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PROJECT TECHNICAL REPORT
TASK E-94

STAGE SIZING DATA FOR AN UNMANNED PLANETARY SAMPLE RETURN MISSION

NAS 9-8166

5 FEBRUARY 1971

Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MANNED SPACECRAFT CENTER
HOUSTON, TEXAS

Prepared by
R. D. Gilbertson

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Advanced Missions Studies
Spacecraft Systems Analysis
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TRW

INTRODUCTION

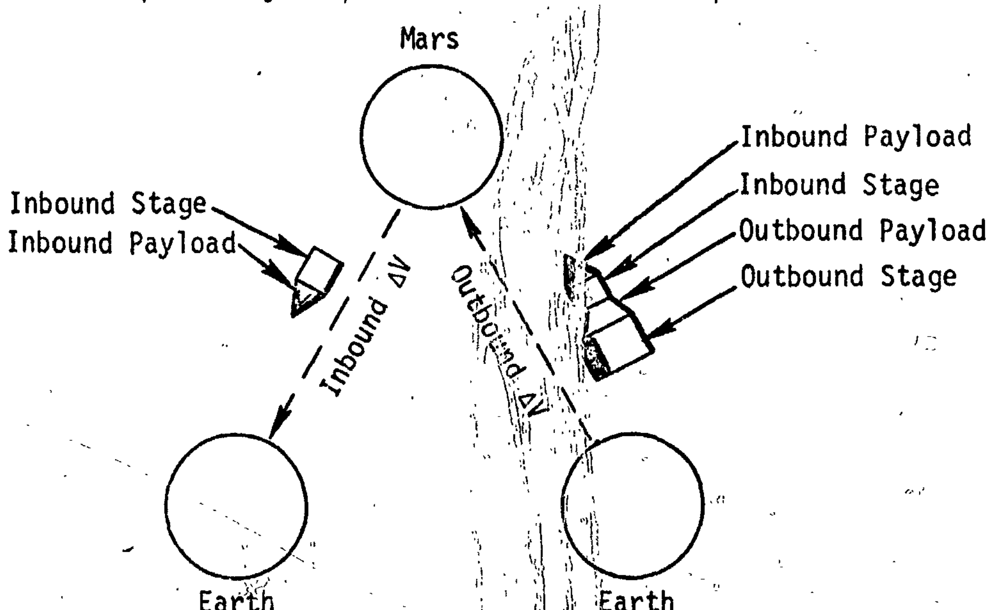
Data were generated which can be used by mission planners for preliminary vehicle stage sizing for unmanned planetary sample return missions. These missions are characterized by an outbound leg (earth to planet) delivering an outbound payload and an inbound leg (planet to earth) delivering an inbound payload. The energy requirements can be asymmetric; that is, the outbound velocity requirement is not necessarily equal to the inbound velocity requirement.

Outbound stage weight ($W_{S_{OUT}}$) and inbound stage weight ($W_{S_{IN}}$) were calculated for a range of values of inbound and outbound payloads (P_{IN} and P_{OUT}) and inbound and outbound velocity requirements (ΔV_{IN} and ΔV_{OUT}). P_{OUT} was varied from 5,000 to 60,000 pounds, P_{IN} ranged from 1,000 to 10,000 pounds, ΔV_{OUT} ranged from 11,000 to 24,000 feet per second, and ΔV_{IN} ranged from 4,000 to 30,000 feet per second.

A TRW Timeshare System program was written to generate the data. The data are presented in figures grouped at the end of this report.

DISCUSSION

A typical unmanned planetary sample return mission is depicted in the following illustration



The basic elements of this mission are: the outbound stage, payload, and velocity requirement; and the inbound stage, payload, and velocity requirement. It should be noted that the outbound payload is not defined to include the inbound vehicle; the sum of these will be referred to as the total outbound payload. The outbound payload could include an orbiter, a lander, and a stage for the planet surface-to-orbit ascent phase.

It should also be noted that the velocity requirements are total requirements for each leg of the mission. For example, the outbound velocity requirement could include trans-Mars injection, midcourse maneuvers, and Mars orbit insertion plus any other maneuvers which would possibly be performed by the outbound propulsive vehicle.

METHOD AND EQUATIONS

The problem is to determine space vehicle stage sizes for outbound and inbound legs of space missions defined by payload and energy requirements.

The impulsive velocity increment imparted to a space vehicle is defined by the ideal rocket equation

$$\Delta V = g_0 I_{sp} \ln\left(\frac{W_0}{W_f}\right) \tag{1}$$

where: g_0 = earth's acceleration of gravity at sea level (ft/sec^2)

I_{sp} = specific impulse (sec)

W_0 = initial vehicle weight (lb)

W_f = final vehicle weight (lb)

For a given mission energy (ΔV) requirement the required mass ratio can then be written as

$$\frac{W_0}{W_f} = e^{\left(\frac{\Delta V}{g_0 I_{sp}}\right)} \equiv R \tag{2}$$

The initial vehicle weight is given by the expression

$$W_0 = K+W_S \tag{3}$$

where: K = vehicle payload (lb)

W_S = stage weight (lb) = weight of propellant + inert stage weight

The final vehicle weight is given by the expression

$$W_f = K+(1-\lambda)W_S \tag{4}$$

where: λ = propellant fraction = $\frac{\text{weight of propellant}}{\text{stage weight}}$

hence the mass ratio can be written as

$$R = \frac{K+W_S}{K+(1-\lambda)W_S} \tag{5}$$

and solving for the stage weight results in the expression

$$W_S = \frac{K(R-1)}{1-R(1-\lambda)} \tag{6}$$

By specifying K, $\Delta V, g_0$, I_{sp}, and λ; equation (6) can be used to solve for the required stage weight. The appropriate value of λ can be found from a scaling law which relates W_S and λ. This scaling law (see Table I) was input to the Timeshare program in tabular form, hence the problem became one of iterating for a value of W_S which satisfies both equation (6) and the scaling law.

The inbound mass ratio, where $P_{IN} = K$, can be expressed as

$$R_{IN} = e^{\left(\frac{\Delta V_{IN}}{I_{sp_{IN}} g_0}\right)} = \frac{P_{IN} + W_{S_{IN}}}{P_{IN} + (1-\lambda_{IN})W_{S_{IN}}} \tag{7}$$

Similarly, the outbound mass ratio, where $P_{IN} + W_{S_{IN}} + P_{OUT} = K$, can be expressed as

$$R_{OUT} = e^{\left(\frac{\Delta V_{OUT}}{I_{sp_{OUT}} g_0}\right)} = \frac{P_{IN} + W_{S_{IN}} + P_{OUT} + W_{S_{OUT}}}{P_{IN} + W_{S_{IN}} + P_{OUT} + (1-\lambda_{OUT}) W_{S_{OUT}}} \qquad (8)$$

Note that the inbound and outbound I_{sp}'s need not be the same and that λ will vary depending on stage weight.

Results

A typical plot of the data is illustrated below.

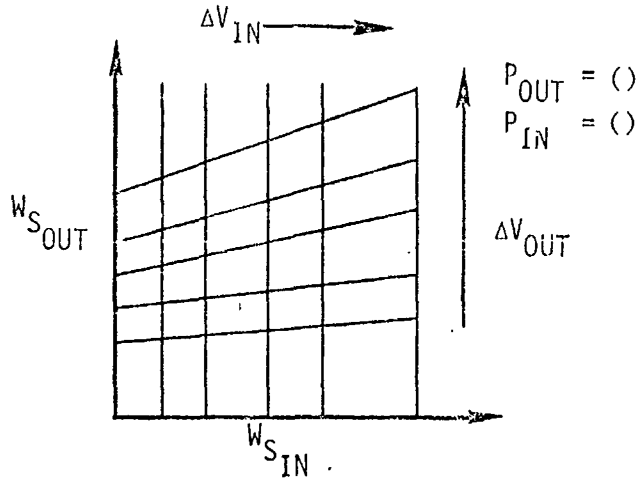


Figure (a) $W_{S_{OUT}}$ VS $W_{S_{IN}}$

These are plots of outbound stage weight ($W_{S_{OUT}}$) versus inbound stage weight ($W_{S_{IN}}$) for specified values of outbound payload (P_{OUT}) and inbound payload (P_{IN}) with the outbound velocity requirement (ΔV_{OUT}) and the inbound velocity requirement (ΔV_{IN}) as the parameters. The ΔV_{IN} curves are vertical lines since $W_{S_{IN}}$, as calculated from equation (6), is a function of P_{IN}, λ_{IN}, and ΔV_{IN} which are constant along any given line. The V_{OUT} curves are not straight lines since $W_{S_{OUT}}$, as calculated from equation (6), is a function of the variables $W_{S_{IN}}$ and λ_{OUT} as well as the constants P_{OUT}, ΔV_{OUT}, and P_{IN}. This is to say that $W_{S_{IN}}$ and P_{IN} are part of the total outbound non propulsive weight, ($P_{OUT} + P_{IN} + W_{S_{IN}}$). This brings up the point that all of the curves plotted at the end of this report, and of the format illustrated in Figure (a), are excerpts of one master plot as illustrated below.

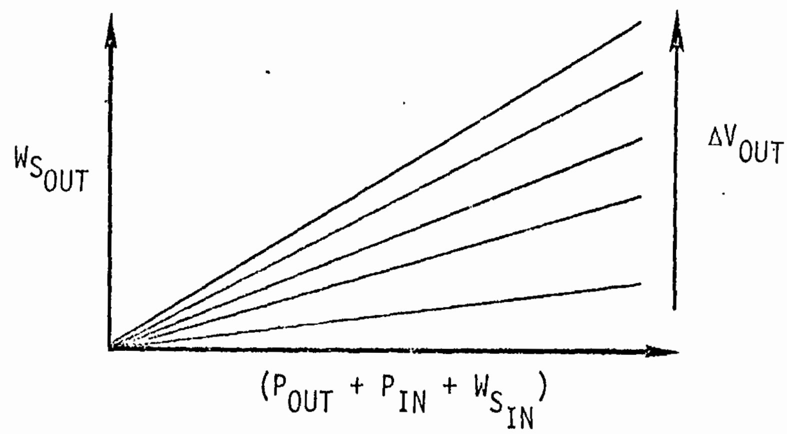


Figure (b) Master Plot

The ΔV_{OUT} curves emanate from the origin of the coordinate system. If λ_{OUT} were a constant, these curves would be straight lines with a slope of $W_{S_{OUT}}/(P_{OUT}$ $P_{IN} + W_{S_{IN}})$

If one now selects values for P_{OUT} and P_{IN}, a coordinate system can be defined for $W_{S_{OUT}}$ versus $W_{S_{IN}}$ whose origin will be displaced from the $P_{OUT} + P_{IN} + W_{S_{IN}}$ origin by the amount $P_{OUT} + P_{IN}$ (see dashed line in Figure (c)).

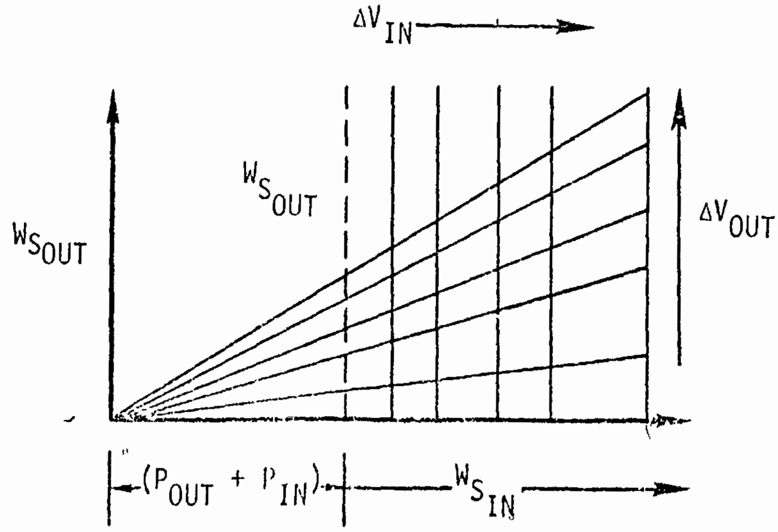


Figure (c) $W_{S_{OUT}}$ VS $W_{S_{IN}}$ On Master Plot

Associated values of ΔV_{IN} can be drawn, and the resulting $W_{S_{OUT}}$ versus $W_{S_{IN}}$ plot in Figure (c) is identical to the $W_{S_{OUT}}$ versus $W_{S_{IN}}$ plot of Figure (a) for the respective values of P_{OUT} and P_{IN}.

Data were generated for all combinations of the following values of input parameters.

P_{OUT} (lb)	P_{IN} (lb)	ΔV_{OUT} (ft/sec)	ΔV_{IN} (ft/sec)
5,000	1,000	11,000	4,000
10,000	2,000	14,000	14,000
20,000	4,000	18,000	20,000
30,000	6,000	20,000	24,000
40,000	8,000	22,000	26,000
50,000	10,000	24,000	28,000
60,000			30,000

Figures 1 through 42 are plots of the data for the 42 combinations of the values of P_{OUT} and P_{IN} shown above.

Although the curves were generated for a value of I_{sp} equal to 460, they can be used for sizing vehicles with other values of I_{sp}. For example, if it is desired to find a stage weight for a vehicle with an I_{sp} equal to 400 and a ΔV equal to 20,000, the appropriate ΔV to refer to on the plot would be:

$$\Delta V(\text{plot}) = 460 \left(\frac{\Delta V}{I_{sp}}\right) = 460 \left(\frac{20,000}{400}\right) \doteq 23,000$$

SUMMARY

Data were generated which can be used to determine outbound and inbound stage weight requirements for specified values of planetary sample return mission payload and energy (ΔV) requirements. The data were calculated by implementing an iterative technique on the TRW Timeshare System. This report contains plots of outbound stage weight versus inbound stage weight for 42 combinations of outbound and inbound payload requirements.

Table I. Scaling Law

Stage Size (W_S)	Propellant Fraction (λ)		
	I_{sp} = 306	I_{sp} = 383	I_{sp} = 460
0	0	0	0
10,000	.9000	.8800	.8000
30,000	.9585	.9336	.8600
40,000	.9671	.9430	.8710
50,000	.9708	.9528	.8762
60,000	.9728	.9580	.8807
70,000	.9743	.9618	.8826
80,000	.9753	.9645	.8847
90,000	.9762	.9667	.8864
100,000	.9768	.9685	.8887
150,000	.9783	.9722	.8928
200,000	.9793	.9743	.8951
250,000	.9800	.9758	.8972
300,000	.9804	.9768	.8983
350,000	.9808	.9775	.8989
400,000	.9811	.9780	.8993
500,000	.9815	.9787	.8997
600,000	.9818	.9792	.9000
700,000	.9821	.9799	.9003
1,000,000	.9827	.9805	.9020
100,000,000	.9830	.9808	.9040

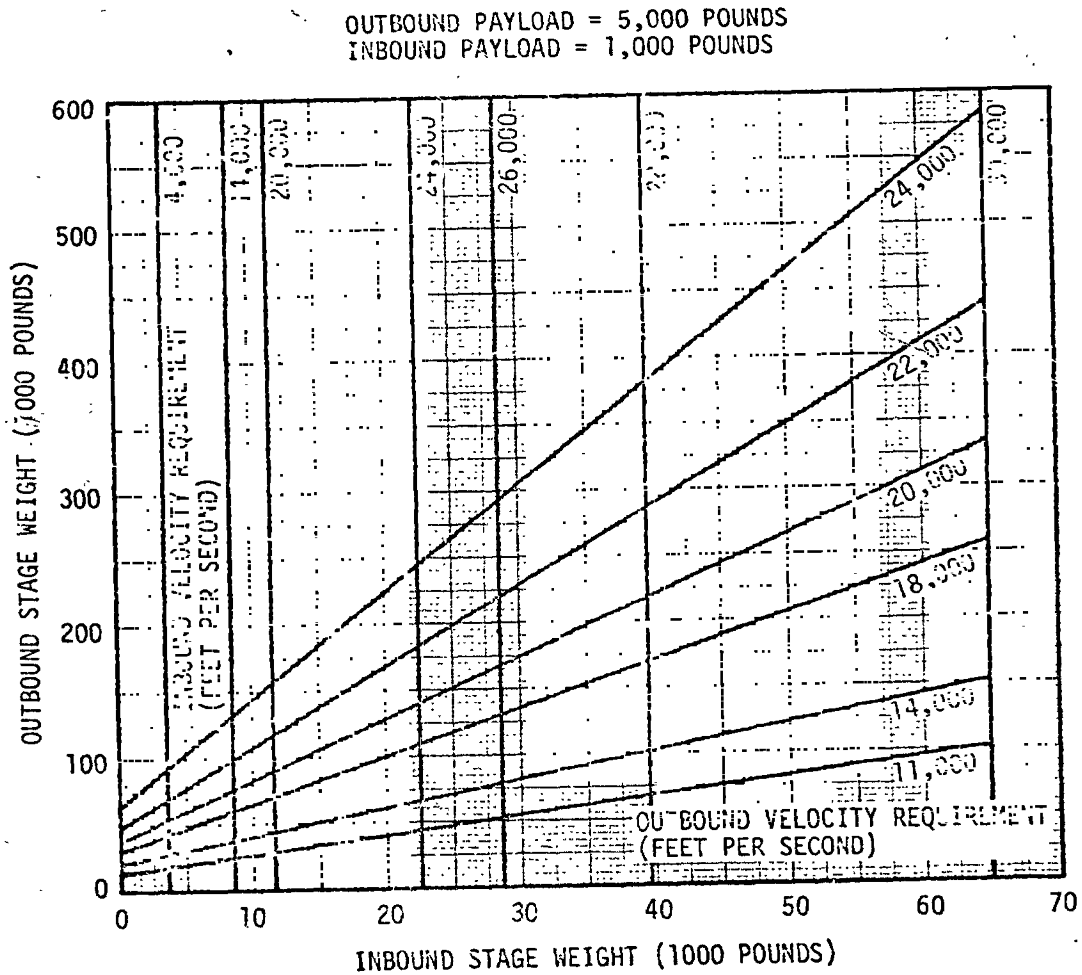


Figure 1. Outbound Stage Weight versus Inbound Stage Weight
(P_{OUT} = 5,000, P_{IN} = 1,000)

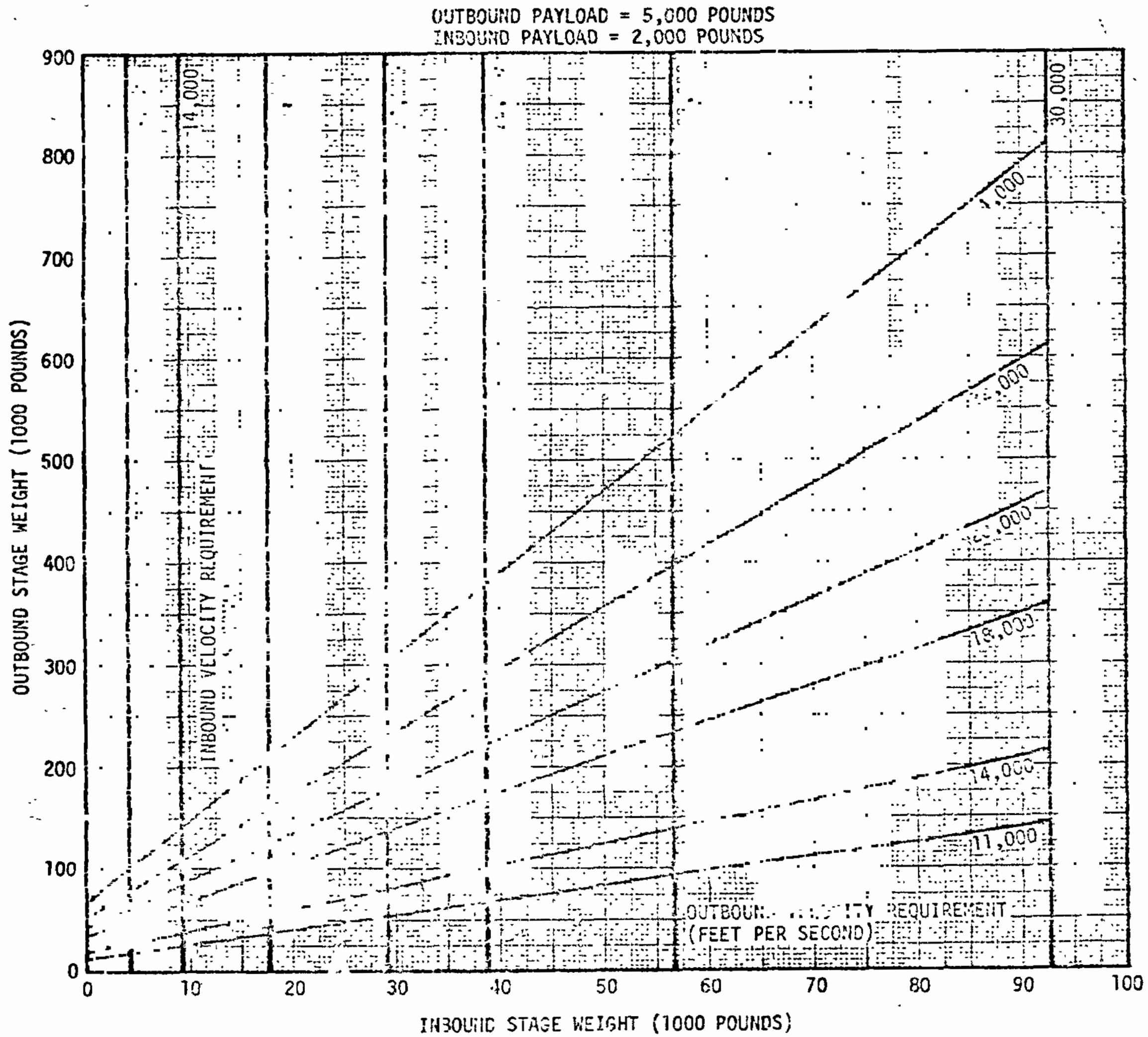


Figure 2. Outbound Stage Weight versus Inbound Stage Weight (P_{OUT} = 5,000, P_{IN} = 2,000)

