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DESIGN CONSIDERATIONS FOR ATTAINING 250-KNOT TEST VELOCITIES AT THE AIRCRAFT LANDING DYNAMICS FACILITY

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CONTENTS

I. SYMBOLS

A	nozzle area
A_c	drag area or frontal area of carriage
A_{cl}	instantaneous carriage acceleration
C_d	coefficient of aerodynamic drag
d	distance along the track
E	modulus of elasticity
F_c	momentum change force
F_d	instantaneous drag force
F_f	friction force
F_{net}	net propulsive force on carriage
K	radius of gyration of a column
L	length of carriage structural tube member
M	mass of carriage
N	factor of safety
P_o	initial L-vessel pressure
S_c	critical buckling stress
S_y	yield stress of material
t_d	time lag factor
V_i	incident water jet velocity
V_j	water jet velocity
V	velocity of the carriage
$\ddot{X}$	acceleration of the carriage
η	exponent for polytropic change in volume (PV^n=constant, η=1.2)
ρ	mass air density

ρ_w	mass water density
ν_o	initial air volume
ν	instantaneous volume of air
θ	bucket return angle
Δ	time increment

II. INTRODUCTION

The existing Aircraft Landing Dynamics Facility was put into operation in 1956. The 110 knot maximum forward speed capability of the facility was sufficient to explore landing and impact problems associated with the commercial transports of that day. However, with the advent of the jet transport in the late 1950's and more recently the wide-body jets, military, and supersonic aircraft, landing speeds are now in the 120 to 180 knot regime. The Space Shuttle and some military aircraft takeoff and/or landing speeds may range up to 220 knots. Studies have been conducted which indicate that heavy lift spacecraft may have landing and/or takeoff speeds in the order of 250 knots.

A Preliminary Engineering Report for the Modification to the Aircraft Landing Dynamics Facility dated August 27, 1979, describes the modifications required to extend the speed capability for the facility from its current speed of 110 knots to 220 knots.

This report evaluates the feasibility of increasing the test speed of the Aircraft Landing Dynamics Facility from the proposed 220 knot design to 250 knots. Two methods of developing the higher speed capability were studied. First, auxiliary water propulsion was evaluated. The 38,590 kg (85,000 lbm) carriage developed for the 220 knot speed capability can be propelled to 250 knots by the addition of dual auxiliary (secondary) water catapults located 67 meters (220 feet) down the track from the primary water catapult (see Figures 1, 2, and 3). Each of the secondary catapults will be nearly as large as the primary catapult system that is required to accelerate the 38,590 kg (85,000 lbm) carriage to 220 knots.

Second, a light-weight, special-purpose carriage was studied. By sufficiently reducing the mass of the carriage a propulsion system capable of propelling a 38,590 kg (85,000 lbm) carriage to 220 knots can be utilized to propel a lighter-weight carriage to 250 knots. The cost of the carriage is approximately the same as the 220 knot carriage ($2.1M). Since this option is substantially less expensive than the auxiliary propulsion option (approximately $8.0M), it was developed in some depth and is presented herein.

III. DESIGN REQUIREMENTS

The specific design requirements for the 250 knot carriage are as follows:

1. The carriage must achieve a velocity of 250 knots within 122 meters (400 ft.).

2. The propulsion system, the track and the arresting gear developed for the 220 knot facility modification must be utilized.

3. The carriage must have a 3 meters by 3 meters (10 ft. by 10 ft.) open bay.

4. The carriage must be capable of imposing 222.5 kn (50,000 lb.) vertical, side, and drag forces on the test specimen.

5. The test specimen drop system must have a vertical drop velocity of 11 kms (10 ft/sec) and an unsprung dead weight of 6,810 kg (15,000 lbm.)

IV. PROPULSION SYSTEM CONSTRAINTS

The propulsion system for the 220 knot system has the following fixed parameters:

1. Initial Air Volume - 141.5 cu. meters (5000 cubic feet)
2. Initial Air Pressure - 20.7 to 22 MPa (3000 to 3200 PSI)
3. Nozzle Diameter - 0.43 meters (17 inches)
4. Water Jet Tilt - 0.90 degrees
5. Catapult Stroke - 122 meters (400 feet)

V. CARRIAGE DYNAMICS

A. Catapult and Propulsion System:

A mathematical model of the propulsion system, using the basic particle-dynamics theory and the continuity equation for flow in nozzles, was developed.

The instantaneous water-jet velocity time history was calculated by iterating the following expression:

$$V_j(I) = \sqrt{\frac{2 P_o \nu_o^{\eta}}{\rho_w \nu(I)^{\eta}}}$$

where ν, the instantaneous air volume varies with time and is given by the following expression

$$\nu(I+1) = \nu(I) + V_j(I)\ A\ \Delta t.$$

Finding a third order polynomial fit of the data generated in the aforementioned iteration, the velocity of the water jet is given by the following expression

$$V_j(I) = C_1 + C_2 t + C_3 t^2.$$

Incorporating a time lag factor, t_d, the equation for the velocity of the water jet hitting the turning bucket is as follows

$$V_j(I) = C_1 + C_2\ (t-t_d) + C_3\ (t-t_d)^2.$$

The net propulsive force on the carriage as a function of time then becomes

$$F_{net}(I) = F_c(I) - F_d(I) - F_f.$$

The force due to the water momentum change, F_c, can be calculated from

$$F_c(I) = \rho_w\ A\ (V_i(I)-V_c(I))^2\ (1 - \cos\Theta),$$

where Θ is the return angle.

The drag and friction forces, F_d and F_f, are given by

$$F_d(I) = C_o\ \frac{L}{2}\ A_c\ (I)\ V_c(I),$$

$$F_f = \text{constant}.$$

The carriage acceleration can be determined from Newton's law as

$$F_{net}(I)=M\ A_{cl}(I),$$

and the carriage velocity from

$$V_c(I) = V_c(I) + A_{cl}(I)\ \Delta t.$$

The expression for the distance traveled then becomes

$$d(I+1) = d(I) + \frac{V_c(I+1) + V_c(I)\ \Delta t}{2}.$$

Finally, the time lag factor is found to be

$$t_d = \frac{d(I)}{v_j(I)}.$$

By assigning the pertinent initial values to the variables and interating in time, the time history of the carriage's performance can be calculated.

From the above rigid-body-dynamics analysis, the maximum weight that can be accelerated to 250 knots with the above defined propulsion system is 25,152 kg (55.6 KIPS). A vertical force of approximately 1,246 kn (280 KIPS) is developed during catapult. This force results from the off-horizontal angle of the water jet bucket. Since the weight of the carriage cannot exceed 25,152 kg (55.6 KIPS), the carriage and the location of the center of gravity of the carriage with respect to the line of thrust of the water jet heavily influences the hold-down force per truck. The front and back truck reactions, as a function of the length of the carriage with the optimum location of the center of gravity of the carriage, are shown in Figure 4. Equal reaction, both front and back, results in the minimum hold-down force per truck. Therefore, the optimum length for the carriage is 122 meters (40 feet). Figures 5 and 6 are plots of the front and back truck reaction vs. catapult distance.

The performance of this system can be seen in the following plots: Figure 7 - Carriage Velocity vs. Catapult Distance; Figure 8 - Carriage Acceleration vs. Catapult Distance; and Figure 9 - Carriage Acceleration vs. Time. The peak acceleration was used in the structural analysis of the carriage.

B. Velocity Decay

The velocity at arrestment can be determined from the following equation:

$$M\ddot{x} = F_f - \frac{1}{2} V^2 \rho A_c C_d$$

(condition after catapult).

A plot of Carriage Decay Velocity vs. Track Length is shown in Figure 10 for two estimates of carriage frontal area. After coasting through the 549 meters (1800 ft.) test section, the arresting velocities are approximately the same as the 220 knot carriage velocity at initiation of arrestment; therefore, the arresting system developed for the 220 knot system will be adequate for the 250 knot carriage.

VI. CARRIAGE STRUCTURAL SYSTEM

The carriage is conceptually similar to the 220 knot carriage - i.e. the structure is tubular, high-strength (yield strength = 689 mpa) truss-work with bucket, nose block and wheels. Figure 11 is a three-view computer generated drawing of the carriage structural model, and Figure 12 is an isometric of the carriage structural model. The hydraulic system and other on-board equipment were not studied in depth since they would be conceptaully the same as the 220 knot carriage.

The weight distribution for the carriage is given in Table 1.

Table 1 - Carriage Weight

Item No.	Component	Weight kg	 (lbm)
1	Bucket	2,724	(6,000)
2	Tubular Structure	6,356	(14,000)
3	Rear Trucks and Hold-Down	4,086	(9,000)
4	Front Trucks and Hold-Down	3,178	(7,000)
5	On-Board Support Equipment	1,090	(2,400)
6	Test Fixture	4,994	(11,000)
7	Nose Block	908	(2,000)
8	Model	1,816	(4,000)
		25,152	(55,000)

The other carriage characteristics are:

1. Carriage Length - 12.2 Meters (40 feet)
2. Carriage Width - 9.15 Meters (30 feet)
3. Carriage Height - 3.66 Meters (12 feet)
4. Bucket Length - 3.66 Meters (12 feet)
5. Frontal or Drag Area - 18.60 Square Meters (200 sq. ft.)
6. Bucket Design Angle - 177 Degrees
7. Expected Water Return Angle - 165 Degrees
8. Vertical eccentricity of carriage C.G. above jet thrust line is 0.33 Meters (12.91 inches)
9. Test Bay - 3 meters x 3 meters x 3.66 meters high
   (10 ft. x 10 ft. x 12 ft. high)

A finite-element model of the carriage was developed to establish the structural adequacy of the carriage . The carriage was idealized as a truss network where only cross sectional area was used to carry the catapult load. The various members were configured from eight standard structural pipe sizes given in Table 2.

