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DESIGN CONSIDERATIONS FOR ATTAINING 200-KNOT TEST VELOCITIES AT THE AIRCRAFT LANDING LOADS AND TRACTION FACILITY

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SUMMARY

Early preliminary design studies are presented which consider the important parameters in providing 200 knot test velocities at the Landing Loads and Traction Facility. Two major components of this facility, the hydraulic jet catapult and the test carriage structure, are considered.

Suitable factors are determined to correlate analytical data for characteristics of the hydraulic jet catapult with data measured from the existing catapult system. The resulting equations are used to calculate test velocities for a range of jet nozzle diameters and carriage weights with both the current 122m (400 feet) and an increased 183m (600 foot) catapult stroke.

Using the catapult characteristics, a target design point is selected and a carriage structure is sized to meet the target point strength requirements. These preliminary design results indicate that to attain 200 knot test velocities a nozzle diameter of .356m (14 inches) is required with a carriage weight of approximately 39 000 kg (85 000 lbm). High strength steel having an allowable stress of 393 MPa (57 000 lbf/in^2) is needed for the structure to withstand the maximum acceleration of 13-14 g's.

Suggestions for additions and refinements to this preliminary study are given that would be needed in working toward a detailed, final carriage design.

INTRODUCTION

The Landing Loads and Traction Facility is the only facility in the world capable of testing full-size aircraft landing gear systems under closely controlled conditions which simulate the take-off and landing operations of an airplane. To accomplish a test, the landing gear specimen is attached to either one of the two carriages pictured in figure 1, the carriage is propelled down the track shown in figure 2 by means of a high-speed water jet catapult system, and the test is conducted as the carriage coasts through the 1200-foot test section which contains the prepared landing surface. The carriage is brought to a stop following the test by engaging steel cables which span the track and are interconnected to 20 aircraft carrier arresting gear engines. Reference 1 describes the facility in some detail.

It has become increasingly obvious in recent years that the current speed capability of the facility, 110 knots, is no longer adequate to study the ground operational problems associated with the higher landing and take-off speeds of modern and proposed aircraft designs. As a first step in an effort to upgrade the facility to meet current and projected aircraft landing gear research needs, a study was undertaken to examine the requirements of a catapult system and a carriage capable of providing test speeds to 200 knots. The purpose of this paper is to present the results of that study. The results include the rationale and assumptions employed in scaling up the existing catapult system and considerations for various jet sizes, carriage masses, and catapult strokes. The results also include carriage design requirements and a discussion of the process used to define the material sizes necessary to provide the needed structural strength. A description of the finite element analysis model is given in the Appendix. Finally, suggested refinements are presented which might contribute to a detailed design of an upgraded catapult/carriage system.

SYMBOLS

Values are given in both SI and U.S. Customary Units. The measurements and calculations were made in U.S. Customary Units. Factors relating the two systems are given in reference 2.

A	cross-sectional area of jet, m^2 (ft^2)
A_c	carriage frontal area, m^2 (ft^2)
a	carriage acceleration or deceleration, m/sec^2 (ft/sec^2)
C_D	aerodynamic drag coefficient
d	distance of carriage from nozzle, m (ft)
E	water jet/turning bucket efficiency
F_a	aerodynamic drag force on carriage, N (lbf)
F_c	force on carriage, N (lbf)
F_d	drag force on carriage due to air drag and rolling resistance, N (lbf)
F_x	force on water vessel foundation support in horizontal plane, N (lbf)
g	acceleration due to gravitation force, m/sec^2 (ft/sec^2)
m	carriage mass, kg (slug)
n	exponent for polytropic change in volume taken equal to 1.2 (pv^n = constant)
p_o	initial pressure of compressed air, N/m^2 (lb/ft^2)
t	time, sec
t_d	delay time for water leaving the nozzle at V_j to reach carriage, sec

V_c	carriage velocity, m/sec (ft/sec)
V_i	instantaneous jet velocity, m/sec (ft/sec)
V_j	instantaneous velocity of efflux, m/sec (ft/sec)
V_o	carriage velocity at beginning of each computation step, m/sec (ft/sec)
v	volume of compressed air, m^3 (ft^3)
v_o	initial volume of compressed air, m^3 (ft^3)
x	horizontal distance of jet from nozzle, m (ft)
y	height of water jet with respect to nozzle, m (ft)
α	angle of nozzle above horizontal plane, deg
β	angle through which water is turned, deg
Δd	distance carriage moves during each time increment, m (ft)
Δt	increment of time, sec
θ	angle through which jet is turned by bucket, deg
ρ	mass density of air, kg/m^3 ($slugs/ft^3$)
ρ_w	mass density of water, kg/m^3 ($slugs/ft^3$)

HYDRAULIC JET CATAPULT SYSTEM

The hydraulic catapult system currently in use is described in reference 3. Components of the system are identified in figure 2 and consist of storage tanks where air is pressurized to 20 MPa (2950 psi), an L-shaped vessel which is filled with 37.9 m^3 (10,000 gallons) of water prior to a test, and a timed, quick-acting valve at the front of the vessel. During catapult the water is pressurized with the air, and the valve is opened to release a high velocity jet of water through a .182 m (7.16 inch) diameter nozzle to impinge on a U-shaped "turning bucket" at the rear of the test carriage. This bucket turns the jet almost 180^o with the returning jet being issued just below the incoming stream. The force on the bucket resulting from this large rate of change of momentum in the jet is the force that accelerates the carriage to the desired velocity. The accelerating distance, or the maximum length of jet travel, is considered to be in the neighborhood of 122 meters (400 feet).

The approach taken to scale up the existing catapult system to provide a 200 knot capability was, first, to develop the equations necessary to match the acceleration pulse produced by the existing catapult system and then, using these equations, to calculate the acceleration pulse for other carriage masses, nozzle sizes, etc.

Development of Catapult Mathematical Model

A faired history of an acceleration pulse obtained during a recent catapult of the test carriage is identified as trace (1) in figure 3, which also includes other traces defined by mathematical expressions developed to describe this actual experimental pulse. For this pulse, the carriage mass was approximately 48 000 kg (106 000 lbm) and only two of the three available air storage tanks were employed providing a total air volume of 90.6 m^3 (3200 ft^3). Theoretical equations from reference 3 were used to attempt correlations with the experimental acceleration trace. The equation for instantaneous jet velocity of efflux in terms of the initial conditions and the instantaneous volume of air charge is:

$$V_j = \sqrt{\frac{2 \, p_o \, v_o^n}{\rho_w v^n}} \qquad (1)$$

This equation does not include the pressure due to the head of water in the vertical portion of the "L" vessel nor the atmospheric pressure term in the more basic pressure equation since these terms are quite small relative to the 20 MPa (2950 psi) initial pressure in the storage tanks.

The jet velocity was computed for the initial conditions and was applied to the following equation

$$v = v_o + V_j A \, \Delta t \qquad (2)$$

which was used to determine the change in air volume during the time period Δt due to the volume of water expelled. In equation (2) the area A was held constant which assumes an instantaneous valve opening. The new air volume v at the end of each time step Δt was then substituted back into equation (1) and this step-by-step computation was continued for a total time of 3 seconds and the resulting water jet velocity was plotted in figure 4 for a Δt of 0.1 sec and a nozzle area of .026 m^2 (.2796 ft^2).

The following third order polynominal was derived for the jet velocity curve of figure 4 using a least squares fit of the data:

$$V_j \text{ (m/sec)} = 201.80601 - 6.8662 + .32784t^2$$

$$V_j \text{ (ft/sec)} = 662.0932 - 22.5269t + 1.0756t^2 \quad (3)$$

This equation was used later in the computation to determine the velocity of the water hitting the turning bucket of the carriage as it moved away from the jet nozzle.

Another equation from reference 1:

$$F_c = \rho_w A (V_i - V_c)^2 (1 - \cos \theta) \quad (4)$$

was used to compute the theoretical instantaneous force accelerating the carriage, where V_i is the velocity of the water stream at the instant of impact upon the bucket. The turning angle of the bucket θ was measured to be 177^o and was assumed to be constant. If the force is known, the acceleration can be determined at any instant by

$$F_c = m\ a \quad (5)$$

The carriage velocity V_c due to the instantaneous acceleration was also computed using

$$V_c = V_o + a\ \Delta t \quad (6)$$

where V_o is considered to be the carriage velocity at the end of the previous time step. Carriage position was computed by summing Δd from

$$\Delta d = \frac{V_o + V_c}{2} \Delta t \quad (7)$$

Time was also summed and V_i was determined from $V_i = V_j$ at $t - t_d$ where t_d (the delay time for water leaving the nozzle at V_j to reach the carriage bucket) was approximated by

$$t_d = \frac{d}{V_j} \quad (8)$$

V_i was computed from

$$V_i \text{ (m/sec)} = 201.80601 - 6.8662 (t - t_d) + .32784 (t - t_d)^2$$
$$V_i \text{ (ft/sec)} = 662.0932 - 22.5269 (t - t_d) + 1.0756 (t - t_d)^2 \quad (9)$$

All of these values were computed in a step-by-step iteration and the resulting theoretical carriage acceleration time history for the existing catapult system is plotted as the number (2) trace in figure 3.

Aerodynamics and rolling friction.- The effects on the acceleration pulse attributed to aerodynamic drag and rolling friction were next applied to the theoretical equations.

The drag force on the carriage was calculated from the speed decay of the carriage using

$$F_d = m\,a \tag{10}$$

where F_d was considered to be the total drag force on a free-rolling carriage and composed of rolling friction, estimated to be a constant 900 N (200 lbf), and aerodynamic drag which was obtained from the following equation

$$F_a = C_D \frac{\rho}{2} A_c V_c^2 \tag{11}$$

In equation (11) carriage frontal area A_c was estimated to be 42 m^2 (450 ft^2) as determined from a front view drawing of the carriage. Equations (10) and (11) were solved in a step-by-step iteration for several assumed drag coefficients C_D until agreement was obtained with data from several experimental test runs of the existing carriage velocity decay over a 305 m (1000 ft) distance. It was found that a C_D of .9 gave good agreement with experimental carriage velocity decay.

Carriage acceleration during the catapult stroke was then recalculated incorporating the effects of air drag and rolling friction and the result is plotted as shown by the number (3) trace in figure 3.

Valve opening effect.- It was readily apparent that to obtain good agreement with the experimental data, the math model would have to be modified to include the effect of the valve opening transient. To this end, a linear force ramp expressed by

$$F_c\ (N) = 6{,}101{,}327\ t$$

$$F_c\ (lbf) = 1{,}371{,}633\ t \tag{12}$$

was used to approximate the force change during valve opening over the time period between t = 0 and t = 0.23 sec. Using this valve opening force ramp the carriage acceleration was recomputed and is shown by the number (4) trace in figure 3.

Effect of water jet/turning bucket efficiency.- It was assumed that trace (4) of figure 3 was the best theoretical representation of the acceleration time history with all major force variables considered. The failure of this trace to agree with the experimental acceleration pulse was attributed to inefficiencies both in the water jet, due to jet dispersion, and in the turning bucket since all of the water was not turned through 177^o. Several efficiency curves were tried before arriving at the one presented in figure 5 which, when applied to the math model for trace (4), provided good agreement between the mathematical and experimental acceleration pulses (compare traces (1) and (5) in figure 3). The equation for the efficiency curve presented in figure 5 as a function of catapult distance is

$$E = .718539 + 4.48337 \times 10^{-3}\, d - 1.36344 \times 10^{-4}\, d^2 + 1.34365 \times 10^{-6}\, d^3 - 6.35038 \times 10^{-9}\, d^4$$ where distance d is in meters

$$E = .718539 + 1.36653 \times 10^{-3}\, d - 1.26668 \times 10^{-5}\, d^2 + 3.8048 \times 10^{-8}\, d^3 - 5.481 \times 10^{-11}\, d^4$$ where distance (d) is in feet (13)

Increased Velocity System

Key to the application of the catapult mathematical model to describe a system which would provide increased carriage test speeds is a knowledge of the maximum available water jet velocity. This velocity was computed as a function of time using equations (1) and (2) and assuming an initial air volume of 136 m^3 (4800 ft^3), as provided by the three existing air bottles, and an initial air pressure of 22 MPa (3200 psi). Figure 6 presents the results of these computations for various nozzle sizes estimated to cover the range needed for carriage operations at speeds to 200 knots. The valve opening for this exercise was considered a step function. The figure shows a decay in jet velocity with time due to the reduction in the air pressure as the air expands to fill the void created by the discharged water. For example, the jet velocity from the .36m (14 in.) diameter nozzle decreases from 210 m/sec (690 ft/sec) to 170 m/sec (560 ft/sec) in three seconds.

Carriage acceleration time histories.- Using the catapult mathematical model, acceleration time histories were computed for carriages of various mass as they were propelled by water issued from five different jet nozzles. For these calculations the aerodynamic drag coefficient, frontal area (A_c) and rolling friction characteristics of the carriages were assumed to be identical to those of the existing carriage. It was also assumed that the jet valve would open in 0.23 seconds to correspond with existing experimental data (see figure 3) and that the force on the carriage during that period would increase linearly to a maximum value. Two generalized conditions were considered. In one condition the catapult stroke was held to 122 m (400 ft), which is the stroking distance of the existing system, and in the other the stroke was extended to 183 m (600 ft). The results from both sets of calculations are discussed separately in the paragraphs which follow.

Catapult stroke = 122 m (400 ft): The computed acceleration time histories for this condition are presented in figure 7. The assumption was made in these computations that the efficiency of a larger diameter jet and a correspondingly larger turning bucket would be identical to that estimated for the existing configuration and presented in figure 5. It was further assumed that the jet angle with respect to the horizontal would remain at the existing 0.9°. Identified on figure 7 are the carriage speeds at the end of the 122 m (400 ft) stroke. Note that for the carriage masses considered, speeds in the 200 knot range are not realized at small nozzle diameters nor with the heavier carriages. Unfortunately, the larger the nozzle, the greater the maximum acceleration experienced by the test carriage.

Catapult stroke = 183 m (600 ft): This condition was considered because increasing the catapult stroke is one method for reducing the maximum carriage accelerations. For the purposes of these calculations a new jet/bucket efficiency curve was estimated by extending the curve of figure 5 over a 183 m (600 ft) distance as shown in figure 8. It is recognized that this estimation is no doubt in some error but no other data are available to describe the efficiency of such a system. The acceleration-time histories for the six carriage masses being examined over this extended catapult stroke are presented in figure 9. Again, the carriage speed at the end of the stroke is identified on the figure. As expected, these speeds are higher than those generated over the shorter stroke for the same carriage mass and jet nozzle size.

To aid in the design of new carriage structures, the maximum acceleration data from figures 7 and 9 are replotted in figure 10 to show more clearly the effect of carriage mass and test velocity on the maximum force exerted on the carriage during catapult.

Other system features.- The purpose of this section is to comment on the influence that increasing the carriage test velocity would have on water consumption, turning bucket design and the water vessel foundation load.

Water consumption: To obtain some idea of the quantity of water needed to conduct high speed carriage tests, a computation was performed using the jet velocity equations (1) and (2). The results of that computation are presented in figure 11 which is a time history of the volume of water expelled from five nozzle sizes. As in all computations, the water is considered to be pressurized initially to 22 MPa (3200 psi) by air in the three available storage bottles. Knowing the duration of the acceleration pulse, the time of jet cutoff necessary to produce a given carriage velocity at the end of the catapult stroke was computed by a trial and error method with the aid of figure 6. With this information, the volume of water consumed was readily calculated for certain test conditions. Two potential 200-knot conditions were examined and their results identified on figure 11. For a 122 m (400 ft) catapult stroke with a 0.36 m (14 in.) diameter nozzle, it is estimated that 23.85 m^3 (6300 gal) of water would be consumed. To obtain a carriage speed of approximately 200 knots with a 600-foot catapult stroke requires only a 0.28 m (11 in.) diameter nozzle and the water consumed for that condition was estimated at 22.33 m^3 (5900 gal). Also identified on the figure is the water consumption for a 109 knot test of the present carriage (48 100 kg (106 000 lbm)) with the existing catapult system.

Turning bucket design: The height y of the jet stream at any horizontal distance x from the nozzle during the catapult stroke can be computed from the expression

$$y = x \sin \alpha - \frac{g}{2}\left(\frac{x}{V_j}\right)^2 \qquad (14)$$

Where α is the angle of the nozzle (initial jet angle) above the horizontal (0.9° in the case of the existing configuration). Using this expression and assuming no effect of wind or air drag, the angle of the water jet relative to the horizontal and the position of the jet with respect to the existing carriage bucket design were computed at the start of the catapult, at the time of maximum jet trajectory, and at the end of the catapult stroke. Figure 12 graphically illustrates these angles and positions for three catapult conditions. Shown in figure 12(a) are those for the existing catapult with two air bottles pressurized to 20 MPa (2950 psi) and a nozzle diameter of 0.182 m (7.16 in.). Note that at the end of the 122 m (400 ft) stroke the angle of the jet is - 1.05°. Figure 12(b) describes the jet positions for the following condition: 0.36 m (14 in.) diameter nozzle, 122 m (400 ft) catapult stroke and three air bottles pressurized to 22 MPa (3200 psi) a combination which has been shown to theoretically propel a 38 600 kg (85 000 lbm) carriage to a speed of approximately 200 knots. The figure shows that at the maximum jet height, where the trajectory angle is zero, the jet would rise above the existing bucket and a larger bucket opening would be needed to accept the enlarged jet. Figure 12(c) describes the jet position for the other 200 knot example wherein the catapult stroke was extended to 183 m (600 ft) and the nozzle diameter was enlarged to only 0.28 m (11 in.). For this condition it was necessary to tilt the nozzle from the current 0.9° to 1.345° to keep the water jet from dropping below the lower edge of the existing bucket at the end of the longer stroke. The assumption is made here that the current bucket cannot be lowered due to potential test surface clearance problems. The figure shows that at its maximum height, the jet would clearly miss the existing bucket and to accommodate such a condition would require a bucket design with a vertical opening approximately twice as large as the existing bucket.

Foundation load: The horizontal load F_x on the water vessel foundation was computed from the expression

$$F_x = \rho_w A \ V_j^2 \cos \beta \tag{15}$$

where β, the angle of the water jet with respect to the horizontal, was assumed to be zero. Applying this expression to the two nozzles considered in the previous examples, the maximum horizontal foundation loads are 4370 kN (983 000 lbf) and 2700 kN (607 000 lbf) for the 0.36 m (14 in.) and 0.28 m (11 in.) diameter nozzles, respectively. The maximum foundation load produced by the current nozzle is 1060 kN (238 000 lbf).

These features and other pertinent characteristics of the existing catapult system and the two 200 knot example systems are summarized in Table 1.

TEST CARRIAGE STRUCTURE

A study was undertaken to arrive at a structural configuration for a new test carriage of minimum weight capable of meeting desired performance requirements. The design variables which were considered for such a configuration were the general layout or topology of the structure, types of material, and the sizes of each structural member. Several structural configurations were considered. The initial configurations resembled the existing large carriage which, although unacceptable, provided useful information to guide the design of subsequent configurations which showed promise of meeting the specified requirements. The purpose of this section of the paper is to review the carriage requirements and to discuss in some detail the results of the configuration study. It should be pointed out that the design effort described herein consisted of sizing carriage structural members to provide adequate strength during all anticipated test operations. Hence, the results presented should be considered as preliminary design information to guide further work needed to arrive at a final design.

Carriage Requirements

Listed below are the basic carriage design requirements. The first two are constraints imposed to assure that the new system will be compatible with the existing facility. The remainder describe desired performance characteristics.

1. The overall dimensions of the new carriage must comply with the following:

Length - up to 21.8 meters (71.7 feet)
Height - up to 9.1 meters (30 feet) (could go higher if needed)
Width - 9.1 meters (30 feet) between centers of two rails (can overhang rails if needed)

2. The vertical and horizontal location and general arrangement of the bucket at the rear of the carriage which is impinged by the hydraulic jet must be approximately the same as on existing carriages. This specification is necessary so that both the new and existing carriages can operate with the same catapult system.

3. The principal performance requirement is that of high speed. The desired speed is specified for two different test article masses.

200 knots with 9072 kg (20 000 lbm) test article
170 knots with 22 680 kg (50 000 lbm) test article

4. The carriage must have a large open test bay to accommodate large test articles. Desired dimensions of this bay are a width of 8.5 meters (28 feet) and length of 12.2 meters (40 feet). This bay could accommodate bulky conventional landing gear on a vertical rail system and also have a single support point in the center for attaching large test articles such as an air cushion landing gear.

5. An implied requirement is that the carriage have a low structural mass to meet the performance given in item 3 above. It was initially estimated that the desired speed performance could be achieved with a total carriage mass (excluding test article) of 29 483 kg (65 000 lbm). The catapult analysis described in the previous section indicated that the high speed performance could be achieved at this mass with reasonable values of propulsion system parameters, such as the nozzle diameter. The subsequent

objective in the design process was to generate a structural configuration whose mass could be held to this 29 483 kg (65 000 lbm) target.

6. The carriage must withstand the inertia loading during catapult and arrestment and:

(a) Applied model forces of up to 222.4 kN (50 000 lbm) each in the vertical drag, and lateral directions during test.

(b) A 66.7 kN (15 000 lbm) side preload on each set of wheels to follow rail deviations as the carriage travels along the track.

No upper limit was specified for the g loading during catapult of the carriage, however this value should be kept as low as possible to minimize possible adverse effects to onboard instrumentation and equipment. Other design specifications were identified but they related to such things as hydraulic systems and roll-back brake systems and were not directly relevant to the design of the basic carriage structure.

The above specifications allow considerable freedom for the design variables in the general layout or topology of the carriage structure, as well as for selection of the types of material and sizes of the structural members. Five different structural configurations were analyzed and all five were of welded tubular steel frame construction. These configurations are described in detail in the following two sections: the first section discusses the results from the preliminary configuration studies and the second discusses a candidate carriage structural configuration which emanated from the earlier studies.

Preliminary Configurations

The first three configurations analyzed had a high test bay surrounded by structural members with vertical side rails to guide the drop of the test article and a separately located low test bay. The first configuration considered, shown in figure 13(a), had the high bay located near the rear of the carriage where the thrust force would enter the carriage. The low test bay was located ahead of the high bay and was spanned by overhead structural members. This configuration resulted in a center of gravity location a substantial height (approximately 4.6 meters (15 ft)) above the top of the track rail. Since the height of the bucket at the rear of the carriage where the catapult thrust force enters the structure was fixed at approximately 1.2 meters (4 ft) above the rail, this large separation of thrust force and carriage center of gravity produced a sizable moment which would cause the front of the carriage to lift from the rails during catapult. The prevention or alleviation of this lift-off problem during catapult became a major consideration in the carriage design.

The carriage center of gravity was moved forward in the second and third configurations by locating the high bay at the front of the carriage as shown in figures 13(b) and 13(c). The third configuration evolved from the second wherein the structure over the low bay was removed. The arrangement of the high test bay of this third configuration was then modified to serve as a high "back-stop" structure shown in figure 13(d). In this fourth configuration, conventional landing gear units would be attached to a fixture which is dropped into the open bay area during test. This fixture would be guided by rails attached to the rear of the back-stop structure. The large open bay of this layout could accommodate large bulky gear configurations. Further, a cantilever boom arrangement could be readily attached to the back-stop and extended to the center of the bay to provide an attachment point for testing of large single or multi-gear landing systems.

