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Soft-Ground Aircraft Arresting Systems

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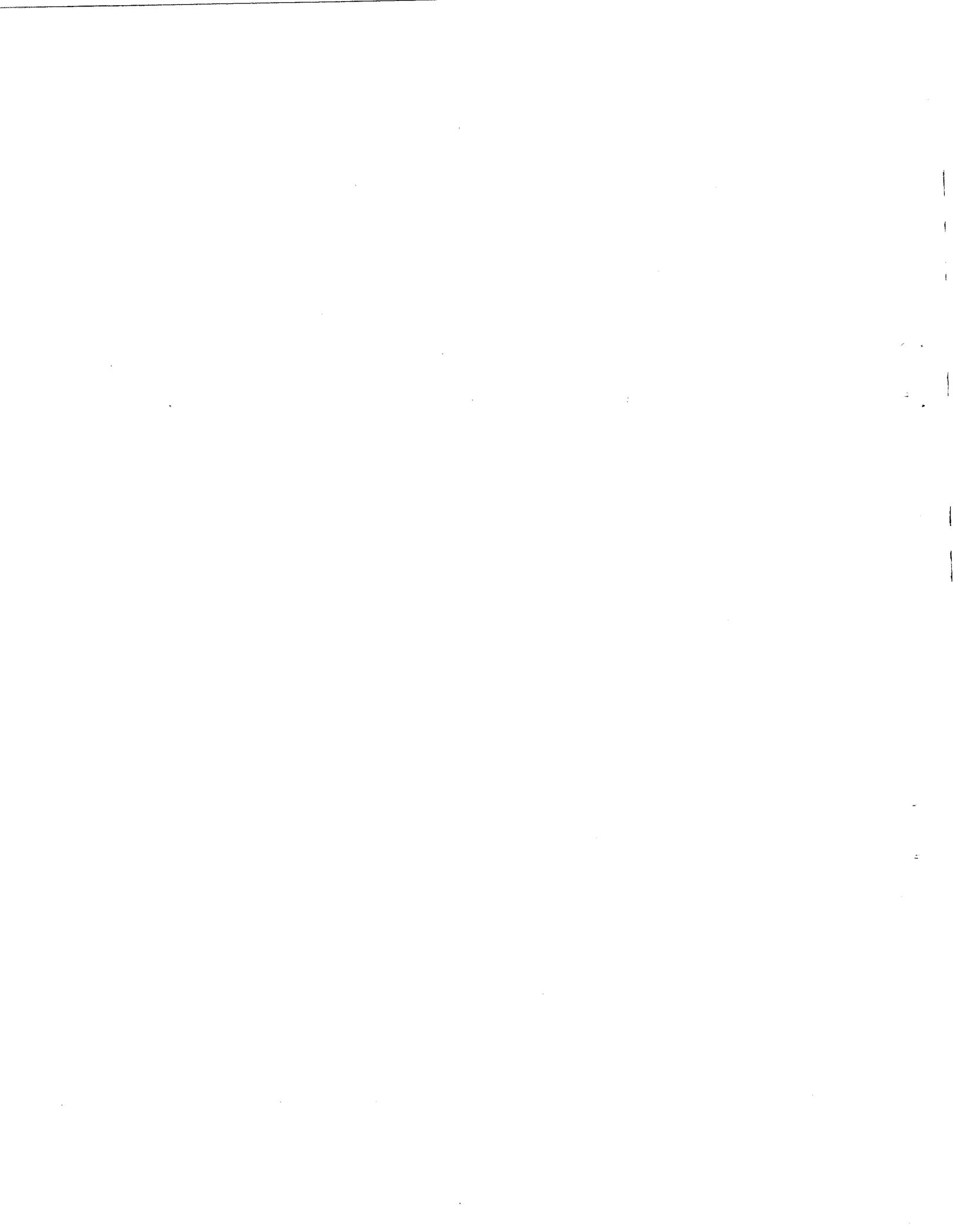


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| 16. Abstract The soft-ground aircraft arresting system study was initiated to determine whether or not aircraft having gross weight of 114,000 pounds to 630,000 pounds could be safely stopped after overrunning the available length of runway. The extended length of runway was limited to 1000 feet and the maximum velocity of the overrunning aircraft was selected to be 70 knots. The system was to be completely passive, have a long life, and easily repaired and maintained. Several arrestor materials such as clay, sand, gravel, water, and plastic foam were considered. An aircraft wheel/arrestor material model was developed and incorporated into a computer program FITER which allowed the determination of the aircraft stopping distance, landing gear loads, dynamic response, and rut depth in the arrestor material. Analyses conducted showed that sand, clay and water systems were not suitable arresting materials. Aircraft arrestment simulations were conducted for gravel and plastic foam arrestors and it was found that all aircraft could be safely stopped in less than 1000 feet. Evaluation of the stopping distance in an arrestor bed with the stopping distance of an extended runway was made and it was found that the arrestor system was needed to assure the safe stopping of an aircraft. Initial arrestor bed configurations were developed along with installation methods and attachment of the arrestor to the extended runway surface. | | | | | |
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FOREWORD

The Contract F33615-86-D-3800 Task 0017 "Soft-Ground Aircraft Arresting Systems" was initiated and monitored by the Structural Integrity Branch of the Air Force Wright Aeronautical Laboratories (AFWAL/FIBE) and the Air Force Civil Engineering Center, Tyndall Air Force Base, Florida for the Federal Aviation Administration (FAA). The objective of the contract is to determine the feasibility of using soft materials like clay, sand, gravel, water, and foam to arrest aircraft in the event of an overrun past the end of the runway.

The principal investigator for Universal Energy Systems, Inc. (UES) was Mr. Robert F. Cook. Dr. R. F. Taylor of the University of Dayton also participated in the material modeling portion of the program. The AFWAL Project Engineer was Mr. Roger Aschenbrenner. This final report covers all technical work completed on the contract from initiation on 2 September 1986 through 31 August 1987.

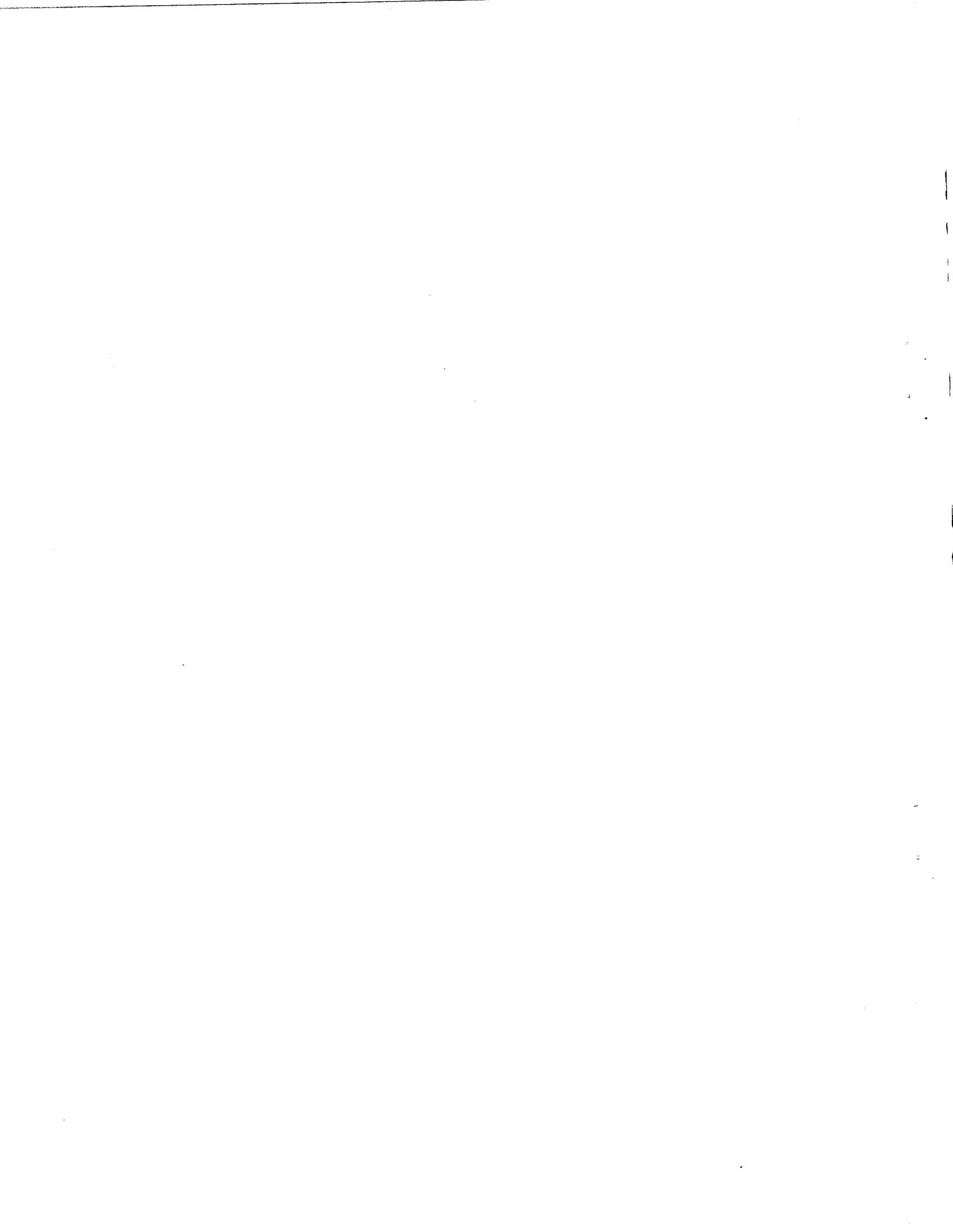


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SECTION 1 INTRODUCTION

Aircraft sometimes overrun the available length of runway during landing or takeoff abort because of poor braking conditions or pilot misjudgment. Snow or ice covered runways can severely limit braking capability. In any case, the aircraft being off the designated runway poses a problem to the airport manager and the airline operator in terms of changing landing and takeoff traffic, getting the aircraft back on the proper surface, and in unloading passengers and cargo. The details of each overrun incident are normally quite different and each requires a different solution. In some cases, the airplane can be unloaded and then towed by a normal tug back to the runway, taxiway, or ramp. If the aircraft is severely damaged or passengers injured, then more sophisticated equipment such as rescue vehicles, cranes, special dollies, etc. are required to tend to passenger needs and to remove the aircraft to a place of repair or disposal.

The material beyond the runway is usually soil. Soil (clay or sand) surfaces are very unpredictable in their arresting capability because their properties are very sensitive to moisture and temperature conditions. Very dry clay can be hard and nearly unpenetratable, and wet clay can cause the aircraft to mire down quickly, causing the landing gear to collapse and leading to further aircraft damage and potential for passenger and crew injury as well as the potential for a fire.

From the above discussion, the objective of this study is to find a means of safely stopping the aircraft during an overrun. The arrestment of the aircraft should minimize structural damage and reduce the time required to get the aircraft back on the normal operating surface. The recovery from an aircraft overrun incident should be predictable and disposed of in a short time with little hazard to passengers or crew. The arrestment system should be easily repaired and have a long service life. Its cost should be commensurate with the potential aircraft damage and airport runway downtime costs.

The primary tasks of the feasibility program for a Soft-Ground Aircraft Arrestment System are to:

1. Develop functional design criteria for the arrestment system.
2. Determine the tire/material interface model for water, foam, and gravel. Tire/material models for clay and sand are already available from other programs.
3. Select the most promising materials for the arrestor system.
4. Apply the selected material to a broad range of aircraft weights.
5. Determine the installation method for the final arrestment materials selected.
6. Develop an experimental program to validate the prediction methods used in the analysis.

The computer code FITER [1], developed for the United States Air Force, AFWAL/FIEM, was modified to accommodate the various tire/material models for the arrestment simulations. This computer program models the six airplane center of gravity degrees of freedom, gear loads, and the flexible structural response at selected locations.

Section 2 of this report describes in detail the first three of the above tasks and the results obtained. Section 3 describes the results obtained from the simulations of all aircraft being arrested by foam and gravel beds. Section 3 also describes the arrestor bed and installation. Section 4 provides the conclusions and recommendations resulting from the study. Appendices A through D provide the results of the literature review, description of the aircraft and the experimental test for the foam material.

SECTION 2 ARRESTOR BED MATERIAL SELECTION

Each task of the Soft-Ground Aircraft Arrestor System listed in Section 1 will be discussed in detail in this section. The aircraft weight range included in this study was 102,000 to 630,000 pounds. For economic reasons, only one aircraft, Aircraft A, was used for the arrestment simulation to select the arrestor material, and then simulations of four additional aircraft were used to demonstrate the capability of the arrestor made of the selected materials. The aircraft weight, inertia, and gear load characteristics are presented in Appendix B.

2.1 ARRESTOR DESIGN CRITERIA

Evaluation of the materials (clay, sand, foam, water, and gravel) selected for the arrestor system required that design criteria be established. The design criteria selected for the arrestor are shown in Figure 1. The reason for their selection is discussed in the following paragraphs.

2.1.1 Braking and Reverse Thrust

Aircraft braking and engine reverse thrust were neglected because the scenarios (see Appendix A) derived from overrun incidents indicated that a very low surface coefficient of friction existed as a result of the ice/snow/water on the runway, or that the overrun was due to a takeoff abort where engine reverse thrust might not be available. Neglecting these possible means of stopping the aircraft provided assurance that the distance estimated to arrest the aircraft would be conservative.

2.1.2 Gear Loads

If damage to the airplane is to be minimal as the result of an encounter with an overrun arrestor system, then the landing gear should not fail (collapse). Keeping the gear loads below limit loads for the

FEASIBILITY STUDY

SOFT-GROUND AIRPLANE ARRESTMENT SYSTEM

- 0 AIRCRAFT BRAKING AND REVERSE THRUST NEGLECTED
- 0 GEAR LOADS TO REMAIN BELOW DESIGN LIMITS AND STRUCTURAL DAMAGE MINIMAL
- 0 DECELERATION OF ALL AIRCRAFT IN LESS THAN 1000 FEET AT ENTRY SPEED OF 70 KTS
- 0 ACCESSIBLE BY GROUND EQUIPMENT (FIRE TRUCKS, TOW VEHICLES, ETC.)
- 0 RAPID REPAIR
- 0 ALL WEATHER OPERATION
- 0 EASILY MAINTAINED AND LONG LIFE
- 0 UNATTRACTIVE TO VERMIN, BIRDS OR OTHER UNDESIRABLE CREATURES

Figure 1. Arrestor Design Criteria

arrestment provides a high probability of a safe arrestment with minimal structural damage. Keeping the landing gear intact also reduces the probability of a wing fuel tank rupture and fuel spillage on those aircraft having engine pods on the wings. Retaining fuel in the fuel tanks during an overrun greatly reduces the probability of a disastrous fire.

2.1.3 Aircraft Deceleration

To be efficient, the arrestor system must stop all potential overrun aircraft within reasonable distance. The FAA Safety Area of one thousand feet beyond the runway end was selected as the maximum distance to be allowed. This would require an average aircraft deceleration of about 0.22 g's for an entry speed of 70 knots to assure a complete stop.

2.1.4 Accessibility by Ground Equipment (Fire/Rescue/Crash Vehicle)

The arrestor system should not prevent fire/crash/rescue vehicle access to the immediate area of the aircraft in the event of a fire or need for rapid removal of possible injured personnel. It should not prevent the evacuation of passengers and crew.

2.1.5 Rapid Repair

Should an incident occur, the arrestor system capability might be degraded and require repair prior to being put back into operational readiness. This repair should be easily accomplished and should be accomplished in a short period of time so as to be available for the next incident.

2.1.6 All Weather Operation

The arrestor system performance should be insensitive to the weather extremes from -65°F to 150°F, in rain, snow, or ice. Snow and ice removal should be limited to only heavy accumulations.

2.1.7 Ease of Maintenance and Long Life

Maintenance of the arrestor system should be minimal. Periodic inspections may be required to assure nothing has caused a change in the arrestor performance. Exposure to the natural elements should cause no change in performance.

2.1.8 Unattractive to Earthly Creatures

The arrestor material should be treated to be naturally unattractive to vermin, birds, or other undesirable creatures which might degrade the material or be hazardous to aircraft operations.

2.2 DETERMINE TIRE/MATERIAL INTERFACE MODEL

The tire/material interface model is required to couple the arrestor to the aircraft so that the deceleration, loads, and dynamic response can be determined. This tire/material interface was accomplished from a review of the literature [2-5] for sand and clay, water, foam, and gravel. Refer to Reference 2 for details of the tire/soil model, since it is rather complex and too lengthy to duplicate in this report. For water, foam, and gravel, the tire/material interface model is shown in Figure 2.

The drag and vertical forces induced by water, gravel, or foam are a function of the density of the material, the horizontal velocity (V) of the wheel axle, and the vertical and horizontal projected areas of the tire exposed to these materials. The projected areas of the tire are (Figure 2):

$$A_F = S \cdot H \quad (1)$$

where $H = Z_m - \delta_t \quad (2)$

- AF Exposed tire frontal area
- AW Exposed tire horizontal area
- FD Tire drag load
- FV Tire vertical load
- H Frontal height
- R Tire radius
- S Tire width
- ZM Reference height of foam
- Z_w Axle vertical displacement
- δ_t Tire deflection

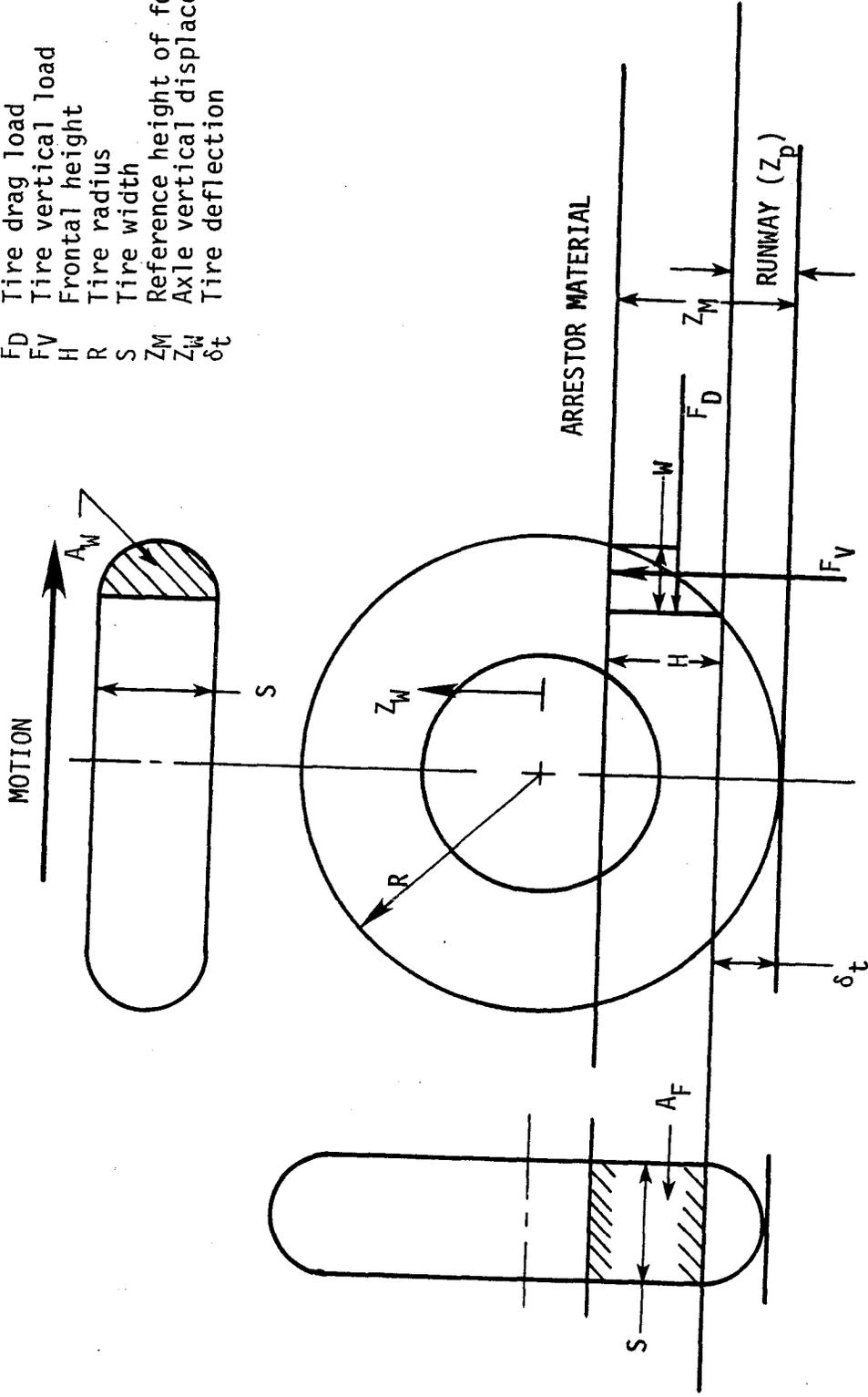


Figure 2. Wheel Interface Model for Foam, Gravel, and Water

and
$$\delta_t = Z_p - Z_w \quad (3)$$

$$A_w = S * W * .66 \quad (4)$$

where
$$W = R^2 - (R - Z_M + \delta_t)^2 - R^2 - (R - \delta_t)^2 \quad (5)$$

The value 0.66 (Eq. (4)) is introduced because the tire projected horizontal area is not rectangular like the tire frontal area and other tire/material interface inefficiencies for a lifting surface. This number should be verified by test in the final selected materials.

The vertical and drag forces are equal to the pressure on the projected tire areas. These pressures vary with the type of material. For foam, the pressure is equal to the crushing strength plus the dynamic pressure. The crushing strength is determined by forcing a plate of a given area into the foam and recording the force as a function of time or displacement. Figure 3 shows an example of how the foam crushing strength is determined. The pressure is also a function of the horizontal velocity (V) of the wheel, i.e., $p = p_c + 1/2\rho V^2$, where ρ is the mass density of the foam and p_c is the crushing strength. The density of foam is very small so the dynamic pressure term can be dropped and the vertical and drag forces are (see footnote):

$$F_V = p_c * A_w * C_L \quad (6)$$

$$F_D = p_c * A_f * C_D \quad (7)$$

For water, the only pressure is the dynamic pressure, but for gravel, there is a crushing strength (equal to about 22 psi) and dynamic pressure. Water has a density of (62./32.2) slugs/ft³ and gravel has a density of about (90./32.2) slugs/ft³.

C_D and C_L are assumed to be equal to one. This assumption should be verified.

NOTE: DATA ARE FOR
POLYSTYRENE FOAM

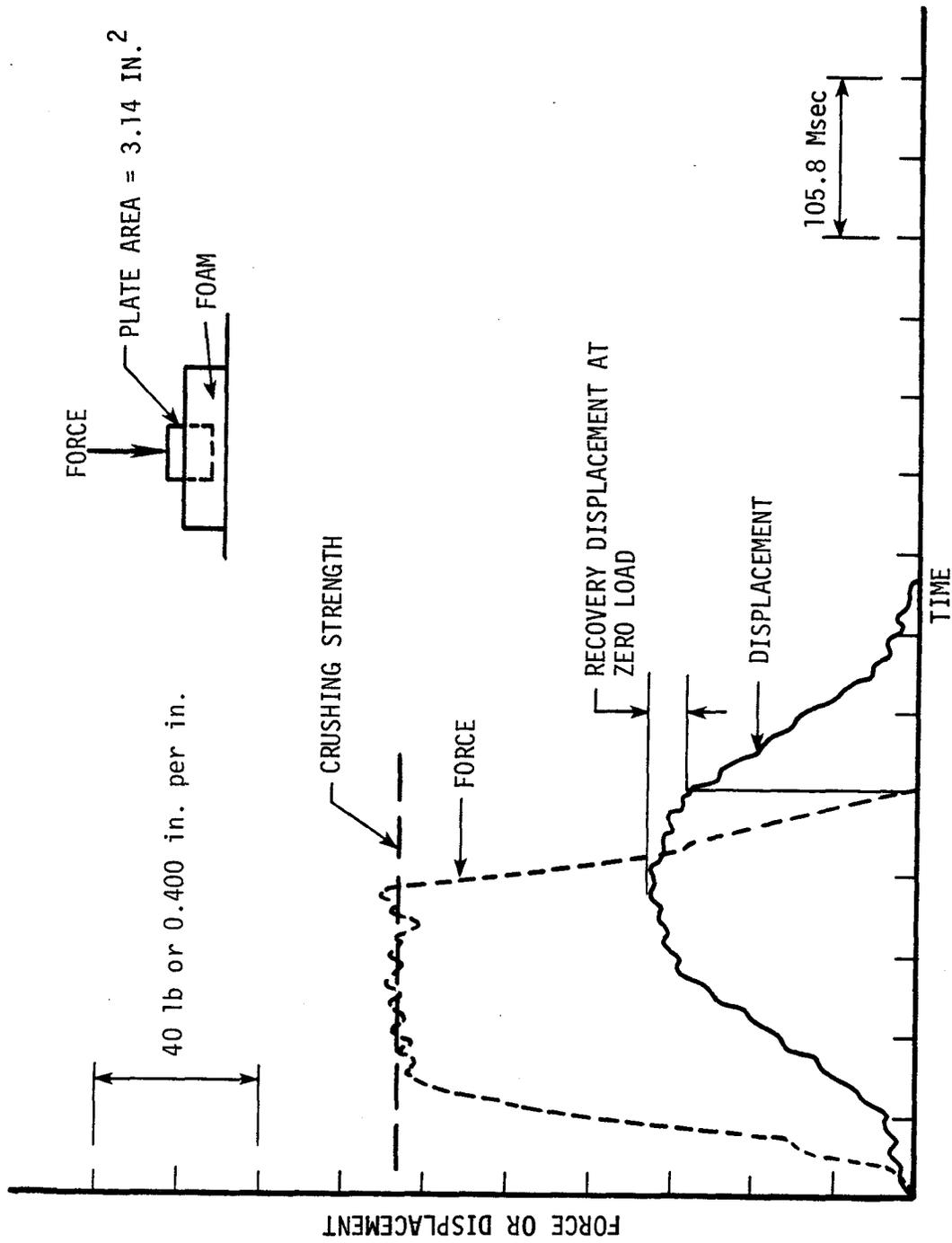


Figure 3. Impact Test Results From Foam Materials

When the tire is deflected, the vertical force F_V also has a component equal to $F_V = K\delta_t$ where K is the tire spring rate. This is added to the gravel or water pressure force to obtain the total vertical load.

The above equations were introduced into the computer program FITER so that the deceleration, gear loads, and structural dynamic response could be determined.

2.3 SELECT ARRESTOR MATERIAL

2.3.1 Clay, Sand, and Water

The arrestor materials were selected using the design criteria (Figure 1) as a basis and for the ability of materials to stop aircraft in the shortest distance. Clay, sand, and water had some major faults in meeting the design criteria but were, nevertheless, considered candidates. Clay, to be effective, would have to be in the CBR range of 2 to 3 and this would be very difficult to maintain under all weather conditions. At temperatures below 32°F, the water in clay could freeze and clay will be useless as an arrestor. At temperatures above freezing, clay would dry out quickly, requiring considerable water addition and reworking to maintain the required strength.

Sand, on the other hand, would have to be relatively dry to be effective. Maintaining the dryness would be somewhat easier but it would have to be contained in waterproof/airtight bags which would be easily ruptured in the event of an overrun. Rain or snow could fill the junctures of the individual bags, making the sand less effective in the event of freezing weather.

Water ponds suffer from problems of stagnation to being attractive to various creatures. In the colder climates, water ponds would be subject to freezing, making them ineffective. Access by rescue/crash/fire vehicles or evacuation of passengers would also be difficult.

Arrestment simulations were conducted, however, to determine the effectiveness of clay, sand, and water in their ideal conditions. Only one aircraft (see Aircraft A, Appendix B) was used to obtain the deceleration characteristics.

Figures 4 and 5 are plots of the aircraft deceleration (in g's) versus horizontal distance traveled (in feet). The clay and sand arrestor beds start at 100 feet as indicated by the steep rise in the deceleration. The smaller increase in deceleration at the beginning of the arrestment was due to just the nose gear being in clay or sand. The oscillations are due to the dynamic characteristics of the aircraft being excited (primarily the pitching mode) when the wheels sank into the soil after leaving the runway. The stopping distance was approximately 650 feet in the clay bed and about 600 feet in the sand bed. The aircraft limit loads for the landing gear were not exceeded during the arrestment.

Figure 6 describes the pond elevation configuration used to determine the deceleration characteristics of water. Figure 7 indicates the aircraft deceleration obtained. Since the only pressure acting on the wheels is the dynamic pressure ($p = 1/2\rho V^2$), the deceleration is reduced as the velocity decreases. At very low velocities, less than 20 knots, the dynamic pressure becomes very small and long distances are required before the aircraft comes to a stop. At the higher speeds, the dynamic pressure is quite high and produced nose gear loads in excess of limit loads. Entry speeds into the pond would be limited to about 50 knots in most cases because of the gear loads.

The limitations and faults of clay, sand, and water in terms of the arrestment system design criteria were considered to be excessive and these materials were therefore discarded as potential arresting materials.

2.3.2 Gravel

Gravel material of smooth-surfaced pebbles graded to ASTM D448-86 [6] size number 57 avoids many of the faults of clay and sand. The pebbles are large enough that the voids allow adequate drainage so

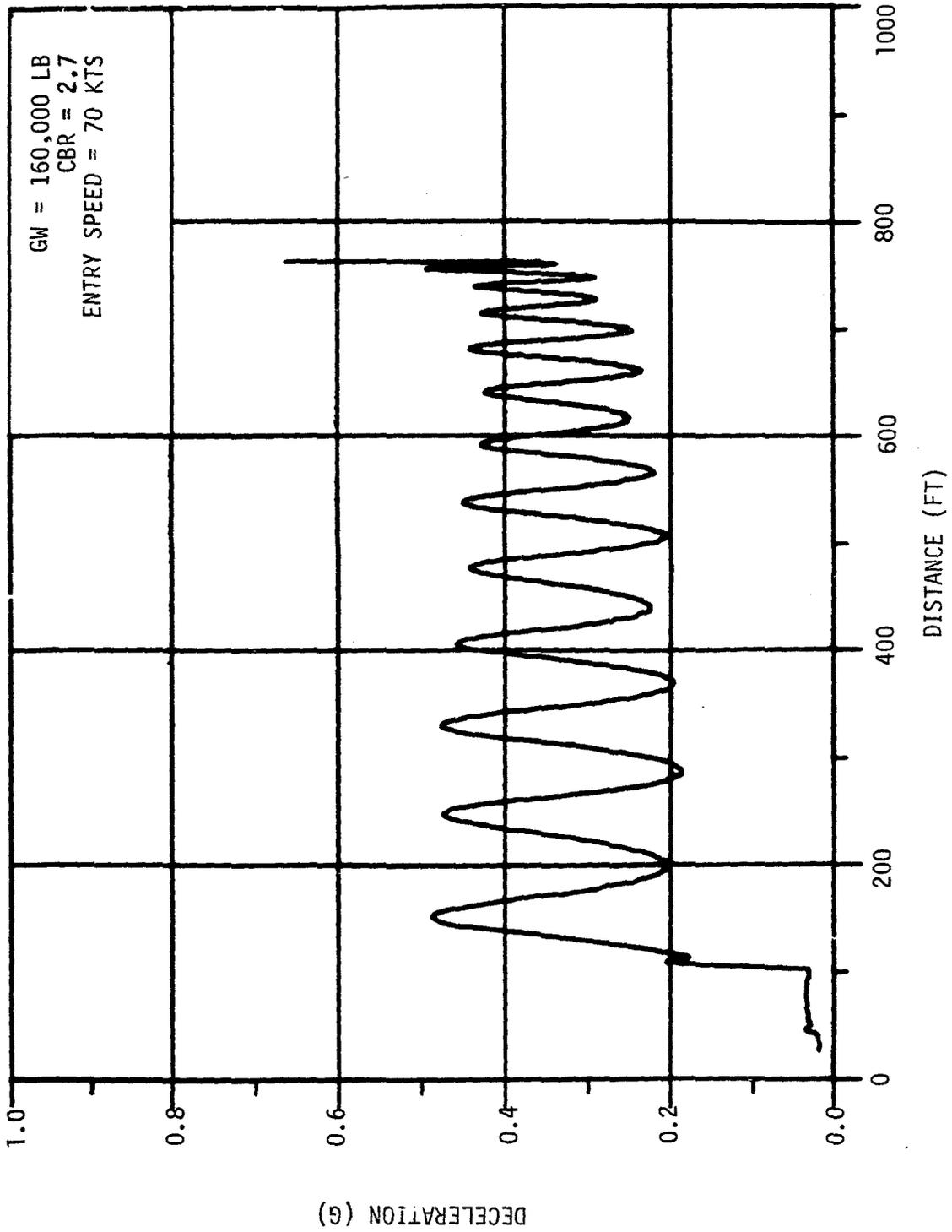


Figure 4. Aircraft A Arrestment in a Clay Bed

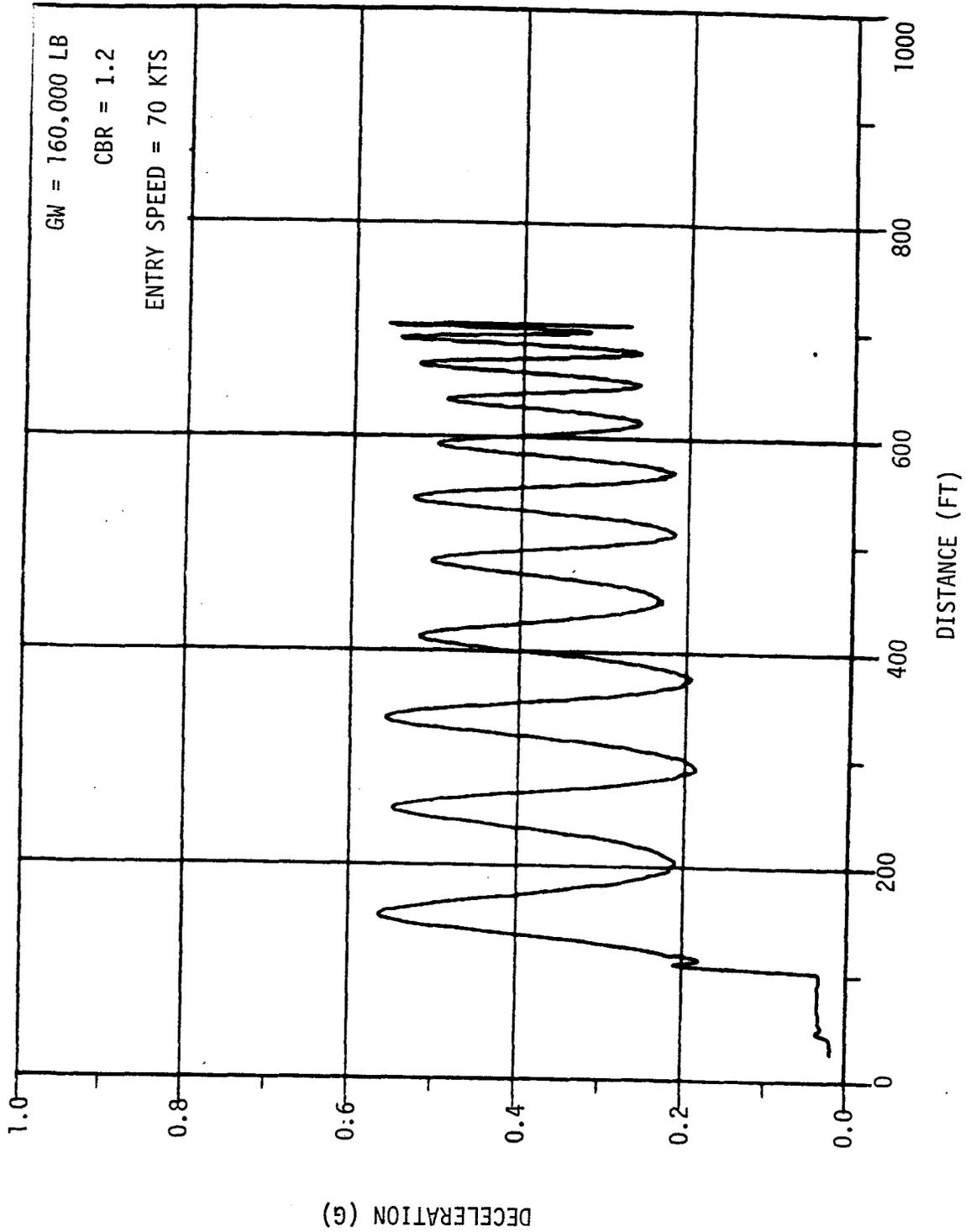


Figure 5. Aircraft A Arrestment in a Sand Bed

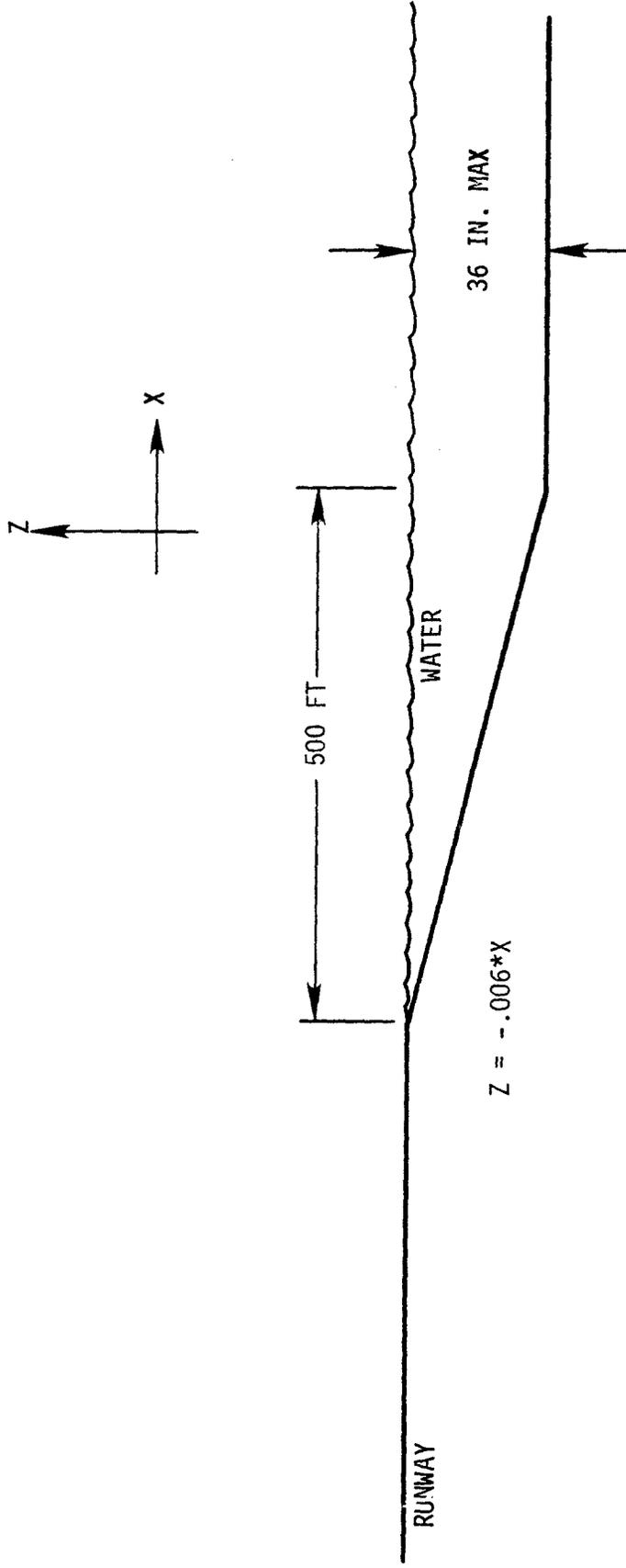


Figure 6. Water Pond Geometry

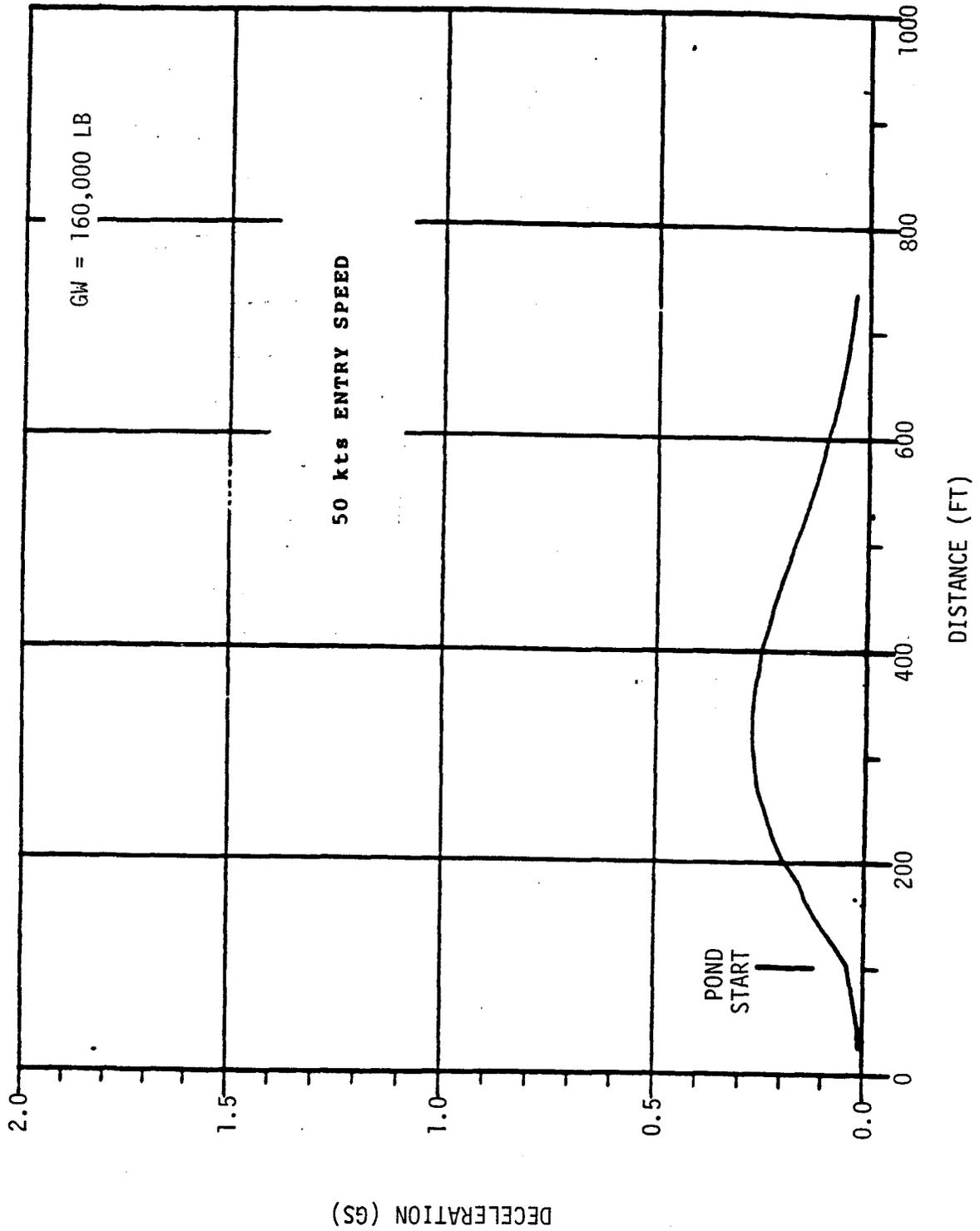


Figure 7. Aircraft A Deceleration in a Water Pond

that freezing in the milder climates would not be a problem. The bond which might occur under very light freezing conditions is easily broken [4] so that the performance parameters as an arrestor would remain reasonably constant. Gravel spray from landing gear (FOD) may be a problem for aircraft engines unless controlled.

Simulations of Aircraft A were made using a gravel bed configuration as shown in Figure 8. The entry speed for the simulated arrestment was 70 knots. An idle thrust of 3,000 pounds was also assumed to be acting on the aircraft. Figure 9 shows the aircraft deceleration characteristics in the gravel bed. Initially, only the free rolling drag is providing the deceleration. The nose gear then contacts the gravel bed and a slight increase in deceleration is obtained. The steep rise in the deceleration curve is obtained when the main gear penetrates the arrestor bed. A maximum deceleration of about 0.68 g's is obtained. The deceleration decreases as the aircraft velocity decreases until the aircraft stops. The velocity profile of the aircraft during arrestment is shown in Figure 10.

Figure 11 presents the rut depth profile of Aircraft A while in the gravel arrestor. The nose gear began planing at the higher speeds and did not reach full penetration until the aircraft velocity was less than 50 knots (see Figure 10). The main gear wheels also planed in the gravel arrestor.

The planing of the nose and main gears in the gravel arrestor is a function of the tire projected horizontal area and the tire lift coefficient which was assumed to be equal to 1, but this is probably not true. The actual value is probably less but is unknown at present.

