise between the ram jet and conventional helicopters.

6 Discussion

It has been shown that, for a helicopter of a given gross weight, the ram jet configuration is capable of a considerably higher payload for flights of very short duration, but that only short flights are possible. The ram jet helicopter will therefore have only a limited specialised application.

However, other possible methods of making use of the ram jet helicopter should not be overlooked. For example, it could be used to collect and deliver equipment in difficult terrain under powered conditions and if range transportation was required it could be towed under autorotational conditions by another aircraft.

The main question in comparing the various configurations would appear to be on the economics, which is outside the scope of this report. Thus, if a short duration, high payload helicopter was considered, it may even be advantageous to construct a larger conventional drive helicopter than the correspondingly smaller ram jet helicopter which would fulfil the same conditions. The higher cost of the conventional engine and associated gearing etc. compared with the simple ram jet engines would have to be balanced against the excessive fuel required by the ram jets. The servicing costs and probable life of the helicopter would also have to be considered.

The pressure jet system operates as a compromise between the other two configurations. The saving in fuel consumption compared with the ram jets must be considered in relation to the considerable complication of the compressor unit and the conduction of the gas mixture along the blades.

In view of the lack of experience with either of the jet propulsion systems on helicopters, the results of this report can only be taken as giving a guide to the payload and endurance relationships of the various configurations, and illustrating the difficulties of obtaining a good compromise between rotor efficiency and engine system efficiency. The optimum operating conditions for each of the configurations has been developed but as this is a function of so many variables such as blade solidity, rotor tip speed, helicopter forward speed required etc., any specific project would have to be considered in detail before a choice of configuration could be made.

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Ref.No.	Author	Title, etc.
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3	Bennett	Notes on B.I.O.S. Mission to Germany to Investigate German Helicopter Developments. January 1946.
4	Denney	Marquardt Jets. American Helicopter Magazine. May 1948.
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Ref.No.	Author	Title, etc.
6	Miller	Jet Propulsion applied to Helicopter Rotors. Journal of Aeronautical Sciences. December 1946.
7	-	Jet Rotors point to 'Copter Payload Gain. Aviation Week. September 1947.

FIG. I

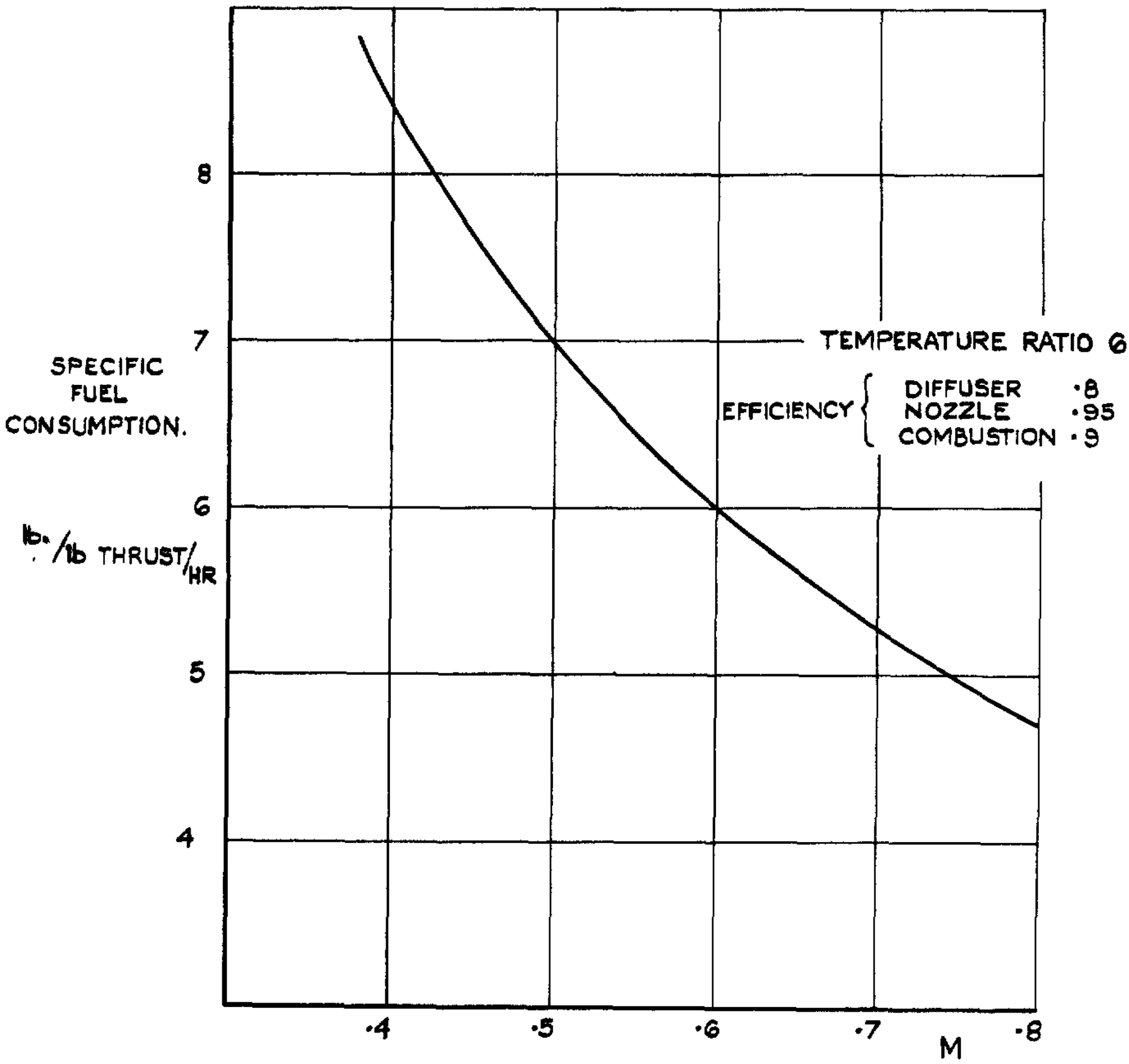

FIG. I FUEL CONSUMPTION OF RAMJET.

FIG. 2.

