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# AIR FORCE MISSILE DEVELOPMENT CENTER TECHNICAL REPORT

DEVELOPMENT OF A NINE INCH DIAMETER,  
MACH 5.5, MONORAIL, ROCKET SLED

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NEW MEXICO**

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Daniel J. Krupovage

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June 1969

AIR FORCE MISSILE DEVELOPMENT CENTER  
DIRECTORATE OF TEST TRACK  
AIR FORCE SYSTEMS COMMAND  
HOLLOMAN AIR FORCE BASE, NEW MEXICO

## FOREWORD

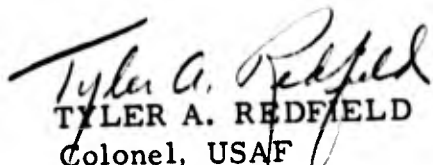
This developmental program was originated by the Directorate of Test Track's Engineering Division under project 6876, High Performance Rain Sled. The objective of this program was to produce an operational monorail sled to carry a nine-inch diameter nose cone through the Test Track's 6000 ft. rain field at velocities up to 6200 feet per second.

The sled design was to be of a modular construction consisting of a forward wedge, slippers, nose cone and body. A solid fuel rocket motor was to be used as a part of the operational sled structure.

The modular construction permitted the replacement of worn parts, i. e. slippers and wedge or an interchange of wedges or slippers coated with a variety of heat shield materials for evaluation purposes.

## PUBLICATION REVIEW

This technical report has been reviewed and is approved.

  
TYLER A. REDFIELD  
Colonel, USAF  
Director of Test Track

## ABSTRACT

A nine inch diameter monorail rocket sled was designed, fabricated and tested at Holloman Air Force Base. The vehicle was designed to allow easy replacement of appendages which were subject to severe aerodynamic heating and/or high wear rates. The monorail vehicle as described was shown to be capable of reaching 6200 feet per second and of being recovered with water brake entrance velocities up to 2000 feet per second. Drag coefficients up to Mach 5 were obtained and are presented in this report.

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## LIST OF SYMBOLS

A	ft <sup>2</sup>	reference area
a	ft/sec	speed of sound
a <sub>c</sub>	ft/sec <sup>2</sup>	Coriolis acceleration
ḃ	radians/sec	angular velocity of sphere (see page 5 )
c <sub>D</sub>		drag coefficient, $\frac{D}{qA}$
c <sub>f</sub>		coefficient of metal to metal friction
c <sub>N</sub>		normal force coefficient, $\frac{N}{qA}$
c <sub>M</sub>		yawing moment coefficient, $\frac{M}{qA\ell}$
F <sub>c</sub>	lb	Coriolis force
D	lb	drag force
g	32.2ft/sec <sup>2</sup>	acceleration of gravity
h	BTU/ft <sup>2</sup> -sec-F	heat transfer coefficient
L	ft	body length
ℓ	ft	reference length
M	ft-lb	yawing moment
m	lb-sec <sup>2</sup> /ft	sled mass, $\frac{W}{g}$
N	lb	normal force
q	lb/ft <sup>2</sup>	dynamic pressure, $1/2\rho V^2$
q̇ <sub>a</sub>	BTU/ft <sup>2</sup> -sec	aerodynamic heating rate
q̇ <sub>f</sub>	BTU/ft <sup>2</sup> -sec	metal to metal frictional heating rate

## LIST OF SYMBOLS

R	ft	radius of sphere (see page 5 )
$R_f$	lb	vertical slipper reaction
$S_b$	$ft^2$	base area of cone
t	sec	time
$T_{av}$	F	adiabatic wall temperature
$T_w$	F	wall temperature
V	ft/sec	velocity
Vol	$ft^3$	enclosed volume of body (see page 5 )
W	lb	weight
$\gamma$	radian/sec	angular velocity of point on sphere (see page 5 )
$\rho$	$lb\text{-}sec^2/ft^4$	air density
$\psi$	radians	angle of yaw

## SECTION I INTRODUCTION

The need for an operational monorail sled with a velocity capability of 7000 feet per second has become imminent. An operational velocity capability for a vehicle is considered to be one in which the vehicle is recovered on the track with only minor material oxidation and slipper wear. Various "customer" inquiries on the high speed test track capability have indicated that this velocity is necessary to collect data on the rain erosion and/or ablation characteristics of radomes and nose cones for various types of missiles. It, also, will be necessary to obtain transmitted data, such as signal strength through radomes, vibration environment of the test item, or pressure distributions on the test item. Information on test item sizes indicate that a nine inch diameter rocket sled vehicle capable of carrying up to a 30 pound external test item and with adequate volume to carry approximately 25 pounds internal payload is necessary. In efforts to approach 7000 feet per second with an operational recoverable vehicle several problem areas have become apparent. These problem areas, listed in what is considered to be the order of importance, are as follows: 1) aerodynamic and metal to metal frictional heating; 2) recovery by auxiliary braking methods; 3) roll stability; 4) on-board telemetry; 5) additional pusher stage techniques and designs; 6) rail gouging. In the period from April 1968 to February 1969 nine in-house runs (49X series) were conducted on the Holloman Air Force Base Test Track to obtain an operational capability up to approximately Mach 5.5 with a nine inch diameter monorail vehicle carrying a 7.5 lb nose cone. Three runs reached approximately 6200 feet per second. One was not recovered on the track.

The following paragraphs explain some of the problem areas, and discuss the results of the nine development sled runs.

Additional information is included concerning the results of sled tests on customer programs using this sled design.

## SECTION II DISCUSSION OF PROBLEM AREAS

The areas listed below are considered to be the primary hinderance to achieving full operational capability of 7000 feet per second. The following discussion brings to light some contributions made to solve the problems.

### Heating

Aerodynamic and metal to metal frictional heating has been a serious problem for several years. The effects of this have been experienced at velocities as low as 4700 feet per second on certain portions of rocket sled vehicles. The air temperature behind a normal shock at Mach 5.5 or approximately 6200 feet per second is 3100°F, based on perfect gas relations. (reference 1) Aerodynamic heat rates at this velocity in the stagnation region are in the order of  $10^3$  BTU/ft<sup>2</sup>-sec, as defined by the following equation.

$$\dot{q}_a = h (T_{aw} - T_w)$$

In the above equation h was assumed to be 0.433 BTU/ft<sup>2</sup>-sec-F. This value is for the stagnation region of a 1/4 inch cylinder with a wall temperature of 500°F (reference 2). The heat transfer coefficient h is a function of the inverse square root of the radius of the cylinder and decreases with increasing wall temperature. If a coefficient of metal to metal friction in the order of 0.1 is assumed, heat rates in the order of  $10^3$  BTU/ft<sup>2</sup>-sec can be appreciated as defined by the following equation.

$$\dot{q}_f = R_f c_f V / 778 A$$

Based on previous experience a quasi-steady state value for  $R_f$  is assumed to be in the order of 3000 pounds for the size vehicle in the velocity range of interest. In the leading edge areas of the vehicle which do not come in contact with the rail, aerodynamic heating appears to be the primary heat input triggering oxidation. The test item tip, down load canard leading edges and flow deflection wedge in front of the slippers are of primary concern for protection against metal loss due to aerodynamic heating and the related oxidation. It is necessary to protect the canards from severe unsymmetrical melting in order to prevent rolling moments. It is also necessary to prevent severe melting of the forward flow deflection wedge because it is used as a

momentum exchange water brake during final stopping of the vehicle. Over the past few years several materials have been tried in order to alleviate the melting problem. Cobaltec 10091, a refractory material, applied by a flame spray process prevents material loss up to approximately 6000 feet per second. However, this material is not always reliably mechanically interlocked with the flame sprayed item, and sometimes flakes off, thus leaving the base metal exposed. Martyte No 1192 an ablative compound applied by being trowled on, was used but did not hold up well. Apparently this material upon heating could not sustain the high viscous shear forces generated on its surface by the aerodynamic environment. Tantalum, a refractory material, was tried, however, a workable method for attachment that would keep the material on during the run was not found. Zirconium oxide, a ceramic material applied by plasma spraying, shows promise well into the 6000 feet per second velocity range. However, it is a brittle material and requires careful handling. Tungtec 10112, a refractory material applied by a flame spray process, showed encouraging results on the last 49X run up to 6200 feet per second.