The landing gear loads developed during the gravel bed arrestment are shown in Figure 12. The peak nose gear vertical load obtained was about 45,000 pounds, and this exceeds the limit load of 44,400 pounds provided by the aircraft manufacturer. However, this peak load is a result of the nose gear planing and climbing the gravel bed grade. The nose wheel then comes down rather sharply, contacting the underlying surface, causing a sharp increase in load. Now, if the wheel planing is

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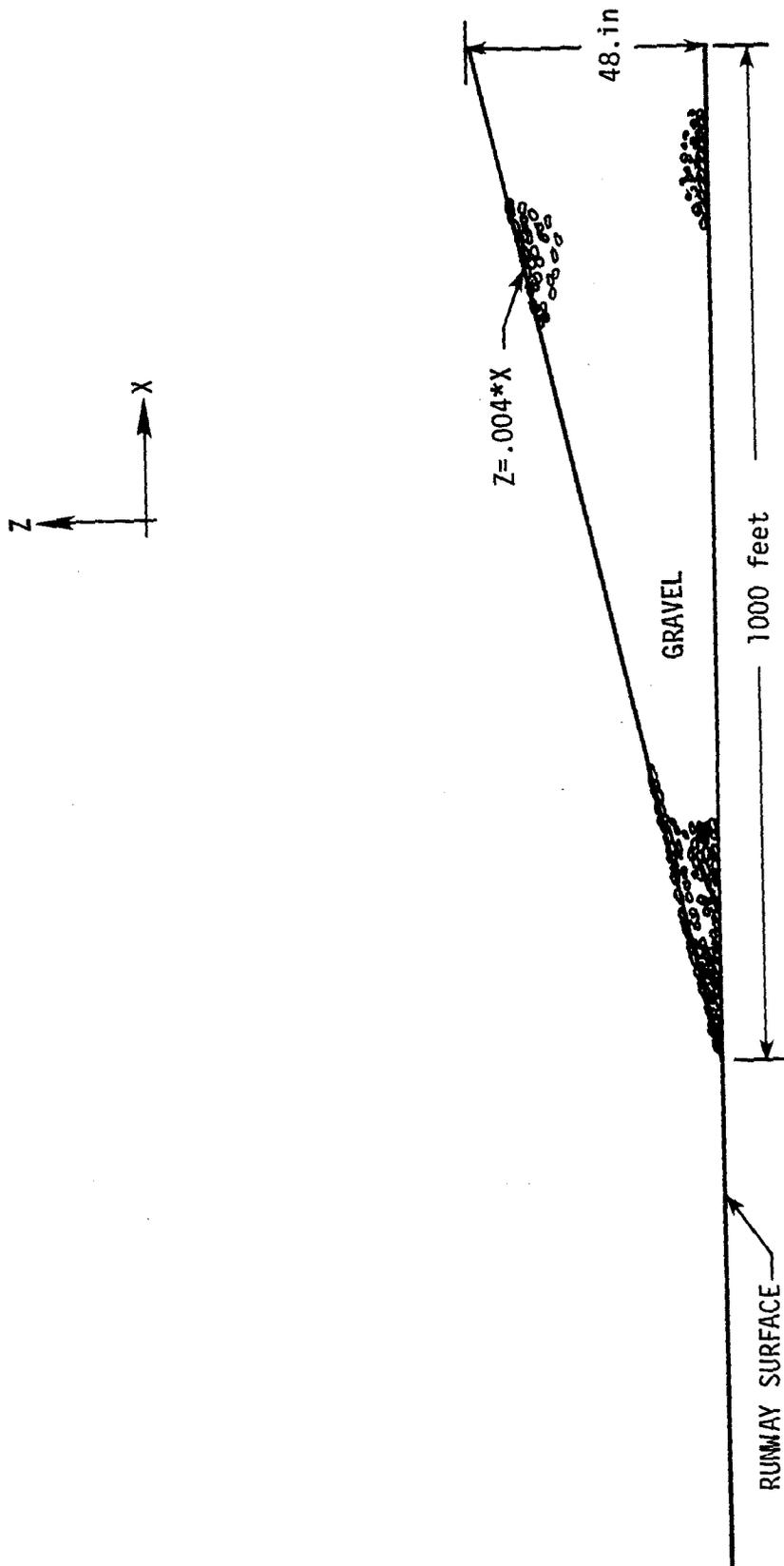


Figure 8. Gravel Arrestor Bed Configuration

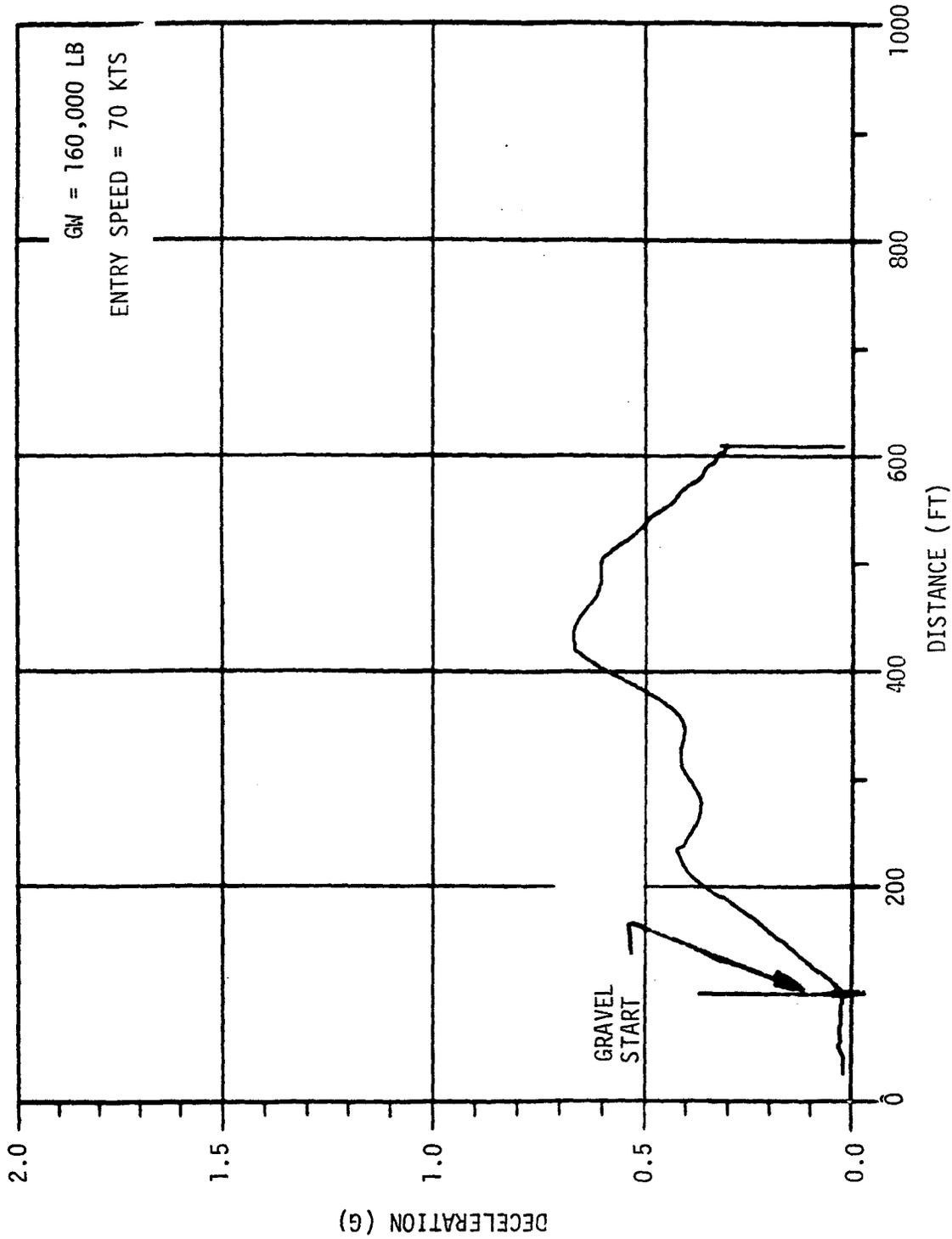


Figure 9. Deceleration of Aircraft A in Gravel Arrestor Bed

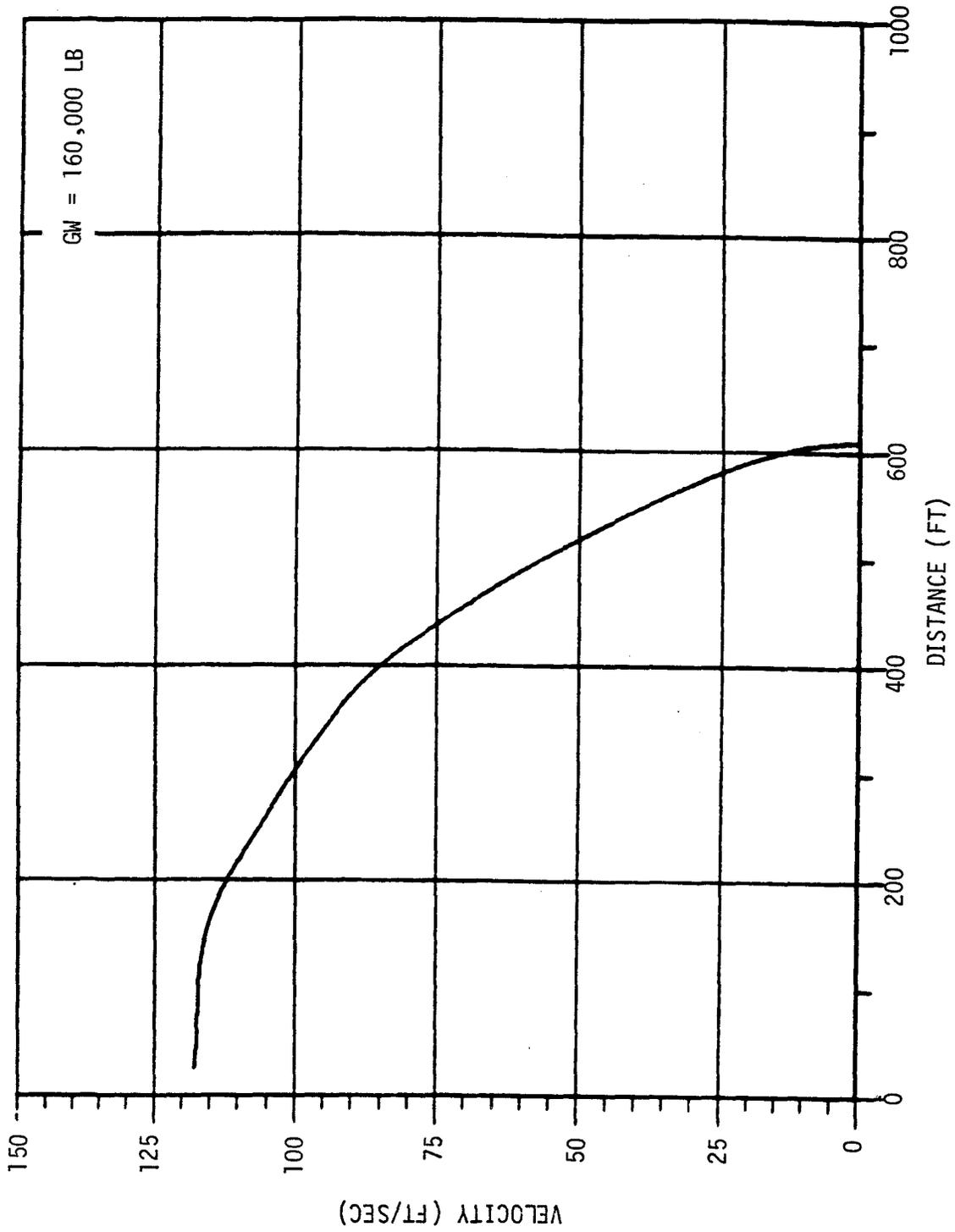


Figure 10. Aircraft A Velocity Profile in Gravel Arrestor Bed

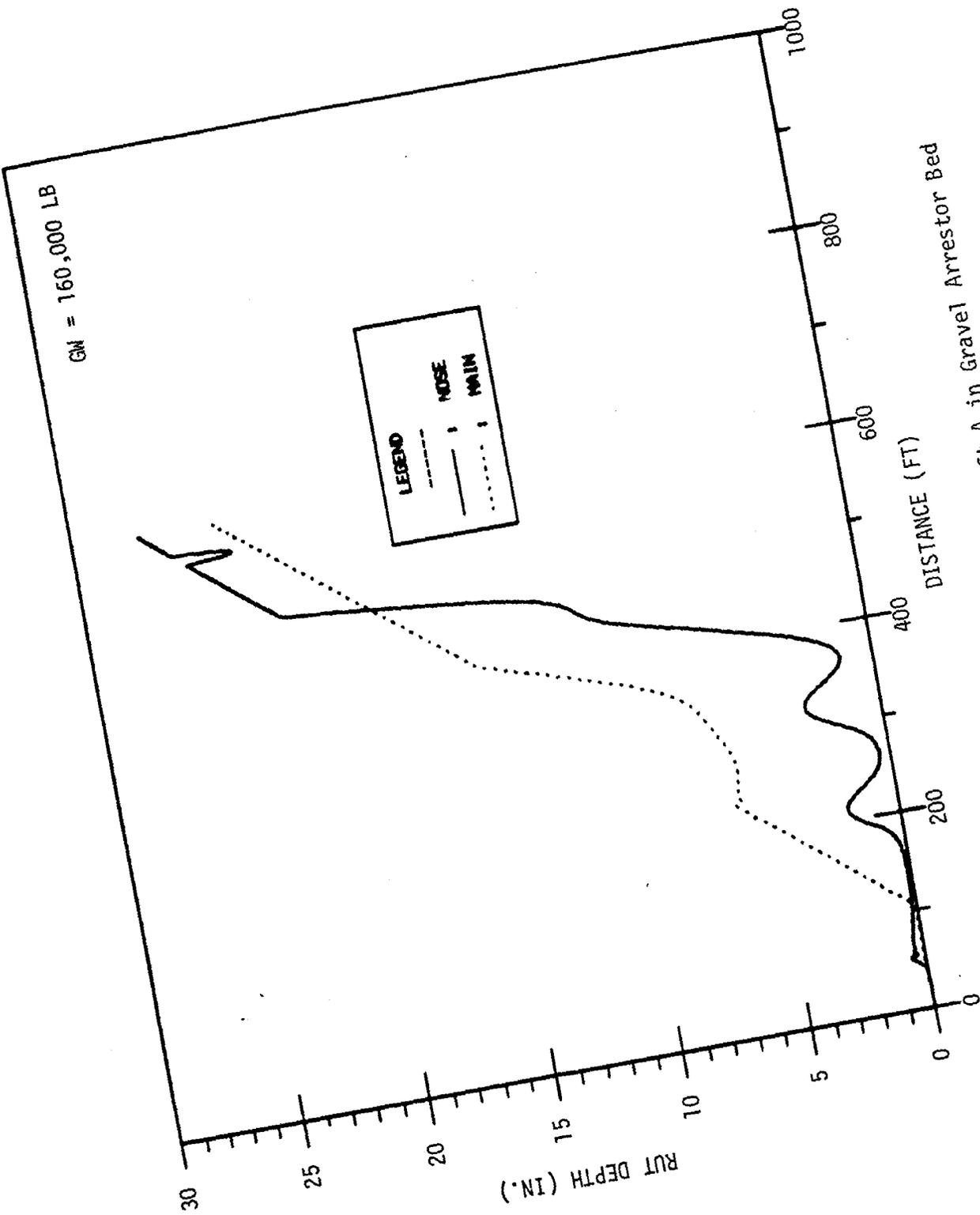


Figure 11. Rut Depth of Aircraft A in Gravel Arrestor Bed

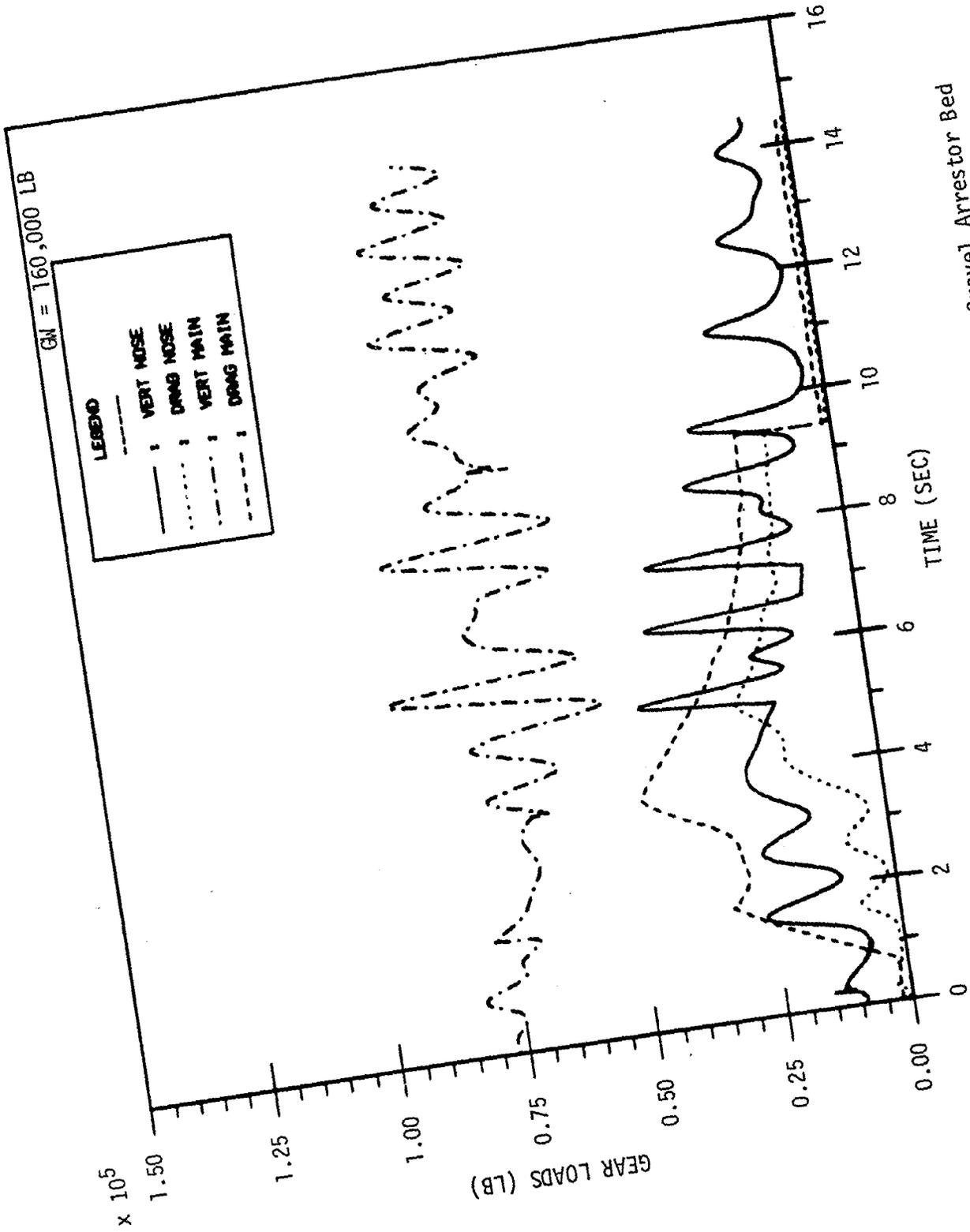


Figure 12. Aircraft A Gear Loads Resulting from Gravel Arrestor Bed

less pronounced, as suspected, the vertical peak loads will be reduced and they will, most likely, be within design limits.

The drag limit load for the nose gear is 25,600 pounds, and it was also exceeded slightly for Aircraft A. The main gear drag and vertical loads for Aircraft A are well within the limit loads of 62,800 and 167,470 pounds, respectively. There is no concern of main gear collapse as a result of the gravel bed arrestor imposed loads.

Even though the nose gear loads exceeded limit loads by a small amount, the prospect of nose gear collapse is not likely since that would require the loads to exceed the ultimate strength of the gear and gear support. The ultimate loads are 1.5 times the limit loads, and the computed loads are considerably less than those values. The aircraft manufacturer would have to be consulted to determine the ultimate loads. With the above factors in mind then, it would appear that a gravel bed is a potential candidate as an arrestor.

2.3.3 Foam

Polystyrene foam was also investigated as a material having potential as an aircraft arrestor. Several polystyrene products were tested in the laboratory by impacting a 2-inch-diameter plate into the foam sample and recording the displacement and force that occurred (see Figure 13). Results obtained from the plate tests were similar to those shown in Figure 3. Appendix C describes the foam tests in detail. The two parameters of concern were the crushing strength of the foam and the amount of recovery after the load was removed. The products which crushed and showed very little elastic recovery were desired since this provides a maximum of energy dissipation. One product was found which exhibited the required characteristics as shown in Figure 3, and the characteristics of this product were used to conduct the arrestor simulations.

Initial simulations of Aircraft A were conducted using the foam bed configuration shown in Figure 14.

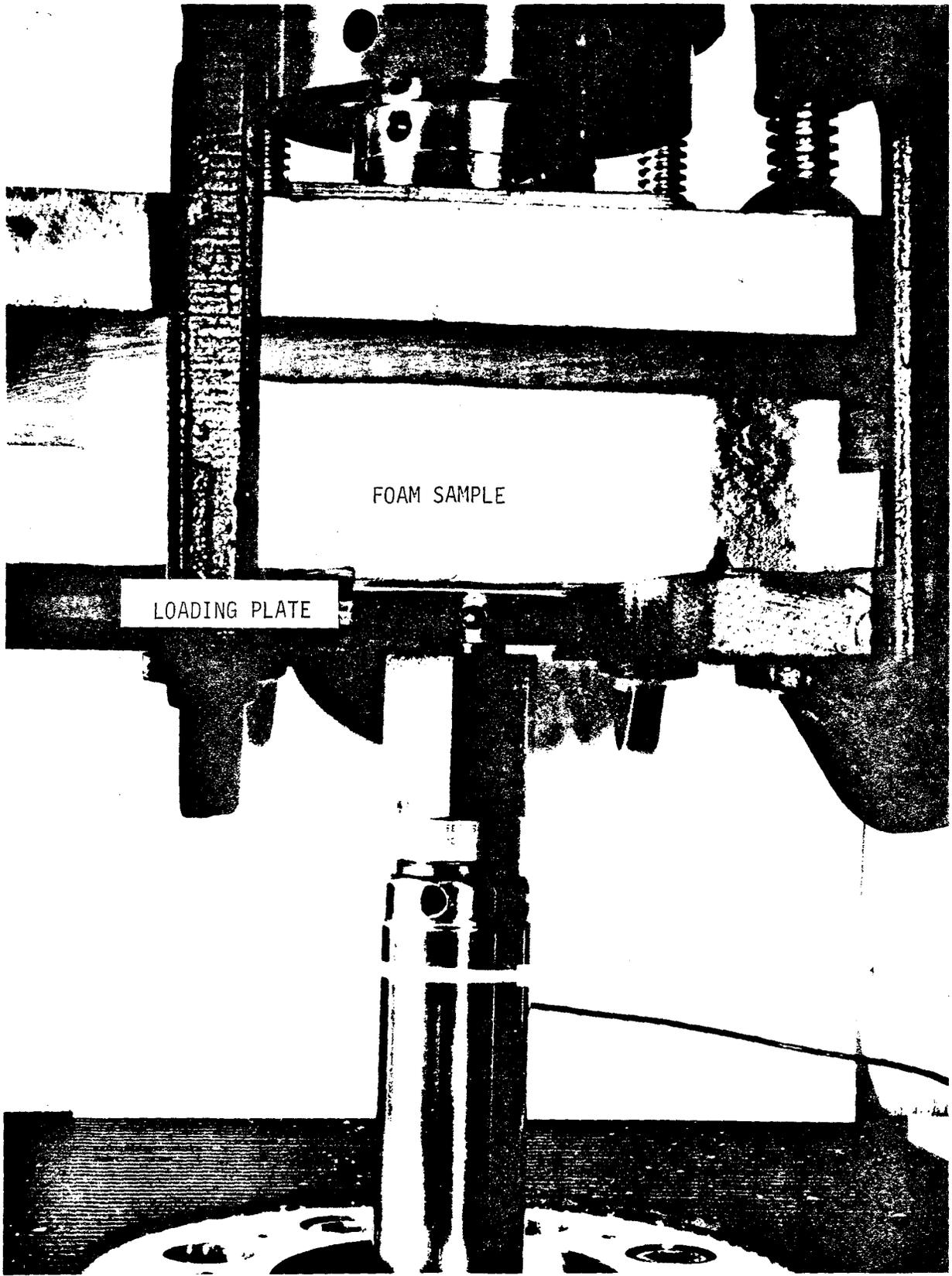


Figure 13. MTS Test Setup for Foam Sample

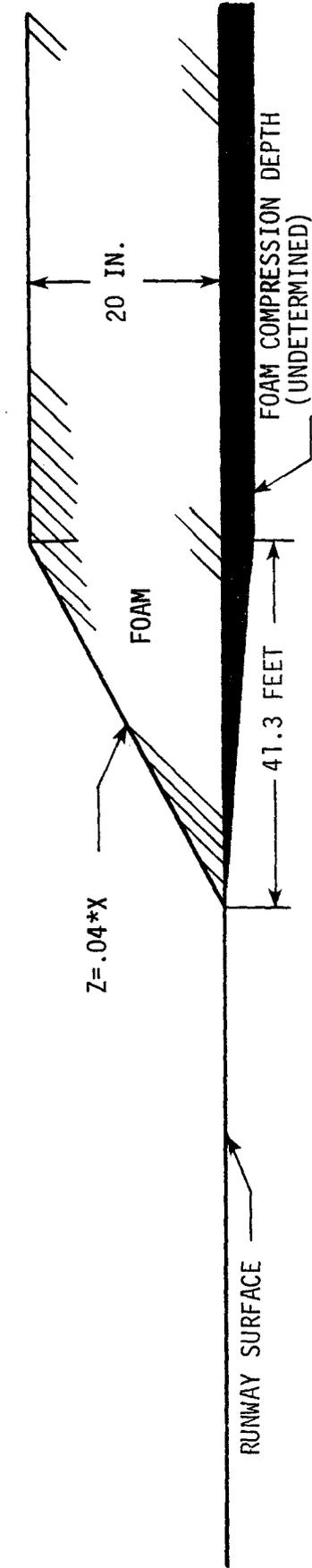
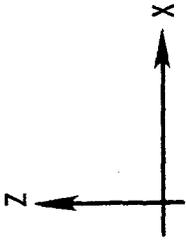


Figure 14. Foam Arrestor Bed Configuration

The purpose of the foam compression depth shown in Figure 14 is to maintain a continuous zero runway profile elevation. The foam crushes at a nearly constant stress until it is compressed to 80 or 90 percent of its original depth. Beyond that depth, the foam becomes quite rigid and this compressed height would then act as a runway surface elevation change and induce additional loads. Some additional studies, however, indicate that the increase in the runway surface profile elevation by an amount equal to one-tenth of the foam bed elevation does not significantly affect the gear loads. This will be discussed further under the foam arrestor bed configurations.

Figure 15 shows the deceleration of Aircraft A in a foam arrestor having a crushing strength of 45 psi. The entry speed of the aircraft was 70 knots, and an idle thrust of 3,000 pounds was assumed to be acting throughout the arrestment. The deceleration reaches a value of slightly more than 0.5 g and remains essentially constant during arrestment. This characteristic indicates that the foam bed is efficient compared to other materials tested. The other materials generally showed a considerable variation in the deceleration as a function of distance.

The velocity profile of Aircraft A during the foam bed arrestment is shown in Figure 16. This indicates that the zero velocity was reached in about 430 feet (the foam bed starts at 100 feet).

The landing gear loads are shown in Figures 17 and 18. Figure 17 shows that the nose gear loads are well within the limit loads for Aircraft A, and Figure 18 shows that the main gear loads are also below limit values. (Limit values are given in Appendix B.)

Figure 19 shows the rut depth was a maximum of 20 inches and that there was no evidence of planing in the foam bed as occurred with gravel.

The foam arrestor bed is clearly the most efficient of all the materials selected for evaluation. According to the foam manufacturer, the material is very stable over a temperature range from cryogenic to 165°F. The material has a flame retardant additive included to minimize the possibility of a fire. Foam is certainly a viable candidate for an arrestor system.

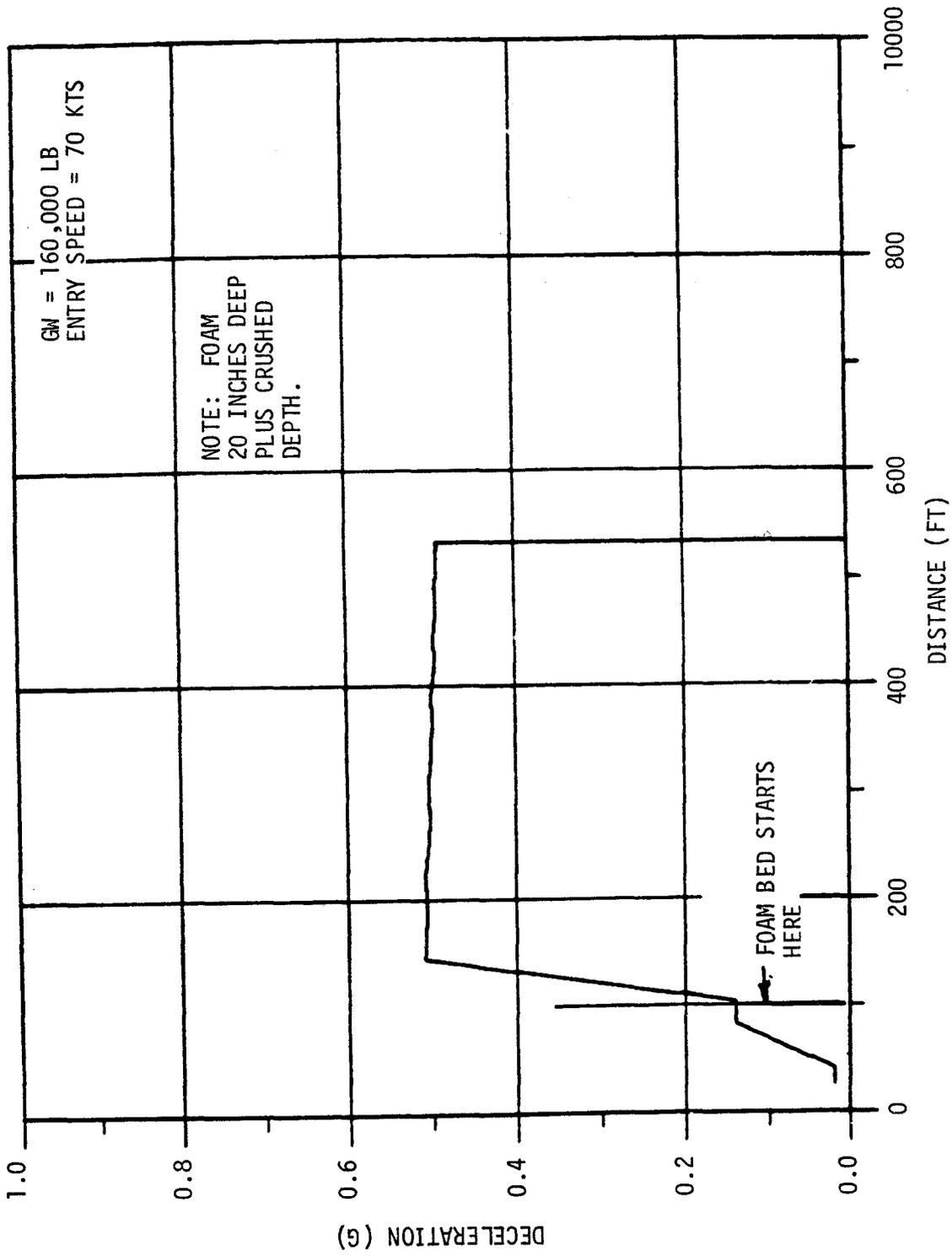


Figure 15. Deceleration G's and Distance in Foam Arrestor for Aircraft A

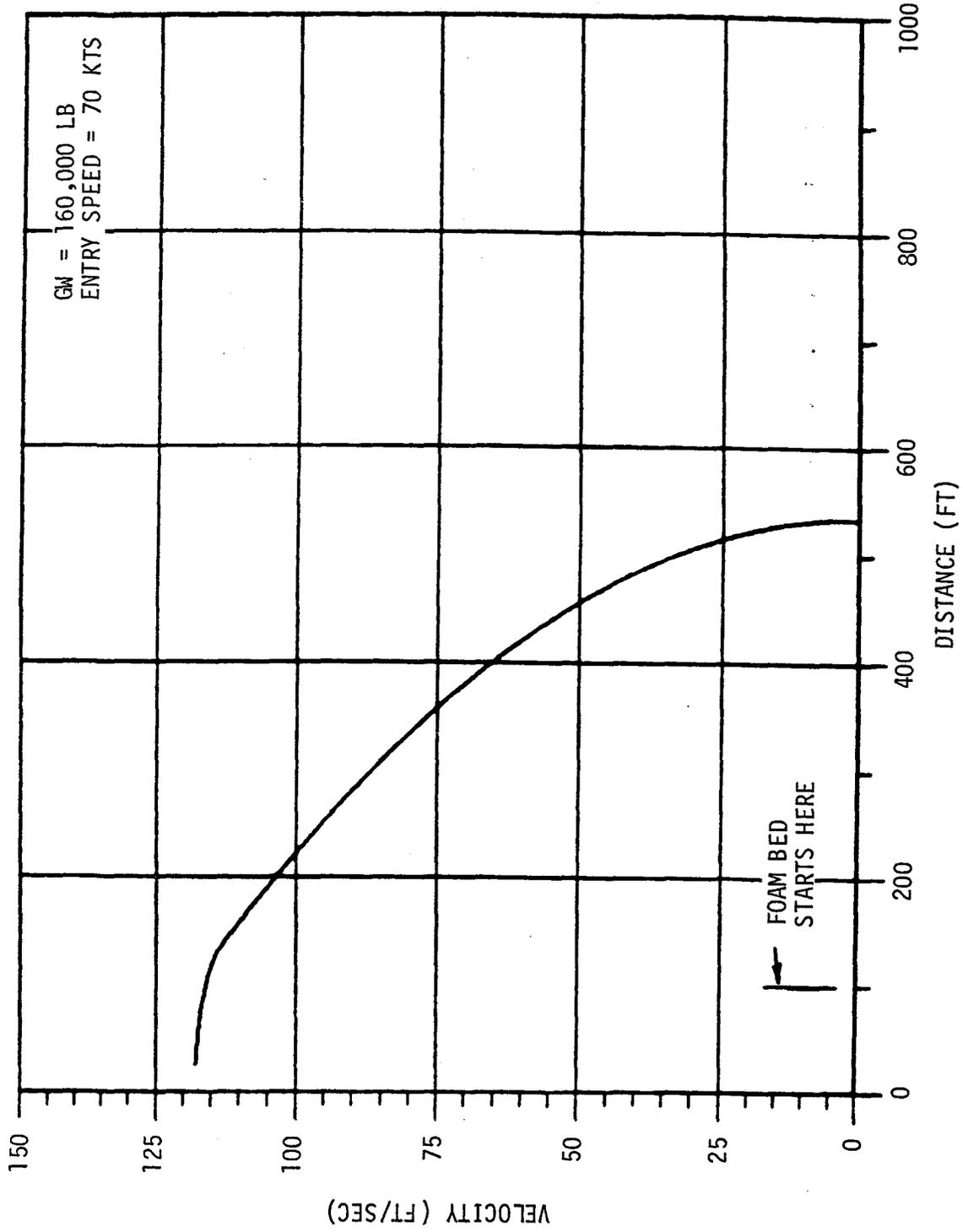


Figure 16. Velocity Profile While in Foam Arrestor for Aircraft A

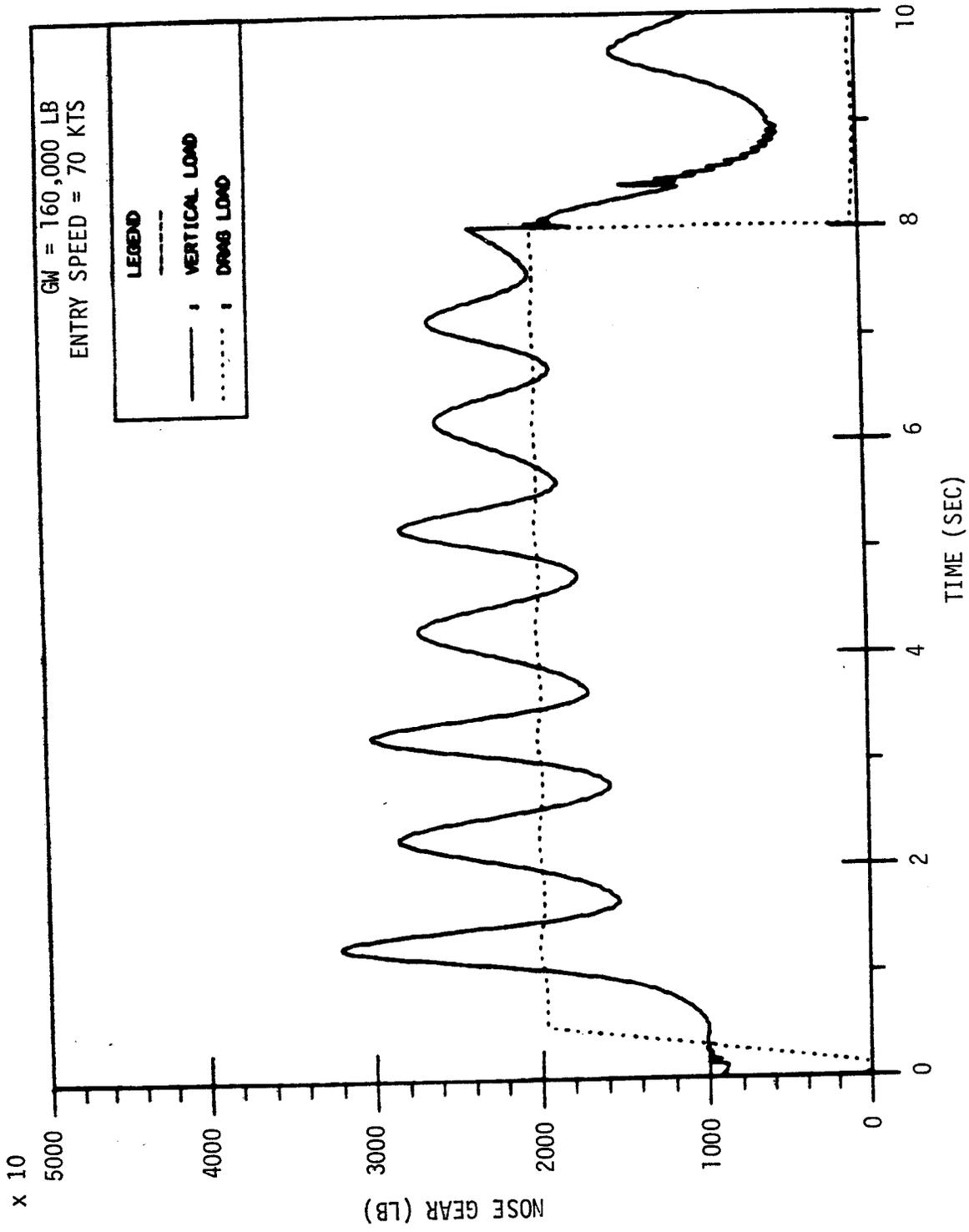


Figure 17. Nose Gear Loads While in Foam Arrestor Bed for Aircraft A

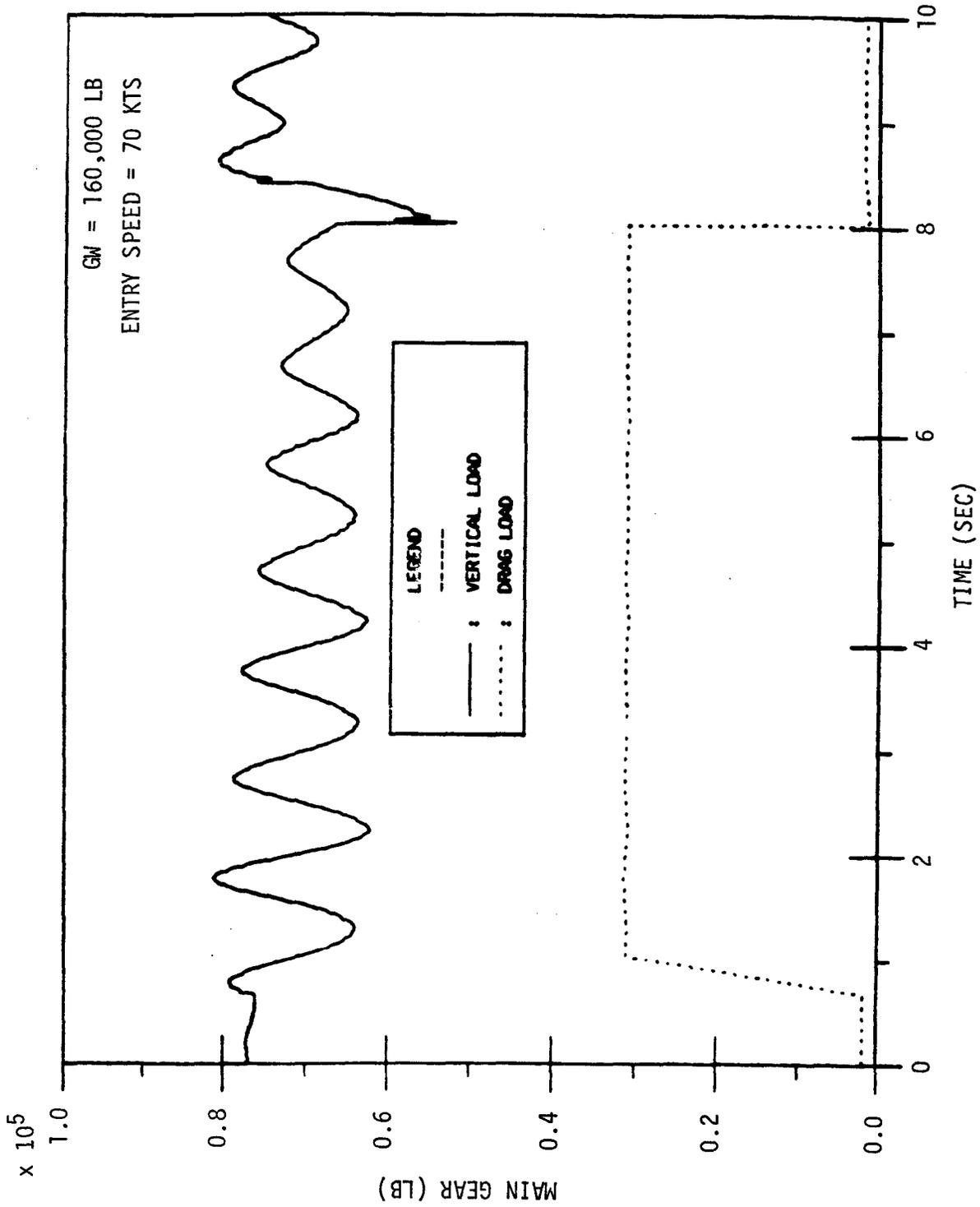


Figure 18. Main Gear Loads While in Foam Arrestor Bed for Aircraft A

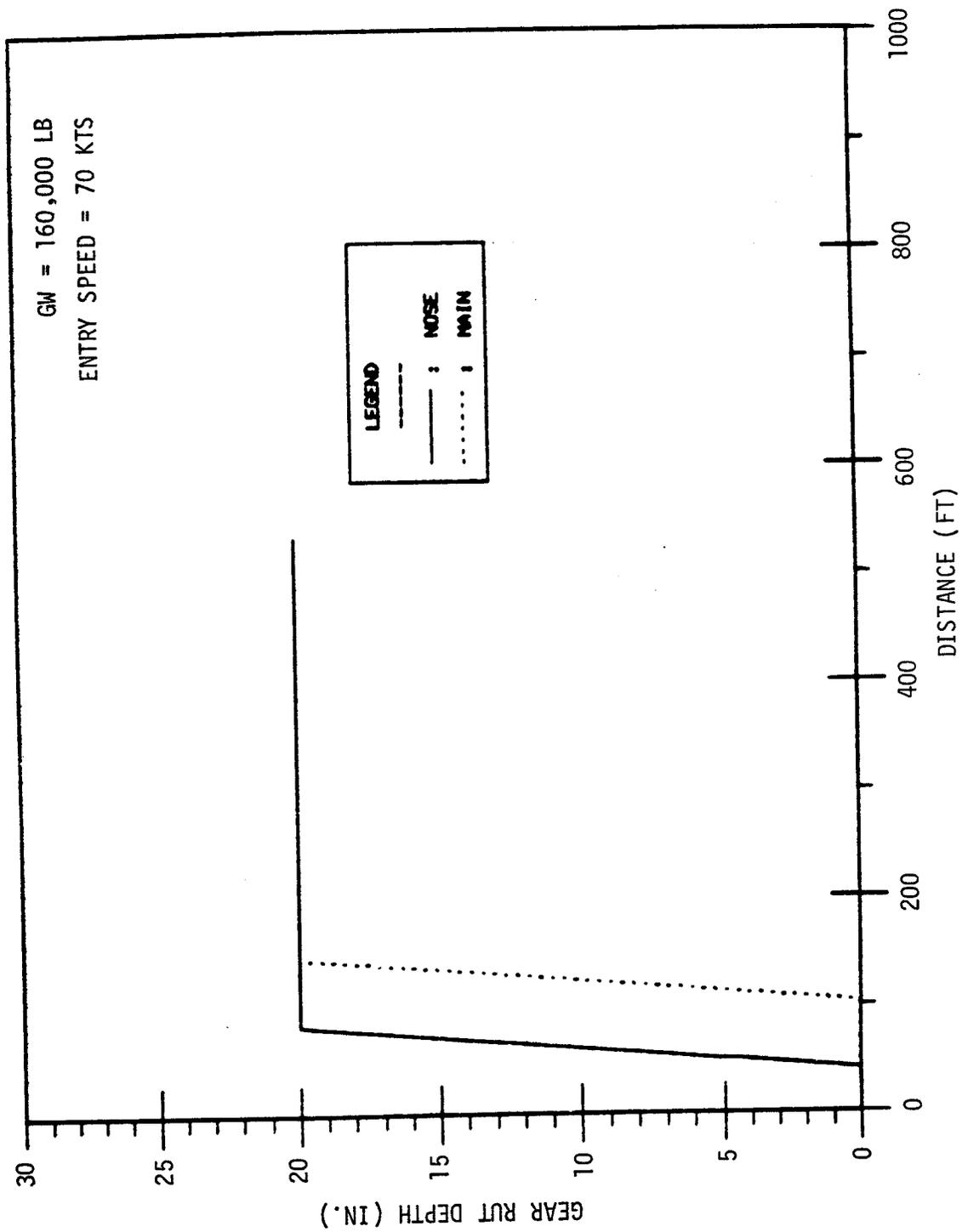


Figure 19. Rut Depth in Foam Arrestor Bed for Aircraft A

SECTION 3

ARRESTOR CONFIGURATION SELECTION AND SIMULATIONS OF ALL AIRCRAFT STUDIES

In Section 2 of this report, it was determined that only two materials had suitable characteristics to decelerate aircraft during an overrun. The materials were gravel and foam. However, only one aircraft type was used in selecting the materials and, to be useful, these two materials must be capable of arresting a broad range of aircraft types covering the gross weight range of current commercial aircraft. It is also necessary to determine whether aircraft which undershoot the runway will be adversely affected by the arrestor. The work accomplished to satisfy these requirements is described below. Aerodynamic lift-and-drag was assumed to be in effect throughout the arrestment.

3.1 GRAVEL ARRESTOR

Simulations of arresting the five aircraft described in Appendix B were conducted using the gravel bed described earlier (Figure 8). The entry speed into the arrestor bed was 70 knots and an idle thrust of 3,000 pounds was assumed in all cases.

3.1.1 Aircraft A

The results of the simulations for this aircraft were presented in Section 2.

3.1.2 Aircraft B

Figure 20 shows the deceleration of Aircraft B as a function of distance. The maximum deceleration was about 0.67 g's. This curve is somewhat different than the one obtained for Aircraft A in that it is quite smooth. It demonstrates the constant gravel bed slope and the gravel dynamic pressure effect. Aircraft B did not plane in the gravel and all wheels remained in contact with the extended runway surface which supports the gravel (Figure 21), thus providing a smooth deceleration. The total distance traveled in the gravel was about 440 feet as shown in Figure 22.