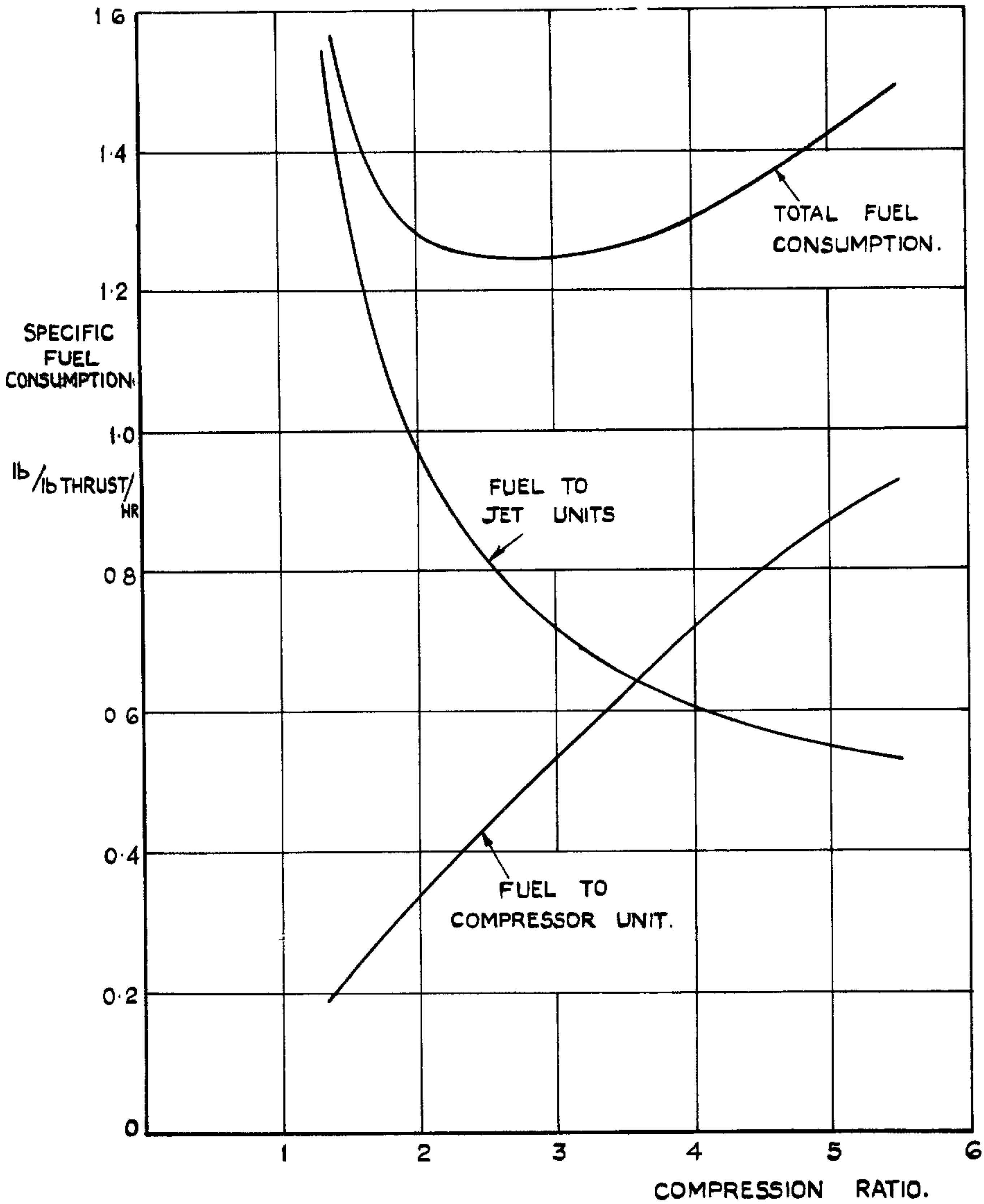

FIG. 2. FUEL CONSUMPTION OF PRESSURE JET SYSTEM.