The large mass of the test article support structure and the test articles would be located near the front of the carriage in the fourth configuration. This arrangement would alleviate the moment which tended to lift the carriage during catapult, however, it would not altogether eliminate it. Thus, it would be necessary to provide a set of hold-down rails in the catapult section of the track and attach additional wheels to the front carriage frame to react to this moment. In this fourth layout, the large open test bay would be located between the large mass of the test article support structure and the thrust bucket thereby requiring heavy side beams to transmit the thrust force along the entire length of the carriage. Since hold-down rails were found to be necessary during the catapult phase of all four preliminary carriage configurations examined, it was decided that the candidate carriage design would be configured with the model support structure at the rear of the carriage next to the thrust bucket to take advantage of the potential savings in mass from not having to employ these heavy side beams.

Candidate Carriage Structural Configuration

Configuration description.- The fifth structural layout, shown in figure 14, was the final model used in this study and will be considered herein as a candidate carriage structural configuration. Characteristics of this configuration will be discussed in this section and details of the finite element structural model used for the analysis and design are given in the Appendix.

The sides and front of the carriage are constructed from built-up beams which transmit the inertia loads during arrestment to the front corners of the structure where the arresting cables are impacted. Also, reaction forces from the tie-down system are carried by these beams during catapult. A truss structure at the rear of the carriage transmits the thrust load from the bucket at the rear center to the back-stop structure and side beams. A platform could be built on top of the truss structure to support an instrument room and any mechanical equipment such as hydraulic pumps, tankages, or an auxiliary power unit required to operate the gear drop system.

Sizing procedure.- The structural members of the carriage were sized to meet strength requirements for five different applied loading conditions:

(1) Inertia of carriage and small test article at catapult.

(2) Inertia of carriage and small test article at arrest.

(3) Maximum forces generated by test article during test.

(4) Inertia of carriage and large test article at catapult.

(5) Inertia of carriage and large test article at arrest.

The small test article mass was 9072 kg (20 000 lbm) and the large test article was 22 680 kg (50 000 lbm). The structural members were all considered to be tubes and were modeled with extensional elements which neglect any bending stiffness. Thus, the structural sizing process involved selecting a set of tube cross-sectional areas that would produce stress levels below a specified material allowable under all loading conditions. A set of discrete member sizes, which correspond to standard tubing was used. In the sizing procedure, the elements were first divided into groups whose members were specified to have the same cross-sectional area. The structure was then analyzed and member sizes adjusted manually in an iterative manner until the highest element stress within each group was below the specified material allowable.

The material used in the early phases of this study was 4130 steel which has a yield strength of 414 MPa (60 ksi) and an allowable of 207 MPa (30 ksi) for a typical slenderness ratio (length/radius of gyration) of 40. It became obvious that a material with a higher allowable was needed to produce a carriage whose mass was close to the target value of 38 555 kg (85 000 lbm). Therefore, 4140 steel with a yield of 621 MPa (90 ksi) and allowable of 296 MPa (43 ksi) was used for the first sizing of the candidate carriage configuration.

First sizing.- The first sizing of the candidate configuration was performed for a maximum thrust force of 4.45 MN (1.0 million pounds) which resulted in a carriage mass of approximately the target value of 38 000 kg (85 000 lbm). A mass statement for this first sizing is presented in Table II. The carriage mass is the total of the payload, (which was specified) non-structural mass, (estimated) and the structural mass (which was calculated at the completion of the sizing process). Only gross estimates were made for the non-structural masses. Values for these systems will need updating when detail design of the wheel trucks, instrumentation, propulsion bucket, arrest system, and test article support produces more accurate information.

This first sizing design point is shown in figure 15 in relation to data from the jet catapult system first presented in figure 10. Figure 15 indicates that with the first sizing a 194 knot test velocity can be achieved with a 122 meter (400 ft) catapult stroke and a 212 knot test velocity for a 183 meter (600 ft) stroke.

The mass of the first sizing was mathematically scaled to give a reasonable approximation of the carriage mass needed for a range of thrust forces and for three material allowables. This scaling produced the dashed curves shown on figure 15 for 4130, 4140, and HY 130 steel.

The curve for the 4130 steel is included to indicate that the carriage performance is only marginally acceptable even for a 183 meter (600 ft) jet catapult stroke. Acceptable performance is shown to be achievable with a 122 meter (400 ft) stroke using the HY 130 steel, which has a 393 MPa (57 ksi) allowable and yield strength of 896 MPa (130 ksi).

A description follows of observations and assumptions which permitted use of the scaling procedure. The maximum thrust force produced during catapult was found to be the loading condition which governed the size of all but a few structural members. The stress levels in the members are directly proportional to the maximum thrust force. Carriage mass depends on member sizes which are directly proportional to the stress levels and inversely proportional to the material allowable. Use of these relationships results in a carriage mass which is directly proportional to the thrust force and inversely proportional to the material allowable. This scaling neglects the effect of discrete member sizes, therefore the curves of figure 15 for each of the three materials should be considered as suggestive of the carriage mass that would result from the complete carriage sizing process.

Second sizing.- A second complete sizing process was performed using the HY 130 steel and a maximum thrust force of 4.89 MN (1.1 million pounds). A carriage mass of 35 600 kg (78 500 lbm) resulted. This design point is shown in figure 15 and the corresponding mass statement is given in Table II. This mass is approximately 2 percent greater than predicted by the scaling process.

The carriage resulting from the second sizing was selected for use in the candidate catapult/carriage system. The carriage appears to have adequate strength but additional structural mass may be required to provide adequate stiffness to prevent buckling or other adverse dynamic behavior. The system would require a catapult nozzle diameter close to 0.343 meters (14 inches) and, during launch, the carriage would experience a maximum acceleration of about 14 g's. The gross parameters of this candidate system are presented in the following section and the details of the final finite element model, including member locations and sizes, are given in the appendix.

Candidate structure.- A summary of the characteristics of the second sizing, referred to as the candidate carriage, is presented in Table III. The total mass of the carriage is the sum of 17 463 kg (38 500 lbm) structural, 9072 kg (20 000 lbm) non-structural, and either 9072 kg (20 000 lbm) or 22 680 kg (50 000 lbm) test article. Use of a high strength steel, namely, HY 130 is required to obtain a structure of this mass. The longitudinal and vertical location of the carriage center of gravity is given both with and without a model positioned for either catapult or arrestment. The maximum g-loading during catapult was computed at 14 g's for the 9072 kg (20 000 lbm) test article and 10 g's for the 22 680 kg (50 000 lbm) test article. The maximum g-loading during carriage arrestment is assumed to be 5 g's for the 9072 kg (20 000 lbm) test article and 4 g's for the 22 680 kg (50 000 lbm) test article. Arrestment loads are actually dependent on the arresting gear system employed and that had not been established prior to this study. The hold-down rail system forces and the deflection of the test article support were determined and are given in Table IV.

A description of the steel tubing used for the carriage structure is presented in Table V. This tubing is a subset of the standard pipe sizes given in reference 4 and was selected for a range of cross-sectional areas. The section number used in the SPAR analysis contained the first two digits of the tube area. The total length and resulting mass of each type tube is given in the last two columns of the table. Limited use is made of type 17 and type 61 tubes because of fabrication problems and possible high costs; it may be more beneficial to change these members to types 22 and 84, respectively. Such considerations were beyond the scope of this study and are representative of additional refinements needed in subsequent studies.

SUGGESTED ADDITIONS AND REFINEMENTS

A list of suggestions for additional studies to refine the design of an upgraded (to 200 knots) catapult/carriage system is given in this section. The list is not complete but does indicate some important aspects of design which were considered beyond the scope of the present study.

General

1. Reassess the carriage requirements which were originally specified to determine whether some could be relaxed or new ones added based on the results of this study.

2. Perform the preliminary design of all other major components needed to upgrade the facility, such as the arresting gear system and the extended track.

3. Determine a cost breakdown required for the candidate system and assess the technical risks associated with this proposed design.

Hydraulic Jet Catapult

1. Perform tests to measure characteristics of the jet produced by the existing nozzle. This is especially important if a 183 m (600 ft) catapult stroke is desired. The trends from such tests are needed to substantiate the performance estimates for the increased thrust system.

2. Determine the modifications to the water vessel foundation needed to react the increased thrust force.

Carriage Structure

1. Examine layout of the structure and try to simplify the design. Reduce the number of joints if possible and eliminate any unnecessary members. Members may need to be relocated to provide joint arrangements which better lend themselves to fabrication.

2. Explore alternate depths and widths of carriage side beams, including tapering the distance between the upper and lower set of stringers.

3. Explore alternate locations for the carriage wheels.

4. Calculate a more accurate representation of the actual carriage mass, one that includes all major items such as propulsion bucket, hydraulic systems, model supports, instrumentation, and material needed to fabricate joints in addition to the idealized structural mass.

5. Consider the slenderness ratio (length/radius of gyration) in establishing strength allowables for each member. Local buckling of the individual members is accounted for in this manner.

6. Assess the stiffness characteristics of the structure by calculating vibration modes and frequencies and by calculating static deflections under specified loads on selected portions of the structure.

7. Calculate overall buckling load for the structure for both catapult and arrestment conditions.

8. Carry out the design of the hold-down rails.

9. Determine the details of the test article support fixture.

CONCLUSIONS

The following conclusions reached during this study can be used to guide additional design studies which are needed to arrive at the details of a catapult system and a final carriage design.

1. Based on assumptions that appear reasonable, it would require a water jet .356 m (14 in.) in diameter to propel a 39 000 kg (85 000 lbm) carriage to 200 knots in 122 m (400 ft) with a maximum acceleration of approximately 13.5 g units.

2. A water jet .279 m (11 in.) diameter would propel the same carriage mass to 200 knots in 183 m (600 ft) at a reduced maximum acceleration of 9 g units but there might be problems with jet efficiency, initial jet angle, and turning bucket dimensions.

3. The SPAR finite element computer program provided the capability to model the structure and represent the inertia forces on the carriage.

4. Automated structural sizing programs at LaRC were not directly applicable in this study since a set of discrete member sizes corresponding to cross-sectional areas of standard tubing was used.

5. A tie-down rail system is needed during catapult to prevent the front of the carriage from lifting off the existing rails.

6. Use of a material having an allowable of 393 MPa (57 000 psi) is required to achieve a carriage structural mass of approximately 20 406 kg (45 000 lbm).

7. Additional design studies are needed to substantiate or further quantify the preliminary design information given in this report.

REFERENCES

1. Tanner, John A.: Fore-and-Aft Elastic Response Characteristics of 34 x 9.9, Type VII, 14 ply-Rating Aircraft Tires of Bias-Ply, Bias-Belted, and Radial-Belted Design. NASA TM D-7449, April 1974.

2. Metric Practics Guide. E-380-72, American Soc. Testing and Mater., June 1972.

3. Joyner, Upshur T.; and Horne, Walter B.: Considerations on a Large Hydraulic Jet Catapult. NACA TN 3203, July 1954.

4. Manual of Steel Construction, Sixth Edition: American Institute of Steel Construction, Inc. 101 Park Avenue, New York, NY 10017.

5. Whetstone, W. D.: SPAR Structural Analysis System Reference Manual - System Level 11. Volume I - Program Execution. NASA CR-145096-1, 1977.

APPENDIX A - FINITE ELEMENT MODEL OF CARRIAGE STRUCTURE

A listing of input data to the SPAR computer program, reference 5, which was used for analysis of the carriage structure is given in this appendix. Comments to explain the various sections of data are given throughout the listing and start with the $ character. Each comment describes the data which immediately follows it.

```
$
$ SPAR INPUT FOR CARRIAGE STRUCTURE
$ THRUST FORCE = -1.1 MILLION POUNDS
$ MATERIAL ALLOWABLE = 57 KSI
$
[XQT TAB $
$ STRUCTURE HAS 236 JOINTS
$ SINCE BAR ELEMENTS ARE USED FOR MODELING
$ ALL ROTATIONAL D.O.F. ARE FIXED
START 236,4,5,6 $
 ONLINE=0 $
MATC $
$ MATERIAL 1 IS STEEL WITH DENSITY
$ INCREASED BY 10 PERCENT TO REPRESENT
$ EXTRA MATERIAL NEEDED IN JOINTS, ETC.
$
$ MATERIAL 2 IS FICTITIOUS MATERIAL USED IN
$ EXTRA MEMBERS TO STABILIZE MODEL OF PRIMARY STRUCTURE.
$
$ MATERIAL 3 HAS STIFFNESS OF STEEL BUT ZERO DENSITY
$ USED FOR CRUDE REPRESENTATION OF MODEL SUPPORT.
       1  30.0+6  0.3  0.33 $
       2  30.0+4  0.3  0.0 $
       3  30.0+6  0.3  0.0 $
JLOC $
$ TABLE OF JOINT LOCATIONS.
$ ORIGIN IS AT CENTER FRONT OF CARRIAGE
$ AND LOCATED 28 INCHES ABOVE THE RAILS.
$ NOTE THAT THE ENTIRE MODEL OF THE SYMMETRIC
$ STRUCTURE IS INPUT.
         1        0.000     180.000      28.000
         2        0.000    -180.000      28.000
         3        0.000     144.000      28.000
         4        0.000    -144.000      28.000
         5        0.000      72.000      28.000
         6        0.000     -72.000      28.000
         7        0.000       0.000      28.000
         8        0.000       0.000      28.000
         9        0.000     180.000      88.000
        10        0.000    -180.000      88.000
        11        0.000     108.000      88.000
        12        0.000    -108.000      88.000
        13        0.000      36.000      88.000
        14        0.000     -36.000      88.000
        15       60.000     180.000      28.000
        16       60.000    -180.000      28.000
        17       60.000     108.000      28.000
        18       60.000    -108.000      28.000
```

2

19	60.000	36.000	28.000
20	60.000	-36.000	28.000
21	60.000	180.000	88.000
22	60.000	-180.000	88.000
23	60.000	144.000	88.000
24	60.000	-144.000	88.000
25	60.000	72.000	88.000
26	60.000	-72.000	88.000
27	60.000	0.000	88.000
28	60.000	0.000	88.000
29	0.000	180.000	118.000
30	0.000	-180.000	118.000
31	60.000	240.000	28.000
32	60.000	-240.000	28.000
33	60.000	240.000	88.000
34	60.000	-240.000	88.000
35	94.400	240.000	28.000
36	94.400	-240.000	28.000
37	94.400	180.000	88.000
38	94.400	-180.000	88.000
39	128.800	240.000	88.000
40	128.800	-240.000	88.000
41	128.800	180.000	28.000
42	128.800	-180.000	28.000
43	163.200	240.000	28.000
44	163.200	-240.000	28.000
45	163.200	180.000	88.000
46	163.200	-180.000	88.000
47	197.600	240.000	88.000
48	197.600	-240.000	88.000
49	197.600	180.000	28.000
50	197.600	-180.000	28.000
51	232.000	240.000	28.000
52	232.000	-240.000	28.000
53	232.000	180.000	88.000
54	232.000	-180.000	88.000
55	266.400	240.000	88.000
56	266.400	-240.000	88.000
57	266.400	180.000	28.000
58	266.400	-180.000	28.000
59	300.800	240.000	28.000
60	300.800	-240.000	28.000
61	300.800	180.000	88.000
62	300.800	-180.000	88.000
63	335.200	240.000	88.000
64	335.200	-240.000	88.000
65	335.200	180.000	28.000
66	335.200	-180.000	28.000
67	369.600	240.000	28.000
68	369.600	-240.000	28.000
69	369.600	180.000	88.000

70	369.600	-180.000	88.000
71	404.000	240.000	88.000
72	404.000	-240.000	88.000
73	404.000	180.000	28.000
74	404.000	-180.000	28.000
75	438.400	240.000	28.000
76	438.400	-240.000	28.000
77	438.400	180.000	88.000
78	438.400	-180.000	88.000
79	472.800	240.000	88.000
80	472.800	-240.000	88.000
81	472.800	180.000	28.000
82	472.800	-180.000	28.000
83	507.200	240.000	28.000
84	507.200	-240.000	28.000
85	507.200	180.000	88.000
86	507.200	-180.000	88.000
87	541.600	240.000	88.000
88	541.600	-240.000	88.000
89	541.600	180.000	28.000
90	541.600	-180.000	28.000
91	576.000	240.000	28.000
92	576.000	-240.000	28.000
93	576.000	240.000	88.000
94	576.000	-240.000	88.000
95	576.000	180.000	28.000
96	576.000	-180.000	28.000
97	576.000	117.500	28.000
98	576.000	-117.500	28.000
99	576.000	55.000	28.000
100	576.000	-55.000	28.000
101	576.000	0.000	28.000
102	576.000	0.000	28.000
103	576.000	180.000	88.000
104	576.000	-180.000	88.000
105	576.000	117.500	88.000
106	576.000	-117.500	88.000
107	576.000	55.000	88.000
108	576.000	-55.000	88.000
109	576.000	0.000	88.000
110	576.000	0.000	88.000
111	576.000	117.500	138.000
112	576.000	-117.500	138.000
113	576.000	55.000	138.000
114	576.000	-55.000	138.000
115	576.000	0.000	138.000
116	576.000	0.000	138.000
117	576.000	55.000	188.000
118	576.000	-55.000	188.000
119	576.000	0.000	188.000
120	576.000	0.000	188.000

4

121	576.000	55.000	238.000
122	576.000	-55.000	238.000
123	576.000	0.000	238.000
124	576.000	0.000	238.000
125	576.000	55.000	288.000
126	576.000	-55.000	288.000
127	576.000	0.000	288.000
128	576.000	0.000	288.000
129	648.000	180.000	28.000
130	648.000	-180.000	28.000
131	648.000	117.500	28.000
132	648.000	-117.500	28.000
133	648.000	55.000	28.000
134	648.000	-55.000	28.000
135	648.000	0.000	28.000
136	648.000	0.000	28.000
137	648.000	180.000	88.000
138	648.000	-180.000	88.000
139	648.000	117.500	88.000
140	648.000	-117.500	88.000
141	648.000	55.000	88.000
142	648.000	-55.000	88.000
143	648.000	0.000	88.000
144	648.000	0.000	88.000
145	648.000	117.500	138.000
146	648.000	-117.500	138.000
147	648.000	55.000	138.000
148	648.000	-55.000	138.000
149	648.000	0.000	138.000
150	648.000	0.000	138.000
151	648.000	55.000	188.000
152	648.000	-55.000	188.000
153	648.000	0.000	188.000
154	648.000	0.000	188.000
155	648.000	55.000	238.000
156	648.000	-55.000	238.000
157	648.000	0.000	238.000
158	648.000	0.000	238.000
159	648.000	55.000	288.000
160	648.000	-55.000	288.000
161	648.000	0.000	288.000
162	648.000	0.000	288.000
163	700.000	0.000	42.000
164	700.000	0.000	42.000
165	700.000	0.000	88.000
166	700.000	0.000	88.000
167	680.000	180.000	28.000
168	680.000	-180.000	28.000
169	676.070	156.608	88.000
170	676.070	-156.608	88.000
171	676.070	73.275	28.000

172	676.070	-73.275	28.000
173	680.000	49.167	88.000
174	680.000	-49.167	88.000
175	712.000	180.000	88.000
176	712.000	-180.000	88.000
177	704.140	133.216	28.000
178	704.140	-133.216	28.000
179	704.140	91.550	88.000
180	704.140	-91.550	88.000
181	712.000	43.333	33.667
182	712.000	-43.333	33.667
183	744.000	180.000	28.000
184	744.000	-180.000	28.000
185	732.211	109.825	28.000
186	732.211	-109.825	28.000
187	732.211	109.825	88.000
188	732.211	-109.825	88.000
189	744.000	37.500	88.000
190	744.000	-37.500	88.000
191	776.000	180.000	88.000
192	776.000	-180.000	88.000
193	759.158	87.368	32.250
194	759.158	-87.368	32.250
195	759.158	127.368	88.000
196	759.158	-127.368	88.000
197	776.000	31.667	39.333
198	776.000	-31.667	39.333
199	808.000	180.000	28.000
200	808.000	-180.000	28.000
201	786.105	64.912	88.000
202	786.105	-64.912	88.000
203	786.105	144.912	28.000
204	786.105	-144.912	28.000
205	808.000	25.833	88.000
206	808.000	-25.833	88.000
207	813.053	42.456	40.750
208	813.053	-42.456	40.750
209	813.053	162.456	88.000
210	813.053	-162.456	88.000
211	840.000	180.000	28.000
212	840.000	-180.000	28.000
213	840.000	180.000	88.000
214	840.000	-180.000	88.000
215	840.000	20.000	45.000
216	840.000	-20.000	45.000
217	840.000	20.000	88.000
218	840.000	-20.000	88.000
219	840.000	140.000	28.000
220	840.000	-140.000	28.000
221	840.000	60.000	28.000
222	840.000	-60.000	28.000

```
        223    840.000    100.000     88.000
        224    840.000   -100.000     88.000
        225    840.000      0.000    148.000
        226    840.000      0.000    148.000
        227    516.000      0.000    238.000
        228    516.000      0.000    238.000
        229    516.000      0.000     53.000
        230    516.000      0.000     53.000
        231    516.000      0.000      0.000
        232    516.000      0.000      0.000
        233    300.000      0.000    188.000
        234    300.000      0.000    188.000
        235    300.000      0.000     53.000
        236    300.000      0.000     53.000
CON=1 $
$ GLOBAL B.C.
$ JOINTS 15 AND 16 ARE AT FRONT WHEEL TRUCKS
$ JOINTS 211 AND 212 ARE AT REAR WHEEL TRUCKS.
  ZERO 3: 15:16:211:212 $
  ZERO 2: 15:211 $
  ZERO 1: 15 $
$ B.C. REQUIRED FOR INDIVIDUAL FRAMES
$ B.C. TO ELIMINATE UNUSED JOINTS
  ZERO 1,2,3: 8:28:102:110:116:120:124:128 $
  ZERO 1,2,3: 130:144:150:154:158:162 $
  ZERO 1,2,3: 164:166:226:228:230:232:234:236 $
JSEQ $
 1/128,227/236,129/226 $
E23 SECTION PROPERTIES $
$ TABLE OF BAR CROSS-SECTIONAL AREAS
$ CORRESPONDING TO STANDARD TUBE SIZES.
  10   1.075 $
  14   1.477 $
  17   1.704 $
  22   2.227 $
  26   2.680 $
  31   3.174 $
  36   3.678 $
  40   4.028 $
  43   4.300 $
  55   5.581 $
  61   6.112 $
  84   8.405 $
 113  11.340 $
 127  12.760 $
 156  15.640 $
 161  16.100 $
 213  21.300 $
$ TO SET UP MASSES FOR VARIOUS LOAD CASES
$ FOR FIXED (INDEPENDENT OF MODEL) MASSES
[XQT TAB $
```