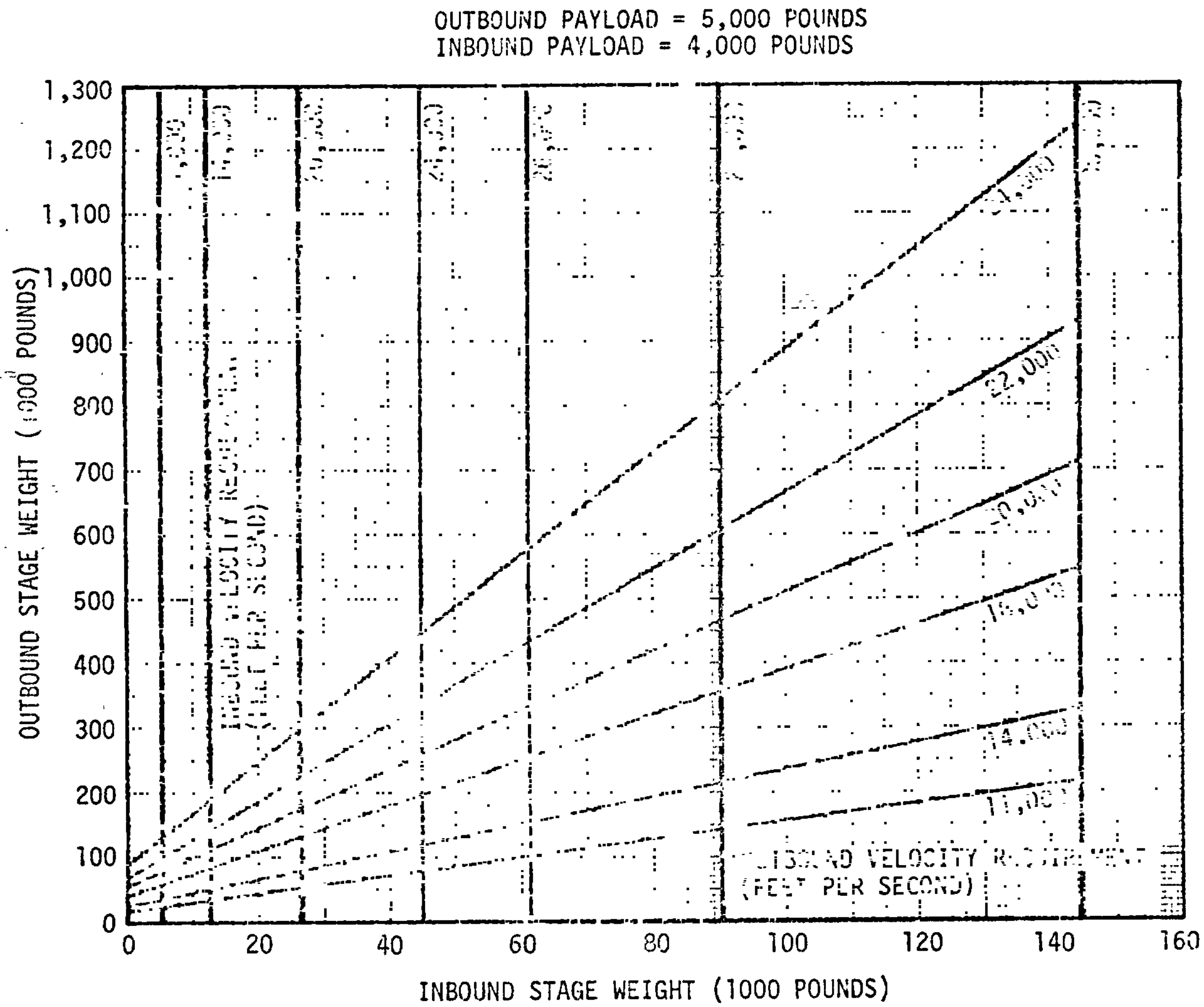


Figure 3. Outbound Stage Weight versus Inbound Stage Weight (P_{OUT} = 5,000, P_{IN} = 4,000)

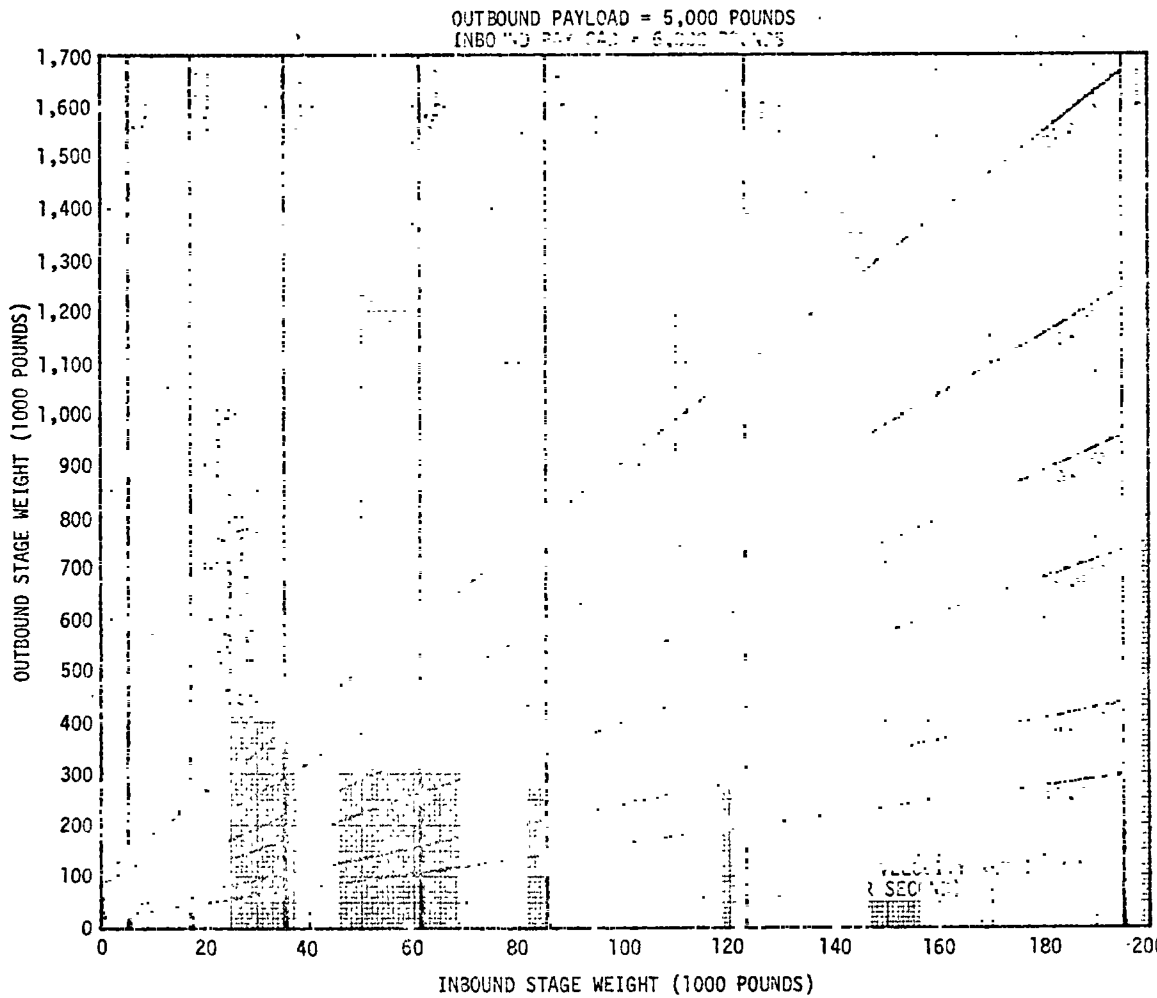


Figure 4. Outbound Stage Weight versus Inbound Stage Weight (P_{OUT} = 5,000, P_{IN} = 6,000)

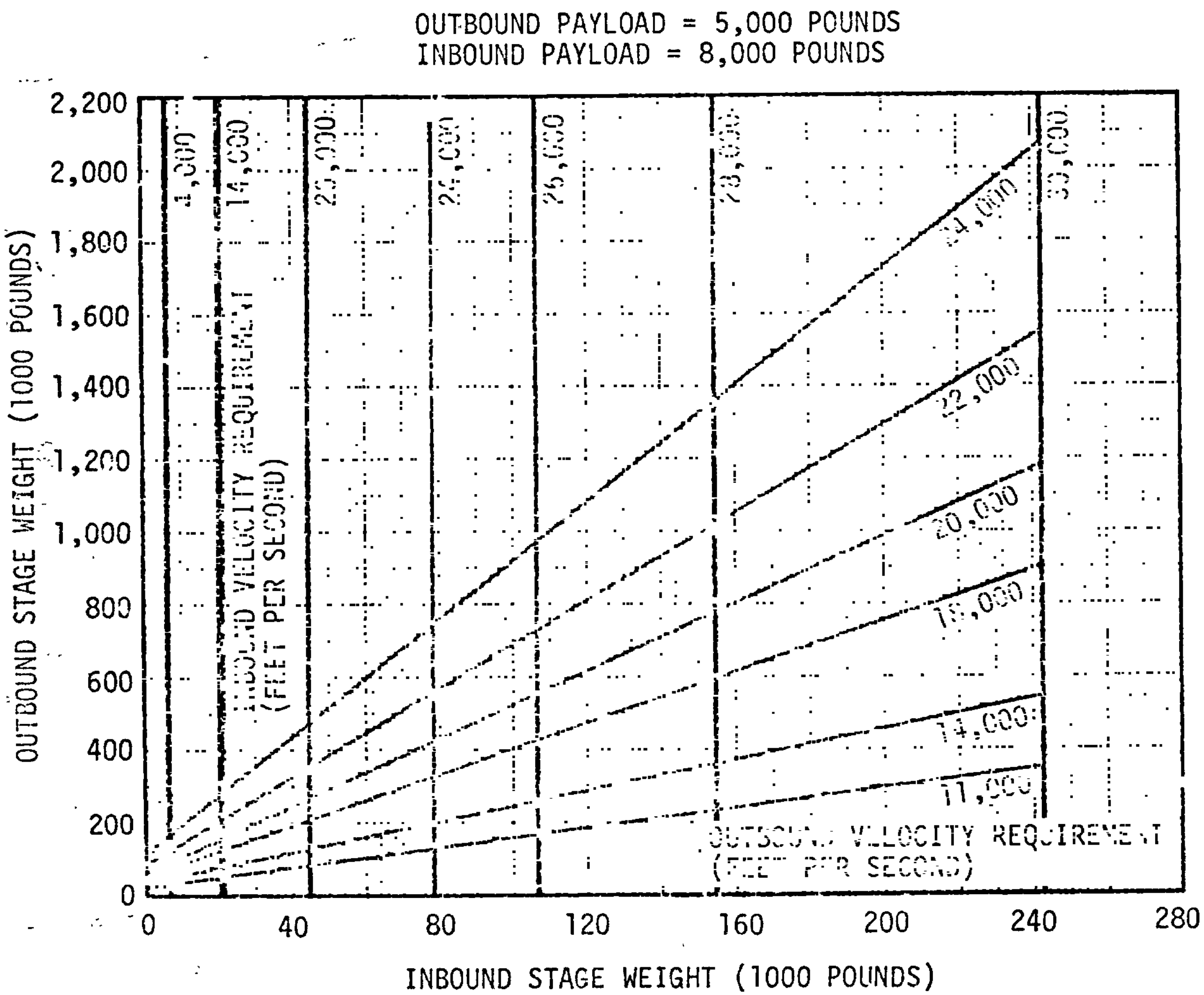


Figure 5. Outbound Stage Weight versus Inbound Stage Weight (P_{OUT} = 5,000, P_{IN} = 8,000)

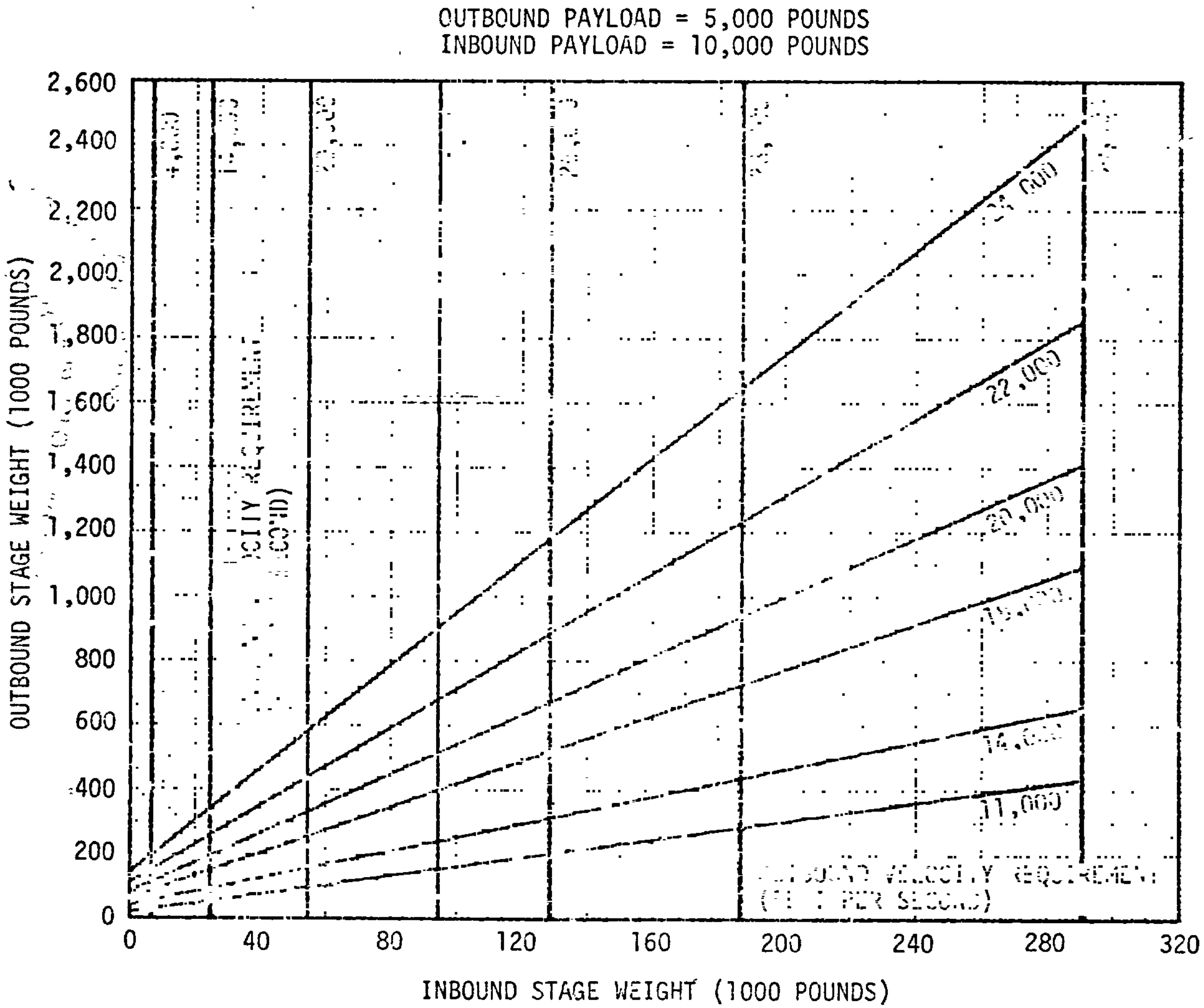


Figure 6. Outbound Stage Weight versus Inbound Stage Weight (P_{OUT} = 5,000, P_{IN} = 10,000)

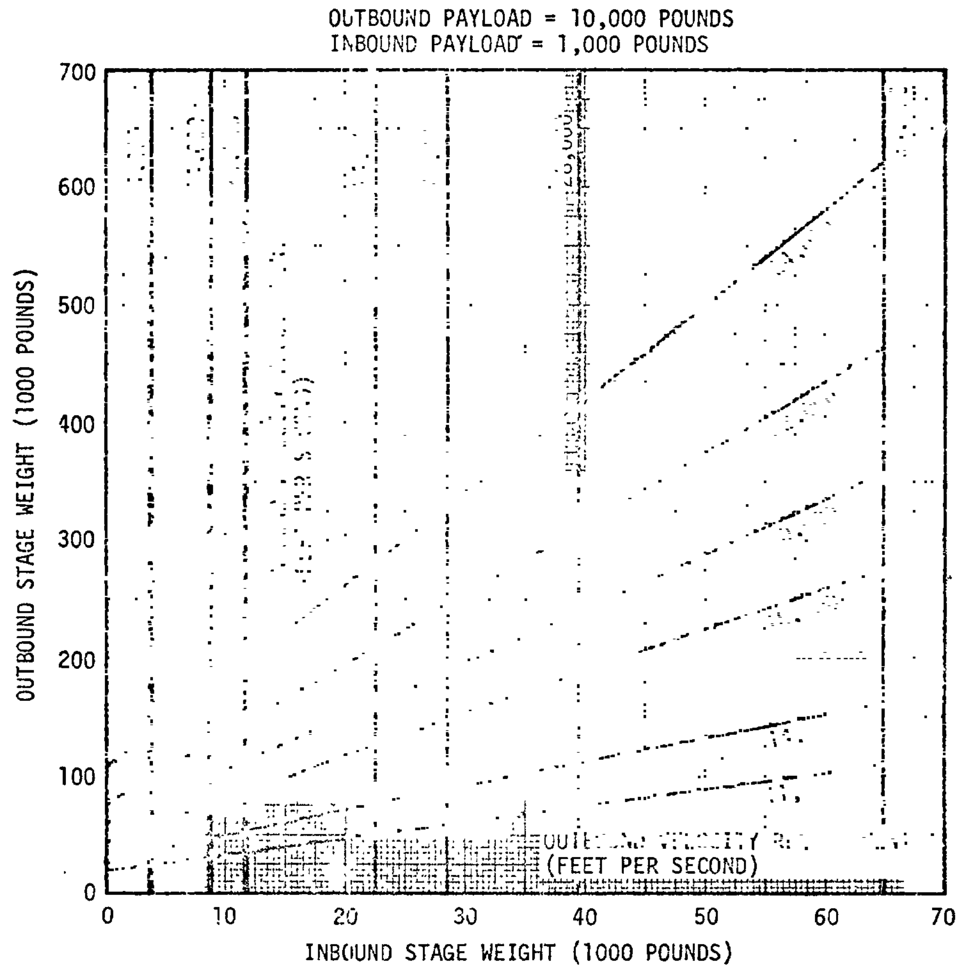


Figure 7. Outbound Stage Weight versus Inbound Stage Weight (P_{CUT} = 10,000, P_{IN} = 1,000)

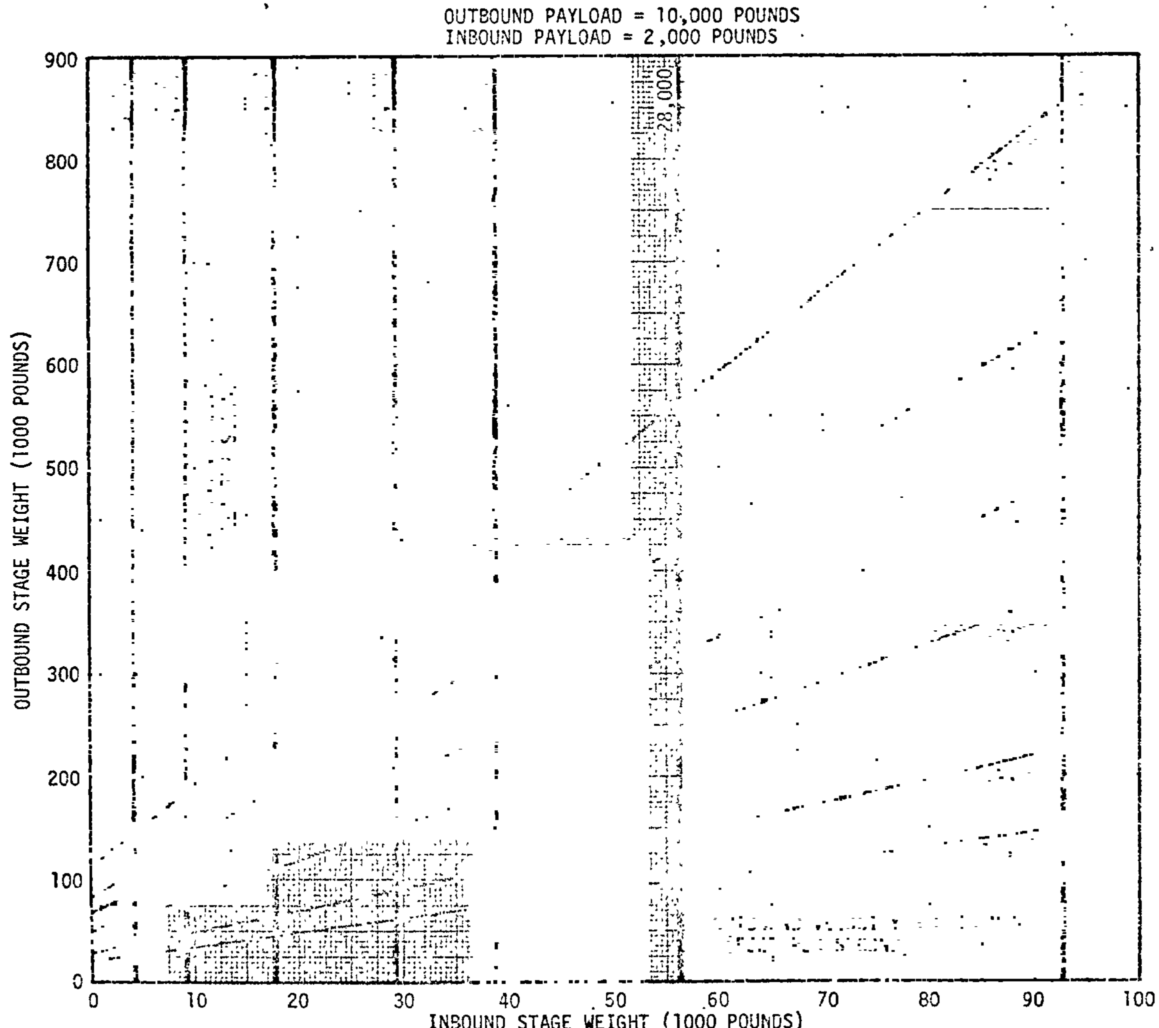


Figure 8. Outbound Stage Weight versus Inbound Stage Weight (P_{OUT} = 10,000, P_{IN} = 2,000)