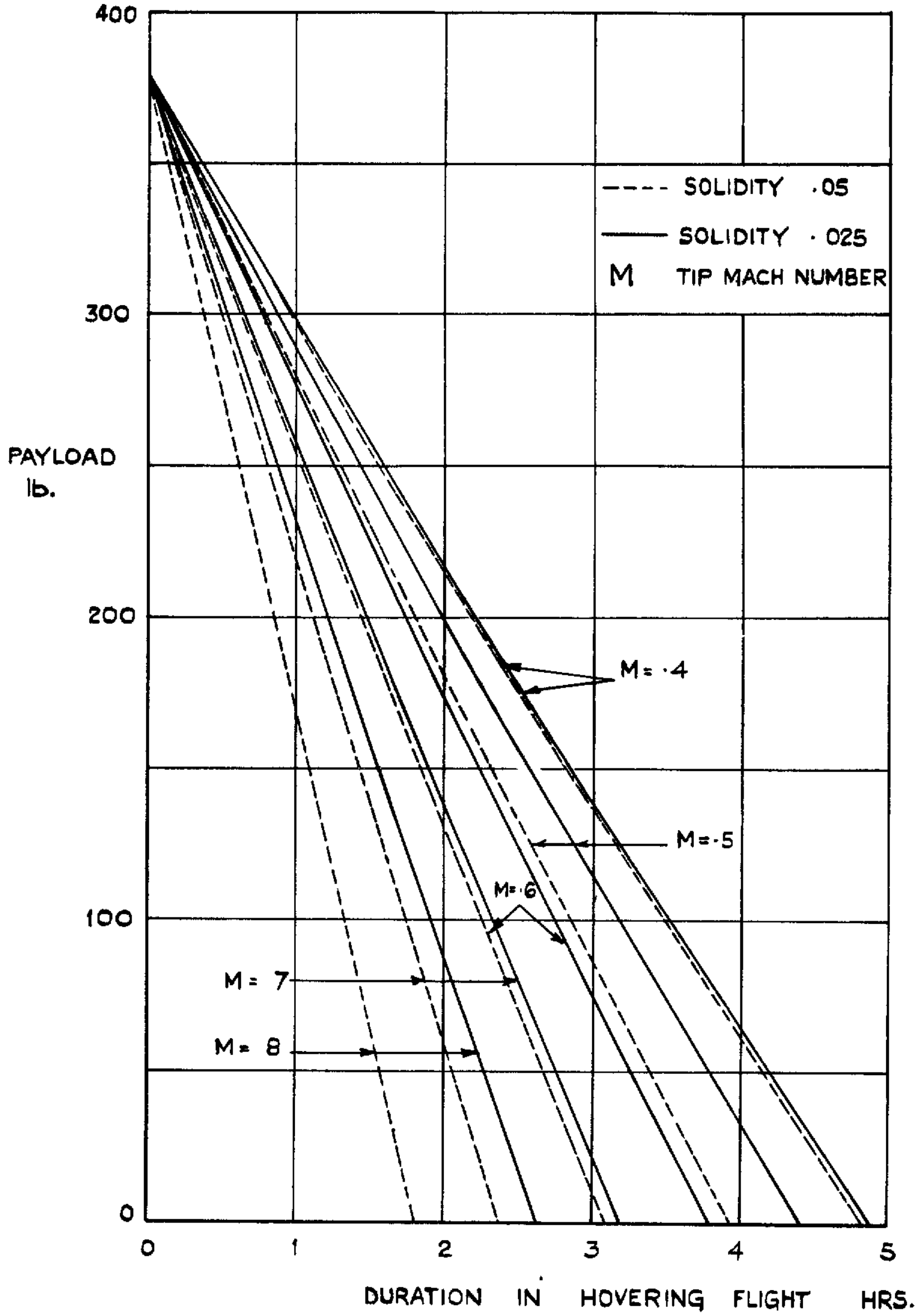

FIG. 3. CONVENTIONAL HELICOPTER – 2,500 LB.

FIG.4

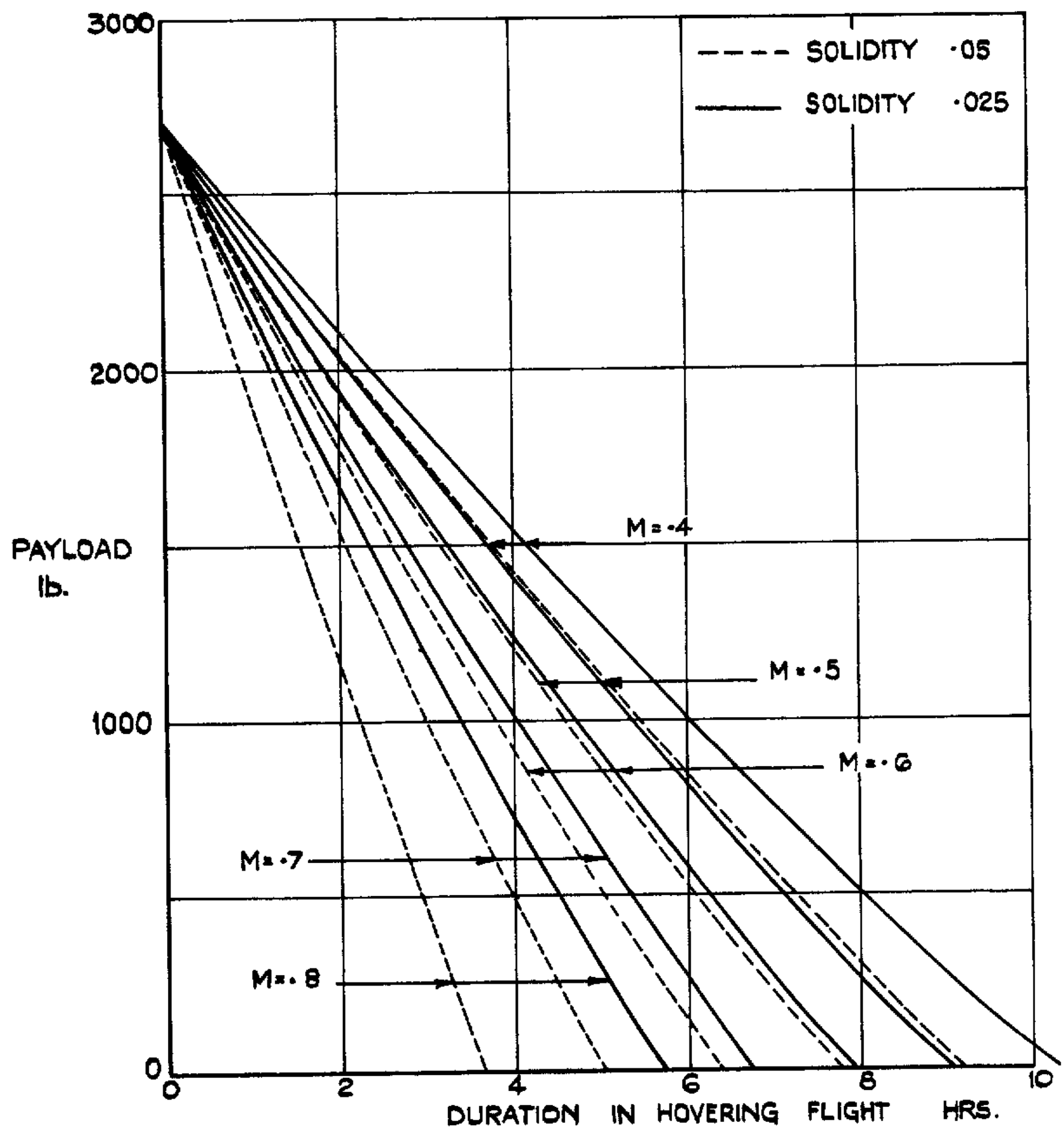

FIG.4 CONVENTIONAL HELICOPTER – 10,000 LB.