7

```
RMASS $
$ FOR TRUCKS
  15,2500.0;16,2500.0 $
  211,2500.0;212,2500.0 $
$ FOR INSTRUMENT CAB $
  187,2000.0;188,2000.0 $
$ FOR PROPULSION BUCKET
  163,4500.0 $
$ FOR NOSE BLOCKS
  29,750.0;30,750.0 $
[XQT DCU $
  CHANGE 1,RMAS BTAB 2 18,RMAS FIX 0 0 $
$ FOR 20,000 LB PAYLOAD IN HIGH POSITION
[XQT TAB $
RMASS $
  227,20000.0 $
[XQT DCU $
  CHANGE 1,RMAS BTAB 2 18,MS15 HIGH 1 1 $
$ FOR 20,000 LB PAYLOAD IN LOW POSITION
[XQT TAB $
RMASS $
  229,20000.0 $
[XQT DCU $
  CHANGE 1,RMAS BTAB 2 18,MS15 LOW 2 2 $
$ FOR 50,000 LB AIR CUSHION MODEL IN HIGH POSITION
[XQT TAB $
RMASS $
  233,50000.0 $
[XQT DCU $
  CHANGE 1,RMAS BTAB 2 18,MS50 HIGH 4 4 $
$ FOR 50,000 LB AIR CUSHION MODEL IN LOW POSITION
[XQT TAB $
RMASS $
  235,50000.0 $
[XQT DCU $
  CHANGE 1,RMAS BTAB 2 18,MS50 LOW 5 5 $
[XQT ELD $
E23 $ BAR ELEMENTS HAVING ONLY AXIAL STIFFNESS
  NMAT=1 $
GROUP 1" FRONT BEAM - STRINGERS
$ FRONT, BOTTOM
 NSECT=10 $
  31,1;32,2 $
  1,3;2,4 $
  3,5;4,6 $
  5,7;6,7 $
$ FRONT, TOP
  33,9;34,10 $
  9,11;10,12 $
  11,13;12,14 $
  13,14 $
```

```
$ REAR, BOTTOM
  31,15;32,16 $
  15,17;16,18 $
  17,19;18,20 $
  19,20 $
$ REAR, TOP
 NSECT=17 $
  33,21;34,22 $
 NSECT=10 $
  21,23;22,24 $
  23,25;24,26 $
  25,27;26,27 $
GROUP 2" FRONT BEAM - BRACING
$ FRONT
 NSECT=22 $
  33,1;34,2 $
  1,9;2,10 $
  31,9;32,10 $
 NSECT=10 $
  9,3;10,4 $
  3,11;4,12 $
  11,5;12,6 $
  5,13;6,14 $
  13,7;14,7 $
$ TOP
 NSECT=22 $
  21,9;22,10 $
 NSECT=10 $
  9,23;10,24 $
  23,11;24,12 $
  11,25;12,26 $
  25,13;26,14 $
  13,27;14,27 $
$ REAR
 NSECT=22 $
  33,31;34,32 $
  31,21;32,22 $
  21,15;22,16 $
 NSECT=10 $
  15,23;16,24 $
  23,17;24,18 $
  17,25;18,26 $
  25,19;26,20 $
  19,27;20,27 $
$ BOTTOM
 NSECT=22 $
  1,15;2,16 $
 NSECT=10 $
  15,3;16,4 $
  3,17;4,18 $
  17,5;18,6 $
```

8

```
5,19;6,20 $
19,7;20,7 $
$ DIAGONAL
NSECT=22 $
9,15;10,16 $
NSECT=10 $
11,17;12,18 $
13,19;14,20 $
$ ARREST STRUCTURE
NSECT=61 $
9,29;10,30 $
NSECT=17 $
11,29;12,30 $
NSECT=61 $
21,29;22,30 $
NSECT=17 $
33,29;34,30 $
GROUP 3" SIDE BEAM - STRINGERS
$ OUTSIDE, BOTTOM
NSECT=55 $
31,35;32,36 $
35,43;36,44 $
43,51;44,52 $
51,59;52,60 $
59,67;60,68 $
67,75;68,76 $
75,83;76,84 $
83,91;84,92 $
$ OUTSIDE, TOP
33,39;34,40 $
39,47;40,48 $
47,55;48,56 $
55,63;56,64 $
63,71;64,72 $
71,79;72,80 $
79,87;80,88 $
87,93;88,94 $
$ INSIDE, BOTTOM
15,41;16,42 $
41,49;42,50 $
49,57;50,58 $
57,65;58,66 $
65,73;66,74 $
73,81;74,82 $
81,89;82,90 $
89,95;90,96 $
$ INSIDE, TOP
NSECT=84 $
21,37;22,38 $
37,45;38,46 $
45,53;46,54 $
```

```
53,61;54,62 $
61,69;62,70 $
69,77;70,78 $
77,85;78,86 $
85,103;86,104 $
GROUP 4" SIDE BEAM - BRACING
$ OUTSIDE
NSECT=10 $
33,35;34,36 $
35,39;36,40 $
39,43;40,44 $
43,47;44,48 $
47,51;48,52 $
51,55;52,56 $
55,59;56,60 $
59,63;60,64 $
63,67;64,68 $
67,71;68,72 $
71,75;72,76 $
75,79;76,80 $
79,83;80,84 $
83,87;84,88 $
87,91;88,92 $
$ TOP
33,37;34,38 $
37,39;38,40 $
39,45;40,46 $
45,47;46,48 $
47,53;48,54 $
53,55;54,56 $
55,61;56,62 $
61,63;62,64 $
63,69;64,70 $
69,71;70,72 $
71,77;72,78 $
77,79;78,80 $
79,85;80,86 $
85,87;86,88 $
87,103;88,104 $
$ INSIDE
15,37;16,38 $
37,41;38,42 $
41,45;42,46 $
45,49;46,50 $
49,53;50,54 $
53,57;54,58 $
57,61;58,62 $
61,65;62,66 $
65,69;66,70 $
69,73;70,74 $
73,77;74,78 $
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10

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 77,81;78,82 $
 81,85;82,86 $
 85,89;86,90 $
 89,103;90,104 $
$ BOTTOM
 15,35;16,36 $
 35,41;36,42 $
 41,43;42,44 $
 43,49;44,50 $
 49,51;50,52 $
 51,57;52,58 $
 57,59;58,60 $
 59,65;60,66 $
 65,67;66,68 $
 67,73;68,74 $
 73,75;74,76 $
 75,81;76,82 $
 81,83;82,84 $
 83,89;84,90 $
 89,91;90,92 $
$ DIAGONAL
 39,41;40,42 $
 47,49;48,50 $
 55,57;56,58 $
 63,65;64,66 $
 71,73;72,74 $
 79,81;80,82 $
 87,89;88,90 $
GROUP 5" FRAME NO.3
$ HORIZONTAL MEMBERS
 NSECT=31 $
 91,95;92,96 $
 95,97;96,98 $
 97,99;98,100 $
 99,101;100,101 $
 93,103;94,104 $
 103,105;104,106 $
 105,107;106,108 $
 107,109;108,109 $
 111,113;112,114 $
 113,115;114,115 $
 117,119;118,119 $
 121,123;122,123 $
 125,127;126,127 $
$ VERTICAL MEMBERS
 91,93;92,94 $
 95,103;96,104 $
 97,105;98,106 $
 105,111;106,112 $
 99,107;100,108 $
 107,113;108,114 $
```

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113,117;114,118 $
117,121;118,122 $
121,125;122,126 $
101,109 $
109,115 $
115,119 $
119,123 $
123,127 $
$ DIAGONAL MEMBERS
NSECT=22 $
93,95;94,96 $
95,105;96,106 $
105,99;106,100 $
99,109;100,109 $
103,111;104,112 $
105,113;106,114 $
107,115;108,115 $
111,125;112,126 $
111,117;112,118 $
113,119;114,119 $
117,123;118,123 $
121,127;122,127 $
GROUP 6" FRAME NO.4
$ HORIZONTAL MEMBERS
NSECT=31 $
129,131;130,132 $
131,133;132,134 $
133,135;134,135 $
137,139;138,140 $
139,141;140,142 $
141,143;142,143 $
145,147;146,148 $
147,149;148,149 $
151,153;152,153 $
155,157;156,157 $
159,161;160,161 $
$ VERTICAL MEMBERS
129,137;130,138 $
131,139;132,140 $
139,145;140,146 $
133,141;134,142 $
141,147;142,148 $
147,151;148,152 $
151,155;152,156 $
155,159;156,160 $
135,143 $
143,149 $
149,153 $
153,157 $
157,161 $
$ DIAGONAL MEMBERS
```

```
NSECT=14 $
 129,139;130,140 $
 139,133;140,134 $
 133,143;134,143 $
 137,145;138,146 $
 139,147;140,148 $
 141,149;142,149 $
 145,159;146,160 $
 145,151;146,152 $
 147,153;148,153 $
 151,157;152,157 $
 155,161;156,161 $
GROUP 7" FRAME NO.5
$ HORIZONTAL MEMBERS
 NSECT=22 $
 211,219;212,220 $
 219,221;220,222 $
 221,215;222,216 $
 215,216 $
 213,223;214,224 $
 223,217;224,218 $
 217,218 $
$ VERTICAL MEMBERS
 211,213;212,214 $
 215,217;216,218 $
$ DIAGONAL MEMBERS
 213,219;214,220 $
 219,223;220,224 $
 223,221;224,222 $
 221,217;222,218 $
 223,225;224,225 $
 217,225;218,225 $
GROUP 8" REAR TRUSSES
$ FROM OUTSIDE OF F.4 TO OUTSIDE OF F.5
$ STRINGERS
 NSECT=26 $
 129,167;130,168 $
 167,183;168,184 $
 183,199;184,200 $
 199,211;200,212 $
 137,175;138,176 $
 175,191;176,192 $
 191,213;192,214 $
$ BRACING
 NSECT=10 $
 137,167;138,168 $
 167,175;168,176 $
 175,183;176,184 $
 183,191;184,192 $
 191,199;192,200 $
 199,213;200,214 $
```

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$ FROM OUTSIDE OF F.4 TO MID OF F.5
$ STRINGERS
NSECT=26 $
129,177;130,178 $
177,185;178,186 $
185,193;186,194 $
193,207;194,208 $
207,215;208,216 $
137,169;138,170 $
169,187;170,188 $
187,201;188,202 $
201,217;202,218 $
$ BRACING
NSECT=10 $
129,169;130,170 $
169,177;170,178 $
177,187;178,188 $
185,187;186,188 $
187,193;188,194 $
193,201;194,202 $
201,207;202,208 $
207,217;208,218 $
$ FROM MID OF F.4 TO OUTSIDE OF F.5
$ STRINGERS
NSECT=26 $
133,171;134,172 $
171,185;172,186 $
185,203;186,204 $
203,211;204,212 $
141,179;142,180 $
179,187;180,188 $
187,195;188,196 $
195,209;196,210 $
209,213;210,214 $
$ BRACING
NSECT=10 $
141,171;142,172 $
171,179;172,180 $
179,185;180,186 $
187,185;188,186 $
185,195;186,196 $
195,203;196,204 $
203,209;204,210 $
209,211;210,212 $
$ FROM MID OF F.4 TO MID OF F.5
$ STRINGERS
NSECT=26 $
133,181;134,182 $
181,197;182,198 $
197,215;198,216 $
141,173;142,174 $
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 173,189;174,190 $
 189,205;190,206 $
 205,217;206,218 $                                                        15
$ BRACING
 NSECT=10 $
 133,173;134,174 $
 173,181;174,182 $
 181,189;182,190 $
 189,197;190,198 $
 197,205;198,206 $
 205,215;206,216 $
GROUP 9" BETWEEN F.3 AND F.4
$ LONGITUDINAL MEMBERS
 NSECT=61 $
 95,129;96,130 $
 NSECT=22 $
 97,131;98,132 $
 99,133;100,134 $
 101,135 $
 NSECT=84 $
 103,137;104,138 $
 NSECT=31 $
 105,139;106,140 $
 107,141;108,142 $
 109,143 $
 111,145;112,146 $
 113,147;114,148 $
 115,149 $
 117,151;118,152 $
 119,153 $
 121,155;122,156 $
 123,157 $
 125,159;126,160 $
 127,161 $
$ HORIZONTAL BRACING
 91,129;92,130 $
 93,137;94,138 $
 129,97;130,98 $
 137,105;138,106 $
 97,133;98,134 $
 105,141;106,142 $
 99,135;100,135 $
 107,143;108,143 $
 115,147;115,148 $
 117,153;118,153 $
 123,155;123,156 $
 125,161;126,161 $
 111,147;112,148 $
$ VERTICAL BRACING
 93,129;94,130 $
 103,129;104,130 $
```

```
105,131;106,132 $
107,133;108,134 $
109,135 $
111,139;112,140 $
113,141;114,142 $
109,149 $
117,147;118,148 $
115,153 $
121,151;122,152 $
119,157 $
125,155;126,156 $
123,161 $
GROUP 10" BUCKET ATTACHMENT AND TOWER BRACING
$ BUCKET ATTACHMENT
NSECT=84 $
163,133;163,134 $
163,135 $
163,141;163,142 $
163,143 $
163,165 $
NSECT=22 $
165,141;165,142 $
165,225 $
$ TOWER BRACING
165,153 $
217,151;218,152 $
217,159;218,160 $
GROUP 11" EXTRA MEMEERS TO STABILIZE REAR TRUSSES
NMAT=2 $
NSECT=40 $
167,185;168,186 $
183,185;184,186 $
199,185;200,186 $
175,187;176,188 $
191,187;192,188 $
219,185;220,186 $
221,185;222,186 $
223,187;224,188 $
181,185;182,186 $
197,185;198,186 $
173,187;174,188 $
189,187;190,188 $
205,187;206,188 $
177,131;178,132 $
193,131;194,132 $
207,131;208,132 $
169,139;170,140 $
201,139;202,140 $
171,131;172,132 $
203,131;204,132 $
179,139;180,140 $
```

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    195,139;196,140 $
    209,139;210,140 $
GROUP 12" MASSLESS MODEL SUPPORT LINKAGES
NMAT=3 $
NSECT=40 $
    227,125;227,126 $
    227,117;227,118 $
    229,107;229,108 $
    229,99;229,100 $
    231,107;231,108 $
    231,99;231,100 $
    233,125;233,126 $
    233,117;233,118 $
    235,113;235,114 $
    235,99;235,100 $
[XQT TOPO $
    ONLINE=1 $
[XQT E $
[XQT EKS $
[XQT K $
[XQT INV $
$ TO SET UP LOAD CASES
[XQT AUS $
$ DEFINE GEAR LOADING DURING TEST
    SYSVEC;GEAR LOAD 1 1 $
        I=1;J=231;50000.0 $
        I=2;J=231;50000.0 $
        I=3;J=231;50000.0 $
$ DEFINE CATAPULT FORCE
$  FOR 1.1 MILLION POUND CATAPULT THRUST.
    SYSVEC;CATF LOAD 1 1 $
        I=1;J=163;-1.1+6 $
        I=3;J=163;48027. $
$DEFINE A UNIT ARREST FORCE
    SYSVEC;ARRF UNIT 1 1 $
        I=1;J=29,30;0.5,0.5 $
$ CARRIAGE WHEEL TRUCK PRELOAD IN Y-DIRECTION
    SYSVEC;CARG PREL 1 1 $
        I=2;J=16;15000. $
        I=2;J=212;15000. $
$ FORM RIGID BODY MOTION VECTORS
    RIGD=RIGID $
$ DEFINE MASS DATA SETS
  DEFINE DEM=DEM DIAG 0 0 $
  DEFINE FIX=RMAS FIX $
  DEFINE M15H=MS15 HIGH
  DEFINE M15L=MS15 LOW
  DEFINE M50H=MS50 HIGH
  DEFINE M50L=MS50 LOW
    RM1=SUM(FIX,M15H) $
    RM2=SUM(FIX,M15L) $
```

```
RM3=SUM(FIX,M15L) $
RM4=SUM(FIX,M50H) $
RM5=SUM(FIX,M50L) $
TM0=SUM(DEM,FIX) $
TM1=SUM(DEM,RM1) $
TM2=SUM(DEM,RM2) $
TM3=SUM(DEM,RM3) $
TM4=SUM(DEM,RM4) $
TM5=SUM(DEM,RM5) $
DEFINE RGD1=RIGD AUS 1 1 1 1 $
DEFINE RGD3=RIGD AUS 1 1 3 3 $
$ GRAVITY LOADS
GL0=PRODUCT(TM0, -1.0 RGD3) $
GL1=PRODUCT(TM1, -1.0 RGD3) $
GL2=PRODUCT(TM2, -1.0 RGD3) $
GL3=PRODUCT(TM3, -1.0 RGD3) $
GL4=PRODUCT(TM4, -1.0 RGD3) $
GL5=PRODUCT(TM5, -1.0 RGD3) $
TW0=XTY(GL0, -1.0 RGD3) $
TW1=XTY(GL1, -1.0 RGD3) $
TW2=XTY(GL2, -1.0 RGD3) $
TW3=XTY(GL3, -1.0 RGD3) $
TW4=XTY(GL4, -1.0 RGD3) $
TW5=XTY(GL5, -1.0 RGD3) $
TW0R=RECIP(TW0) $
TW1R=RECIP(TW1) $
TW2R=RECIP(TW2) $
TW3R=RECIP(TW3) $
TW4R=RECIP(TW4) $
TW5R=RECIP(TW5) $
$ C.G. CALCULATION $
DEFINE RY=RIGD AUS 1 1 5 5 $
MRY0=PROD(TM0,RY) $
MRY1=PROD(TM1,RY) $
MRY2=PROD(TM2,RY) $
MRY3=PROD(TM3,RY) $
MRY4=PROD(TM4,RY) $
MRY5=PROD(TM5,RY) $
ZRY0=XTY(RGD3, -1.0 MRY0) $
ZRY1=XTY(RGD3, -1.0 MRY1) $
ZRY2=XTY(RGD3, -1.0 MRY2) $
ZRY3=XTY(RGD3, -1.0 MRY3) $
ZRY4=XTY(RGD3, -1.0 MRY4) $
ZRY5=XTY(RGD3, -1.0 MRY5) $
XRY0=XTY(RGD1,MRY0) $
XRY1=XTY(RGD1,MRY1) $
XRY2=XTY(RGD1,MRY2) $
XRY3=XTY(RGD1,MRY3) $
XRY4=XTY(RGD1,MRY4) $
XRY5=XTY(RGD1,MRY5) $
XCG0=PROD(ZRY0,TW0R) $
```

```
XCG1=PROD(ZRY1,TW1R) $
XCG2=PROD(ZRY2,TW2P) $
XCG3=PROD(ZRY3,TW3P) $
XCG4=PROD(ZRY4,TW4R) $
XCG5=PROD(ZRY5,TW5R) $
ZCG0=PROD(XRY0,IW0R) $
ZCG1=PROD(XRY1,TW1R) $
ZCG2=PROD(XRY2,TW2R) $
ZCG3=PROD(XRY3,TW3R) $
ZCG4=PROD(XRY4,TW4R) $
ZCG5=PROD(XRY5,TW5R) $
$ CATAPULT INERTIA LOADS
ICLH=PRODUCT(TM1, 1.0 RGD1) $
ICLL=PRODUCT(TM4, 1.0 RGD1) $
TABLE(NI=1,NJ=708);DUMA $
TRAN(SOURCE=ICLH) $
VCLH=RPROD(TW1R, 1.1+6 DUMA) $
TABLE(NI=1,NJ=708);DUMD $
TRAN(SOURCE=ICLL) $
VCLL=RPROD(TW4R, 1.1+6 DUMD) $
SYSVEC;FCLH $
TRAN(SOURCE=VCLH) $
SYSVEC;FCLL $
TRAN(SOURCE=VCLL) $
$ ARREST INERTIA LOADS
IALH=PRODUCT(TM2, -5.0 RGD1) $
IALL=PRODUCT(TM5, -4.0 RGD1) $
RALH=XTY(IALH, -1.0 RGD1) $
RALL=XTY(IALL, -1.0 RGD1) $
TABLE(NI=1,NJ=708);DUMB $
TRAN(SOURCE=ARRF) $
VALH=RPROD(RALH,DUMB) $
VALL=RPROD(RALL,DUMB) $
SYSVEC;FALH $
TRAN(SOURCE=VALH) $
SYSVEC;FALL $
TRAN(SOURCE=VALL) $
$ TEST INERTIA LOADS
ITL=PRODUCT(TM3, -1.0 RGD1) $
TABLE(NI=1,NJ=708);DUMC $
TRAN(SOURCE=ITL) $
VITL=RPROD(TW3R, 50000. DUMC) $
SYSVEC;FITL $
TRAN(SOURCE=VITL) $
$ SUM THRUST,INERTIA,CARRIAGE PRELOAD,GRAVITY LOADS
$ CASE 1 - 20,000 LB. MODEL - HIGH POSITION - CATAPULT.
DEFINE CPLD=CARG PREL 1 1 $
DEFINE FBUK=CATF LOAD 1 1 $
TMP1=SUM(FBUK,VCLH) $
DUM1=SUM(TMP1,CPLD) $
SAVE FORC 1 1=SUM(DUM1,GL1) $
```

```
$ CASE 2 - 20,000 LB. MODEL - LOW POSITION - 5G ARREST.
  TMP2=SUM(FALH,IALH) $
  DUM2=SUM(TMP2,CPLD) $
  SAVE FORC 2 1=SUM(DUM2,GL2) $
$ CASE 3 - GEAR LOAD DURING TEST.
  DEFINE GRLD=GEAR LOAD 1 1 $
  TMP3=SUM(GRLD,FITL) $
  DUM3=SUM(TMP3,CPLD) $
  SAVE FORC 3 1=SUM(DUM3,GL3) $
$ CASE 4 - 50,000 LB. MODEL - HIGH POSITION - CATAPULT.
  TMP4=SUM(FBUK,VCLL) $
  DUM4=SUM(TMP4,CPLD) $
  SAVE FORC 4 1=SUM(DUM4,GL4) $
$ CASE 5 - 50,000 LB. MODEL - LOW POSITION - 4G ARREST.
  TMP5=SUM(FALL,IALL) $
  DUM5=SUM(TMP5,CPLD) $
  SAVE FORC 5 1=SUM(DUM5,GL5)
 DEFINE L1=SAVE FORC 1 1 $
 DEFINE L2=SAVE FORC 2 1 $
 DEFINE L3=SAVE FORC 3 1 $
 DEFINE L4=SAVE FORC 4 1 $
 DEFINE L5=SAVE FORC 5 1 $
 APPL FORC 1 1=UNION(1.0 L1,1.0 L2,1.0 L3,1.0 L4,1.0 L5) $
IXQT DCU $
 PRINT 1,JLOC $
 PRINT 1,TW0 $
 PRINT 1,TW1 $
 PRINT 1,TW2 $
 PRINT 1,TW3 $
 PRINT 1,TW4 $
 PRINT 1,TW5 $
 PRINT 1,XCG0 $
 PRINT 1,ZCG0 $
 PRINT 1,XCG1 $
 PRINT 1,ZCG1 $
 PRINT 1,XCG2 $
 PRINT 1,ZCG2 $
 PRINT 1,XCG3 $
 PRINT 1,ZCG3 $
 PRINT 1,XCG4 $
 PRINT 1,ZCG4 $
 PRINT 1,XCG5 $
 PRINT 1,ZCG5 $
$ PRINT 1,RCLH $
$ PRINT 1,RCLL $
$ PRINT 1,RALH $
$ PRINT 1,RALL $
$ PRINT 1,FCLH $
$ PRINT 1,FCLL $
$ PRINT 1,FALH $
$ PRINT 1,FALL $
```

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[XQT SSOL $
[XQT VPRT $
  PRINT APPL FORC 1 1 $
  PRINT STAT DISP 1 1 $
  JOINTS 1,236,1 $
  FILTER=1,0,1,0,1,0,1,0,1,0,1,0 $
  PRINT STAT REAC 1 1 $
[XQT GSF $
  RESET L1=1,L2=5 $
$[XQT PSF $
$ RESET L1=1,L2=5 $
[XQT AUS $
 DEFINE S1=STRS E23 1 1 $
 DEFINE S2=STRS E23 1 2 $
 DEFINE S3=STRS E23 1 3 $
 DEFINE S4=STRS E23 1 4 $
 DEFINE S5=STRS E23 1 5 $
TABLE(NI=9,NJ=742):SONE TABL 1 1 $
  TRAN(SOURCE=S1,SBASE=0,ILIM=4,SSKIP=2,DBASE=0,DSKIP=5,JLIM=742) $
TABLE(NI=9,NJ=742):STWO TABL 1 1 $
  TRAN(SOURCE=S1,SBASE=5,ILIM=1,SSKIP=5,DBASE=4,DSKIP=8,JLIM=742) $
  TRAN(SOURCE=S2,SBASE=5,ILIM=1,SSKIP=5,DBASE=5,DSKIP=8,JLIM=742) $
  TRAN(SOURCE=S3,SBASE=5,ILIM=1,SSKIP=5,DBASE=6,DSKIP=8,JLIM=742) $
  TRAN(SOURCE=S4,SBASE=5,ILIM=1,SSKIP=5,DBASE=7,DSKIP=8,JLIM=742) $
  TRAN(SOURCE=S5,SBASE=5,ILIM=1,SSKIP=5,DBASE=8,DSKIP=8,JLIM=742) $
 DEFINE SS1=SONE TABL 1 1 $
 DEFINE SS2=STWO TABL 1 1 $
  STRS TABL 1 1=SUM(SONE,1.754-5 STWO) $
  STRS TABL 2 2=SUM(SONE,STWO) $
[XQT DCU $
 TOC 1 $
$  STRS TABL 1 1 CONTAINS RATIO OF ACTUAL STRESS TO ALLOWABLE STRESS
$   (ALLOWABLE STRESS = 57 KSI).
$  STRS TABL 2 2 CONTAINS ACTUAL STRESS VALUES.
  PRINT 1,STRS TABL 1 1 $
  PRINT 1,STRS TABL 2 2 $
```