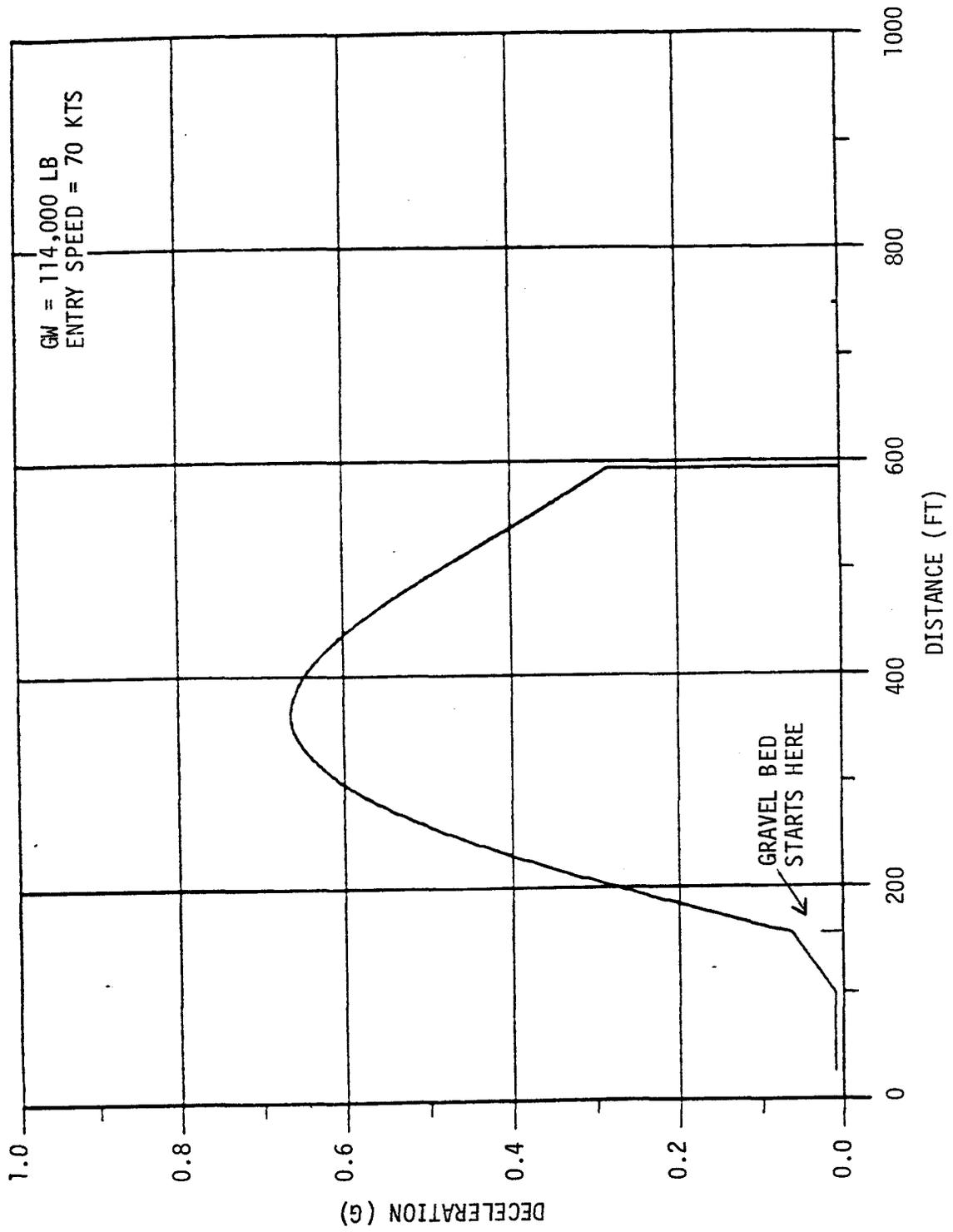


Figure 20. Aircraft B Deceleration in Gravel Arrestor

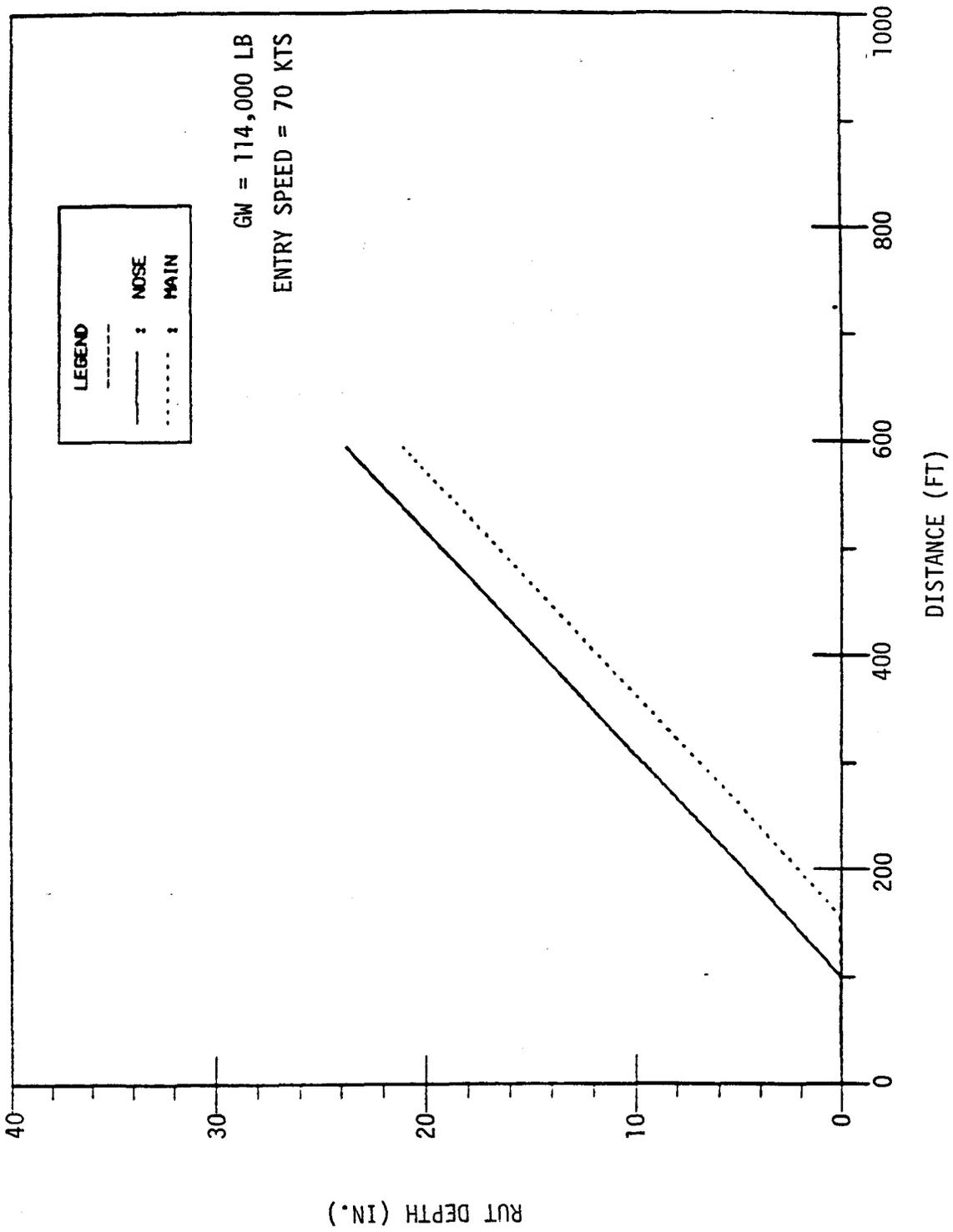


Figure 21. Aircraft B Rut Depth Profile in Gravel Arrestor

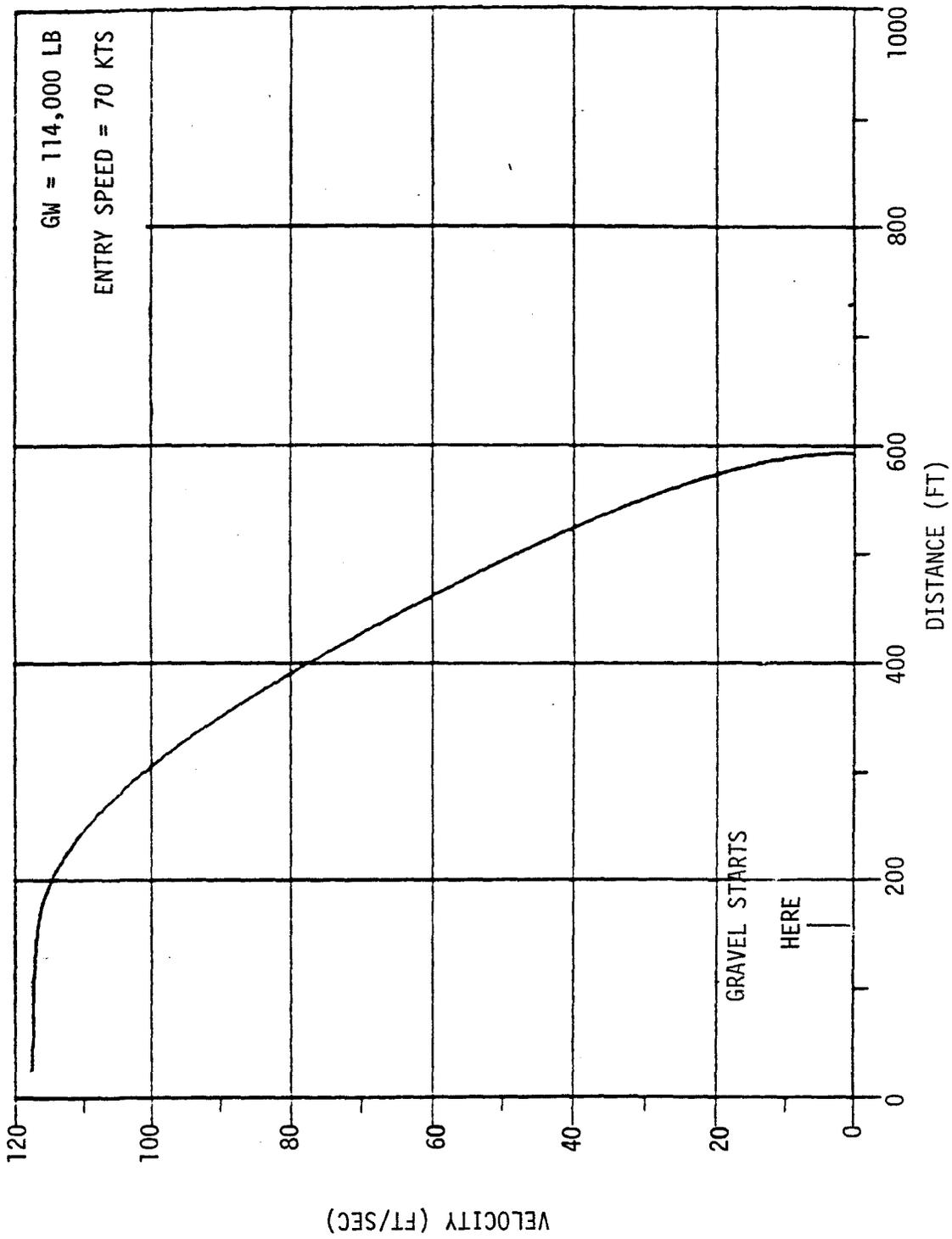


Figure 22. Aircraft B Velocity Profile in Gravel Arrestor

The maximum gear vertical loads while in the gravel bed (Figure 23) were always below the limit loads imposed by the manufacturer of the aircraft (see Appendix B). The nose gear drag load was slightly excessive but is satisfactory considering the analytical accuracy of the simulation.

Figure 24 shows the acceleration levels in the vertical plane at the pilot's position and at the center of gravity of Aircraft B. The acceleration levels are quite low, indicating a rather smooth ride while in the gravel arrestor.

3.1.3 Aircraft C

Aircraft C is somewhat larger than Aircraft A or B (335,000 pounds) and the gravel bed produced less deceleration (0.48 g's) as shown in Figure 25. Aircraft C has a four-wheel truck for the main gear (dual-tandem) and only the two wheels on the front axle are effective in producing drag unless the front two wheels of the truck plane in the gravel. Then the two rear wheels will also produce drag in the remaining gravel below the rut of the front two wheels. This latter effect (rutting) of the two front wheels of the bogey planing is included in the computer simulation, but it did not occur for this aircraft as shown in Figure 26. Figure 26 shows that all wheels stayed on the extended runway surface supporting the gravel for the full aircraft arrestment since the full gravel depth was used.

Figure 27 shows the velocity profile of Aircraft C and shows that Aircraft C traveled approximately 600 feet in the gravel bed before it came to a stop.

The landing gear loads produced during the gravel arrestment of Aircraft C were all less than the manufacturer's limit loads (see Appendix B). This result is shown in Figure 28. It should be noted that the loads shown are axle loads for the main gear truck. The vertical axle loads on the main gear are nearly equal and not distinguishable on the graph. The drag loads on the main gear show that the front axle

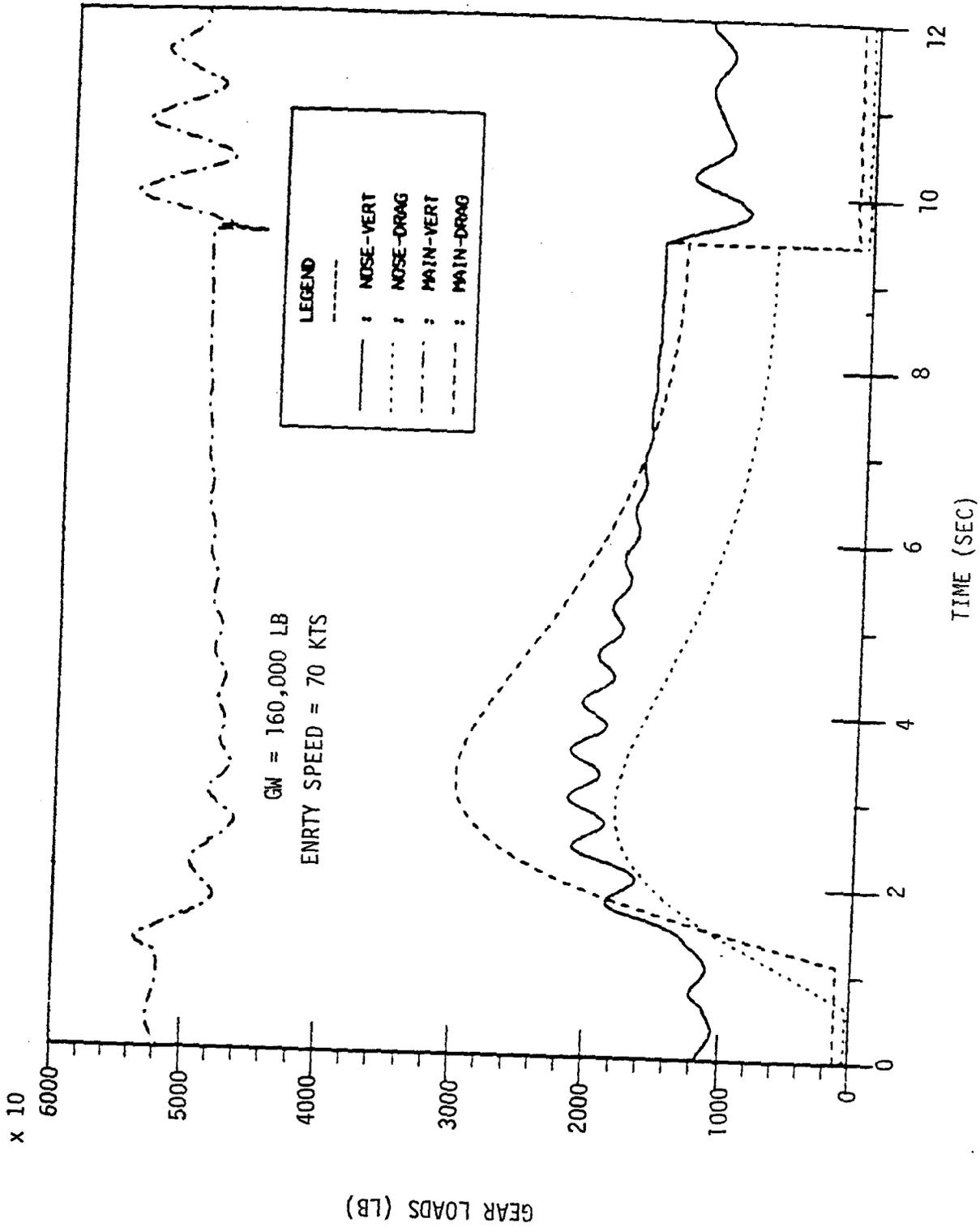


Figure 23. Aircraft B Landing Gear Loads in a Gravel Bed Arrestor

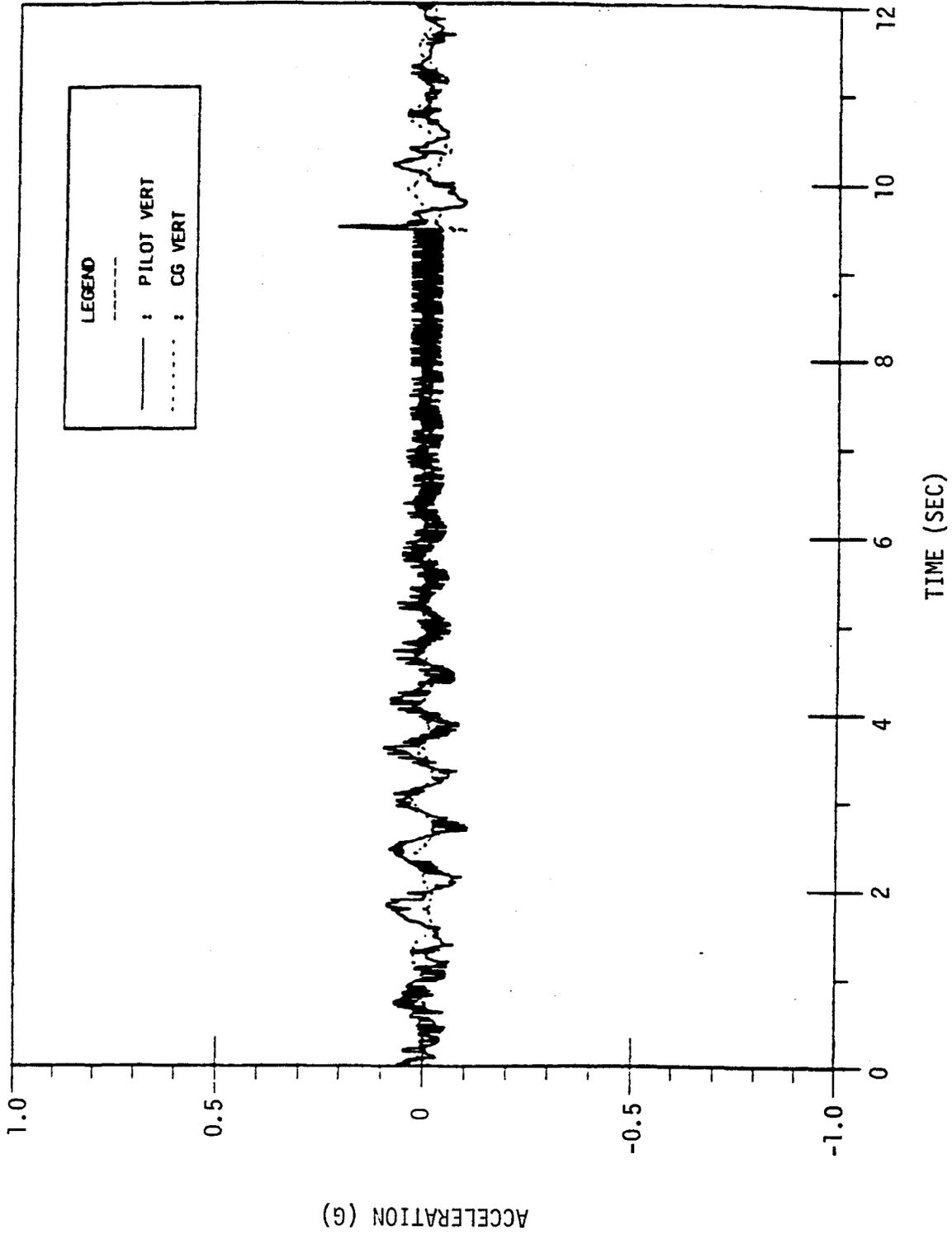


Figure 24. Aircraft B Ride Quality During a Gravel Arrestment

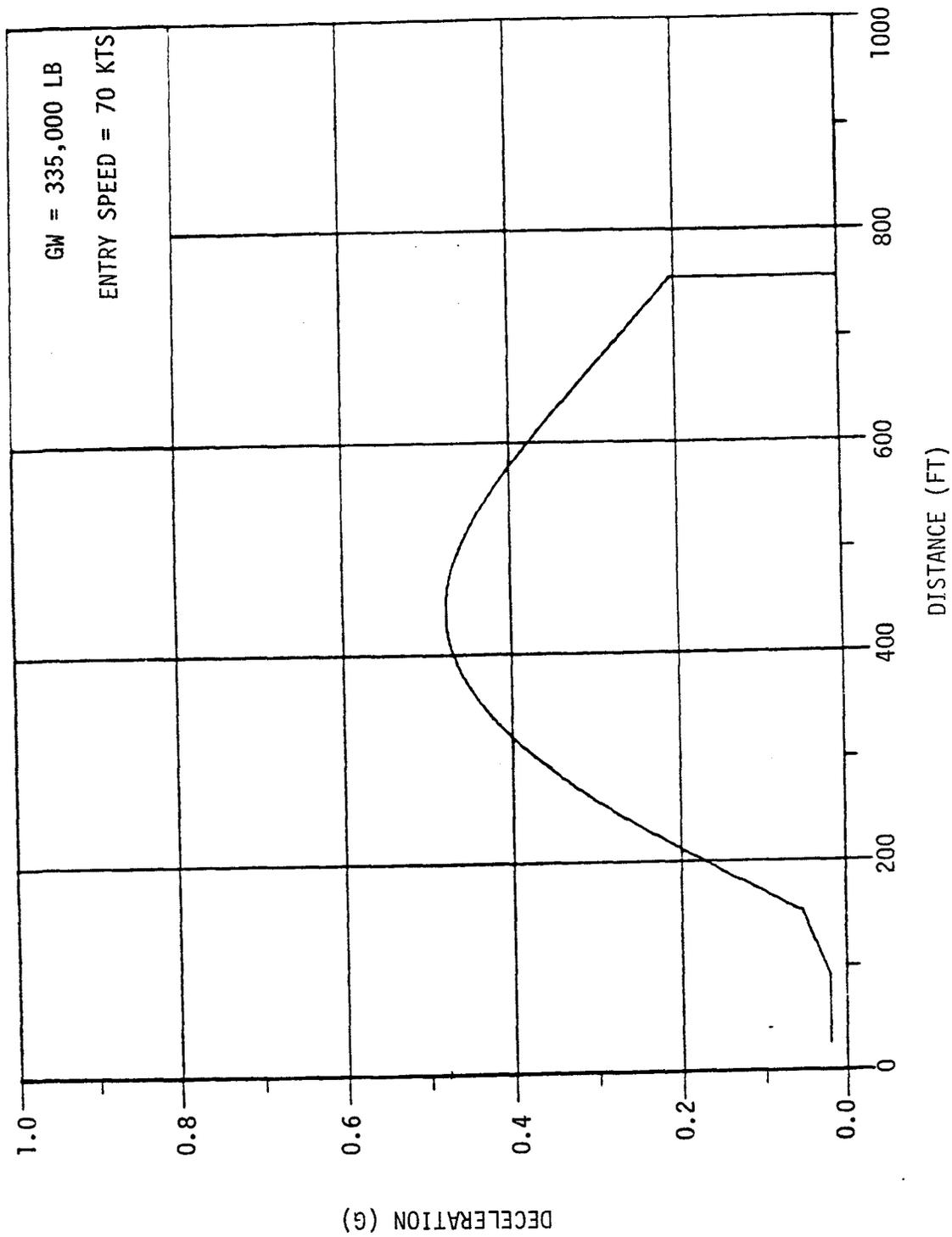


Figure 25. Aircraft C Deceleration in Gravel Arrestor

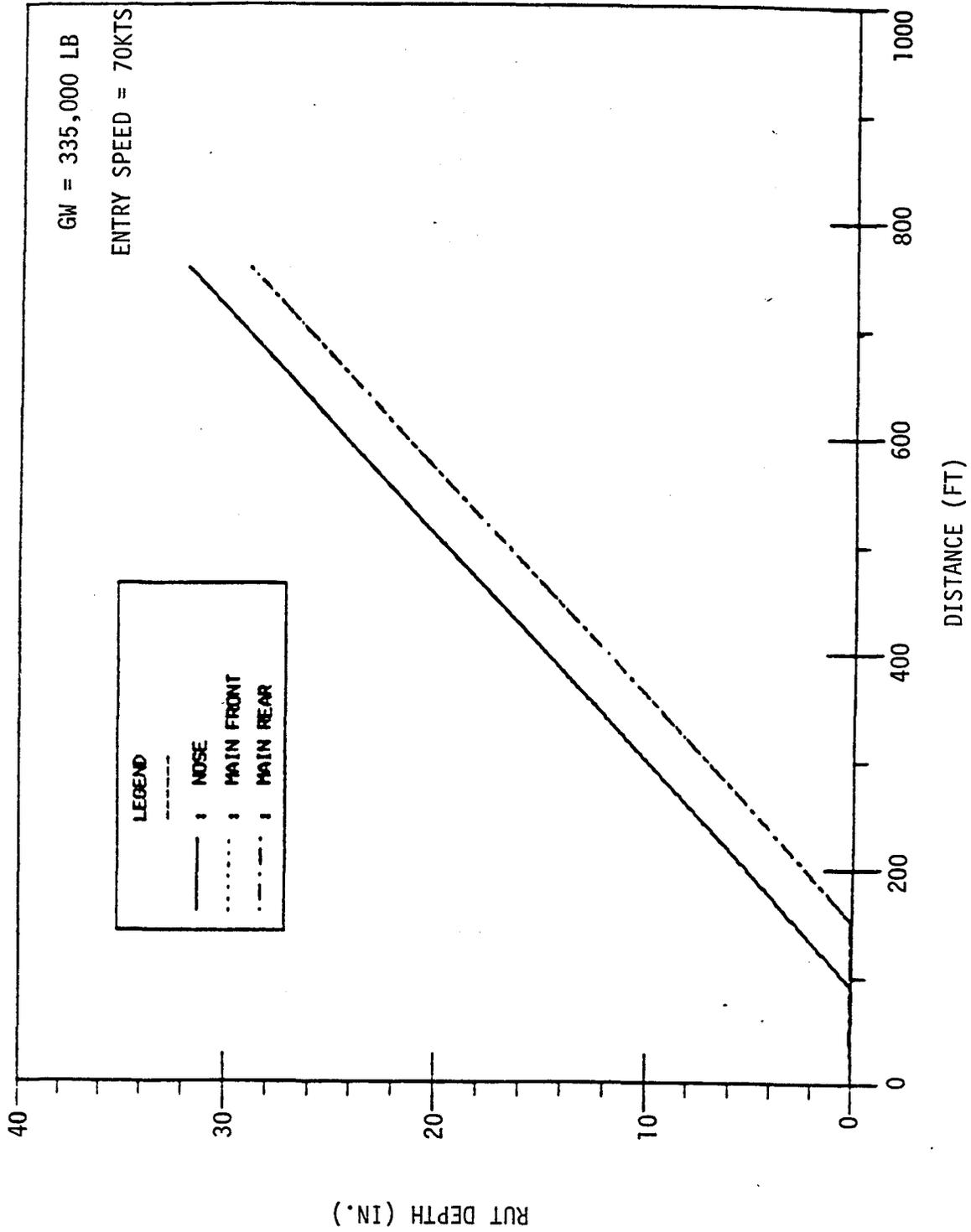


Figure 26. Aircraft C Rut Depth in Gravel Arrestor

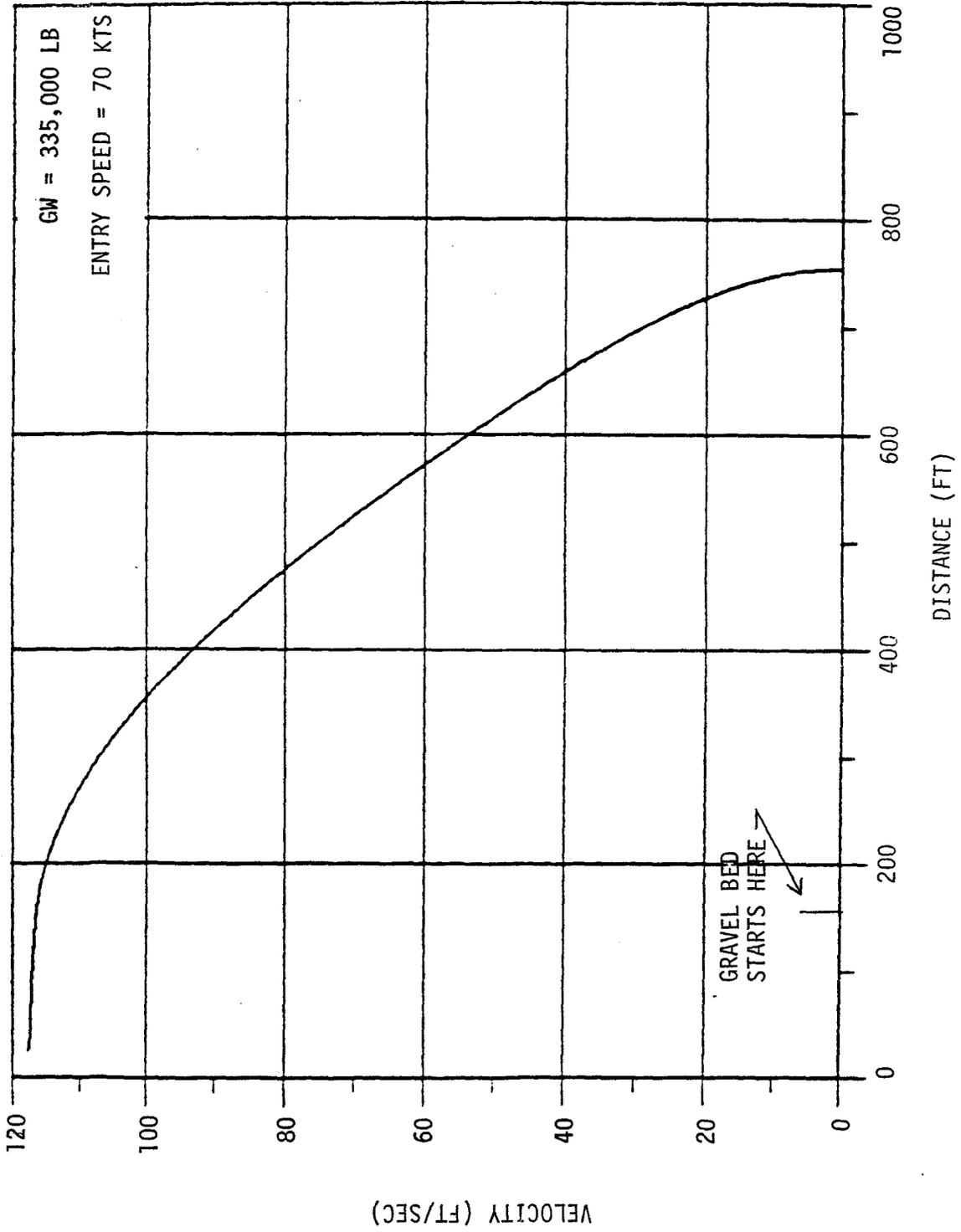


Figure 27. Aircraft C Velocity Profile in Gravel Arrestor

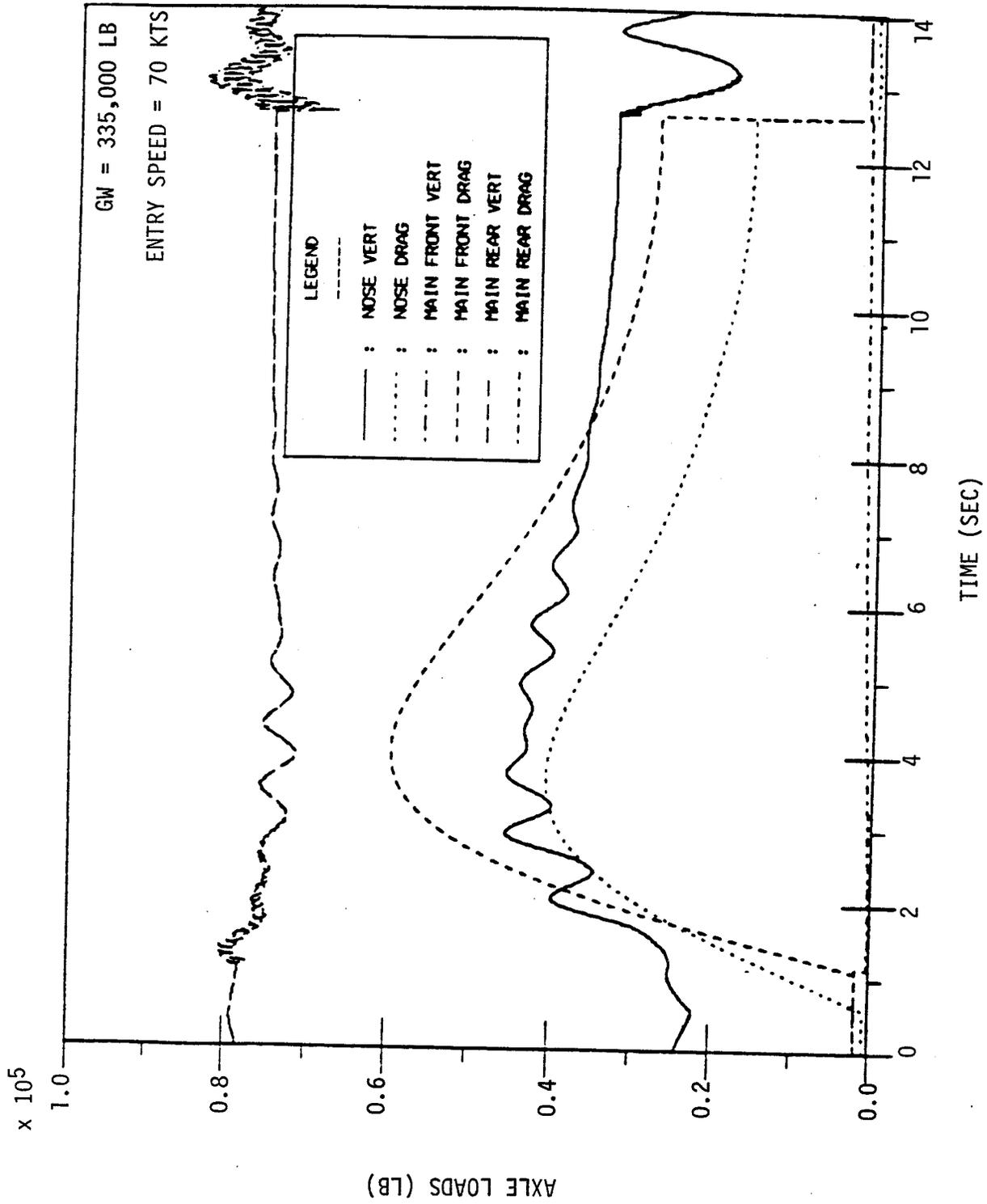


Figure 28. Aircraft C Landing Gear Loads During a Gravel Arrestment

wheels produced the major portion of the load and that the rear axle wheels produced almost no load. The reason for this result is that the rear wheels were in the rut formed by the front wheels of the bogey.

The high frequency oscillation shown for the main gear vertical loads is primarily due to truck pitching and it may not occur on the real aircraft. The damping on the truck beam was estimated in the computer analysis and may not be realistic for the aircraft. The problem is a minor one in any case.

Figure 29 indicates the ride quality during the gravel bed arrestment of Aircraft C. These acceleration levels are minimal and of no concern for this aircraft.

3.1.4 Aircraft D

Aircraft D has a landing gear configuration similar to that of Aircraft C. The nose gear has dual wheels and the main gear consists of a four-wheeled bogey (dual-tandem).

The deceleration of Aircraft D is shown in Figure 30. The peak deceleration was about 0.43 g's. The initial part of the deceleration curve shows a characteristic planing of the nose landing gear, and this is substantiated by Figure 31 which indicates that the nose gear did plane during the early part of the arrestment. This, of course, reduces the effectiveness of the arrestor. Figure 32 shows that the Aircraft D stopping distance was about 675 feet in gravel.

All gear loads for Aircraft D were well below the manufacturer's specified limit loads. The gear loads during the gravel arrestment are shown in Figure 33. As with Aircraft C, the axle loads have been plotted and, since the main gear vertical loads for the front and rear axles of the bogey are almost equal, the plot appears as only one curve. The drag loads on the main gear axles are significantly different as in the case of Aircraft C.

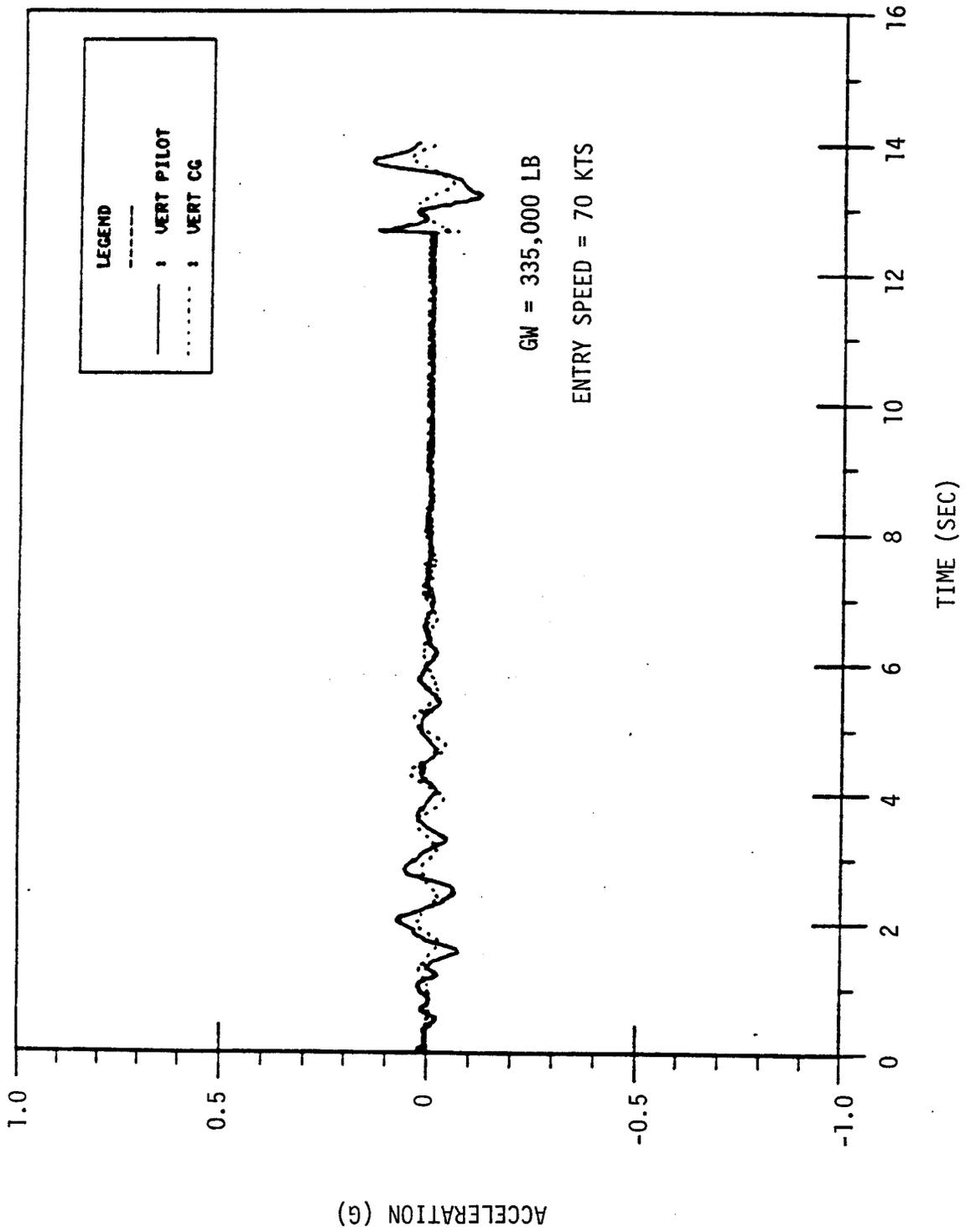


Figure 29. Aircraft C Dynamic Response During a Gravel Bed Arrestment

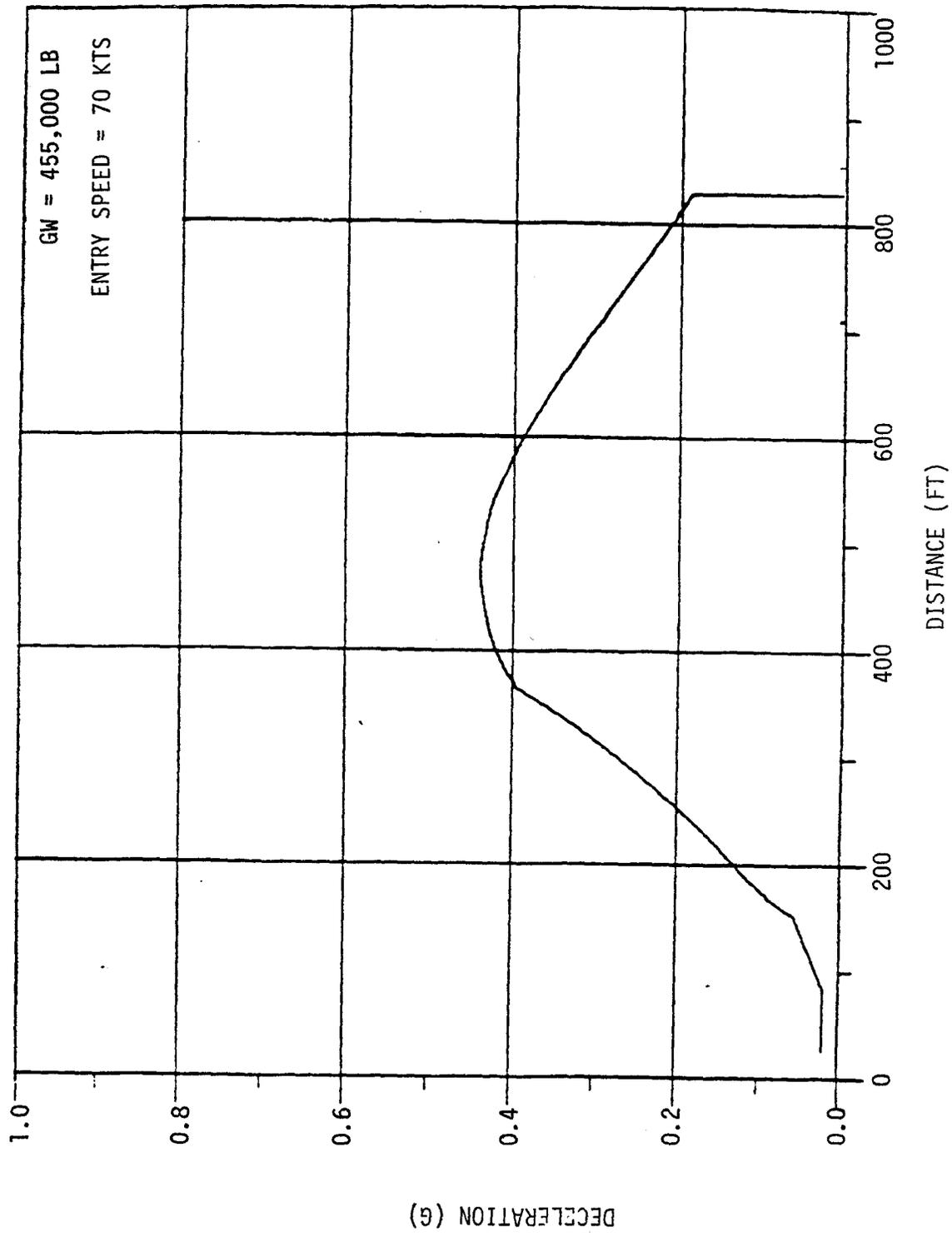


Figure 30. Aircraft D Deceleration in Gravel Bed

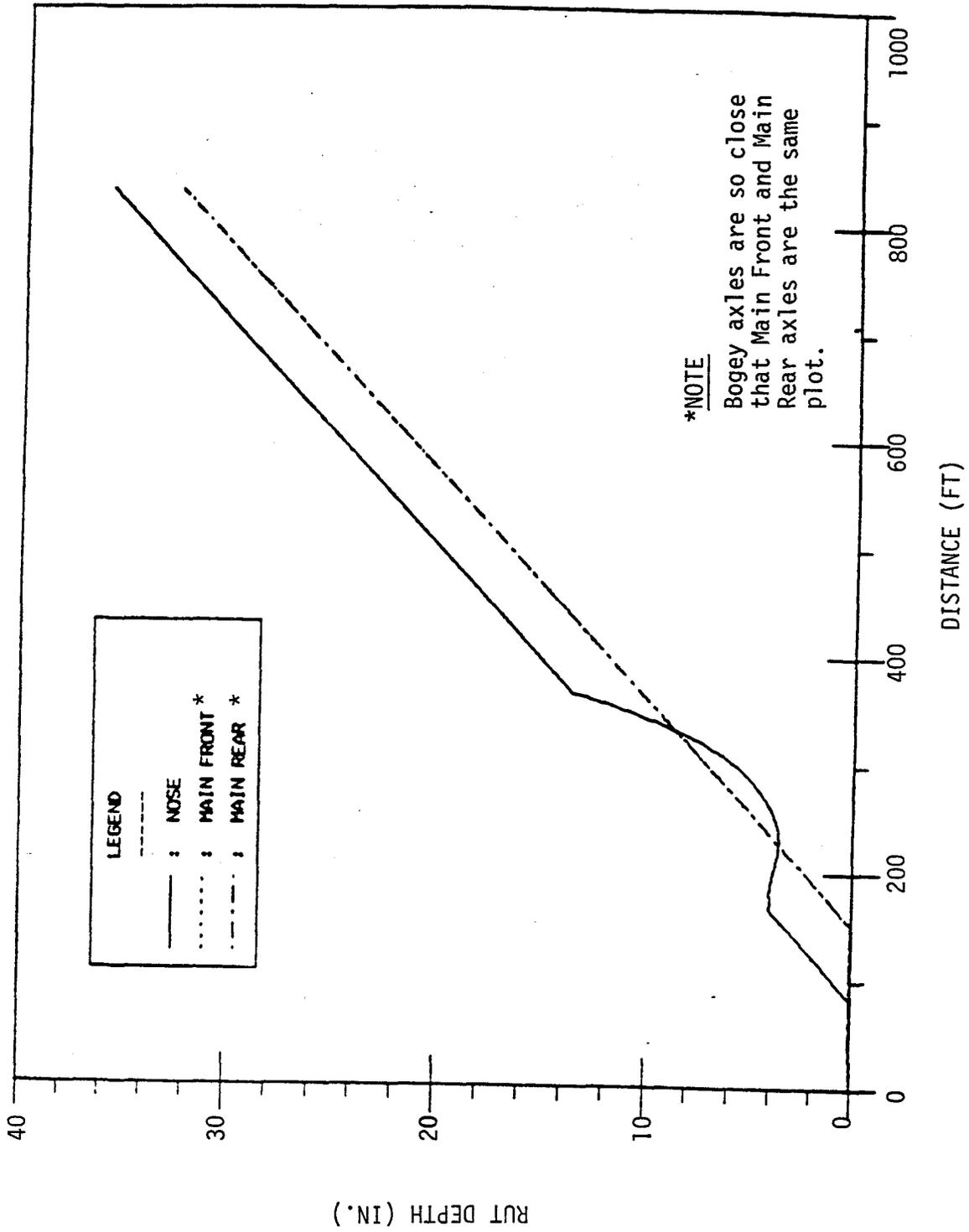


Figure 31. Aircraft D Rut Depth Obtained in Gravel Arrestor

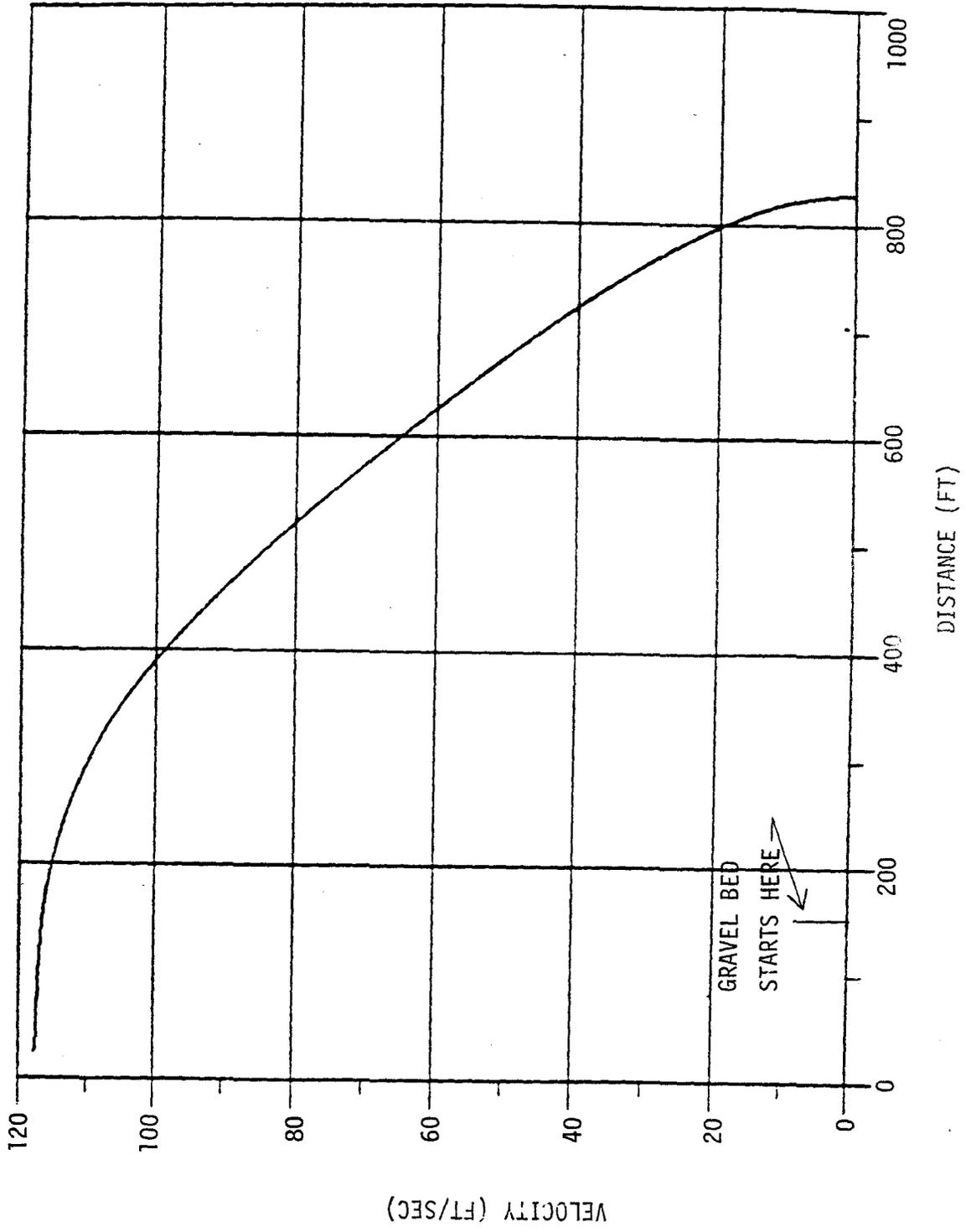


Figure 32. Aircraft D Velocity Profile During a Gravel Arrestment

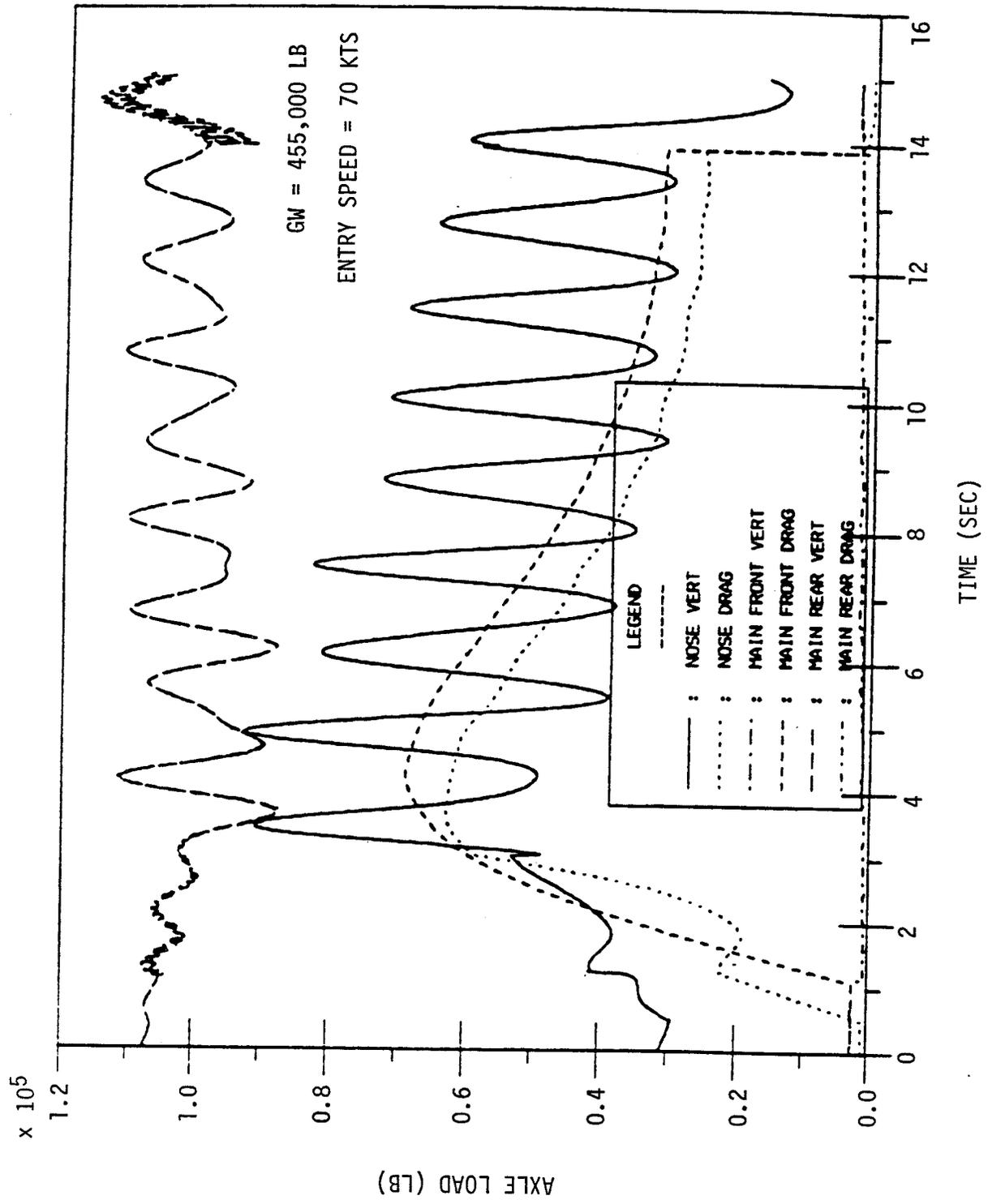


Figure 33. Aircraft D Gear Loads During a Gravel Bed Arrestment

Figure 34 shows the vertical acceleration levels obtained at the cockpit and center of gravity locations in the aircraft. The acceleration levels are relatively small and are well below the normal tolerance level.