Several methods which exist and may be adapted to solve the heating problem are: the use of refractory or ablative materials, of heat sinks, (passive cooling) and of transpiration cooling (active cooling). Refractories appear to be the most easily adapted for sled use at least up to and possibly above approximately 6200 fps. This technique has the advantage of low weight and constant configuration. Ablative materials offer a decrease in mass as material is lost but result in configuration change. Heat sinks offer a constant configuration but increase the mass of the sled system. Transpiration cooling systems increase the vehicle mass but keep the configuration constant.

### Recovery

The limited length of the test track (35,588 ft) puts a constraint on rocket sleds which becomes increasingly severe as the sleds are pushed to higher and higher velocities. As the payload weight approaches 50 pounds and sled speeds exceed 6000 feet per second, the nine inch diameter monorail sleds with relatively low drag configurations exceed water brake entry.

velocities of 2000 feet per second. Ballistic coefficients (i. e.  $W/c_dA$ ) for this type of nine inch diameter vehicle are in the order of 700 pounds per square foot for high supersonic velocities. Other sled runs (3C series) have demonstrated a safe entrance velocity for water filled polystyrene trays of 1950 feet per second. Entrance velocities into polystyrene trays can be increased. However, the system is limited by the maximum allowable braking forces and deceleration levels which are acceptable for the sled structure and payload. The water is placed in the trays which are located over the rail. The length of the water braking area is limited by the amount of track left after the sled has been decelerated by air drag to an estimated safe water entrance velocity. At the entrance point the water height in the trays is limited by the maximum allowable braking force and as the velocity decreases by the sled/brake geometry. Aerodynamic drag brakes which could be extended at booster burnout or shortly thereafter, would provide a means of keeping the water brake entrance velocities below the known safe limit. However, there was no operational extendable aerodynamic drag brake available at the time this run series was conducted. Fixed aerodynamic drag plates cause, as a rule, too much of a reduction in peak velocity to be useful.

### Roll Stability

Large monorail vehicles have shown a tendency to roll. The primary effect of this roll is severe unsymmetric wear of slipper bearing surfaces. On one run of the 49X sled run series one of the lower lips of the slippers was completely worn causing the sled to leave the track. The cause of the roll is not completely understood. Recently much effort was made to align the sled with the centerline of the rail. The alignment effort has in general kept the sled centerline in the horizontal plane, within  $\pm 0.050$  of an inch of the rail centerline. The rail used for alignment purposes is located on a portable 20 foot model section of the track and girder which is specially aligned for this application. Looking at the horizontal plane of the sled with the rear slipper fixed to the centerline of the rail, a  $\pm 0.050$  inch misalignment of the front slipper produces an angle of yaw of approximately three tenths of one degree. According to slender body theory for a cone cylinder this misalignment produces a force near the base of the cone of about 120 pounds, as calculated by the following equations for the force and moment coefficients referenced to the apex of the cone (reference 3).

$$C_N = \frac{N}{q S_b} = 2 \psi$$

$$C_M = \frac{M}{q L S_b} = 2 \left[ \frac{\text{Vol}}{L S_b} - 1 \right] \psi$$

The same angle of yaw resulting from misalignment could also be produced by side-on winds. For example, a 30 mph (26 knots) wind 90° perpendicular to the direction of travel produces an effective angle of yaw of 0.5 degree for sleds traveling 5000 feet per second. If the sled was pivoted around the rear slipper the resulting offset of the front slipper would be .090 of an inch. The order of magnitude of the forces generated by this sidewind is the same as that of the structural misalignment discussed before. Sled tests on this program were conducted at winds of less than five knots, regardless of direction. If the sled is yawed either by a non-parallel air-stream or structural misalignment, the booster thrust vector produces a component in a direction to increase the yaw tendency and also the roll. The sled longitudinal center of gravity is located aft of the booster-sled interface and moves forward as propellant is burned. Depending on the location of the center of pressure, the sled longitudinal inertia could have either a restoring or biasing effect. The location of the center of pressure is not known at this time. Even with alignment and wind restrictions the sleds have rolled east when traveling from south to north on the track. The structural alignment varied from sled to sled (i.e. both east and west) none-the-less, the sleds that did roll, rolled east. Coriolis force would produce an eastward roll but calculations show this force to be around one pound for these sleds traveling around 6000 feet per second. This force can be approximated by the following equation for a point moving on the meridian of a rotating sphere (reference 4).

$$F_c = ma_c = m [2\gamma R (\sin \nu t) \dot{b}] \text{ where } t \text{ is } 0 \text{ at the equator}$$

The possibility of one other force also exists. If the path of travel is curved in the horizontal plane a centrifugal force would be generated. A radius of curvature of 10<sup>6</sup> feet would produce a force in the order of 200 lbs on these nine inch sleds when traveling at approximately 5000 feet per second. Indications of track lateral linearity measurements are that the track within the limit of specified tolerances follows more closely a predetermined straight line at

the north end than at the south end. This means that sleds starting from the north end might be subjected to less centrifugal force during the high speed portion of the run than those starting from the south end. At the south end the center of the observed curvature is west of the rail, and centrifugal forces due to this curvature would provide an eastward roll. It is important to note that regardless of what force initiates the roll the other forces previously mentioned increase the roll tendency and do not produce restoring moments. Dynamic forces (i. e. highly transient forces) could enter into the roll-yaw stability of these sleds but there is not sufficient information available on these forces and their influences at the present time.

### Telemetry

At the time of this run series the Track organization did not have a sled mounted vibration isolated telemetry package capable of measuring several channels of information that had experienced sled vibration environments above 5000 feet per second. A vibration isolated telemetry system had performed marginally on another sled program up to approximately 5000 feet per second, however, it was not tried at higher velocities. The telemetry package was a proportional bandwidth system with a frequency response up to 2 KHz. The types of end instruments to be used with this package (e. g. pressure transducers, accelerometers, thermocouples) are selected dependent on the test requirements.

### Pushers

As a final stage vehicle is required to reach 7000 feet per second, optimization of pusher design becomes important. The optimization should consist of minimizing structural weight and selecting the most economical propulsion system. A short boost phase is desirable when the stopping of the vehicle is necessary and also for reducing the time of aerodynamic heating. There are runs which have a constraint on the amount of track used to boost to a given velocity, such as, rain erosion tests. The rain erosion area lies between T. S. 20, 700 and 26, 700 feet. A sled fired from the north end (T. S. 35, 500) has 8800 feet of track to reach the desired rain entrance velocity. This limitation will require optimization of the pusher sleds if rain entrance velocities are to approach 7000 feet per second.