Table 2 - Carriage Structural Members

Section No.	Pipe Size cm	(in.)	Area sq.cm	(sq. in.)
1	2.54	(1.0)	3.23	(0.494)
2	3.81	(1.5)	5.16	(0.799)
3	5.08	(2.0)	7.00	(1.070)
4	6.35	(2.5)	11.00	(1.700)
5	7.62	(3.0)	14.40	(2.230)
6	8.89	(3.5)	17.53	(2.680)
7	10.16	(4.0)	20.45	(3.170)
8	11.43	(4.5)	27.74	(4.300)

Since the loads at catapult (26 "g's") are much larger than the arresting loads (~4 "g's"), catapult loads (including hold-down forces) were used in all structural analyses. The maximum loading during catapult occurs .23 seconds after valve motion is initiated.

The stresses for both tension and comparison members were evaluated using catapult loads. For column buckling, the following criterion was used:

Short columns

$$\frac{K}{L} \leq \left(\frac{L}{K}\right)_1$$

$$\text{where, } \left(\frac{L}{K}\right)_1 = \sqrt{\frac{2\pi^2 EN}{S_y}} = 76.95$$

for $E = 207$ gpa (30,000,000 psi)

$S_y = 689$ mpa (100,000 psi)

$N = 1.$

$$Scr = S_y - \left(\frac{S_y}{2\pi}\right)^2 \frac{1}{NE} \left(\frac{L}{K}\right)^2$$

Long column

$$\frac{L}{K} > \left(\frac{L}{K}\right)_1$$

$$Scr = \frac{N\pi^2 E}{\left(\frac{L}{K}\right)^2}$$

For this preliminary analysis, the allowable buckling stress, S_b(allowable), was taken to be:

$$S_b(\text{allowable}) < Scr.$$

Tension members were evaluated by the following criterion:

$$S(\text{allowable}) \leq .87\ S_y;$$

or $$S(\text{allowable}) \leq .80\ S_{ult}$$

Evaluation of the finite element analysis indicates that all of the stress criteria are satisfied for this governing load case. Other load cases may require local resizing of members, but they would not have a significant impact on weight.

VII. SPECIAL CONSIDERATIONS:

A. Reaction Bucket

In order to develop a velocity of 250 knots, the reaction bucket on the carriage must be effective. It is suspected that the effective water turning angle for the present buckets is only 165° even though the bucket surface turns 177°. This incomplete turning results in a reduced horizontal force on the carriage and an increased vertical force which must be reacted by the hold-down system. Since the magnitude of the hold-down force heavily influences the carriage design, a test program is being developed to determine the effective turning angle of the bucket and, hence, the magnitude of the hold-down force.

As a result of the uncertainty of the turning angle, two design concepts were developed for the bucket. The first concept is basically a scaled up version of the existing design, and the second is a horizontally oriented split pelton type bucket.

Concept one is shown in Figure 13. For reference, the current bucket is also shown on that figure. The advantages of this bucket are:

- Simple construction
- Known performance potential
- Water returned to the track in the same manner as the current design.

The disadvantage is the previously mentioned large upward component of force.

Concept two is shown in Figure 14. The advantages of this design are:

- Eliminates vertical component of force and drastically reduces hold-down requirements
- Used widely in turbines

The disadvantages are:

- A containment wall and new water collection system would be required
- Relatively complex construction
- This concept weighs nearly twice the present-type bucket. This problem is alleviated if a more complex construction is used as indicated by configurations 1 and 2 in Figure 14.

The conclusion of this evaluation was to baseline the first concept (i.e. a sealed-up version of the present bucket) for the 250 knot carriage. Loads resulting from this bucket design were used in the design of the carriage presented in this report. The vertical loads may be reduced as a result of tests to determine the effective turning angle of the current bucket design.

B. Wheels

It was determined that the wheel/truck system used on the 220 knot carriage to accept down and side loads would be satisfactory for the 250 knot carriage. However, since the 250 knot carriage is lighter than the 220 knot carriage, the hold-down wheels would be a different configuration to accommodate the larger net uplift force. Each hold-down truck would have four wheels which each has the capability of 64.5 kn. (14,500 lbs.) at 8060 RPM. These wheels would each be 0.305 meter (12 inches) in diameter.

With a bearing load of 32.26 kn. (7,250 lbs.) at 8060 RPM, either roller or ball bearings should be workable. For catapult hold-down loads 76.25 meters (250 feet) of hold-down track is required (see Figure 5 and 6). Hold-down forces during the test phase are relatively small and do not govern the design. Figure 15 shows the arrangement of the hold-down wheels.

VIII. CONCLUSIONS

Results of this study show that it is feasible to construct a special-purpose carriage which can be propelled to 250 knots utilizing the propulsion and arresting systems being developed for the 220 knot facility modification. The hold-down track would have to be extended through the test section to allow test specimen loads to 222.5 kn (50,000 lbs.).

The project cost of this carriage and the additional hold-down track is approximately 3.1M in FY '81 dollars.