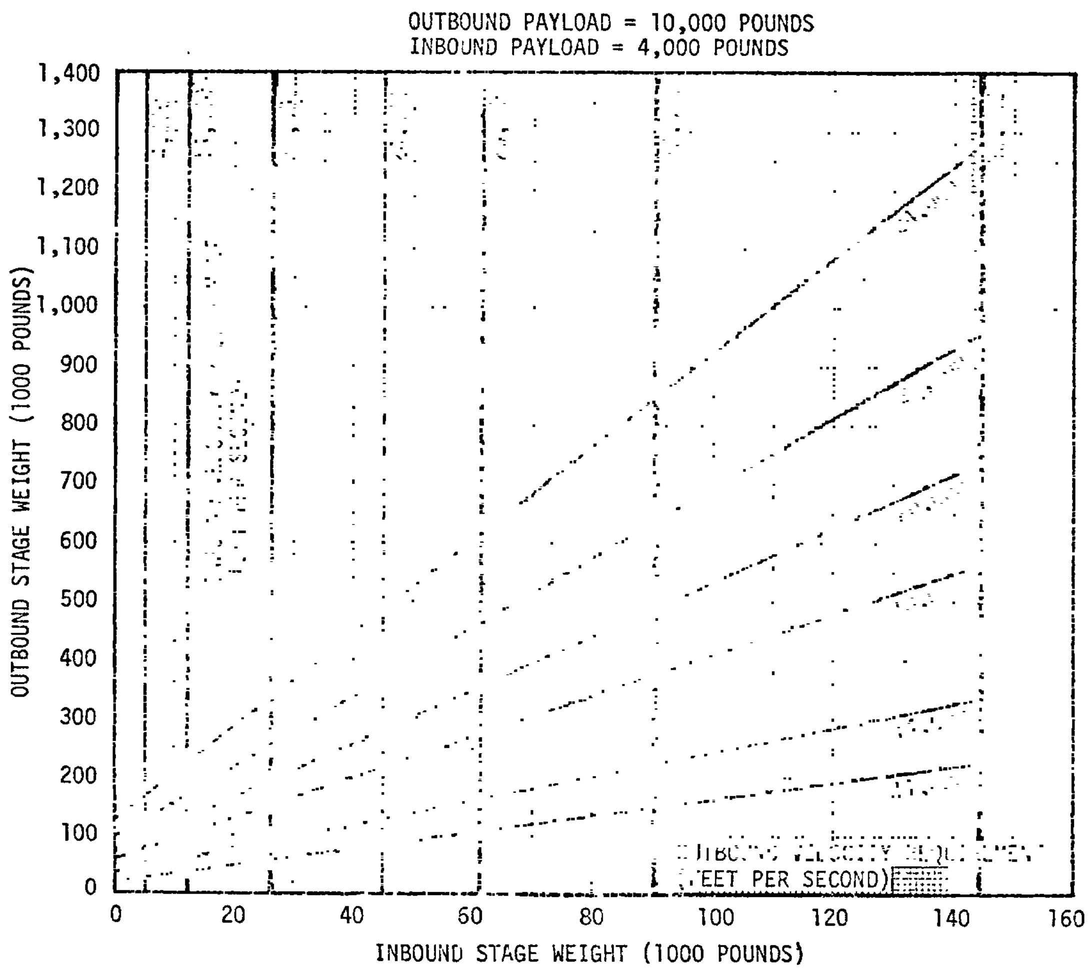


Figure 9. Outbound Stage Weight versus Inbound Stage Weight (P_{OUT} = 10,000, P_{IN}=4,000)

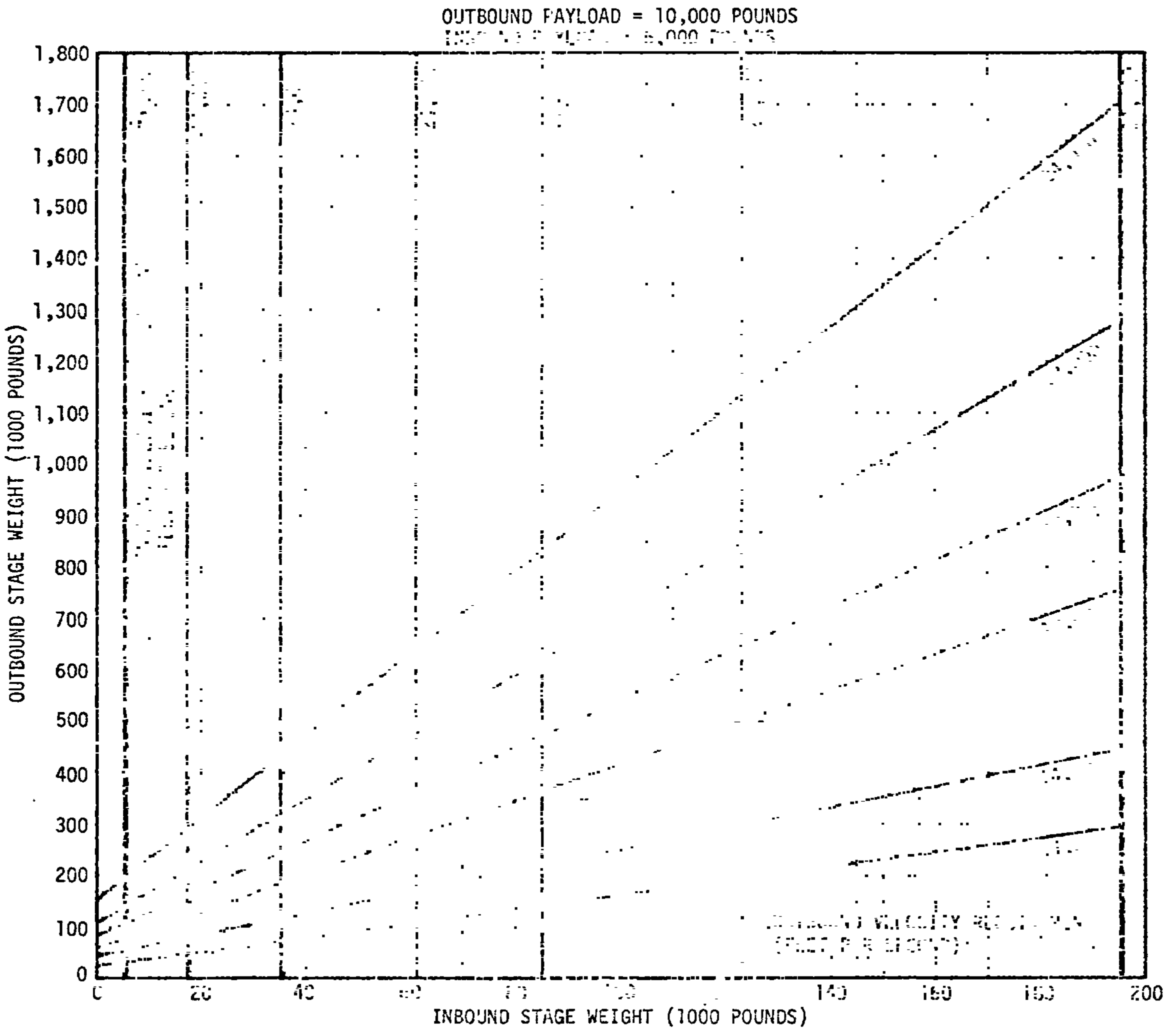


Figure 10. Outbound Stage Weight versus Inbound Stage Weight
(P_{OUT} = 10,000, P_{IN} = 6,000)

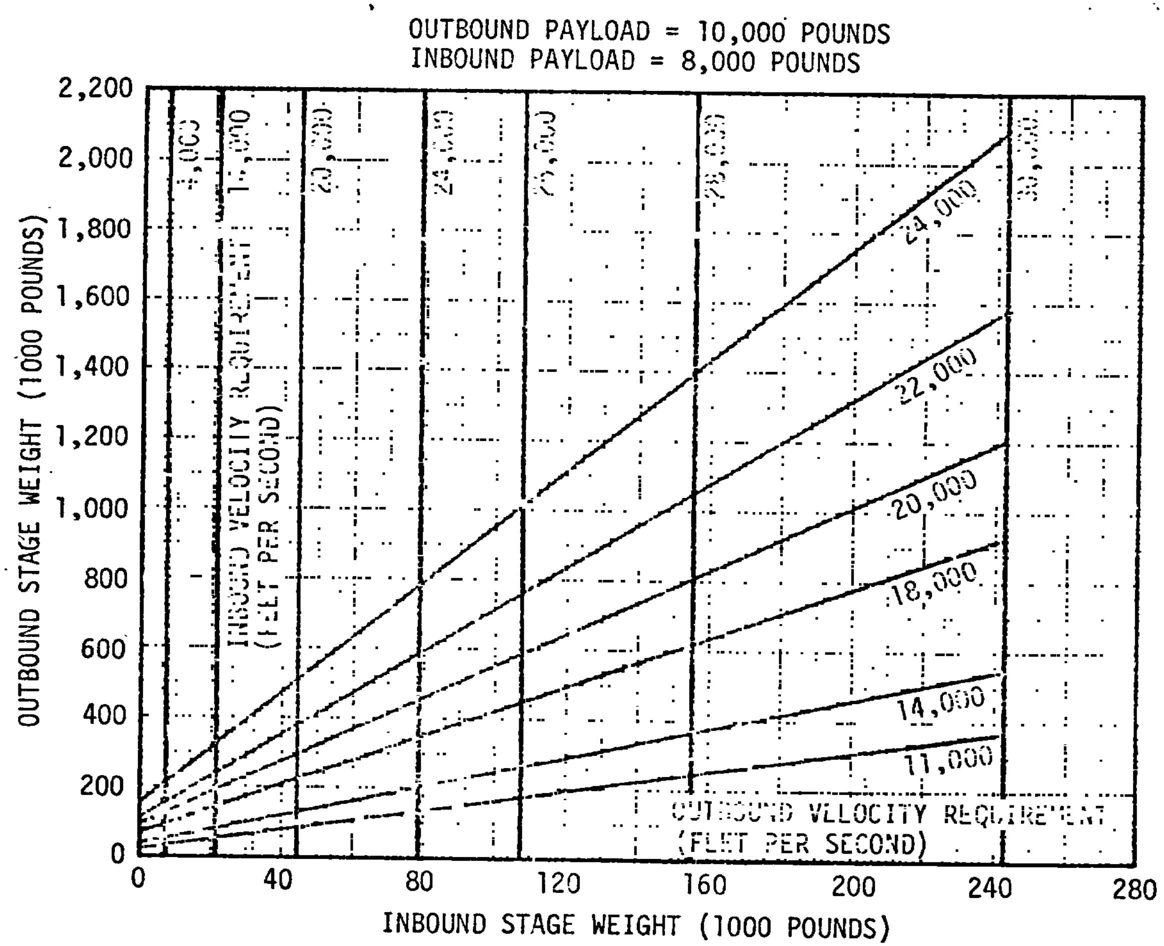


Figure 11. Outbound Stage Weight versus Inbound Stage Weight
(P_{OUT} = 10,000, P_{IN} = 8,000)

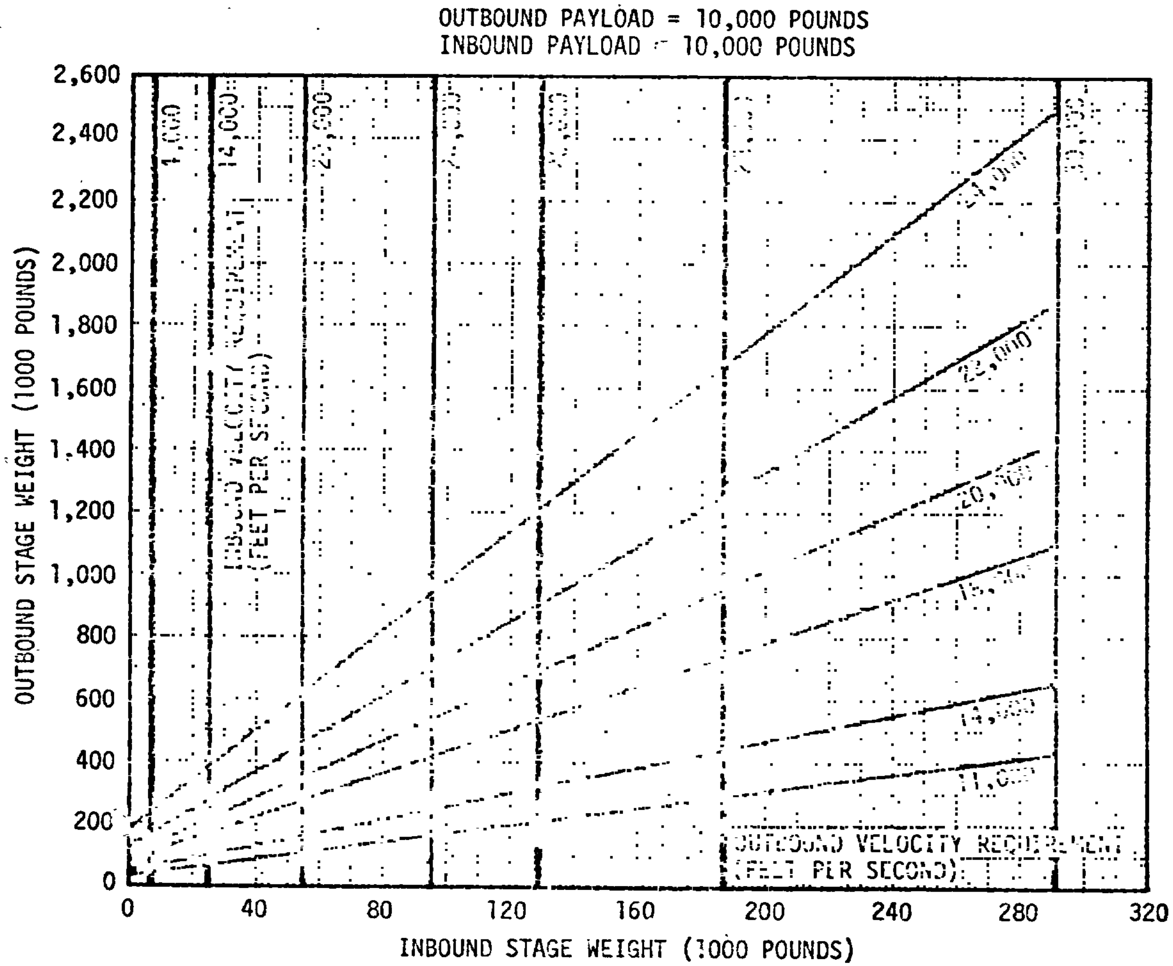


Figure 12. Outbound Stage Weight versus Inbound Stage Weight
(P_{OUT} = 10,000, P_{IN} = 10,000)

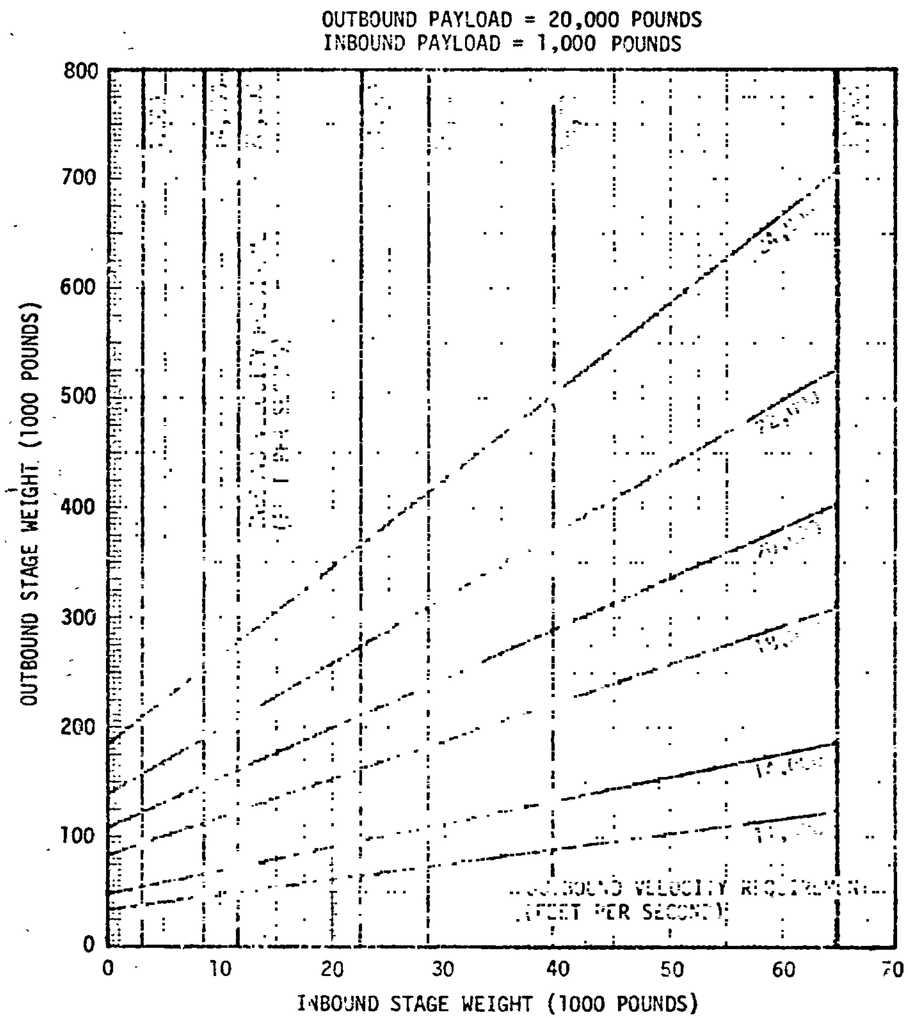


Figure 13. Outbound Stage Weight versus Inbound Stage Weight (P_{OUT} = 20,000, P_{IN} = 1,000)