## Rail Gouging

A rail gouge is a fan or tear-drop shaped portion of the rail surface which is removed during a high velocity sled run. The surface material removed can be up to approximately 1/8 inch deep. This same pattern of material removal at times has been observed on the slipper sliding surfaces. The gouging does not take place until the rocket sled has reached approximately 6000 feet per second during the acceleration phase. The occurrence of gouging increases as the sled velocity increases and continues during the sled deceleration phase even after the sled has gone below 6000 feet per second. The mechanism of this type of local failure is not fully understood at this time. An investigation of the rail gouging problem was made by Ohio State University and is reported in reference 5. This investigation succeeded in producing similar gouges in the laboratory by means of high speed impacts under very shallow impact angles. No mention is made in reference 5 of the melting of the sled components and its possible ramifications. Reference 5 states that "Critical combinations of pressure and velocity create conditions which contribute to the occurrence of gouging. Under critical conditions the local surface finish appears to be the gouge-triggering parameter." There are indications that the molten particles of the sled become trapped between the slipper and rail thus causing or contributing to the gouging. As sleds approach 6000 feet per second with inadequate or no aerodynamic heat protection on the leading edges of various parts of the sled these parts begin to melt. As the sled velocity increases the melting becomes more severe with the maximum rate of material loss occurring during the deceleration phase below the maximum velocity. Several runs during which no significant melting at high velocities occurred showed only insignificant gouging of the rail. During run 49X-A9 which is discussed in this report, in the absence of severe melting, no rail gouging was observed. Also three runs conducted under another run series (15R) in which the sleds achieved velocities between 6100 and 6500 feet per second showed no gouging as long as no significant melting of sled components occurred. Coating the rail surface with lime appears to lessen the tendency for gouging. Reference 5 shows that certain other coatings tried in the laboratory reduced the gouging. Continued gouging of the rail will deteriorate sections of the rail thus necessitating costly and time consuming replacement of the damaged sections.

SECTION III  
TEST VEHICLE

The vehicle used in this test series is shown in Figures 1 and 2. The following is a list of dimensions and weights.

Dimensions:

Overall length	114.88 in
Cone half angle	14°
Cone base diameter	9.0 in
Centerline Height above rail	7.65 in
Distance between leading edge of forward and aft slipper	100.74 in

Weight:

Forward section including slipper	90.5 lbs
Aft section including slipper	16.0 lbs
Cone	7.5 lbs
Total Structural Weight	<u>114.0 lbs</u>

Booster Case Weight	93.0 lbs
Burnout Weight	<u>207.0 lbs</u>
Propellant Weight	235.0 lbs
Initial Total Weight	<u>442.0 lbs</u>

Frontal Area (cross sectional area)

9 inch diameter cylinder	63.617 in <sup>2</sup>
Pylon between cylinder and slipper bottom surface	18.75 in <sup>2</sup>
Canards and side lower lips of slipper	8.75 in <sup>2</sup>
Total	<u>91.117 in<sup>2</sup></u>

or  
0.633 ft<sup>2</sup>

The following list summarizes the sled weights and propulsion used on the runs. Aborted or incomplete runs have been omitted. All runs were made with one Gila IV rocket motor as final stage propulsion

Run No	Cone Wt lbs	FINAL STAGE		Sled Wt lbs	PUSHERS	
		Inst Wt lbs			1st Stage	2nd Stage
49X-A1	7.5	None		107	None	-
49X-A3	7.5	25 (Ballast)		107	6-HVARs	-
49X-A4	7.5	None		107	1-Cajun	-
49X-A5	7.5	None		107	1 Cajun	-
49X-A6	7.5	None		107	6-HVARs	1 Cajun
49X-A7	7.5	None		111	6-HVARs	1 Cajun
49X-A9	7.5	None		107	1 Lacrosse	-

## SECTION IV RESULTS OF SLED RUNS

Figure 3 presents the drag coefficient as a function of Mach number. The data are the result of the evaluation of time and distance information obtained by two different techniques. One technique is the use of an electro-optical (ribbon frame camera) system for space-time measurements. These measurements were then reduced to velocity, time and distance by a contractor (Computing and Software Incorporated), and returned to the Track organization for analysis and evaluation. Data obtained are then analyzed to give drag coefficients by averaging the time and distances over velocity increments in the order of approximately 200 feet per second. Another technique was the use of spot velocity information. Spot velocity information gives the time history of the sled run at fixed track station locations. The average velocity between two track stations not more than 200 feet apart, is calculated. This velocity and distance profile was compared with the computer estimate, which is based on assumed drag coefficients. The drag coefficients are reevaluated until the computed and actual velocity and distance profiles match.

Figure 4 presents the actual velocity and distance profiles obtained by spot velocity measurements on the runs of this test series. The final stage geometry was identical on all runs except for the addition of a small antenna as noted in the discussion of the results of individual runs.

Figure 5 presents expanded data on the water braking phase of the run. Data from other test series have been added to show that this type of sled can be stopped from high velocities with variable payload weights. Table 1 presents the amounts of water filled polystyrene foam trays and polyethylene bags used for these braking profiles.

Table 2 presents test environmental details for each run in the series.

### Sled Run 49X-A1

For this mission the leading edge surfaces of the wedge, slippers and canards were coated with flame sprayed Cobaltec 10091. An antenna (Electronic Specialty Co LB-247) was mounted on top of the vehicle and subjected to this high speed environment.

Post run inspection of the sled disclosed the following results:

a. No problems occurred with the basic sled structure and no adverse aerodynamic heating effects were observed.

b. The antenna showed erosive oxidation in the area of the leading edge of the teflon ring. (See Figure 6)

#### Sled Run 49X-A2

The sled run was aborted due to operational problems.

#### Sled Run 49X-A3

Except for the installation of new Cobaltec 10091 coated wedge and slippers the modular sled components were similar to those used on sled run 49X-A1. In addition to evaluating sled components at a higher velocity, a second type of antenna (Dome and Margolin Inc., AT-741/A) was mounted on top the sled body (See Figure 6).

Post run inspection of the sled disclosed the following results:

a. Approximately 10% of the leading edge of the antenna was eroded and charred from heat generated during the sled run.

b. Minor erosion occurred to the left sides of the front and rear slippers in the form of a notch. Occurrence of these notches was typical on all runs. (See Figures 7 and 8) No observable erosion occurred to the right sides of the front and aft slipper or to the wedge, nose cone or canards. The notches in the left sides of the front and aft slipper may have started due to a crack in the slipper Cobaltec coating, allowing the leading edge of the 4130 steel to start melting in the area of high heat concentration. The notch in the rear slipper may have occurred for the same reason, however on the rear slipper the cracking of the Cobaltec may have been due to hot metal particles from the front slipper impacting the rear slipper. Small cracks and minor flaking of the Cobaltec coating were observed on the wedge after the run. This may be due to a difference in the coefficient of expansion and contraction of 4130 steel wedge and Cobaltec coating.

c. Less than 10% of the inside metal surface of the slipper was worn away or eroded during the test.

d. A study of photographic data showed an unsymmetrical braking with the 3" double layflat water bags. This could be attributed to unsymmetrical installation of the bags on the rail.

#### Sled Run 49X-A4

Except for the installation of new Cobaltec 10091 coated wedge and slippers the modular sled components were the same as the previous test of this series. Alignment of the sled before the run showed that the rear slipper was approximately 0.1 inch to the port side of the centerline of the rail. This was beyond previously established limitations of  $\pm 0.050$  inch but it was decided to let the sled run this way in order to observe its tendency to roll. An antenna, the same type as used on run 49X-A3 was mounted on top of the sled. On this run a phenolic block was placed in front of the lower portion of the antenna.

Post run inspection of the sled disclosed the following results:

a. The sled stopped in a severely rolled condition as shown in Figure 9. It is likely that the misalignment produced or at least contributed to the roll. A hardness test of the slippers disclosed that due to an oversight they had not been heat treated to the prescribed 120,000 psi design condition.

b. The front slipper attachment bolts were slightly loose.

c. Severe compaction of polyethylene bags was found between the slippers and the rail and in front of the wedge which may have enhanced the severe roll condition after entering the water brake. The buildup of polyethylene bags was typical on all runs on which they were used. (See Figure 10).

d. The antenna atop the sled was eroded by approximately 25%. The phenolic block 1 1/2 inches in height that was installed in front of the antenna base experienced approximately 10% erosion on its leading edge. However, it did prevent erosion of the metallic antenna base structure. (See Figure 6)

e. No significant erosion or structural damage occurred to the wedge, canards, nose cone or sled body.