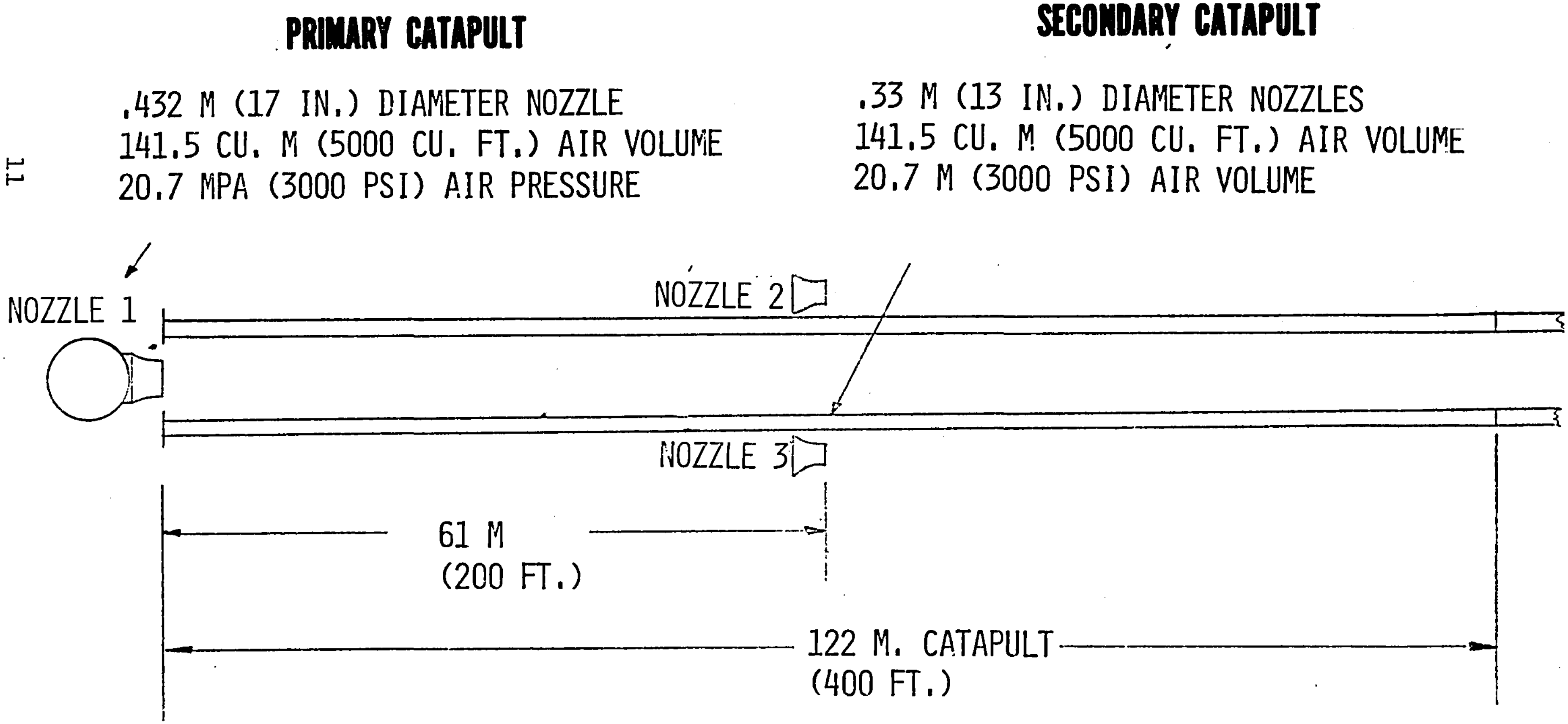


Figure 1. SECONDARY CATAPULT

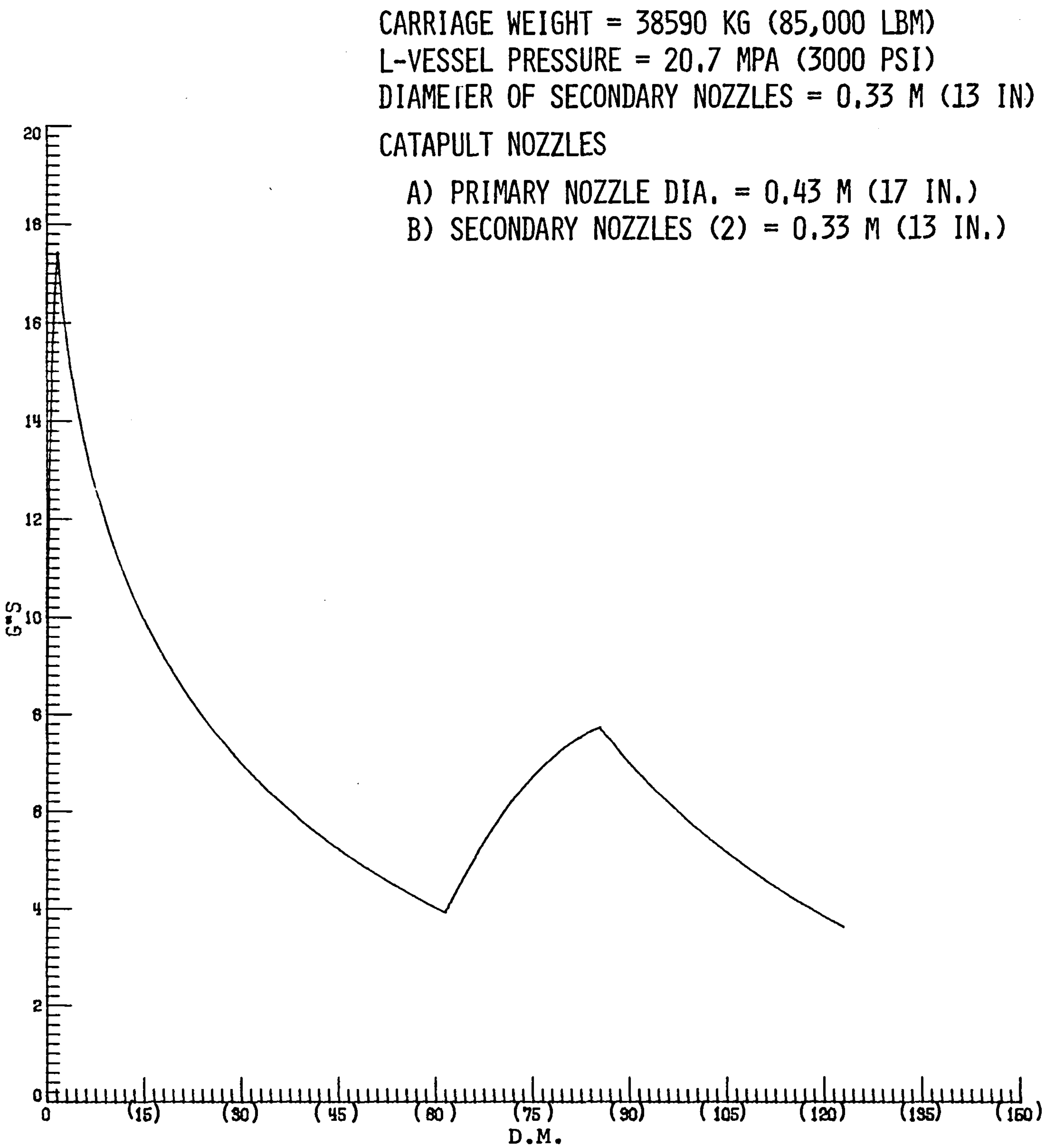

CARRIAGE WEIGHT = 38590 KG (85,000 LBM)
L-VESSEL PRESSURE = 20.7 MPA (3000 PSI)
DIAMETER OF SECONDARY NOZZLES = 0.33 M (13 IN)
CATAPULT NOZZLES
A) PRIMARY NOZZLE DIA. = 0.43 M (17 IN.)
B) SECONDARY NOZZLES (2) = 0.33 M (13 IN.)

FIGURE 2 - CARRIAGE ACCELERATION VS. DISTANCE WITH SECONDARY CATAPULT

CARRIAGE WEIGHT = 38590 KG (85,000 LBS.)
L-VESSEL PRESSURE = 22.0 MPA (3200 PSI)
DIAMETER OF SECONDARY NOZZLES = 0.33M (13 IN.)