Table I.- Pertinent Parameters for Three Catapult Cases

	Existing System	200 Knot Systems	
Catapult Stroke	122m (400 ft)	122m (400 ft)	183m (600 ft)
Volume of compressed air, m^3 (ft^3)	90.6 (3200)	136 (4800)	136 (4800)
Initial pressure of compressed air, MPa (psi)	22 (3200)	22 (3200)	22 (3200)
Initial jet velocity, m/sec (ft/sec)	201 (662)	210 (689)	210 (689)
Initial jet angle (water vessel angle), deg	0.9	0.9	1.345
Jet velocity of end of catapult stroke, m/sec (ft/sec)	187 (615)	191 (626)	192 (630)
Nozzle diameter, m (in.)	.182 (7.16)	.356 (14)	.279 (11)
Carriage mass, kg (lbm)	48 000 (106 000)	39 000 (85 000)	39 000 (85 000)
Maximum acceleration of carriage, g units	3	13.5	9
Maximum force on carriage, kN (lbf)	1414 (318 000)	5104 (1 147 000)	3403 (765 000)
Carriage velocity at end of catapult stroke, knots	112	203	197
Maximum jet trajectory height above nozzle, m (in.)	.475 (18.7)	.505 (19.9)	1.14 (44.7)
Estimated vertical opening of turning bucket, m (in.)	1.02 (40)	1.17 (46)	1.78 (70)
Water volume expelled, m^3 (gal)	11.7 (3100)	23.8 (6300)	22.33(5900)
Horizontal foundation load on water vessel, kN (lbf)	1054 (237 000)	4373 (983 000)	2700 (607 000)

Table II.- Mass Statement for Candidate Configuration

	First Sizing		Second Sizing	
Payload				
Small Test Article & Test Fixture	9072kg	(20 000 lbm)	9072kg	(20 000 lbm)
Non-Structural				
Wheels & Trucks (4 @ 1134kg (2500 lbm))	4536kg	(10 000 lbm)		
Instrument Cab	1815kg	(4 000 lbm)		
Propulsion Bucket	2041kg	(4 500 lbm)		
Arrest Nose Blocks (2 @ 340kg (750 lbm))	680kg	(1 500 lbm)		
	9072kg	(20 000 lbm)	9072kg	(20 000 lbm)
Structure				
Idealized structural mass for first sizing	18 551kg	(40 900 lbm)	15 875kg	(35 000 lbm)
Miscellaneous structural mass (10% of idealized)	1855kg	(4 090 lbm)	1588kg	(3 500 lbm)
	20 406kg	(44 990 lbm)	17 463kg	(38 500 lbm)
Total	38 550kg	(84 990 lbm)	35 607kg	(78 500 lbm)

Table III.- Characteristics of Candidate Carriage Structure

TOTAL MASS	For 9072kg (20 000 lbm) test article	35 607kg (78 500 lbm)
(Mass Statement given in Table II)	For 22 680kg (50 000 lbm) test article	49 215kg (108 500 lbm)

MATERIAL -	Type	HY 130
	Yield Strength	869 MPa (130 ksi)
	Allowable	393 MPa (57 ksi)

C. G. LOCATION

(X measured horizontally from wheel trucks)

(Z measured vertically from rail surface)

WITHOUT TEST ARTICLE	X_{CG} Z_{CG}	12.90m (508 in.) 1.91m (75 in.)
With 9072kg (20 000 lbm) test article in raised position at catapult	X_{CG} Z_{CG}	12.95m (510 in.) 2.95m (116 in.)
With 9072kg (20 000 lbm) test article in lowered position during test and arrest	X_{CG} Z_{CG}	12.95m (510 in.) 1.75m (69 in.)
With 22 680kg (50 000 lbm) test article in raised position at catapult	X_{CG} Z_{CG}	10.46m (412 in.) 3.23m (127 in.)
With 22 680kg (50 000 lbm) test article in lowered position during test and arrest	X_{CG} Z_{CG}	10.46m (412 in.) 1.52m (60 in.)

Table IV.- Characteristics of Candidate Carriage Structure

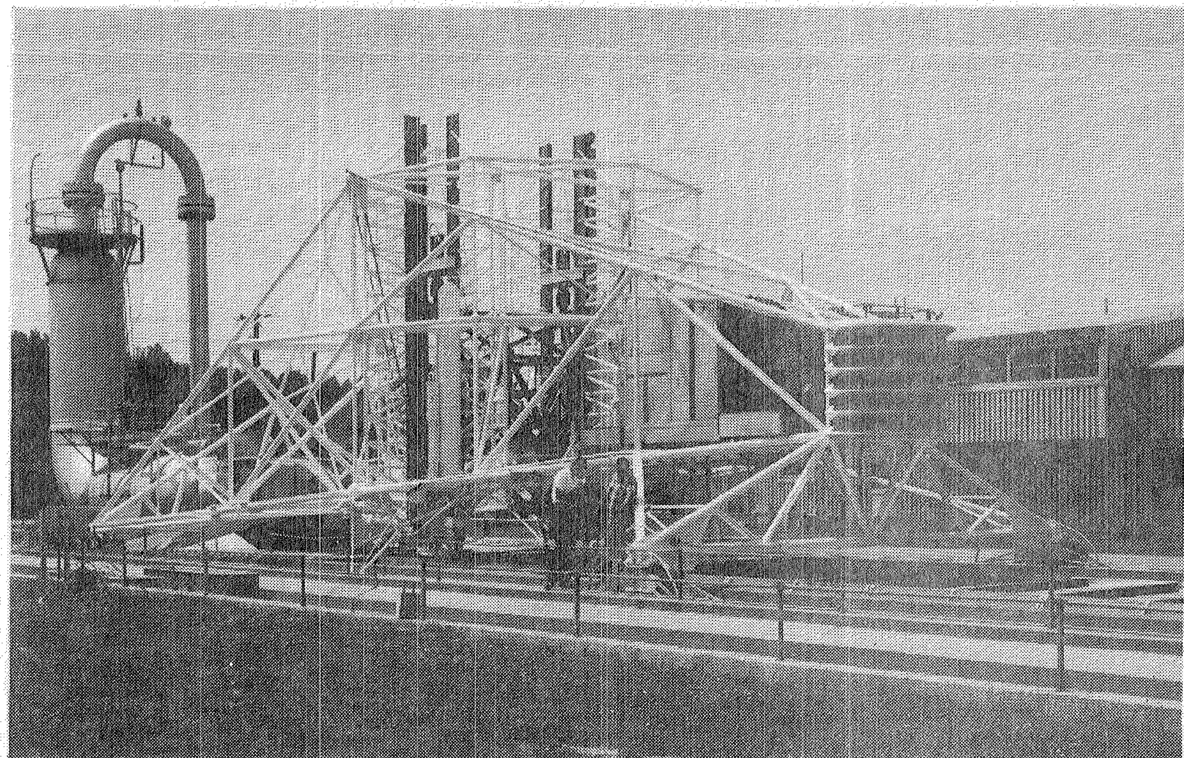
Maximum g-loading during catapult (calculated)	
For 9072kg (20 000 lbm) test article	14 g's
For 22 680kg (50 000 lbm) test article	10 g's
Maximum g-loading during arrest (assumed)	
For 9072kg (20 000 lbm) test article	5 g's
For 22 680kg (50 000 lbm) test article	4 g's
Maximum total holddown force during catapult	
For 9072kg (20 000 lbm) test article	357.6 kN (80 400 lbf)
For 22 680kg (50 000 lbm) test article	306.9 kN (69 000 lbf)
Deflection of support for 9072kg (20 000 lbm) test article during test	
For F_{drag} = 222.4 kN (50 000 lbf) and	Longitudinal Deflection= 0.74 cm (.29 in.)
F_{side} = 222.4 kN (50 000 lbf)	Side Deflection = 2.08 cm (.82 in.)

Table V.- Tubes Used for Carriage Structure Design

Sectional Number Used in SPAR Analysis	Nominal Diameter cm	(in)	Outside Diameter cm	(in)	Inside Diameter cm	(in)	Area cm^2	(in^2)	Inertia cm^4	(in^4)	Total Length Used in Carriage m	(ft)	Total Mass kg	(lb)
10	5.08	(2)	6.033	(2.375)	5.250	(2.067)	6.936	(1.075)	27.721	(.666)	462.1	(1516)	2661	(5867)
14	5.08	(2*)	6.033	(2.375)	4.925	(1.939)	9.529	(1.477)	36.129	(.868)	48.5	(159)	383	(845)
17	6.35	(2 ½)	7.303	(2.875)	6.271	(2.469)	10.994	(1.704)	63.683	(1.530)	11.6	(38)	106	(233)
22	7.62	(3)	8.890	(3.500)	7.793	(3.068)	14.374	(2.228)	125.577	(3.017)	179.8	(590)	2146	(4732)
26	8.89	(3 ½)	10.160	(4.000)	9.012	(3.548)	17.290	(2.680)	199.292	(4.788)	88.1	(289)	1265	(2788)
31	10.16	(4)	11.430	(4.500)	10.226	(4.026)	20.477	(3.174)	301.060	(7.233)	281.0	(922)	4779	(10535)
36	8.89	(3 ½*)	10.160	(4.000)	8.545	(3.364)	23.729	(3.678)	261.393	(6.280)	-		-	
40	6.35	(2 ½**)	7.303	(2.875)	4.498	(1.771)	25.987	(4.028)	119.500	(2.871)	-		-	
43	12.70	(5)	14.130	(5.563)	12.819	(5.047)	27.742	(4.300)	631.007	(15.16)	-		-	
55	15.24	(6)	16.828	(6.625)	15.405	(6.065)	36.006	(5.581)	1171.275	(28.14)	78.6	(258)	2351	(5184)
61	12.70	(5)	14.130	(5.563)	12.225	(4.813)	39.432	(6.112)	860.350	(20.67)	8.5	(28)	279	(616)
84	15.24	(6*)	16.828	(6.625)	14.633	(5.761)	54.226	(8.405)	1685.321	(40.49)	42.7	(140)	1921	(4236)
													15892	(35036)

* Extra Strong

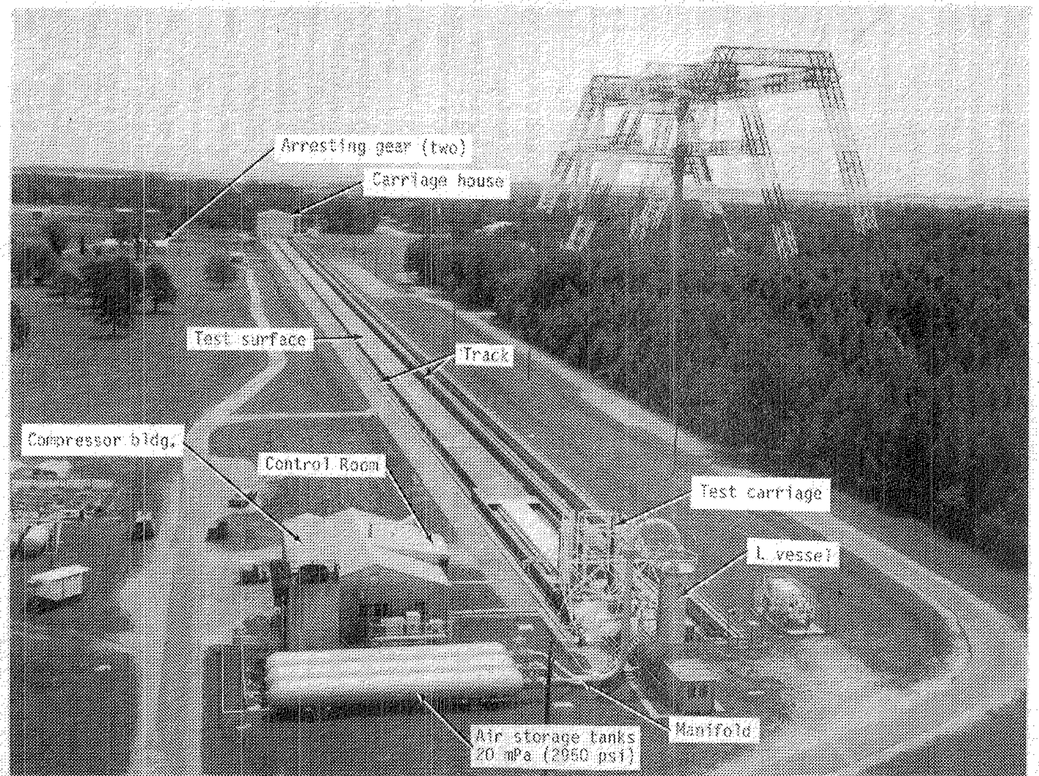
** Double-Extra Strong



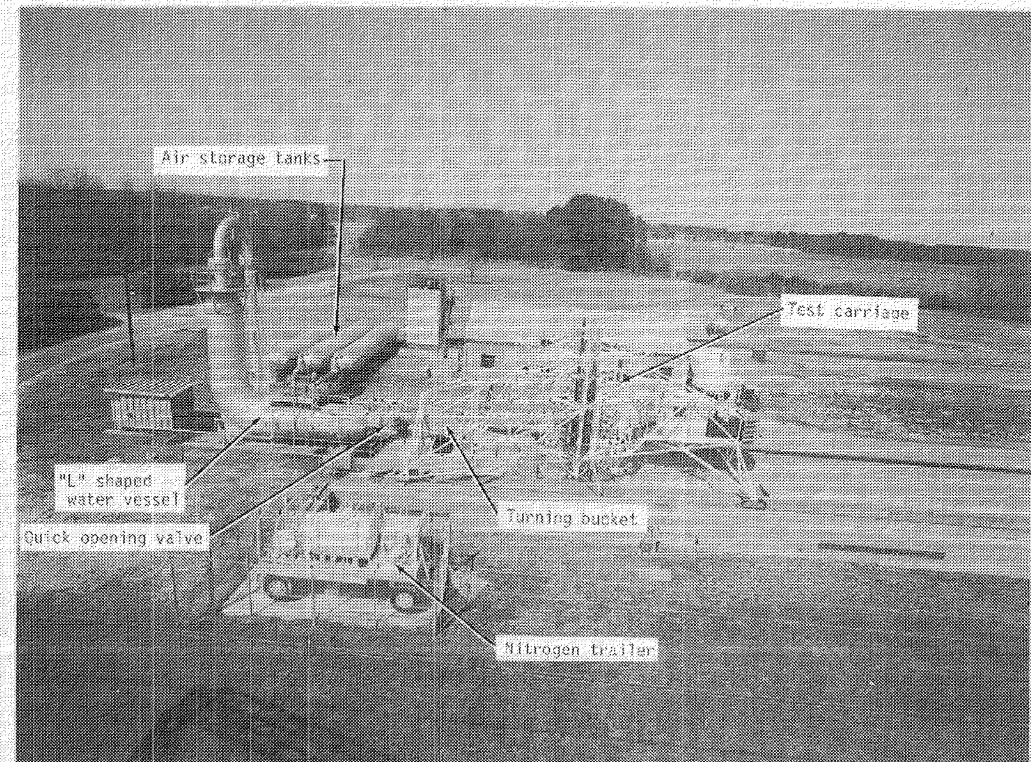
(a) Large carriage, 48 000 kg (106 000 lbm)

(b) Small carriage 29 000 kg (65 000 lbm)

Figure 1.- Test carriages used at the Landing Loads and Traction Facility



(a) Overall view



(b) Closeup view

Figure 2.- Hydraulic jet catapult system at the Landing Loads and Traction Facility

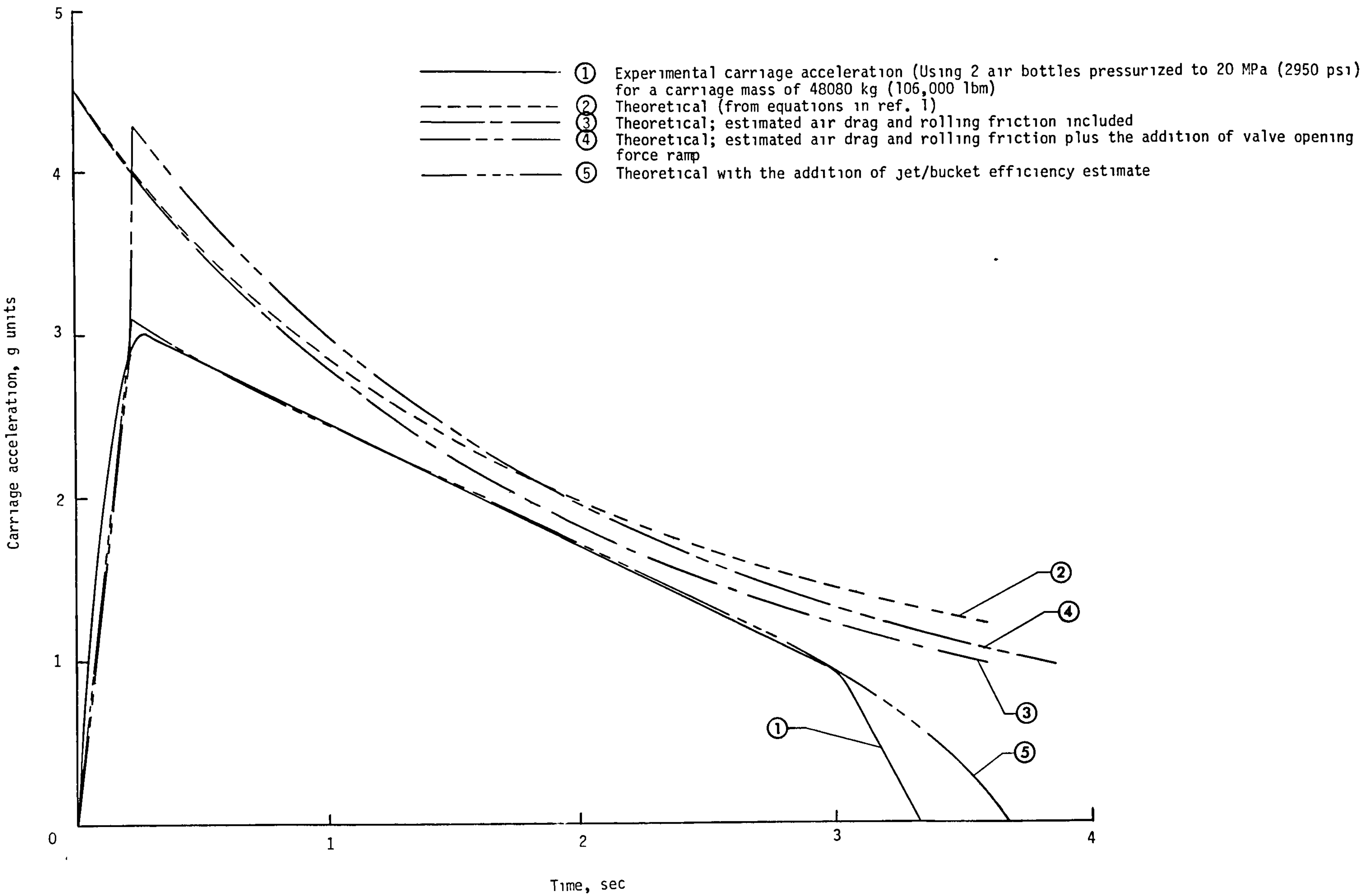


Figure 3.- Actual and calculated carriage acceleration time histories used in the development of equations to describe the existing catapult stroke.