3.1.5 Aircraft E

Aircraft E is the largest aircraft simulated in this study. Aircraft E has a gross weight of 630,000 pounds and has both wing mounted and body (fuselage) mounted main gear. The main gears are located on different butt lines so that they do not track in the same plane. This makes the wheels of the leading axles all effective in producing drag. Figure 35 shows the peak deceleration was about 0.49 g's, and Figure 36 shows that the aircraft remained in contact with the extended runway surface throughout the arrestment (no planing).

Figure 37 shows the velocity profile of Aircraft E during the gravel bed arrestment. From this figure, it is also evident that the stopping distance was about 560 feet in the gravel bed.

Limit load data for Aircraft E landing gear are not available but the loads obtained are on the same order as those obtained on Aircraft D which were well below limit values. The landing gear loads are shown in Figure 38. It should be noted that the loads are plotted as gear loads rather than axle loads because of a plot program limitation. The loads shown in Figure 38 are double for the main gear because the computer program FITER does not allow more than three struts, so only half of the aircraft is simulated. The nose gear loads plotted are true value.

The dynamic response of the aircraft was not computed because the computer program does not have the capability to establish the initial static gear loads. At present, the static loads are estimated which is sufficiently accurate for the analysis but not for the dynamic response purposes.

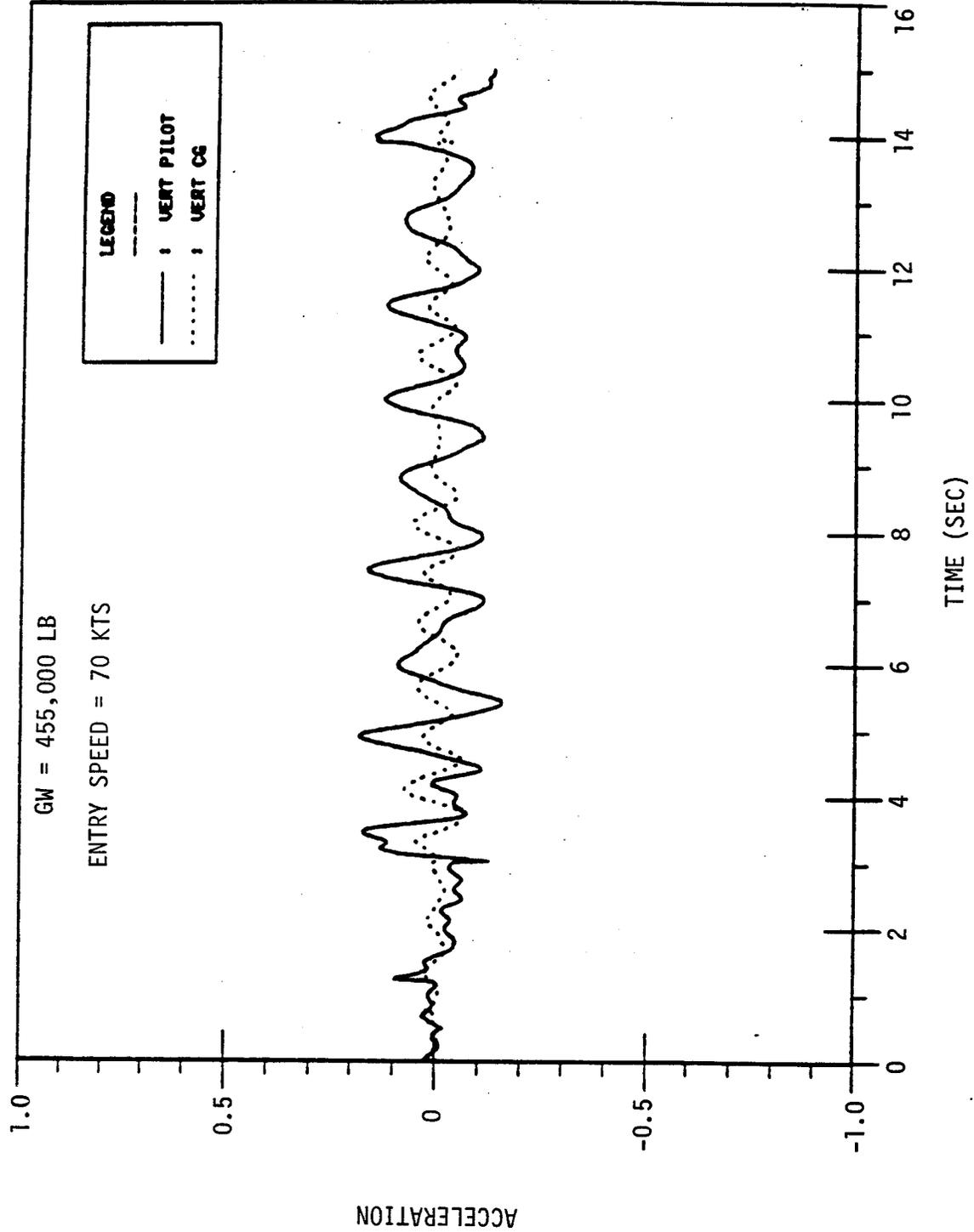


Figure 34. Aircraft D Dynamic Response During a Gravel Bed Arrestment

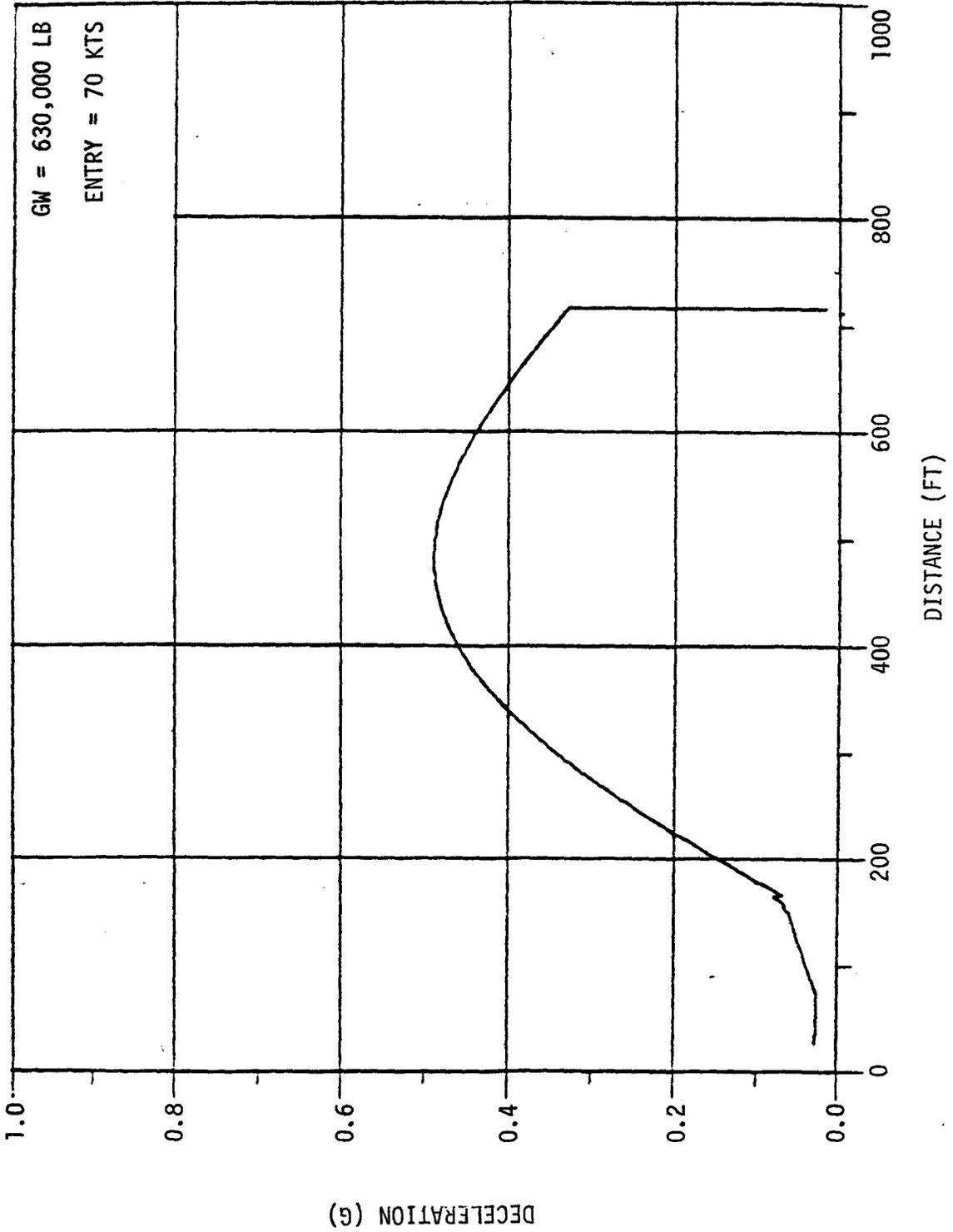


Figure 35. Aircraft E Deceleration During a Gravel Bed Arrestment

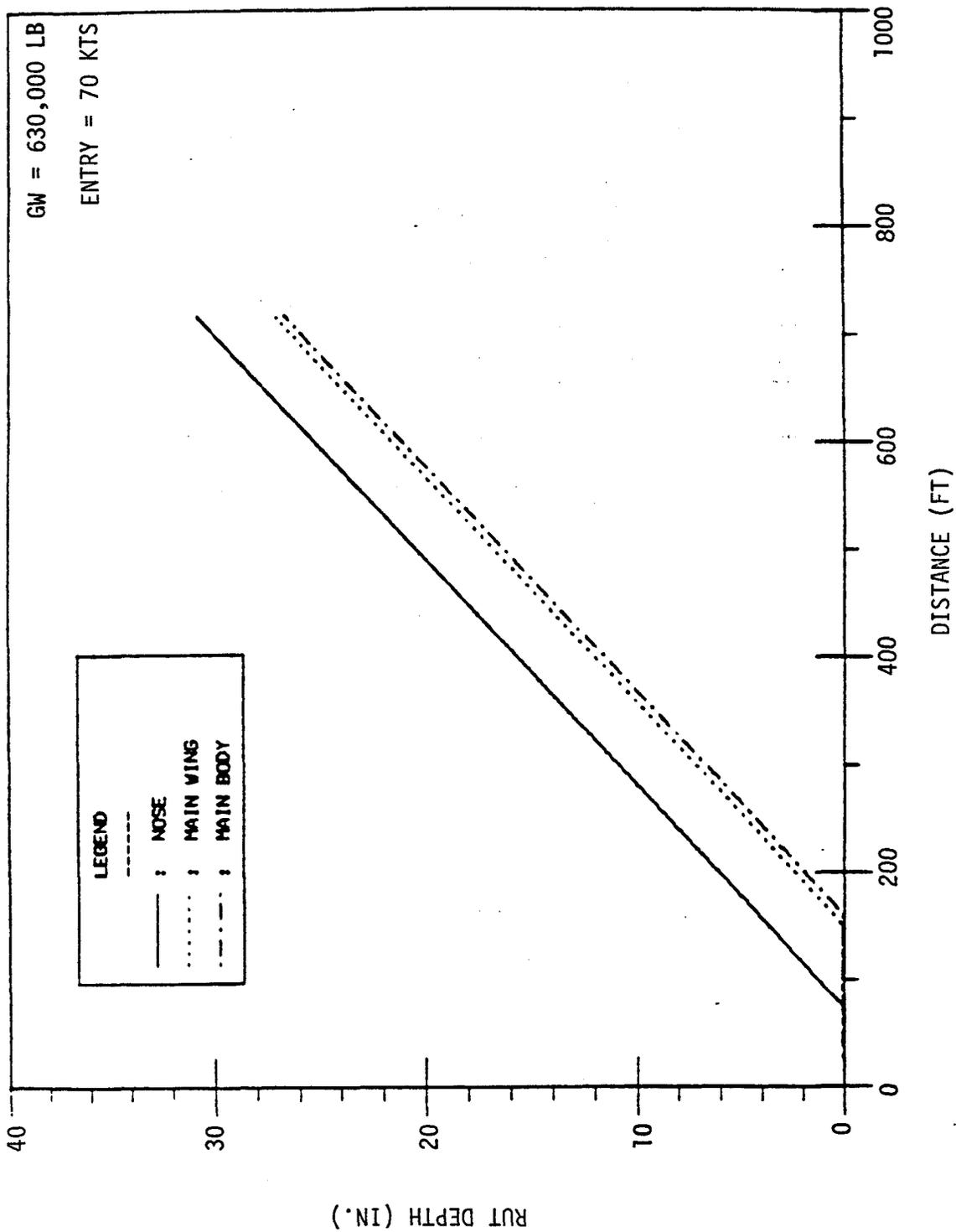


Figure 36. Aircraft E Rut Depth in a Gravel Bed Arrestment

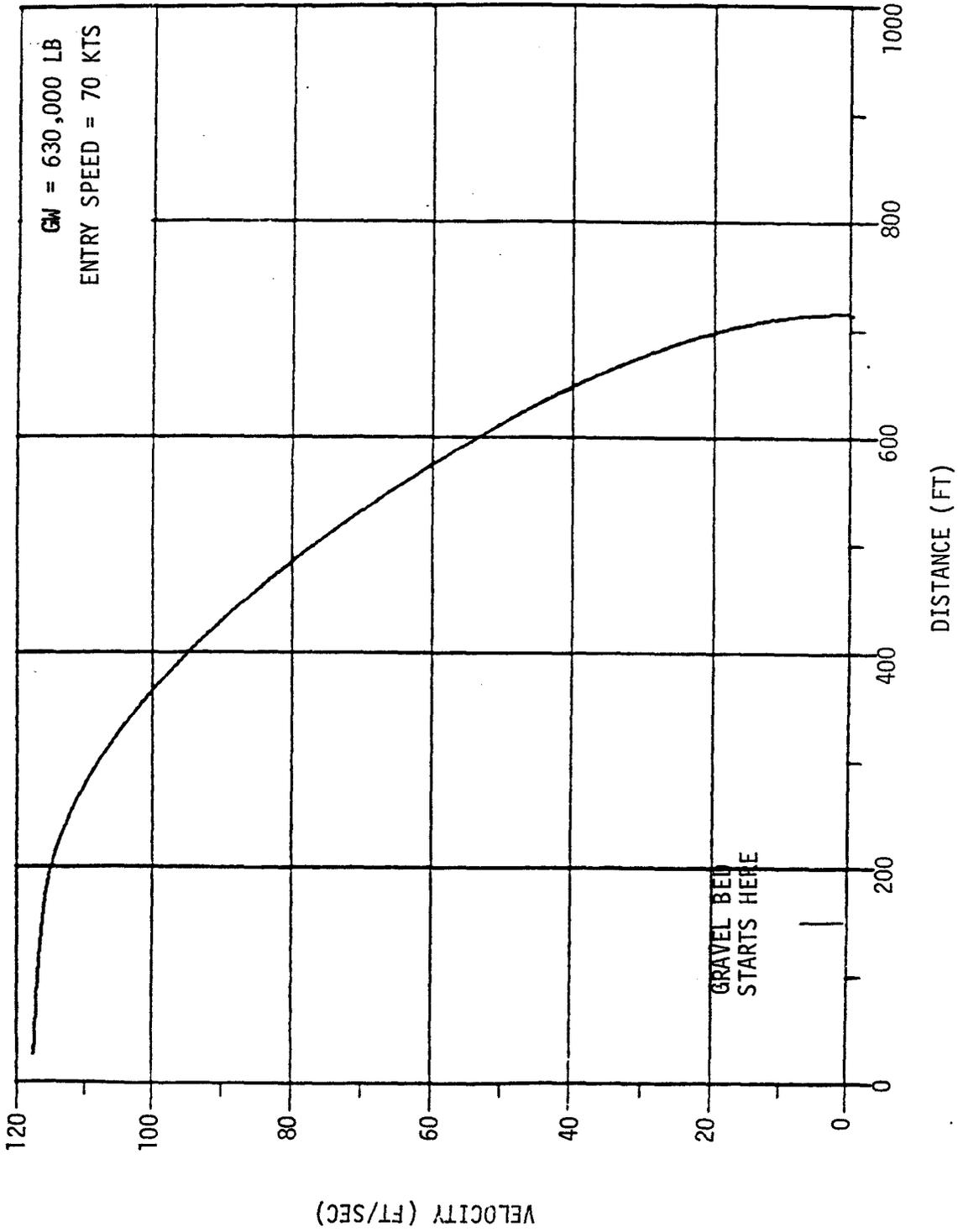


Figure 37. Aircraft E Velocity Profile During A Gravel Bed Arrestment

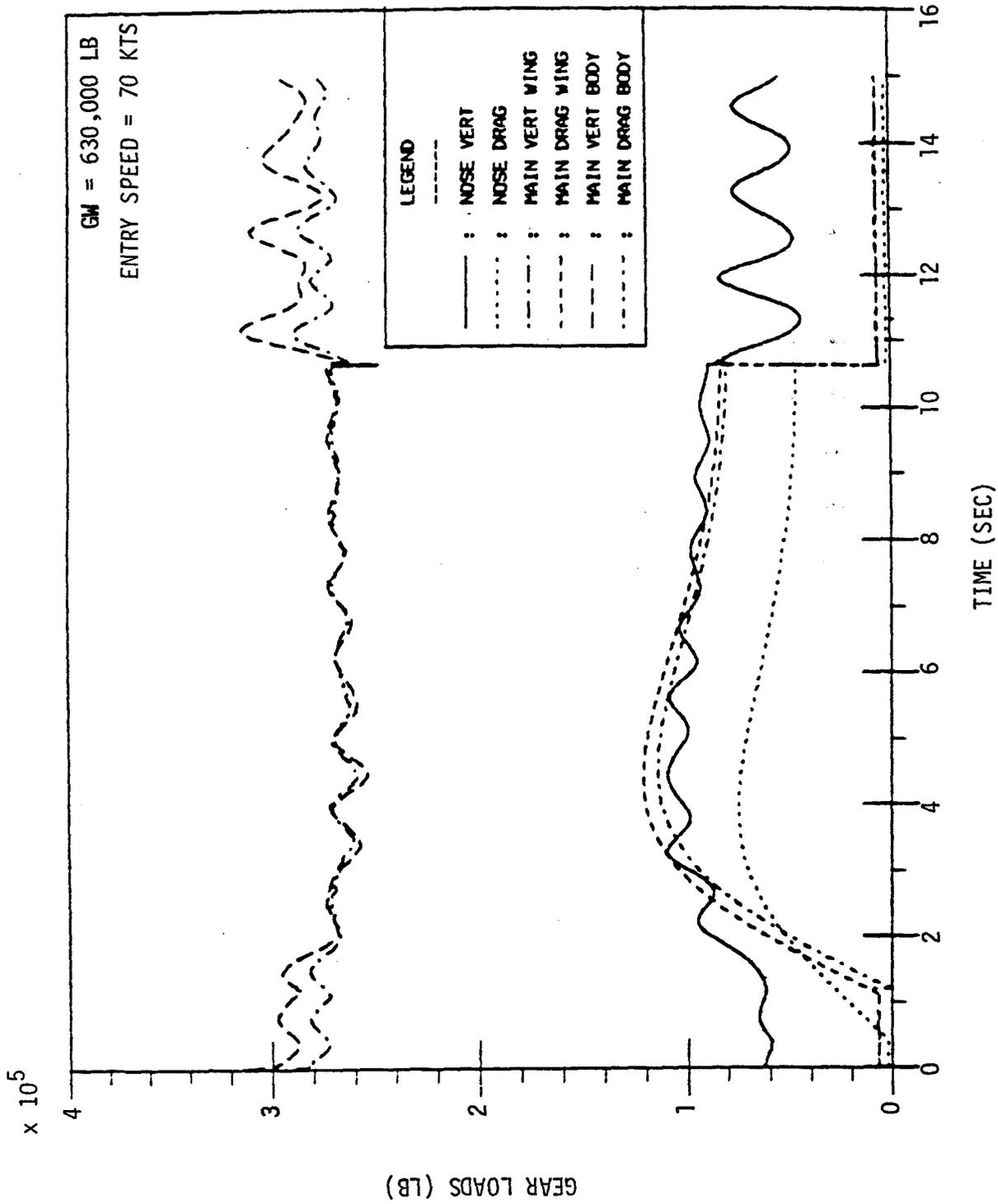


Figure 38. Aircraft E Landing Gear Loads During a Gravel Bed Arrestment

3.1.6 Gravel Arrestor Bed Summary

The gravel bed arrestor performance appears to be suitable for stopping commercial aircraft during an overrun at entry speeds of 70 knots or less. The relatively low cost of the material makes it attractive for use as an overrun arrestor in areas of the United States (and other parts of the world) not subject to heavy freezing. The ability to access the arrestor with fire/crash/rescue vehicles has not been evaluated in detail, but it would appear that some problems might exist. British tests, however, indicated that their fire/crash/rescue vehicles had no difficulty in maneuvering in the gravel bed arrestor.

Gravel spray from the nose gear could cause engine damage if pebbles were ingested. The spray could also impinge on flaps, gear doors and struts, and hydraulic or electrical lines. This latter type of damage is expected to be relatively minor.

The gravel arrestor is relatively inert and therefore would cause little concern from an environmental standpoint. Gravel is also noncombustible so that it would not contribute to fires should they occur.

Long term problems with gravel such as compaction, dust accumulation, and others have not been evaluated in this study, but it certainly should be done before the gravel bed arrestor is considered acceptable.

3.2 FOAM ARRESTOR

Simulations of the five aircraft described in Appendix B were also conducted using a foam material as the energy adsorber. Several foam arrestment bed configurations were tried, but the configuration finally selected is shown in Figure 39. This bed is 24 inches deep and consists of a bottom layer, 12 inches thick, having a crushing strength of 60 psi, and a top layer, also 12 inches thick, having a crushing strength of 45 psi. The arrestment performance for each of the aircraft simulated is

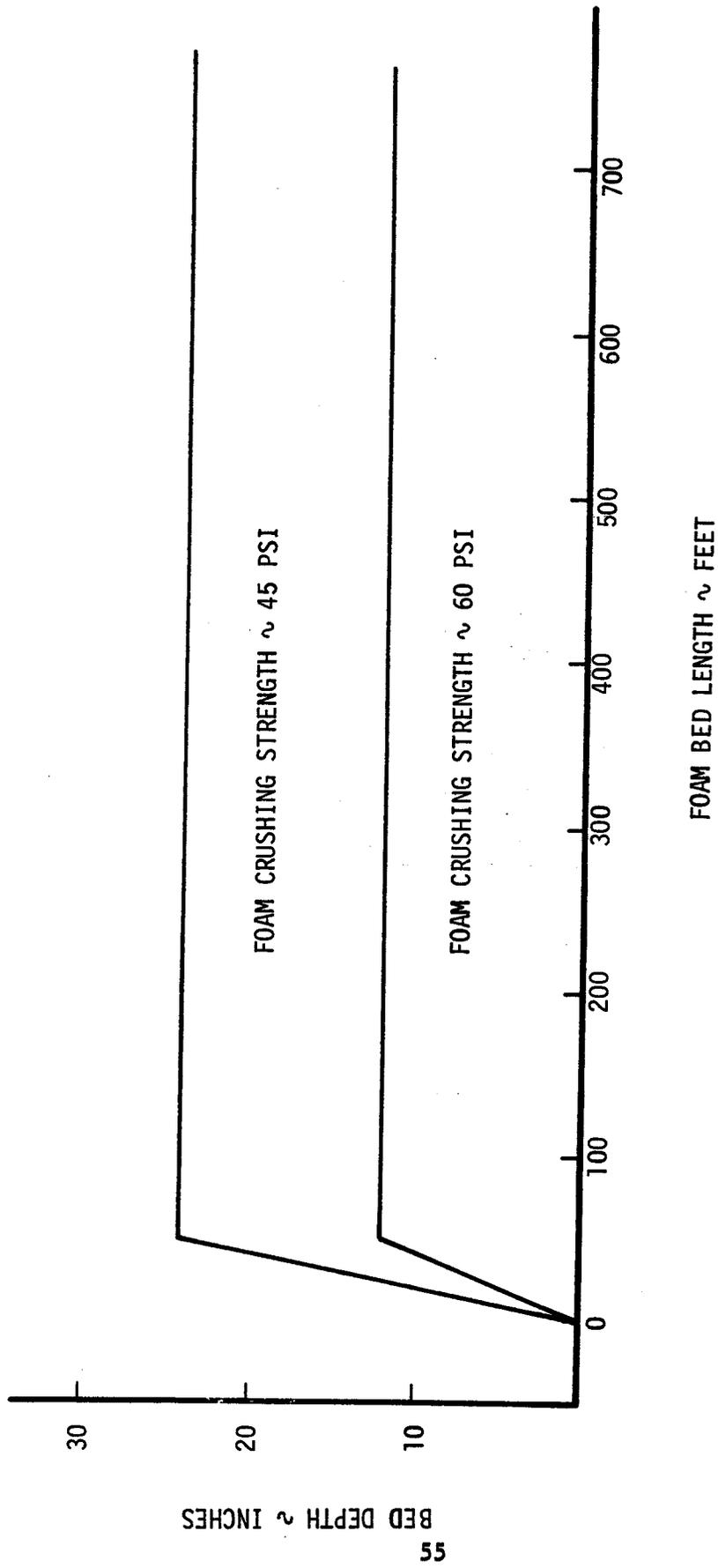


Figure 39. Double Layered Foam Arrestor Bed

presented in the following discussion. The entry speed was 70 knots, as before, and an idle thrust of 3,000 pounds was assumed to be applied on all simulations.

3.2.1 Aircraft A

The performance of Aircraft A in the foam arrestor is shown in Figures 40 through 44. Figure 40 shows that the maximum deceleration obtained was about 0.7 g's and that the level of deceleration was maintained throughout the remainder of the arrestment. The velocity profile during the arrestment is shown in Figure 41. This figure shows that the stopping distance in the foam arrestor was 310 feet. Figure 42 shows the rut depth of 24 inches in the foam made by both the nose and main gears. The nose gear planed for a short distance but then penetrated the foam fully. Figure 43 shows the gear loads obtained during the arrestment. The main gear loads were below the manufacturer's specified limits, and the nose gear loads were only slightly above the limits. There would be little likelihood of gear failure.

Figure 44 shows the aircraft response during the arrestment and after the aircraft stops. The dynamic response in the forward area of the aircraft reached levels which would be quite noticeable to the passengers.

3.2.2 Aircraft B

Aircraft B is the smallest aircraft simulated. A deceleration peak of about 0.78 g's was obtained in the foam arrestor as shown in Figure 45. The velocity decay, Figure 46, shows that the stopping distance in the foam was about 300 feet. There was no evidence of wheel planing in the foam bed as shown in Figure 47 since the full bed depth was obtained. The landing gear loads on both the nose and main gears were below the manufacturer's limit values. Landing gear loads are shown in Figure 48. The dynamic response (Figure 49) of the aircraft became rather severe at the stopping point, reaching a peak of about 0.8 g.