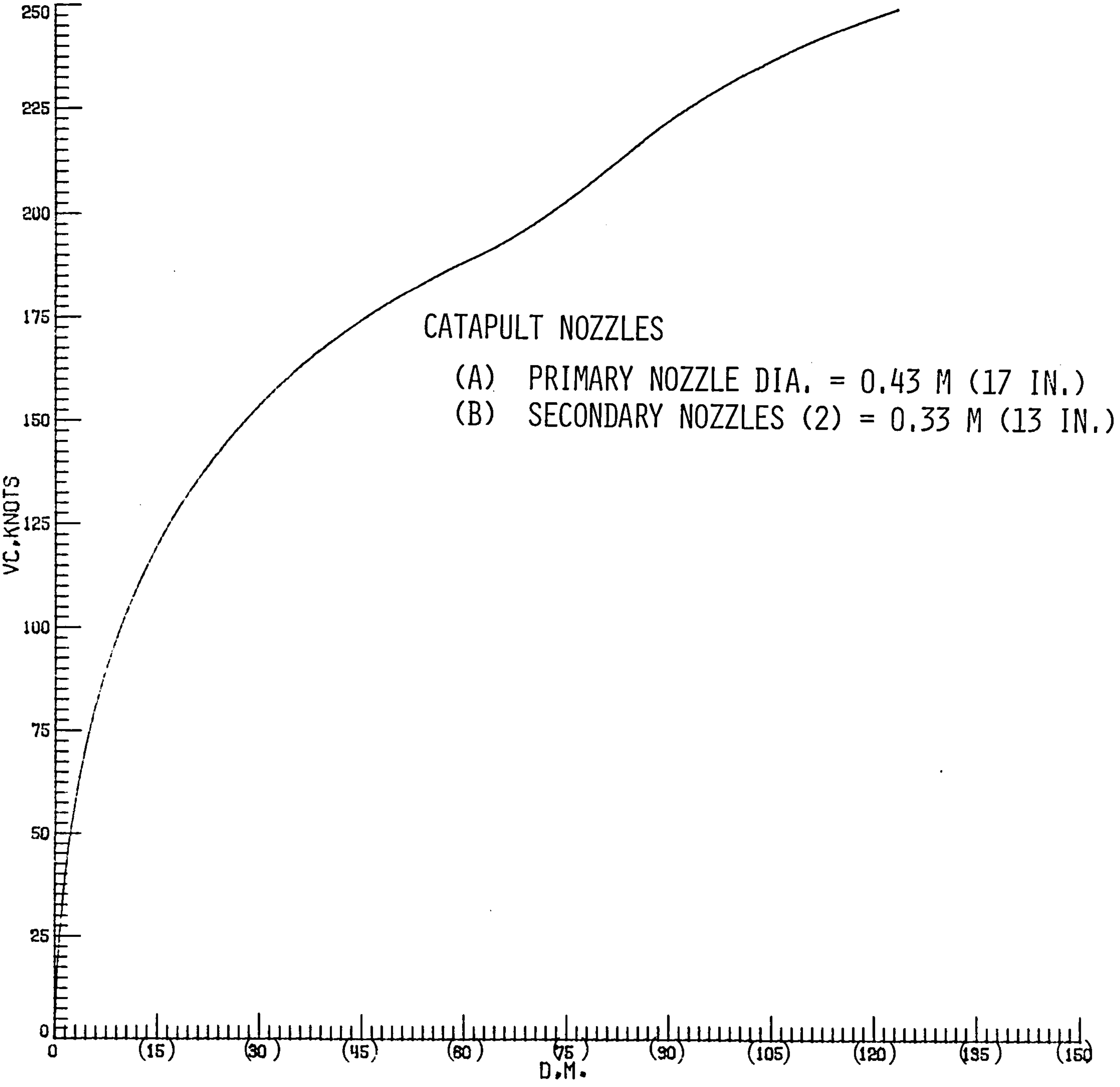


FIGURE 3 - CARRIAGE VELOCITY VS. DISTANCE WITH SECONDARY CATAPULT

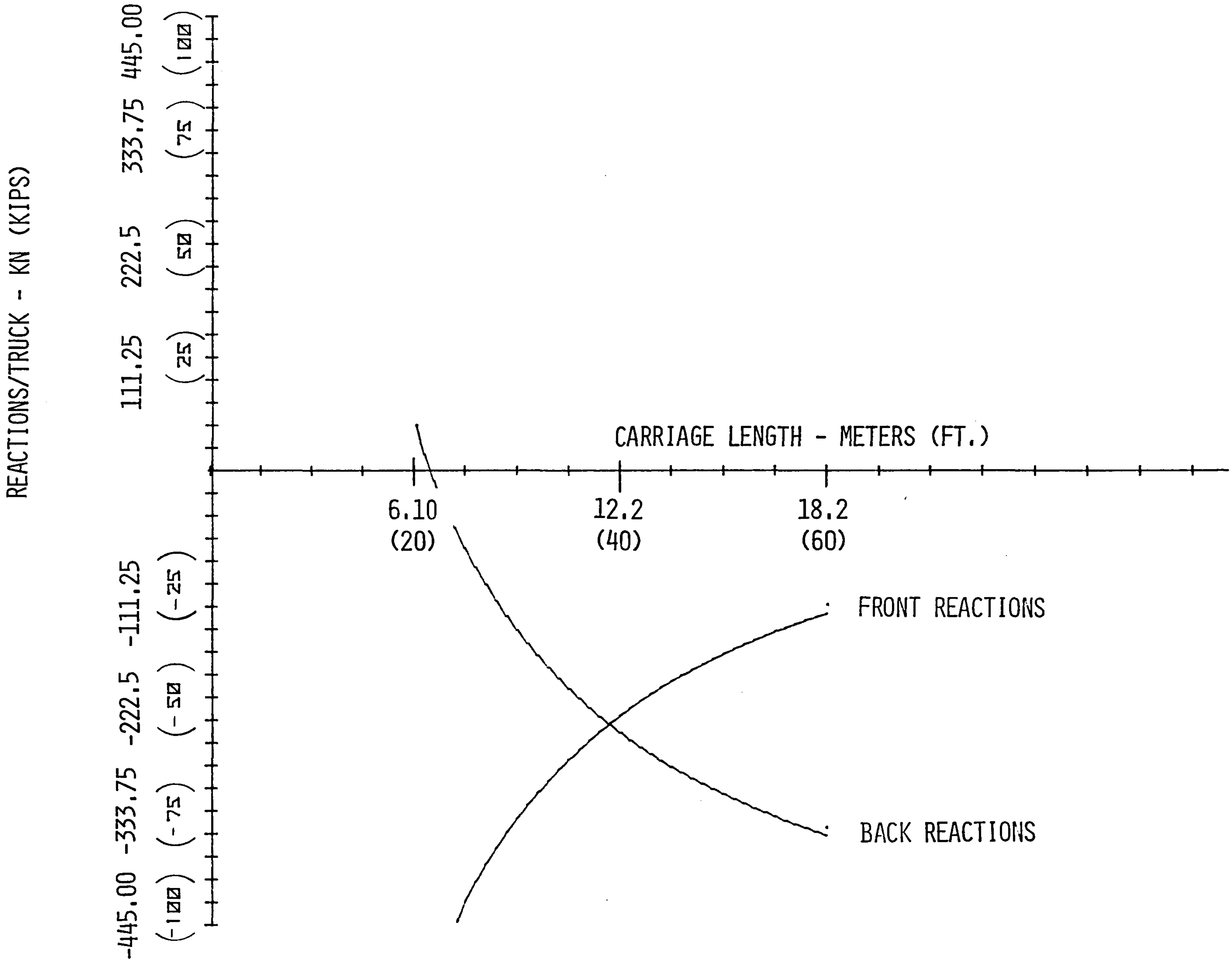
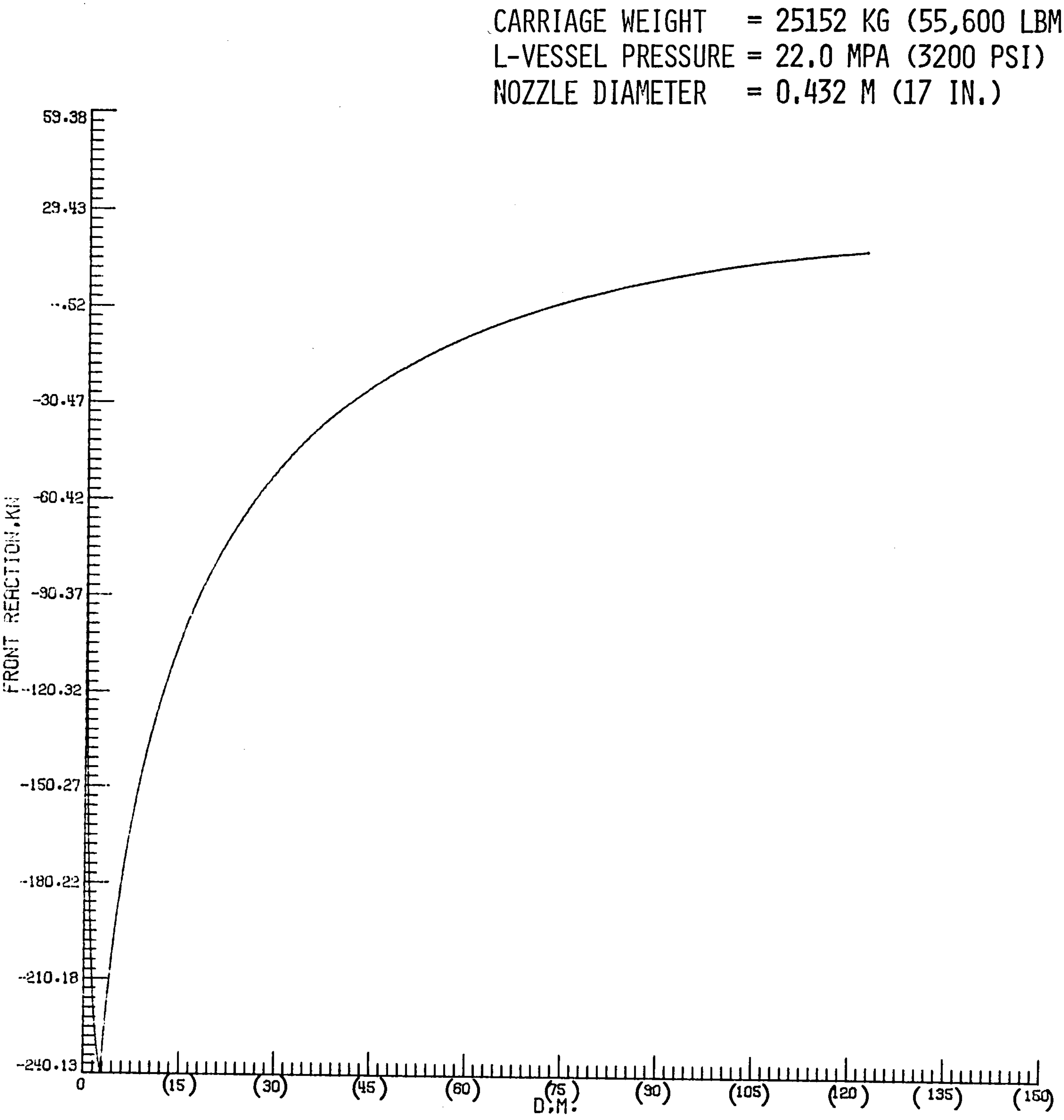


FIGURE 4 - TRUCK REACTION VS. CARRIAGE LENGTH



CARRIAGE WEIGHT = 25152 KG (55,600 LBM)
L-VESSEL PRESSURE = 22.0 MPA (3200 PSI)
NOZZLE DIAMETER = 0.432 M (17 IN.)

FIGURE 5 - CARRIAGE FRONT TRUCKS REACTIONS VS. DISTANCE

CARRIAGE WEIGHT = 25152 KG (55,600 LBM)
L-VESSEL PRESSURE = 22.0 MPA (3200 PSI)
NOZZLE DIAMETER = 0.43 M (17 IN.)

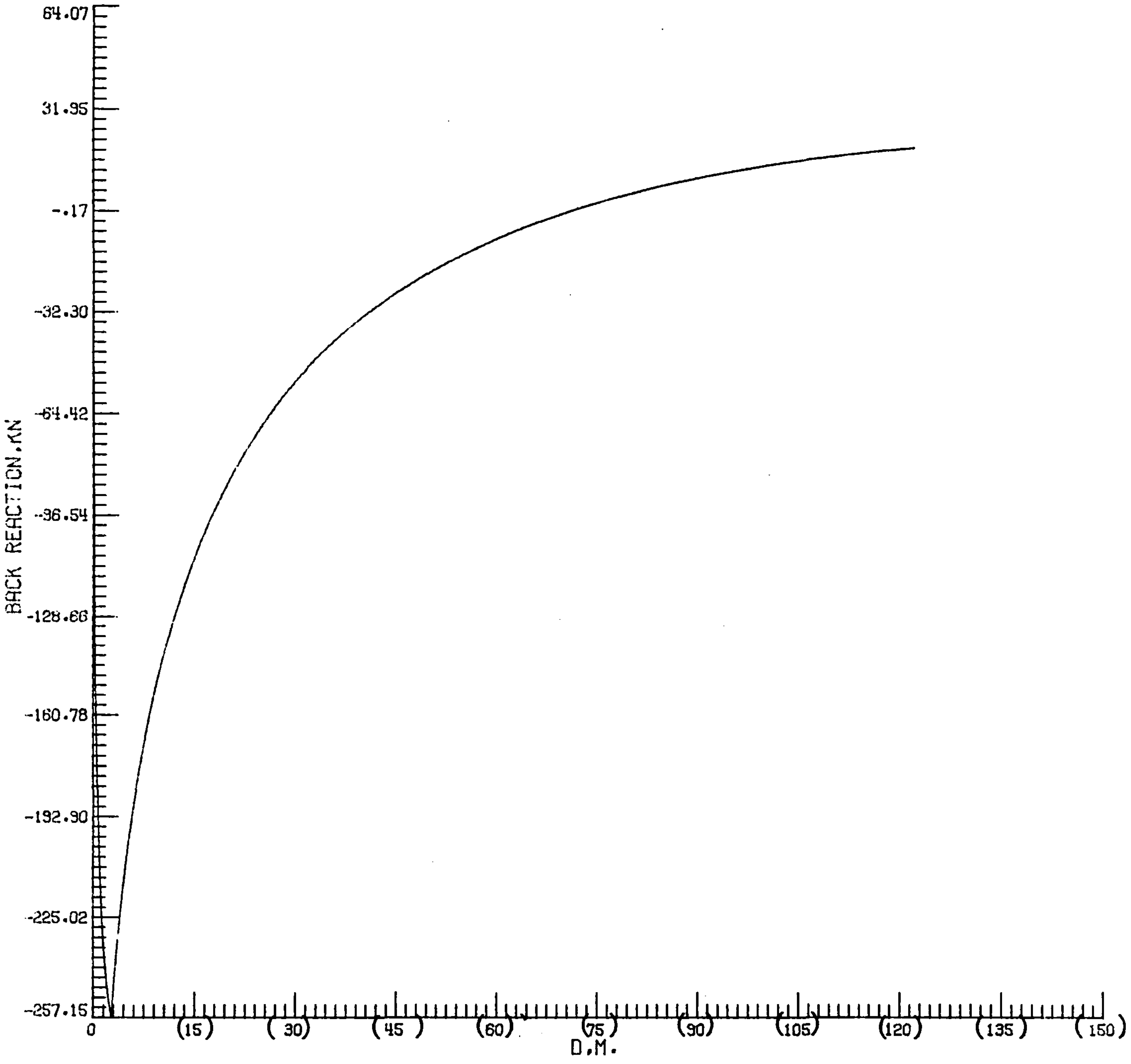


FIGURE 6 - CARRIAGE REAR TRUCKS REACTIONS VS. DISTANCE

CARRIAGE WEIGHT = 25152 KG (55,600 LBM)
L-VESSEL PRESSURE = 22 MPA (3200 PSI)
NOZZLE DIAMETER = 0.43 M (17 IN.)