### Sled Run 49X-A5

This test was essentially a repetition of sled run 49X-A4 with the following changes: (1) the forward slipper bolts were torqued to 70 ft-lbs, and cotter pinned to prevent loosening from heat and vibration. (2) In bending the slippers during fabrication, it was found that a slight crown sometimes developed on the top outside surface of the slipper. Therefore the top outside surface of the slipper (the one at the interface between sled and slipper) was milled flat. (3) A thorough inspection and hardness test were made on each slipper before being installed on the sled. (4) The water tray braking profile was programmed for a less severe braking force than was previously used when the sled entered the water trays, as indicated by the lower heights in Table 1.

Post test inspection of the sled condition showed the following:

- a. No indication of sled roll during the run.
- b. Moderate erosion of the wedge, slippers and canards was observed.
- c. The forward slipper attachment bolts had not loosened.

### Sled Run 49X-A6

As for all previous sled runs a new wedge and slippers with integral canards and with Cobaltec 10091 coating on the leading edge surfaces were installed on the sled for this run. The forward slipper attachment bolts were torqued to 70 ft-lbs and cotter pinned. This is required on all future runs.

A post run inspection showed the following:

- a. The forward slipper attachment bolts had not loosened.
- b. Moderate to severe erosion to the wedge tip and canards was observed and only moderate erosion damage to the slippers occurred. There was negligible roll of the sled as indicated by the evenness of wear to the inside surfaces of the slipper.
- c. The nose cone tip was melted back approximately 1/2 an inch. (See Figure 11).

e. The polyethelene water bag buildup caused a dent in the cone. (Figure 10) An overall assessment of wedge, slipper and canard erosion damages indicate that flame sprayed Cobaltec 10091 used as a heat shield offers reasonably good protection up to sled velocities of 5,800 ft/sec.

#### Sled Run 49X-A7

The sled structure for this test was the same as for the previous tests with the exception of the forward wedge section and slippers. The forward section of the wedge, which previously was steel, coated with Cobaltec 10091, was replaced by a solid piece of copper. (See Figure 12) The leading edge of the copper was rounded to a half inch radius as opposed to the 1/8" radius on the steel wedge. The copper block was intended to act as a heat sink. A method for calculating the temperature distribution in a two dimensional wedge, with time varying boundary condition, by the method of finite differences was developed by the Track Engineering Division (MDTE) and programmed by Computation Division (MDRC) at Holloman AFB. These calculations showed that the copper would conduct the heat off the wedge surface and keep the surface temperature of the copper below its melting point up to approximately Mach 6.0.

The sled left the rail in the vicinity of track station 20,000. The cause of the failure is not known. A review of 16mm high speed camera film showed that the sled was rolling to the east prior to leaving the rail. Film data also disclosed that the entire wedge was intact and in the proper position with the sled body during peak velocity (See Figure 13) and just prior to leaving the rail.

A post run inspection of the recovered sled parts showed the following:

a. The three bolts fastening the wedge to the sled body were sheared from the sled body. There is strong evidence that the sled body and wedge separated near track station 21,701 where heavy copper deposits were found in the steel water dam bracket that crosses the track trough.

b. Damage to the concrete in the track trough also indicated impacting of the nose cone and slippers at which time it is suspected that the nose cone also was ripped from the sled body.

c. An inspection of the track rail after the run revealed a large gouge in the top of the rail at track station 9050 (See Figure 14). Small deposits of copper were found in the gouge. No other gouges were observed. Image motion camera coverage of the sled at T.S. 10,400 showed a small deformation (about 1/2 inch in length and 1/8 inch high) on the lower part of the wedge at the copper wedge and track interface. (See Figure 13) It is assumed that a breakwire stretched across the rail used for timing or camera starting was the cause of the loss of copper. The use of wire stretched across the track was discontinued on all future runs of this series. The laboratory data reported by Ohio State University in reference 5 indicates that copper has very unfavorable gouging characteristics. No direct relationship between the gouge and the run failure could be established. All indications are that the expected heat sink effect of the copper wedge was achieved.

#### Sled Run 49X-A8

This test was essentially a rerun of tests 49X-A6 with the wedge slippers and canards forward edge surfaces coated with flame sprayed Cobaltec. This test was run in support of project 133B. The test was unsuccessful due to malfunctioning of one rocket motor igniter.

#### Sled Run 49X-A9

A flame sprayed Tungtec 10112 (tungsten-carbide) coating was applied to the forward surface of a new wedge installed on the sled for this test. The leading edge of the new slippers and canards were flame sprayed with Cobaltec as on previous tests. This test was the only run of the series fired from north to south. As was previously mentioned there are indications that the rail alignment at the north end of the track was more favorable for high speed runs than at the south end. The test was conducted under conditions of a wet rail from earlier rain showers, and moderate fog.

Post run examination of the sled components showed the following:

a. No wear or erosion damage to the wedge and normal wear to the slippers with slight erosive damage to the leading edge of the slippers and canards was observed. The Tungtec 10112 did not deteriorate. The sled was considered to be in excellent condition and had no indication of roll. Figure 15 shows the sled at the approximate maximum velocity of 6200 feet per second.

b. No rail gouging was observed. Gouging has been observed on other test vehicles in this velocity regime and also on run 49X-A6 which achieved the same velocity. The vehicle components on this run and on run 49X-A6 were identical. On run 49X-A6 significant melting of the wedge and the slippers occurred, while on this run melting of these items was negligible. The occurrence of melting was the only apparent difference observed. It is, therefore, concluded that presence of the molten metal is a contributing factor to the occurrence of rail gouging.

The maximum velocity was approximately 100 feet per second lower than predicted. There are indications that the wet rail and fog reduced the velocity. Examination of Figure 4 shows that on run 49X-A6D and 49X-A7D with a lower staging velocity (approximately 200 feet per second less) the same maximum velocity was obtained as on this run. The final stage sled configuration and weight was identical on run 49X-A6D and this run. Figure 4 also shows that the coast trajectories on runs 49X-A6D and this run diverge. Since the final stage sleds are identical the lower maximum velocity and divergence of the coast profile are attributed to a drag increase due to the fog and/or water on the rail.

## SECTION V CONCLUSIONS

1. The monorail rocket sled tested is capable of operating up to a velocity of 6200 feet per second with minor deterioration of the wedge, slippers and canards.
2. The monorail rocket sled tested can carry a 25 pound internal payload and a 7.5 pound external payload up to 6100 feet per second and be recovered on the track.
3. The concept of removable and replaceable slippers and wedge is practical for monorail sleds of the nine inch diameter size achieving velocities up to 6200 feet per second.
4. The monorail vehicle tested can enter polystyrene foam water trays up to velocities of approximately 2000 feet per second with the deceleration limited to 50 g's.
5. The presence of molten metal from the sled vehicle is a contributing factor to the occurrence of rail gouging.
6. Flame sprayed Cobaltec 10091 used as a heat shield offers reasonably good protection against melting due to aerodynamic heating up to a velocity of 5800 feet per second.

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6. Owczarek, Jerzy A., "Fundamentals of Gas Dynamics," International Textbook Company, Scranton, Pennsylvania, 1964.
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RUN	LENGTH IN FEET OF POLYSTYRENE WATER TRAY HEIGHTS OF								LENGTH IN FEET OF POLYETHYLENE WATER BAGS (DOUBLE LAY FLAT)	
	1/4"	3/8"	1/2"	3/4"	1"	1 1/4"	1 1/2"	2 1/2"	3"	
	49X-A1					1000				1000
49X-A3					1000				2000	
49X-A4					1000				2000	
49X-A5		400	400	400	400				1400	
49X-A6		400	400	400	400				1400	
* 49X-A9	400		400	400		400			1100	
* 6I-C2	400		400	400		400			1100	
17R-E3		400	400	400				400	1400	
3C-A2		400	400	400			400		1400	

\*Started with 400 feet of empty styrofoam trays.