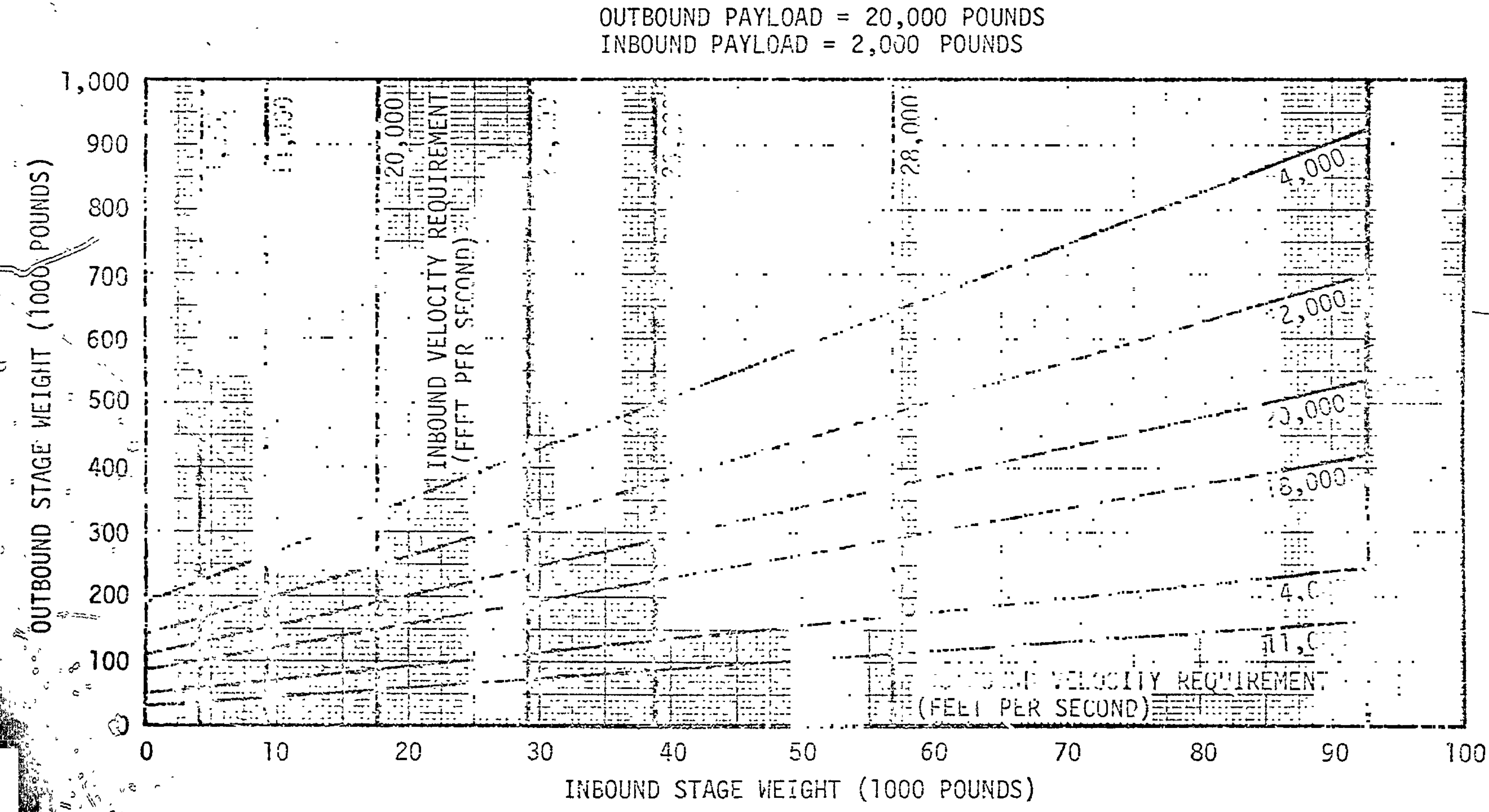


Figure 14. Outbound Stage Weight versus Inbound Stage Weight
(P_{OUT} = 20,000, P_{IN} = 2,000)

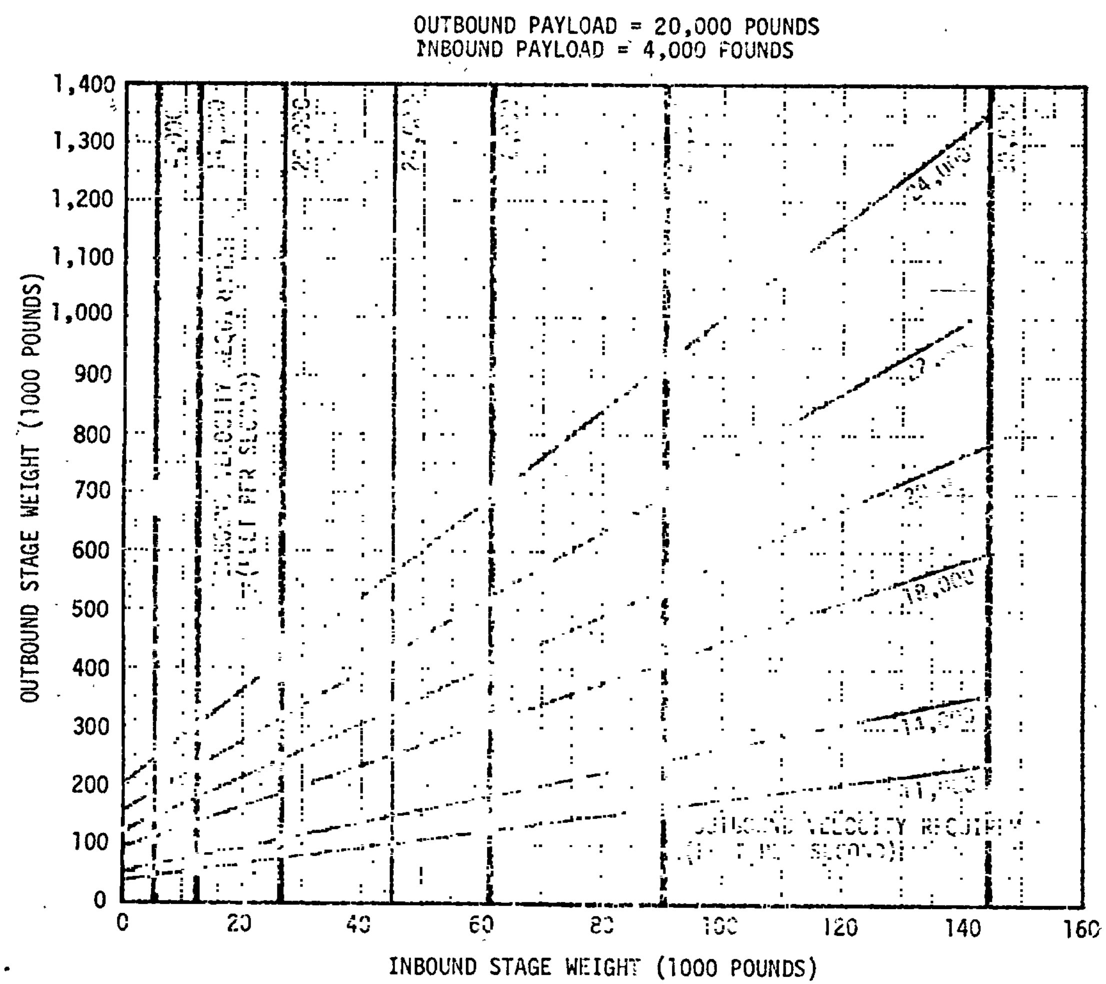


Figure 15. Outbound Stage Weight versus Inbound Stage Weight
(P_{OUT} = 20,000, P_{IN} = 4,000)

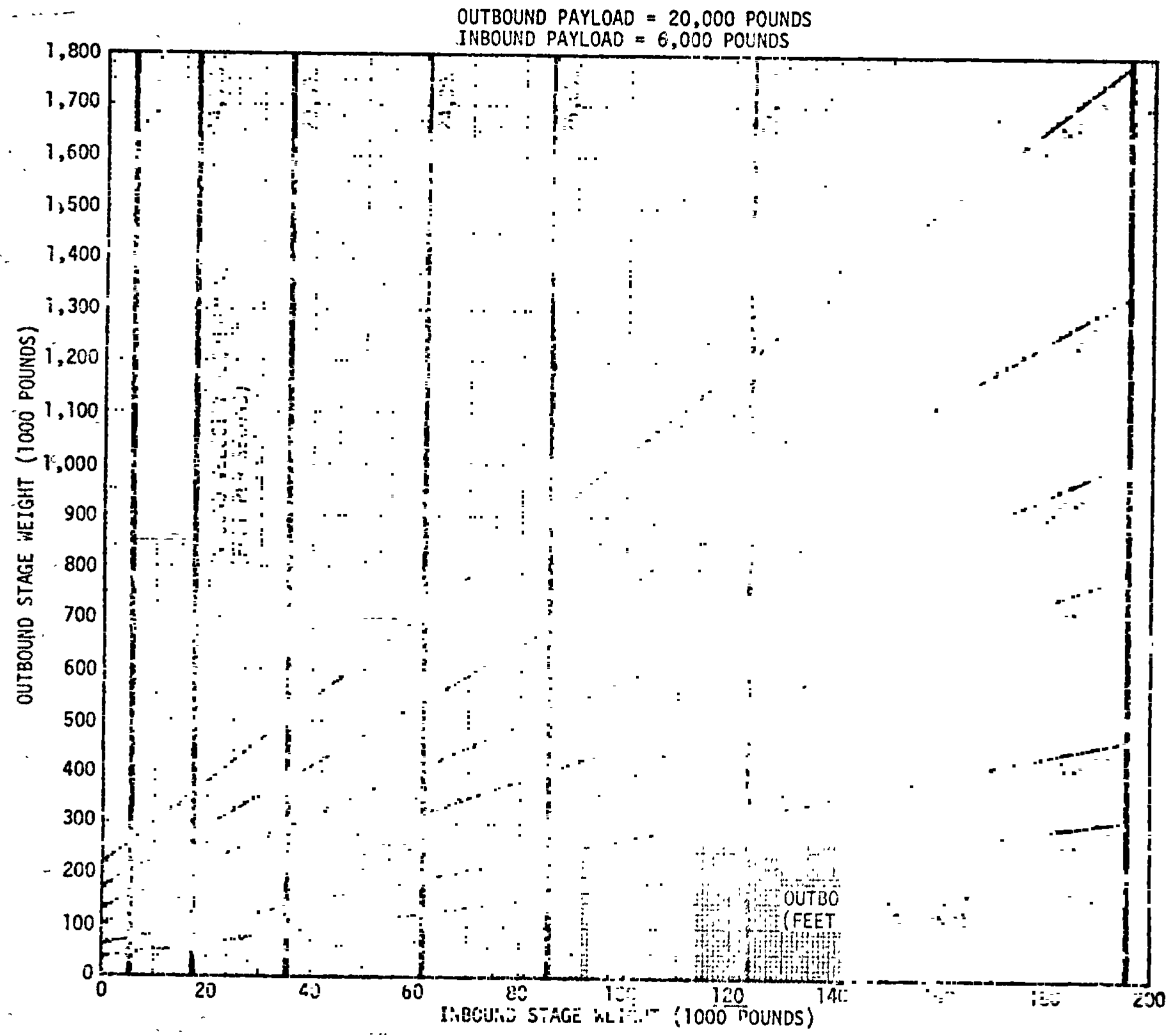


Figure 16. Outbound Stage Weight versus Inbound Stage Weight
(P_{OUT} = 20,000, P_{IN} = 6,000)

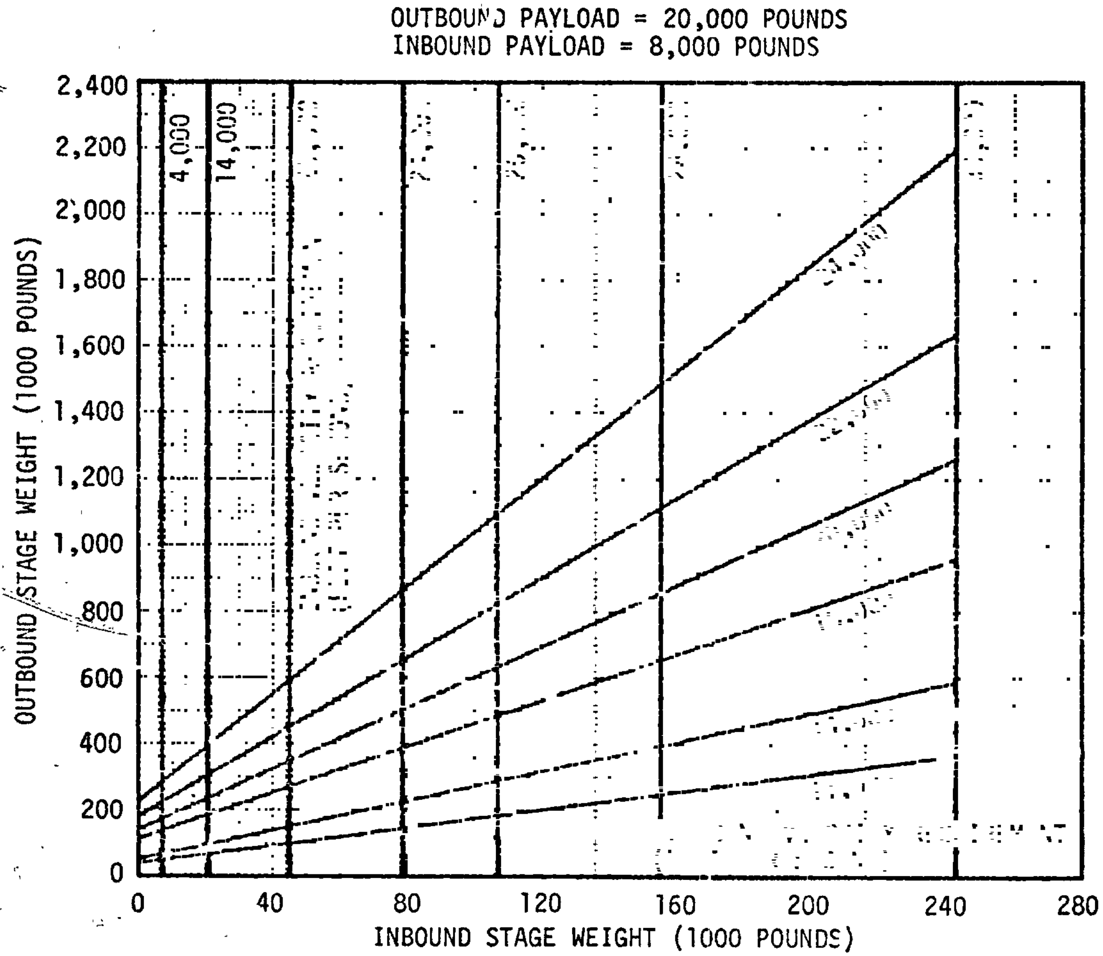


Figure 17. Outbound Stage Weight versus Inbound Stage Weight (P_{OUT} = 20,000, P_{IN} = 8,000)

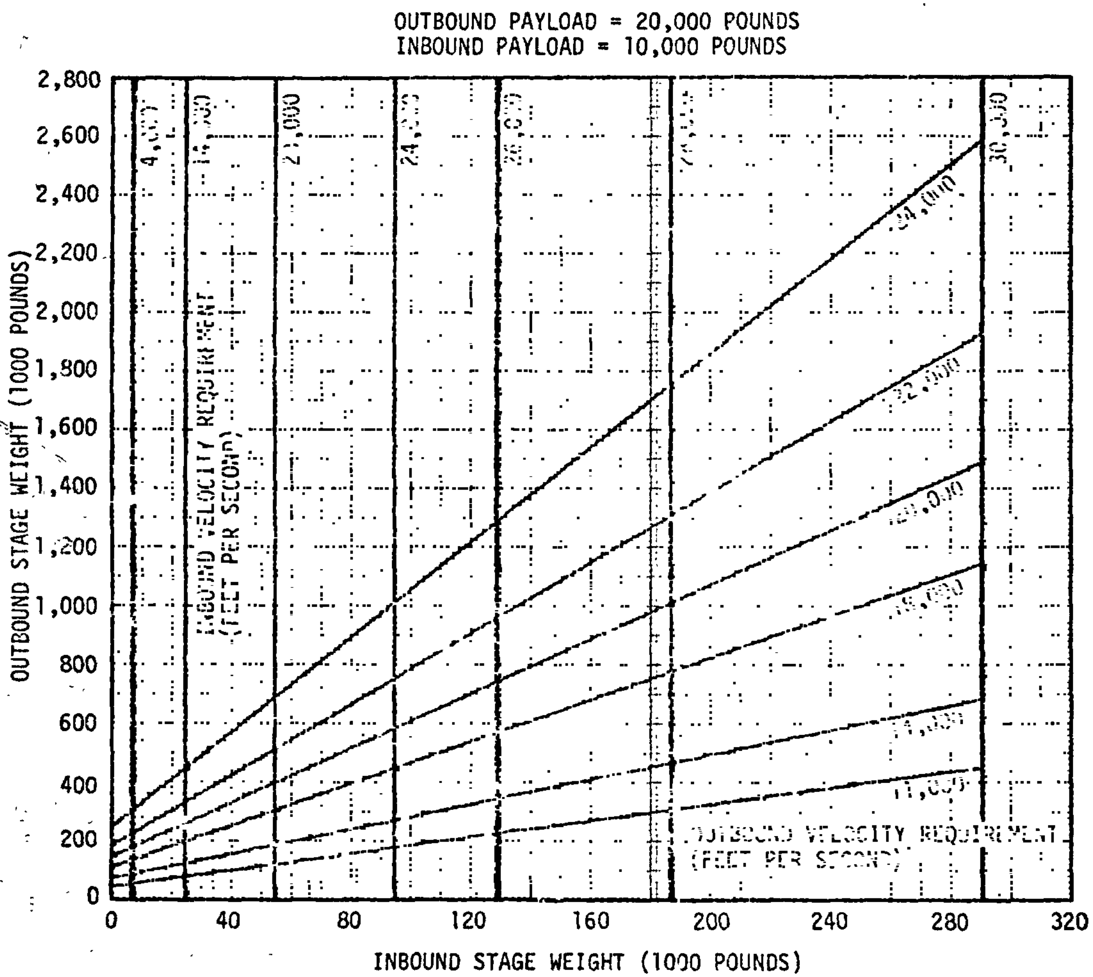


Figure 18. Outbound Stage Weight versus Inbound Stage Weight (P_{OUT} = 20,000, P_{IN} = 10,000)

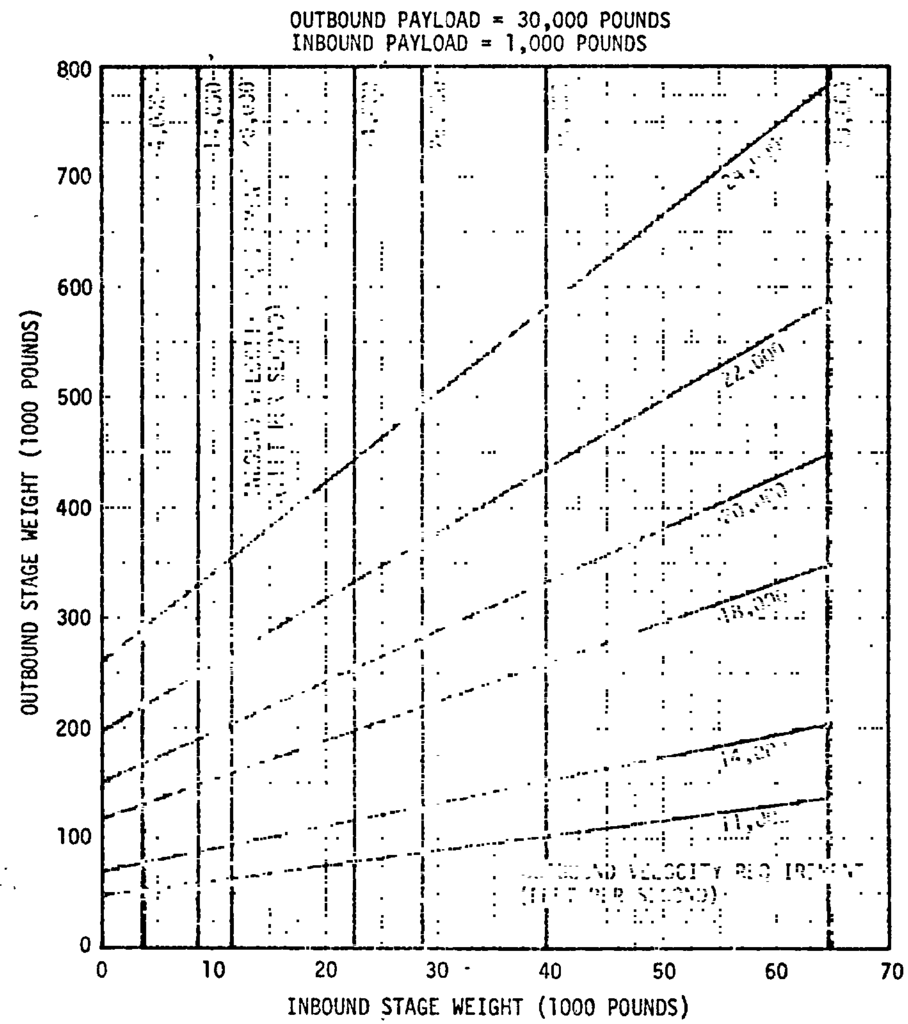


Figure 19. Outbound Stage Weight versus Inbound Stage Weight (P_{OUT} = 30,000, P_{IN} = 1,000)