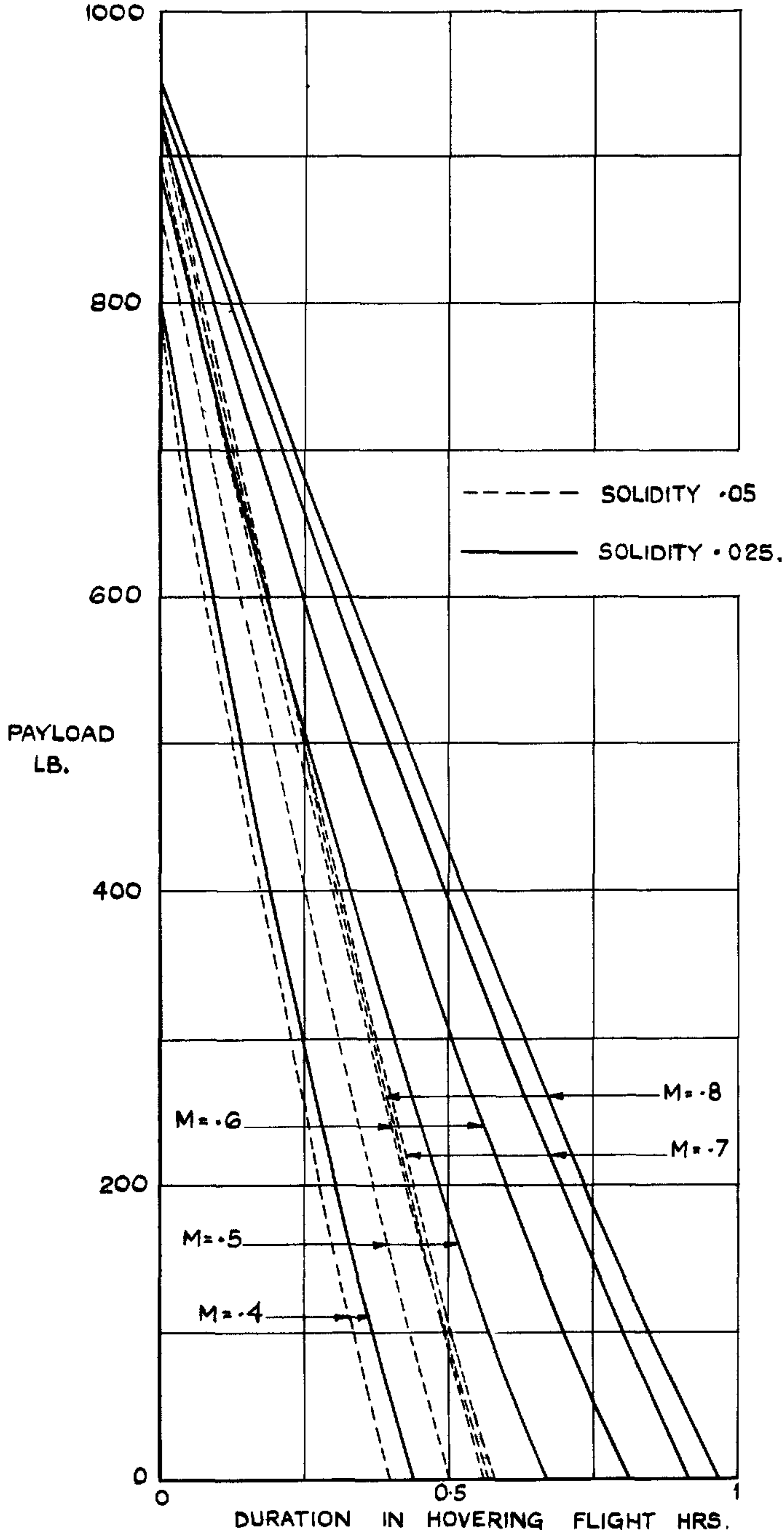

FIG. 5 RAMJET HELICOPTER 2,500 LB.

FIG. 6.