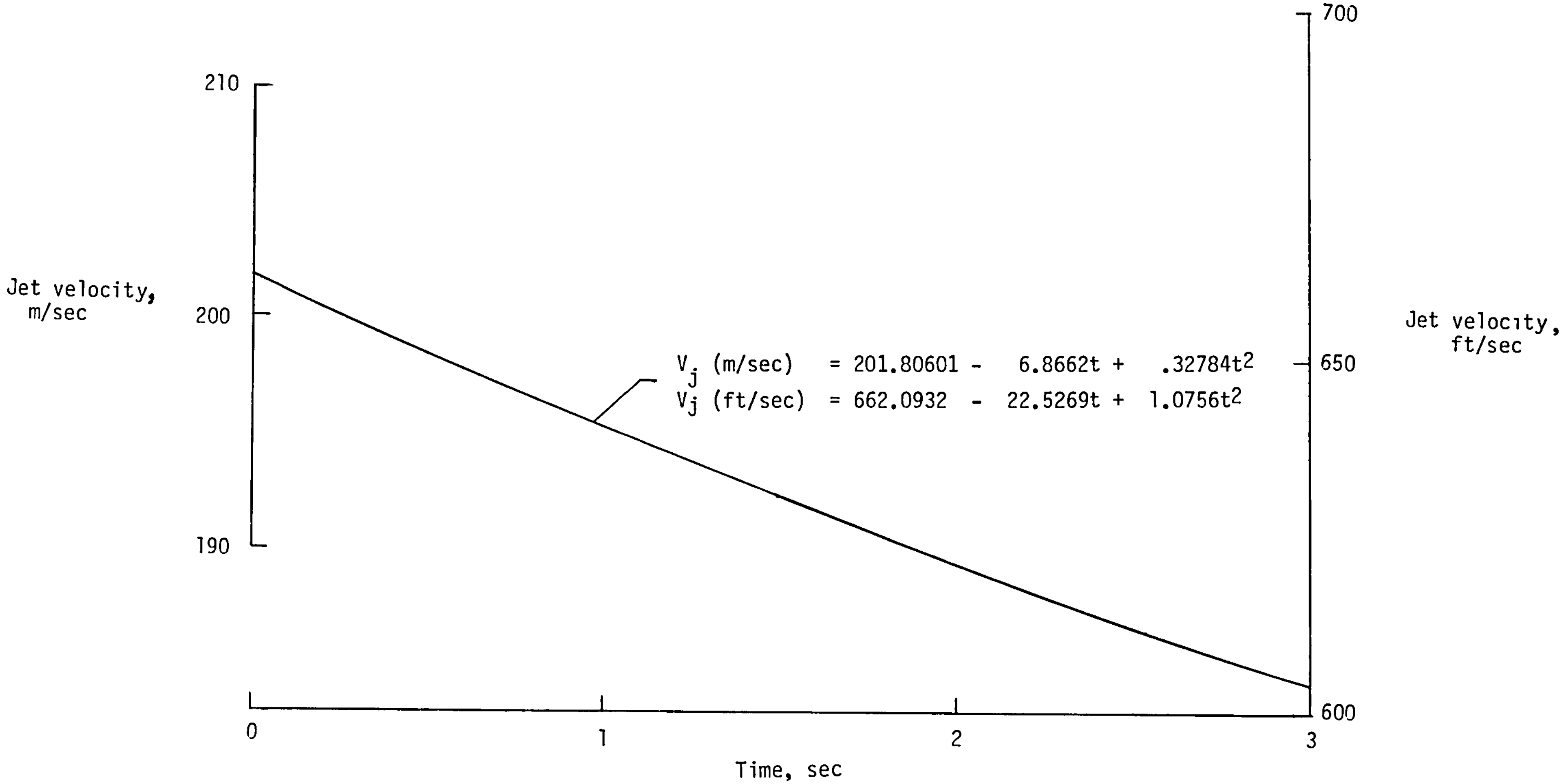


Figure 4.- Calculated water jet velocity for 2 existing air bottles pressurized to 20 MPa (2950 psi) assuming an instantaneous valve opening and a nozzle diameter of 0.182 m (7.16 in.).

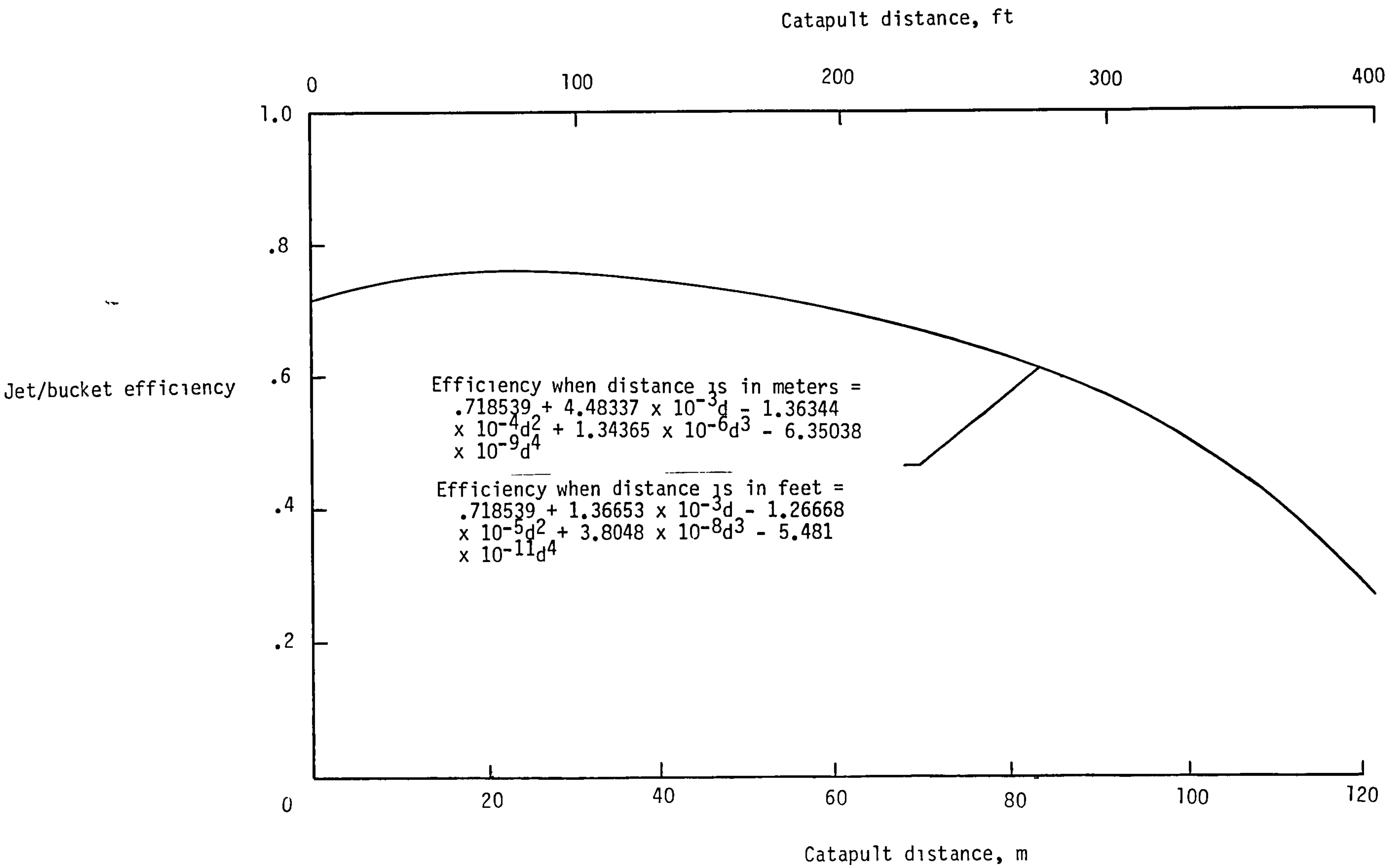


Figure 5.- Estimated efficiency for combination of water jet and turning bucket during catapult stroke.

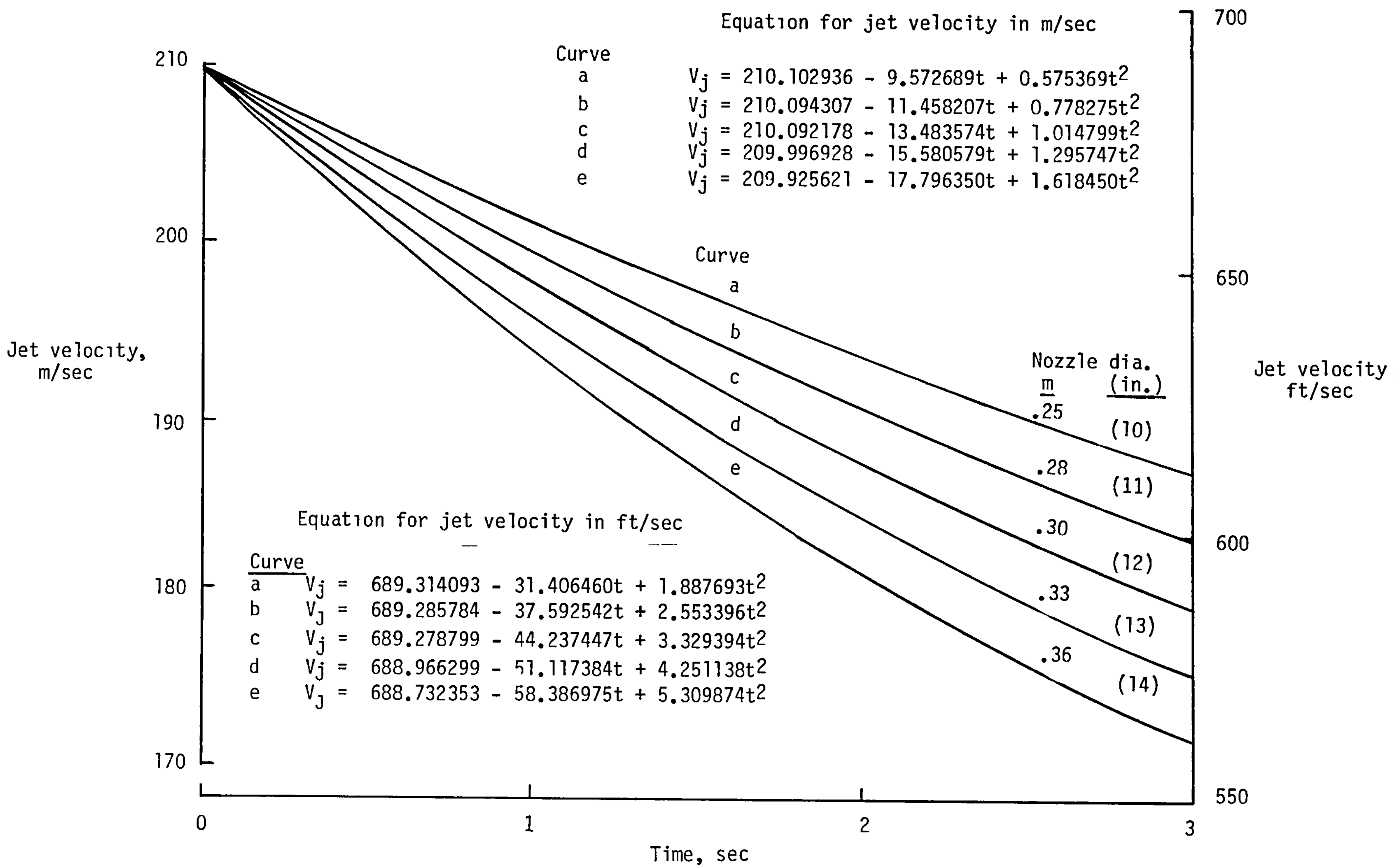
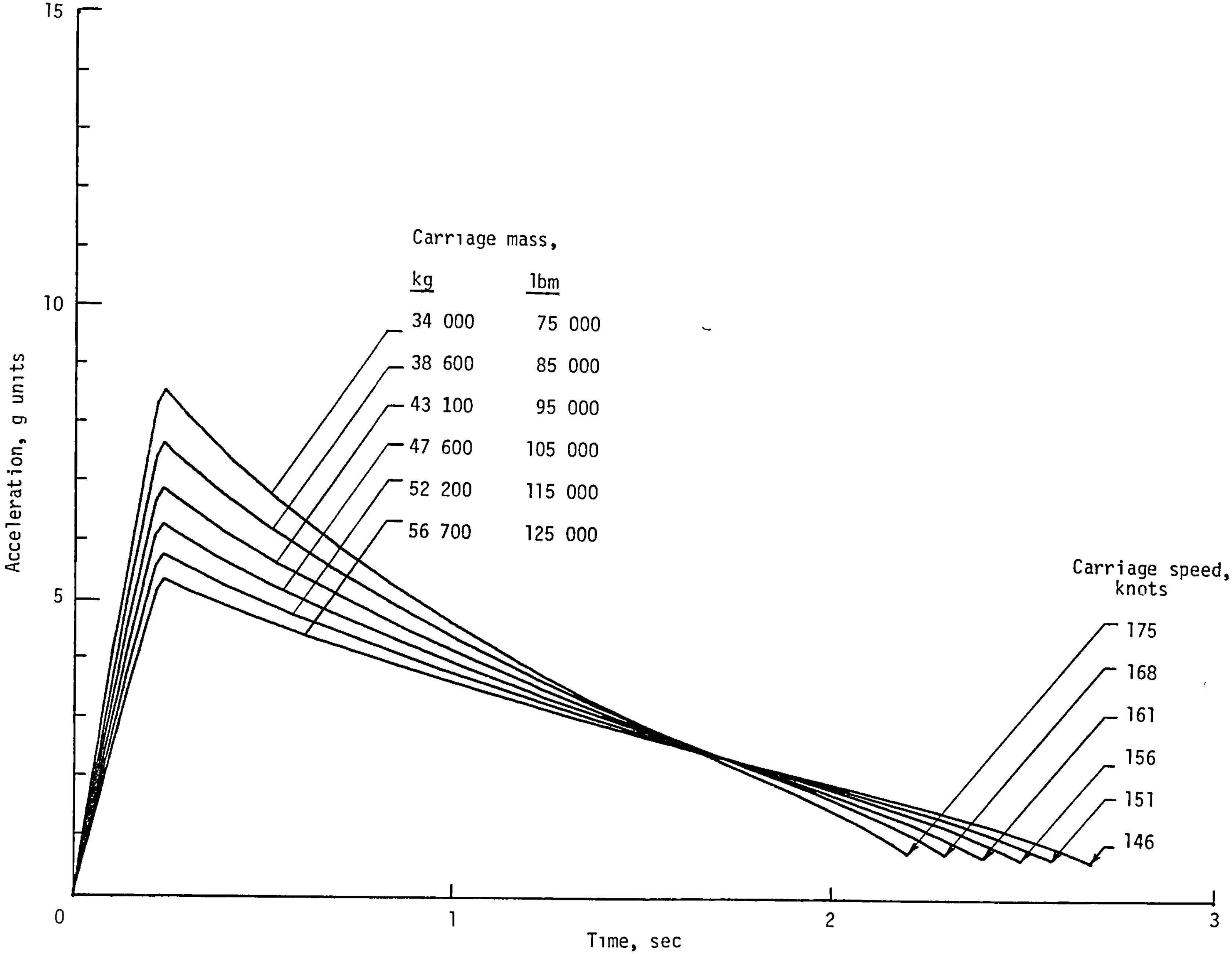
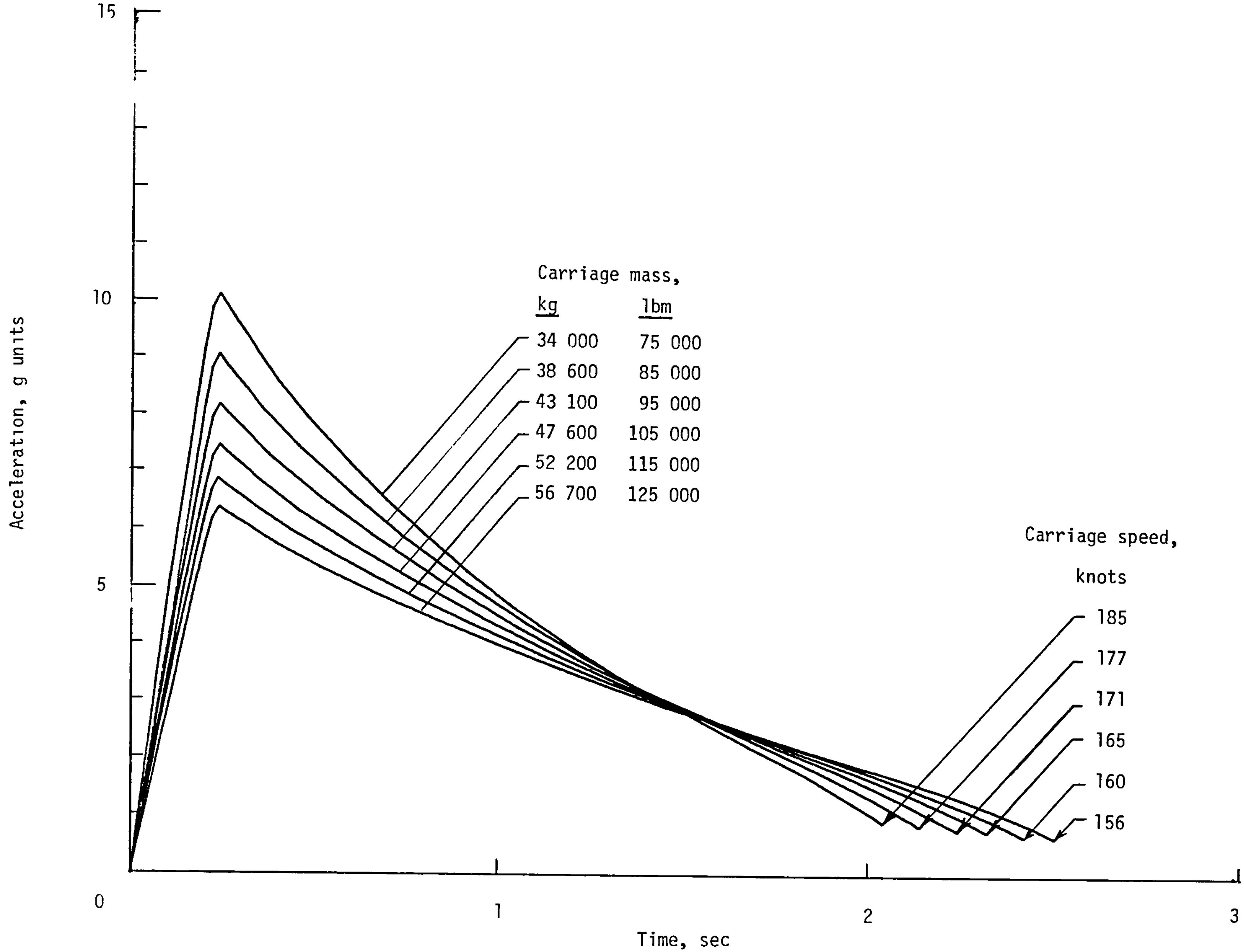


Figure 6.- Calculated water jet velocity (maximum) for three (3) existing air bottles pressurized to 22 MPa (3200 psi) assuming an instantaneous opening of the valve.



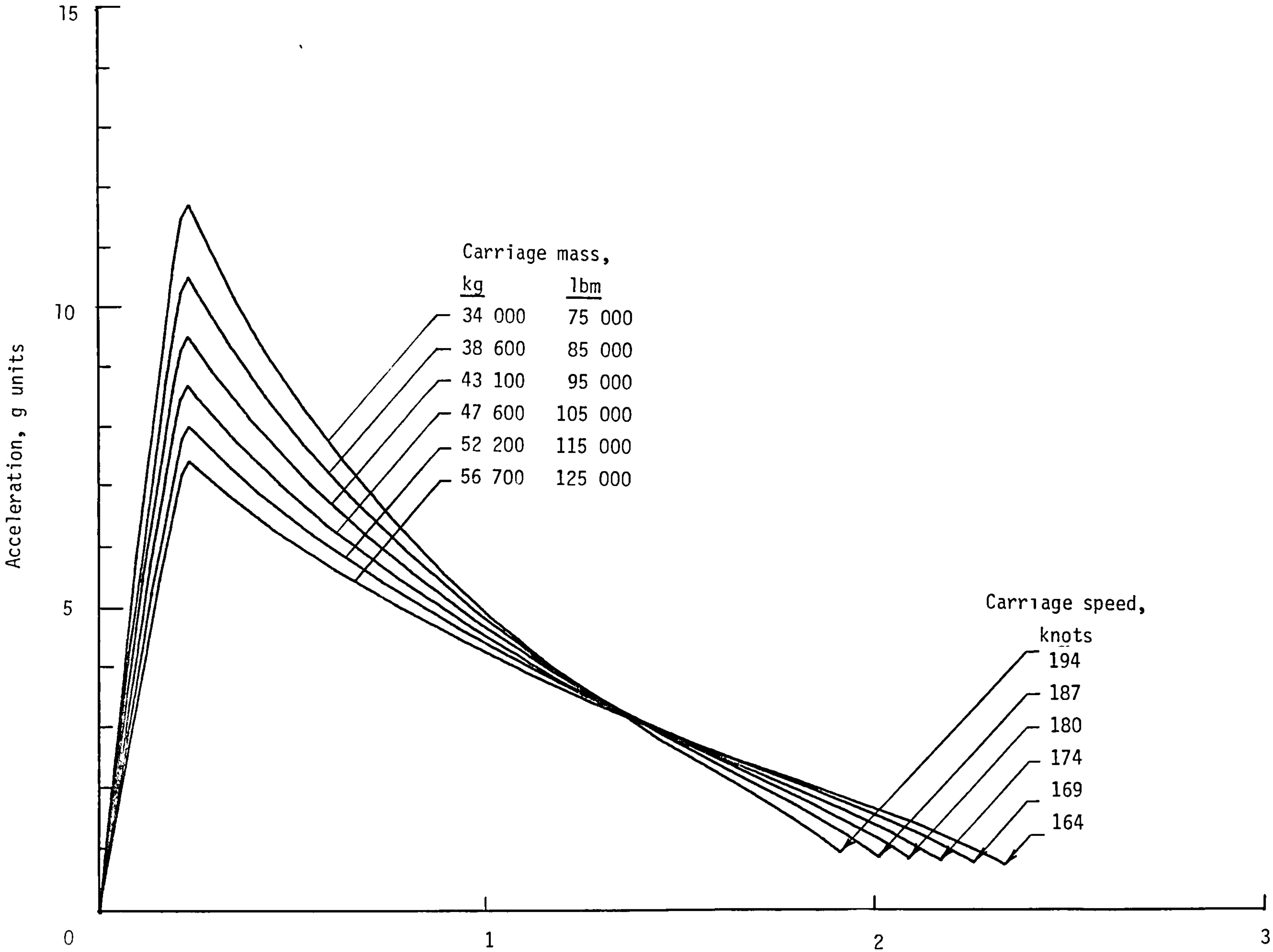
(a) Nozzle diameter, 0.25 m (10 in.)

Figure 7.- Carriage acceleration and maximum velocity for a 122 m (400 ft) catapult stroke using three (3) air bottles pressurized to 22 mPa (3200 psi) and a carriage frontal area of 41.8 m^2 (450 ft^2).