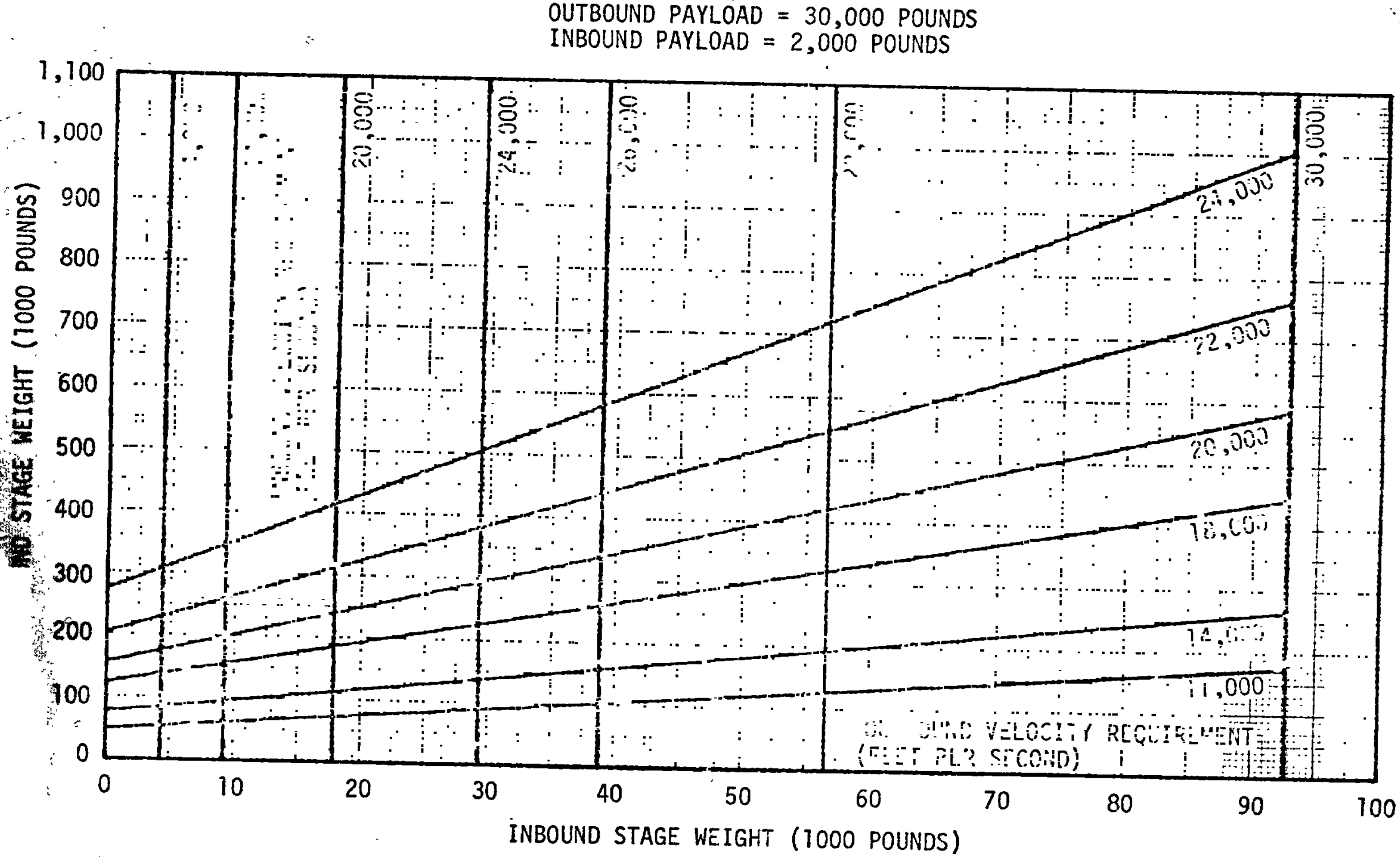


Figure 20. Outbound Stage Weight versus Inbound Stage Weight (P_{OUT} = 30,000, P_{IN} = 2,000)

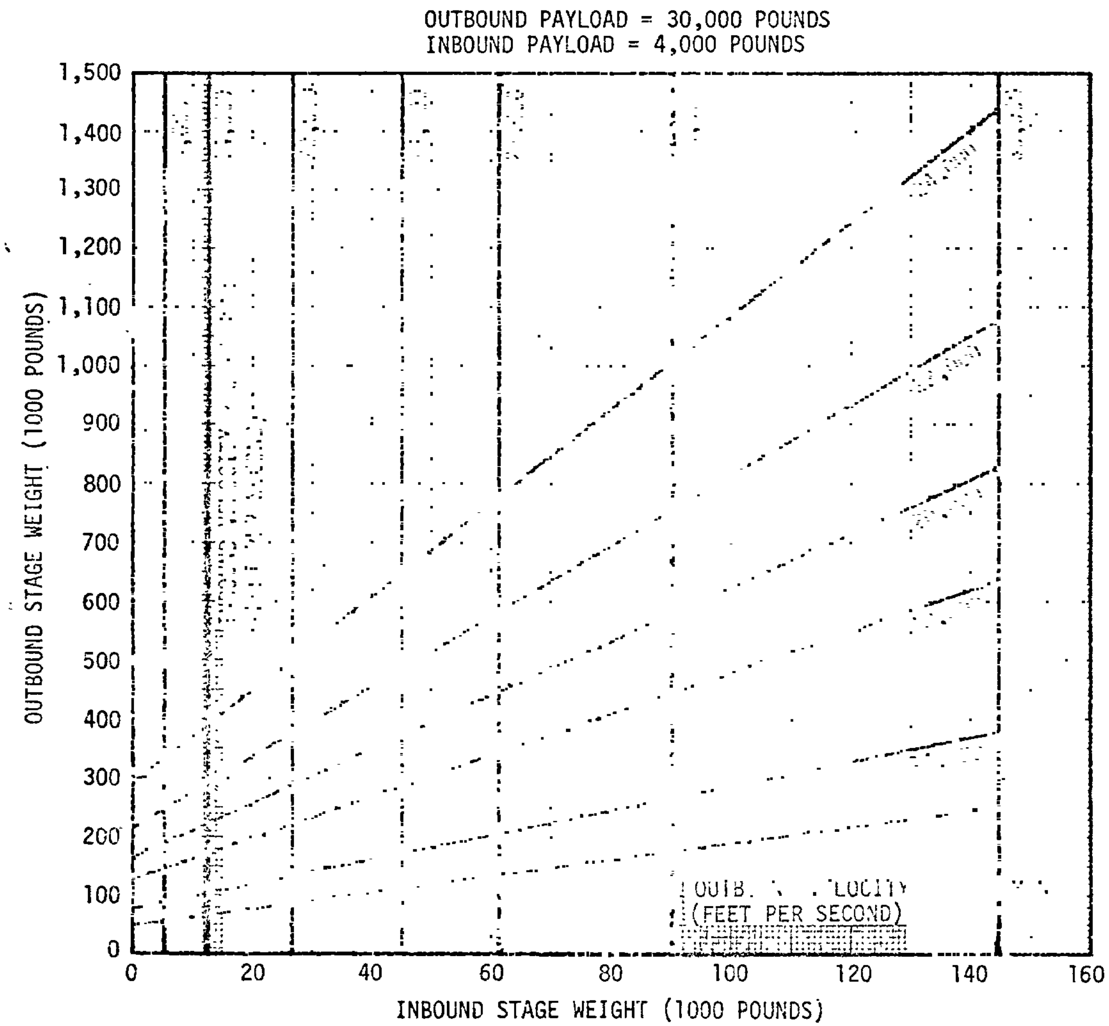


Figure 21. Outbound Stage Weight versus Inbound Stage Weight (P_{OUT} = 30,000, P_{IN} = 4,000)

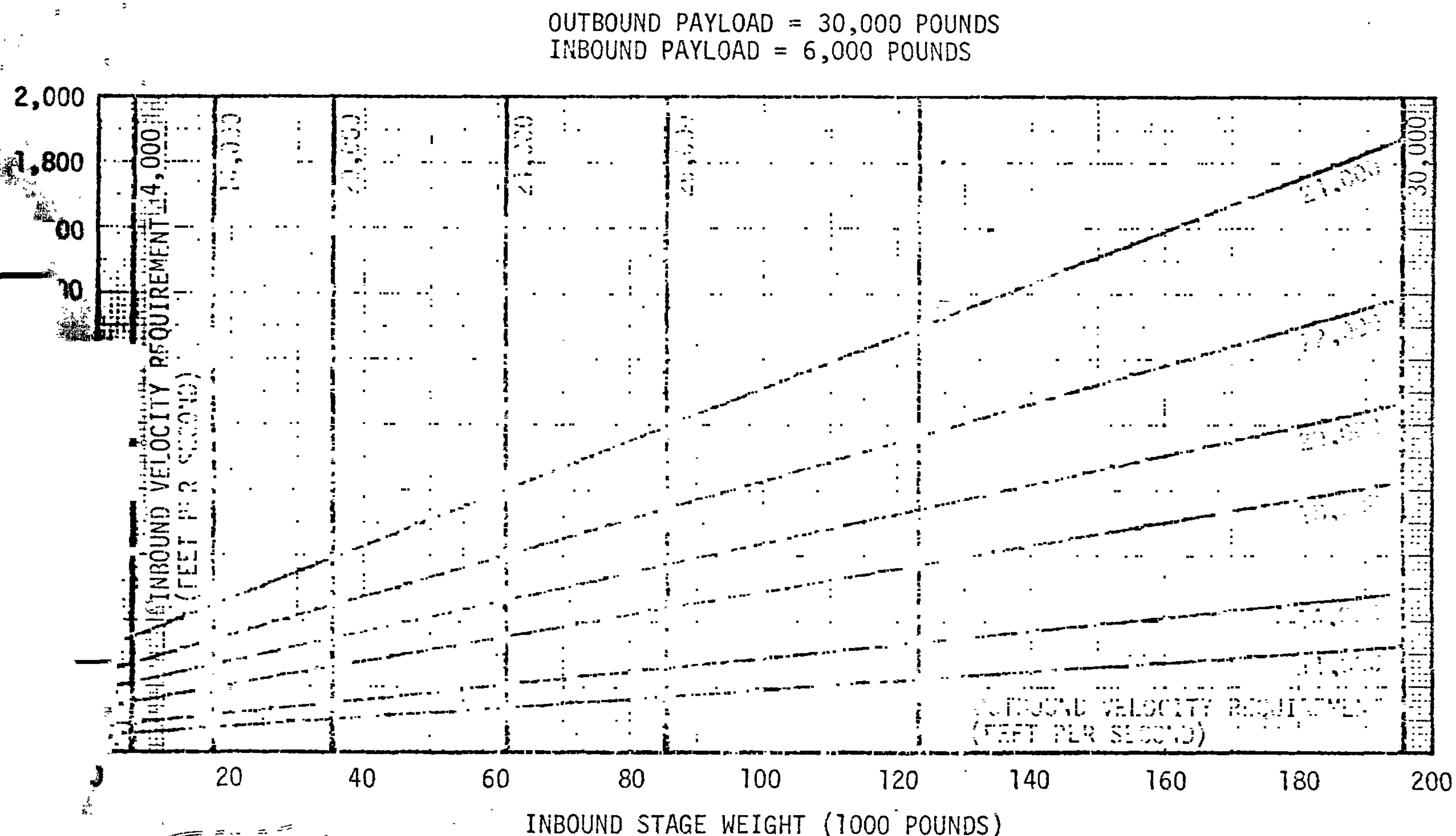


Figure 22. Outbound Stage Weight versus Inbound Stage Weight
(P_{OUT} = 30,000, P_{IN} = 6,000)

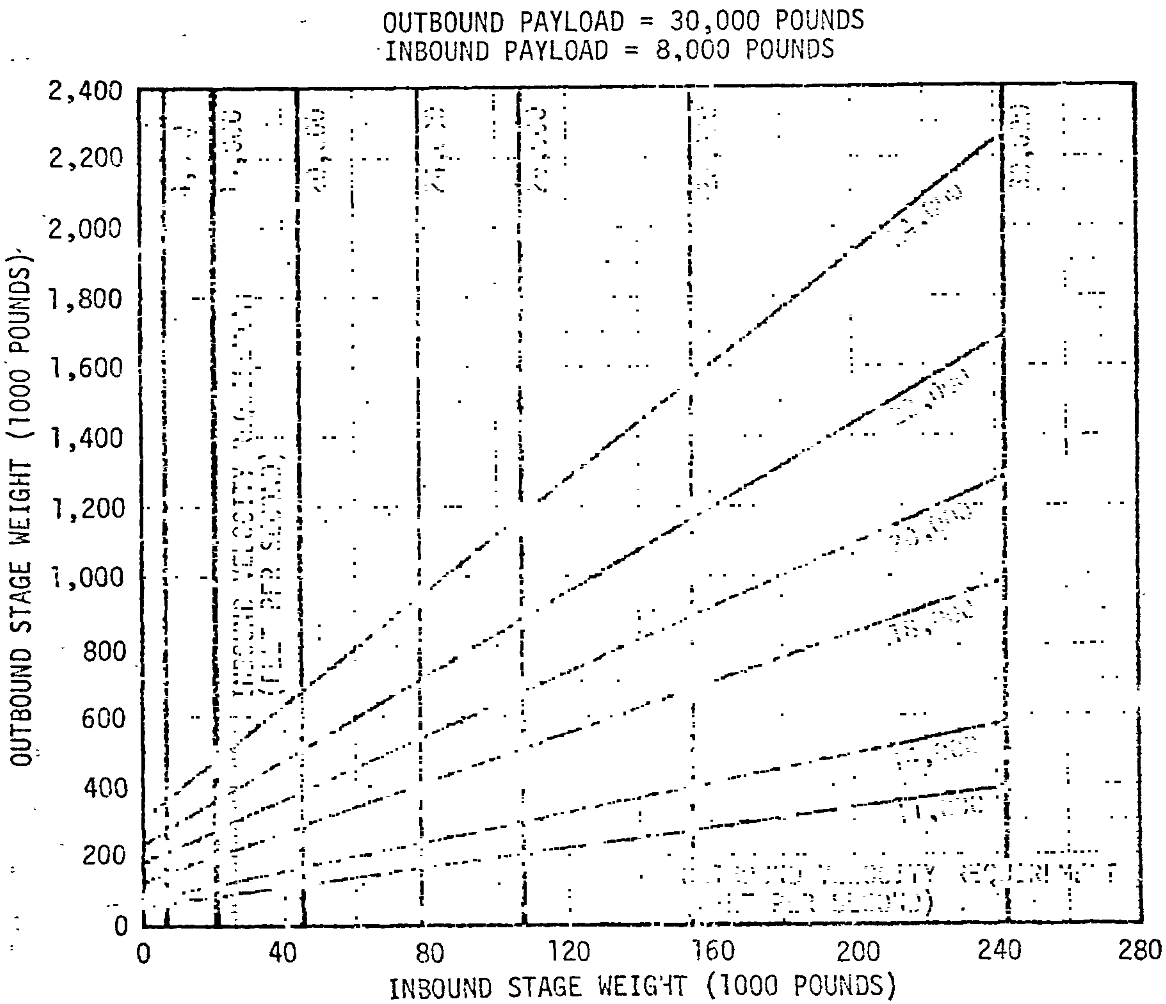


Figure 23. Outbound Stage Weight versus Inbound Stage Weight
(P_{OUT} = 30,000, P_{IN} = 8,000)

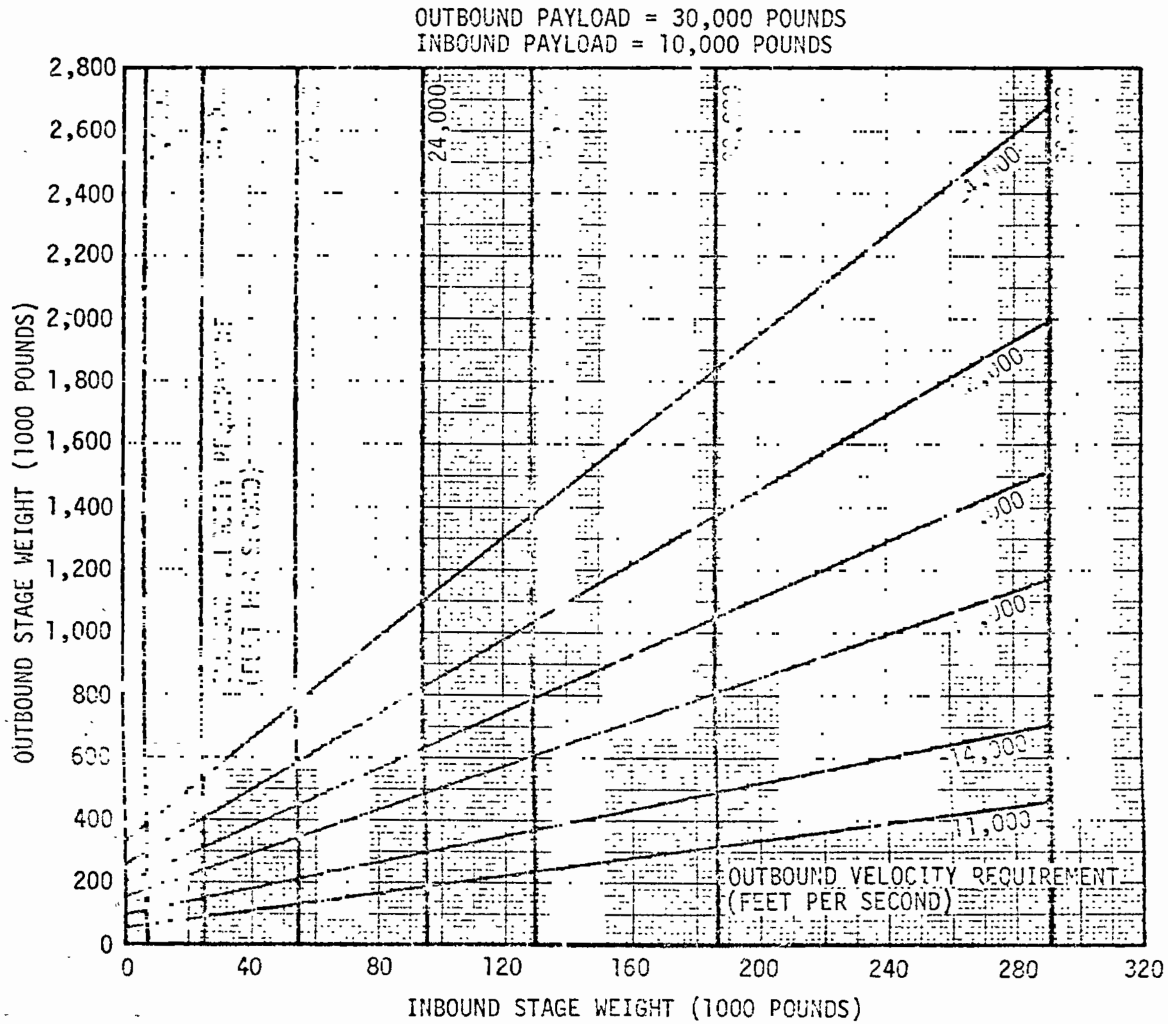


Figure 24. Outbound Stage Weight versus Inbound Stage Weight (P_{OUT} = 30,000, P_{IN} = 10,000)

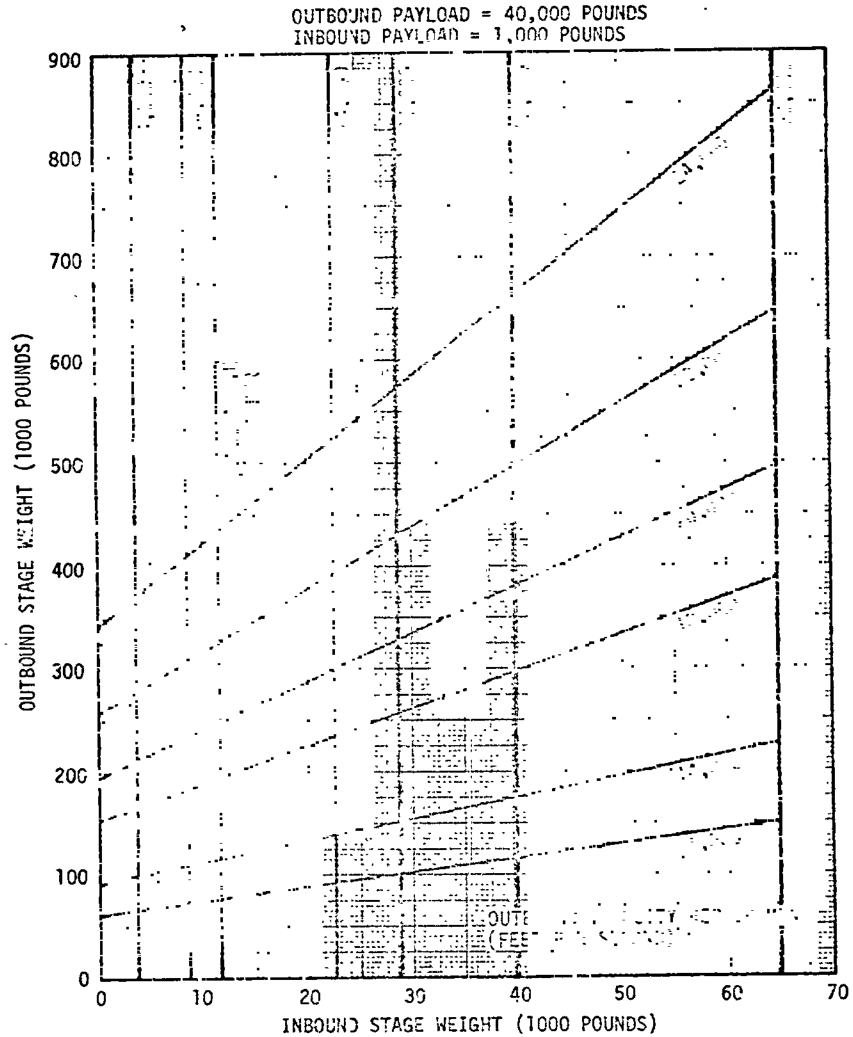


Figure 25. Outbound State Weight versus Inbound Stage Weight (P_{OUT} = 40,000, P_{IN} = 1,000)