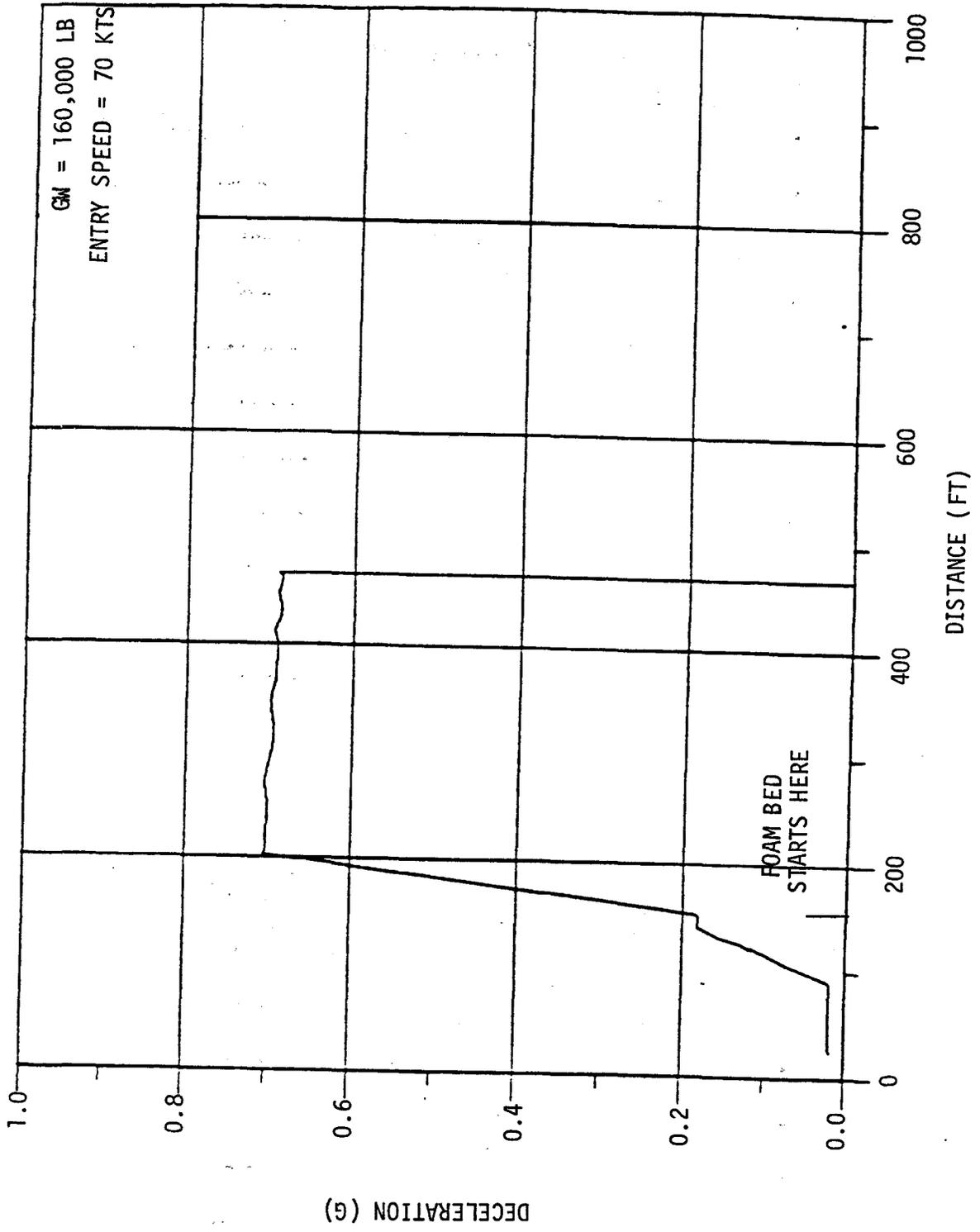


Figure 40. Aircraft A Deceleration in a Foam Bed Arrestor

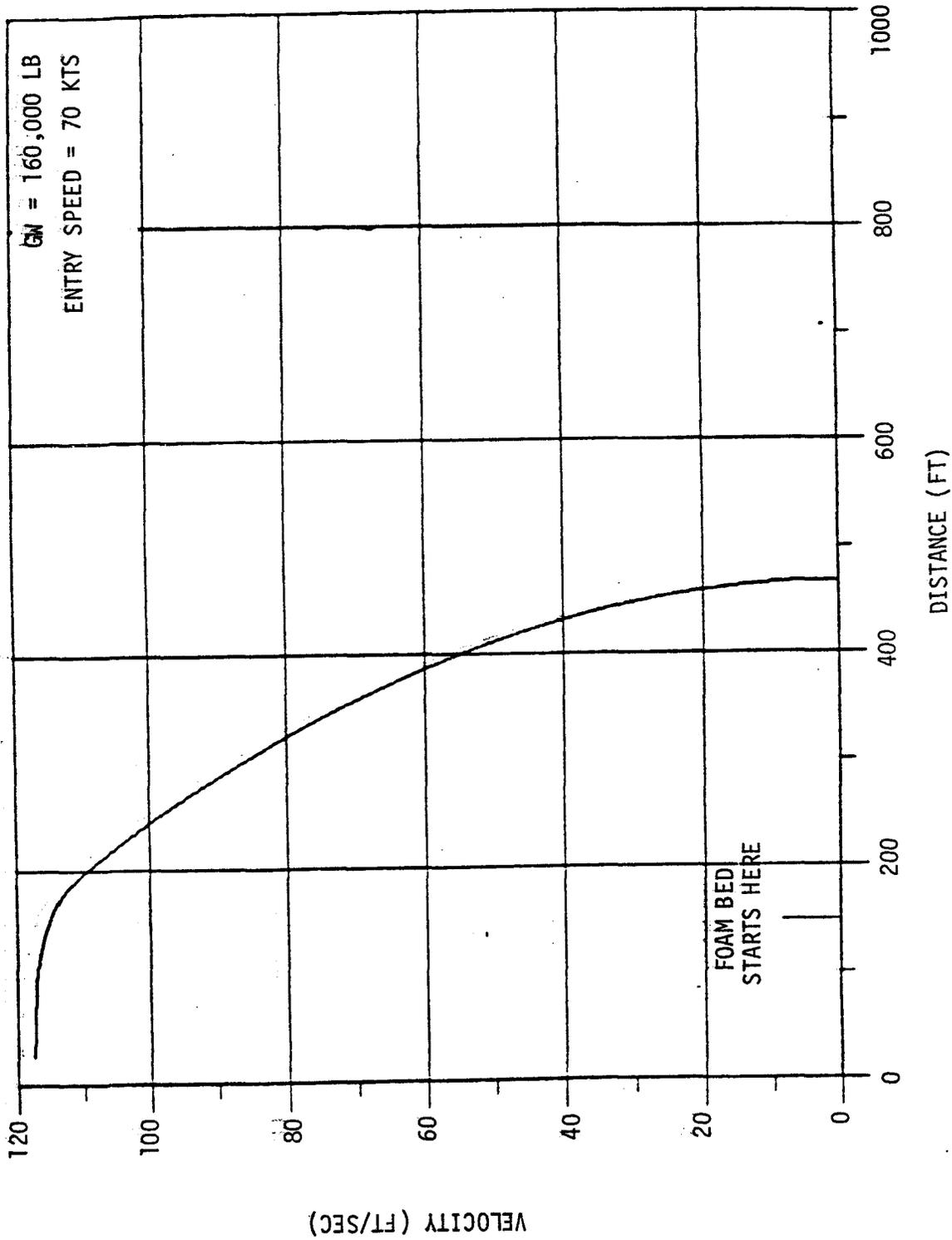


Figure 41. Aircraft A Velocity Profile During a Foam Bed Arrestment

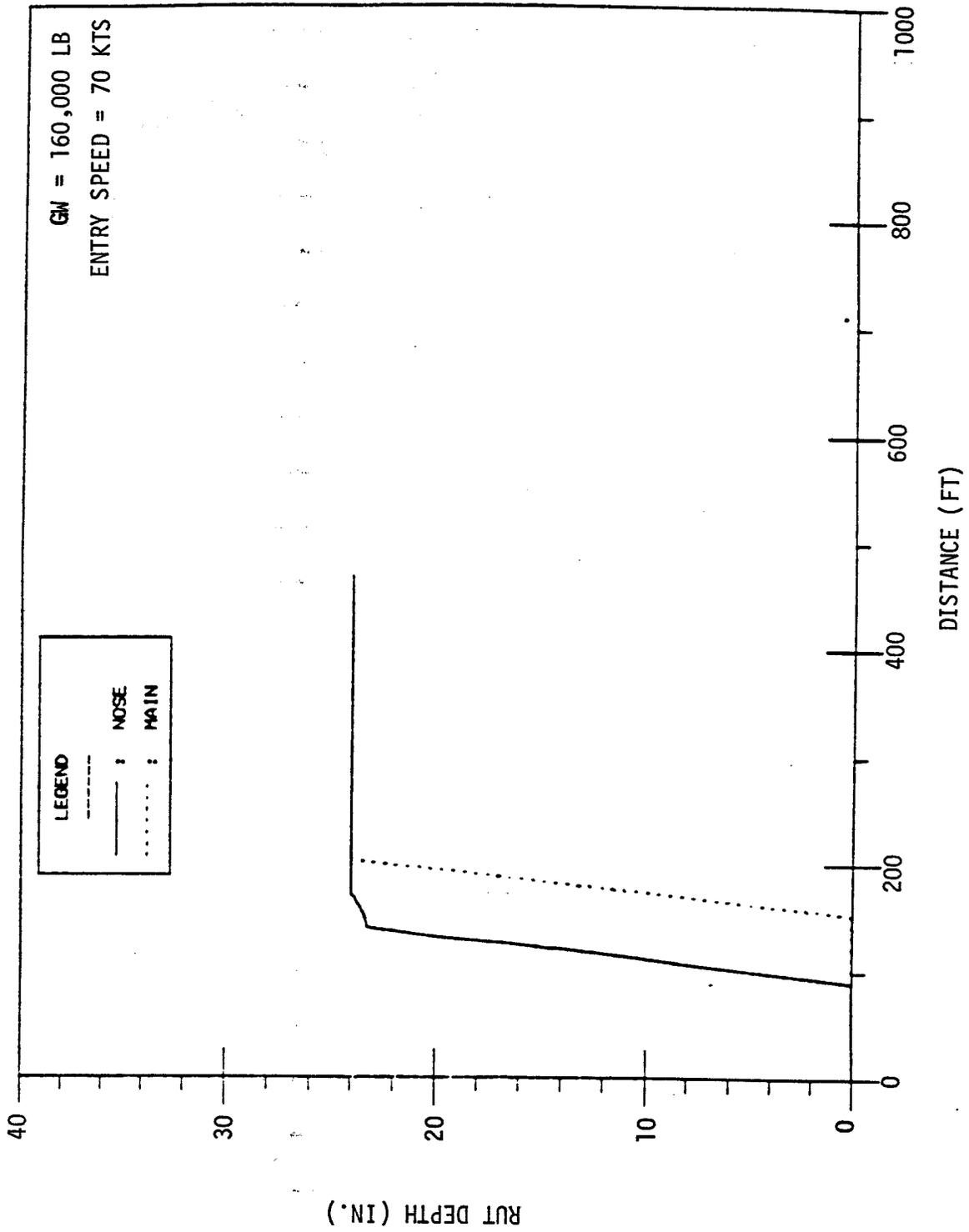


Figure 42. Aircraft A Rut Depth in a Foam Arrestor Bed

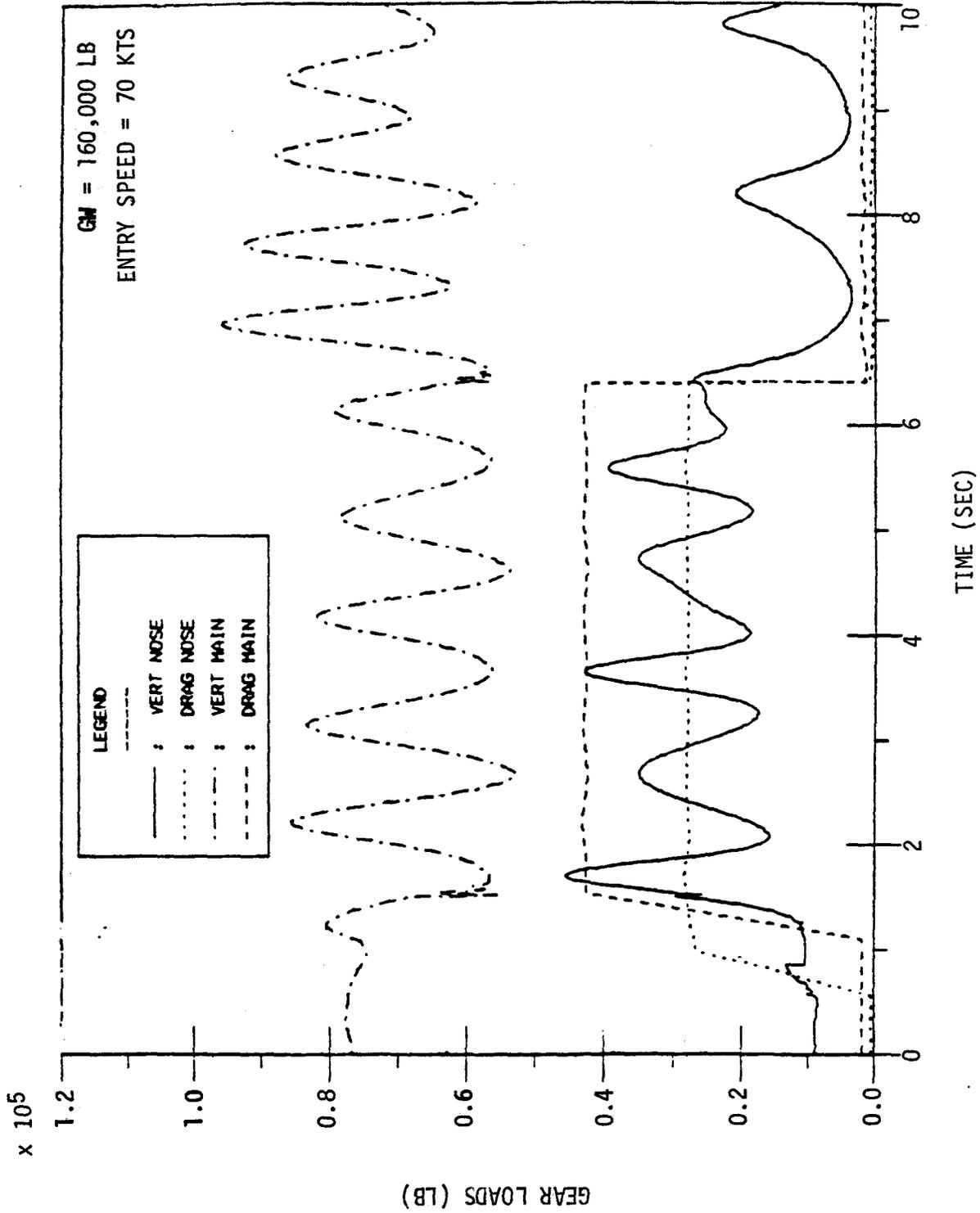


Figure 43. Aircraft A Landing Gear Loads During a Foam Bed Arrestment

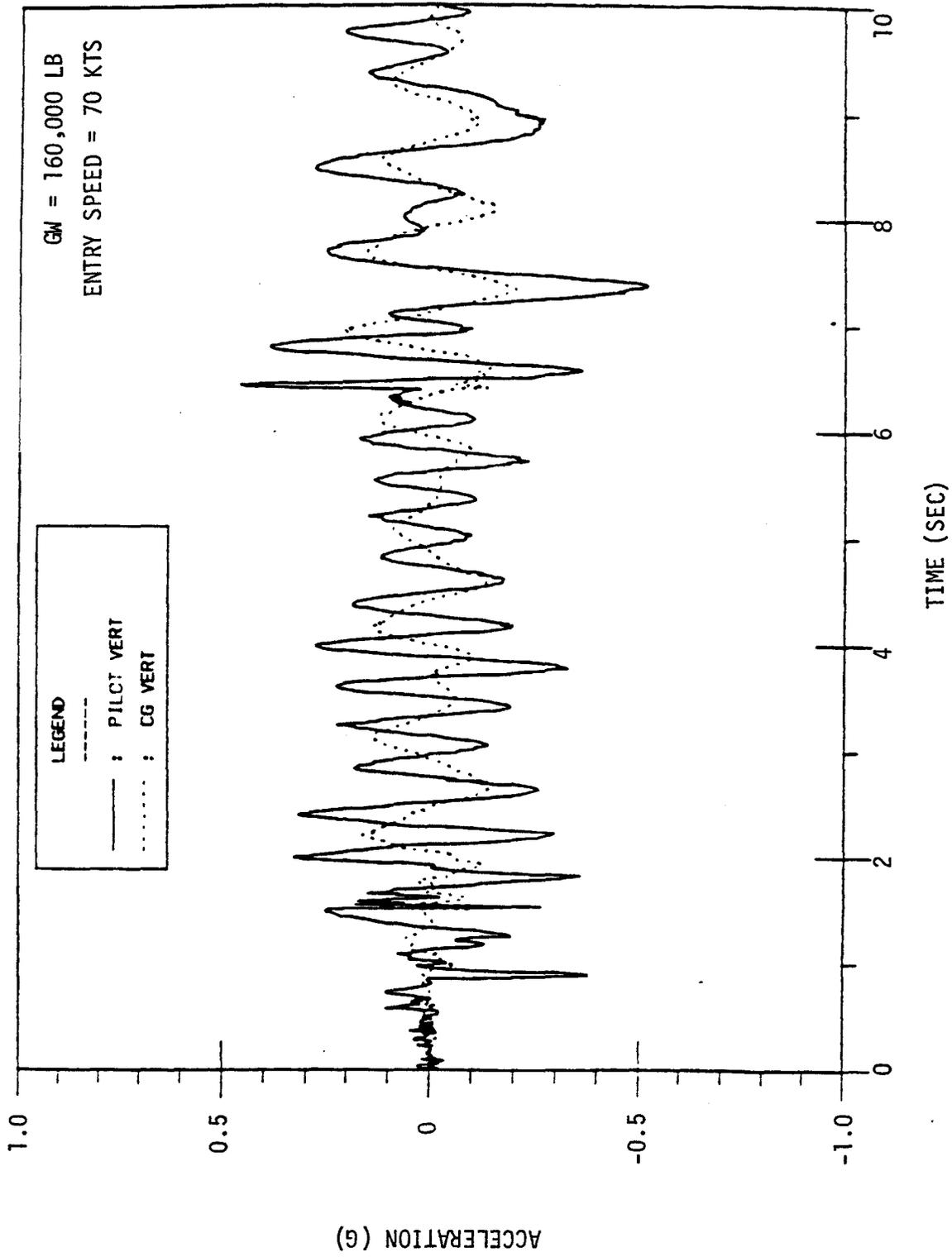


Figure 44. Aircraft A Dynamic Response During a Foam Bed Arrestment

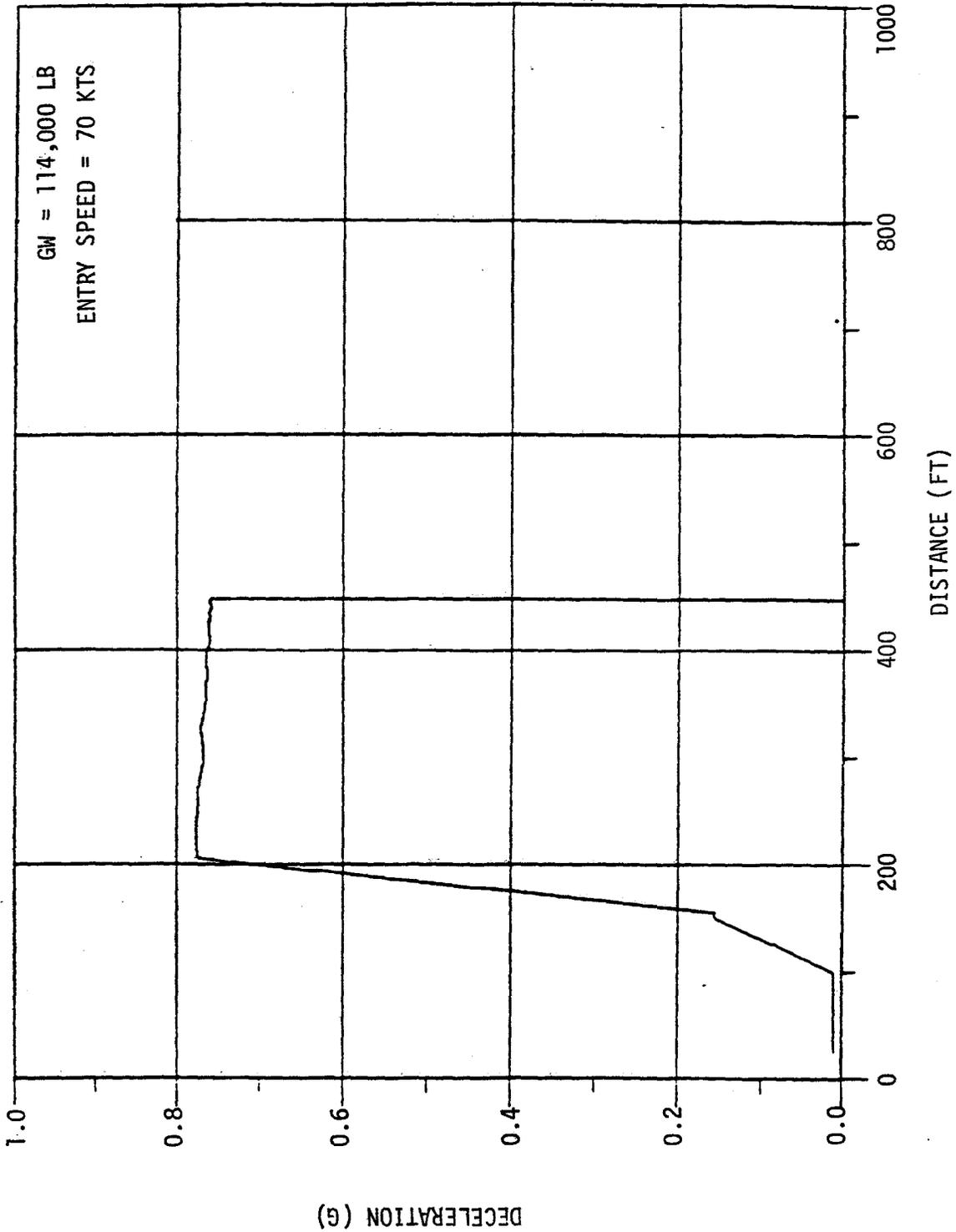


Figure 45. Aircraft B Deceleration in a Foam Arrestor Bed

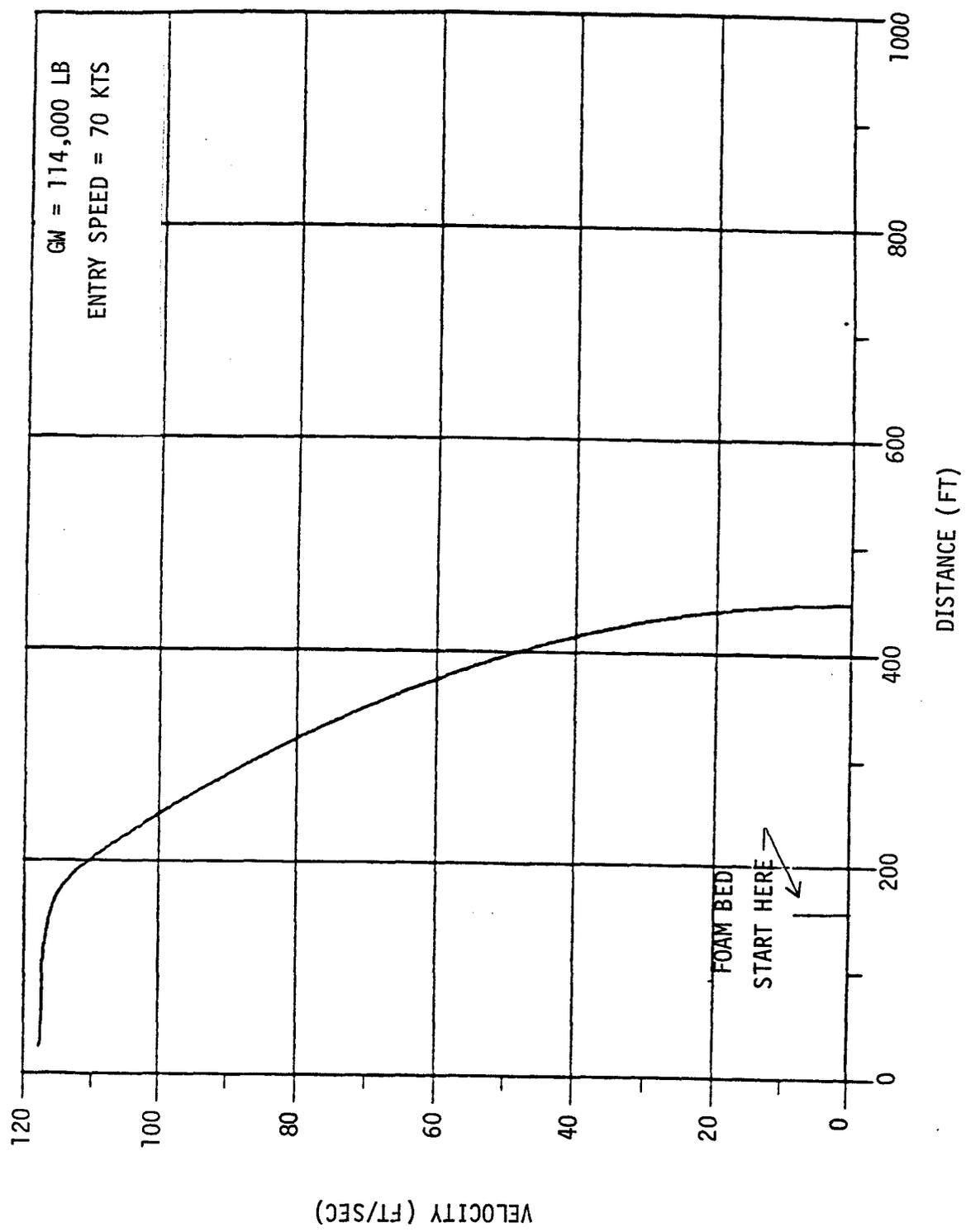


Figure 46. Aircraft B Velocity Profile During a Foam Bed Arrestment

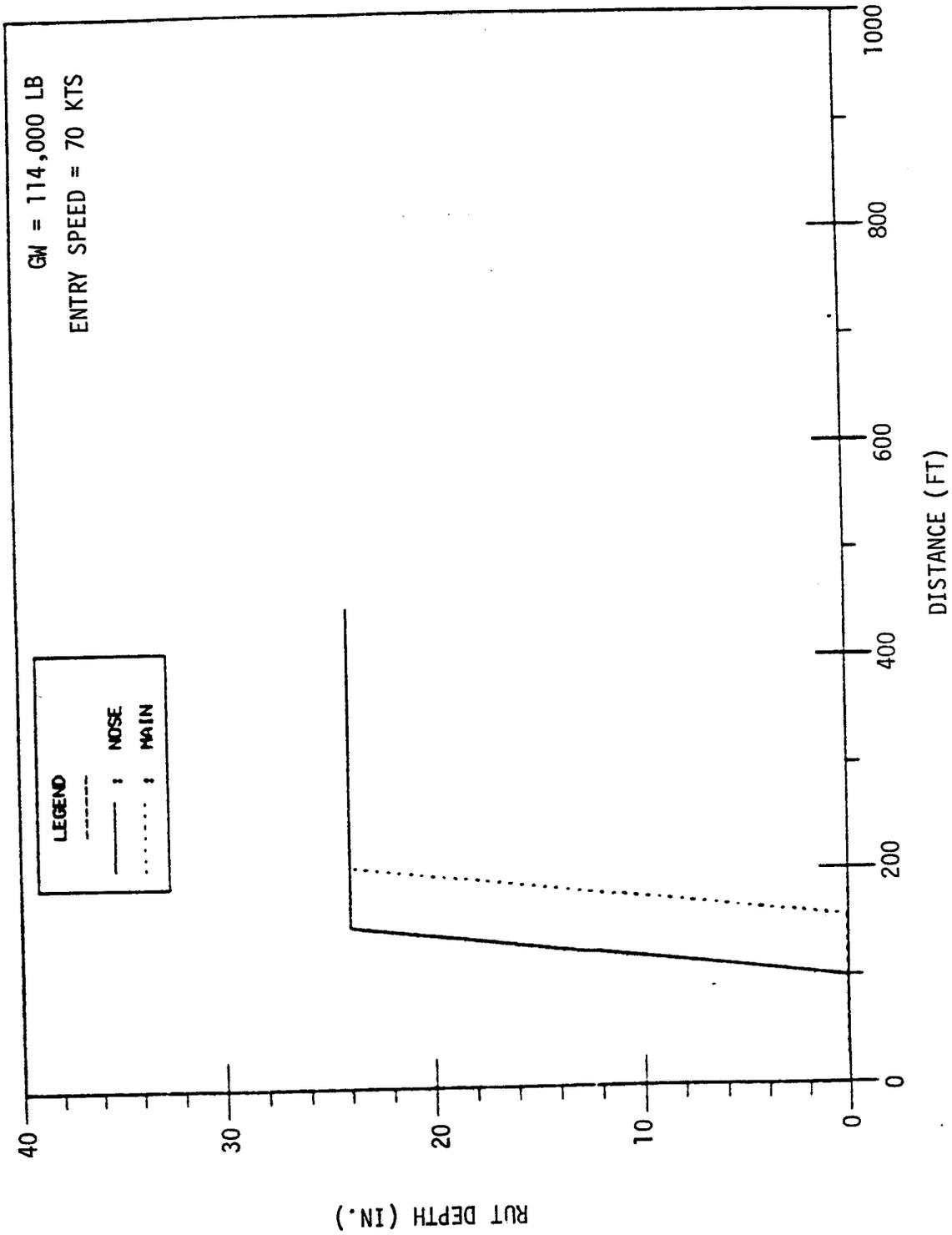


Figure 47. Aircraft B Rut Depth in the Foam Arrestor Bed

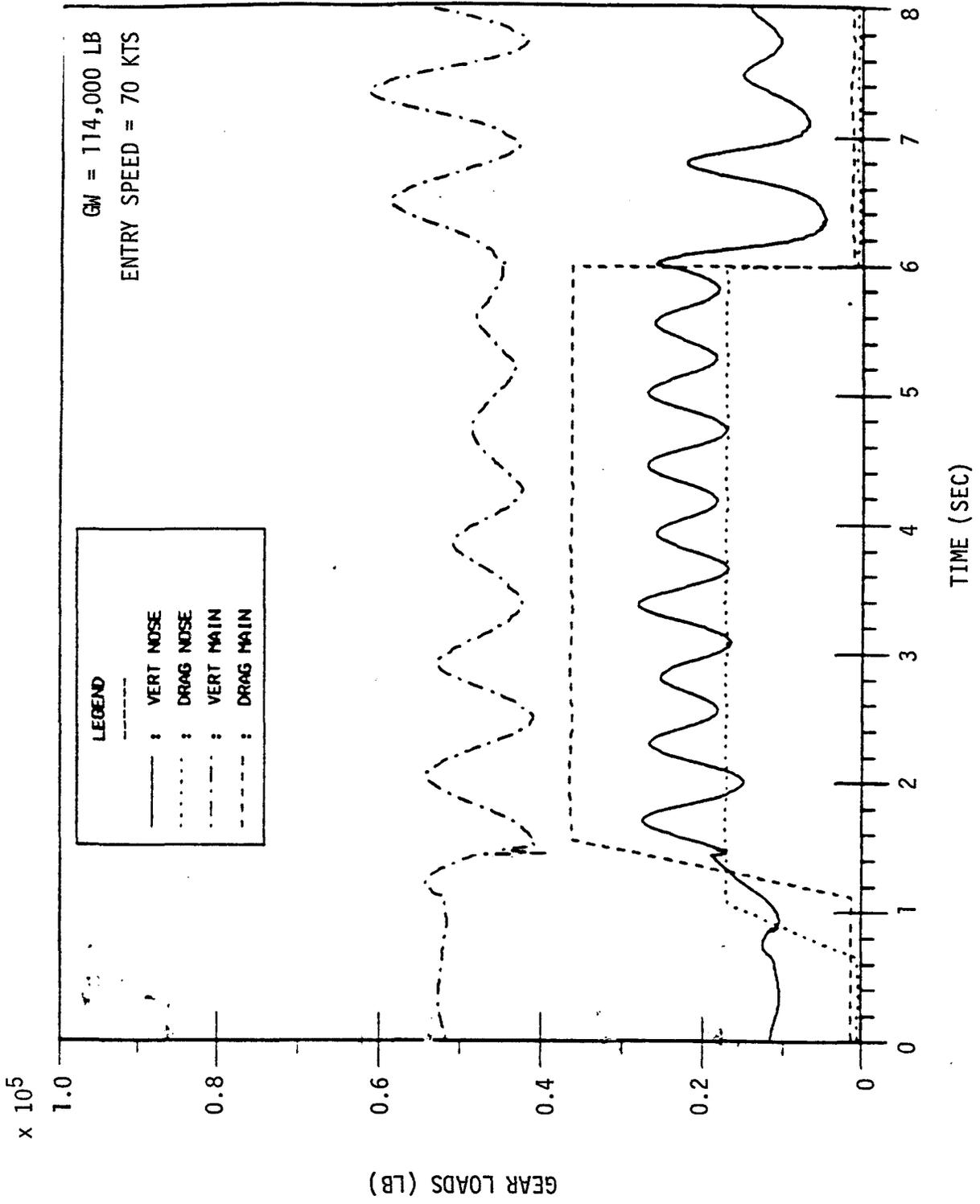


Figure 48. Aircraft B Landing Gear Loads During a Foam Bed Arrestment

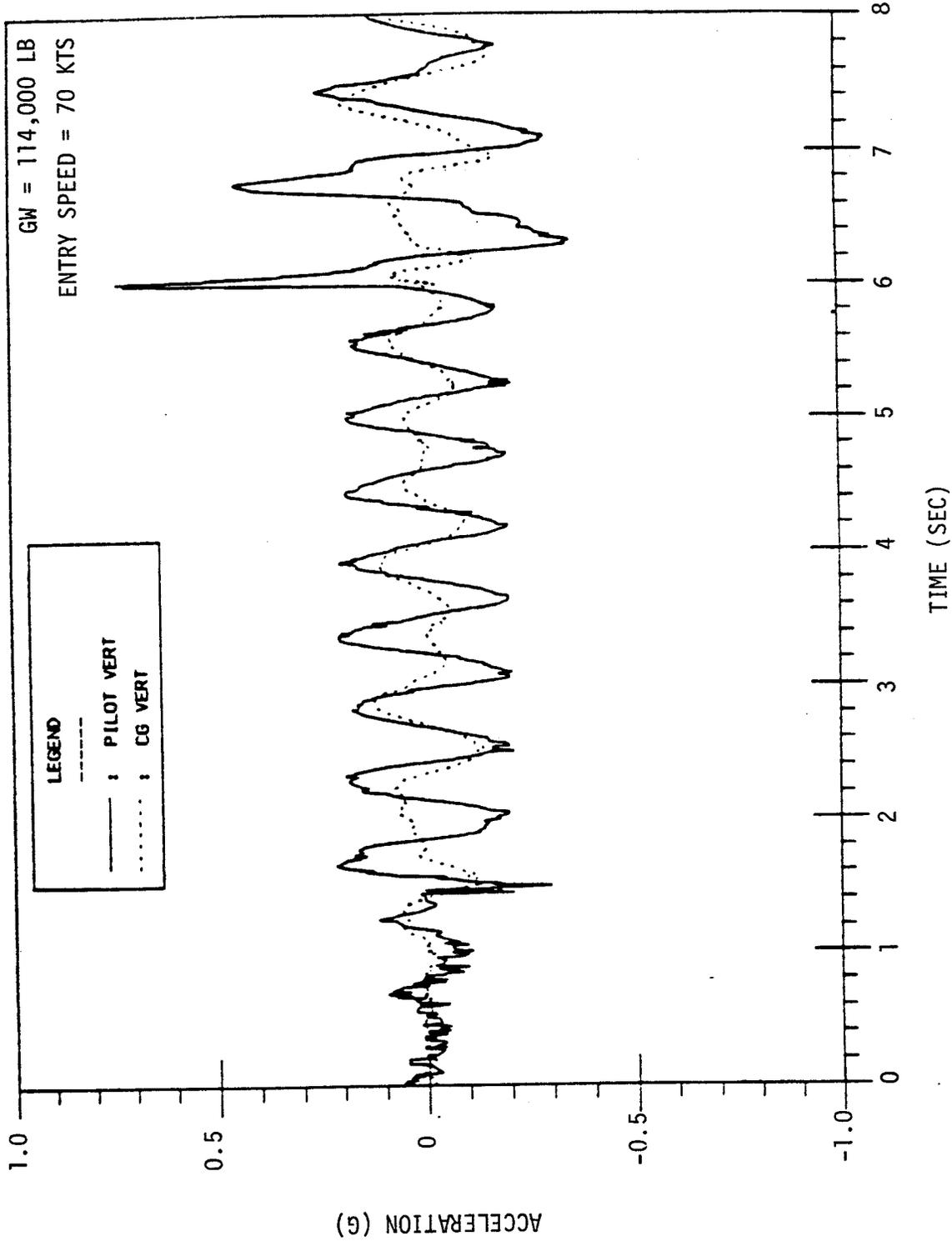


Figure 49. Aircraft B Dynamic Response During a Foam Bed Arrestment

3.2.3 Aircraft C

The deceleration performance of Aircraft C was less than the previous aircraft, reaching a peak deceleration of about 0.42 g as shown in Figure 50. The velocity profile of Aircraft C is shown in Figure 51 and the distance required for stopping in the foam arrestor was about 530 feet. Figure 52 shows that the aircraft wheels did not plane in the foam arrestor in that the entire available foam bed depth was used. The landing gear loads for Aircraft C were all well below the manufacturer's limit loads (Figure 53). It should be noted that the axle loads have been plotted and only the loads for one main gear are shown. The drag loads on the rear axle of this aircraft are very low because the foam was crushed by the leading axle wheels. The high frequency oscillations evident on the main gear vertical trace is due to bogey pitching. Figure 54 shows the dynamic response of Aircraft C during the arrestment and after the forward speed reached zero. These levels of acceleration are expected to be tolerable by most passengers.

3.2.4 Aircraft D

The deceleration of Aircraft D in the foam arrestor attained a peak value of about 0.33 g (Figure 55). The velocity profile during the arrestment is shown in Figure 56 and the stopping distance in the foam bed was about 660 feet. The aircraft showed no tendency to plane in the foam bed, as indicated in Figure 57. The landing gear loads were all well below manufacturer's limit loads. The computed loads are shown in Figure 58. The bogey vertical loads are nearly equal and the trace shown is for both axles. Figure 59 shows the dynamic response during the arrestment. No alarming acceleration values were evident during the arrestment.

3.2.5 Aircraft E

The deceleration results for Aircraft E arrestment in the foam bed are shown in Figure 60. The peak deceleration obtained was about 0.38 g which is considerably higher than Aircraft D even though Aircraft E is