All heights were determined so as to keep the deceleration below 50 g's.

TABLE I. SCHEDULE OF WATER BRAKE TRAYS AND BAGS

Run No	Date	Time	Ambient Temp (°F)	Barometric Pressure (in of Hg)	Relative Humidity (%)	Wind Velocity Knots	Wind Direction (°)	Maximum Velocity (fps)	Water Braking Velocity (fps)
49X-A1	23Apr68	1100	49	26.060	30	8	10	4789	570
49X-A2	8May68	0912	-	-	-	-	-	-	-
49X-A3	9May68	1014	73	25.830	18	10	150	5245	1030
49X-A4	17May68	1100	66	25.825	27	6	300	5718	981
49X-A5	14Jun68	0900	75	25.880	35	4	50	5723	1029
49X-A6	28Jun68	1000	89	25.795	20	5	330	6235	1782
49X-A7	4Sep68	1043	81	25.885	34	2	130	6130	No Data
49X-A8	26Sep68	1024	68	26.005	23	0	-	721	-
49X-A8	14Feb69	0619	40	25.615	33	0	-	6189+	1109

TABLE 2. TEST CONDITIONS AND RESULTING VELOCITIES

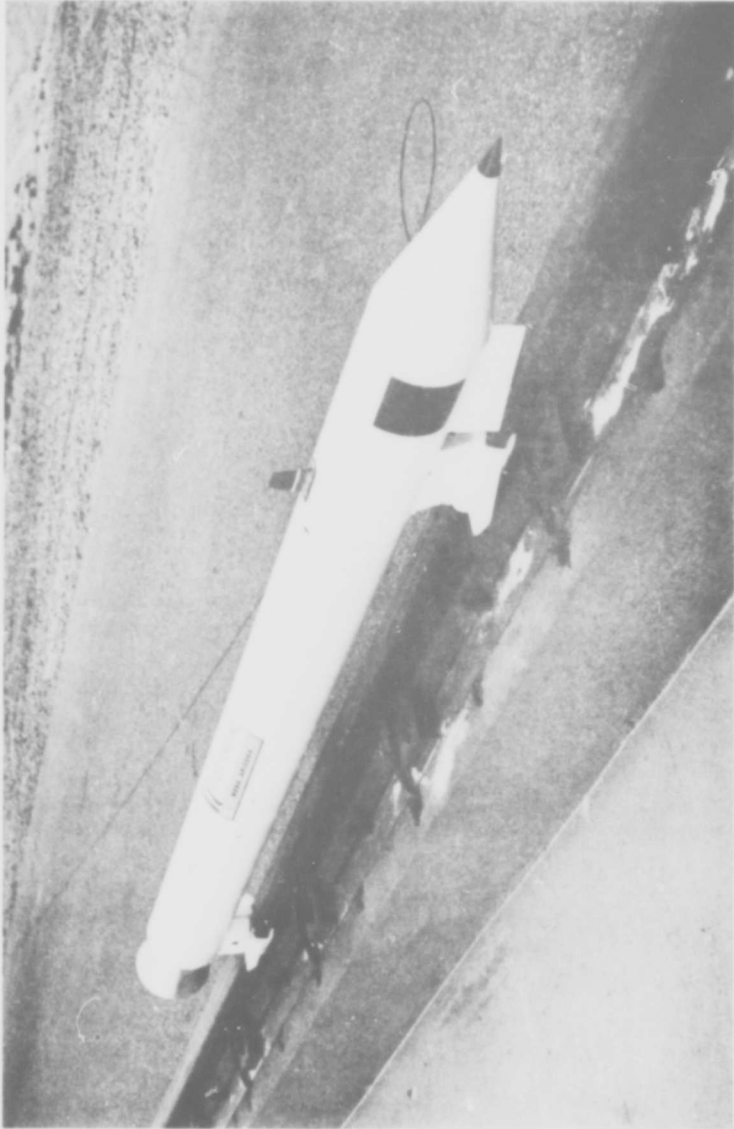


FIGURE I 49X TEST SERIES MONORAIL SLED

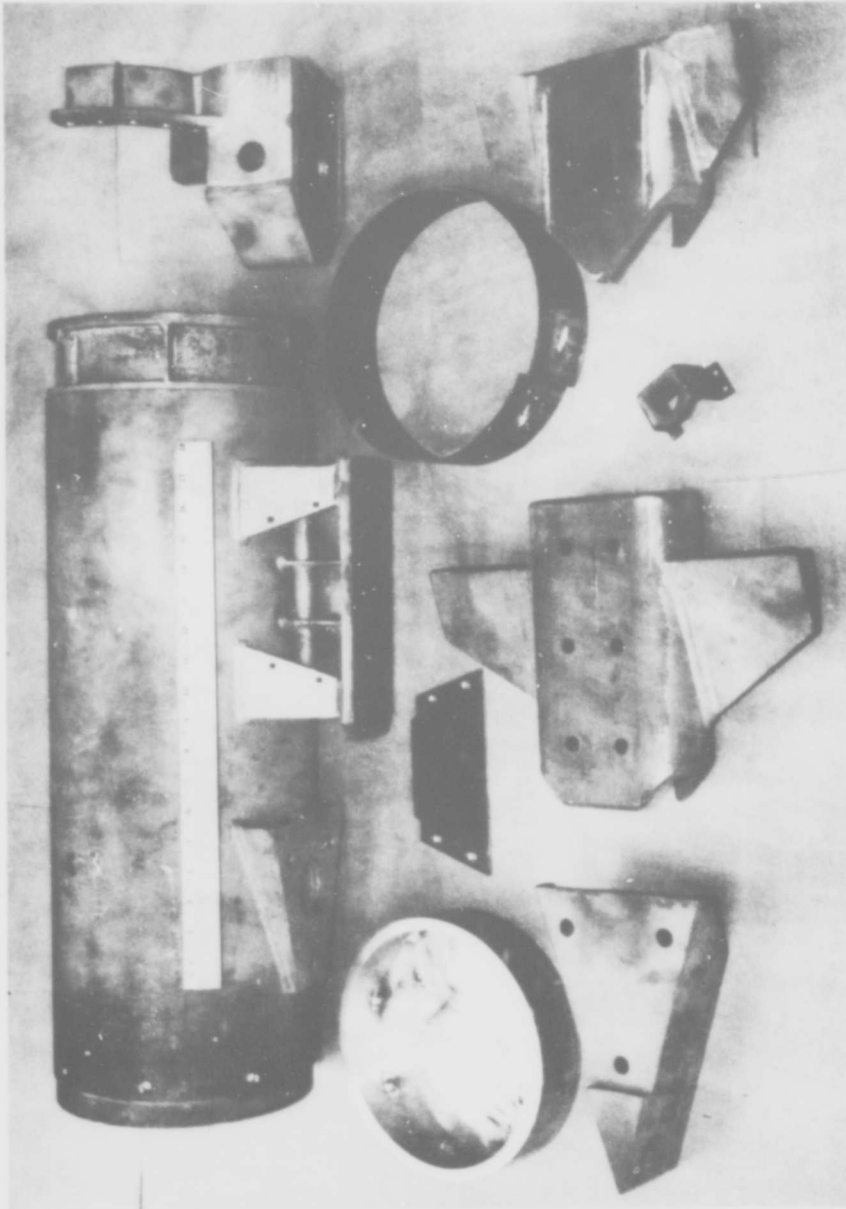


FIGURE 2 49 X SERIES MONORAIL SLED COMPONENTS

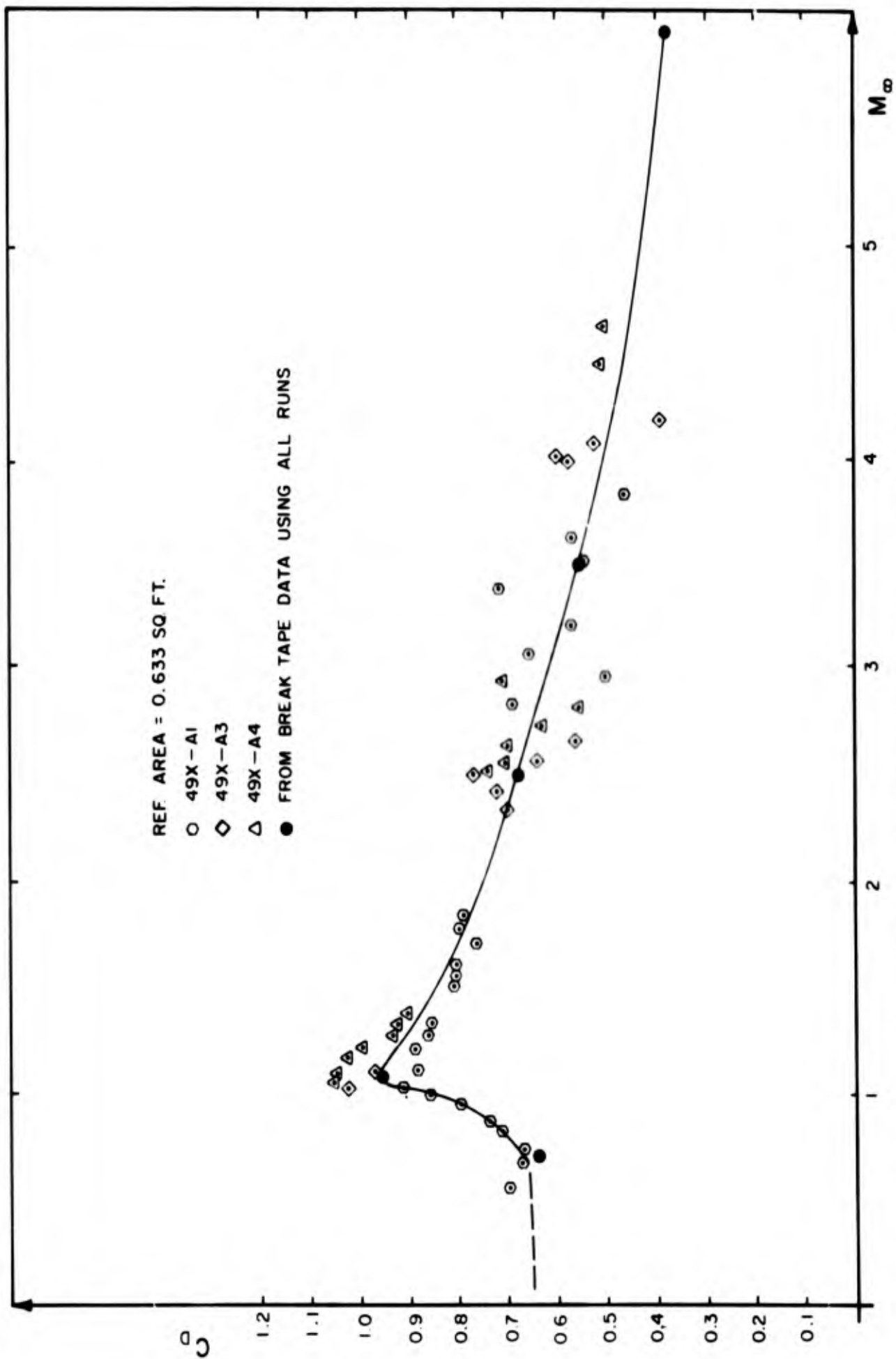