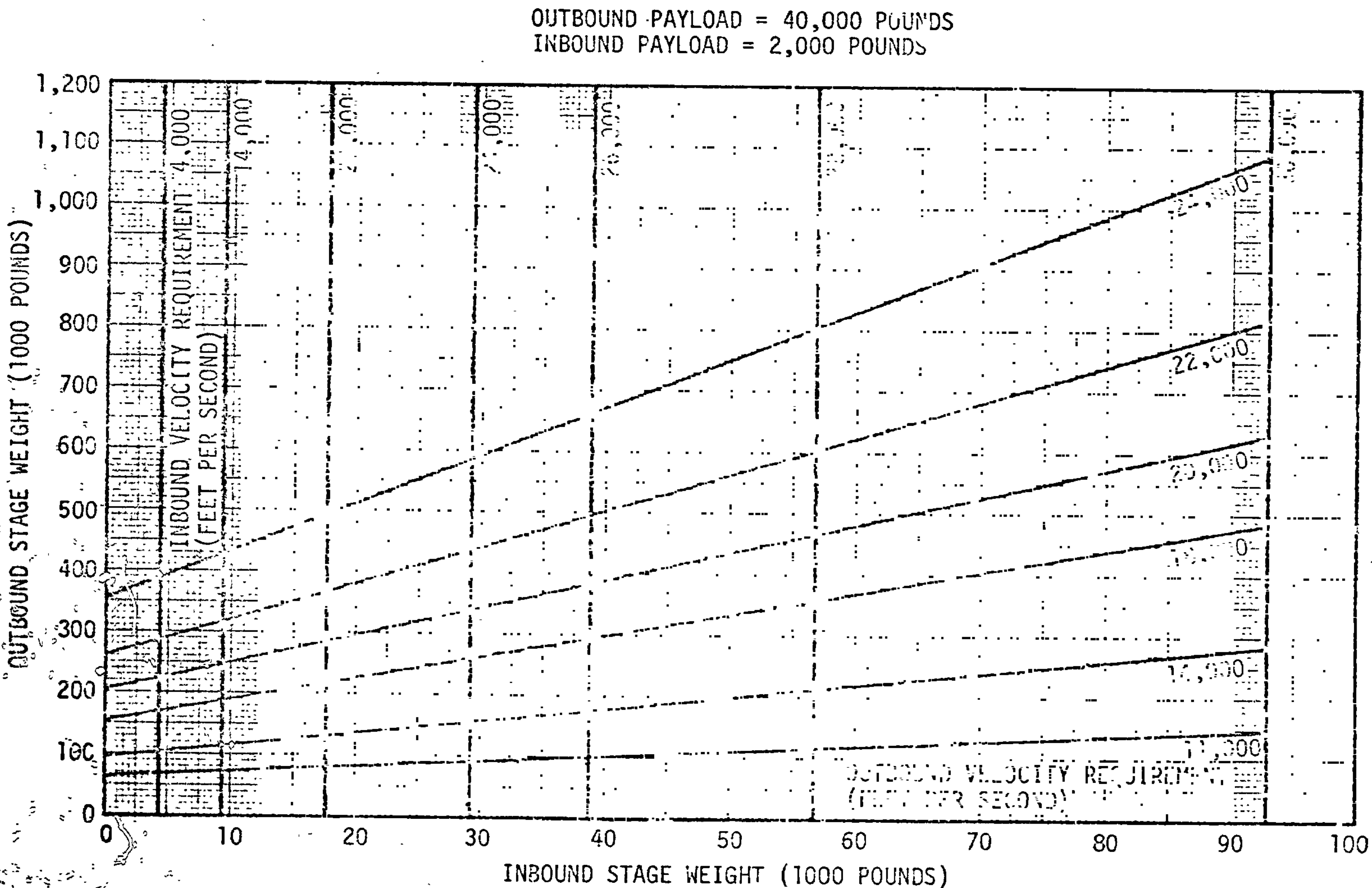


Figure 26. Outbound Stage Weight versus Inbound Stage Weight
(P_{OUT} = 40,000, P_{IN} = 2,000)

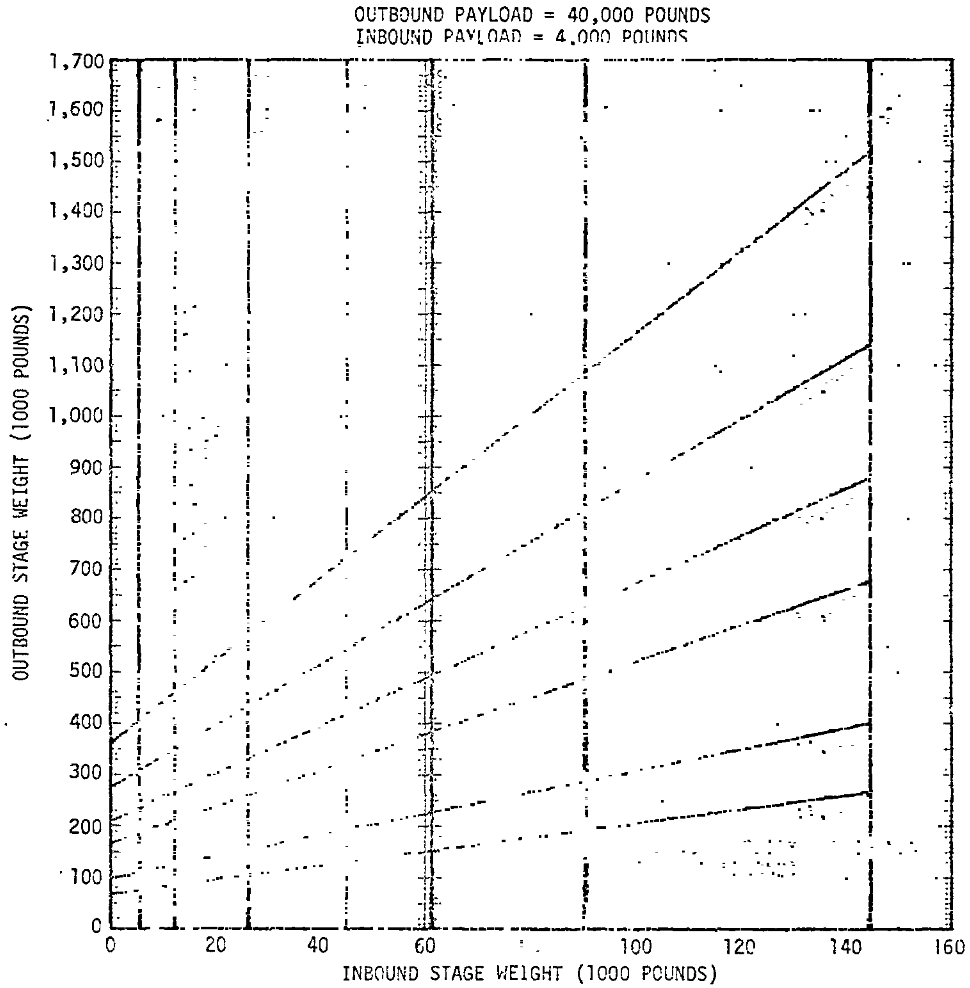


Figure 27. Outbound Stage Weight versus Inbound Stage Weight (P_{OUT} = 40,000, P_{IN} = 4,000)

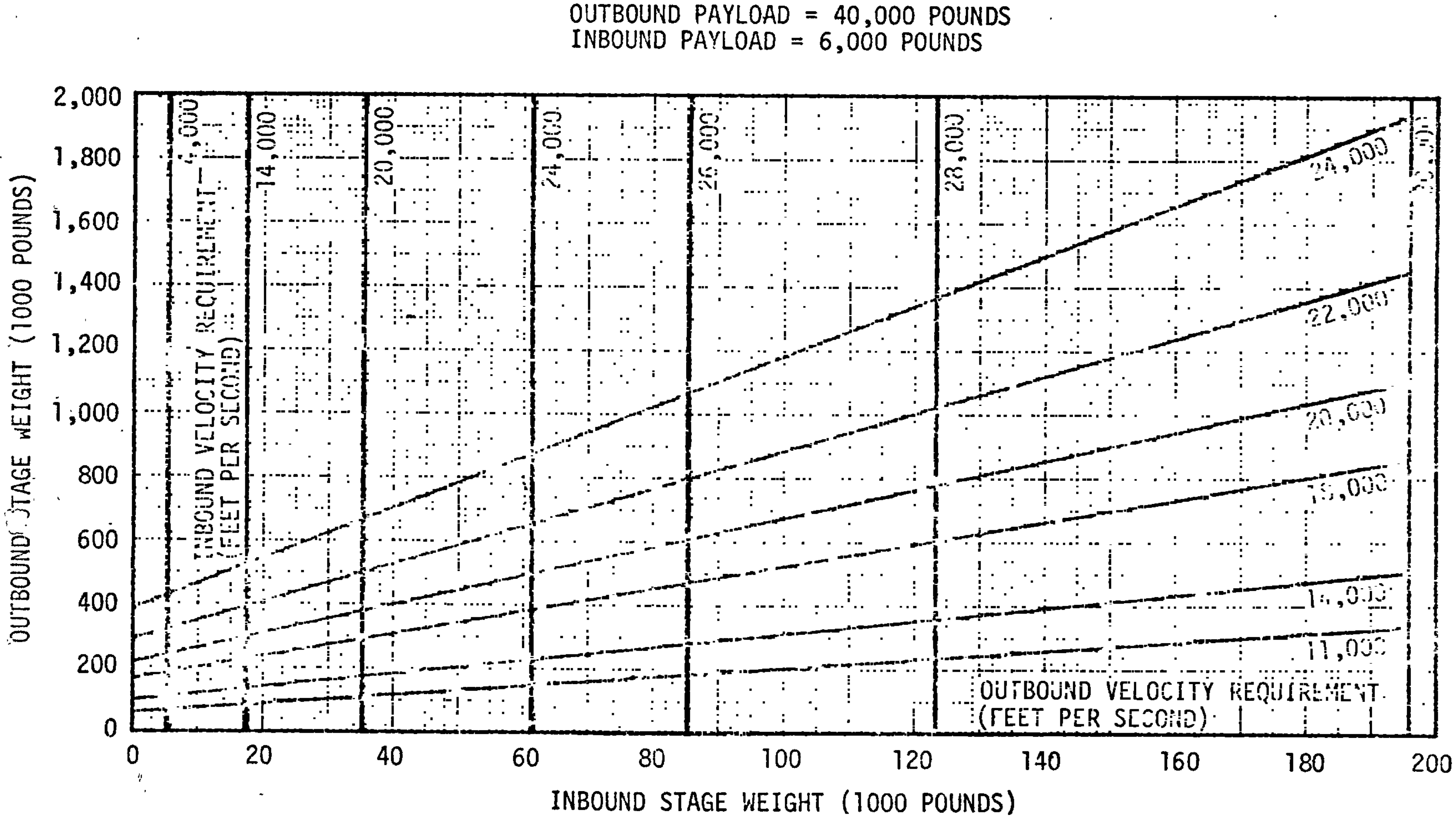


Figure 28. Outbound Stage Weight versus Inbound Stage Weight (P_{OUT} = 40,000, P_{IN} = 6,000)

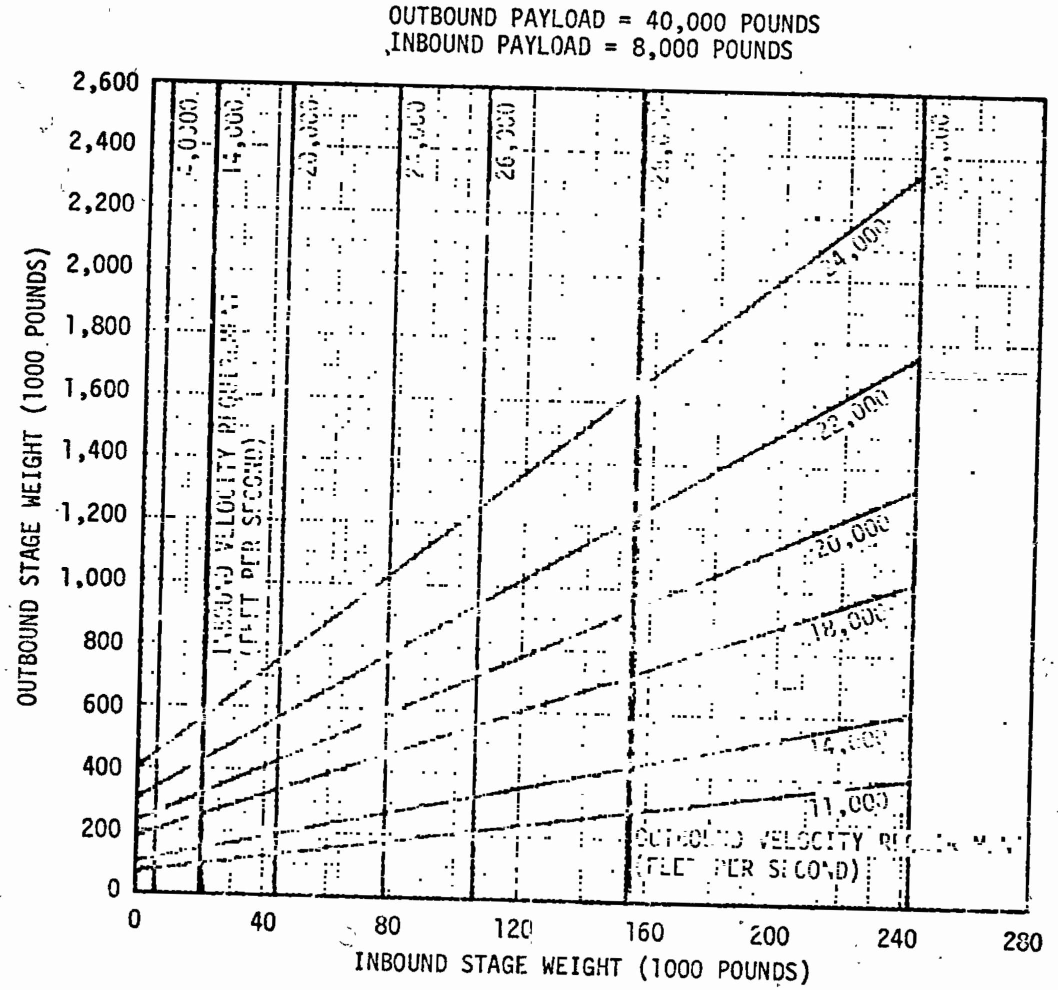


Figure 29. Outbound Stage Weight versus Inbound Stage Weight (P_{OUT} = 40,000, P_{IN} = 8,000)

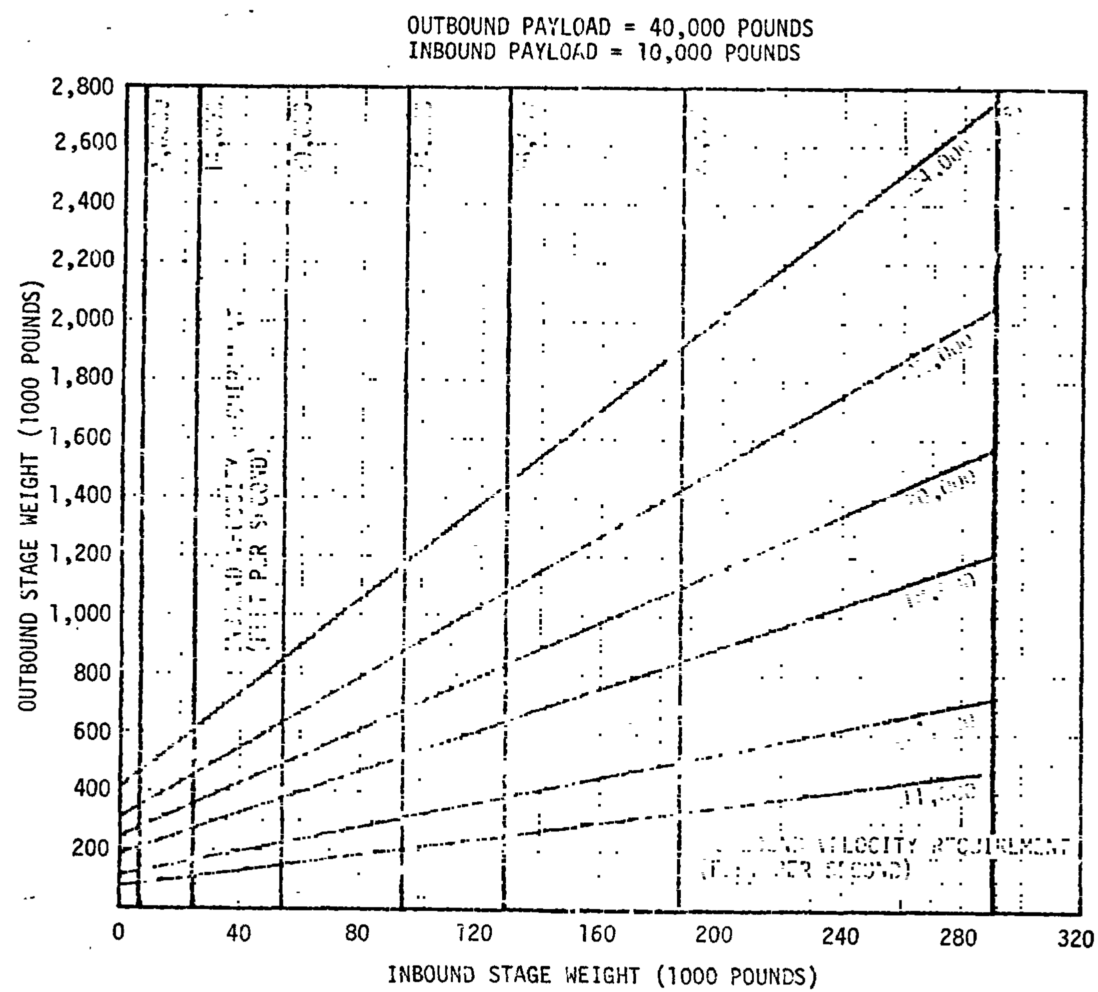


Figure 30. Outbound State Weight versus Inbound Stage Weight (P_{OUT} = 40,000, P_{IN} = 10,000)

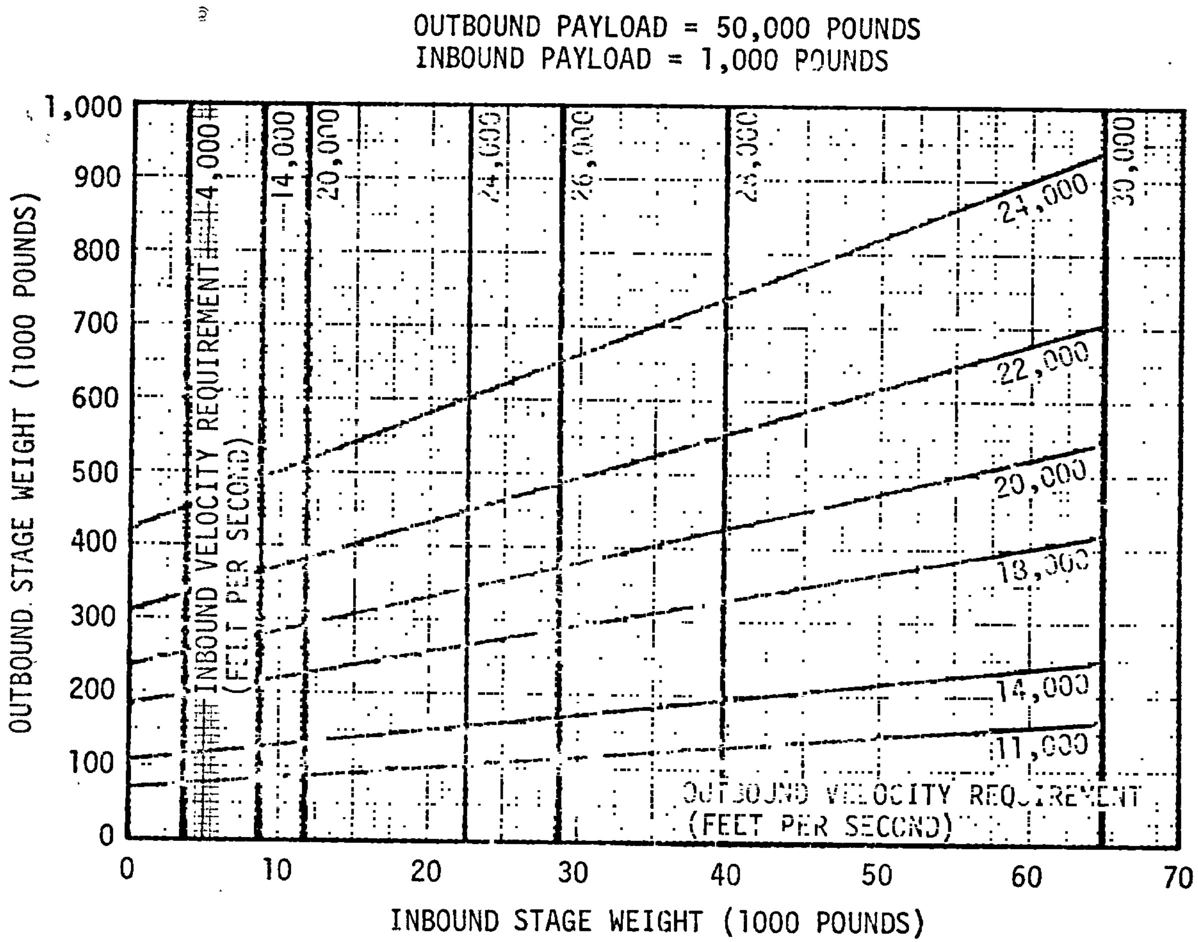


Figure 31. Outbound Stage Weight versus Inbound Stage Weight (P_{OUT} = 50,000, P_{IN} = 1,000)