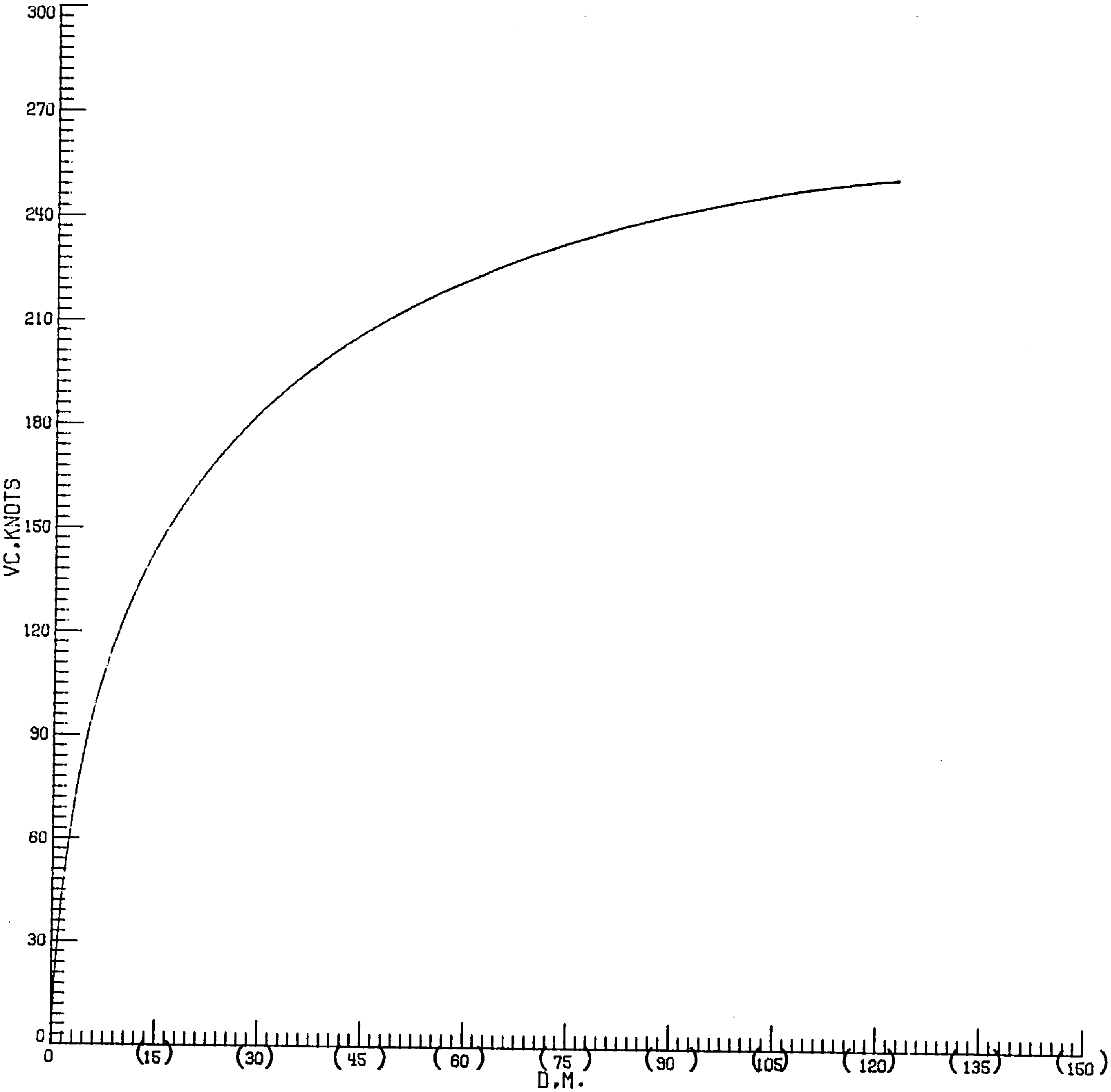


FIGURE 7 - CARRIAGE VELOCITY VS. CATAPULT DISTANCE

CARRIAGE WEIGHT = 25152 KG (55,600 LBM)
L-VESSEL PRESSURE = 22 MPA (3200 PSI)
NOZZLE DIAMETER = 0.43 M (17 IN.)

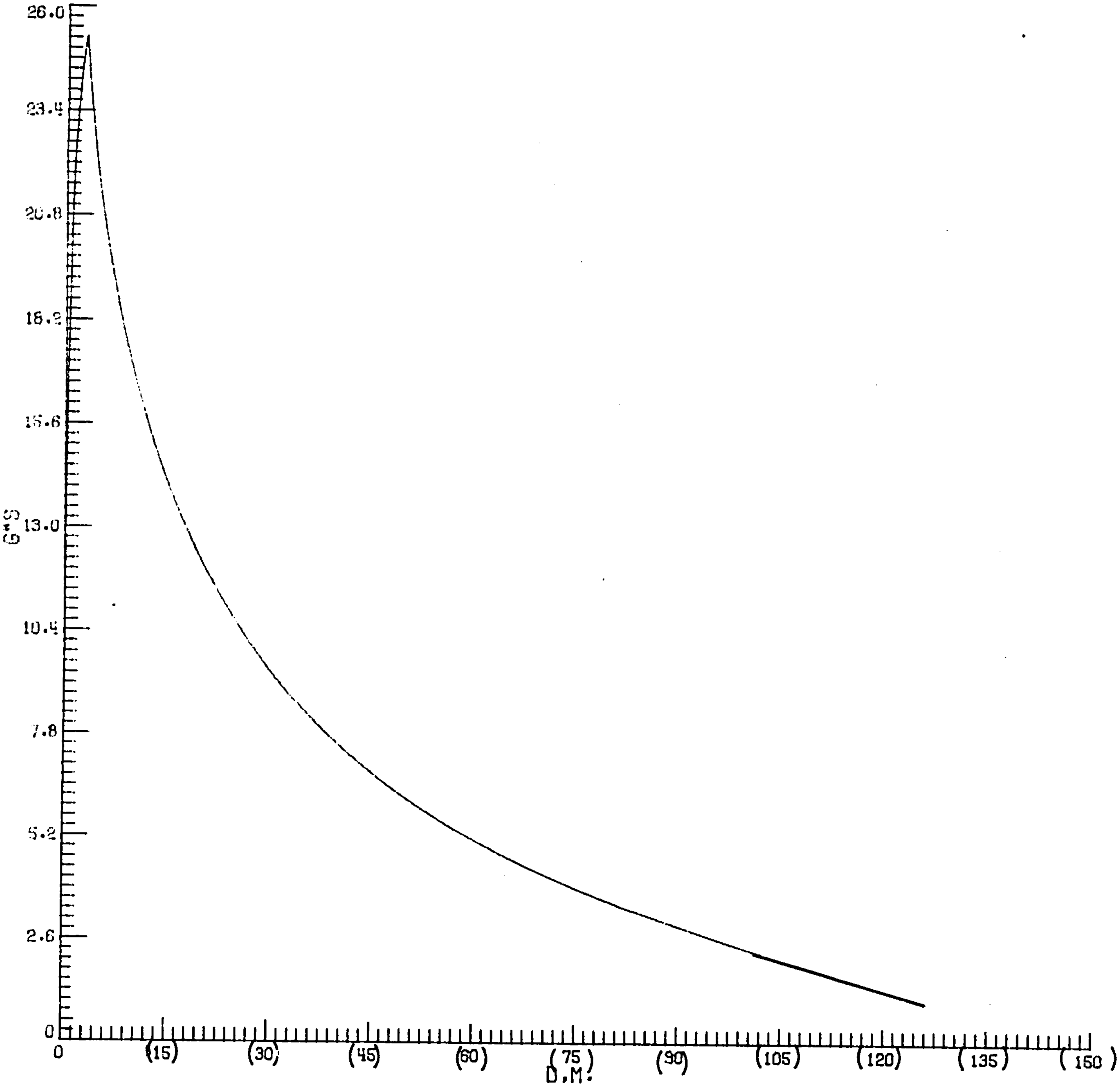


FIGURE 8 - CARRIAGE ACCELERATION VS. CATAPULT DISTANCE

CARRIAGE WEIGHT = 25152 KG (55,000 LBM)
L-VESSEL PRESSURE = 22 MPA (3200 PSI)
NOZZLE DIAMETER = 0.43 M (17 IN.)