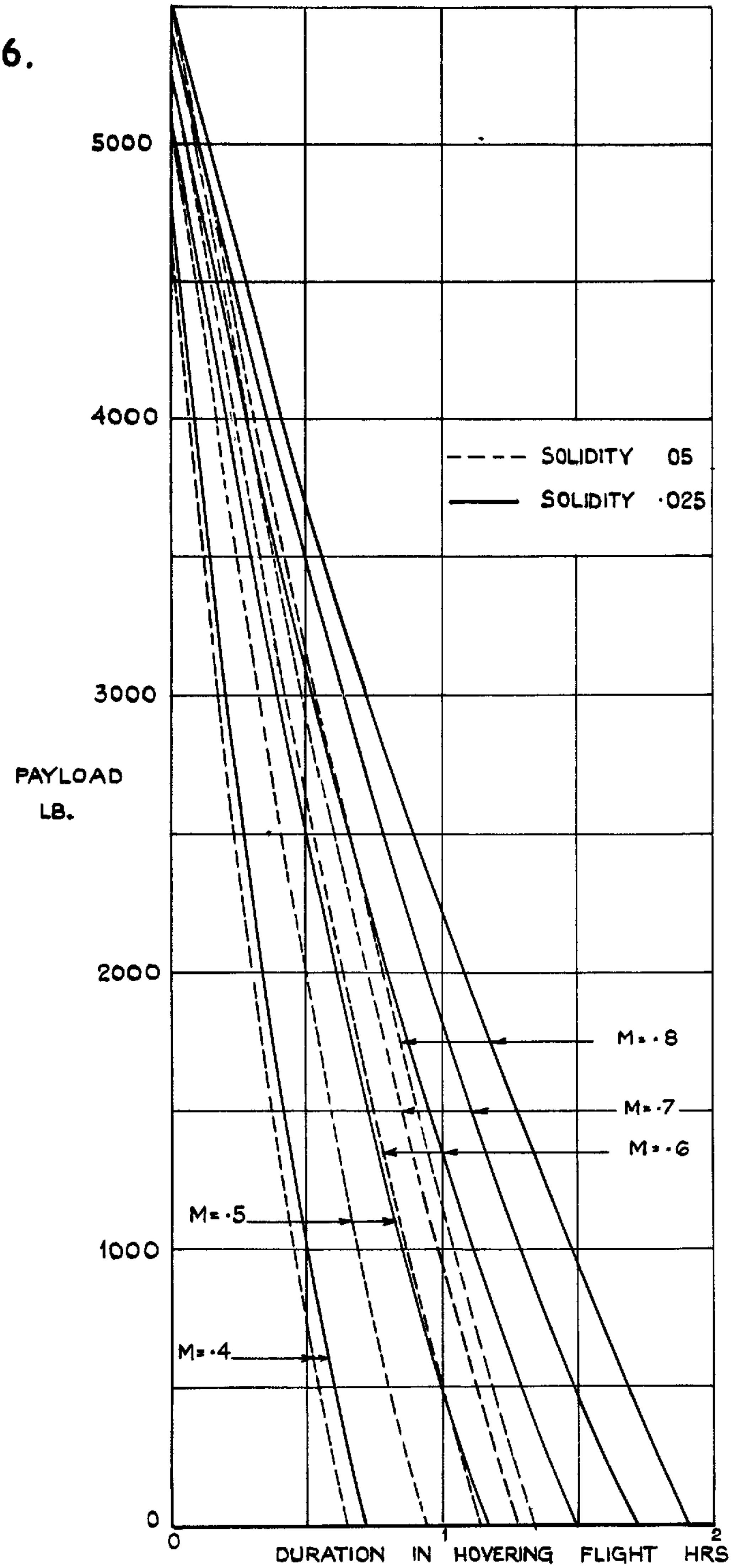

FIG. 6. SINGLE ROTOR RAM JET HELICOPTER - 10,000 LB.

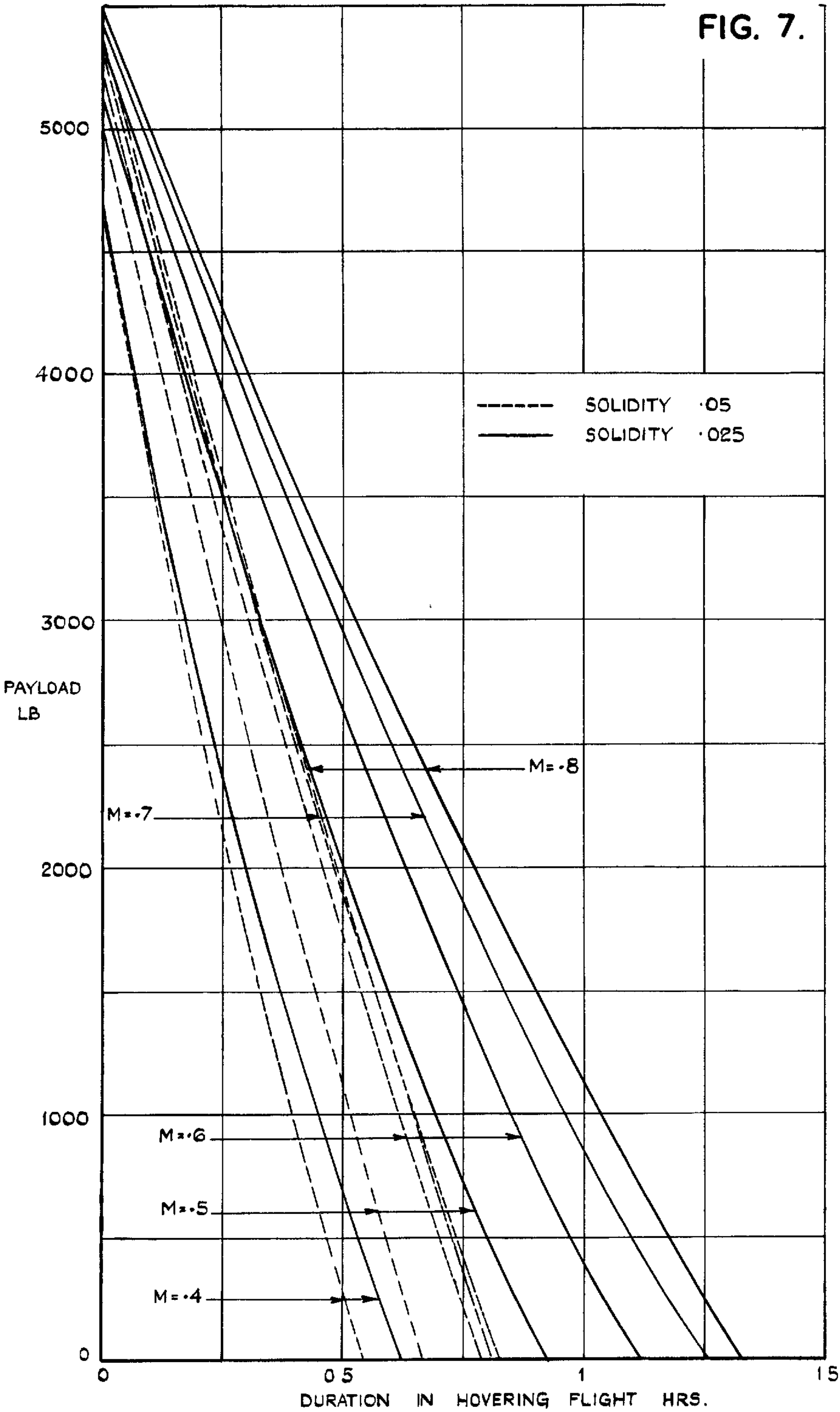

FIG. 7 TWIN ROTOR
RAM JET HELICOPTER - 10,000 LB.