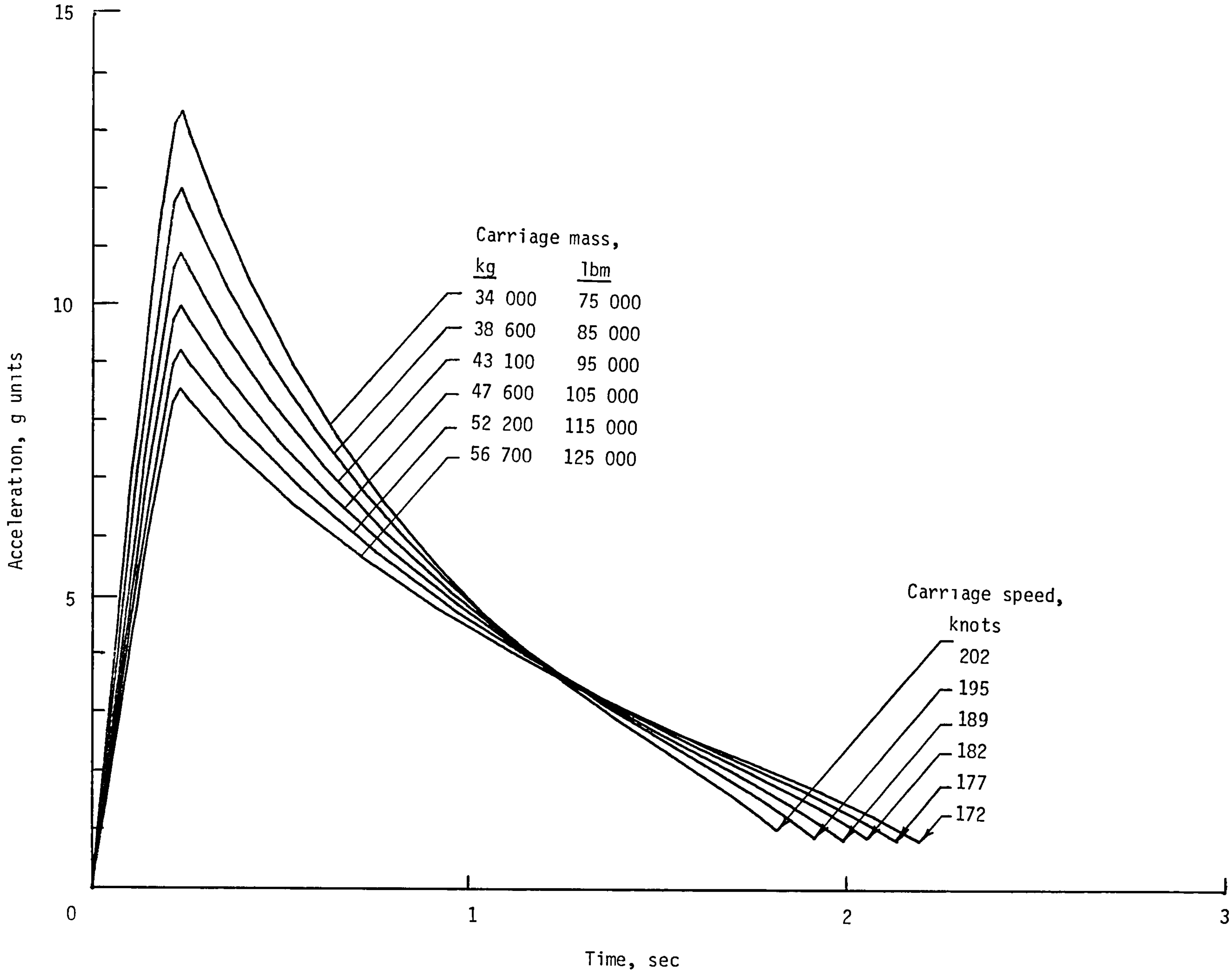
(b) Nozzle diameter, 0.28 m (11 in.)

Figure 7.- Continued.



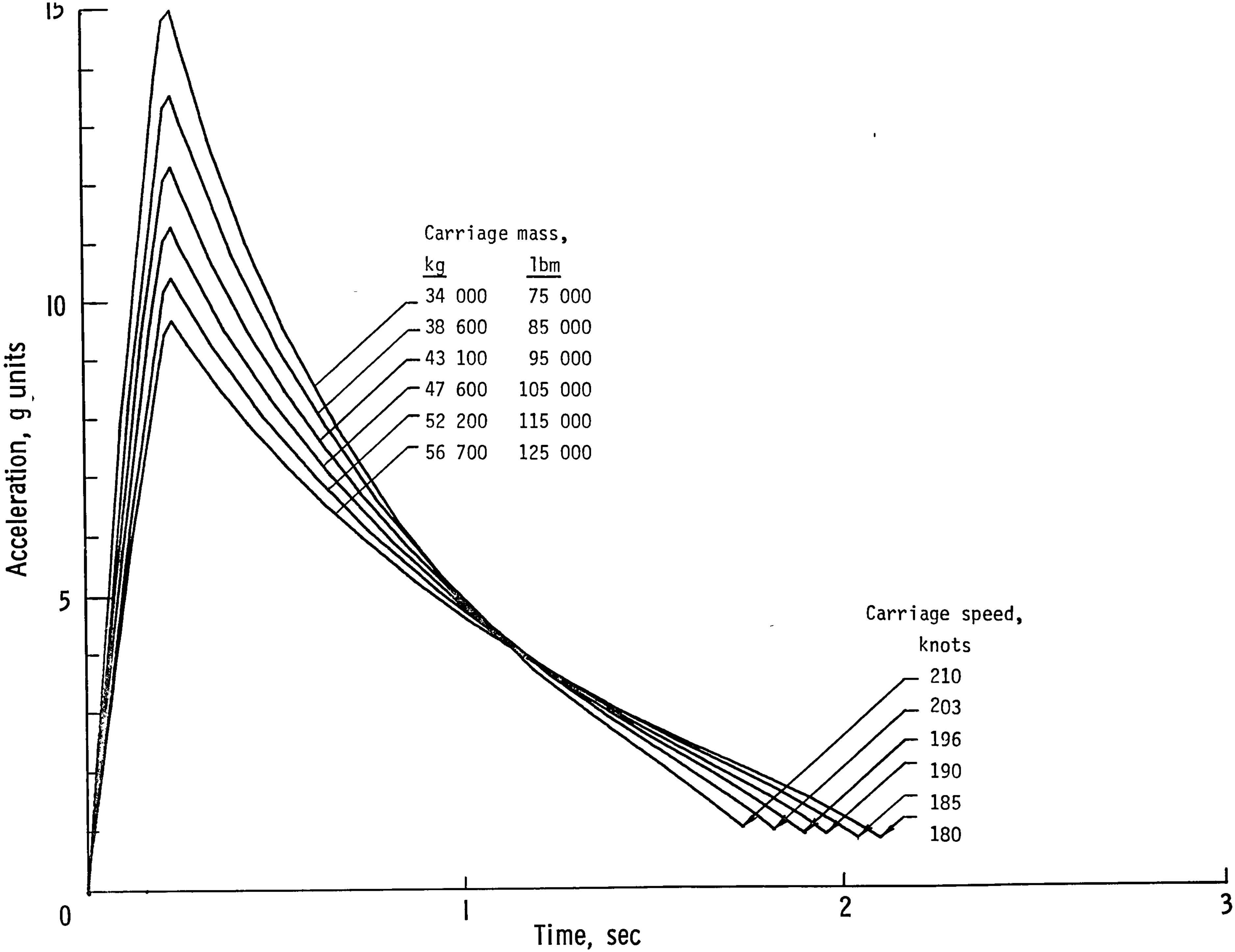
(c) Nozzle diameter, 0.30 m (12 in.)

Figure 7.- Continued.



(d) Nozzle diameter, 0.33 m (13 in.)

Figure 7.- Continued.



(e) Nozzle diameter, 0.36m (14 in)

Figure 7.- Concluded.

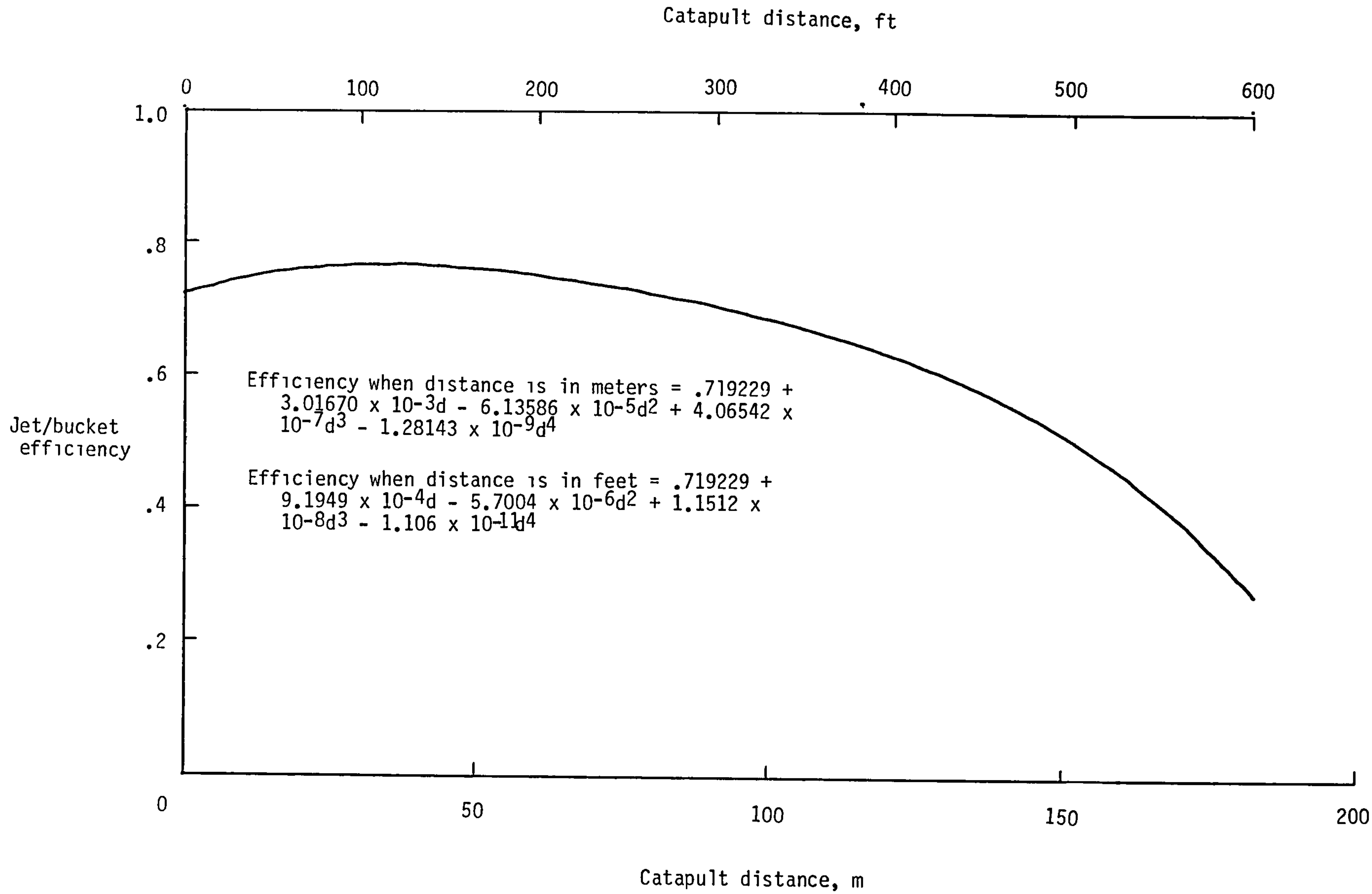
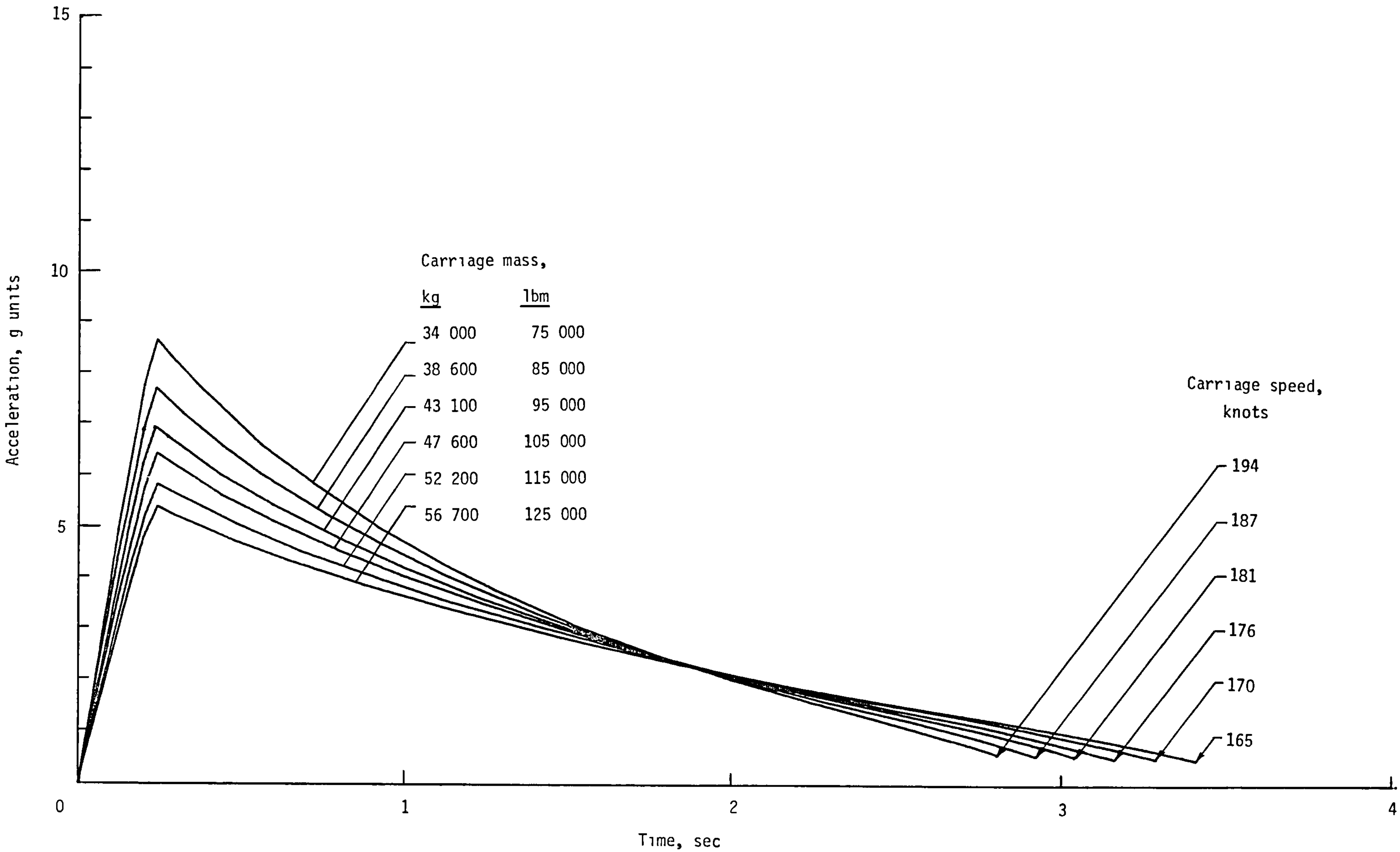
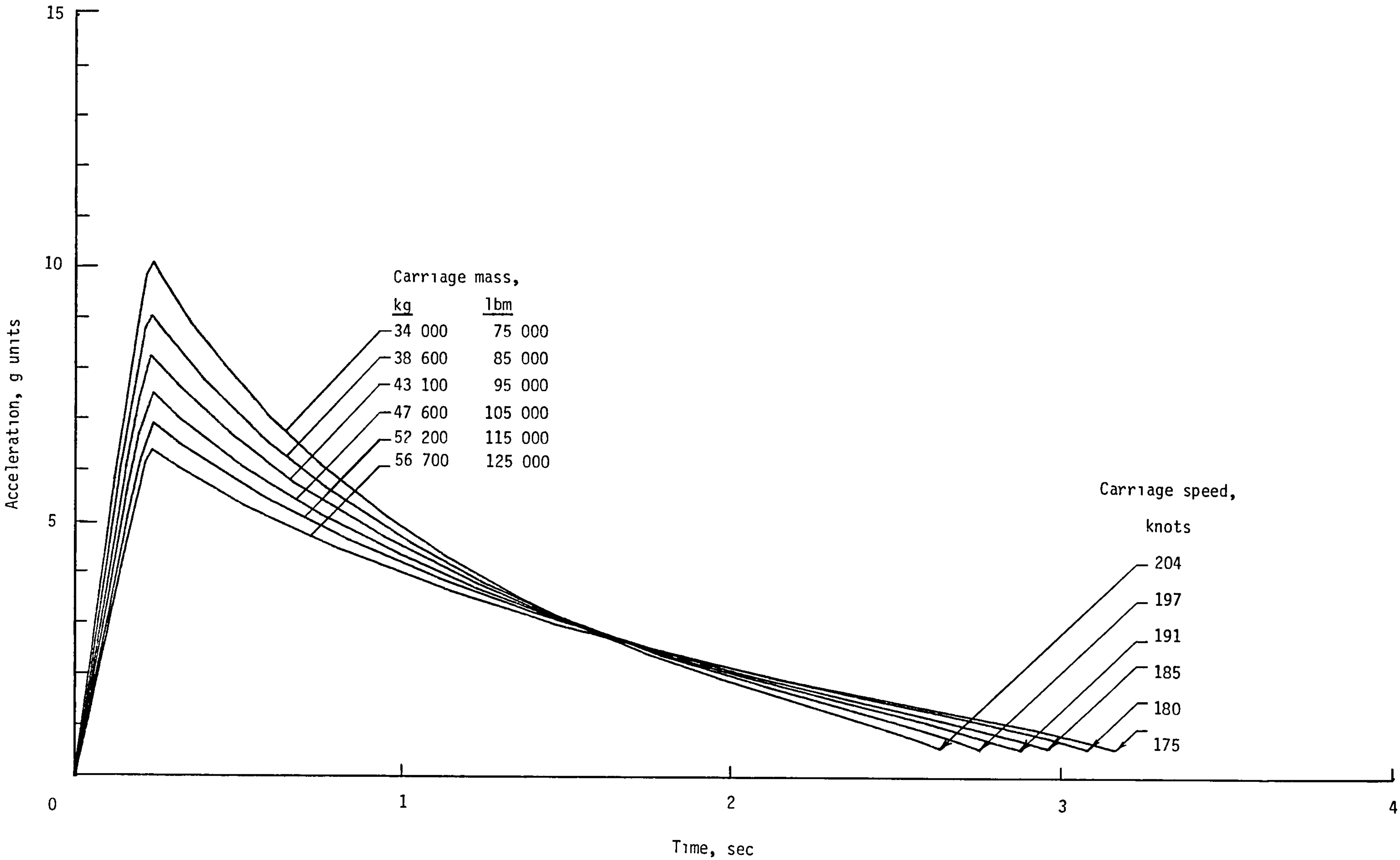


Figure 8.- Hypothesized efficiency for combination of water jet and turning bucket during 183 m (600 ft) catapult stroke (Estimated efficiency curve of figure 5 stretched to 183 m (600 ft).



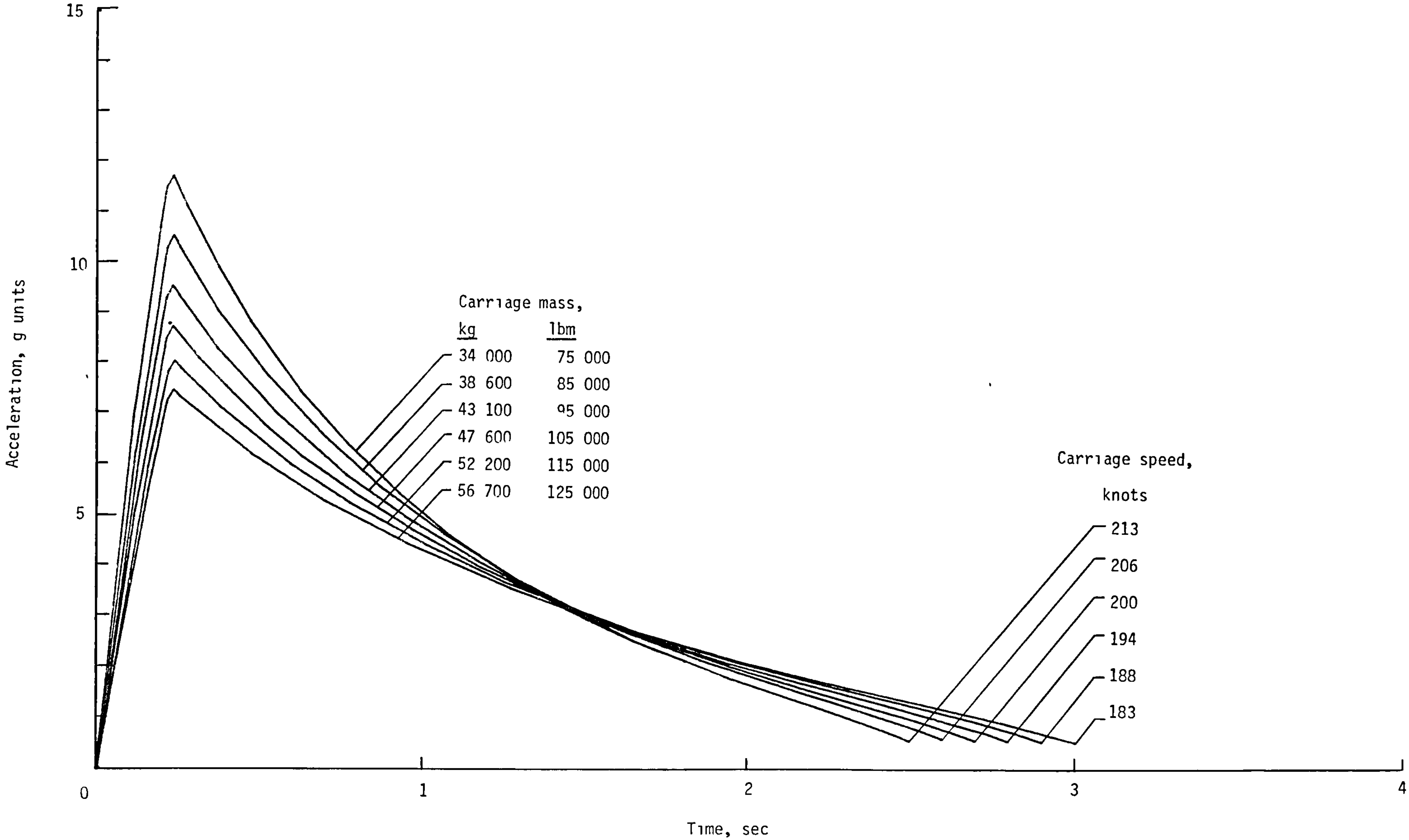
(a) Nozzle diameter 0.25 m (10 in.)

Figure 9.- Carriage acceleration and maximum velocity for a 183 m (600 ft) catapult stroke using three (3) air bottles pressurized to 22 mPa (3200 psi) and a carriage frontal area of 41.8 m^2 (450 ft^2).