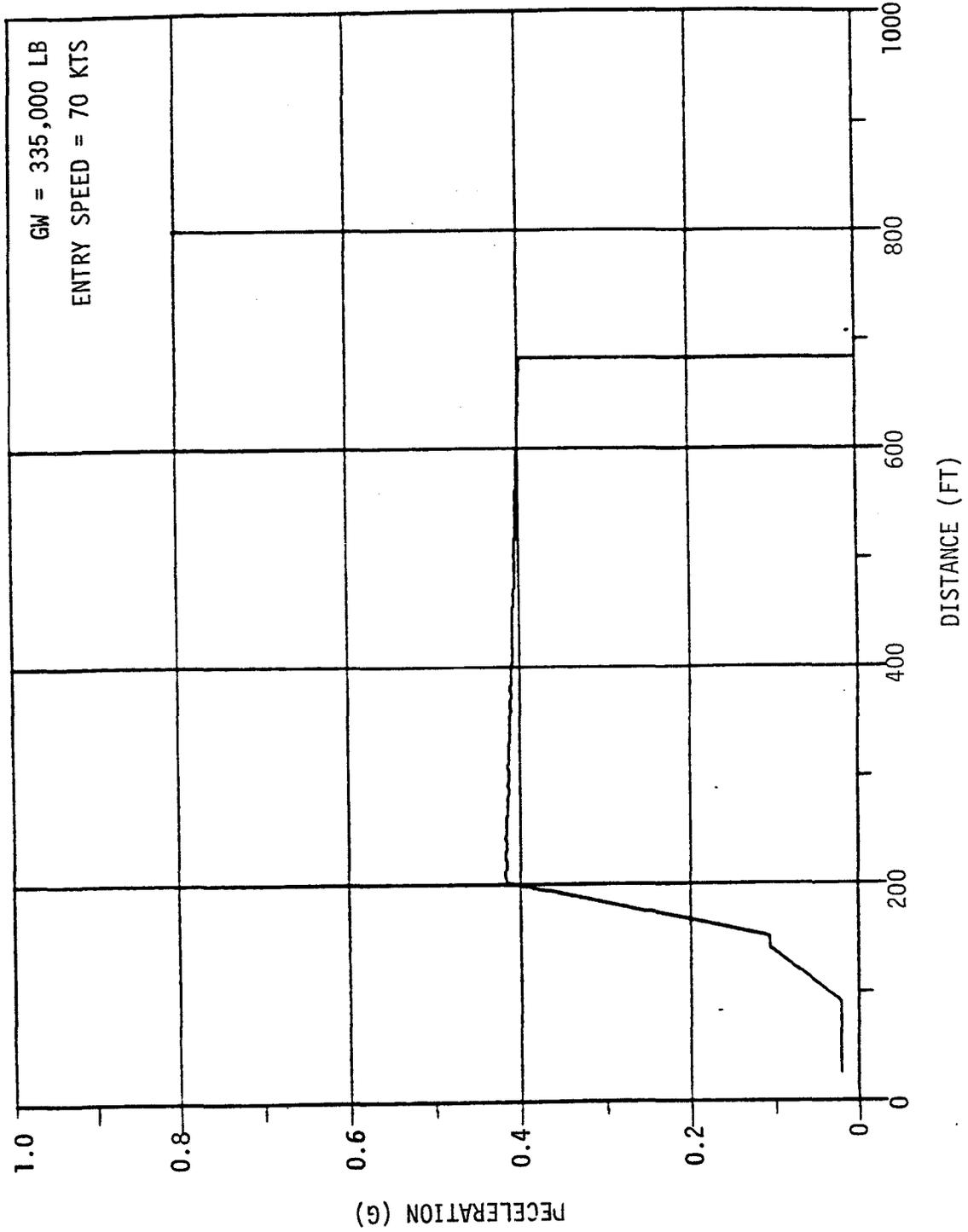


Figure 50. Aircraft C Deceleration in a Foam Arrestor Bed

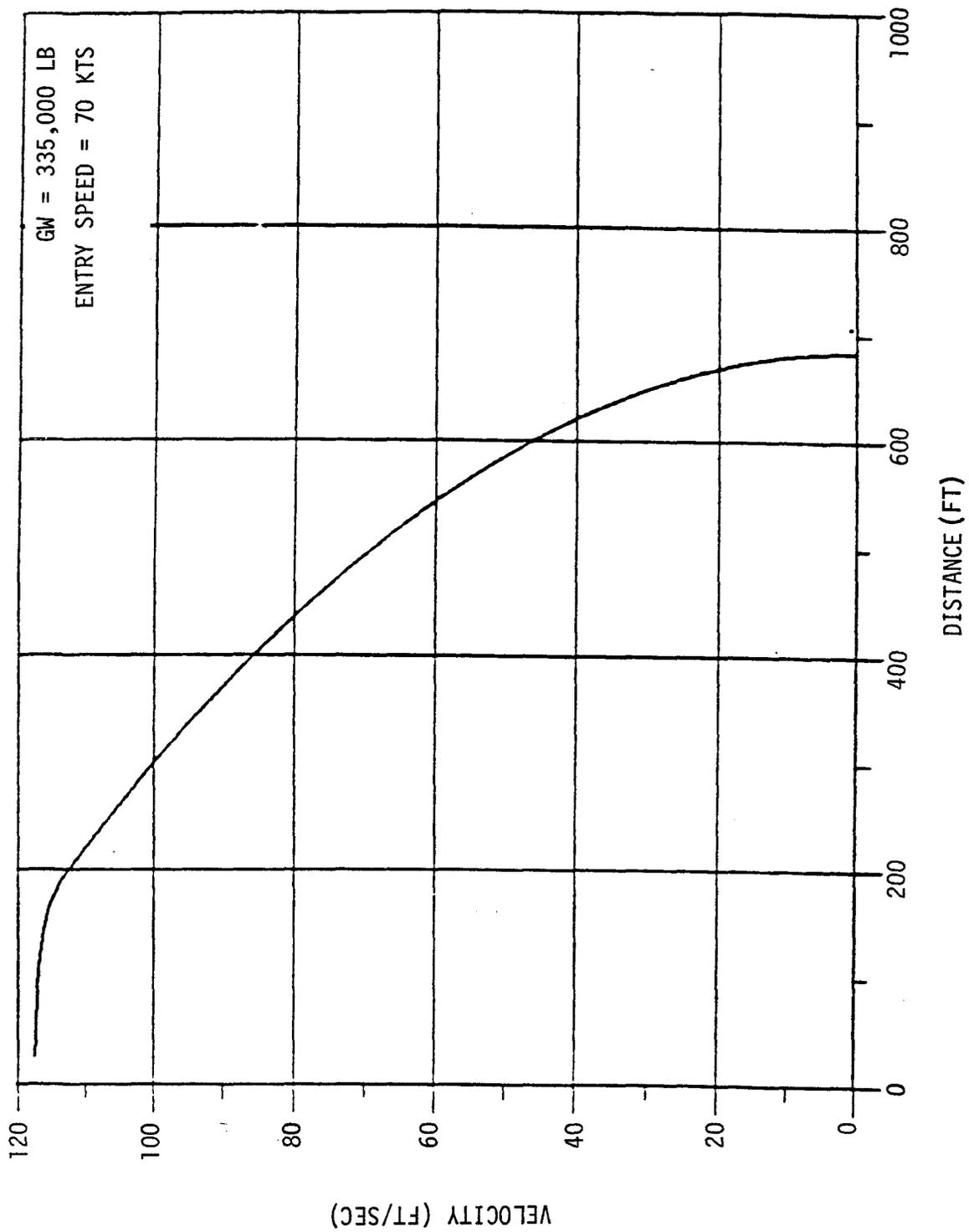


Figure 51. Aircraft C Velocity Profile in a Foam Arrestor

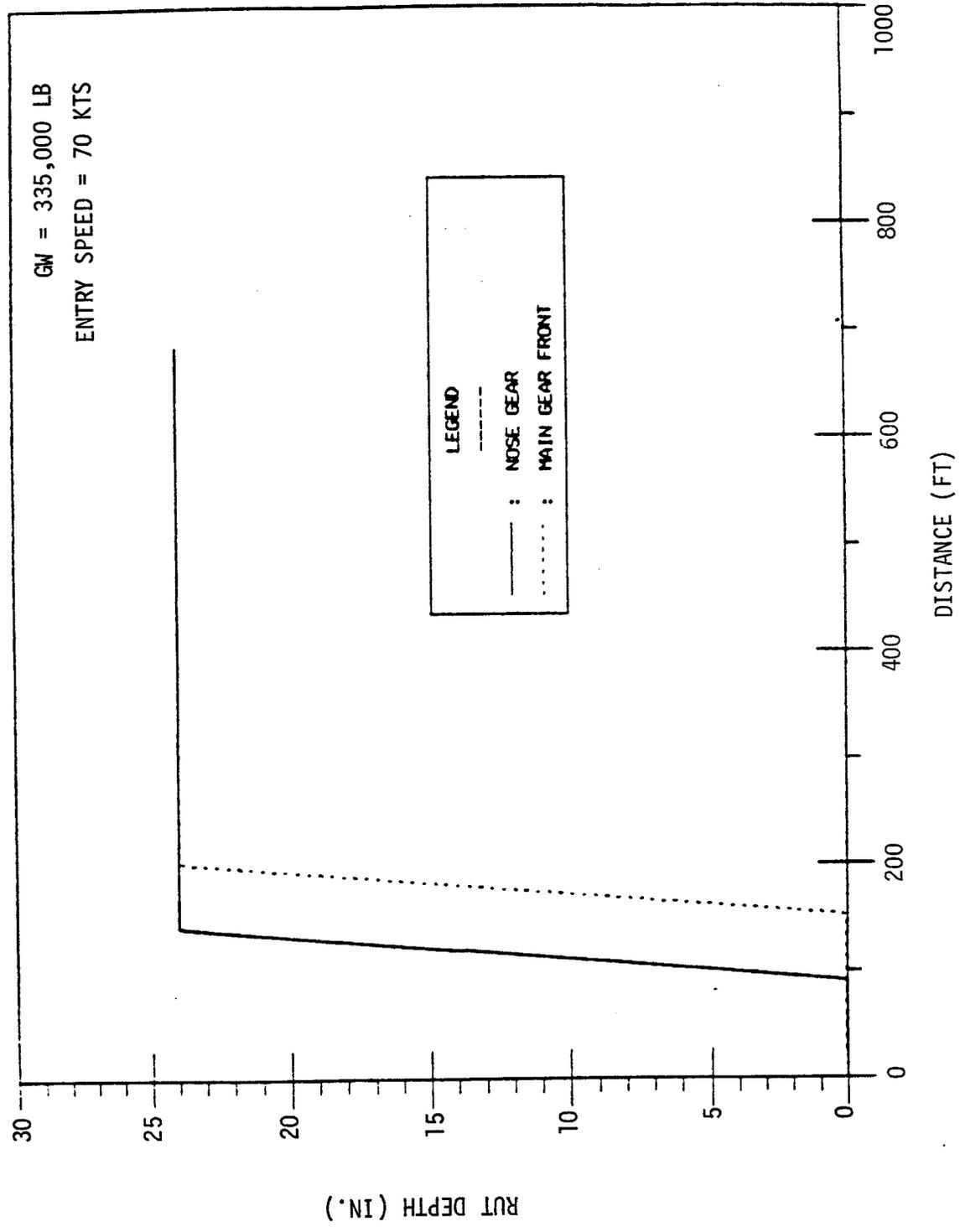


Figure 52. Aircraft C Rut Depth Obtained During a Foam Bed Arrestment

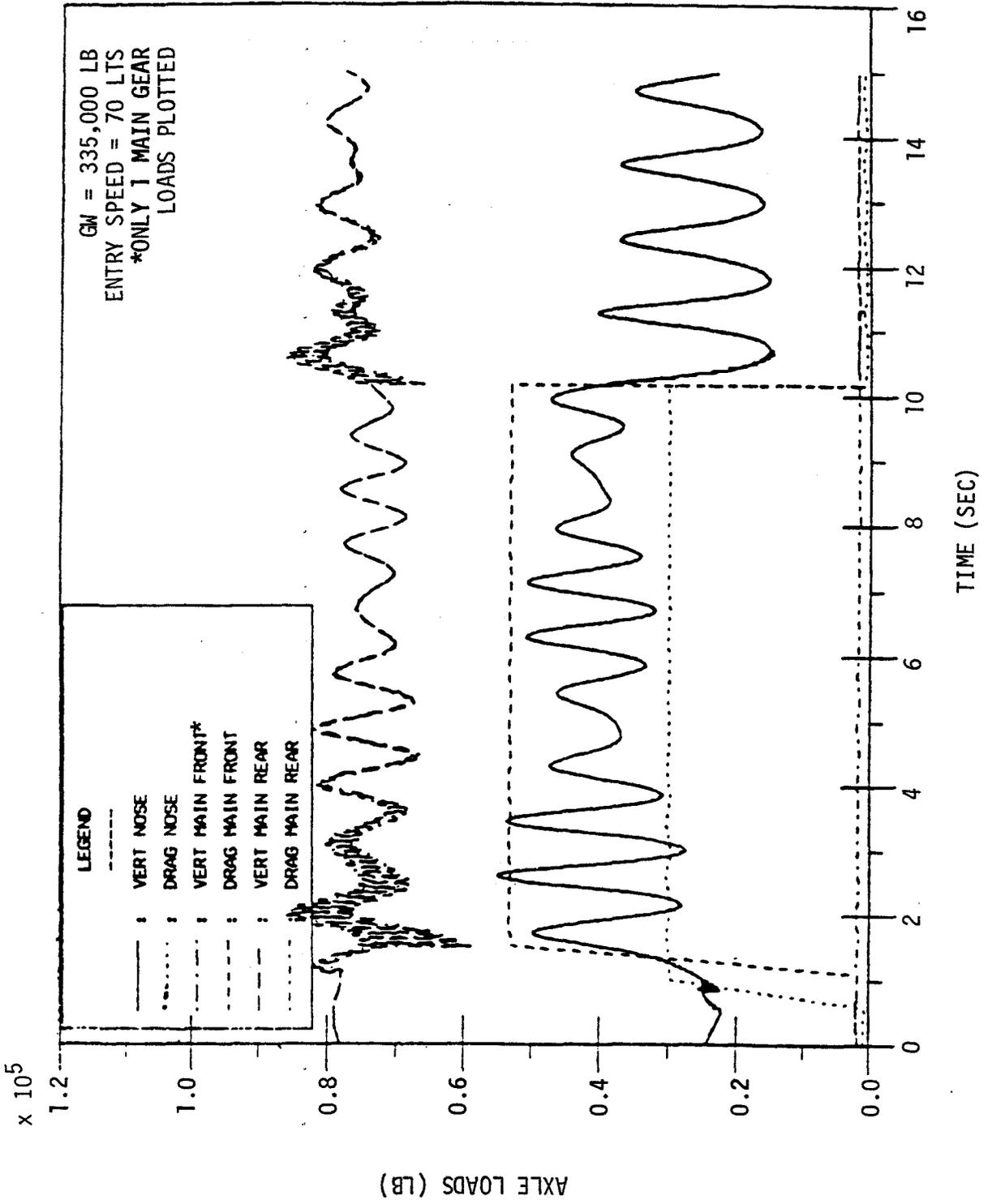


Figure 53. Aircraft C Landing Gear Loads During a Foam Bed Arrestor

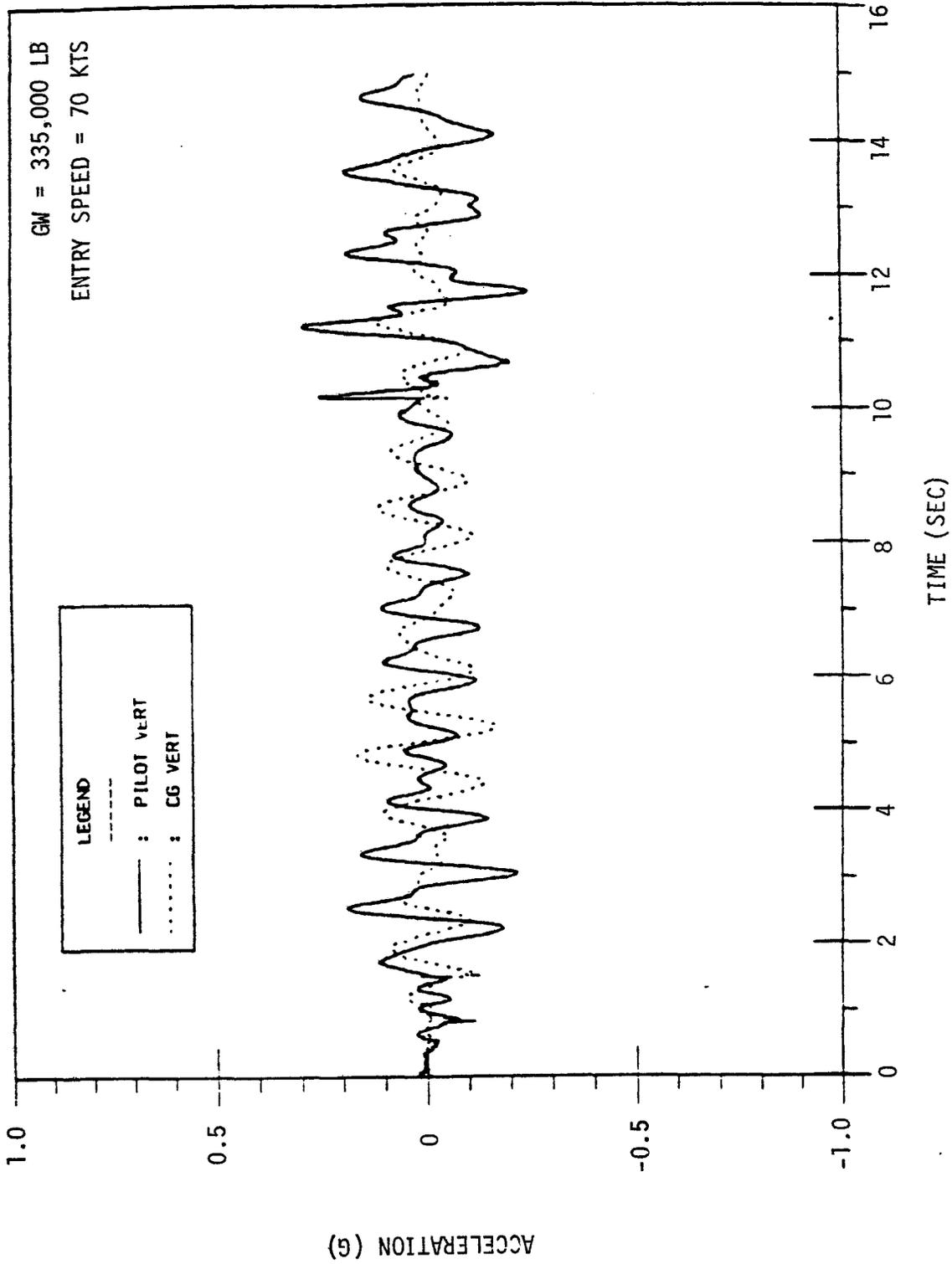


Figure 54. Aircraft C Dynamic Response During a Foam Bed Arrestment

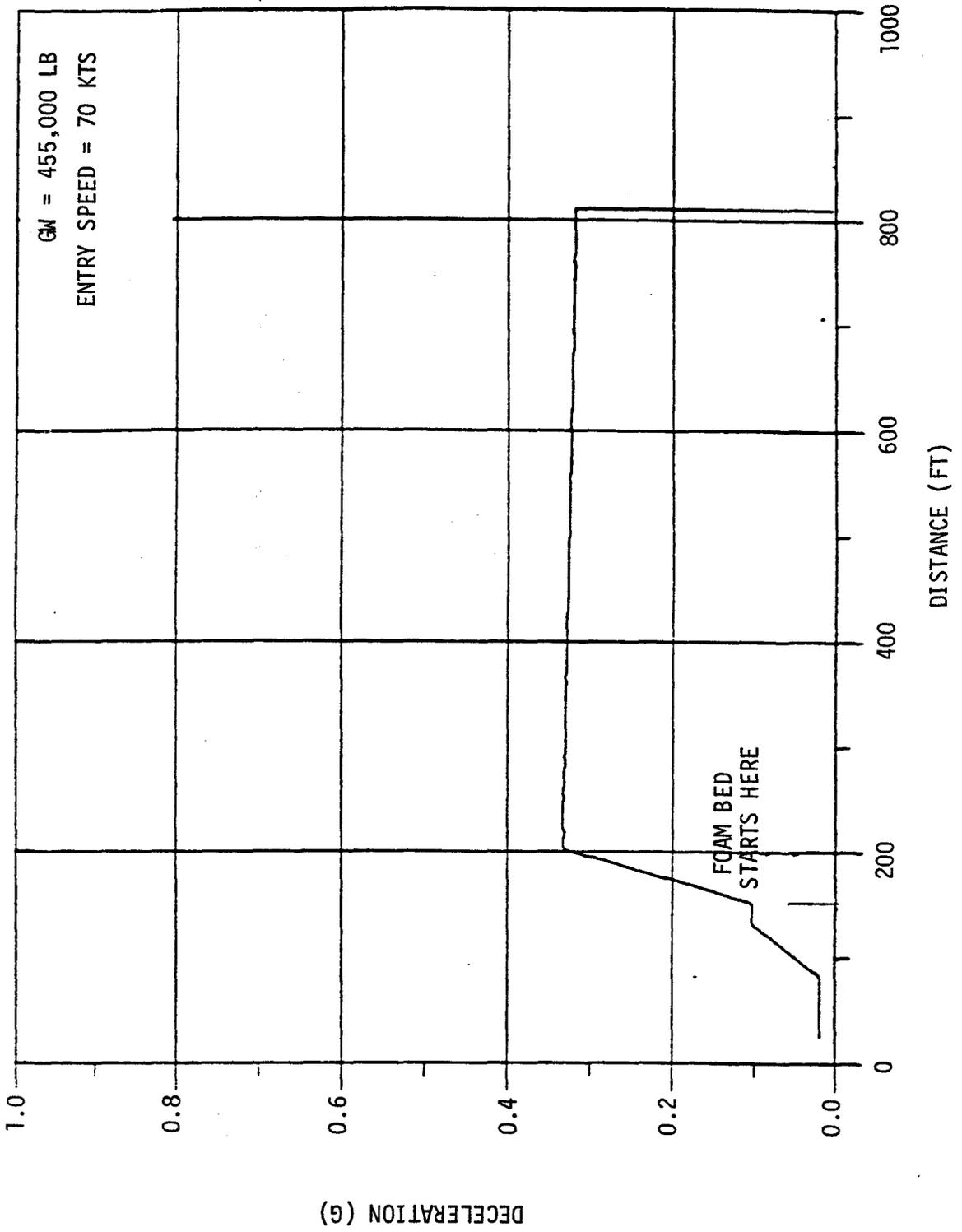


Figure 55. Aircraft D Deceleration in a Foam Bed Arrestor

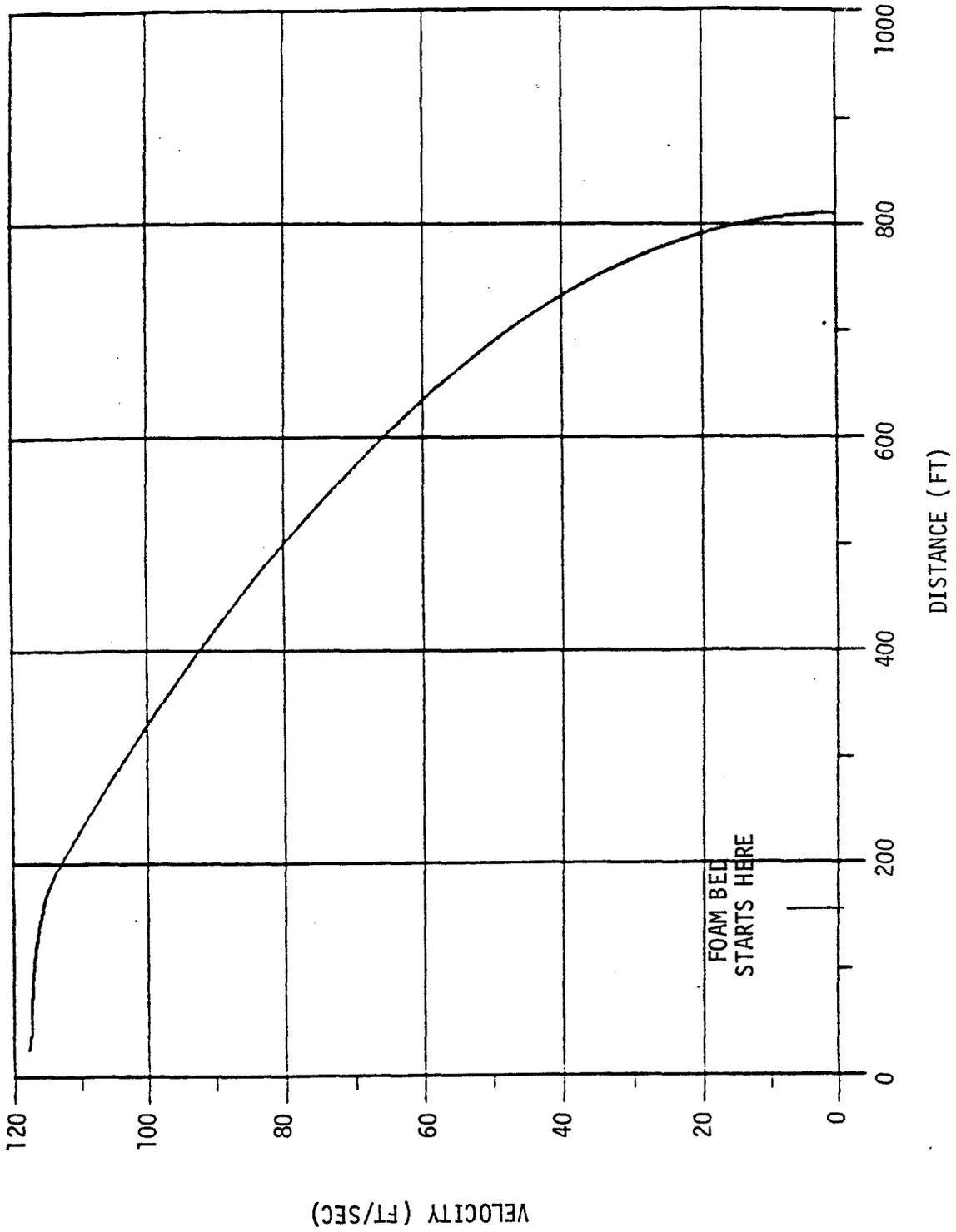


Figure 56. Aircraft D Velocity Profile During a Foam Bed Arrestment

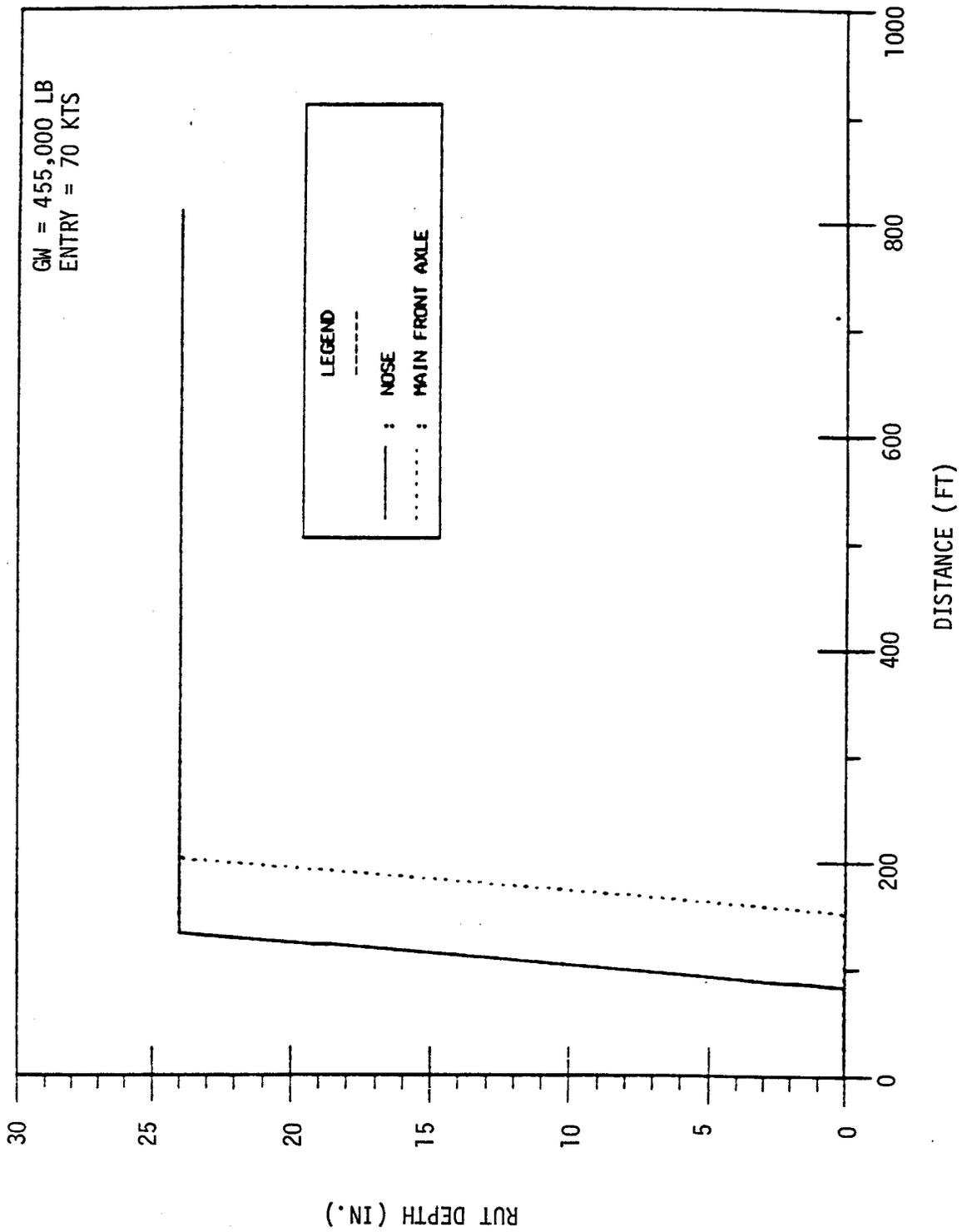


Figure 57. Aircraft D Rut Depth Obtained During a Foam Bed Arrestment

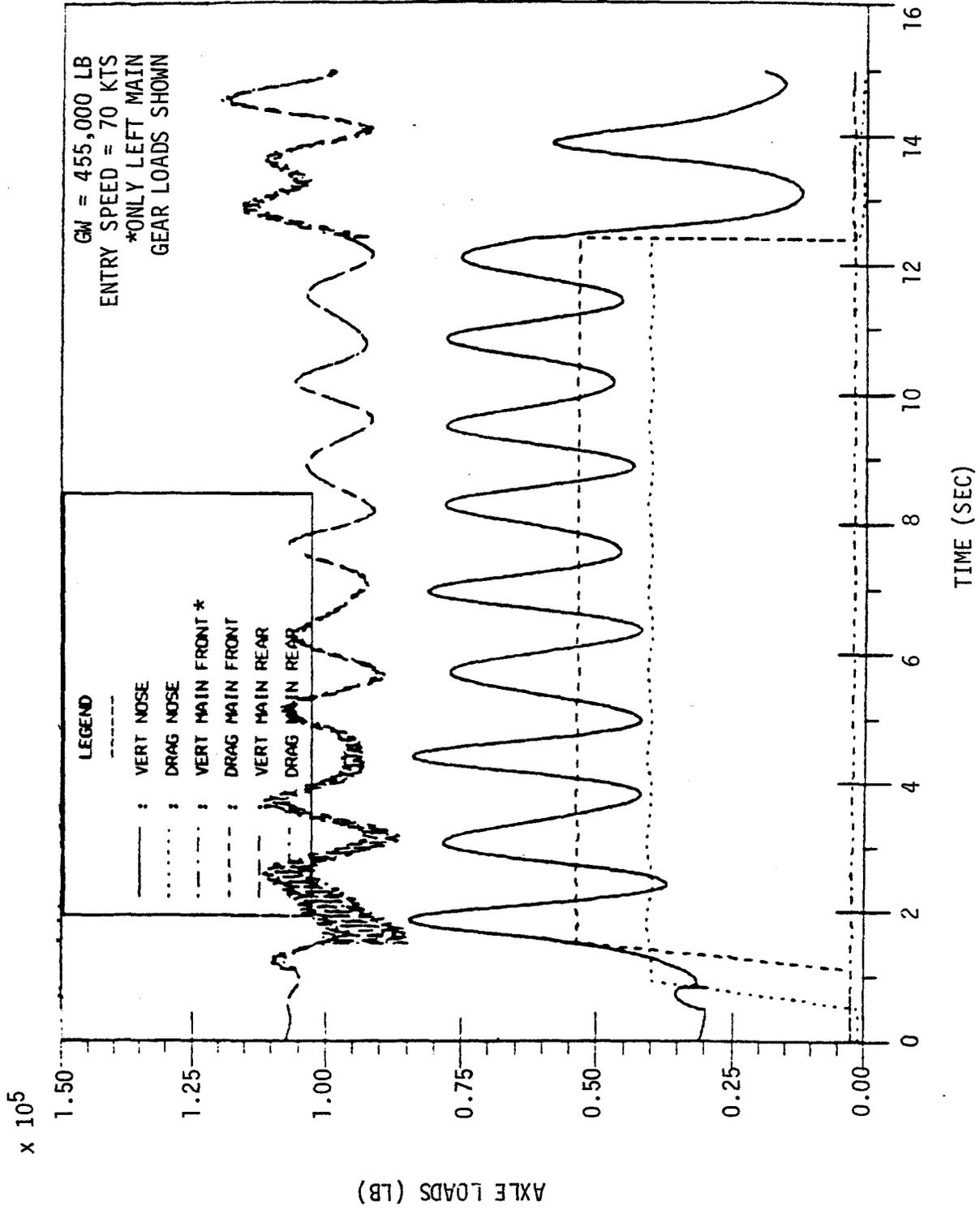


Figure 58. Aircraft D Landing Gear Loads During a Foam Bed Arrestment

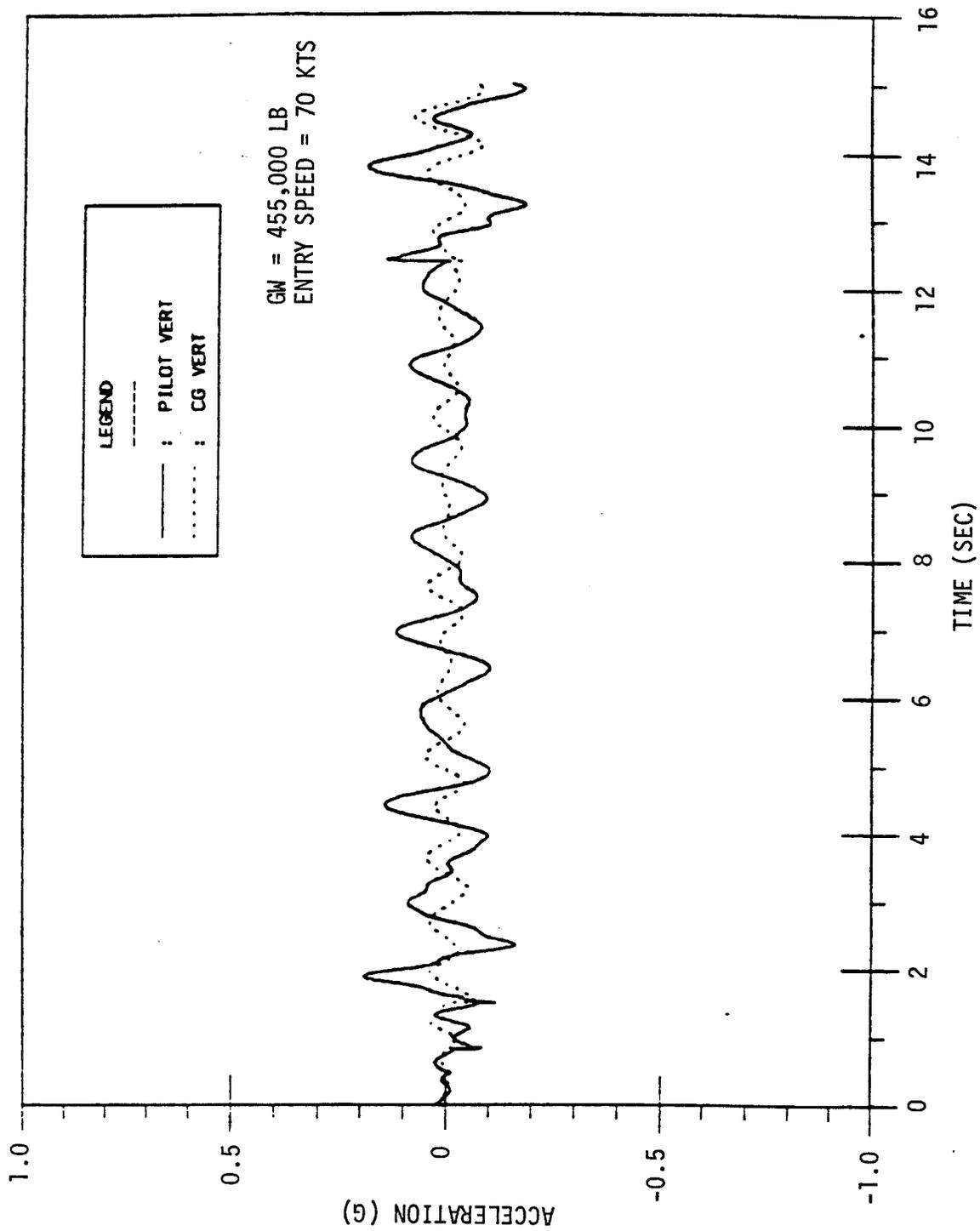


Figure 59. Aircraft D Dynamic Response During a Foam Bed Arrestment

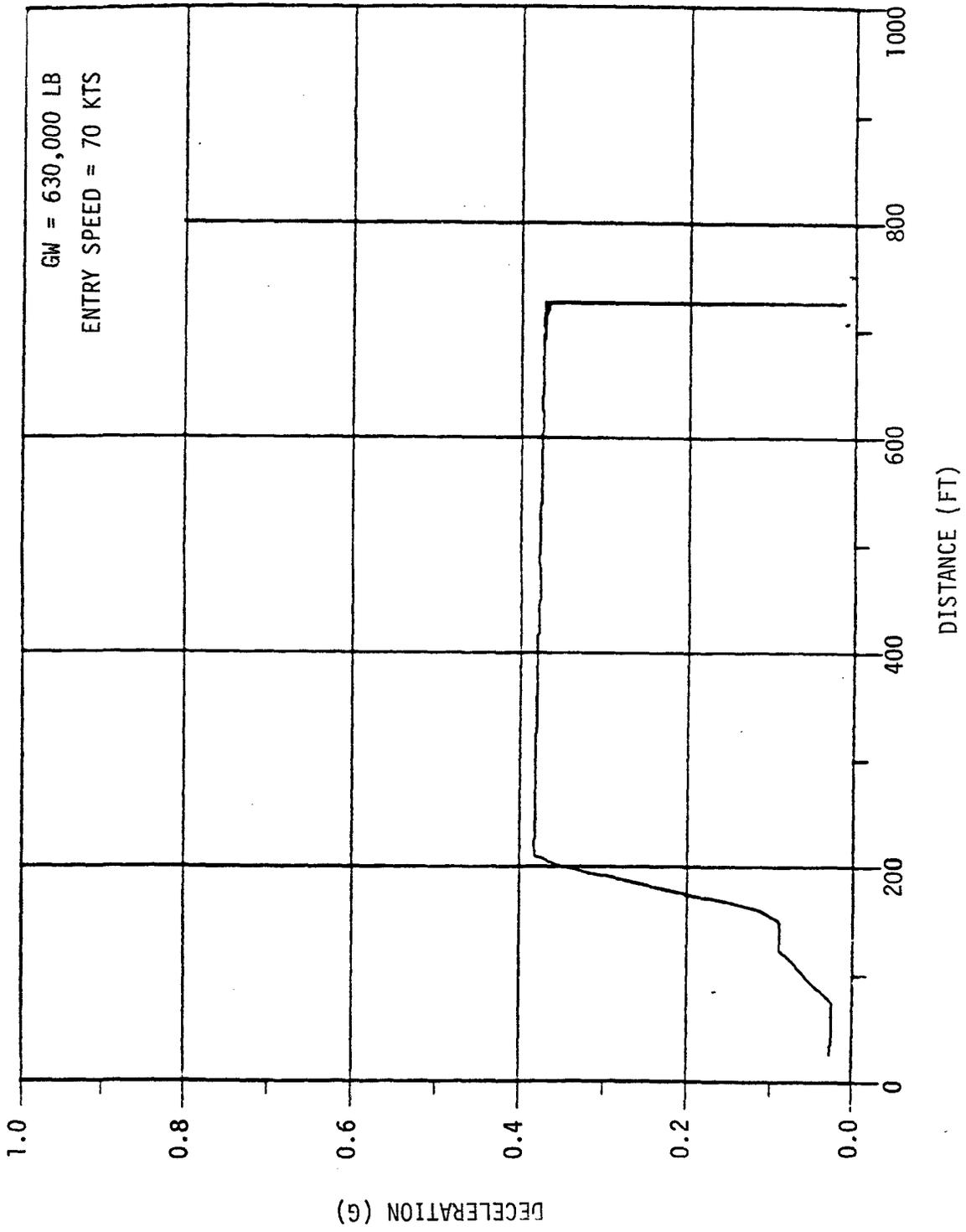


Figure 60. Aircraft E Deceleration in a Foam Arrestor Bed

much heavier. The reason for the increased deceleration performance of Aircraft E results from the extra set of main landing gear. Figure 61 shows the velocity profile of Aircraft E in the foam arrestor and also shows that the stopping distance in the foam was about 575 feet. There was no tendency for the wheels to plane in the foam bed as shown in Figure 62. The landing gear loads are shown in Figure 63. The manufacturer's limit loads are not known for this aircraft. The plotted loads for the main gear are the total for both axles of the bogey as well as both struts. The very high frequency results at the end of the vertical load traces are due to bogey pitching, and are a result of inadequate damping in the computer simulation. The dynamic response computed for this aircraft is not accurate because the static loads on the main gear were estimated since the system is redundant.

3.2.6 Foam Arrestor Bed Summary

The foam bed is by far the most efficient of all materials evaluated for stopping aircraft as evident from the deceleration of the aircraft which is nearly constant over the complete arrestment. The foam material density is very low so that any chunks that may tear loose and impinge on the aircraft structure are not likely to cause damage. The foam material should maintain its characteristics over the full temperature range encountered in the United States (and other parts of the world), thus providing dependable arrestments each time regardless of the local weather conditions. Foam is combustible but self-extinguishing. The foam for the arrestor is closed-cell and therefore moisture resistant although a sealer is desirable. It must be replaced when damaged by an overrun incident.

3.3 UNDERSHOOT LANDINGS IN ARRESTOR AREA

There is considerable evidence that aircraft pilots touch down prior to reaching the runway threshold. Some airports have safety areas paved for this purpose as well as for overruns. Tire skid marks are very evident in the safety area to prove this point. Since the foam arrestor will be located in the safety area, a determination of the consequences of landing on the arrestor is required. It was surmised that the smaller

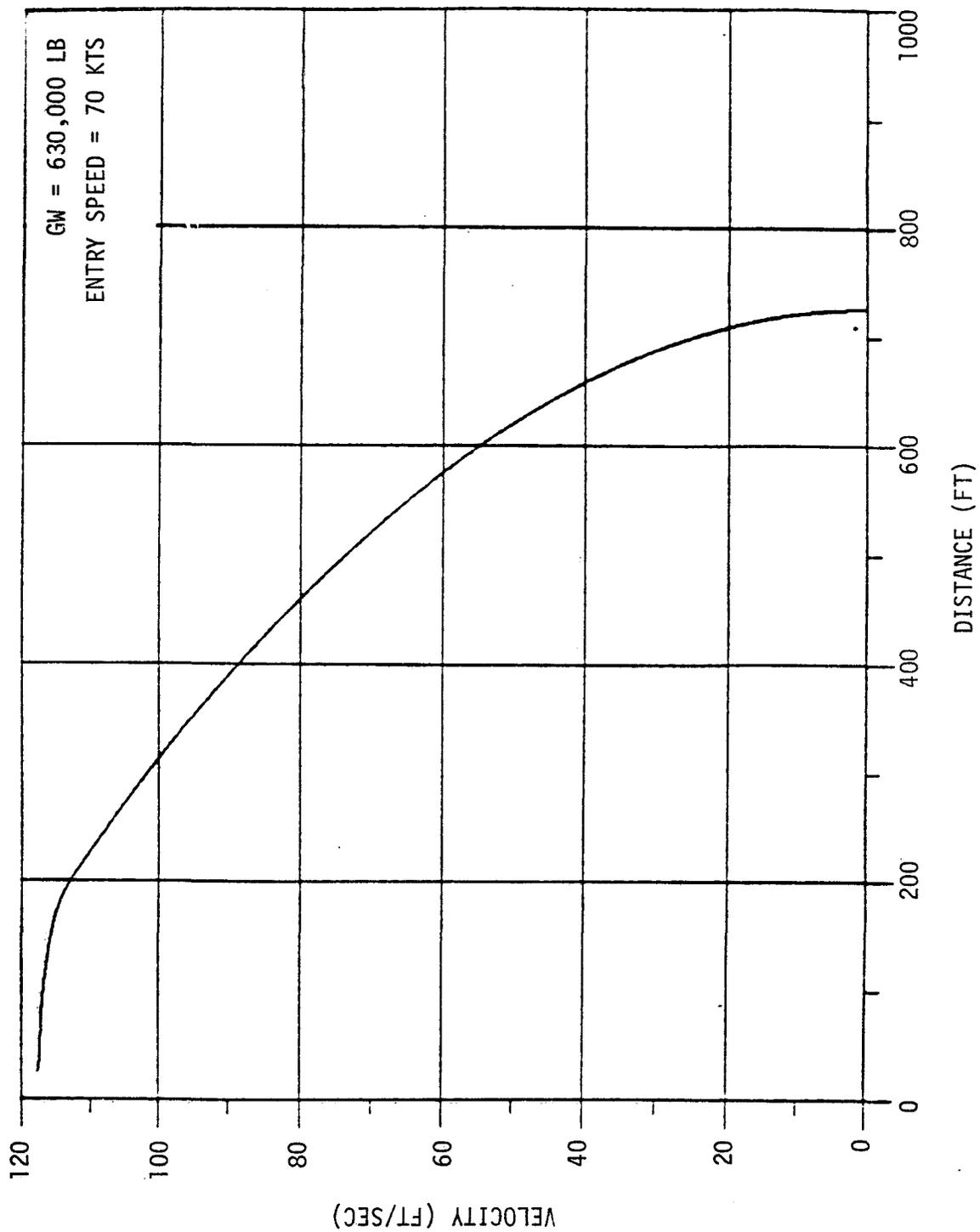


Figure 61. Aircraft E Velocity Profile During a Foam Bed Arrestment

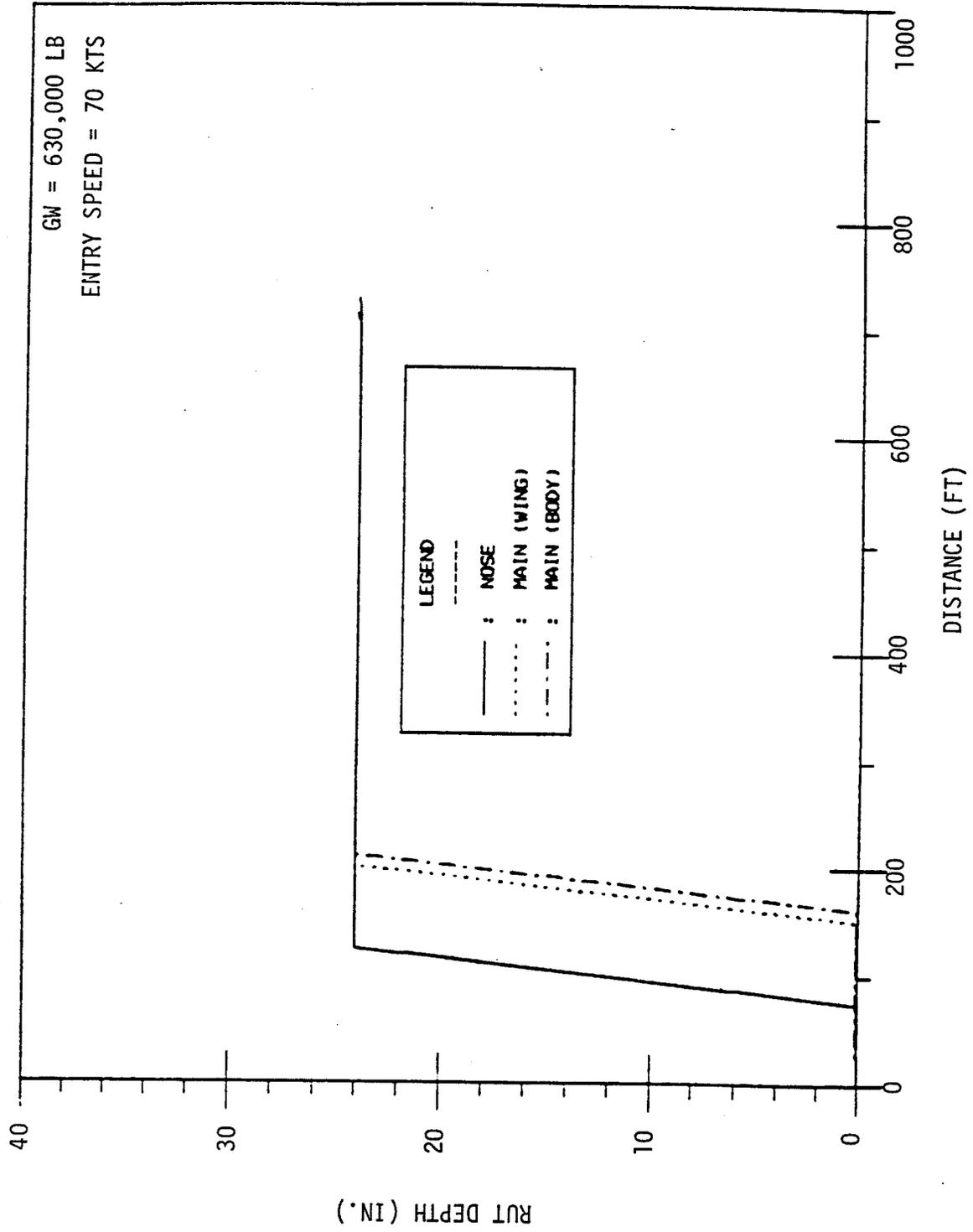


Figure 62. Aircraft E Rut Depth During a Foam Bed Arrestment

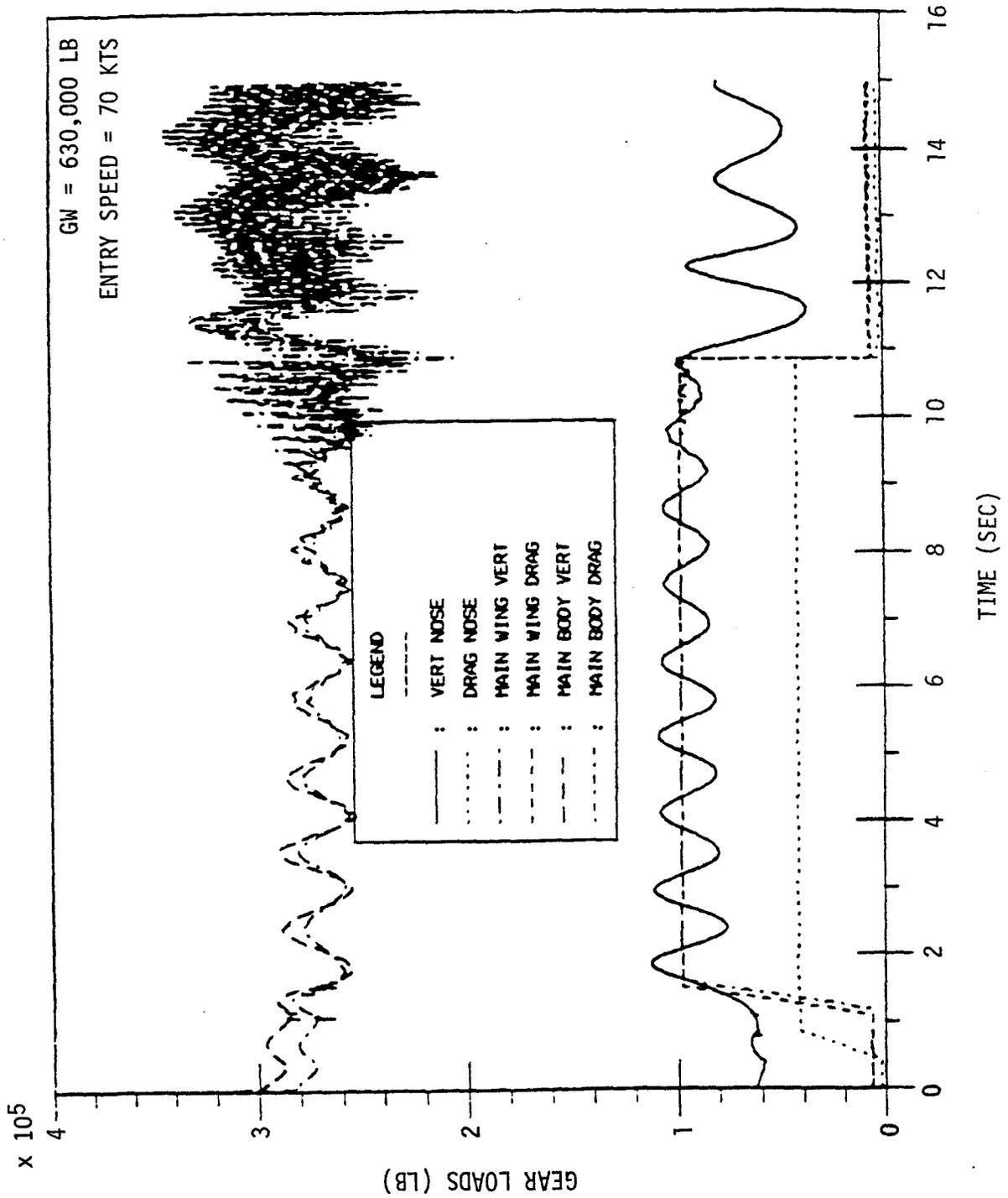


Figure 63. Aircraft E Landing Gear Loads During a Foam Bed Arrestment

aircraft would most likely be affected by the foam arrestor high drag characteristics since their pitching inertia would be the smallest. On this basis, then, a simulated landing of Aircraft B was considered to be representative of the effects to be encountered.

The landing simulation of Aircraft B was made at its maximum landing weight of 102,000 pounds and an estimated landing speed of about 170 knots. A sink speed of 2.5 ft/sec was used and the touchdown was set at 500 feet before the runway threshold. Two cases, one with the foam arrestor in place and one with the arrestor removed, were simulated since flight control data for the aircraft were not available.

Figure 64 shows the angle of attack history of the aircraft during the landing without the arrestor in place. The pilot control was set up in the program to control the elevator position when the angle of attack changed beyond 0.05 radians. This apparently was too coarse for a smooth approach but is considered adequate for the purpose here. Figure 65 shows the main landing gear loads upon contact with the surface, showing that the aircraft bounced after ground contact. The main gear loads are well below limit values. The touchdown was about 150 feet before the threshold of the runway.

The simulated landing of Aircraft B with the arrestor in place is shown in Figures 66 to 68. Figure 66 shows the rut depth in the foam arrestor during the landing. A penetration of about 10 inches was obtained before the wheels left the arrestor and made contact with the ground. Figure 67 shows the angle of attack history. Comparison of this figure with Figure 66 shows that there is very little change in the pitch attitude history. Figure 68 shows the gear loads during contact with the foam arrestor and subsequent ground contact. Comparison of these loads with those in Figure 65 shows the loads to be very similar. Touchdown was only about 100 feet before the runway threshold in this case. This undershoot landing simulation shows that landing on the arrestor is not likely to cause loss of control of the aircraft. It should be noted, however, that this has been only a cursory examination of the undershoot problem and further analyses should be conducted.

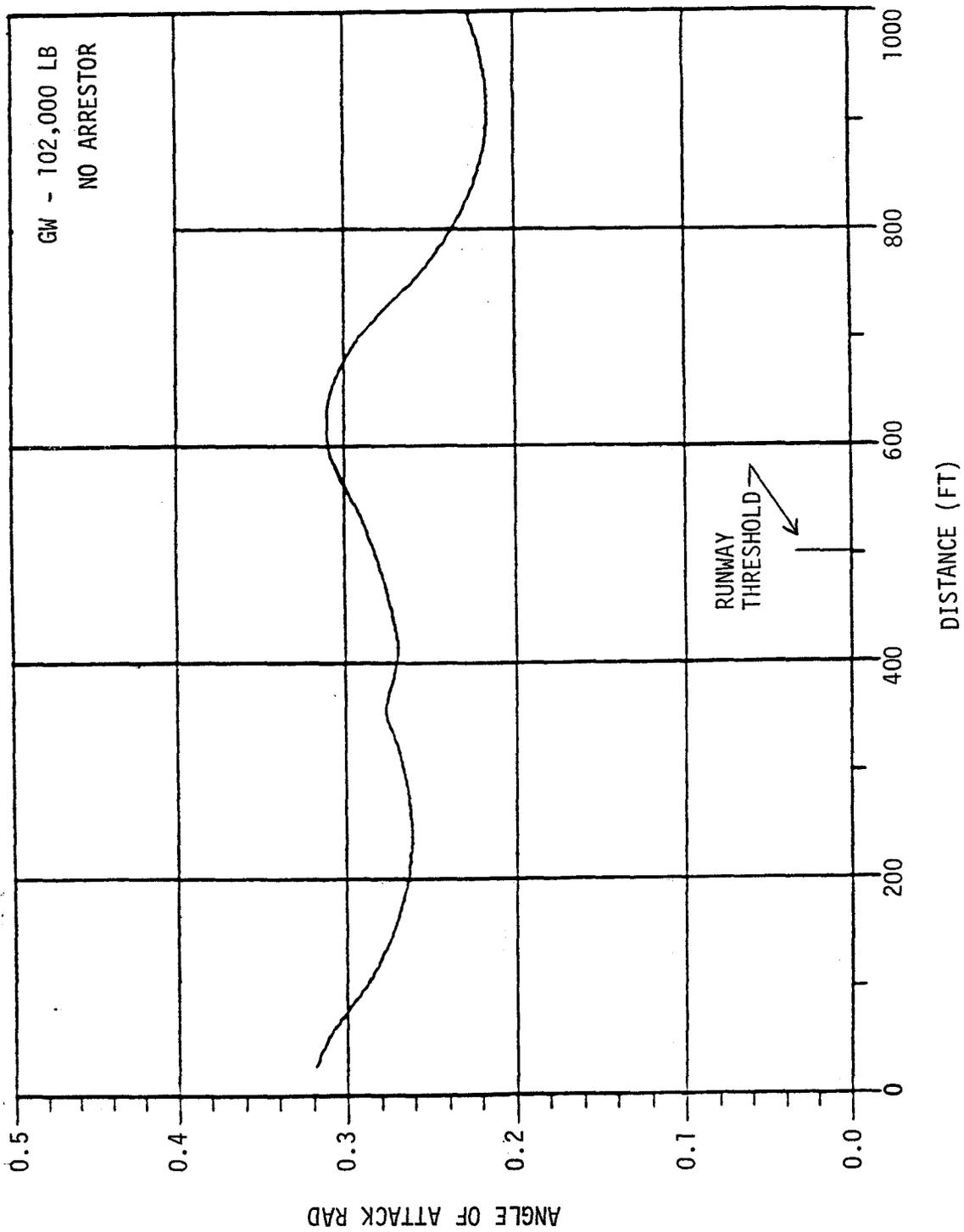


Figure 64. Aircraft B Angle of Attack During Simulated Landing on Safety Area

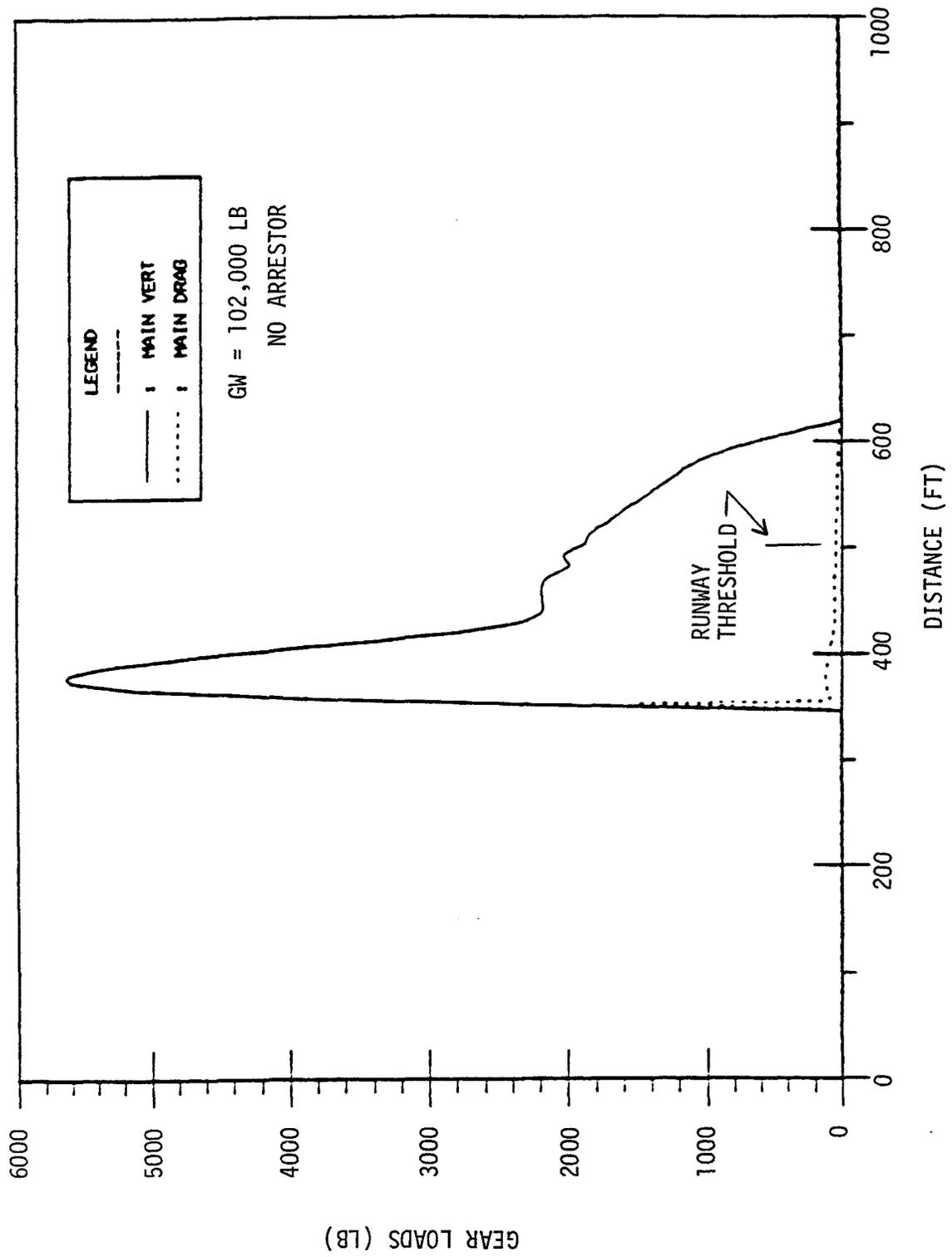


Figure 65. Aircraft B Main Landing Gear Loads During a Simulated Landing

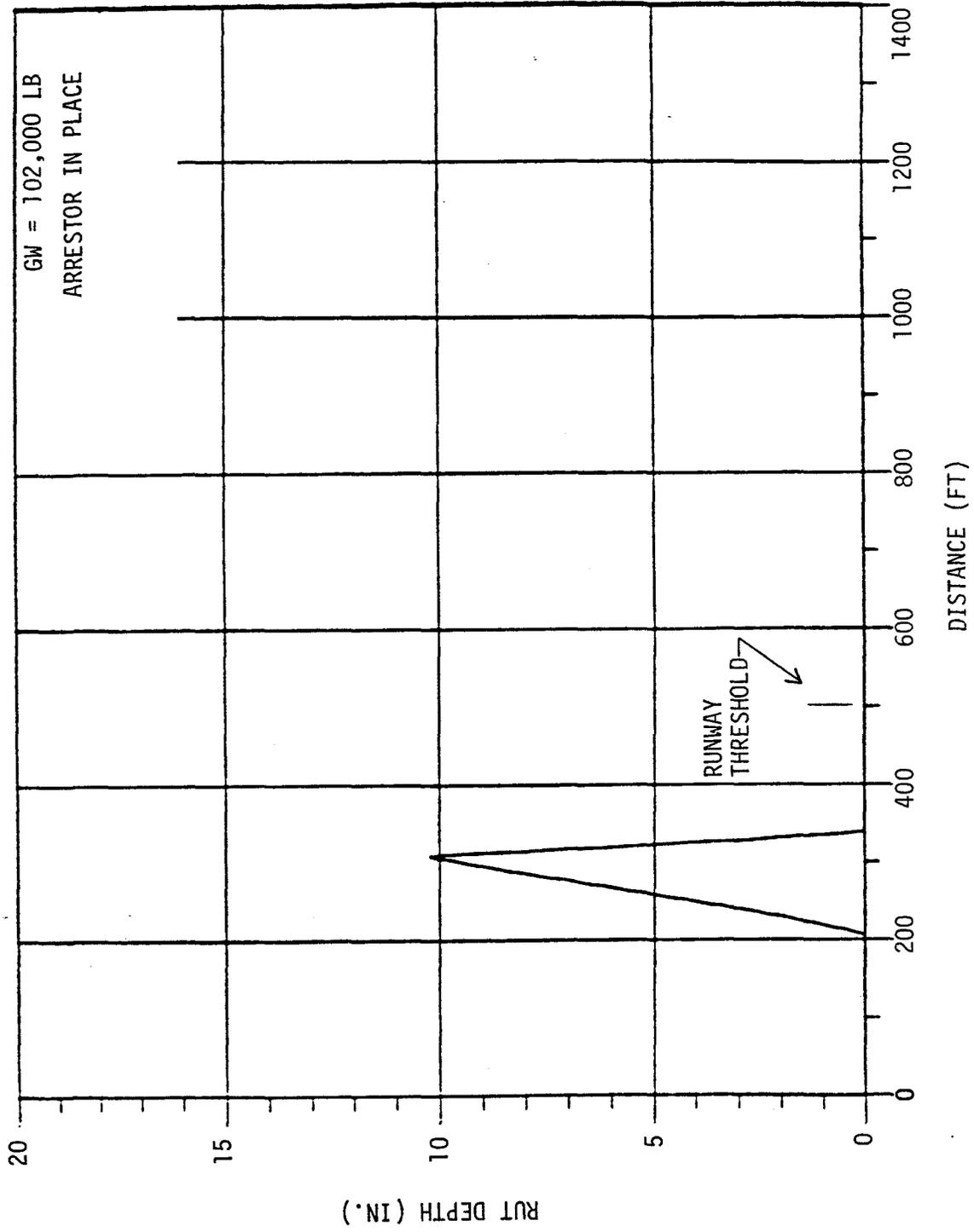


Figure 66. Aircraft B Rut Depth During Simulated Landing on the Foam Arrestor

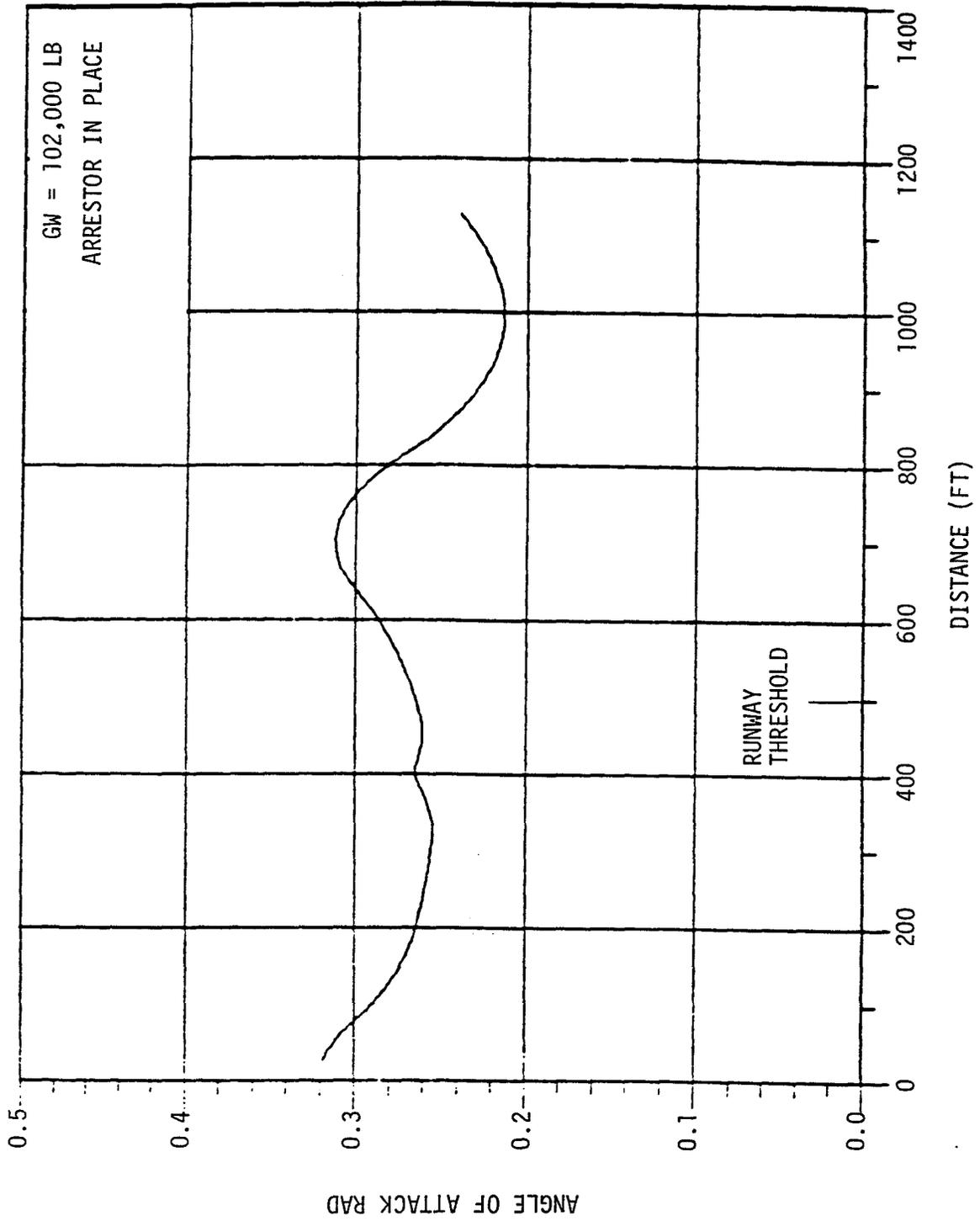


Figure 67. Aircraft B Angle of Attack During Simulated Landing on the Foam Arrestor

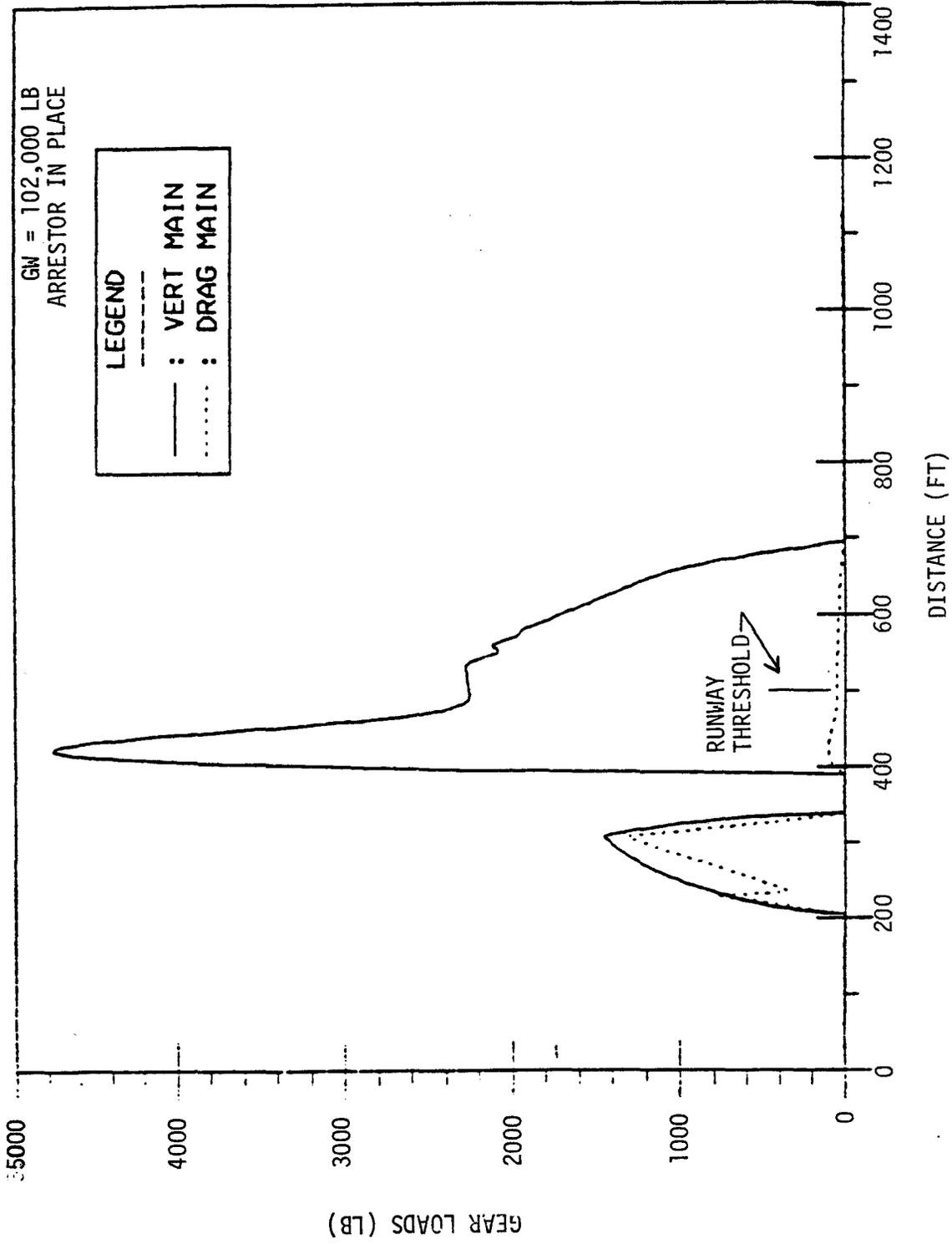


Figure 68. Aircraft B Landing Gear Loads During Simulated Landing on the Foam Arrestor

3.4 FOAM ARRESTOR BED INSTALLATION

During the course of this study, it was assumed that the arrestor bed would be situated on a rigid base and that it would not move when contacted by an aircraft during an overrun. It was also assumed that the foam bed was homogeneous and that there were no spaces in the foam. These assumptions translate into installation requirements by requiring that the foam bed be placed on an extended runway surface having sufficient strength to not significantly deflect under the aircraft wheels. This means that the overrun area surface will require a substantial subgrade of crushed rock and then be surfaced with about 8 inches of reinforced concrete. However, since the area will receive only limited traffic, a construction of less strength than taxiways and runways could be used.

Figure 69 shows a possible installation layout of the arrestor. Frangible light systems may be used with the foam cut out to prevent obscuring the light. NOTAMS should be issued indicating the arrestor is operational and in place. Normal foot traffic on the foam arrestor is considered acceptable for repair of lights.

Attachment of the foam to the surface should be positive. One possibility would be to attach a wire mesh to the surface with lag screws through steel straps as shown in Figure 70. Wires could be attached to the mesh and then poked through the foam slabs or blocks provided by the foam manufacturer. A thin washer could be placed over the wire and then the wire twisted so that it would not pass back through the washer. This arrangement should provide adequate strength to prevent the foam bed from moving during contact by an aircraft or from the high winds from storms or jet exhaust. Further details of attachment are best held until some schemes have been experimentally tried and evaluated.

Earlier in the report, it was stated that the compressed height of the foam bed might require that the extended runway be depressed about 0.1 of the bed height so that the surface elevation profile as seen by the aircraft wheels would remain at a zero level. An additional

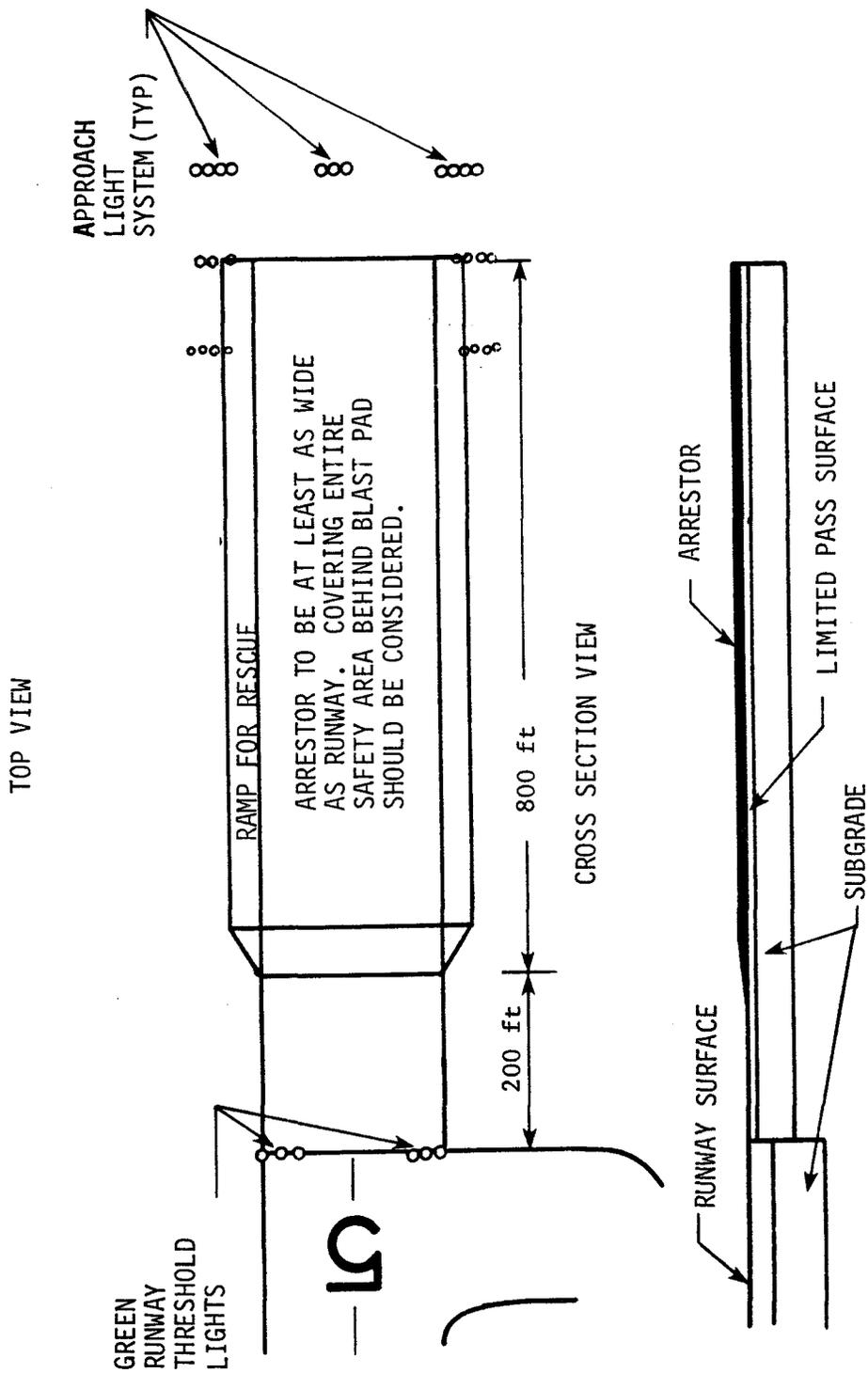


Figure 69. Runway Configuration with Arrestor in Place

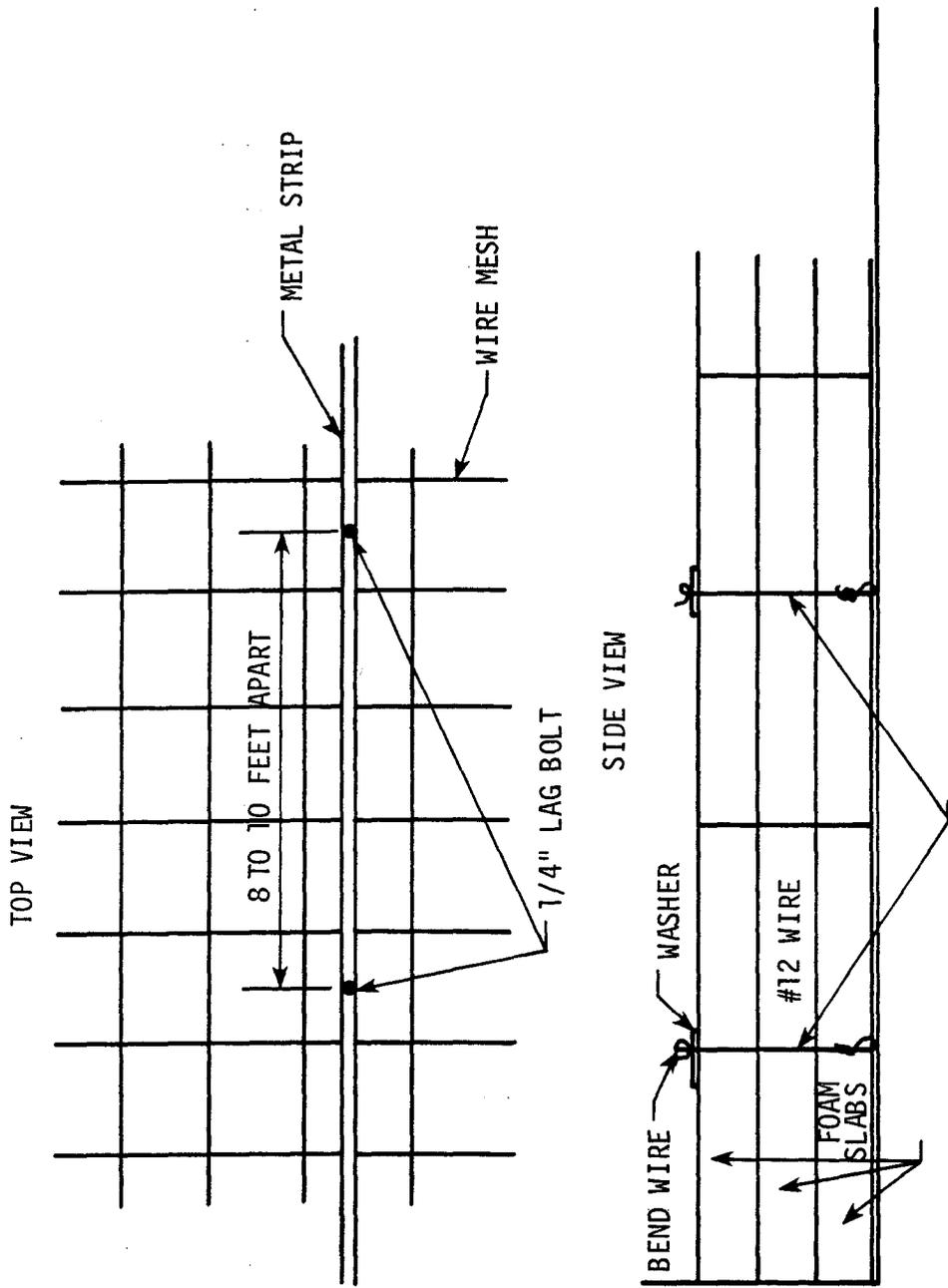


Figure 70. Possible Attachment Scheme for Foam Arrester

arrestment simulation of Aircraft A was conducted with the surface profile elevation increased by 0.1 of the foam bed (Figure 39) height (designated "Rough Surface"). Figure 71 shows the gear loads resulting from the rough surface. The vertical load is only slightly higher for the nose gear than obtained by depressing the extended runway surface (see Figure 43). The drag loads are less for both the nose and main gears because the amount of foam depth is decreased as shown in Figure 72 (compare with Figure 42). There was also a 16 percent increase in the stopping distance (Figure 73) as a result of the decreased foam height. The stopping distance was 360 feet on the rough surface as compared to 310 feet. It should be noted that increasing the foam depth will decrease the stopping distance, but it will also increase the surface roughness. Figure 74 shows the dynamic response of Aircraft A resulting from the arrestment. The response is about 20 percent higher as a result of the rough surface as indicated by comparison with the smooth surface (Figure 44). The acceleration levels are, however, still tolerable.