FIG.8

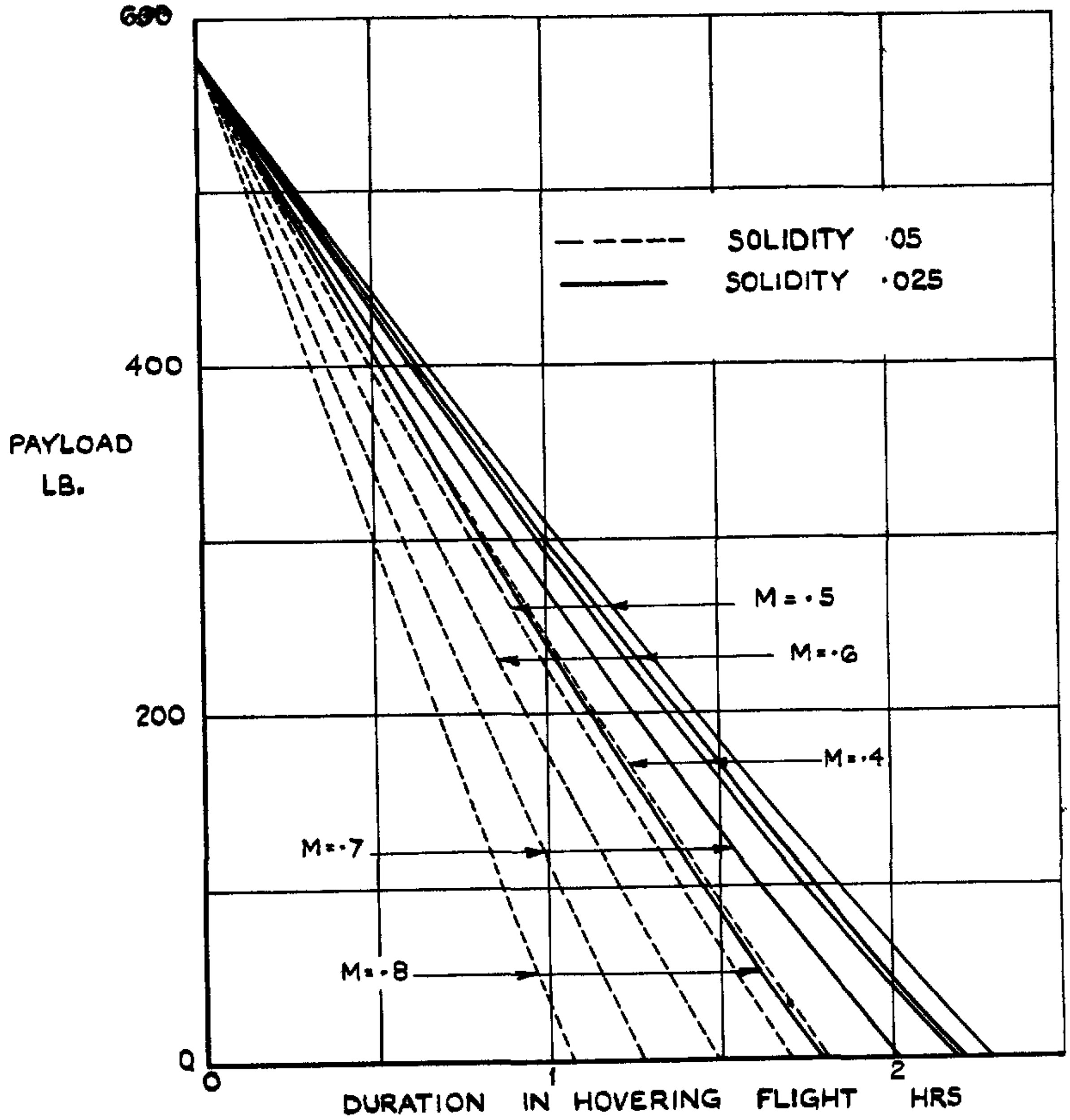

FIG.8 PRESSURE JET HELICOPTER — 2,500 LB.

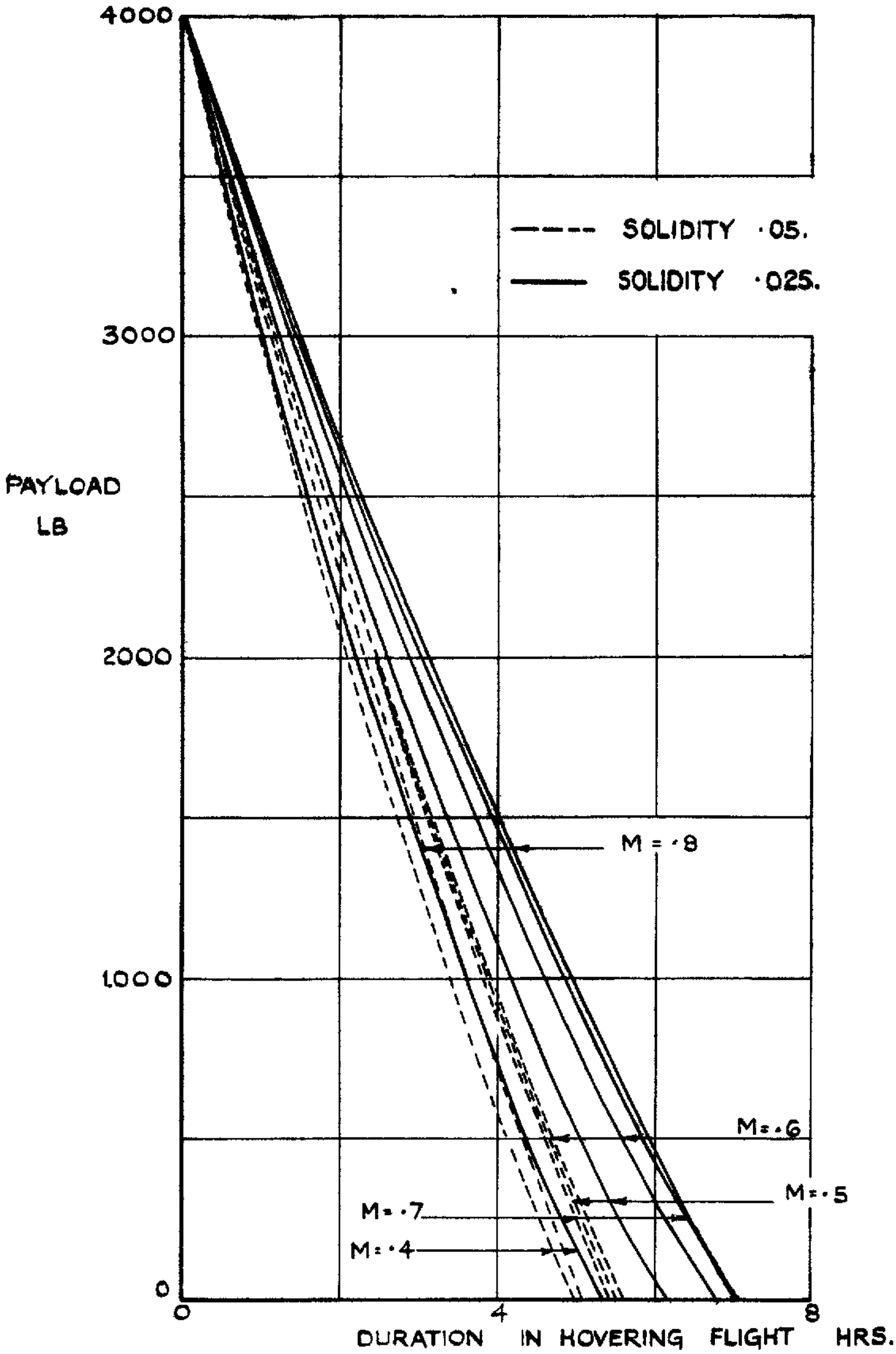

FIG. 9 SINGLE ROTOR PRESSURE JET HELICOPTER - 10,000 LB.