FIGURE 3 DRAG COEFFICIENT AS A FUNCTION OF MACH NUMBER

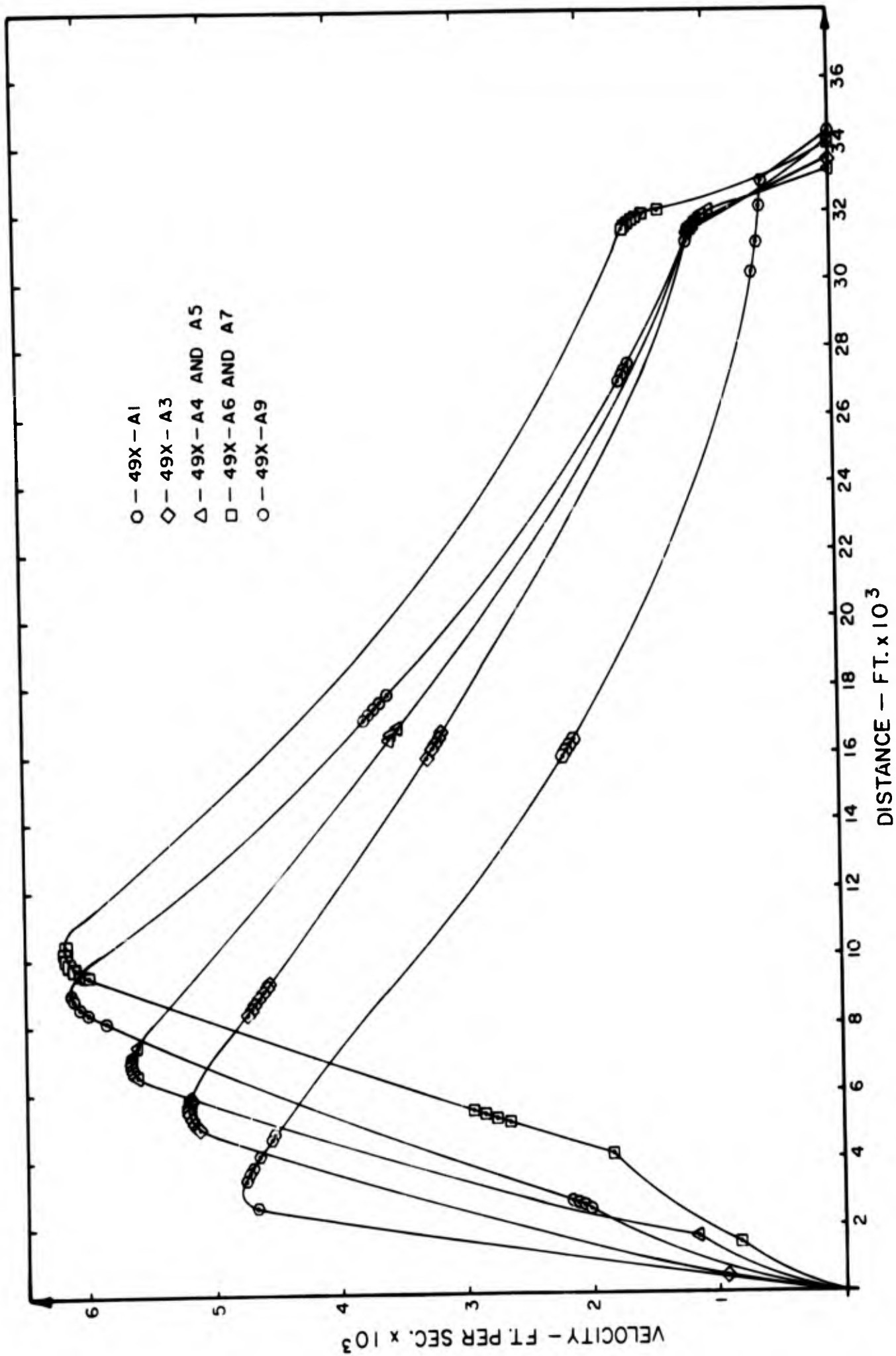


FIGURE 4 SLED VELOCITY AS A FUNCTION OF TRACK DISTANCE

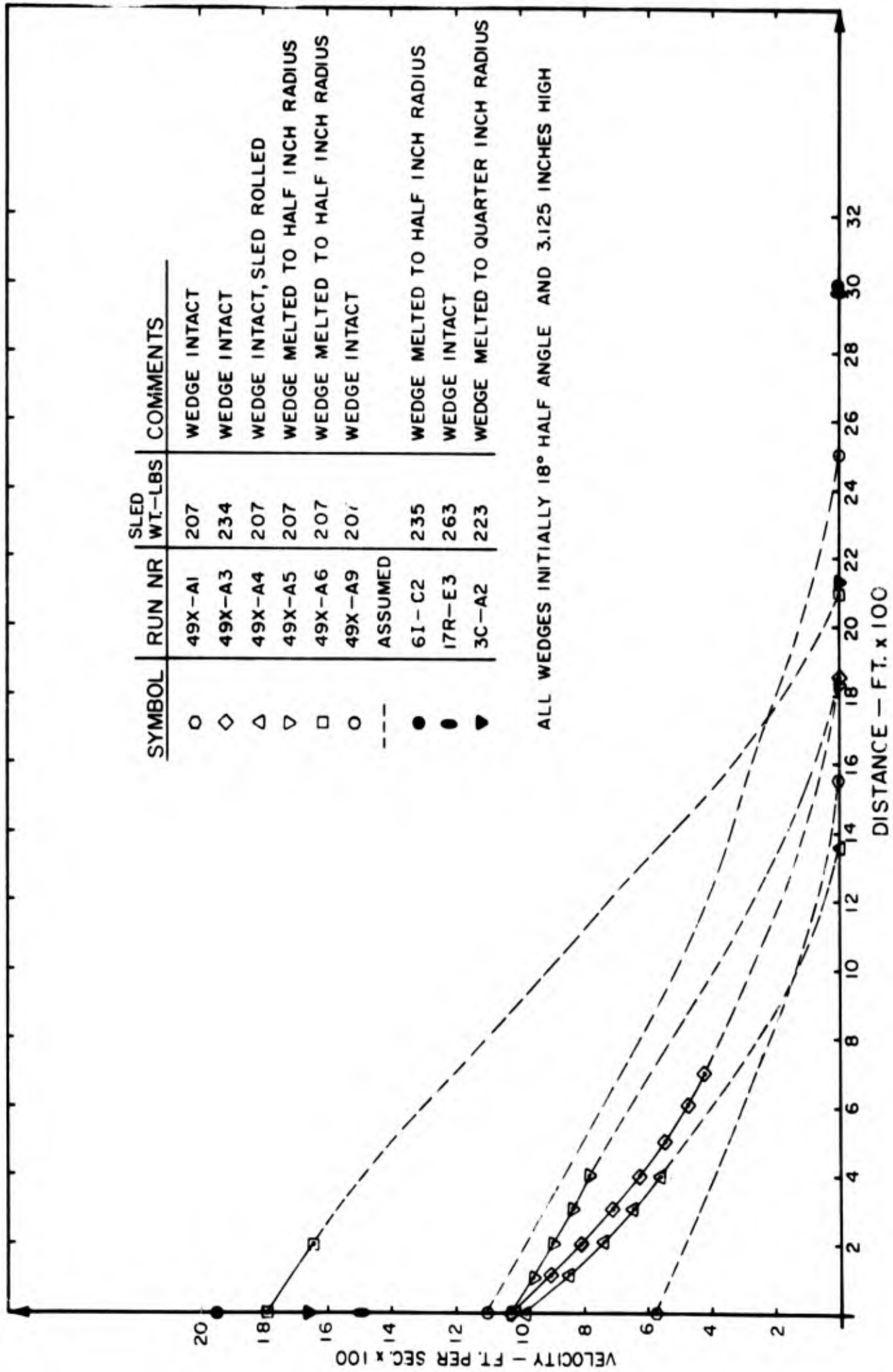


FIGURE 5 WATER BRAKING VELOCITY AS A FUNCTION OF TRACK DISTANCE



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FIGURE 6 POST - RUN CONDITION OF ANTENNAS



FIGURE 7 PRE - RUN AND POST - RUN CONDITION OF FRONT SLIPPER ON RUN 49 X - A 6

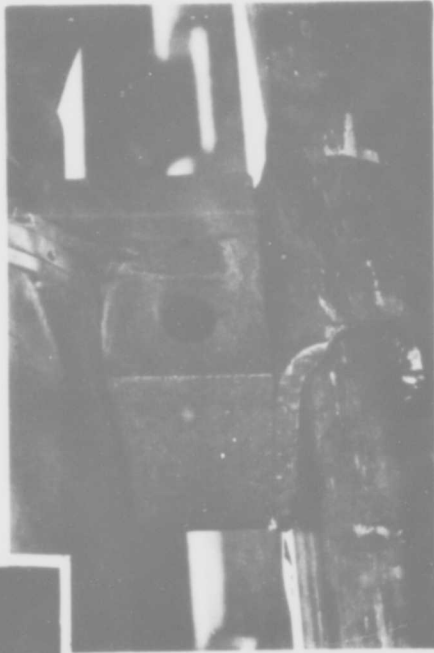
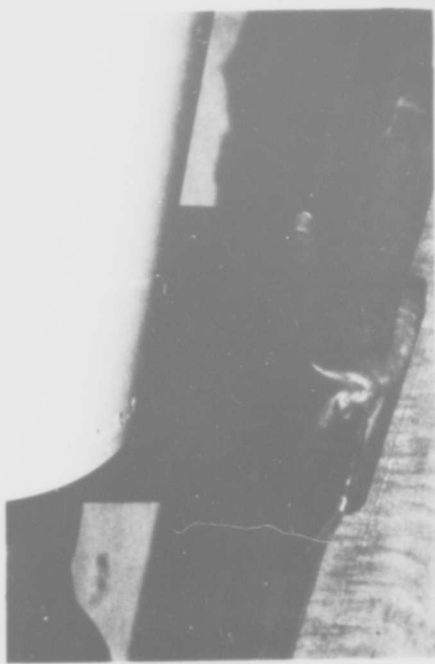