As a result of the above comparison, it appears that depressing the extended surface by an amount equal to the height of the foam bed is beneficial and probably should be adhered to in the foam bed placement. This should not be a difficult problem since the elevation change would only be about 2.4 inches.

3.5 ANALYSIS OF RESULTS

Discussions in the first part of the report dealt with the specific items of the feasibility of an overrun arrestor. However, there are other considerations which also must be discussed such as the:

1. Improvement provided by the arrestor over just an extended runway,
2. The overall efficiency of the arrestor.

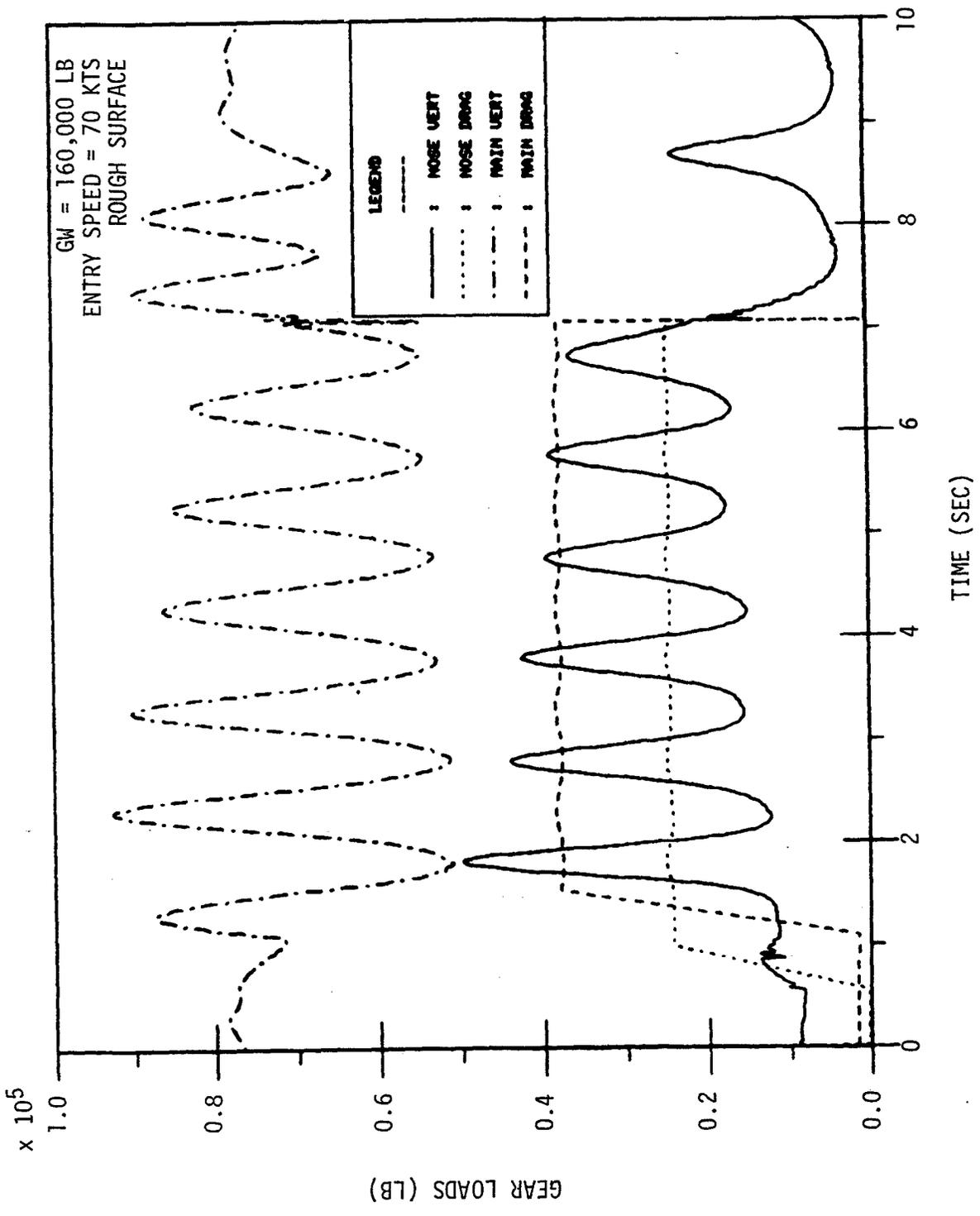


Figure 71. Aircraft A Landing Gear Loads During a Foam Bed Arrestment

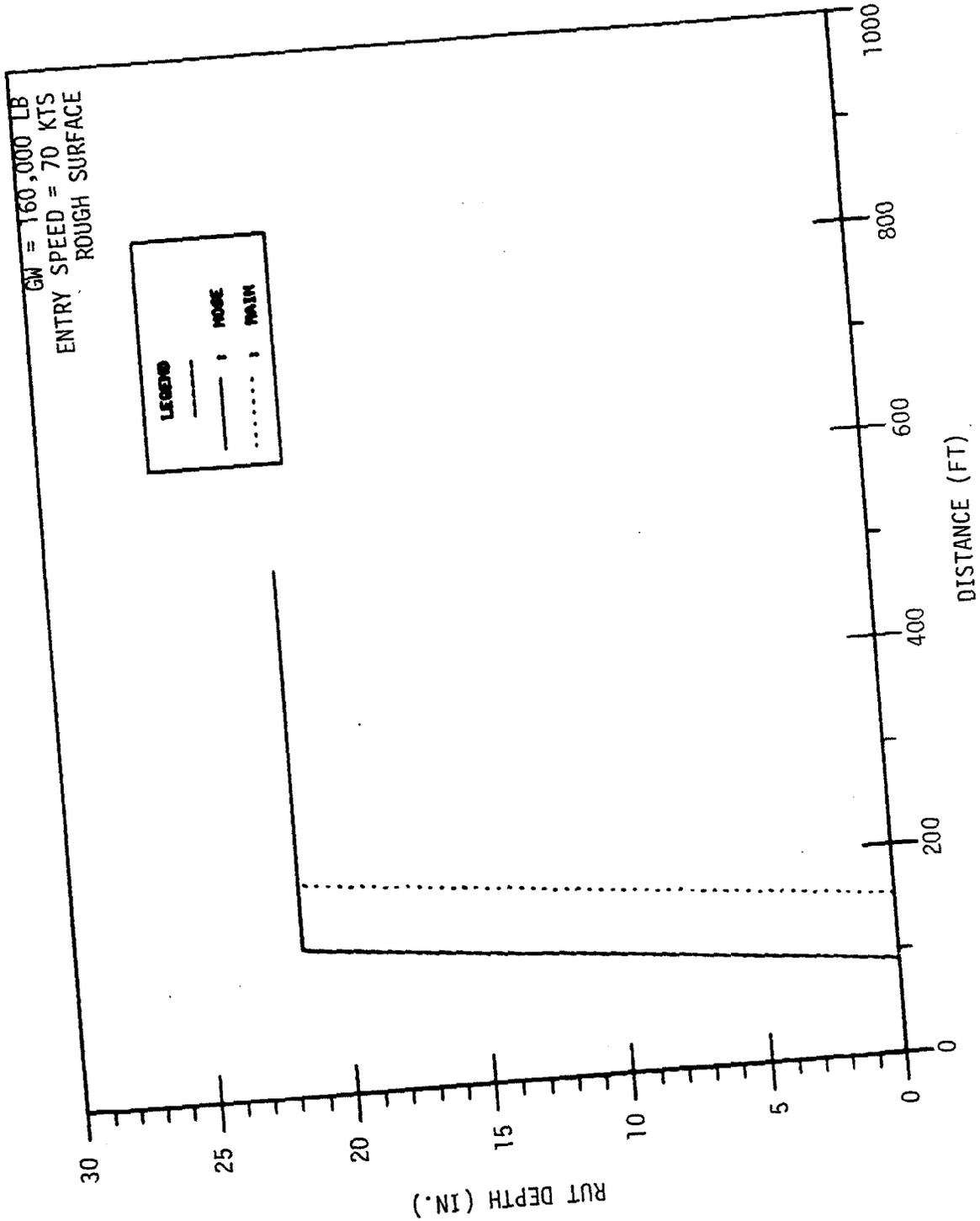


Figure 72. Aircraft A Rut Depth in Foam Bed

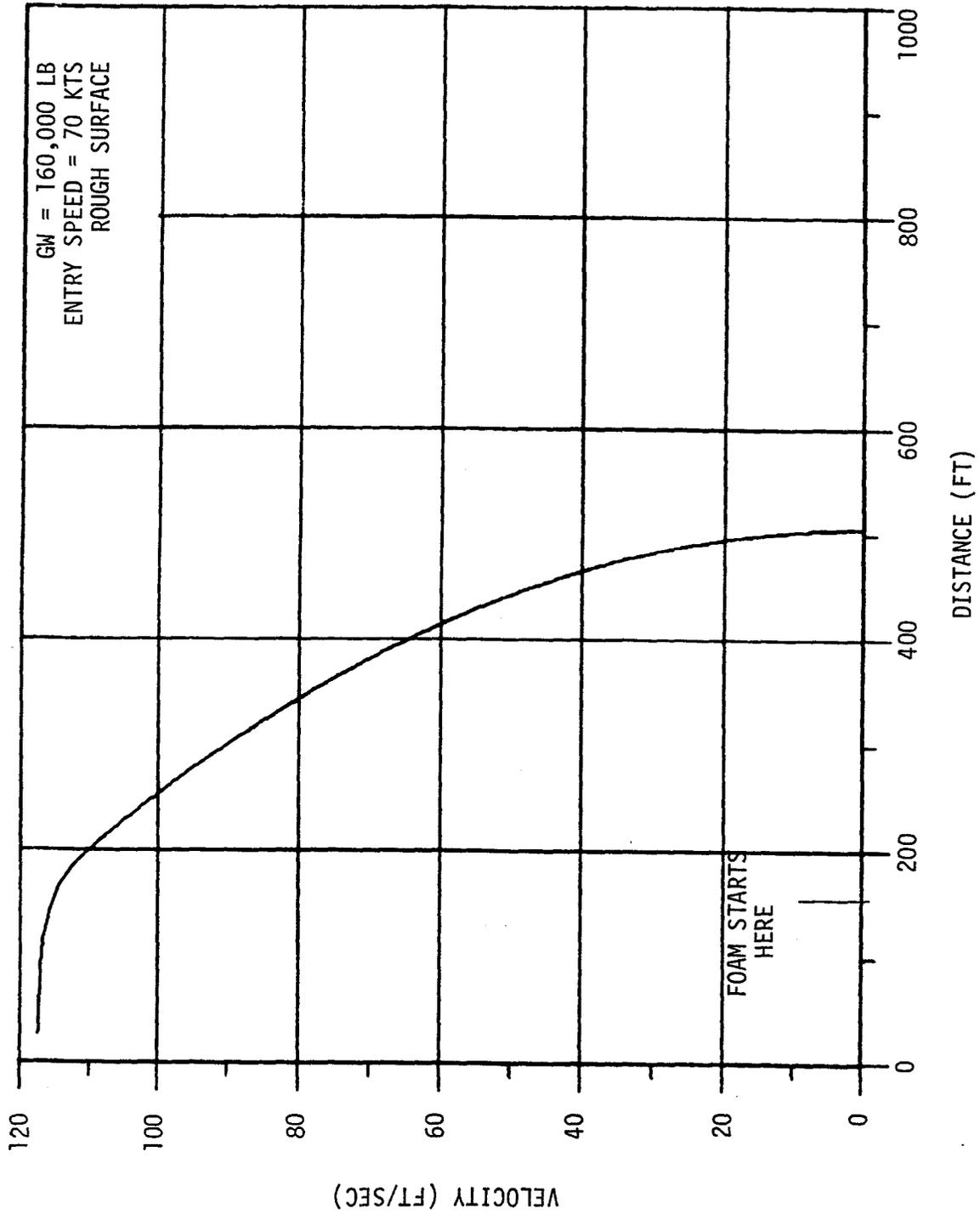


Figure 73. Aircraft A Velocity Profile During a Foam Bed Arrestment

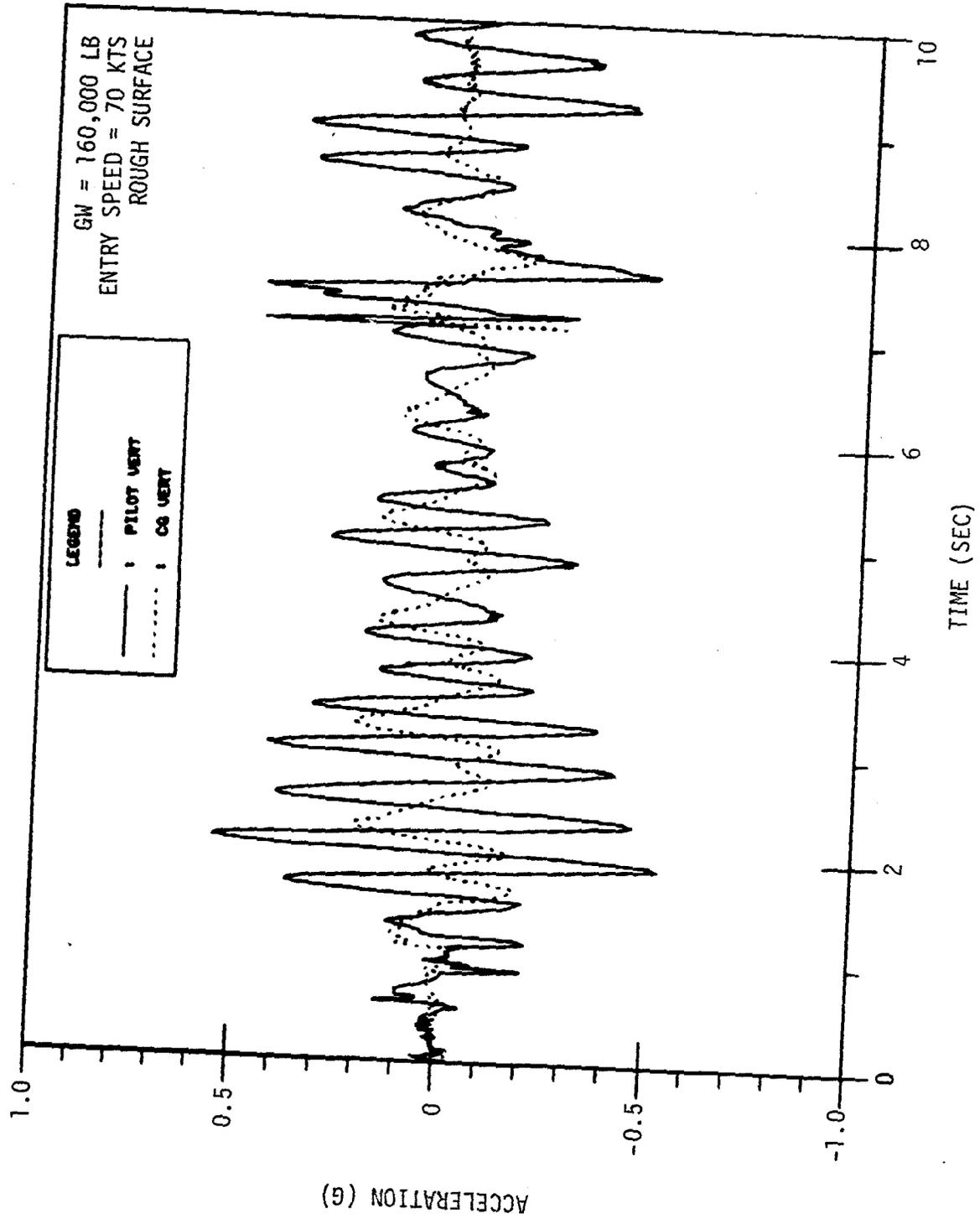


Figure 74. Aircraft A Dynamic Response During a Foam Bed Arrestment

3.5.1 Arrestor vs Extended Runway

The addition of 1,000 feet of runway surface certainly would provide a sufficient distance for a safe stop for some aircraft under normal runway conditions or aircraft speeds. It is relatively easy to determine the amount of deceleration required to stop an aircraft in a specific distance for a given initial velocity. Figure 75 is a plot showing deceleration versus stopping distance for various velocities. This plot shows that a deceleration of at least 0.11 g must be maintained for speeds greater than 50 knots if the aircraft is to stop in 1,000 feet. For an airplane weighing 160,000 pounds, the main gear would support about 144,000 pounds requiring a surface coefficient of friction, $\mu = 0.12$. For ice or snow covered runways or very wet runways, this coefficient of friction cannot be achieved and a distance greater than 1,000 feet would be required to stop the aircraft. Since the scenarios from the literature review (Appendix A) indicated that most overruns occurred under these types of conditions, an arrestor appears to be necessary for assured safe stopping of aircraft.

3.5.2 Arrestor Efficiency

From the analysis conducted earlier in this section, the nose gear of the smaller aircraft approached limit drag values while the main gear were taxed to a much lesser degree. To be efficient, the arrestor should have loaded both the nose and main gear to near limit values. The reason this cannot occur, of course, is the fact that the nose gear on most aircraft are not designed for braking like the main gear. Figure 76 shows a comparison of the expected loads in the foam arrestor and limit loads for all simulated aircraft.

Another factor concerning the efficiency is that a bed 150 to 200 feet wide by about 800 feet long and 2 feet high is required when the total wheel track volume in the arrestor during an incident is only a small portion that total volume. This large arrestor bed area is required because the aircraft may not stay on the centerline of the

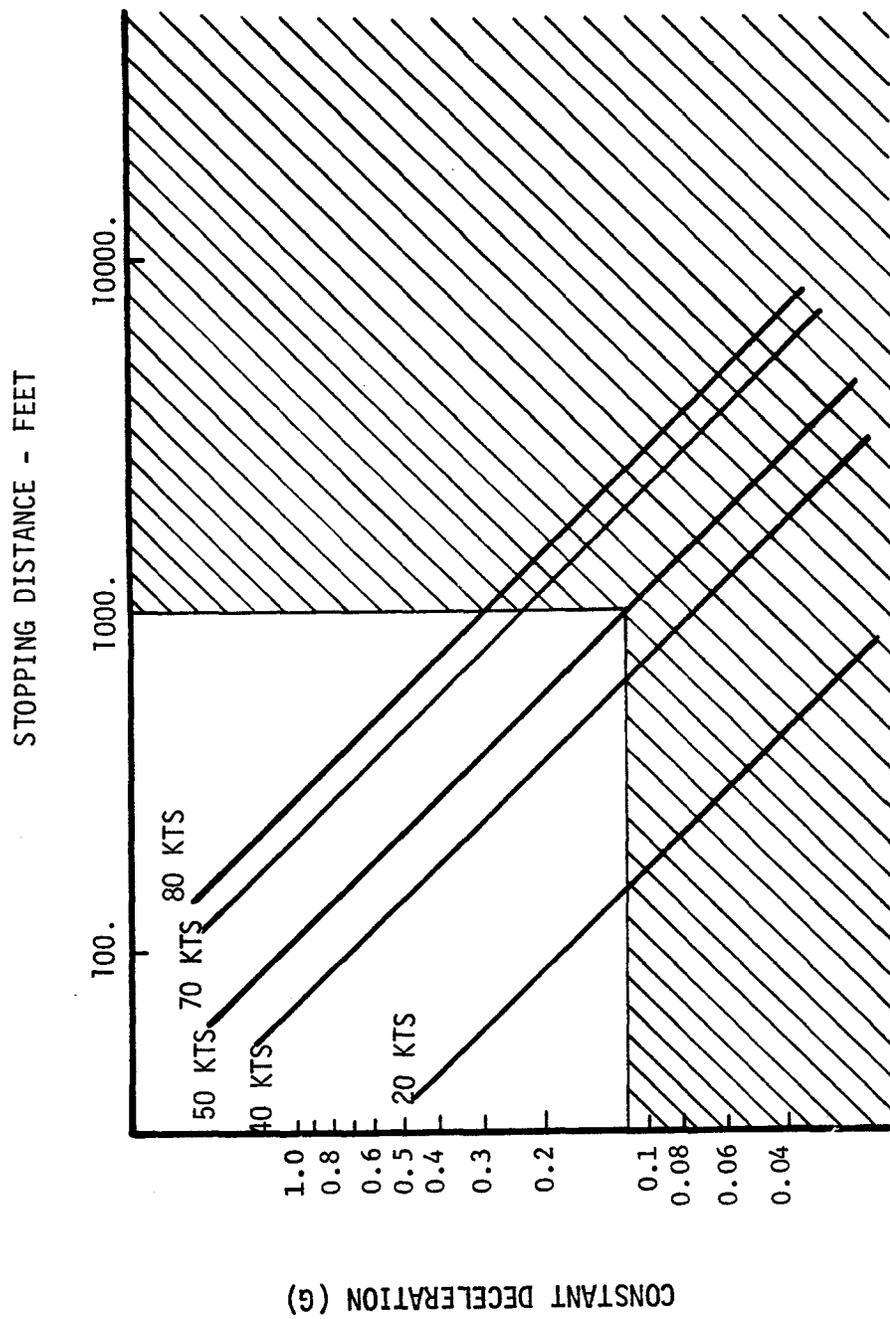
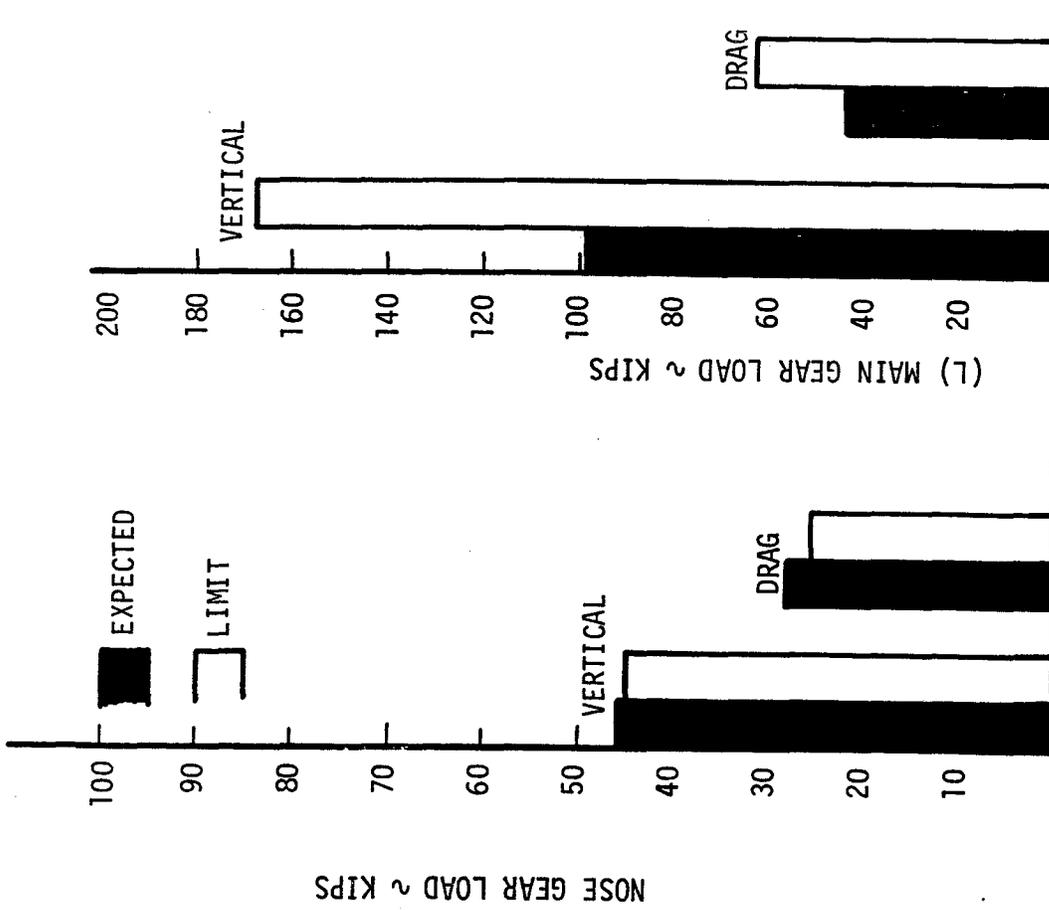


Figure 75. Chart For Determining Stopping Distances

AIRCRAFT A
 GW = 160,000 LB
 ENTRY SPEED = 70 KTS



AIRCRAFT B
 GW = 114,000 LB
 ENTRY SPEED = 70 KTS

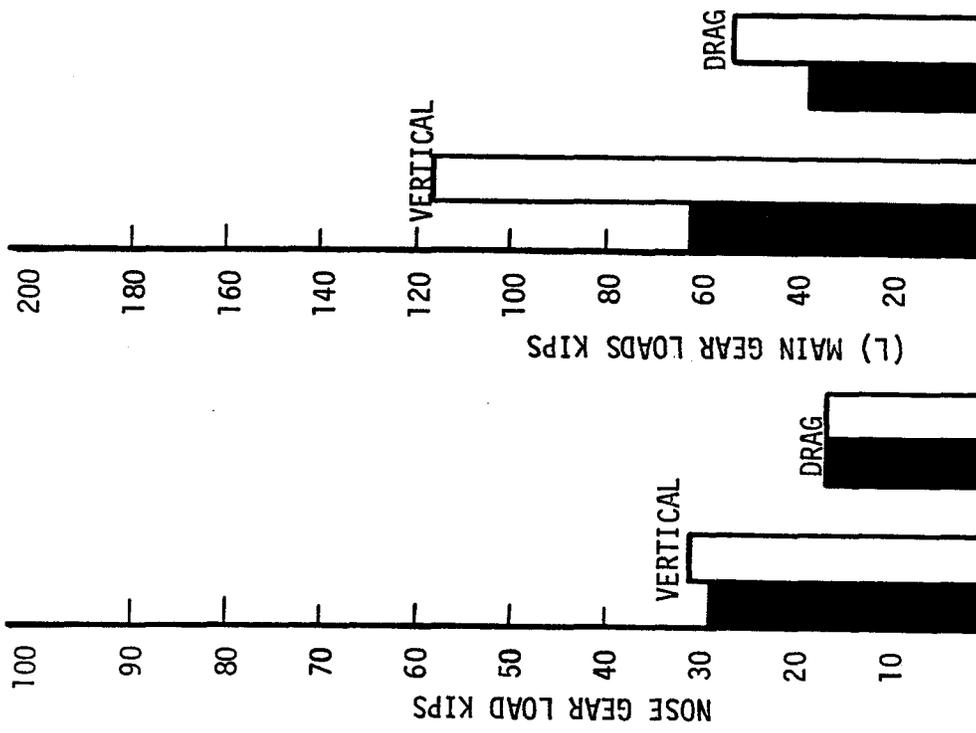
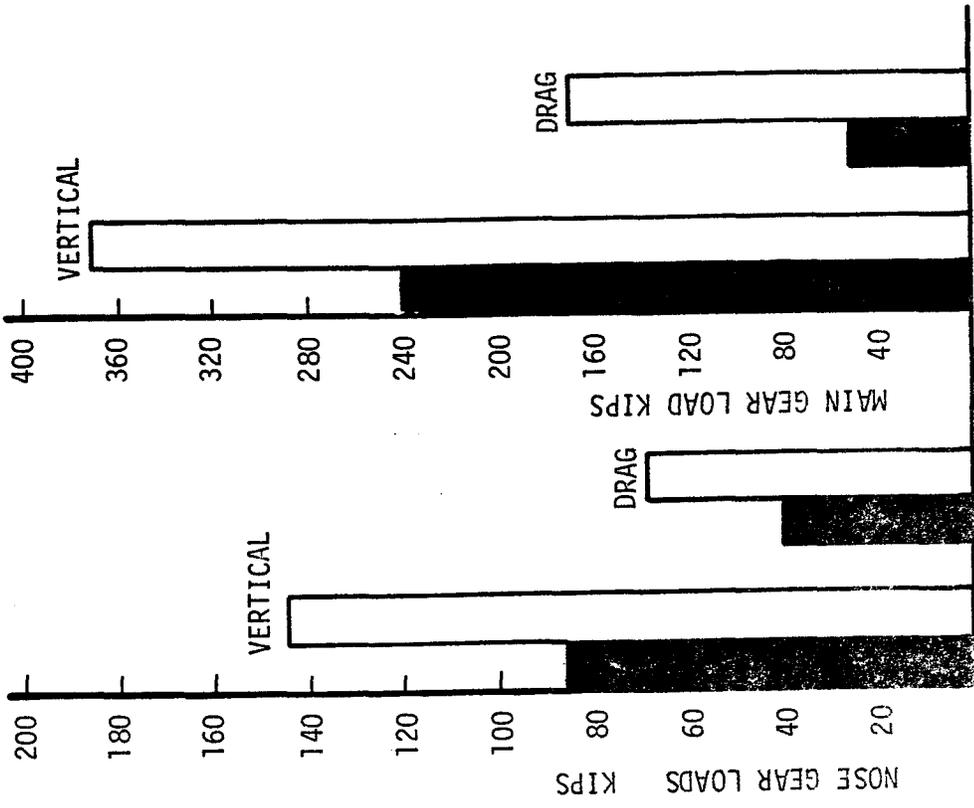


Figure 76. Comparison of Expected Load and Limit Loads While in a Foam Arrestor

AIRCRAFT D
 GM = 455,000 LB
 ENTRY SPEED = 70 KTS



AIRCRAFT C
 GM = 335,000 LB
 ENTRY SPEED = 70 KTS

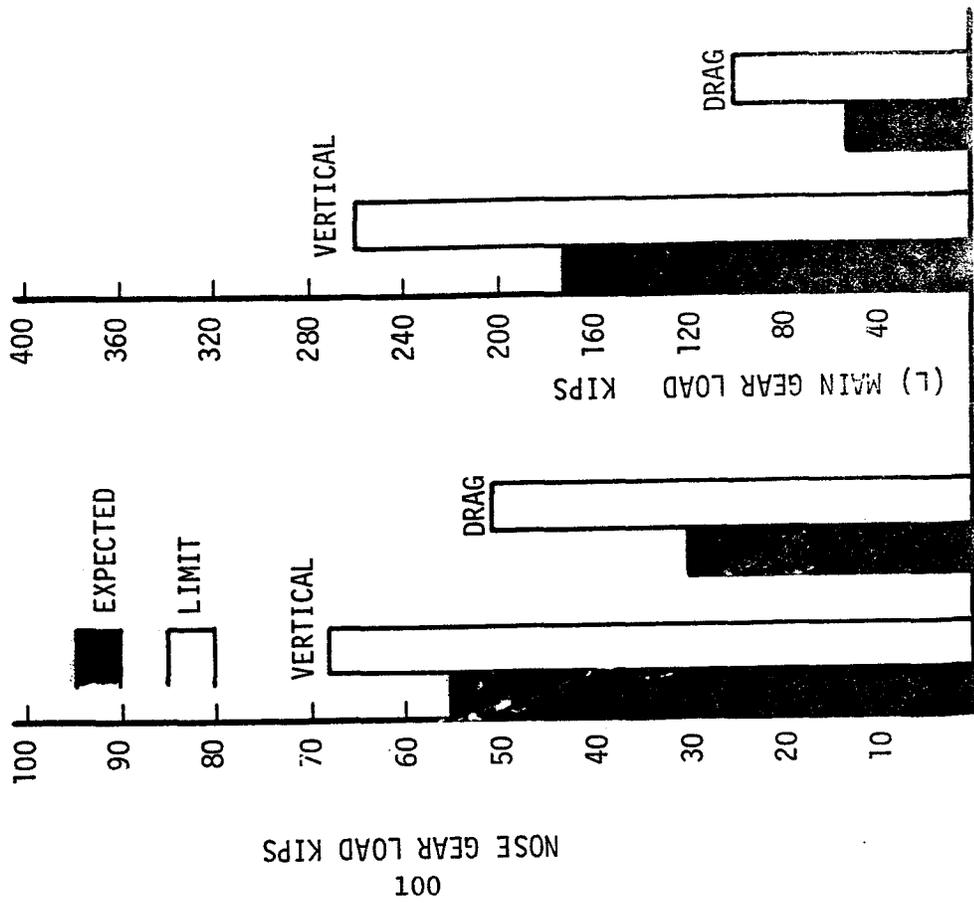


Figure 76. (Continued)

runway during an overrun incident. Table 1 shows the wheel rut volume required for each aircraft to come to a complete stop as well as the percent of the total bed volume used.

TABLE 1
COMPARISON OF RUT VOLUME WITH
ARRESTOR TOTAL VOLUME

| AIRCRAFT | NOSE RUT LENGTH (FT) | NOSE RUT WIDTH* (FT) | MAIN RUT LENGTH (FT) | MAIN RUT WIDTH* (FT) | TOTAL VOLUME OF RUTS** (FT) ³ | % OF TOTAL BED VOLUME (240000FT ³) |
|----------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|---|---|
| A | 370 | 2.5 | 310 | 6.7 | 6004 | 2.5 |
| B | 350 | 1.5 | 300 | 6. | 4650 | 1.9 |
| C | 590 | 3. | 530 | 8.0 | 12020 | 5.0 |
| D | 725 | 3.2 | 660 | 8.4 | 15728 | 6.5 |
| E | 660 | 4. | 575 | 16. | 23680 | 9.8 |

*Space Between Dual Wheels Was Estimated.

**Assume 2 Feet Deep Overall Entry Speed 70 Knots.

The above inefficiencies in the arrestor bed could be overcome by more complex arrangements which would allow the main gear to pick up additional drag loads. For example, a cable might be picked up by the main gear and this cable attached to drag device. The type of system would improve the system efficiency and would certainly shorten the aircraft stopping distance. Studies of such alternate types of arrestors were beyond the scope of this study but they should be considered in the overall feasibility studies.

3.6 SUMMARY OF RESULTS

In general, it was found that aircraft can be safely stopped in less than 1,000 feet for overruns with initial velocities of 70 knots or less using foam or gravel arrestor beds. Table 2 shows the distances traveled in the foam and gravel arrestor beds for the five aircraft simulated. This distance does not include any safety area distance traveled prior to making contact with the arrestor. This latter distance must be added to the figures in Table 2. These results show foam arrestor bed to be the most efficient system.

TABLE 2
DISTANCE TRAVELED BY AIRCRAFT DURING ARRESTMENT

| AIRCRAFT | GRAVEL BED (FT) | FOAM BED (FT) |
|----------|--------------------|------------------|
| A | 475 | 310 |
| B | 440 | 300 |
| C | 600 | 530 |
| D | 675 | 660 |
| E | 560 | 575 |

Aircraft landing gear loads were, in most cases, less than limit loads and certainly below ultimate loads so that landing gear collapse should not occur as a result of contact with the foam or gravel arrestors. The nose gear was always the more critical component. This lack of structural failure greatly reduces the risk of a fuel tank rupture and potential for a fire.

Foam bed repair in the event of an incident will only affect about 10 percent or less of the total volume of the arrestor bed. Gravel bed repair will probably be limited to regrading to the proper slope.

Foam and gravel bed installations require a rigid base to assure that gear loads are not exceeded due to sinkage (or ruts) in the extended runway surface. The foam arrestor bed must be firmly attached to the base to prevent damage due to high winds or jet exhaust. The gravel beds may require protection from jet exhaust if the velocities are too high.

The foam and gravel arrestor beds should be at least as wide as the runway to assure aircraft capture for off-center entries. Satisfactory arrestments for aircraft being ± 50 feet from the runway centerline are considered to be within the scope of this study although only centerline engagements were analyzed.

SECTION 4
CONCLUSIONS AND RECOMMENDATIONS

4.1 CONCLUSIONS

1. Both foam and gravel materials are viable candidates for aircraft overrun arrestors. Both materials have the potential to safely stop aircraft over a broad gross weight range, in less than 1,000 feet for entry speeds of 70 knots or less. A soft-ground aircraft arrestment system is considered feasible.

2. Wheel/foam and wheel/gravel analytical models need to be verified by experimental testing.

3. Analysis of rescue/fire/crash vehicle mobility on the arrestor material is required. Reference 4 indicates adequate mobility on gravel, and Reference 5 indicates adequate mobility on foam.

4. Other foam arrestor bed configurations and foam crushing strengths should be examined to determine a more near optimum gear load distribution for all aircraft. Contact of other parts of aircraft components should be more thoroughly examined to assure that they are not compromised by the arrestor.

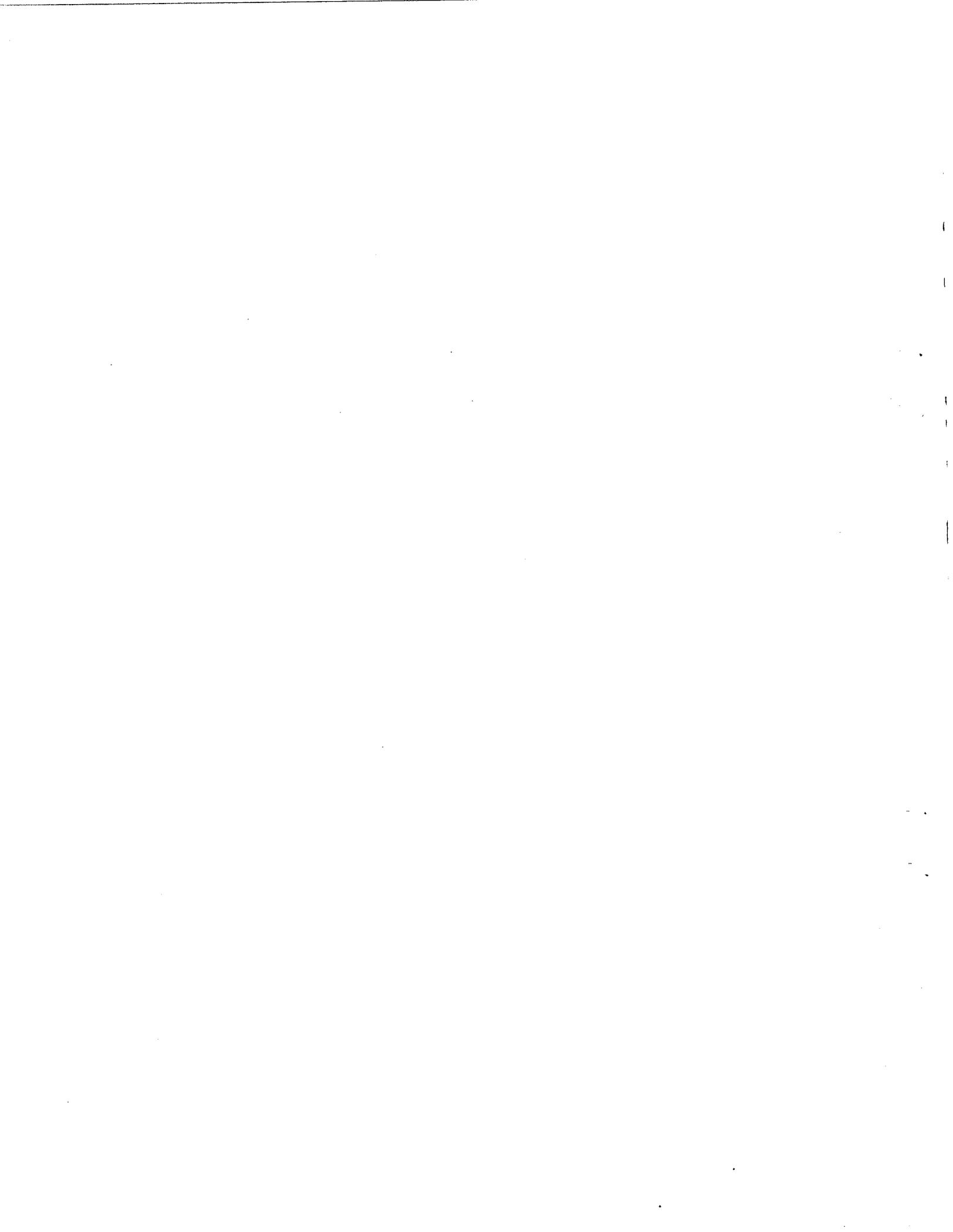
5. The gravel bed configuration requires closer scrutiny to assure aircraft components other than the landing gear are clear at the distance the aircraft penetrates into the bed. Other gravel bed configurations are certainly possible and may be desirable. FOD may be a problem for gravel arrestors.

4.2 RECOMMENDATIONS

Conduct an experimental program to verify the analytical wheel/foam and wheel/gravel models. Appendix D describes a plan to validate both the foam and gravel arrestor prediction methods. Full scale aircraft arrestment tests are also recommended and they are briefly described at the end of Appendix D.

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2. Phillips, N.S., Cook, R.F., Aircraft Operation on Soil Surfaces - Computer Routine Revisions and Improvement," Volume I, ESL-TR- 82-29, March 1984.
3. Thompson, W.C., "Investigation of Water-Pond Arresting of a Dynamic Model of a Jet Transport," NASA-TN-D-732, December 1960.
4. Bade, E., "Soft-Ground Arresting of Civil Aircraft," Royal Aircraft Establishment Technical Report 68032, February 1968.
5. Gwynne, G.M., "Aircraft Arresting Using Foamed Plastic Overrun Areas," Royal Aircraft Establishment NAD Note No. 282, March 1971.
6. ASTM D 448-86, "Standard Classification for Sizes of Aggregate for Road and Bridge Construction."
7. Gerardi, A.G., "Collection of Commercial Aircraft Characteristics for Study of Runway Roughness," FAA-RD-76-64, May 1977.



APPENDIX A

LITERATURE REVIEW OF SOFT-GROUND AIRCRAFT ARRESTMENT SYSTEMS AND REVIEW OF AIRCRAFT OVERRUN ACCIDENTS

INTRODUCTION

The reports provided by the FAA Project Engineer concerning soft-ground aircraft arrestment systems were reviewed to determine if they contain data useful for this program. The program requires that the dynamic gear loads and deceleration be determined for various weight classes of aircraft while operating in the overrun material. The computer simulation includes modeling of the landing-gear tire/soft ground material interface and, therefore, very specific information was needed. It was not expected that this specific type of data would be found, nor was it found. However, very useful information was found in terms of basic supporting strengths of materials, stopping distances of aircraft, advantages and disadvantages of materials, plus many others. The report review was considered quite useful in supporting this program.

The accident computer printouts were reviewed and summarized.

DISCUSSION

The primary materials used for overrun arrestment systems were gravel and urea formaldehyde foam. Water ponds were also tested as a source for arrestment. Soft clay, tilled, was also considered as an arrestment material and has been demonstrated in several actual aircraft overruns. However, from the report review it was determined that the inconsistency of natural material properties sometimes led to loss of aircraft through gear failure. It appears that a material with consistent properties that will yield predictable aircraft stopping distances without damage to the landing gear or aircraft would be required. It was also mentioned that the use of auxiliary equipment, tail hooks for example, should not be required for the aircraft.

From the literature review, it was concluded that the use of soft materials was attractive as decelerators, but that much work in terms of quantifying the aircraft deceleration resulting from operation in the material was required.

Brief summaries of the reports and the accident data are provided in the following pages.

SUMMARY OF OVERRUN ACCIDENTS

| Aircraft/ Weight | Date | T.O./ Land | Runway Condition | Comments |
|------------------------|----------|---------------|---------------------|--|
| DC-8-71 200,000 lb | 07/20/83 | Landing | Wet | Overrun, #5114 Chicago O'Hare; no injury A/C damage: none |
| DC-10-30 365,000 lb | 01/23/82 | Landing | Fog/Ice | Overrun, #3853 Boston-Logan Fatal + injuries A/C destroyed |
| DC-10-10 410,000 lb | 02/03/82 | T.O. | Wet | Overrun, #1334 Philadelphia Intl.; Injury A/C damage: minor |
| B737-2H4 110,000 lb | 02/15/82 | Landing | Unk | Overrun, #5026 LA Intl., no injury A/C damage: none |
| B727-200 191,000 lb | 02/19/82 | Landing | Wet | Overrun, #5069 Harlingen, TX, no injury A/C damage: none |
| DC-9-30 109,000 lb | 02/18/82 | Landing | Ice | Overrun, #5085 Pellston, MI; no injury A/C damage: none |
| DC-9 Unk | 03/17/80 | Landing | Wet | Overrun, #1-0015 Baton Rouge, LA; Injury A/C damage: substantial |
| A/C 111 Unk | 07/09/78 | Landing | Unk | Overrun, #1-0010 Rochester, NY; Injury |

SUMMARY OF OVERRUN ACCIDENTS (cont'd)

| Aircraft/ Weight | Date | T.O./ Land | Runway Condition | Comments |
|---------------------|----------|---------------|---------------------|---|
| B727 Unk | 04/05/76 | Landing | Fog/Snow | Overrun, #1-0003 Ketchikan, AK; Injuries, A/C destroyed |
| B727 Unk | 04/27/76 | Landing | Dry | Overrun, #1-0005 St. Thomas, VI; Fatal + injuries |
| B747 Unk | 05/06/76 | Landing | Unk | Overrun, #1-0006 Chicago, IL; no injury A/C damage: substantial |
| L188 Unk | 03/12/76 | Landing | Unk | Overrun, #1-0025 Udrivik, AK; No injury A/C destroyed |
| B737 Unk | 03/31/75 | Landing | Snow | Overrun, #1-0001 Casper, WY; Injury A/C damage: substantial |
| FH-227 Unk | 06/13/75 | Landing | Wet | Overrun, #1-0014 New Bedford, MA; no injury A/C damage: substantial |

REPORT: Advisory Group for Aeronautical Research and Development
Report 226, October 1958

TITLE: Emergency Stopping of Aircraft Which Overrun Airfield Runways

AUTHOR: S. Thomlinson

Various mechanical methods of stopping aircraft are discussed: Systems such as nylon barriers, drag chains, hydraulic rams, etc.

Soft ground arrestment is discussed but not in quantitative terms.

APPLICATION TO PRESENT STUDY: Many of the mechanical systems have potential for application should the interest arise. The water squeezer, for example, appears attractive as well as the drag chain. By causing arresting wire engagement at several points along the overrun, various aircraft weights could be accommodated. All of the above are basically passive and would be activated at the point of overrun by the nose gear. (No help for tail sitters.)

REPORT: Boeing 727-737 Operation from Unimproved Airfields,
D6-42025R7, May 1984

AUTHOR: Anon

Brochure presents information concerning the operation of aircraft on gravel and other unimproved runways. Overruns not discussed.