FIG. 10.

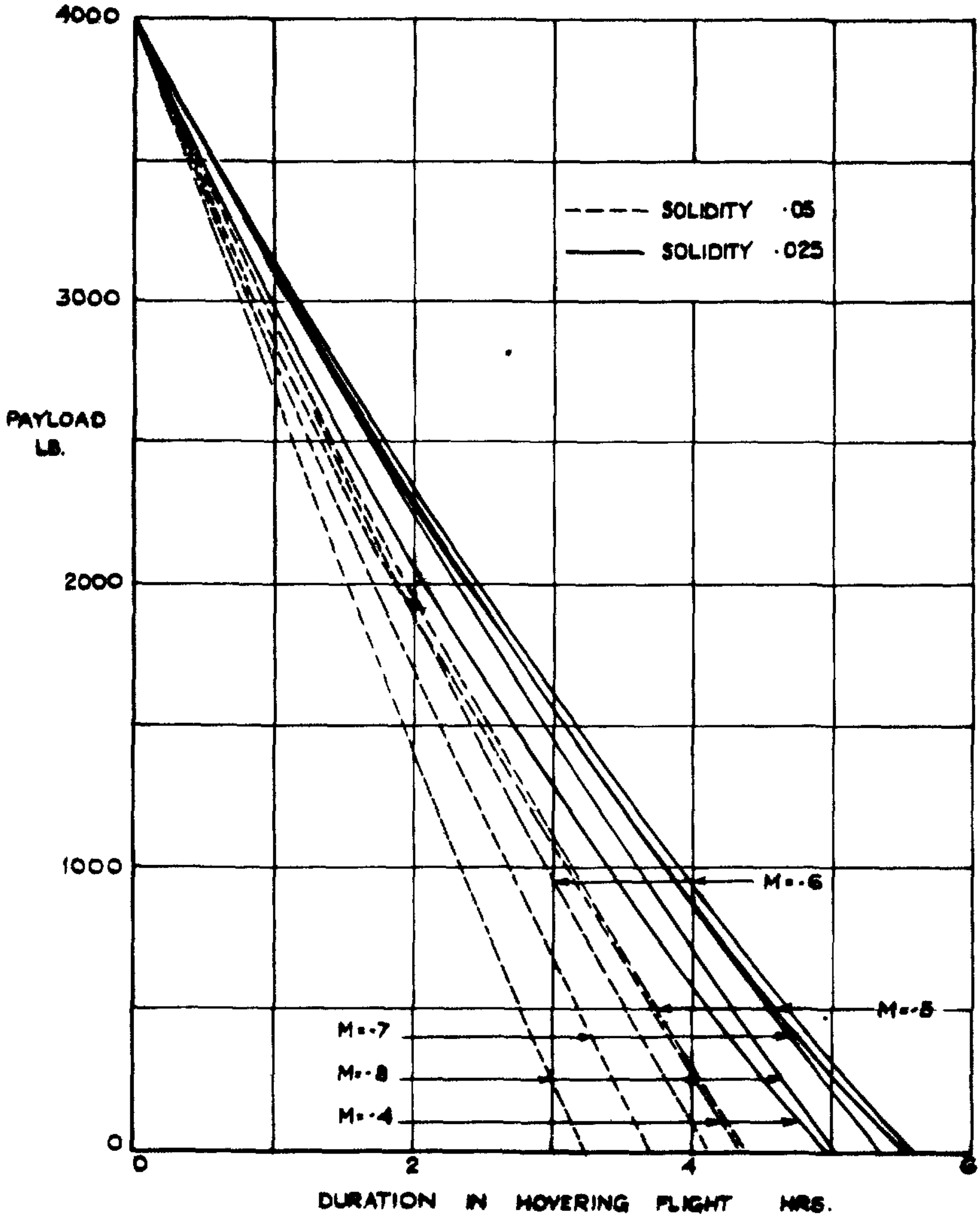

FIG. 10 TWIN ROTOR PRESSURE JET HELICOPTER - 10,000 LB.