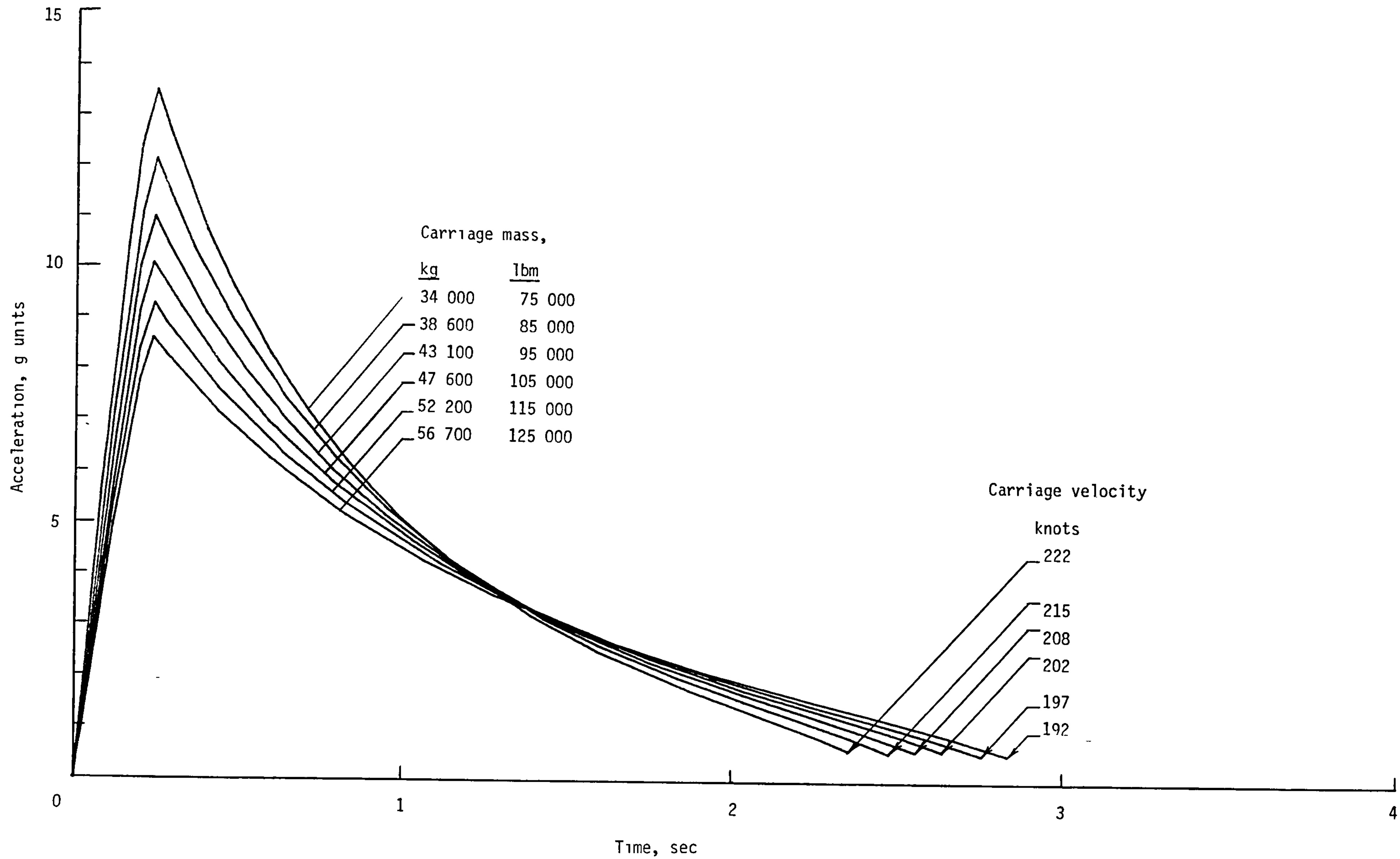
(b) Nozzle diameter 0.28 m (11 in.)

Figure 9.- Continued.



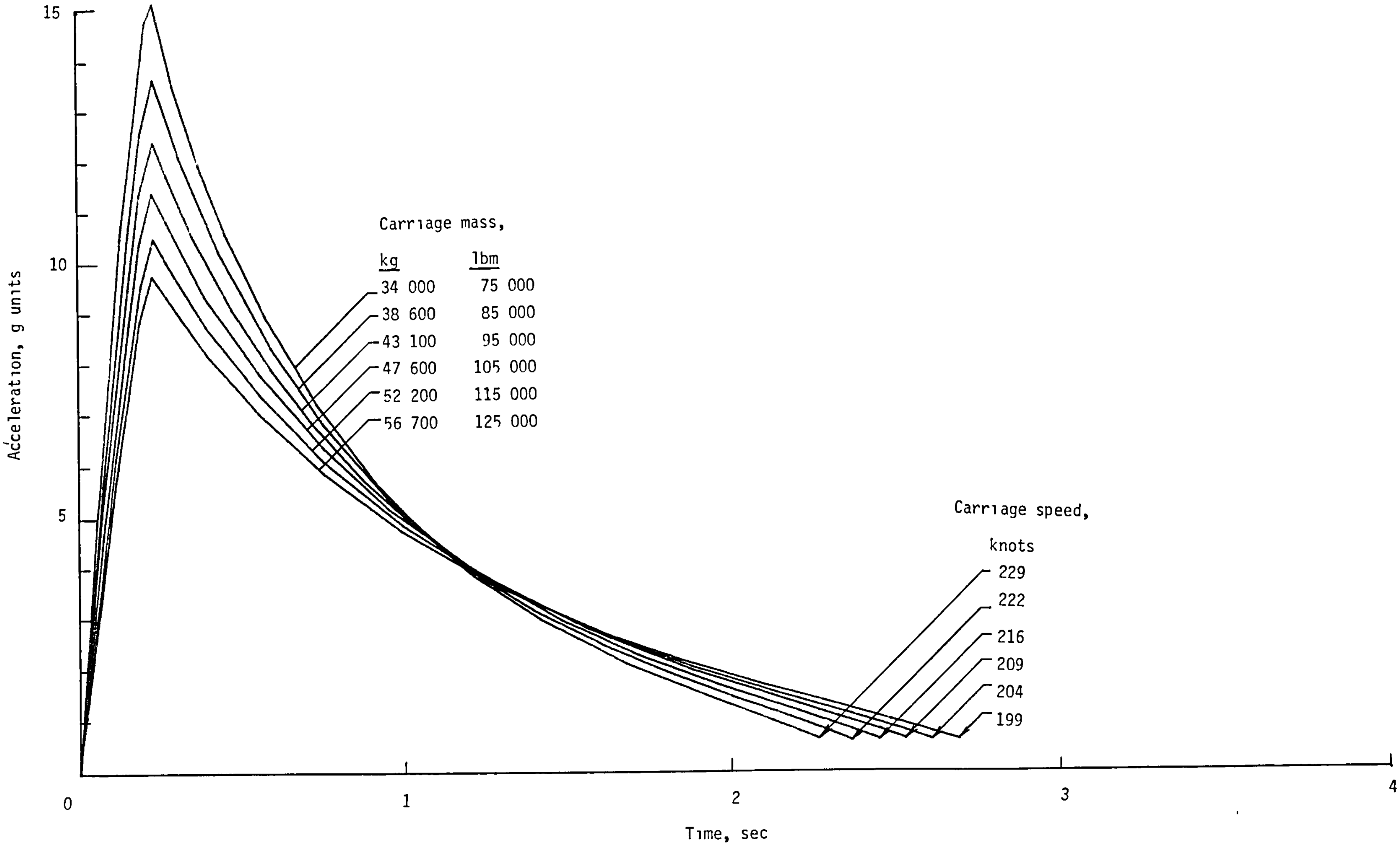
(c) Nozzle diameter 0.30 m (12 in.)

Figure 9. - Continued.



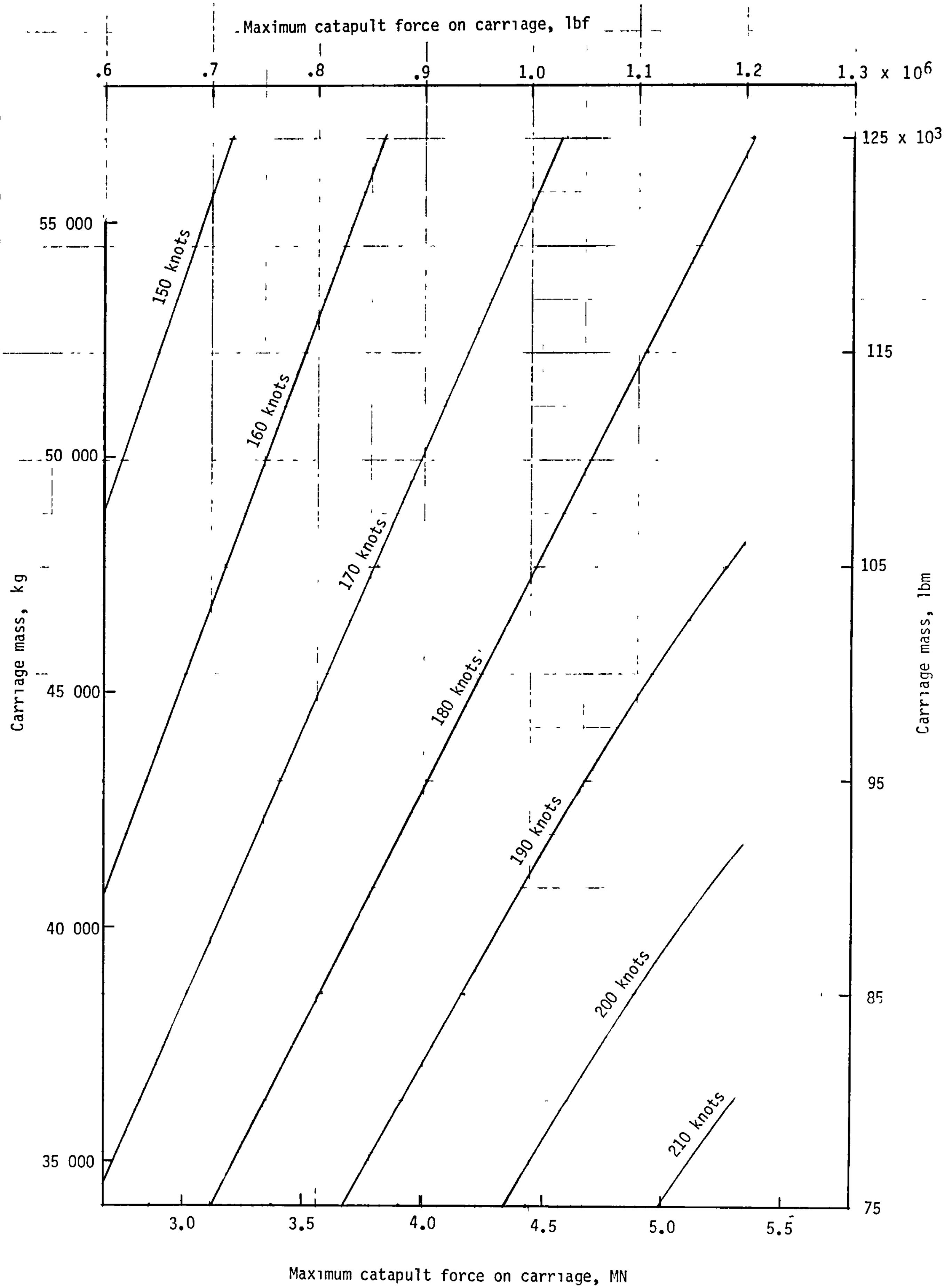
(d) Nozzle diameter, 0.33 m (13 in.)

Figure 9.- Continued.



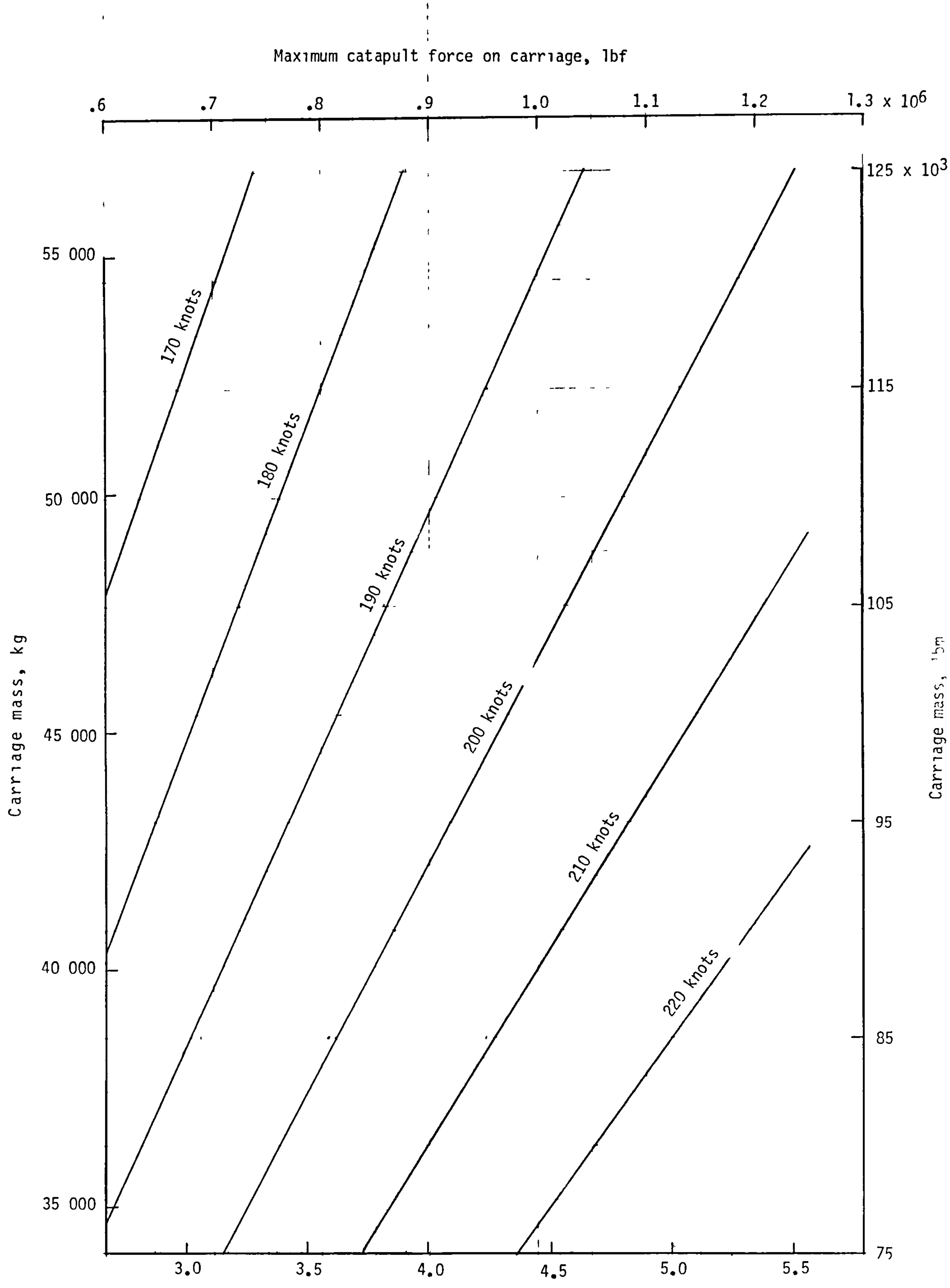
(e) Nozzle diameter 0.36 m (14 in.)

Figure 9.- Concluded.



(a) 122 m (400 ft) catapult stroke

Figure 10.- Maximum force on carriage at the point of peak acceleration during catapult.



Maximum catapult force on carriage, MN

(b) 183 m (600 ft) catapult stroke

Figure 10.- Concluded.

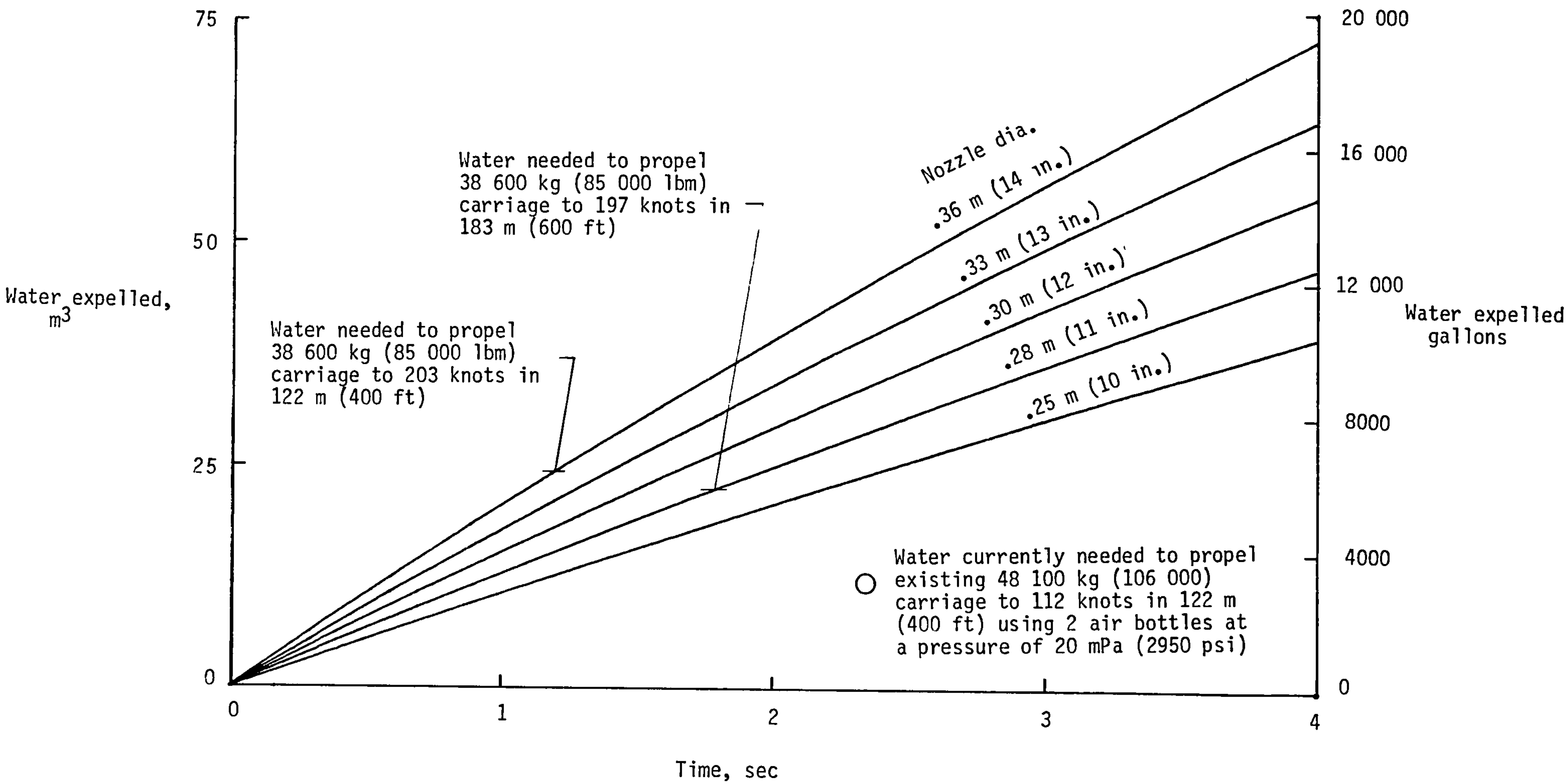
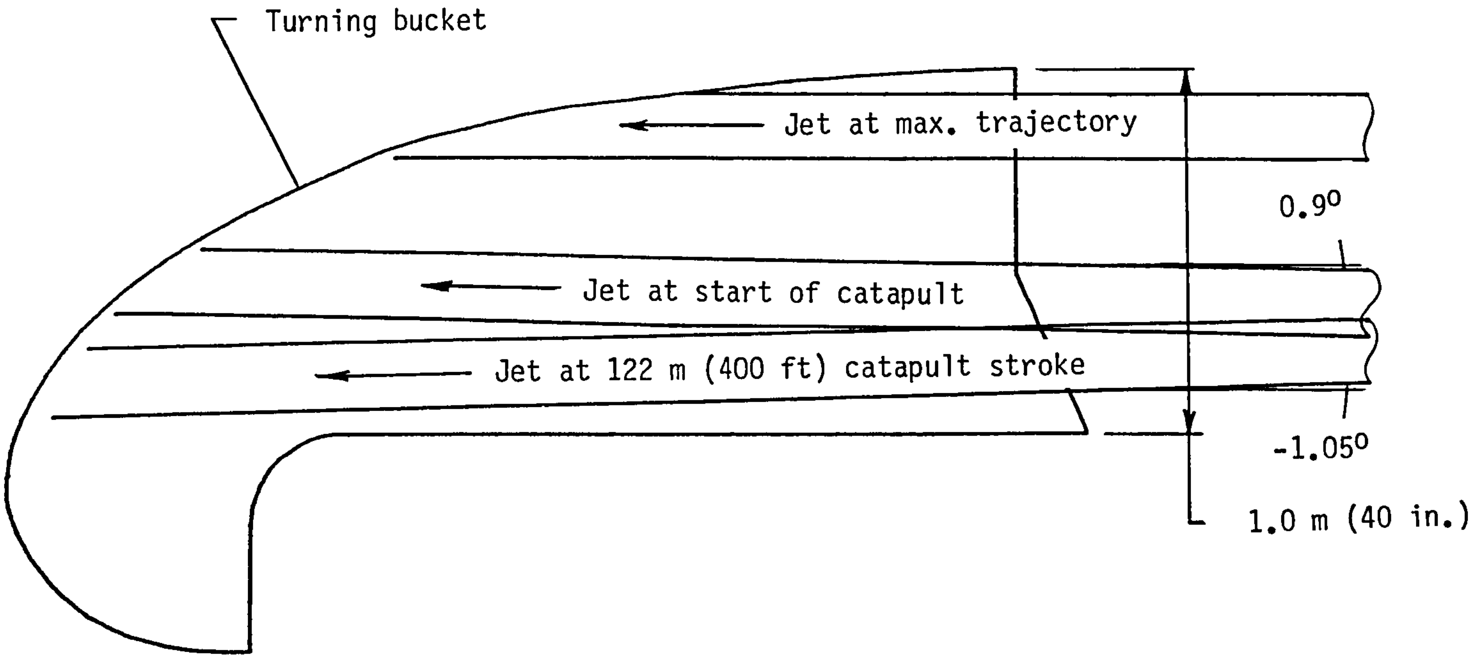
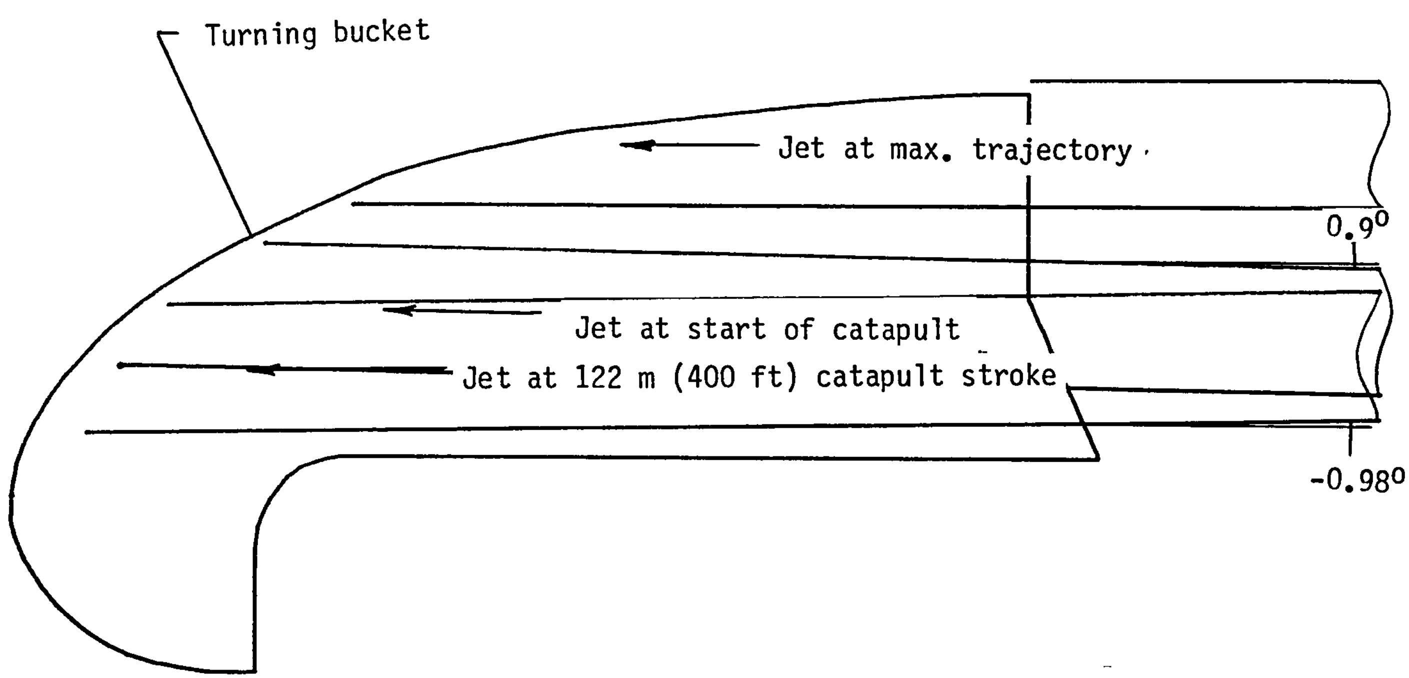


Figure 11.- Water consumption for various nozzle sizes using 3 air bottles at an initial pressure of 22 mPa (3200 psi).