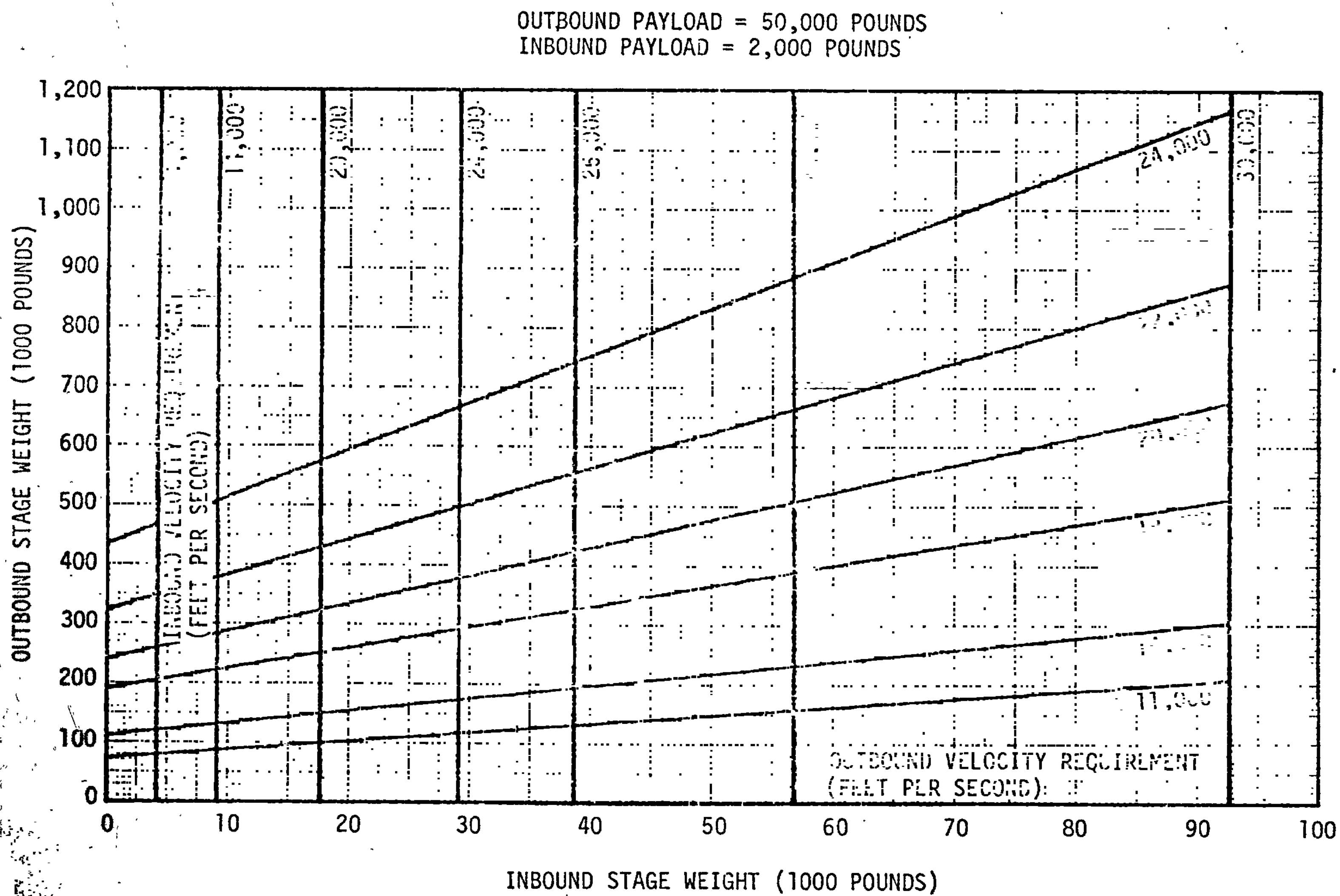


Figure 32. Outbound Stage Weight versus Inbound Stage Weight (P_{OUT} = 50,000, P_{IN} = 2,000)

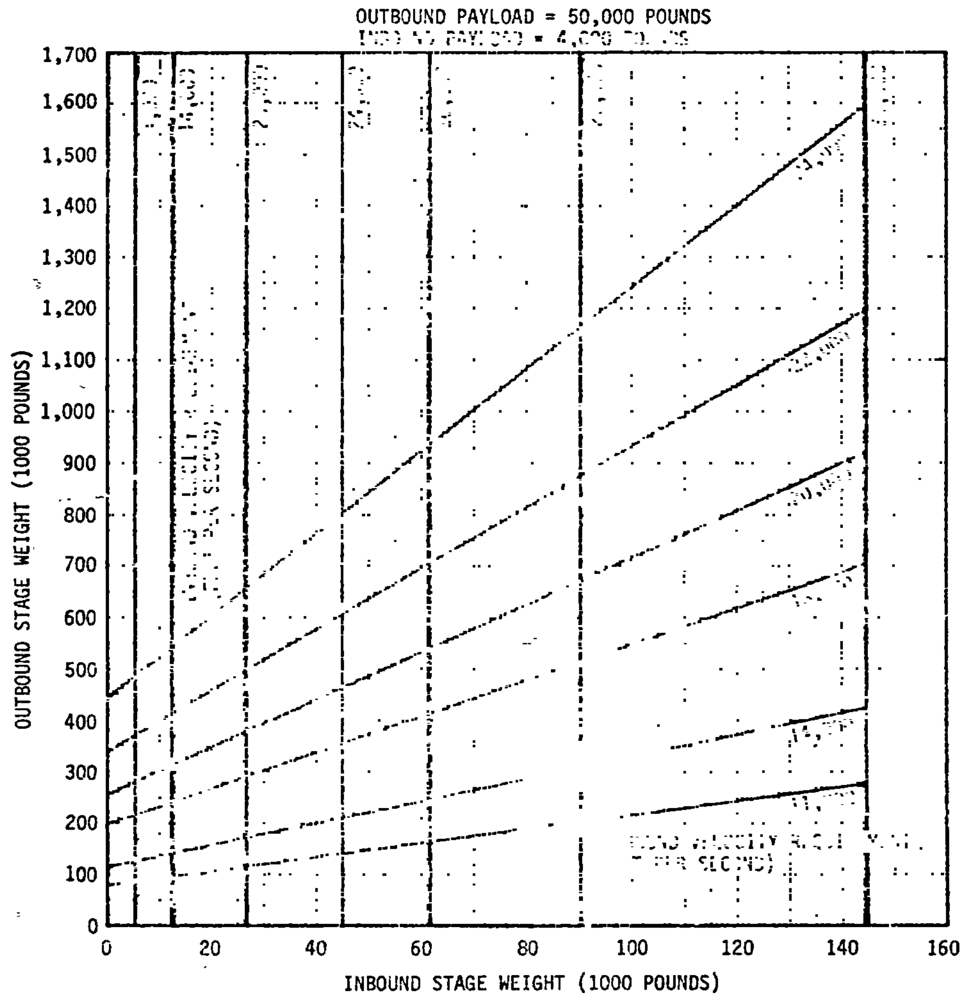


Figure 33. Outbound Stage Weight versus Inbound Stage Weight (P_{OUT} = 50,000, P_{IN} = 4,000)

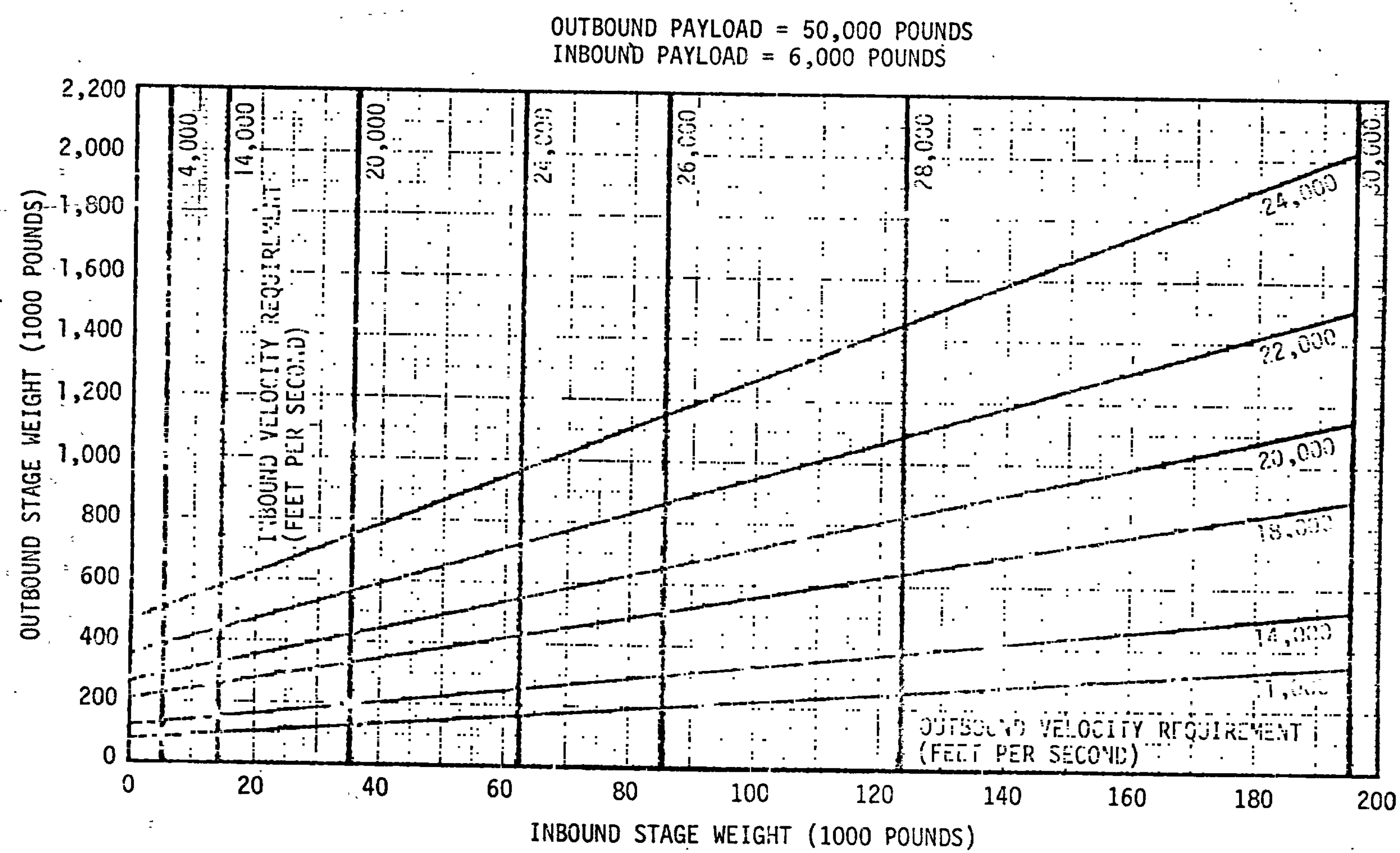


Figure 34. Outbound Stage Weight versus Inbound Stage Weight (P_{OUT} = 50,000, P_{IN} = 6,000)

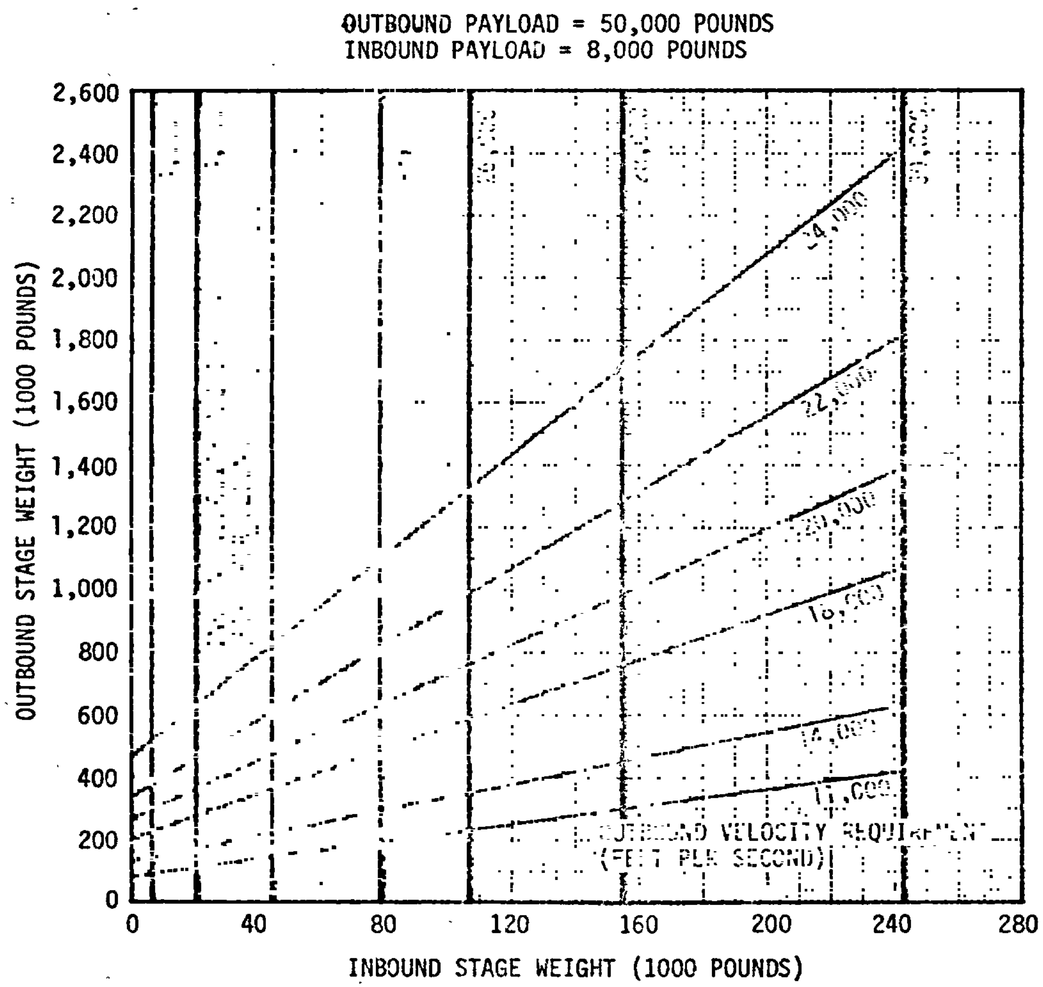


Figure 35. Outbound Stage Weight versus Inbound Stage Weight (P_{OUT} = 50,000, P_{IN} = 8,000)

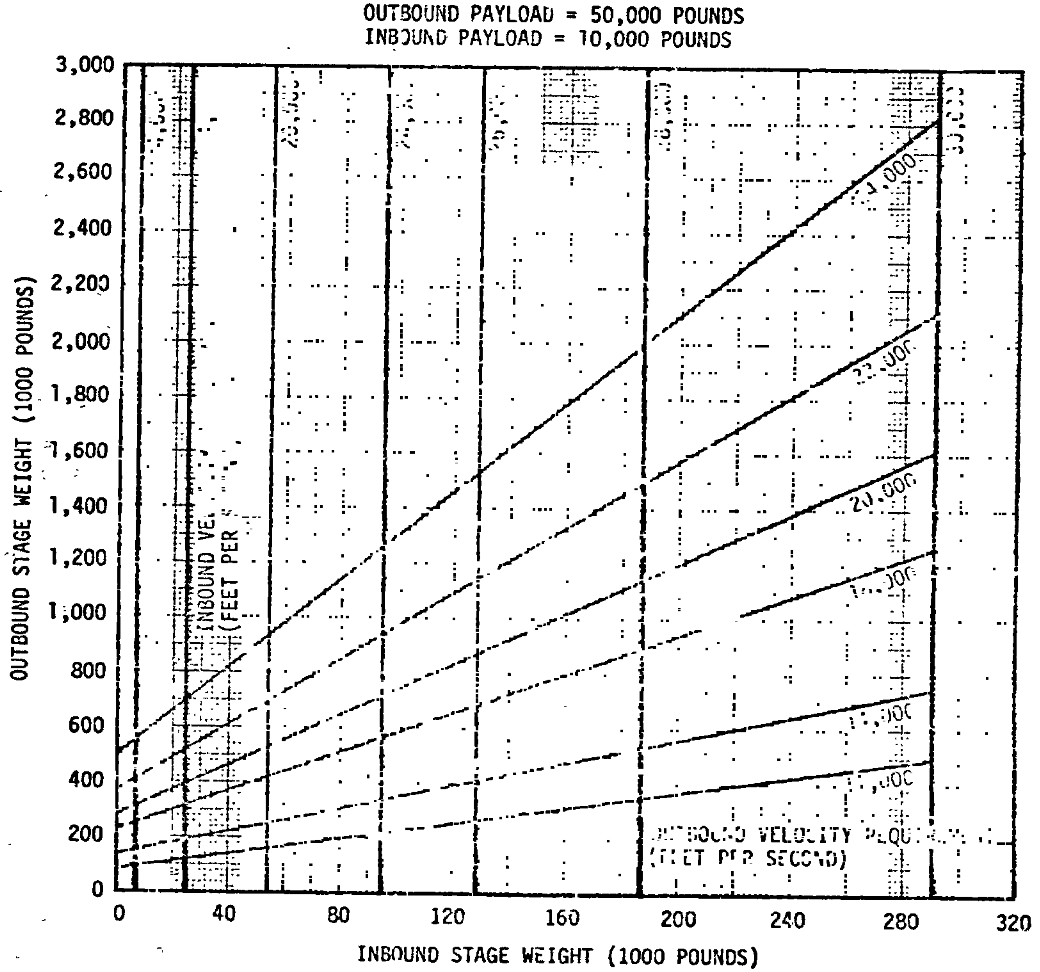


Figure 36. Outbound Stage Weight versus Inbound Stage Weight (P_{OUT} = 50,000, P_{IN} = 10,000)

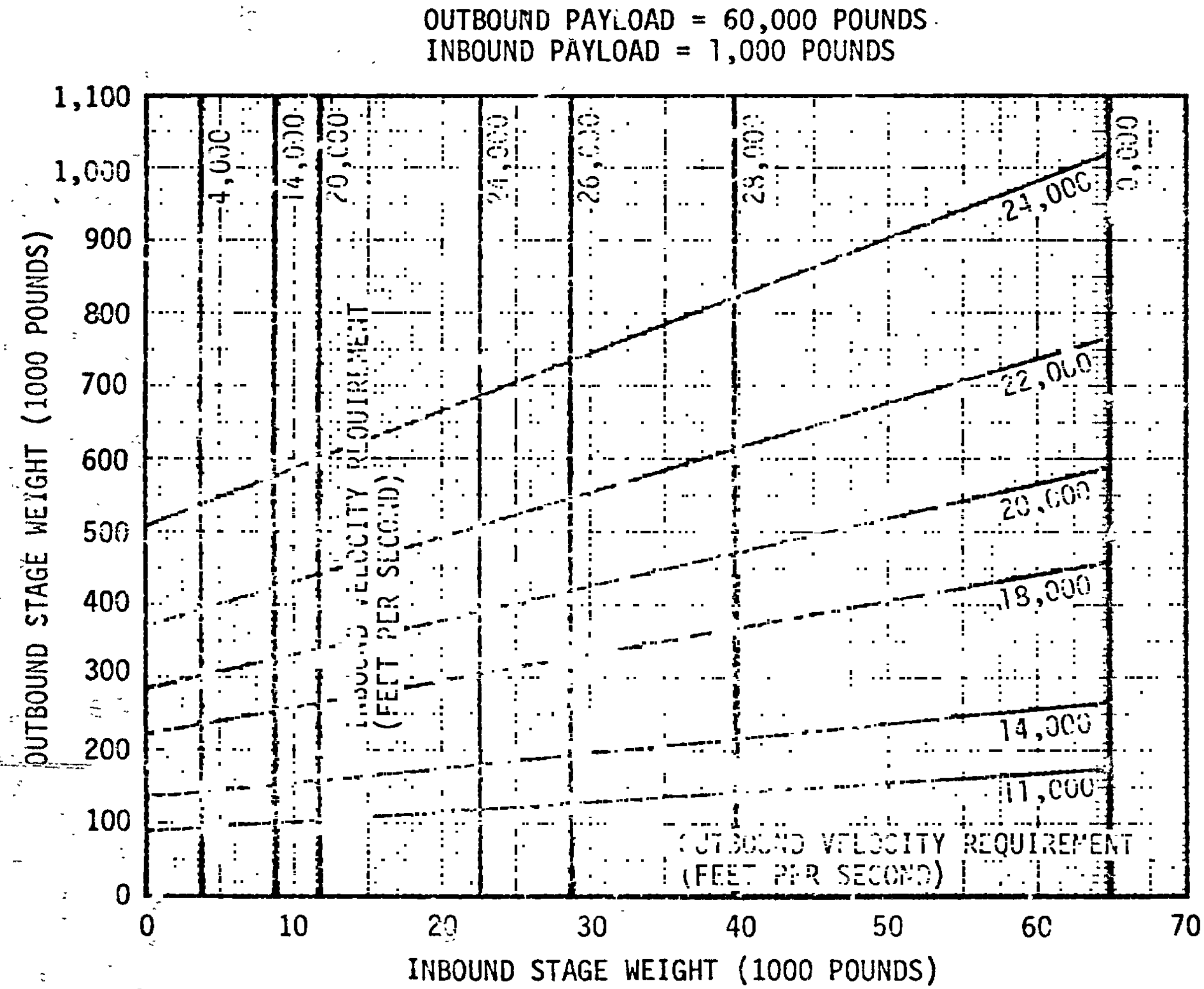


Figure 37. Outbound Stage Weight versus Inbound Stage Weight (P_{OUT} = 60,000, P_{IN} = 1,000)