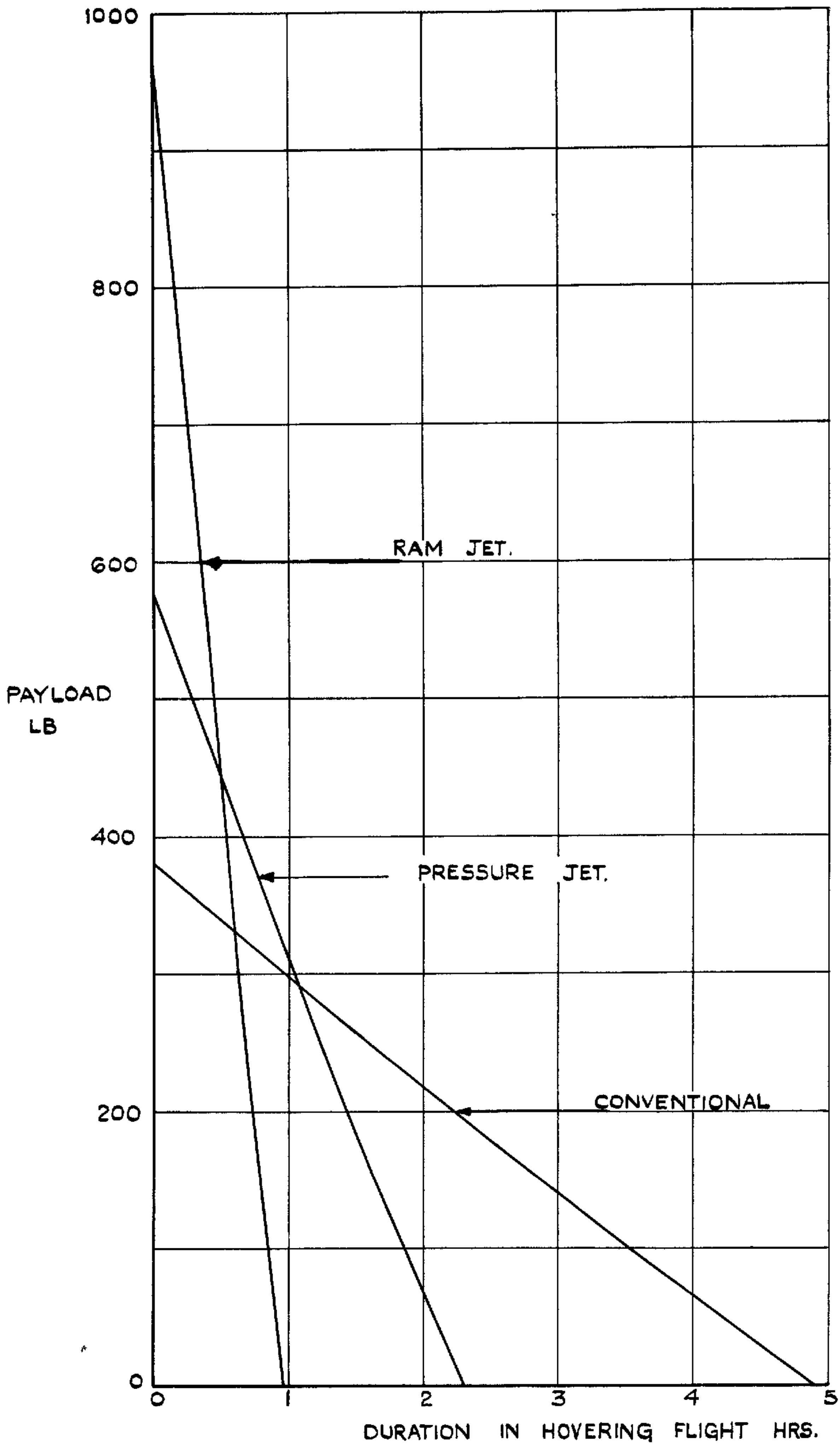

FIG. 11 COMPARISON OF OPTIMUM CONFIGURATIONS. 2,500 LB. HELICOPTERS.

FIG. 12

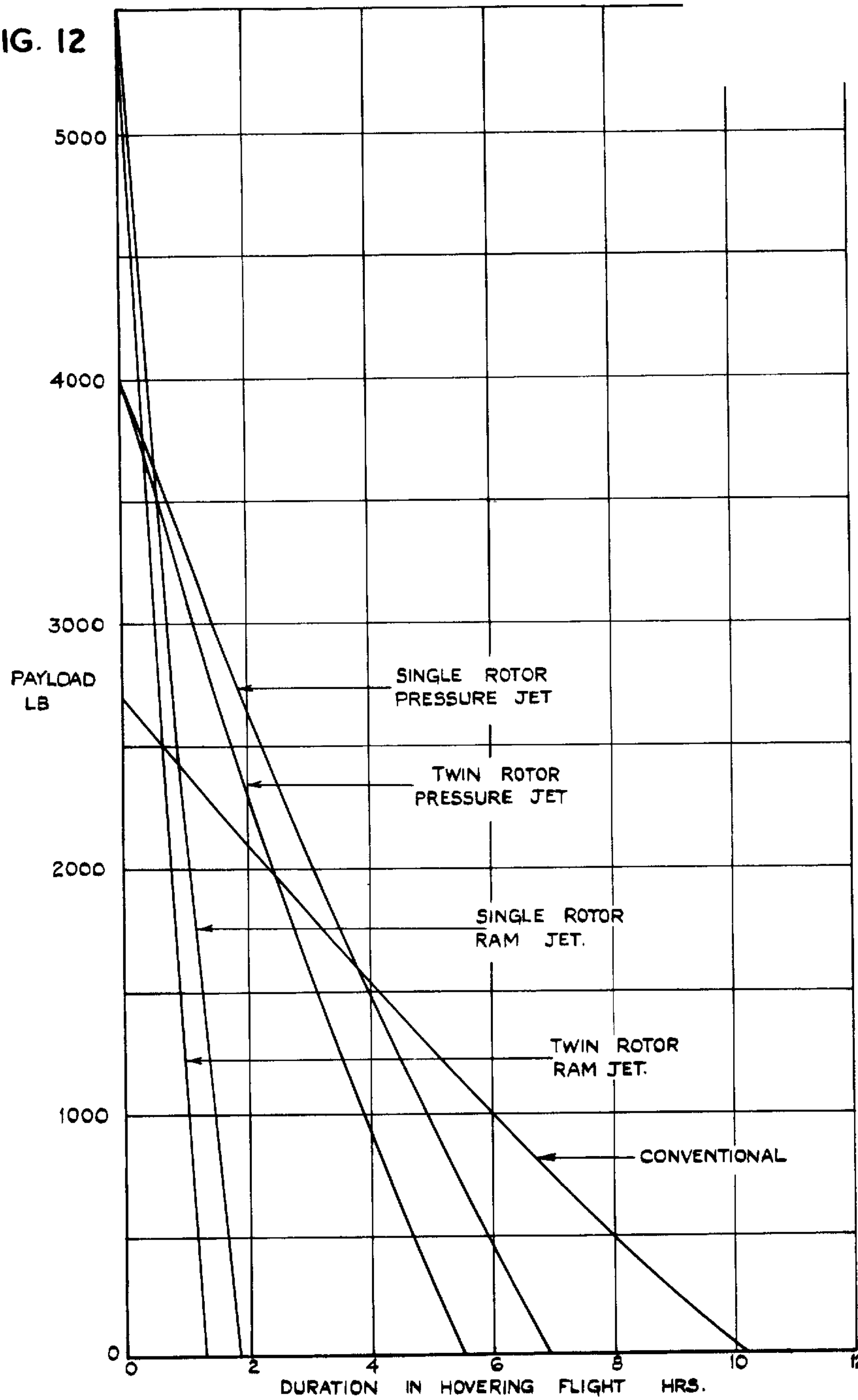

FIG. 12. COMPARISON OF OPTIMUM CONFIGURATIONS.
10,000 LB. HELICOPTERS.

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