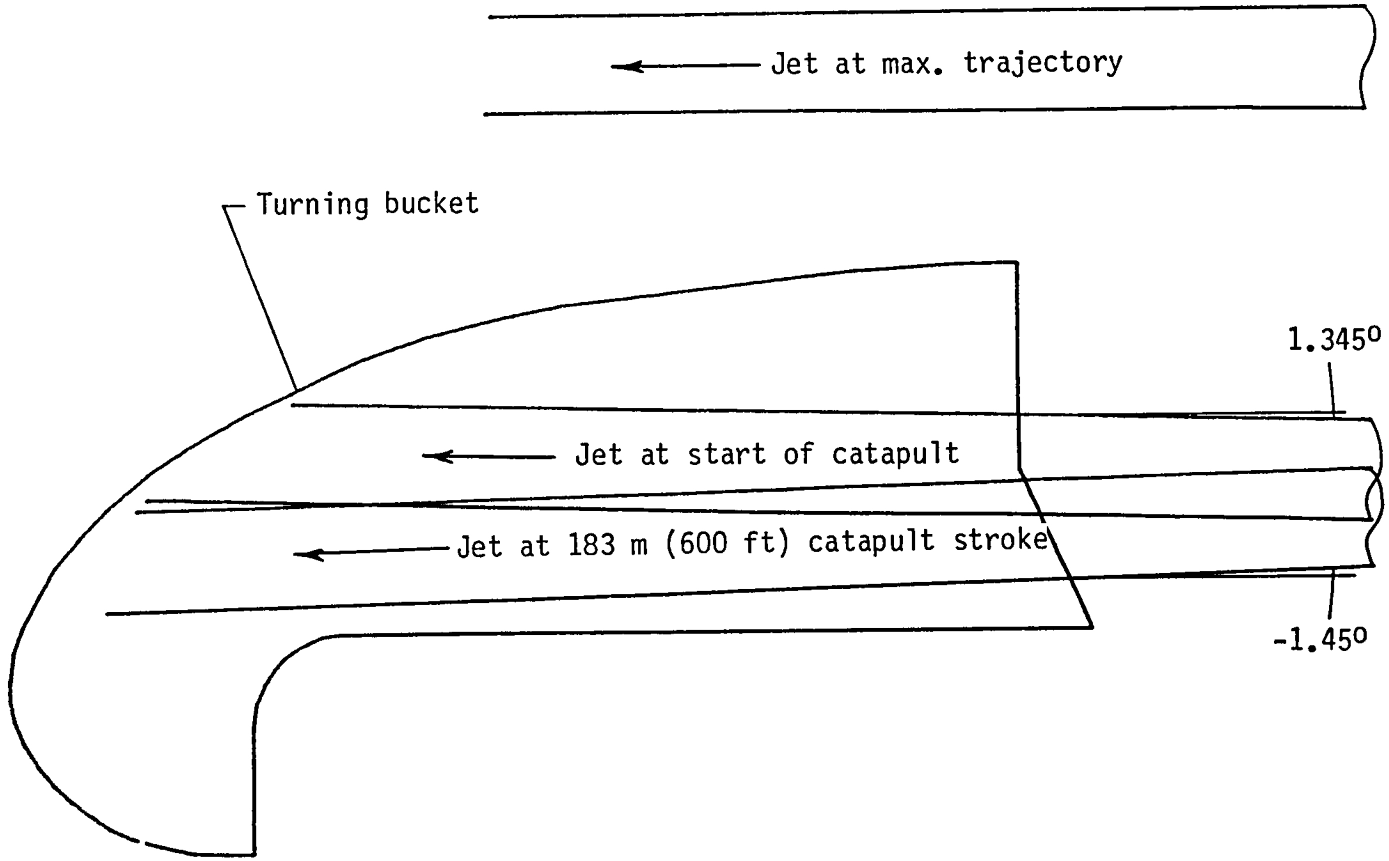
(a) Current catapult design using 2 air bottles pressurized to 20 mPa (2950 psi)
(Nozzle diameter 0.182 m (7.16 in.))

Figure 12.- Theoretical position of water jet with respect to existing carriage bucket size and location.



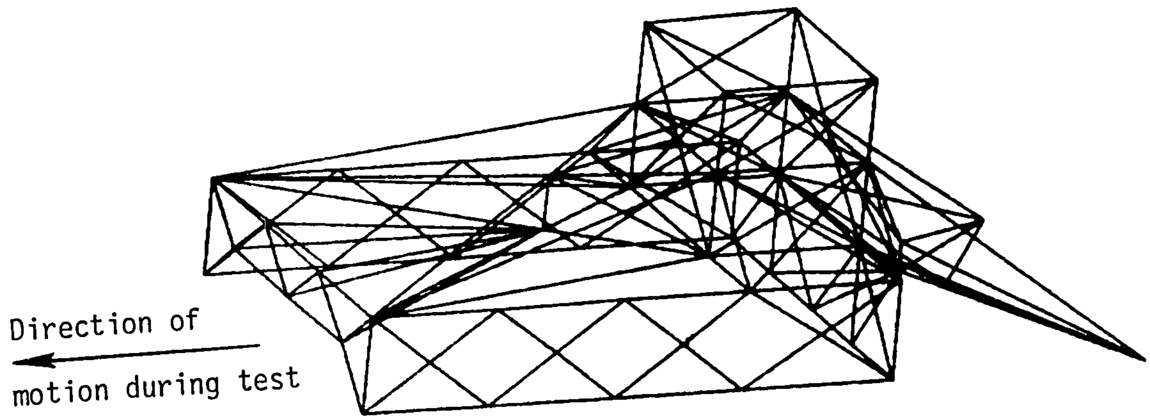
(b) Trajectory using 3 air bottles pressurized to 22 mPa (3200 psi) for a catapult stroke of 122 m (400 ft) (Nozzle diameter 0.36 m (14 in.))

Figure 12.- Continued.

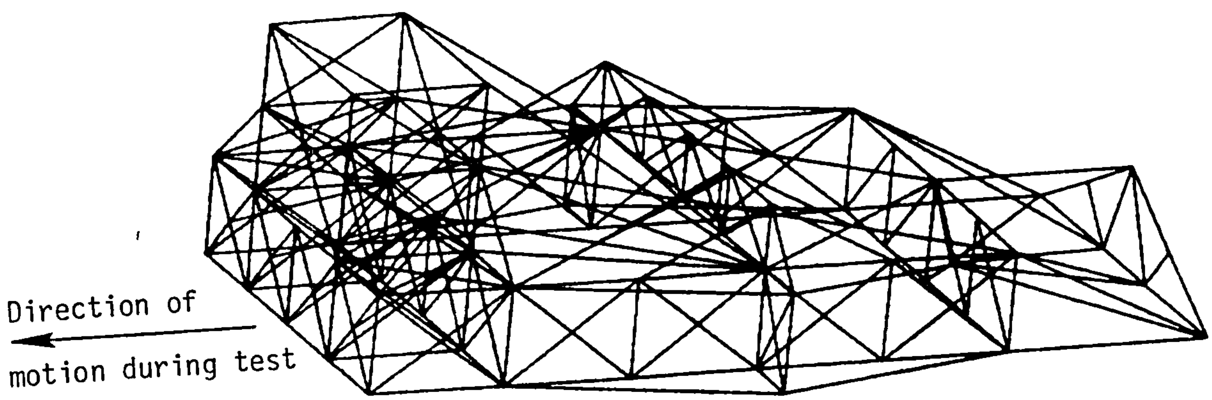


(c) Trajectory using 3 air bottles pressurized to 22 mPa (3200 psi) for a catapult stroke of 183 m (600 ft) (Nozzle diameter 0.28 m (11 in.))

Figure 12.- Concluded.

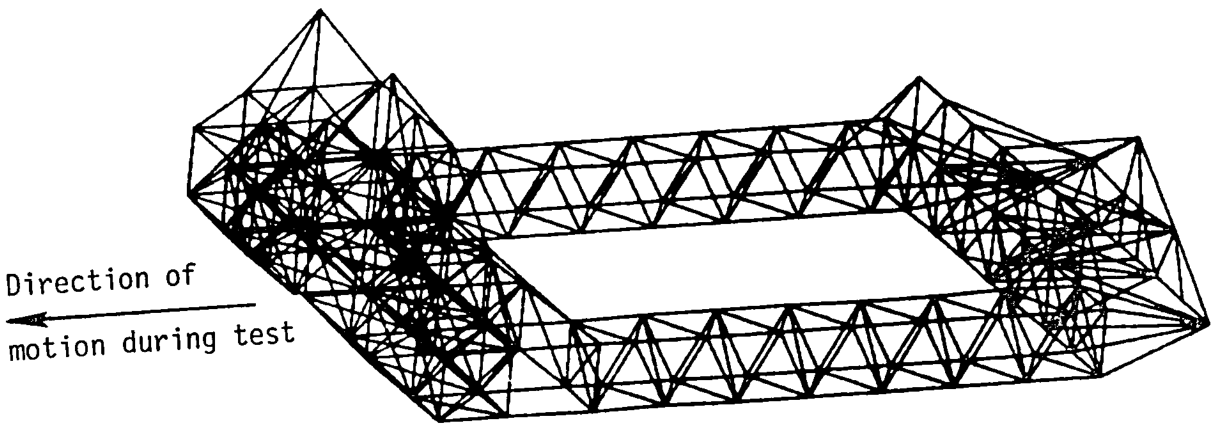


(a) Configuration 1.

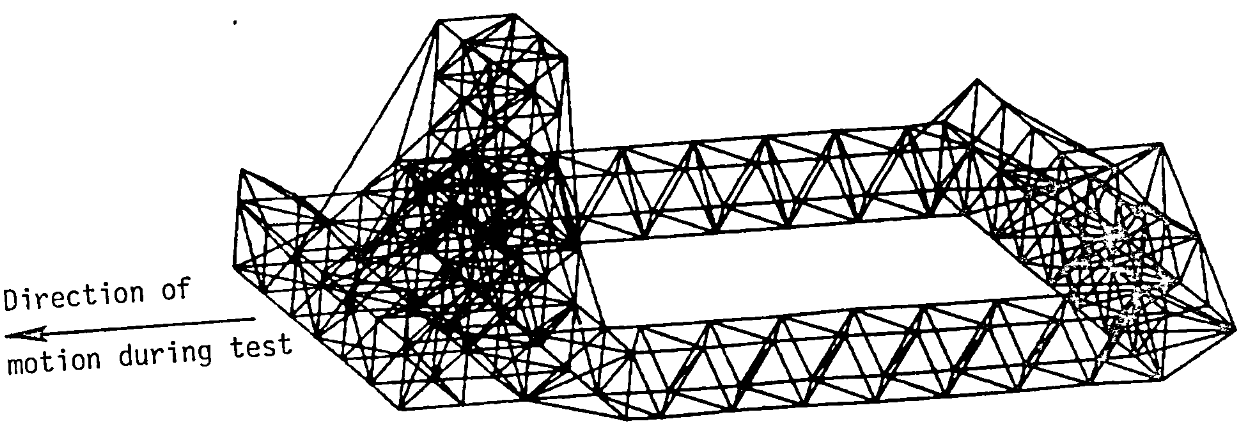


(b) Configuration 2.

Figure 13.- Computer aided design of preliminary carriage structural configurations.



(c) Configuration 3.



(d) Configuration 4.

Figure 13.- Concluded.

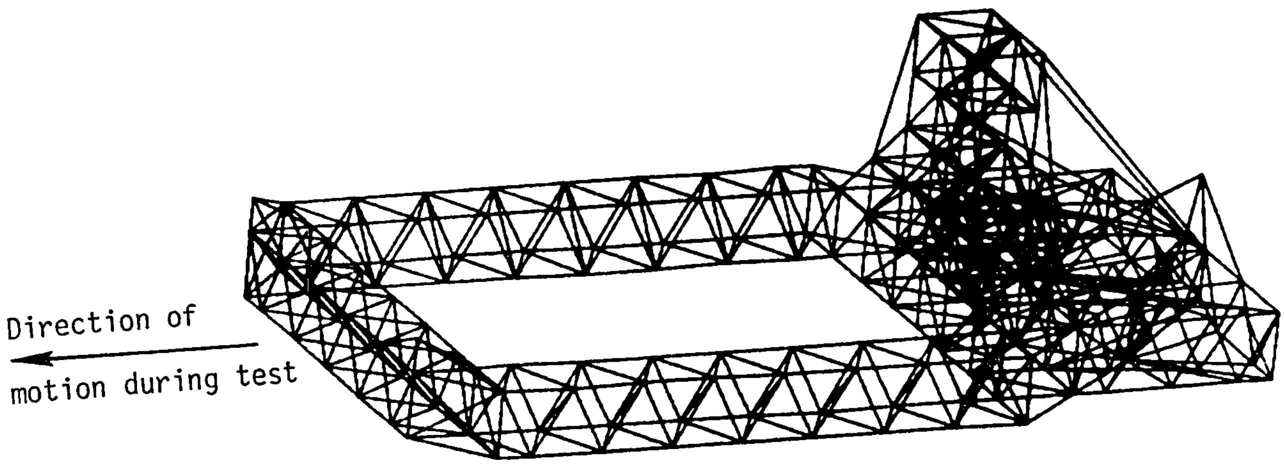
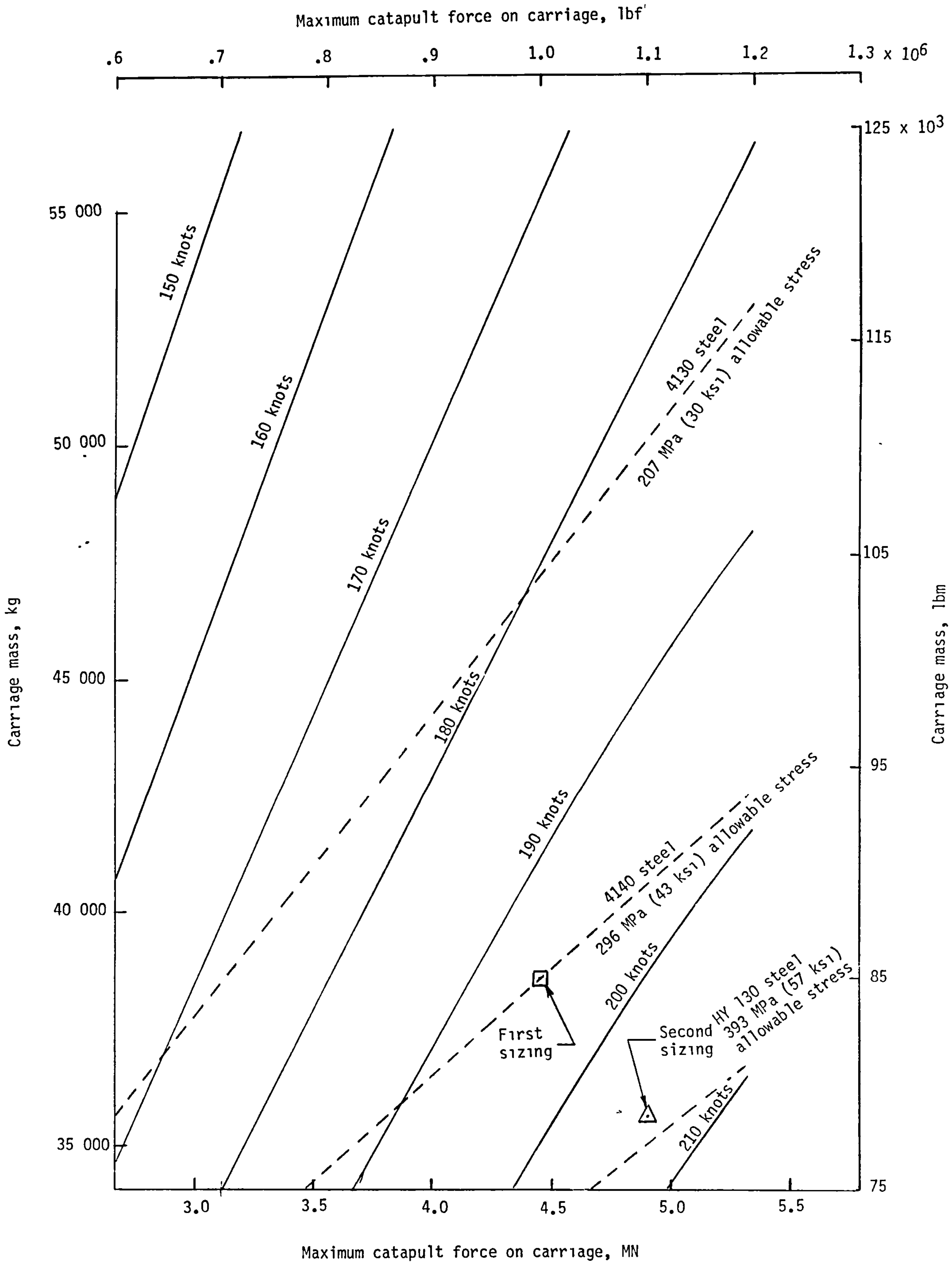
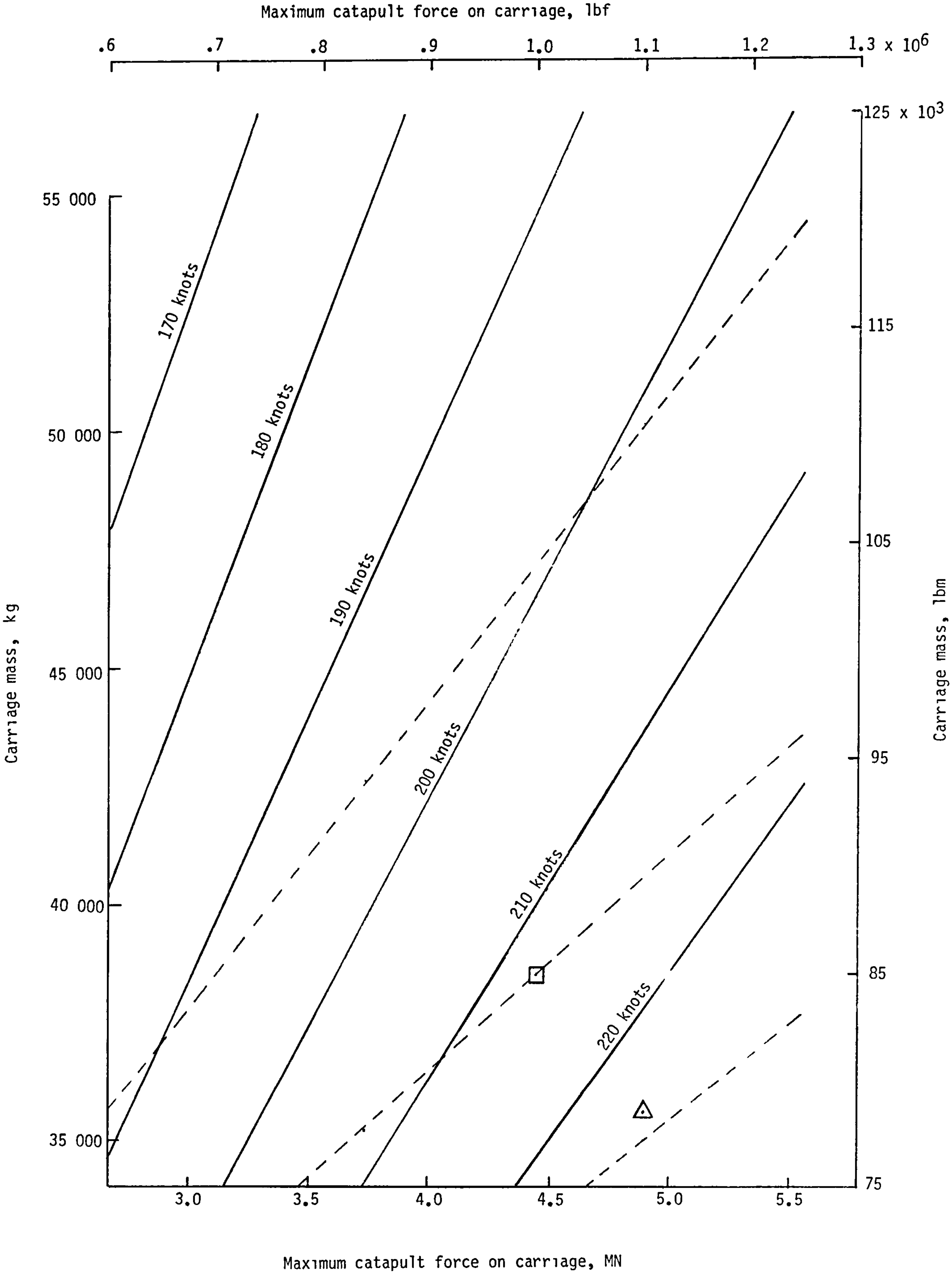


Figure 14.- Candidate carriage structural configuration.



(a) 122 m (400 ft) catapult stroke

Figure 15.- Effect of material selection on carriage structural design weight.



(b) 183 m (600 ft) catapult stroke

Figure 15.- Concluded.

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15 Supplementary Notes		

16 Abstract

Early preliminary design studies are presented which consider the important parameters in providing 200 knot test velocities at the Landing Loads and Traction Facility. Two major components of this facility, the hydraulic jet catapult and the test carriage structure, are considered.

Suitable factors are determined to correlate analytical data for characteristics of the hydraulic jet catapult with data measured from the existing catapult system. The resulting equations are used to calculate test velocities for a range of jet nozzle diameters and carriage masses with both the current 122m (400 feet) and an increased 183m (600 foot) catapult stroke.

Using the catapult characteristics, a target design point is selected and a carriage structure is sized to meet the target point strength requirements. These preliminary design results indicate that to attain 200 knot test velocities a nozzle diameter of .356m (14 inches) is required with a carriage mass of approximately 39 000 kg (85 000 lbm). High strength steel having an allowable stress of 393 MPa (57 000 lbf/in^2) is needed for the structure to withstand the maximum acceleration of 13-14 g's.

Suggestions for additions and refinements to this preliminary study are given that would be needed in working toward a detailed, final carriage design.

17 Key Words (Suggested by Author(s)) Research equipment Water jet Catapult Structural design Aircraft landing tests Propulsion systems	18 Distribution Statement Unclassified - Unlimited Subject Category 09

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