APPLICATION TO CURRENT EFFORT: None.

REPORT: NASA TN D-732 December 23, 1960

TITLE: Investigation of Water Pond Arresting of a Dynamic Model of
a Jet Transport

AUTHOR: William C. Thompson

Report describes model aircraft entering a water pond arrestor system. The pond was both covered with a plastic film and uncovered. High decelerations were obtained upon entry to the pond until the depth of water was reduced by programmed bottom slope. Reasonable decelerations obtained.

APPLICATION TO PRESENT STUDY: Water ponds have potential in areas not subject to sustained freezing water. Cost of pond installation is likely to be high. Attraction to birds, frogs, etc.

REPORT: Royal Aircraft Establishment TR 74002, February 1974

TITLE: Urea Formaldehyde Foamed Plastic Emergency Arresters for Civil Aircraft

AUTHOR: G. M. Gwynne

Report describes tests of Comet 3B in urea formaldehyde foam arrestor beds. Foam beds had tapered entrance 1:12.5 with light density foam over heavy density foam. Demonstrated removal of aircraft from foam bed and traffic of rescue vehicle.

APPLICATION TO PRESENT STUDY: Develop "soil model" for second pass to include effects of bogey gear.

REPORT: Royal Aircraft Establishment TR 71015, February 1971;
TR 71231, November 1971

TITLE: (TR 71015) Soft Ground Arresting of Civil Aircraft:
(TR 71231) Development of a Model Technique for Investigating the Performance of Soft Ground Arresters for Aircraft

AUTHORS: E. Bade; J. Barnes

Both reports investigated modeling techniques for testing gravel arrestors.

APPLICATION TO PRESENT STUDY: These reports did not contain information of use for the present study.

REPORT: Royal Aircraft Establishment TR 69001, January 1969

TITLE: Soft Ground Arresting of Civil Aircraft--Influence of Gravel Depth and Tire Inflation Pressure

AUTHOR: E. Bade

Experimental tests were conducted using the British Lightning aircraft on gravel test beds to determine the effect of gravel bed depth and aircraft tire pressure on aircraft deceleration. Gravel bed depth of 18 inches increased the deceleration over that in a 12-inch deep bed. A 30-inch deep bed showed no significant increase in deceleration. Reduced tire pressure reduced the deceleration.

APPLICATION TO PRESENT STUDY: Determine that test bed materials are sufficiently deep to ensure boundary effects are minimal.

REPORT: Royal Aircraft Establishment TR 68032, February 1968

TITLE: Soft Ground Arresting of Civil Aircraft

AUTHOR: E. Bade

Investigations were made into the use of aerated concrete and gravel as materials for stopping overrunning aircraft. The aerated concrete was compression tested but the crushing load varied considerably. Gravel samples of 3/4 to 1/4 inch in size were compression tested and the results indicated crushing strengths of about 13 to 30 psi. When frozen the crushing strength increased tenfold; however, this was limited to a small thickness of about 3 inches in overnight soak. Vehicle testing was conducted showing significant decelerations could be obtained. No trajectory problems were encountered but pitching of the aircraft was induced when the main gear entered the gravel bed. Gravel beds are subject to jet blast and aircraft jet exhaust should be at least 100 feet from bed.

APPLICATION TO PRESENT STUDY: Gravel material has similar characteristics to sand and may produce similar deceleration results.

REPORT: Royal Aircraft Establishment, Bedford Naval Air Department
NAD Note 282, March 1971

TITLE: Aircraft Arresting Using Foamed Plastic Overrun Areas

AUTHOR: G. M. Gwynne

Report shows that 50 psi foam (crushing strength) is adequate to support most aircraft at a depth equal to the tire radius. The usable foam depth is about 80 percent of its initial value. Discussion of using soft foam layer over hard layer to accommodate all weights of aircraft. Conclusions indicate foam material would probably not be suitable for all aircraft.

APPLICATION TO PRESENT STUDY: No new information.

REPORT: Royal Aircraft Establishment Tech Memo Naval 213, April 1970

TITLE: Preliminary Feasibility Study of the Arresting of Aircraft in a Foamed Plastic Overrun Area

AUTHOR: T. G. Randall

The use of urea formaldehyde foam in an overrun area is considered. Report concluded that the system is feasible technically.

Content of Interest: Urea formaldehyde foam absorbs water. Material is noncombustible. Material crushed elastically to about 50 psi and then crushes at a uniform stress to about 30 percent of initial thickness, then becomes much stiffer. Wheel load is supported by uplift equal to one-half the footprint length times cross-section of tire times the foam crushing strength. Drag force is obtained by assuming that the crushing stress is applied to the vertical projection area of contact times the tire width. The actual drag force is found by adjusting the upthrust until it matches the wheel loading. This then determines the depth that the wheel will sink into the foam. Experimental tests were conducted using a dummy F-4C aircraft to traverse foam beds at tow, 60, and 100 knot speeds. The foam produced decelerations of about 0.2 g in 11-inch deep foam beds.

APPLICATION TO PRESENT STUDY: Report contains methods for predicting static forces (drag and vertical loads) from foam material. No technical foam characteristics were provided for application to FITER computer program.

REPORT: Wright Air Development Division, WADD Tech Note 60-167, September 1960

TITLE: Open Water Pond Concept for Arresting Large Jet Aircraft

AUTHOR: J. C. Welch, Capt., USAF

This report describes the methods of analysis for determining the distance to stop aircraft by a water pond. The water drag on the landing gear is computed using incompressible flow characteristics for lift and drag. The lift is used to determine wheel planing and drag provides the deceleration force.

APPLICATION TO PRESENT STUDY: Provide analysis methods as well as useful comments for water pond decelerators.

REPORT: Advisory Group for Aeronautical Research and Development Report 413, January 1963

TITLE: The Problems of Designing for the Takeoff and Landing of High Speed Aircraft

Report discusses various arrestor gear such as brake parachute, arrestor gear (Navy), and thrust reversers. Wing loading and other aerodynamic performance parameters are discussed in connection with takeoff and landing performance.

APPLICATION TO CURRENT STUDY: none

REPORT: FAA Report No. RD-65-4, January 1965

TITLE: A Study of Arresting Gear

AUTHOR: M. G. Beard

Report discusses the potential cost savings of using arresting gear to prevent overruns. This information was used to forecast future overruns and their potential costs.

APPLICATION TO PRESENT STUDY: None other than demonstrating the need for an arrestment system.

REPORT: JFK1A-Runways 4R-22L Safety Overrun Study, August 4, 1985

TITLE: A Study of Arresting Gear

AUTHOR: W. B. Horne

The report considered several materials for an overrun at JFK1A. The recommended short term solution was a gravel, sand and gravel, and water overrun area. Long term solution suggested looking at foam materials.

APPLICATION TO PRESENT STUDY: Provided good background information for climatic conditions, review of overrun materials. Data specific to the material for modeling purposes were not given.



APPENDIX B
AIRCRAFT SIMULATION DATA

The primary data for the geometry, tire curves, and landing gear strut information for Aircraft A through E were taken from Reference 7. The weights and gear limit loads for Aircraft A through D and listed in this appendix were obtained from the aircraft manufacturers.

AIRCRAFT DATA

AIRCRAFT A

- o Tire Pressure (Note: if tires are serviced at different pressures for various gross weights, please indicate)
Nose 95 to 105 MAX. (psig) 32 x 11.5 - 15, 12 PLY TIRES
Main 167 to 173 MAX. (psig) 50 x 21 - 20, 30 PLY TIRES
- o Maximum T.O. Weight 209,500 (lb)
- o Moment of Pitch Inertia I_{yy} 61.224×10^6 (lb sec² in.)
- o CG Fuselage Station 766.3", Main Gear Strut Fuselage Station 819.9", Nose Gear Strut Fuselage Station 60.9 (in.)
DISTANCES FROM NOSE
- o Maximum Landing Weight 161,000 (lb)
- o Moment of Pitch Inertia I_{yy} 62.748×10^6 (lb sec² in.)
- o CG Fuselage Station 746.4" from nose
- o Limit Drag and Vertical Load envelope for nose and main gear (include side load effect if possible)

$$DNG = 25.6 \times 10^3 \text{ LB (LIMIT),}$$

$$VNG = 44.4 \times 10^3 \text{ LB (LIMIT),}$$

$$SNG = 15.87 \times 10^3 \text{ LB (LIMIT)}$$

$$DMG = 69.47 \times 10^3 \text{ LB (LIMIT),}$$

$$VMG = 195.2 \times 10^3 \text{ LB (LIMIT),}$$

$$SMG = 76.33 \times 10^3 \text{ LB (LIMIT)}$$

AIRCRAFT DATA

AIRCRAFT B

Aircraft Dimensions

- o Wheelbase 56.1 (ft)
- o Overall Length 125.6 (ft)

Tire Inflation Pressures

- o Nose Gear 148 (psig) max at 114,000 lb to 116 (psig) at 90,000 lb
- o Main Gear 160 (psig) max at 114,000 lb to 120 (psig) at 90,000 lb

Maximum Takeoff Weight 114,000 (lb)

- o Moment of Pitch Inertia 2.34×10^7 fwd CG; 2.75×10^7 aft CG (lb sec² in.)
- o C.G. Height Above Ground 99 (in.)
- o C.G. Fuselage Station 704 fwd CG; 739 aft CG (in.)
- o Main Gear Strut Fuselage Station 771.8 (in.)
- o Nose Gear Strut Fuselage Station 98.0 (in.)

Maximum Landing Weight 102,000 (lb)

- o Moment of Pitch Inertia 2.74×10^7 fwd CG; 2.36×10^7 aft CG (lb sec² in.)
- o C.G. Height Above Ground 99 (in.)
- o C.G. Fuselage Station 703 fwd CG; 750 aft CG (in.)

Limit Gear Loads

| <u>Gear</u> | <u>Vertical</u> | <u>Drag</u> | <u>Side</u> |
|-------------|-----------------|-------------|-------------|
| Main | 115,358 | 53,839 | 43,595 (lb) |
| Nose | 32,072 | 17,032 | 10,896 (lb) |

AIRCRAFT DATA

AIRCRAFT C

- o Tire Pressure (Note: if tires are serviced at different pressures for various gross weights, please indicate)
 - Nose 109 to 119 MAX. (psig) 39 x 13, 16 PLY TIRE
 - Main 189 to 199 MAX. (psig) 46 x 16, 28 and 30 PLY TIRES
- o Maximum T.O. Weight 335,000 (lb)
- o Moment of Pitch Inertia I_{yy} 76.39×10^6 (lb sec² in)
- o CG Fuselage Station 843.6", Main Gear Strut Fuselage Station 917.0", Nose Gear Strut Fuselage Station 209.0 (in) DISTANCES FROM NOSE
- o Maximum Landing Weight 247,500 (lb)
- o Moment of Pitch Inertia I_{yy} 74.5×10^6 (lb sec² in)
- o CG Fuselage Station 873.6" FROM NOSE.
- o Limit Drag and Vertical Load envelope for nose and main gear (include side load effect if possible)

$D_{NG} = 50.4 \times 10^3$ LB (LIMIT),

$V_{NG} = 68.2 \times 10^3$ LB (LIMIT),

$S_{NG} = 27.5 \times 10^3$ LB (LIMIT)

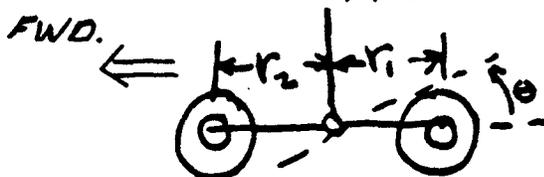
$D_{MG} = 102.67 \times 10^3$ LB (LIMIT),

$V_{MG} = 261.47 \times 10^3$ LB (LIMIT),

$S_{MG} = 114.8 \times 10^3$ LB (LIMIT)

Boeing 707-320C (Model Boeing 707-320C -- data available are for aircraft with wheelbase 59.0 ft, fuselage length 152.92 ft)

- o Same as above, plus:



Is θ limited to some maximum angle;
 if so, what is max angle 29° Total (deg)
 $+\theta = +16^{\circ}45'$ to $17^{\circ}45'$ max
 $-\theta = -9^{\circ}45'$ to $-11^{\circ}15'$ max

- o Main Gear Pitch Inertia 5.3×10^3 to 6.0×10^3 lb sec² in. (DEPENDS ON BRAKING EFFECTIVENESS)

- o r_1 28 in., r_2 28 in.

AIRCRAFT DATA

AIRCRAFT D

Aircraft Dimensions

- o Wheelbase 72.4 (ft)
- o Overall Length 170.5 (ft)

Tire Inflation Pressures

- o Nose Gear 165 (psig) max at 458,000 lb to 135 (psig) at 275,000 lb
- o Main Gear 190 (psig) max at 458,000 lb to 120 (psig) at 275,000 lb

Maximum Takeoff Weight 455,000 (lb)

- o Moment of Pitch Inertia $2.1 - 2.8 \times 10^8$ (lb sec² in.)
- o C.G. Height Above Ground 193 (in.)
- o C.G. Fuselage Station 1346.7 fwd CG; 1384.0 aft CG (in.)
- o Main Gear Strut Fuselage Station 1,442.0 (in.)
- o Nose Gear Strut Fuselage Station 573.4 (in.)

Maximum Landing Weight 363,500 (lb)

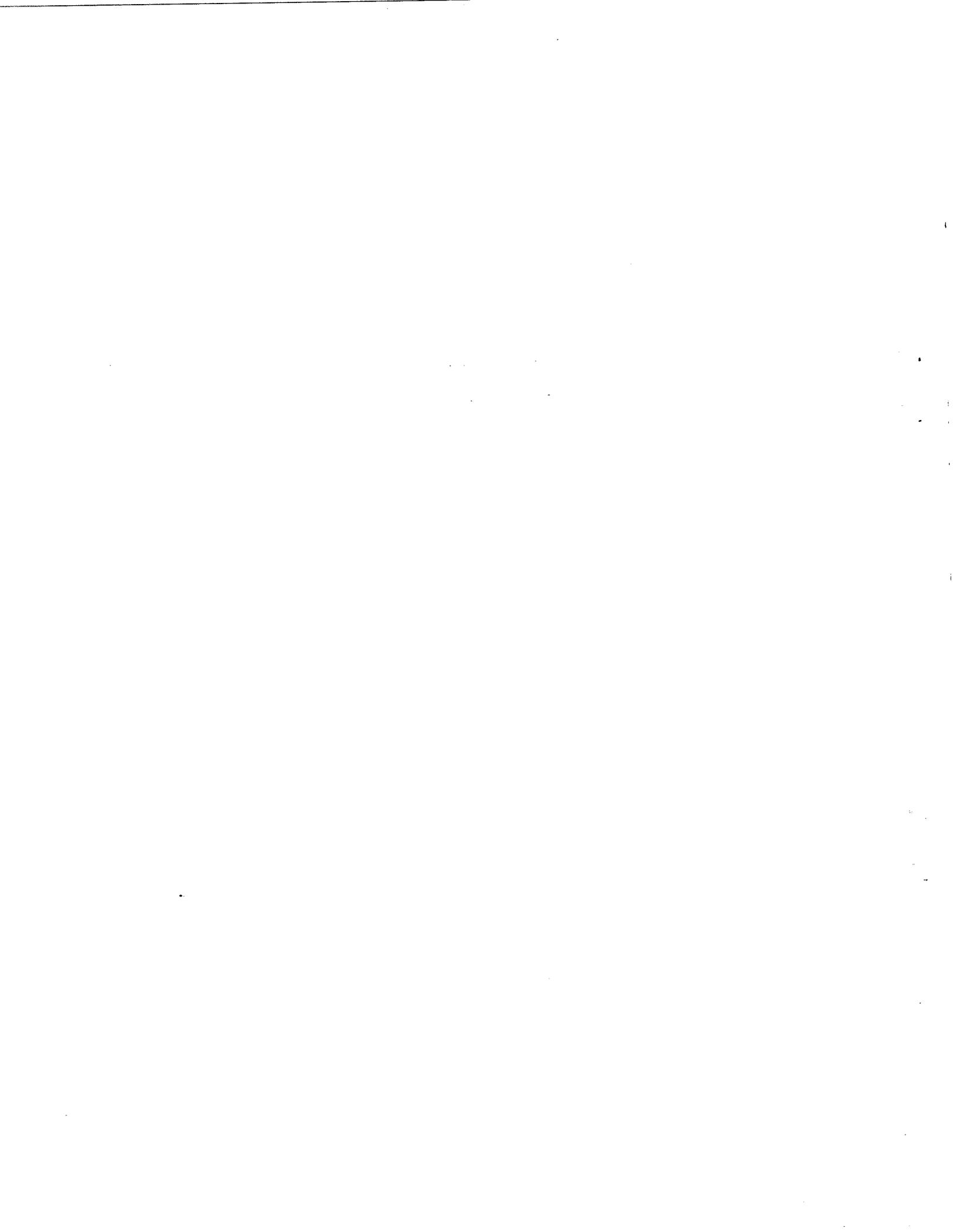
- o Moment of Pitch Inertia $1.3 - 2.3 \times 10^8$ (lb sec² in.)
- o C.G. Height Above Ground 193 (in.)
- o C.G. Fuselage Station 1341.9 fwd CG; 1392.4 aft CG (in.)

Limit Gear Loads

| <u>Gear</u> | <u>Vertical</u> | <u>Drag</u> |
|-------------|-----------------|-------------|
| Main | 374,700 | 171,750 |
| Nose | 143,900 | 68,700 |

Main Gear "Bogey" Data

- o Length: front axle to strut 32 (in); strut to rear axle 32 (in.)
- o Main Gear Pitch Inertia 1.2×10^4 (lb sec² in.)
- o Max Pitch Angle: fwd wheels up 16 (deg); rear wheels up 26 (deg)



APPENDIX C
LABORATORY TESTING OF FOAM AND GRAVEL

Compression tests of polystyrene foam and gravel were conducted in the Structures Laboratory of the University of Dayton to determine the crushing strength of these materials.

The foam tests were conducted using a MTS hydraulic test machine which was programmed to provide a displacement curve as shown in Figure C-1. The plate (see Figure 13, Section 2) was adjusted manually so that it was barely in contact with the sample before the displacement was activated. The load on the plate was measured by a load cell located just under the plate when the plate was displaced into the foam sample.

The above tests were conducted on five different types of polystyrene for eight different pulse time periods, and foam curves such as Figure C-1 were obtained. The foam characteristics of Figure C-2 were used in the analyses. The original of all data collected has been provided to the United States Air Force project engineer since the data were too voluminous to include in this report.

Attempts were made to use the spring and damper in series soil model (Reference 1) but this proved to be unsuccessful because the foam did not behave in the same manner as soil. It was found that the foam deflected linearly during the first 10 percent of the thickness but then it maintained a constant stress thereafter with positive displacement. This made the foam modeling much simpler and the model finally used is described in Section 2.

Similar tests also were conducted on graded gravel number 57 (Reference 6). The gravel was loaded into a large garbage can and the MTS machine plunger was inverted so that it traveled downward into the gravel. The pulse shape was triangular as shown in Figure C-3. For the long pulse times, the gravel indicated a fairly constant stress (about 26 psi) for about the first 0.4 inch and then began to rise. This crushing stress agreed reasonably well with the British results

SM P1 #16

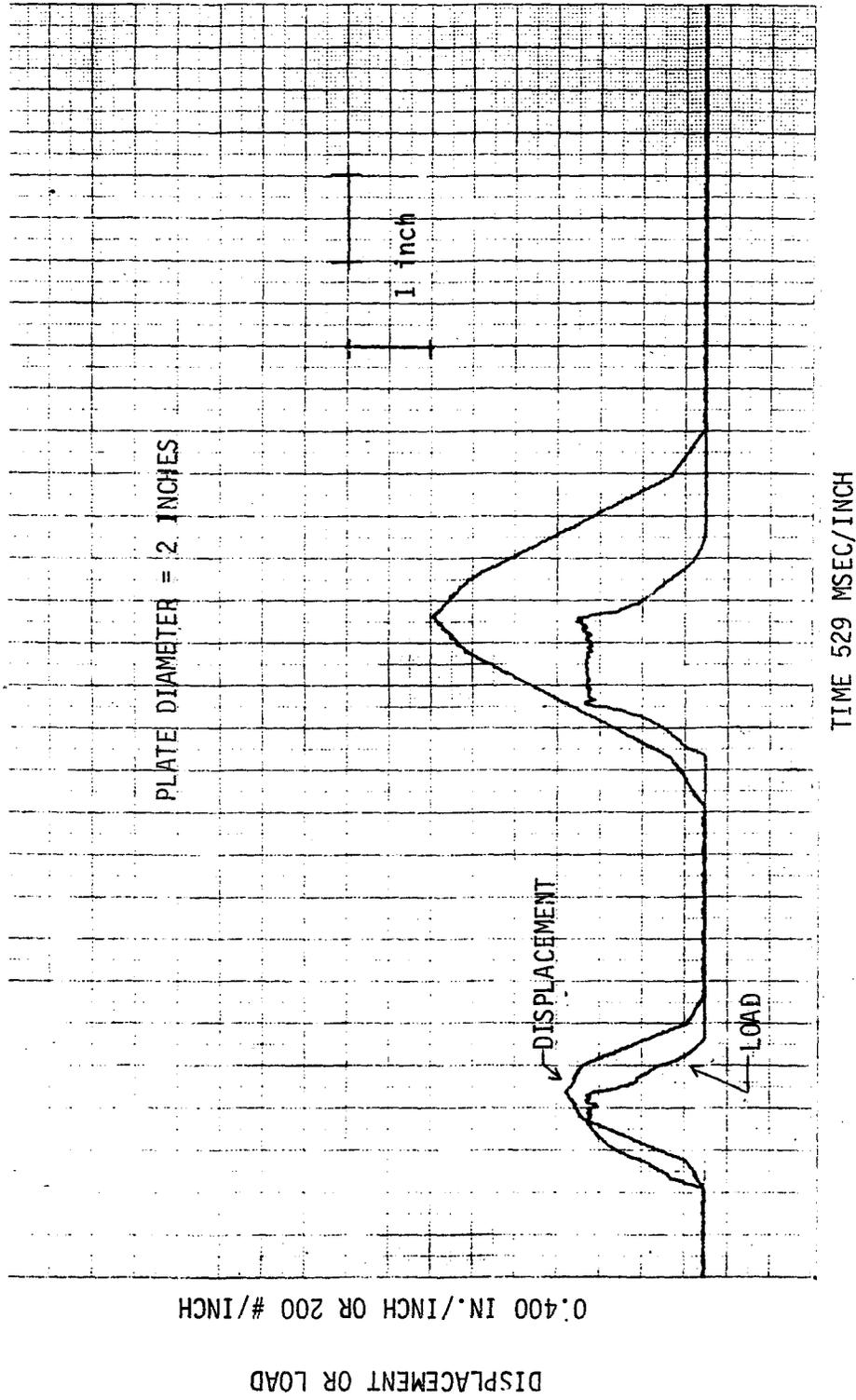


Figure C-1. Record From Compression Test of a Polystyrene Foam Sample Designated SM

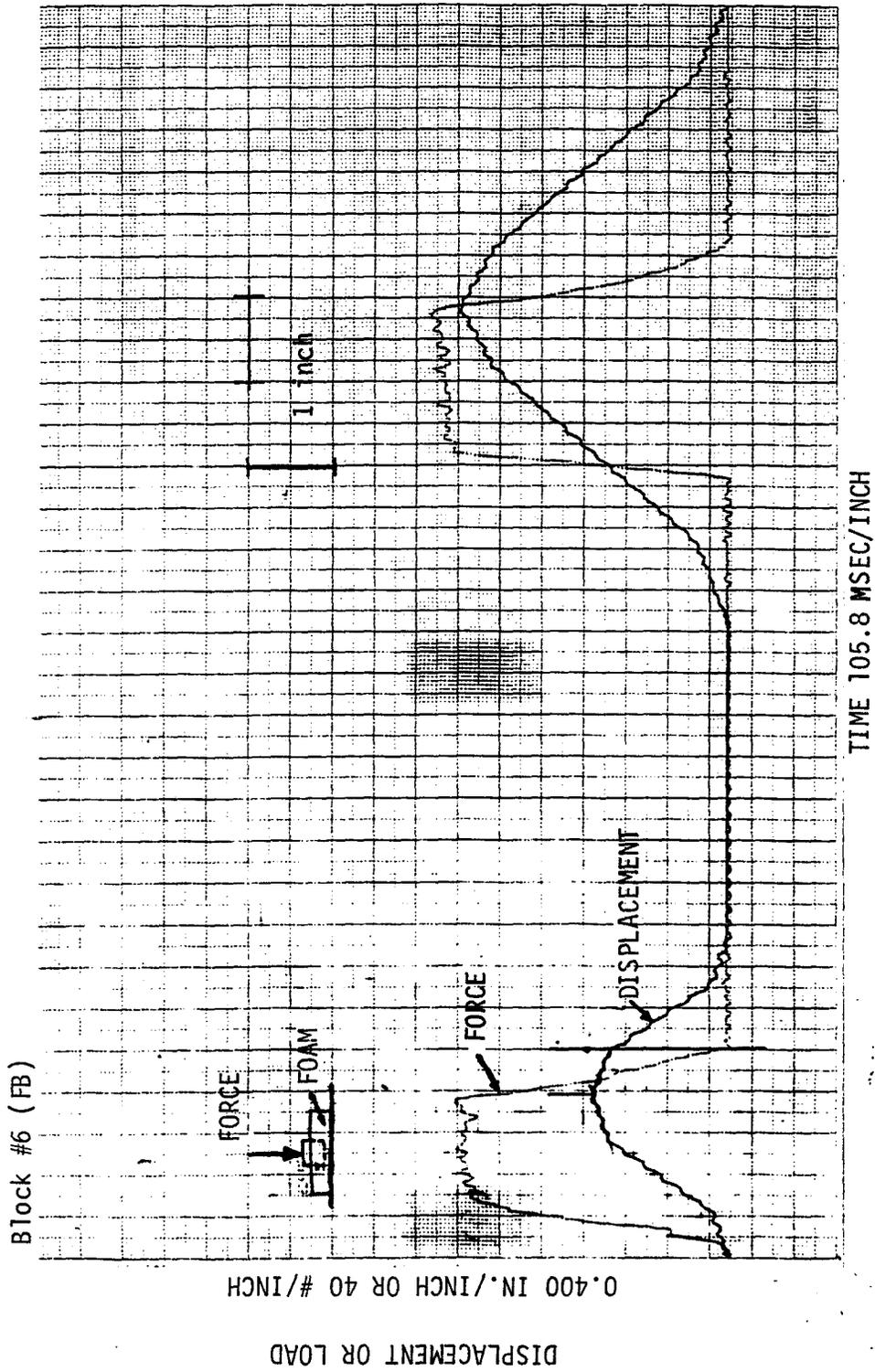


Figure C-2. Record From Compression Test of a Polystyrene Foam Sample Designated FB

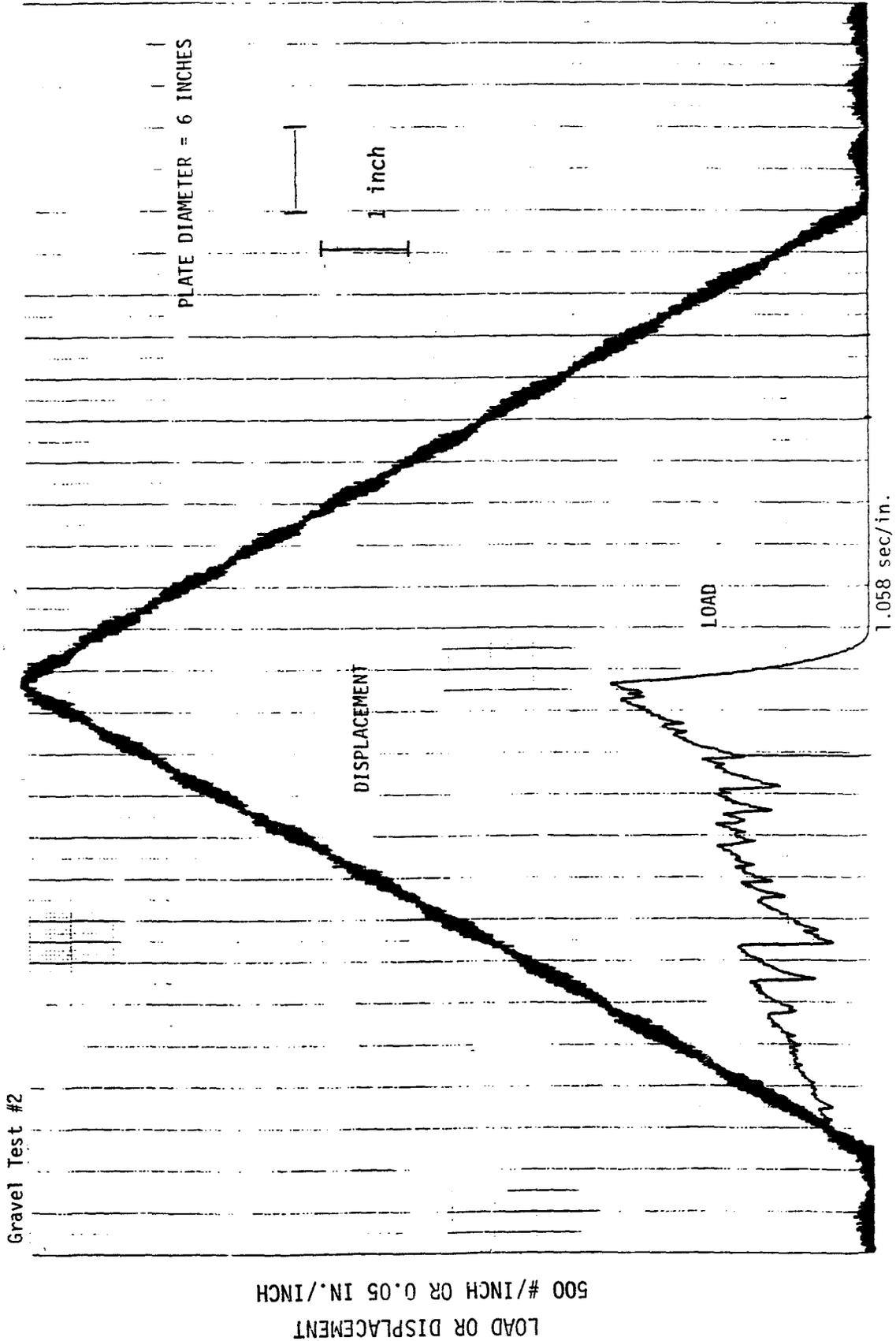
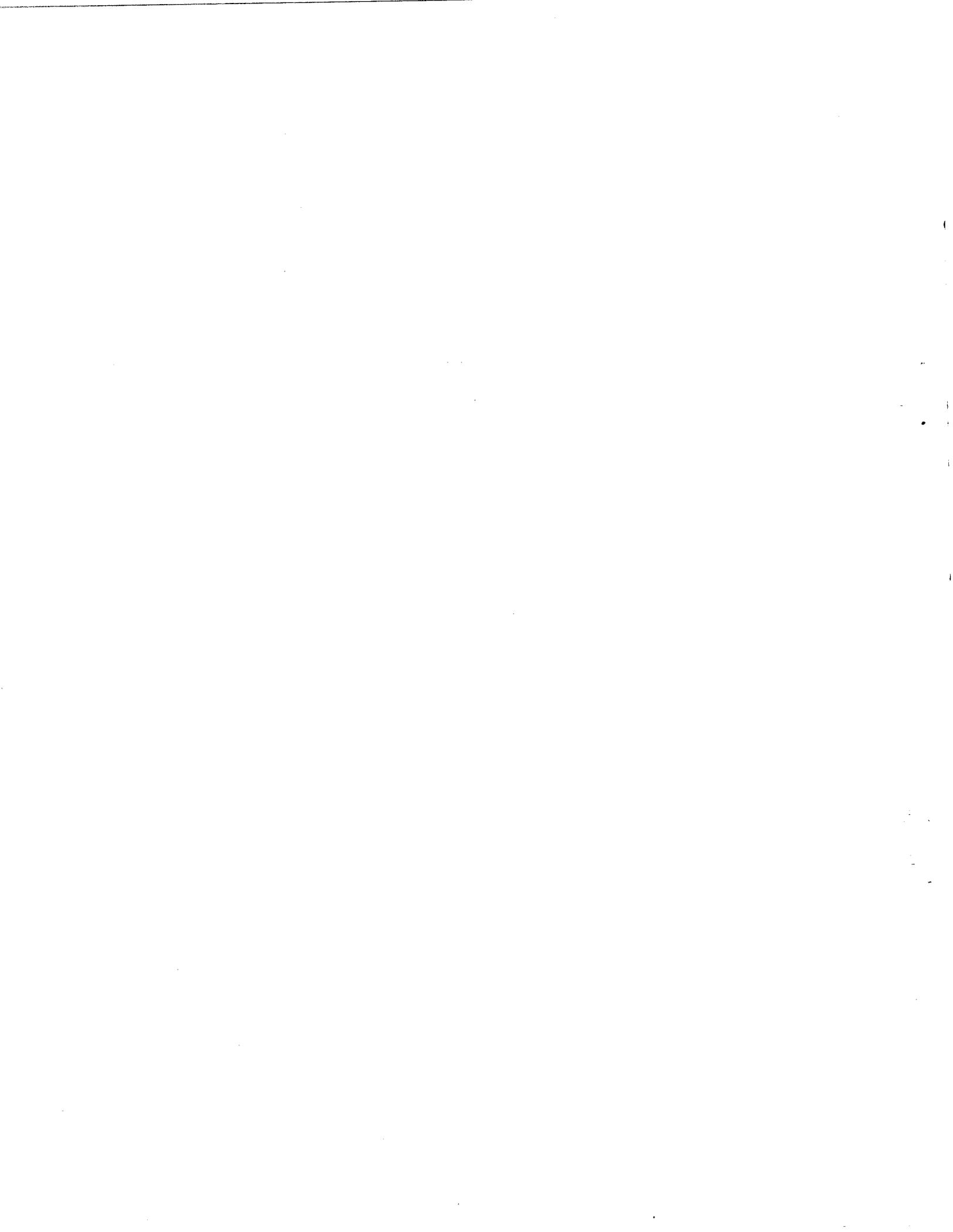


Figure C-3. Record From Compression Test of Gravel (ASTM D-448-86 #57)

(Reference 4). The rapid rise in the stress level was probably due to the container for the gravel being too small. The test results were scattered but they were considered adequate to conduct the present study. Experimental testing of this type gravel is required to verify the analytical model used (see Section 2).



APPENDIX D
PROPOSED ARRESTOR TEST PROGRAM

1. INTRODUCTION

During the feasibility study portion of the Soft-Ground Aircraft Arrestment System program, certain assumptions were made regarding the foam or gravel beds used in the arrestment of aircraft. A listing of the assumptions follows.

- 1.1 The foam bed is secured to the ground plane so that it will not move during engagement.
- 1.2 The entire tire width and height will be engaged in the foam to the full depth of the foam. That is, there will be no voids in the foam as a result of horizontal shearing of the foam by the tire.
- 1.3 The surface boundary from the runway to the end of the foam/gravel bed is rigid. There is no sinkage of the wheels into the surface covered by foam or gravel during any part of the aircraft arrestment phase.
- 1.4 The wheel tracks into the foam leave adequate width for any leading wheels of a following strut to engage the full depth of foam. For example, the DC-10-30 mid-body gear will follow in the nose gear track and will be largely ineffective in producing drag. However, all leading wheels of Boeing 747 struts would be effective since they are in separate tracks.
- 1.5 The wheel/foam or wheel/gravel model predicts the correct vertical and drag force.
- 1.6 Braking does not affect foam bed performance.

To validate the analyses already conducted to determine the stopping distance of aircraft in foam or gravel, it is necessary to conduct some experimental tests. The experimental program must be designed to confirm the correctness of the above assumptions and to determine what modifications to the analyses will be required to assure accurate results for future predictions.

2. TEST OBJECTIVES

2.1 The test objectives are to validate the analytical prediction methods used during the feasibility study. These analytical prediction methods were developed using information contained in the literature, and only limited confirmation was available. The foam material obtained from Dow Chemical has not been tested for use as an arrestor and its characteristics must also be verified. Yawed (cornering) tests have been included for nonperpendicular bed entry.

2.2 Develop some cost information on the placement of foam and gravel arrestor beds.

3. TEST WHEEL ASSEMBLY

The experimental program should be conducted at the Naval Aircraft Engineering Center, Lakehurst, NJ, or NASA Langley Landing Dynamics Facility, Hampton, VA. The tests would involve determining the vertical, drag, and side forces (time histories) developed on a wheel when it traverses foam and gravel test beds. The test wheel can be mounted on an aircraft landing gear strut or just an axle attached rigidly to the test carriage or "Dead Load Vehicle." An F-4C fighter main gear with the tire deflated to about 180 psi would be suitable. Adequate instrumentation (strain gage bridge, accelerometers, etc.) must be added to the wheel model to measure the loads (vertical, drag, side, and brake torque), the velocity, wheel rotation, and the dead load deceleration.

4. FOAM ARRESTOR BED

The foam arrestor bed configuration should be a constant depth and a maximum depth not greater than the test wheel diameter. If an F-4C main gear is used, the thickness would be a maximum of 24 inches. A 6-foot ramped section will be added to the front of the foam bed. The length of the bed should be a minimum of 26 feet and the width will be 8 feet. This will allow the use of standard size foam blocks. Foaming "in place" is not considered appropriate due to quality control of the foam strength.

The test beds will be built up in 2.0-inch thick slabs, each 2 feet by 8 feet, and each slab glued on the abutting edges and on the face surface of the blocks. The foam will be constrained to the ground by a wire attaching it to a wire mesh which will be fastened to the surface by lag screws. Two foam bed depths should be tested, one 12 inches deep and one 24 inches deep if the F-4C main gear is used. Only one gravel bed needs to be tested, a constant slope to a height of 24 inches in 50 feet. This choice of foam depths would change if larger landing gears are used.

The crushing strength of the foam beds should be 45 psi (12-inch deep bed) and 45 and 60 psi (24-inch deep bed). The gravel should be #57 aggregate (ASTM D448-86).

5. INSTRUMENTATION AND CALIBRATION

The test gear should be instrumented with strain gages to measure loads and moments about three perpendicular axes (three loads and three moments). If a full strut is used, the strut stroke also be measured. Wheel rotation and brake pressure should also be measured. Carriage or dead load velocity should be measured. Details of the instrumentation will be determined as a part of the follow-on program. All instrumentation must be calibrated while using the intended recording system.

6. TEST SCHEDULE OUTLINE

The following is a sequence of events required to successfully complete the test program.

6.1 Preliminaries

Select test facility and select test gear.

Determine participating organization responsibilities.

Define arrestor bed configuration and obtain materials.

6.2 Instrument and calibrate the test gear.

6.3 Conduct test program. Provide still and motion picture coverage.

6.4 Compare results with analytical studies.

6.5 Resolve differences between analytical and experimental studies.

6.6 Restore test facility to original configuration.

6.7 Write report.

A test schedule for the above outline has been prepared and is shown in Figure D-1. The entire testing is expected to take about 12 months to complete. A total of 28 tests is believed necessary to assure conclusive results on both foam and gravel materials.

It may be possible to shorten the test schedule if the foam beds can be replaced in a quicker time. An average of five days has been allowed to conduct each foam test since the entire bed will have to be replaced. Gravel tests should be completed faster but the same time was allowed.

The placement and replacement of foam beds should be performed by one team of people at the test site. The team could be made up of local

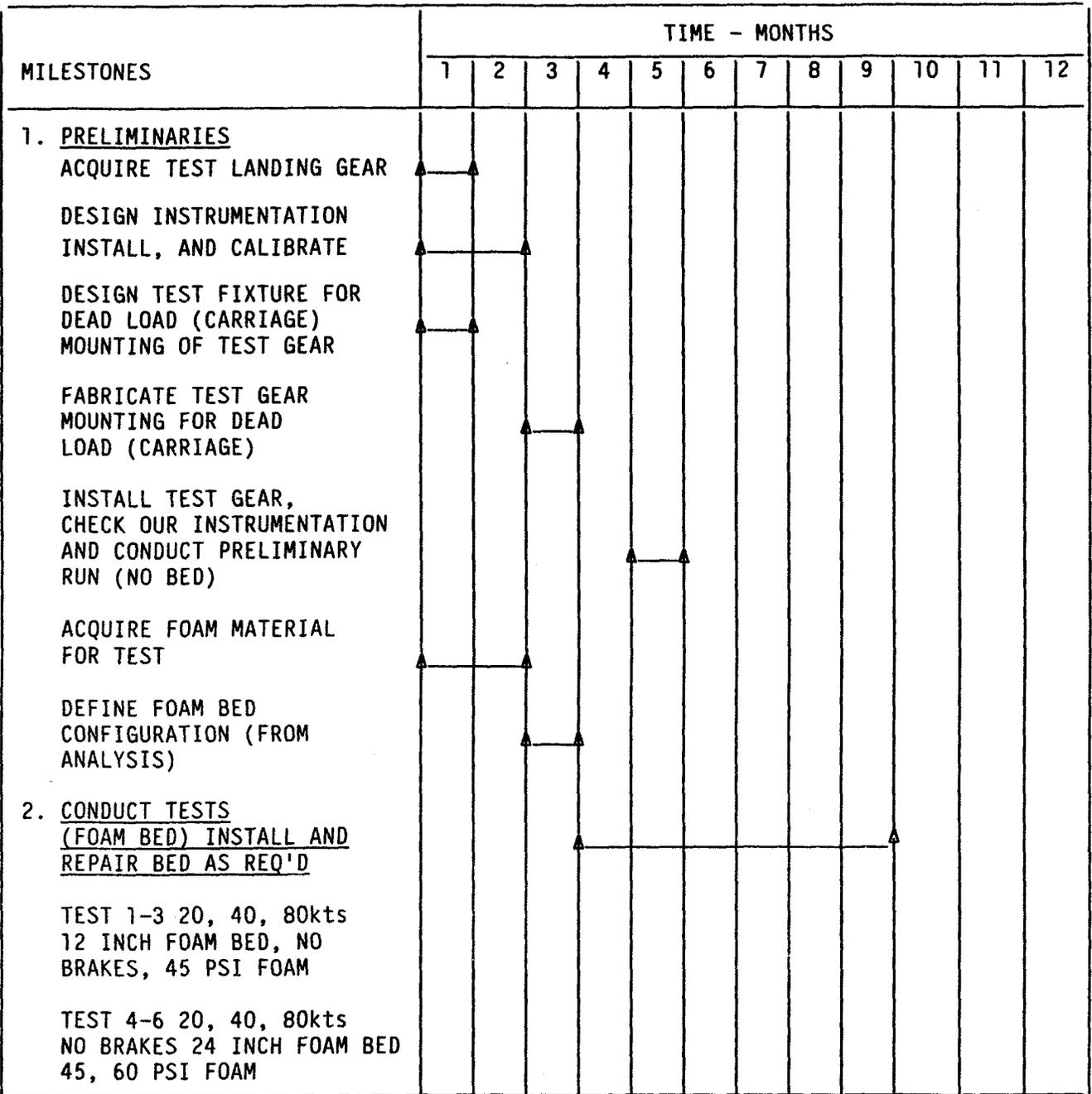


Figure D-1. Foam/Gravel Arrestor System Test Schedule

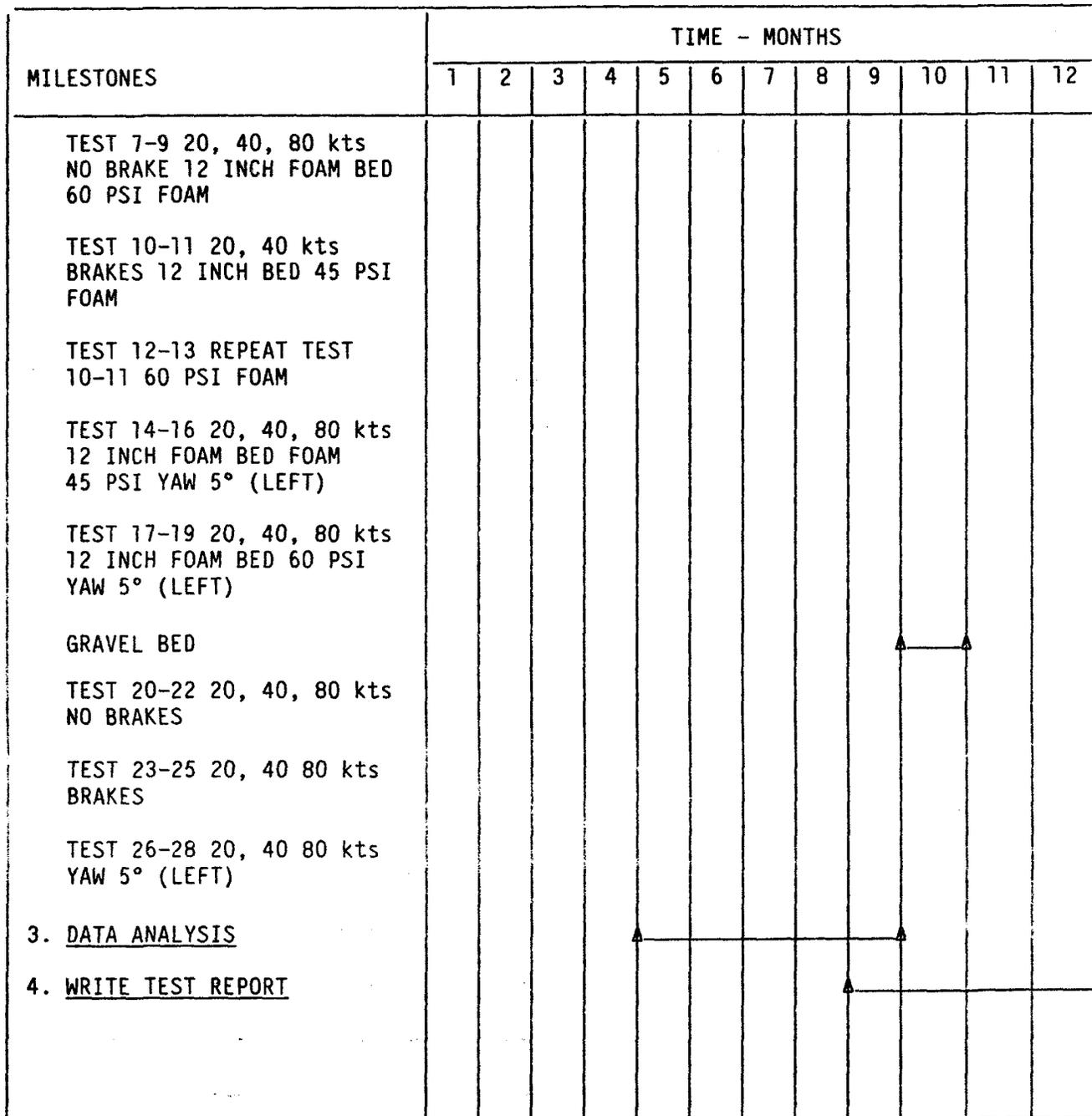


Figure D-1. Foam/Gravel Arrestor System Test Schedule (cont'd)

employees or by employment of local personnel. This will provide some indication of the time required for a full bed replacement. The above also applies to the gravel bed replacement and repair.

7. MISCELLANEOUS TESTS

7.1 Temperature and Jet Blast Effects

The distance from the jet blast should be determined in order to assure that the arrestor bed is not blown away or melted. The arrestor bed should be exposed to full thrust exhaust blast from a Boeing 747 or DC-10 aircraft engine. Temperature and velocity profiles should be determined.

8. FULL SCALE TESTS

The above plan only covers the validation of the analytical methods and the performance of the Dow Chemical foam/gravel selected. We believe that a full scale test of the arrestor bed is also needed to provide the using community with the required confidence to install an aircraft arrestor system. This test should be done after the attached experimental program is completed but it might be desirable to initiate arrangements for aircraft to test and for a site to conduct the tests.

At least two or three full scale aircraft should be tested on arrestment beds which are only as wide and as long as required for the test. A full size (200 x 800 foot) bed would not be required.

The soft-ground aircraft arresting system study was initiated to determine whether or not aircraft having gross weight of 114,000 pounds to 630,000 pounds could be safely stopped after overrunning the available length of runway. The extended length of runway was limited to 1,000 feet and the maximum velocity of the overrunning aircraft was selected to be 70 knots. In addition, the system was to be completely passive, have a long life and easily repaired and maintained. Several arrestor material such as clay, sand, gravel, water, and plastic foam were

considered. An aircraft wheel/arrestor material model was developed and incorporated into a computer program FITER which allowed the determination of the aircraft stopping distance, landing gear loads, dynamic response and rut depth in the arrestor material analyses conducted showed that sand, clay and water system were not suitable arresting materials due their inability to retain stable properties. Gravel and plastic foam were found to be suitable materials for an aircraft arrestor. Aircraft arrestment simulations were conducted for gravel and plastic foam arrestors and it was found that all aircraft could be safely stopped in less than 660 feet while in the arrestor bed. Evaluation of the stopping distance in an arrestor bed with the stopping distance of an extended runway were made and it was found that the arc arrestor system was needed to assure the safe stopping of an aircraft. Initial arrestor bed configurations were developed along with installation methods and attachment of the arrestor to the extended runway surface.

9. LABORATORY TESTS.

Laboratory testing of the arrestor bed foam or gravel materials should be conducted to validate their characteristics under all weather conditions. Samples should be taken from the test materials and each subjected to plate impact tests to determine:

- a. Foam effective compression depth.
- b. Wet and frozen foam characteristics.
- c. Wet and frozen gravel characteristics.

Laboratory testing of foam ground attachment methods should be conducted.

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