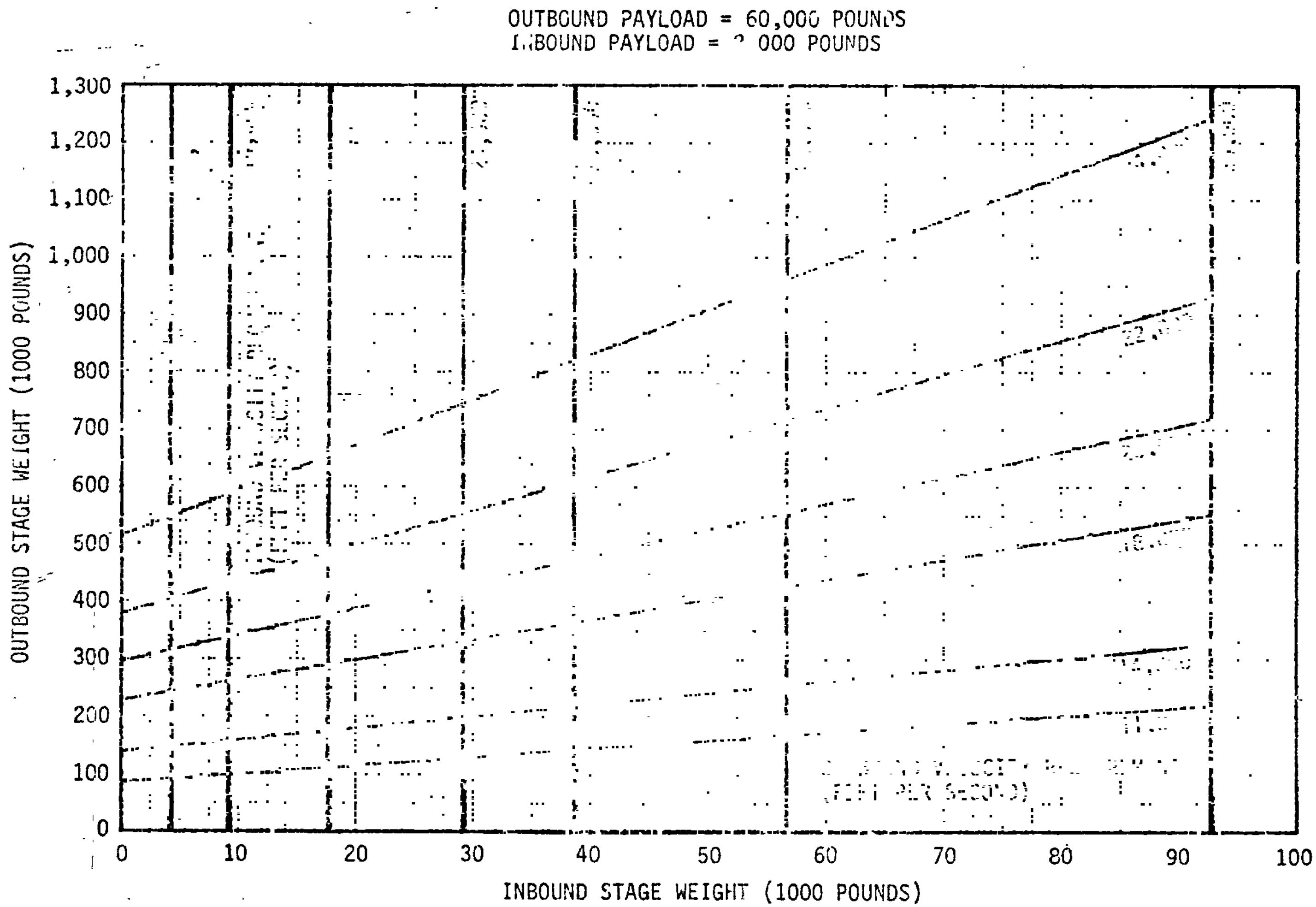


Figure 38. Outbound Stage Weight versus Inbound Stage Weight (P_{OUT} = 60,000, P_{IN} = 2,000)

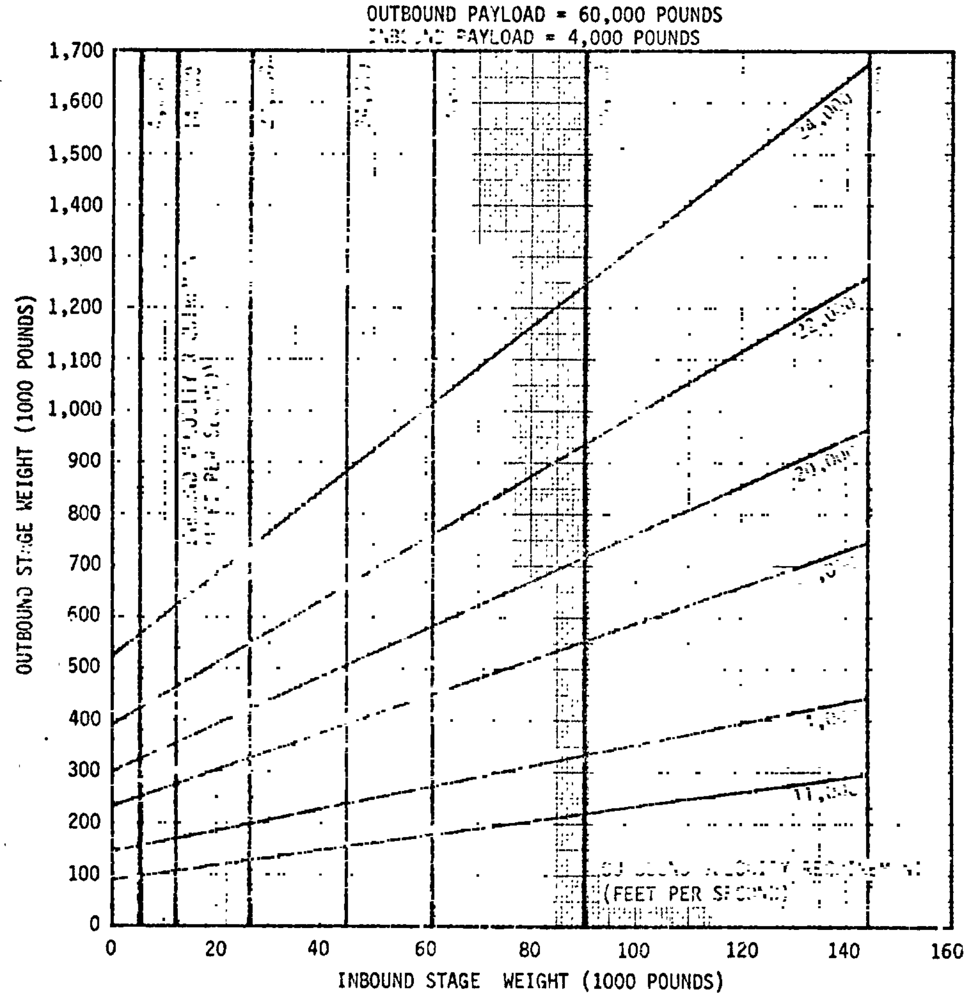


Figure 39. Outbound Stage Weight versus Inbound Stage Weight (P_{OUT} = 60,000, P_{IN} = 4,000)

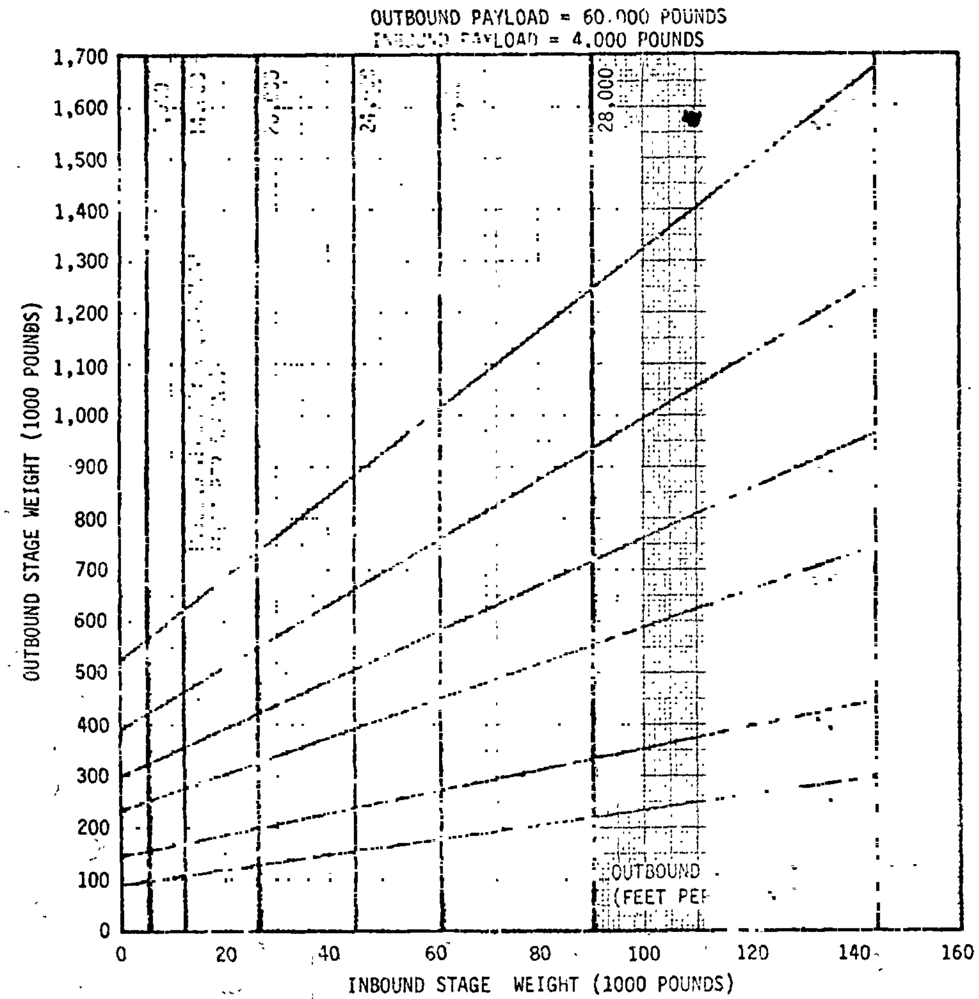


Figure 39. Outbound Stage Weight versus Inbound Stage Weight (P_{OUT} = 60,000, P_{IN} = 4,000)

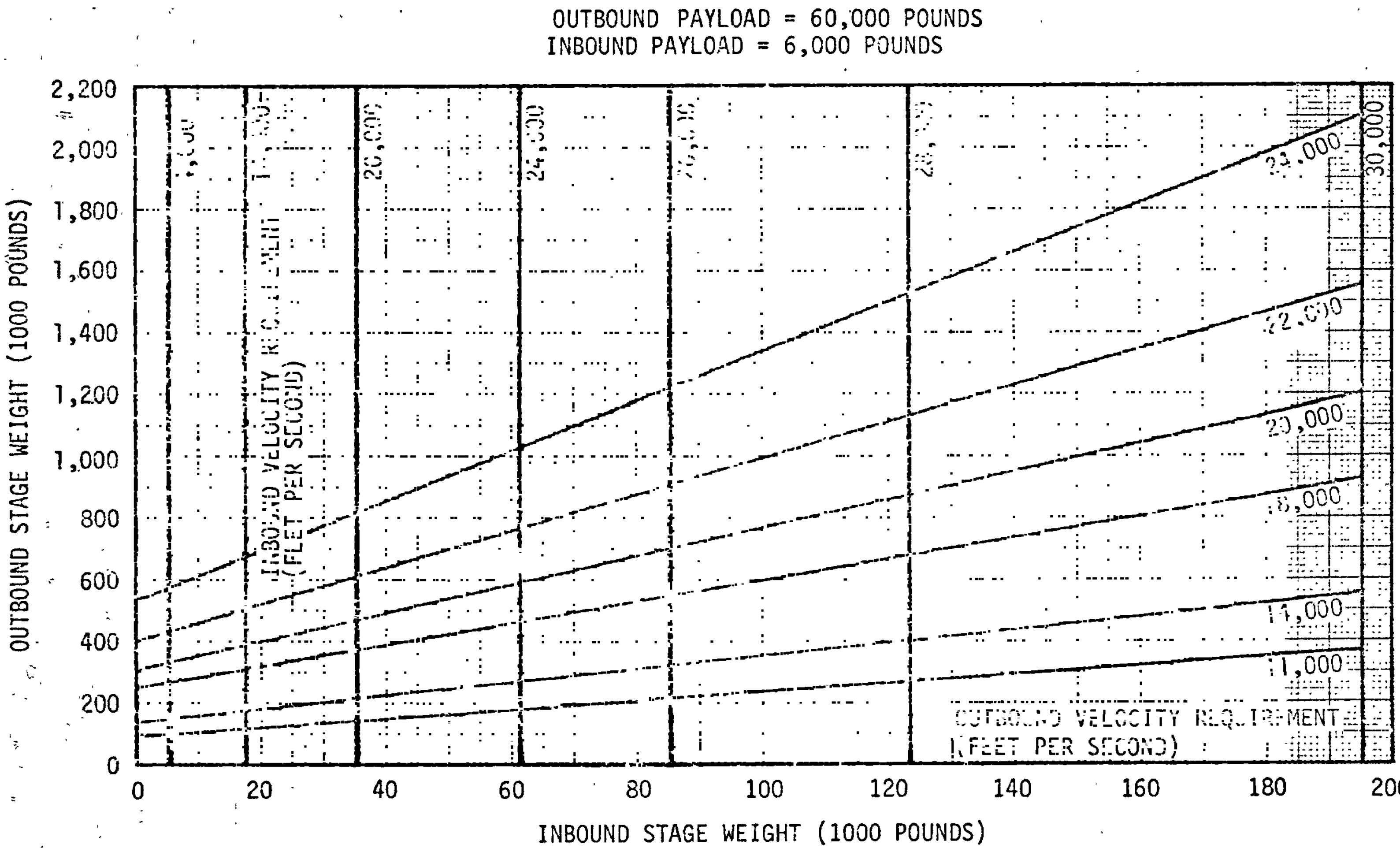


Figure 40. Outbound Stage Weight versus Inbound Stage Weight
(P_{OUT} = 60,000, P_{IN} = 6,000)

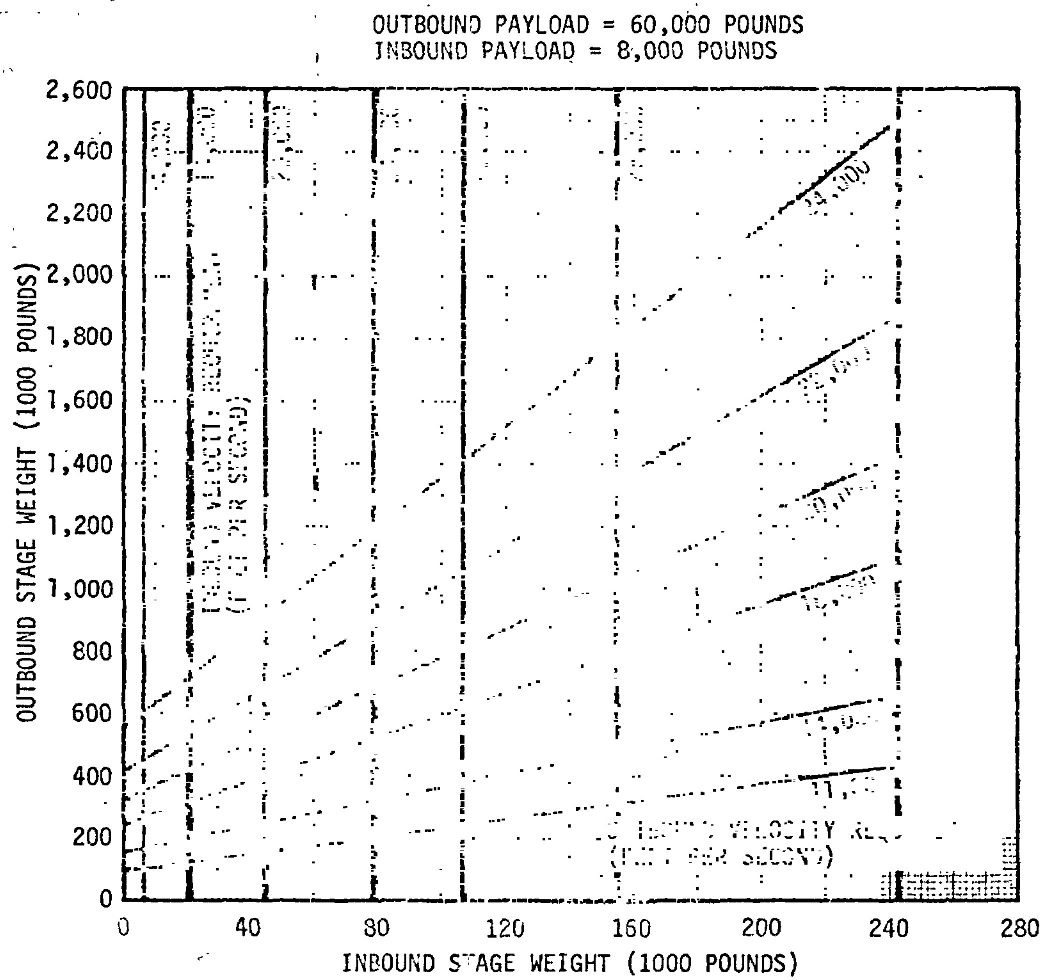


Figure 41. Outbound Stage Weight versus Inbound Stage Weight ($P_{OUT} = 60,000$, $P_{IN} = 8,000$)

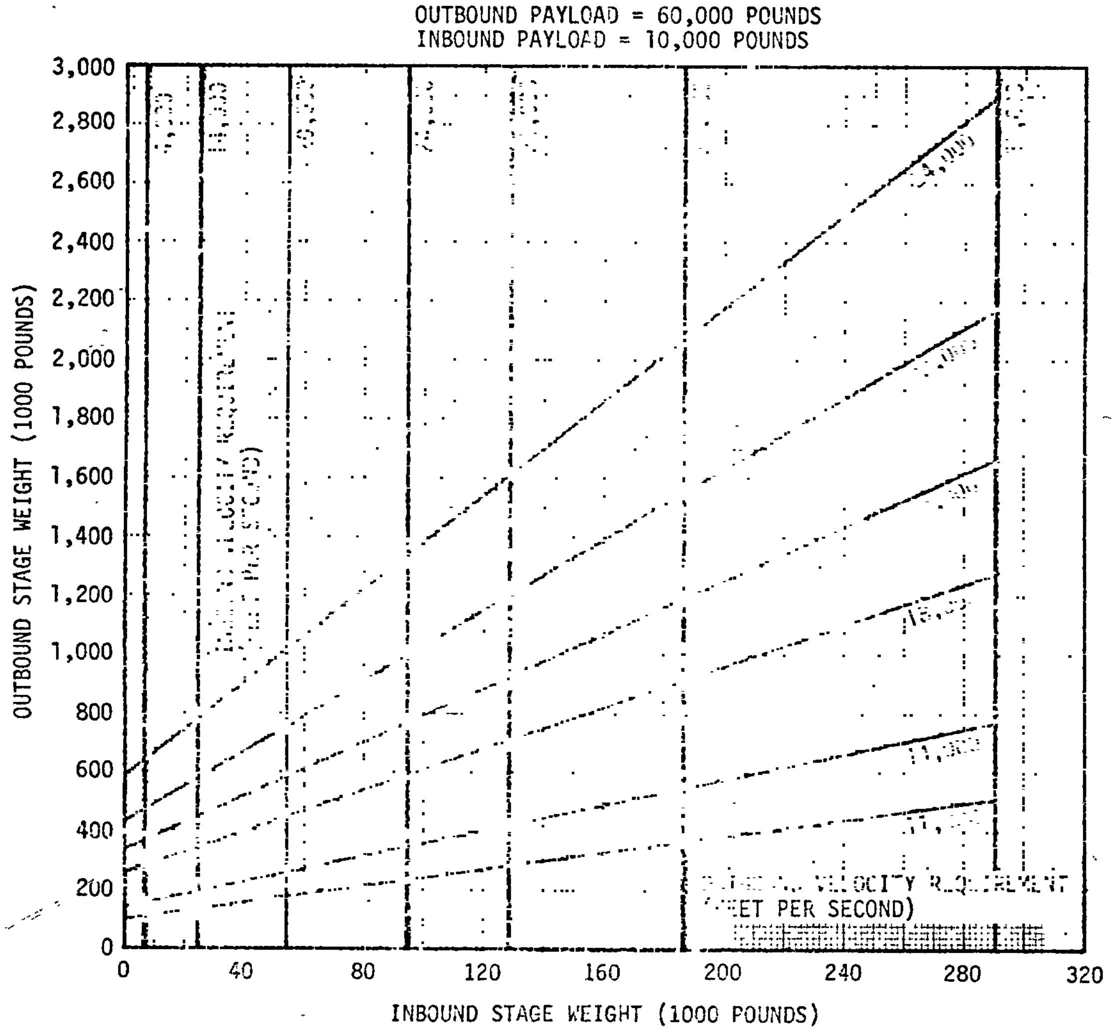


Figure 42. Outbound Stage Weight versus Inbound Stage Weight (P_{OUT} = 60,000, P_{IN} = 10,000)