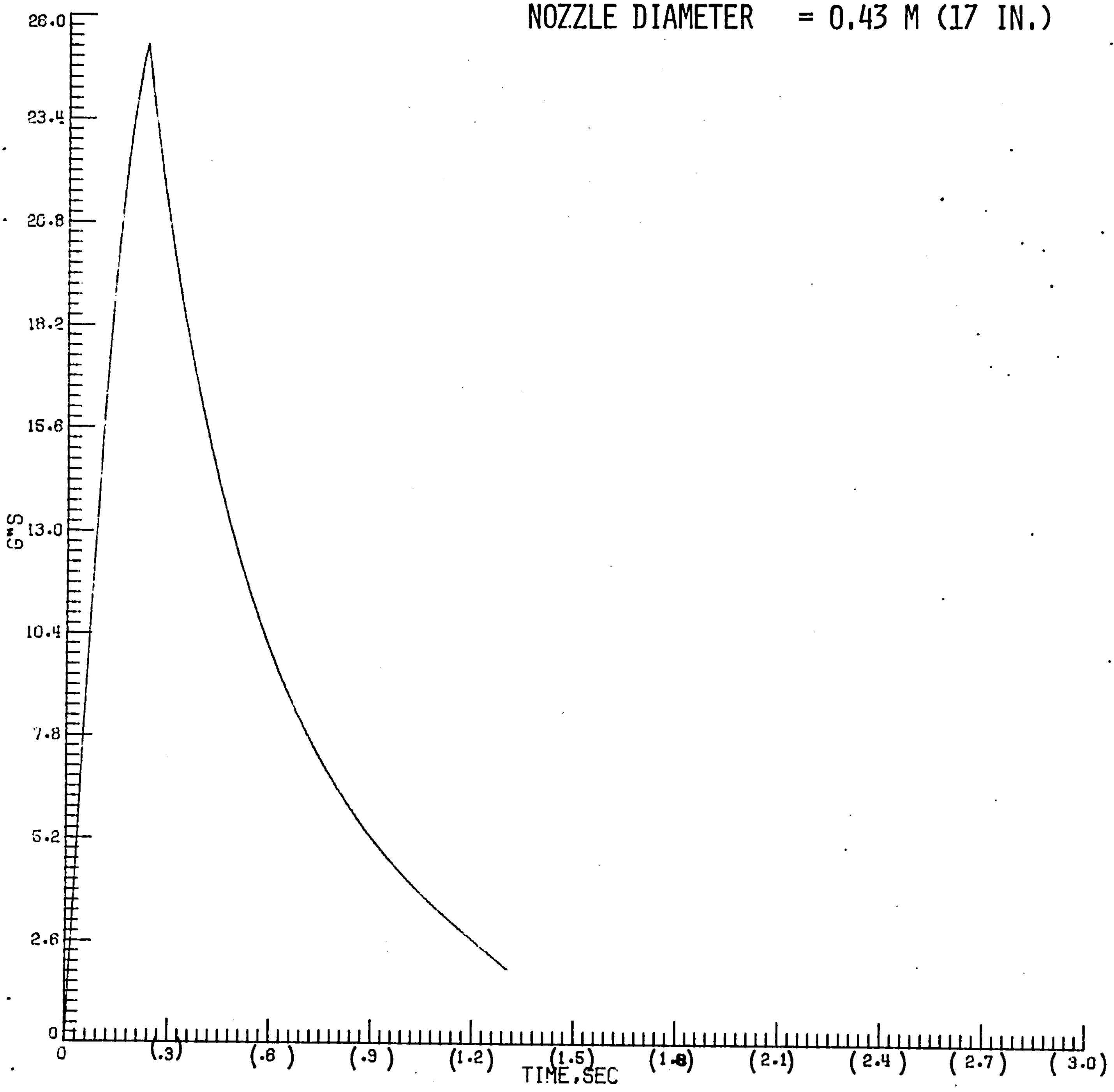


FIGURE 9 - CARRIAGE ACCELERATION VS. TIME

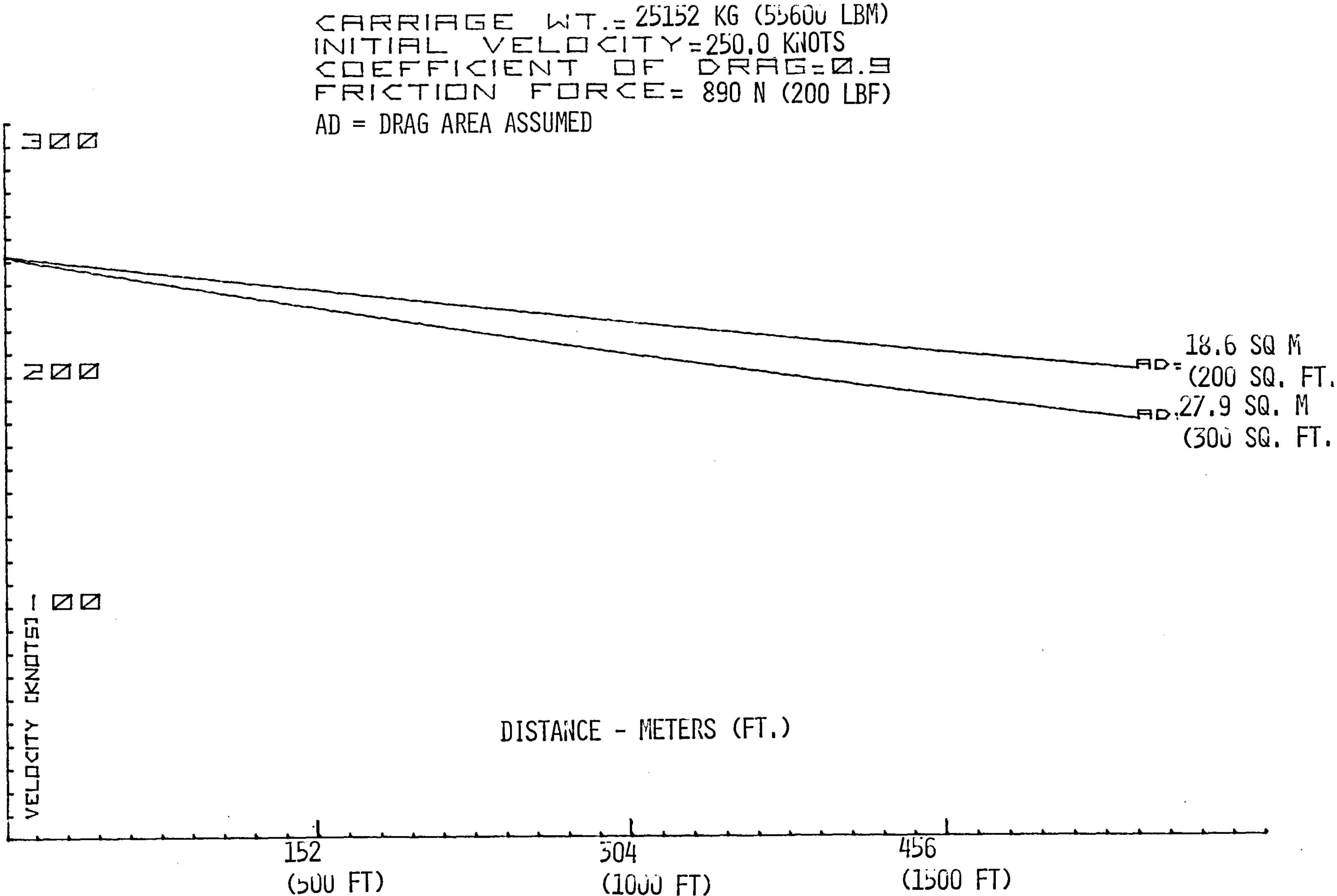
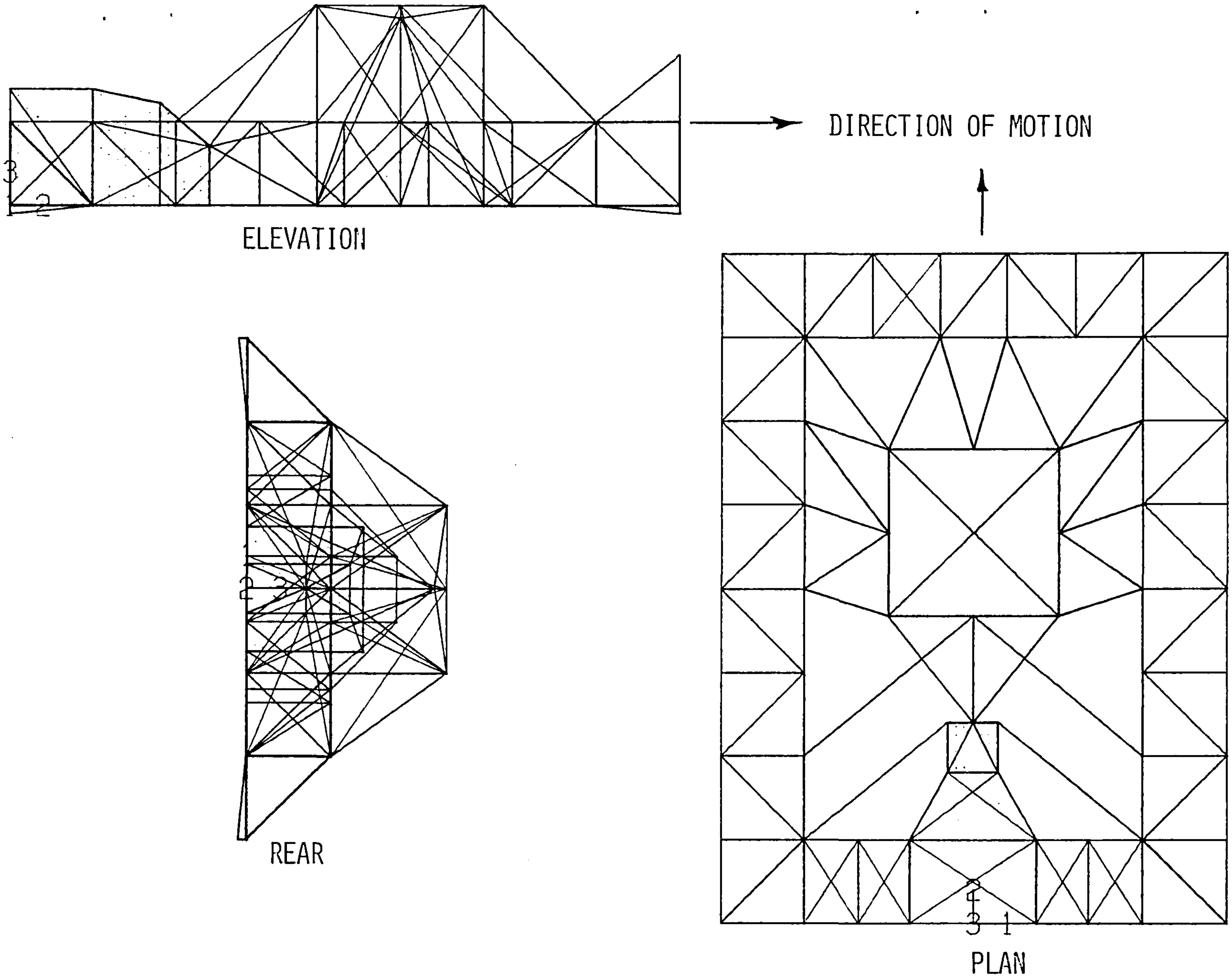


FIGURE 10 - VELOCITY DECAY VS. TRACK LENGTH
(AFTER A 122 M CATAPULT STROKE)


ELEVATION

REAR

PLAN

FIGURE 11 - 250-KNOT CARRIAGE CONCEPT
(3 VIEWS)

0 3.35 M
SCALE

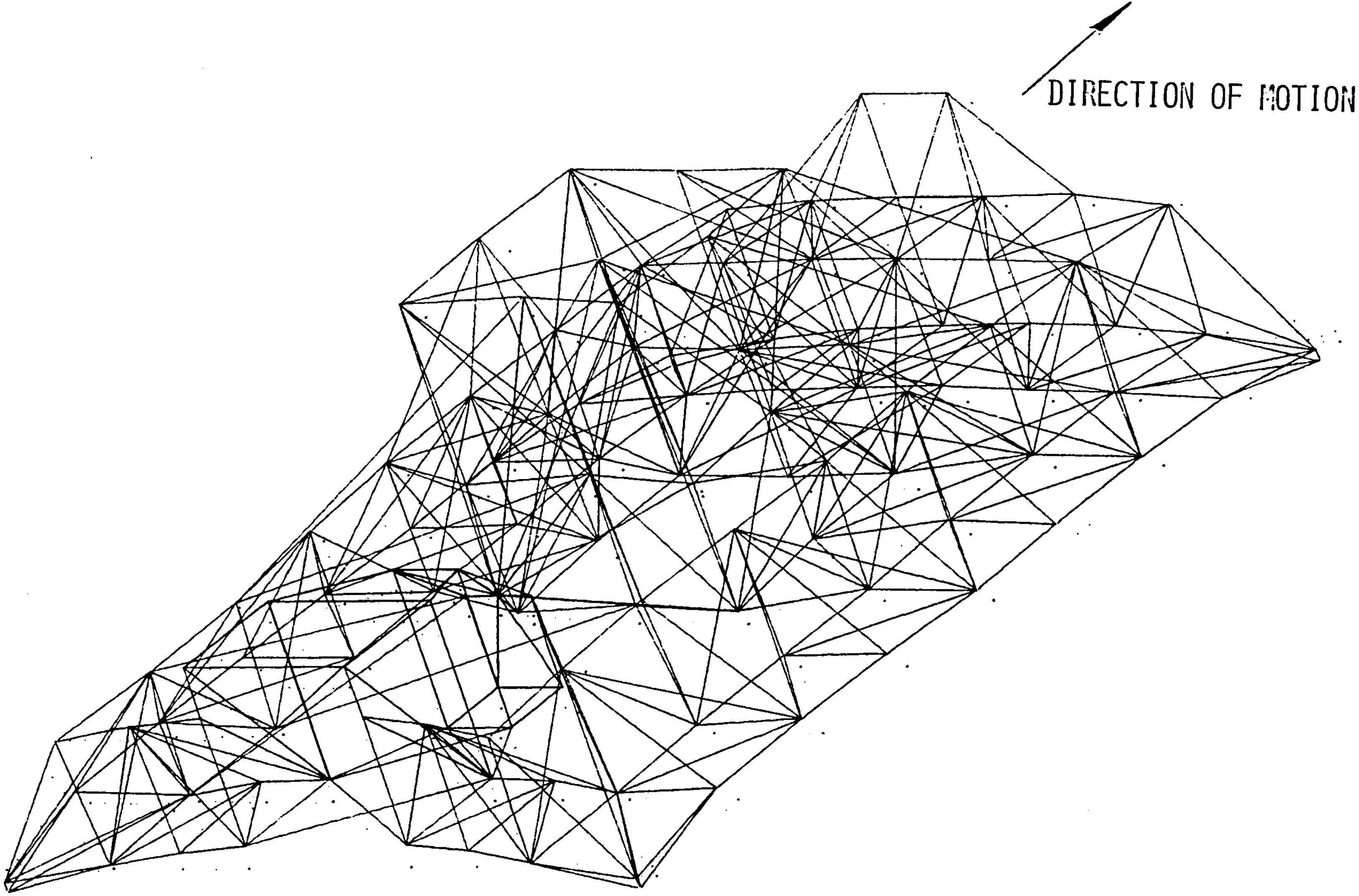


FIGURE 12 - 250-KNOT CARRIAGE CONCEPT

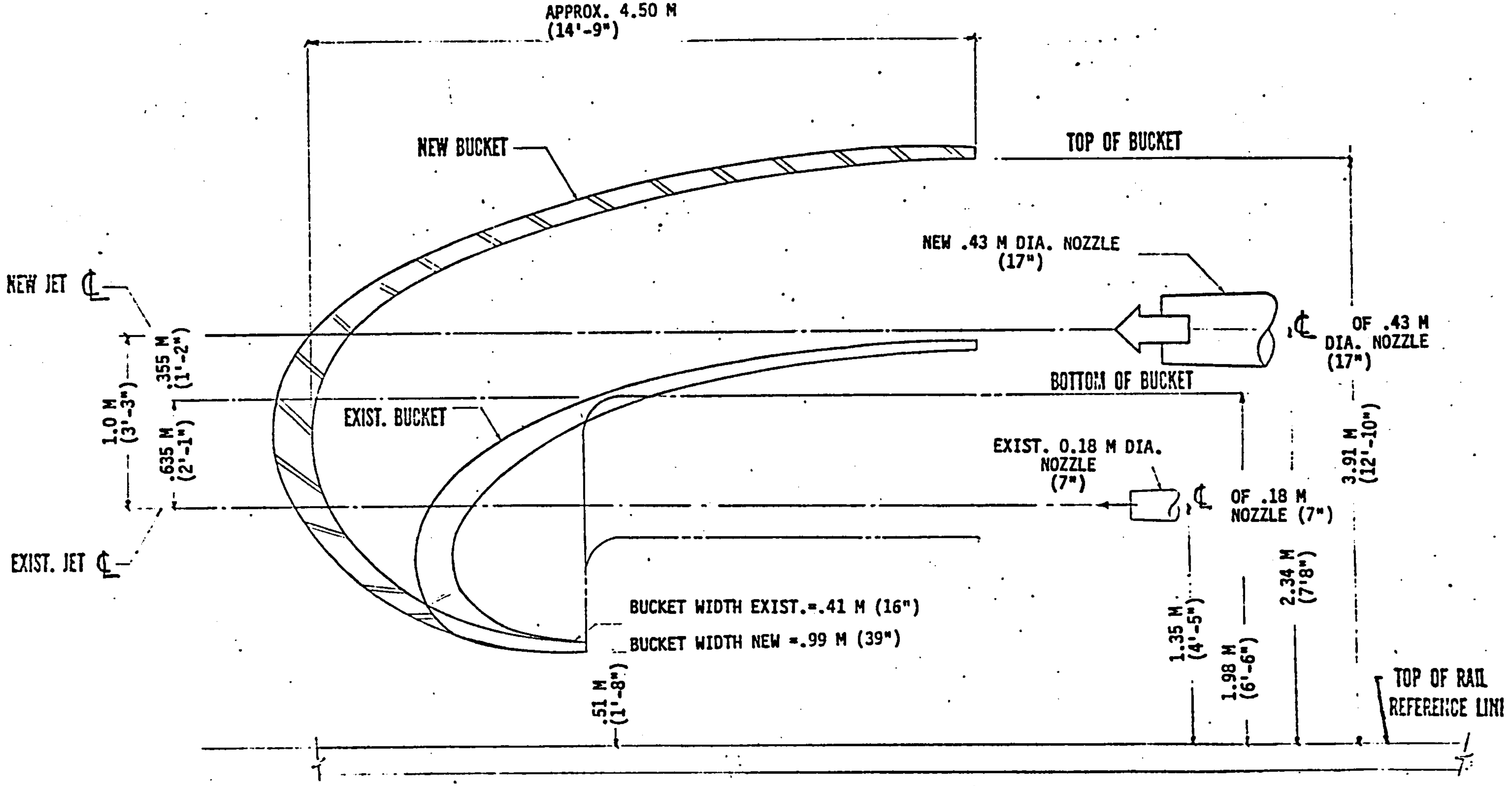
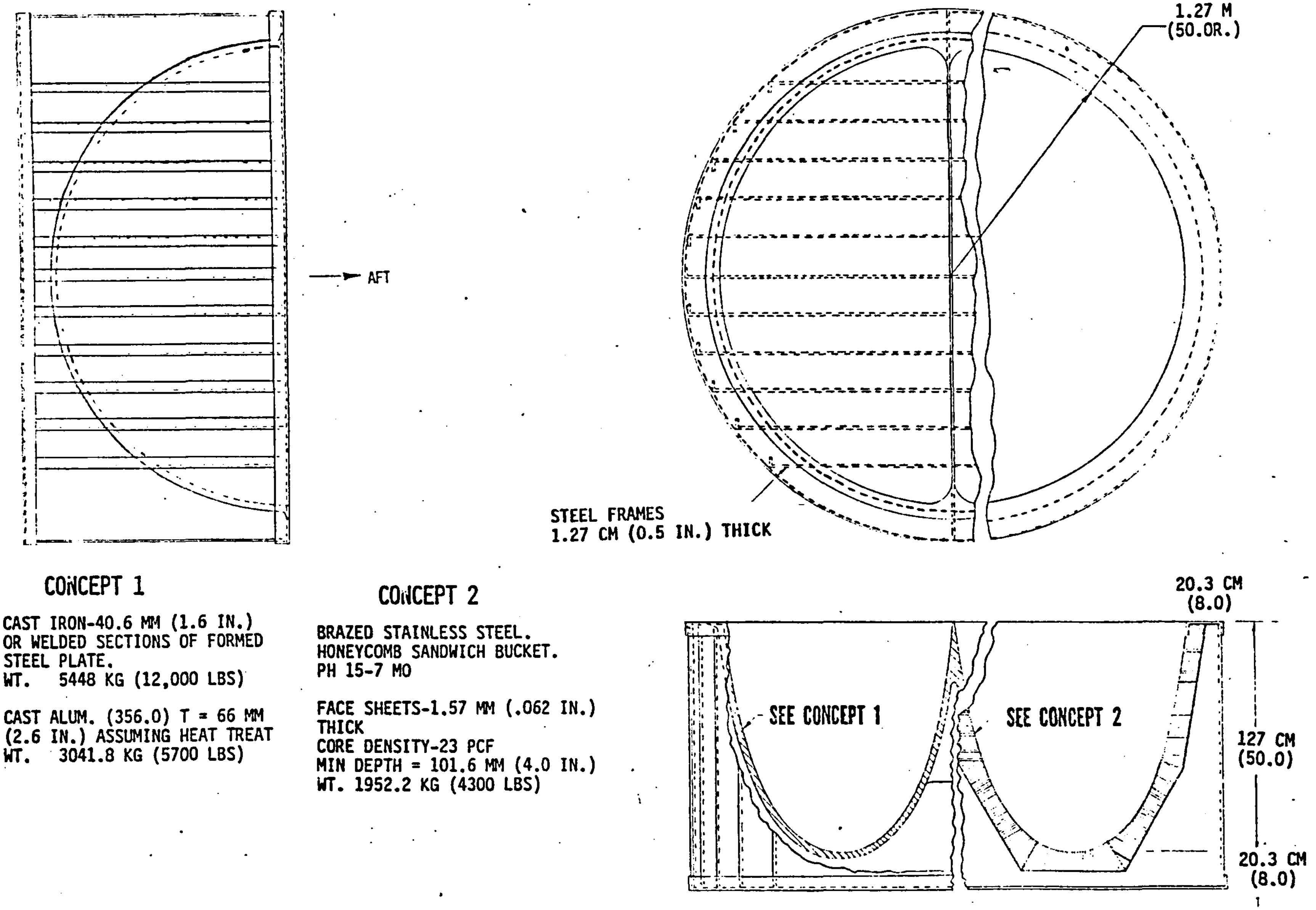


Figure 13. BUCKET SECTION



CONCEPT 1

CAST IRON-40.6 MM (1.6 IN.)
OR WELDED SECTIONS OF FORMED
STEEL PLATE.
WT. 5448 KG (12,000 LBS)

CAST ALUM. (356.0) T = 66 MM
(2.6 IN.) ASSUMING HEAT TREAT
WT. 3041.8 KG (5700 LBS)

CONCEPT 2

BRAZED STAINLESS STEEL.
HONEYCOMB SANDWICH BUCKET.
PH 15-7 MO

FACE SHEETS-1.57 MM (.062 IN.)
THICK
CORE DENSITY-23 PCF
MIN DEPTH = 101.6 MM (4.0 IN.)
WT. 1952.2 KG (4300 LBS)

Figure 14. PELTON PROPULSION BUCKET CONCEPTS

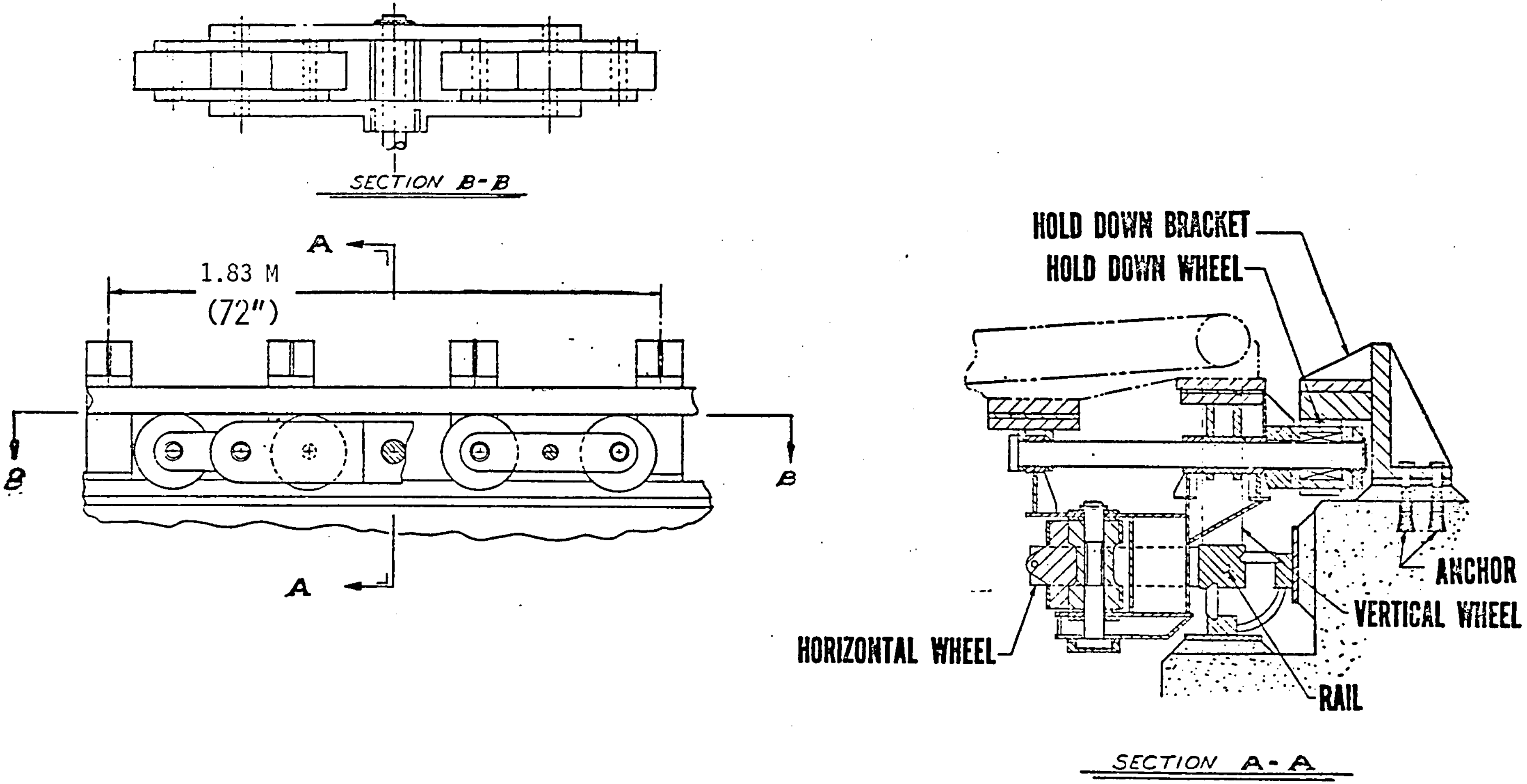


Figure 15. HOLD DOWN SYSTEM

X. REFERENCES

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

2. Giles, Gary L. and Stubbs, Sandy M.: Design Considerations for Attaining 200-Knot Test Velocities at the Aircraft Landing Loads and Traction Facility, NASA TM 80096, May 1979.

3. Whetstone, W. D.: SPAR Structural Analysis System Reference Manual - System Level - 14. Volume I - Program Execution. NASA Cr-145096-1, 1977.

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16. Abstract

Preliminary design studies are presented which consider the important parameters in providing 250-knot test velocities at the Aircraft Landing Dynamics Facility. Four major components of this facility, the hydraulic jet catapult, test carriage structure, reaction turning bucket, and wheels, are considered.

Using the hydraulic-jet catapult characteristics, a target design point is selected and a carriage structure is sized to meet the required strength requirements. These preliminary design results indicate that to attain 250-knot test velocities for a given hydraulic jet catapult system, a carriage mass of 25,424 kg (56,000 lbm.) cannot be exceeded.

Suggestions for future developments and/or additional test programs that would be required for a more efficient and economical design are given.

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