FIGURE 8 PRE - RUN AND POST - RUN CONDITION OF REAR SLIPPER ON RUN 49 X - A 6



FIGURE 9 POST-RUN VIEW OF SLED IN ROLLED POSITION ON RUN 49 X - A 4



FIGURE 10 POLYETHYLENE WATER BAG MATERIAL BUILD UP ON RUN 49 X - A 6

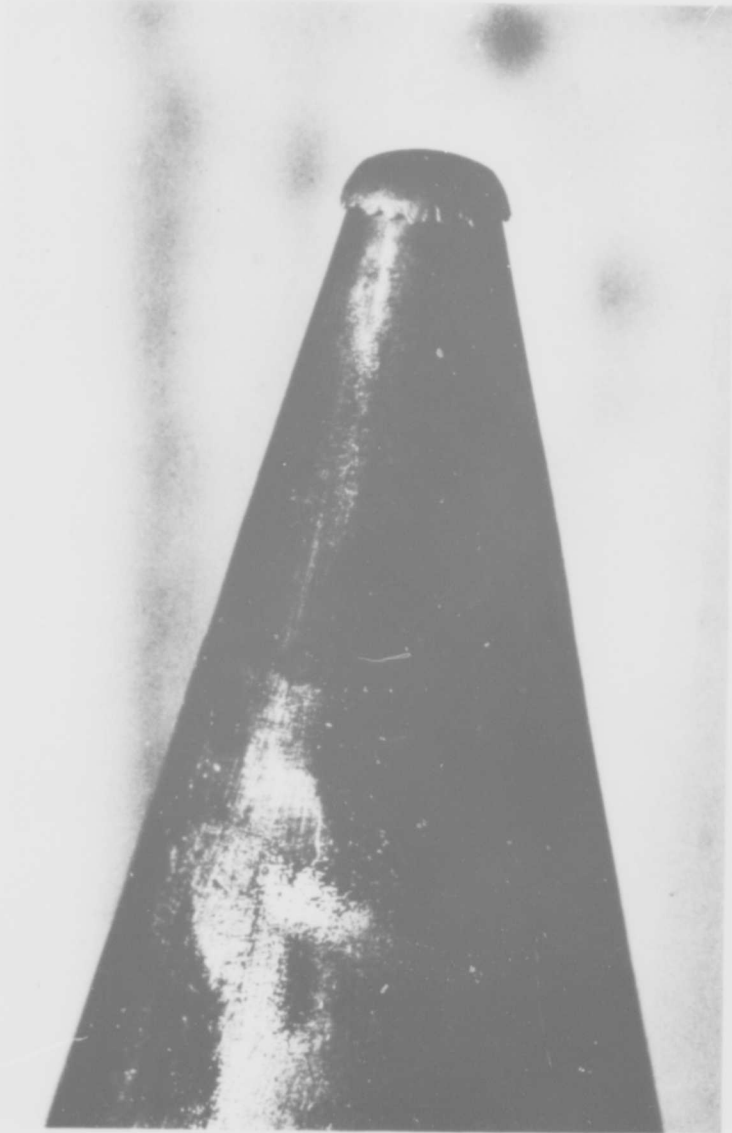


FIGURE II CLOSE UP OF MELTED CONICAL NOSE TIP



FIGURE 12 COPPER WEDGE ATTACHMENT

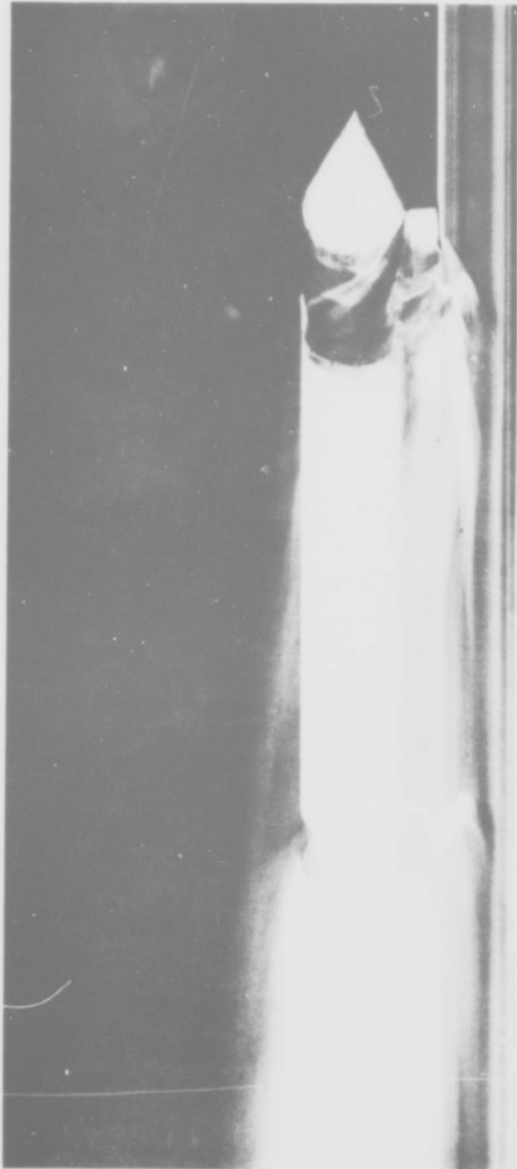


FIGURE 13 IMAGE MOTION PHOTOGRAPH OF SLED WITH COPPER WEDGE AT  
6100 FEET PER SECOND



FIGURE 14 GOUGE ON TOP SURFACE OF RAIL



FIGURE 15 IMAGE MOTION PHOTOGRAPH OF SLED WITH TUNGTEC COATED WEDGE  
AT 6200 FEET PER SECOND

## APPENDIX

The following figures have been included to show other sled configurations that were run but not a part of the 49X series. Each of the following series was assigned a different vehicle but the assigned vehicle was used throughout the particular program.

Figure 1-A shows the overall sled configuration used on the 14R test series. There were five runs in this series. All sled runs were fired from north to south. Three runs were made with no internal payload and no fin on the rear. One run was made with a 30 pound internally packaged transpiration cooling system and no fin. The last run was a repeat of the previous one with the fin added. The maximum velocity ranged from 5400 to 5700 feet per second. No sled related problems were noted in this test series.

Figure 2-A shows the 34 pound nose cone tested on the 17R series. There were nine runs in this test series. All sled runs were fired from north to south. Thirty pounds of internally mounted telemetry was also added to the vehicle. The remainder of the sled was identical to that used on the 49X series. No sled related problems were noted in this test series.

Figure 3-A shows the nose geometry tested on the 3C series. There were three runs in this test series. Seven pounds of internal instrumentation was on board. All other details of the sled configuration were the same as those of the 49X series. The maximum velocity ranged from 5500 to 6500 feet per second. A noticeable starboard roll was noted on a 6200 feet per second run. The run was conducted with the sled traveling from south to north. The final run with a maximum velocity of 6500 feet per second was fired from north to south. Post run inspection of the vehicle showed that no roll had occurred.

Figure 4-A shows the sled configuration used on run series 6I. There was one run in this test series. The vehicle carried an internally mounted telemetry package which weighed 30 pounds. Maximum velocity of the run was 6100 feet per second with a water brake entrance velocity of approximately 1950 feet per second. The vehicle was run from north to south on the track. Post run inspection indicated no sled related problems had developed.

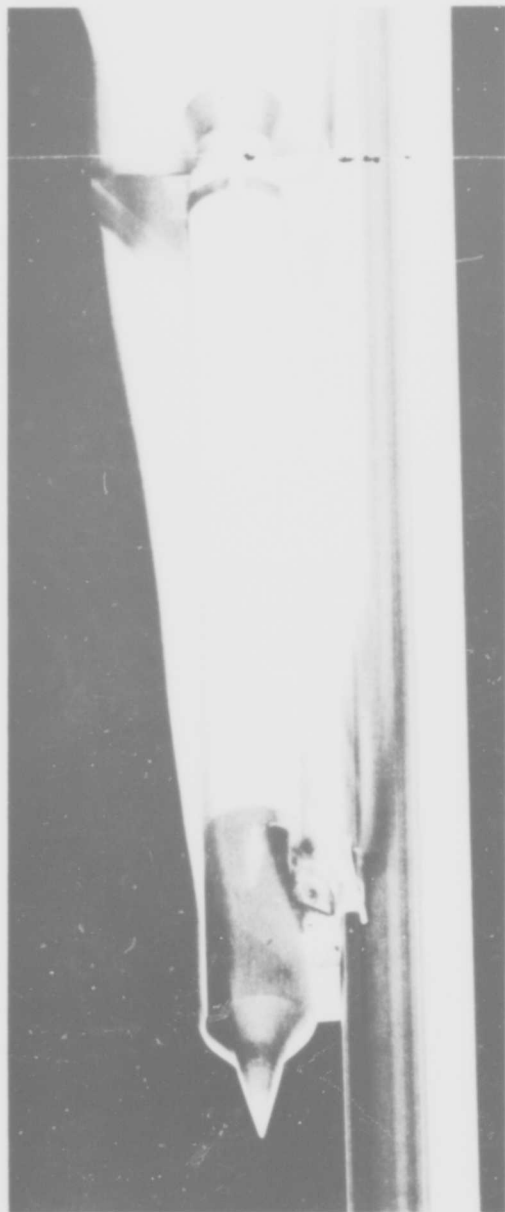


FIGURE 1-A IMAGE MOTION PHOTOGRAPH OF TEST CONFIGURATION ON  
RUN SERIES 14-R

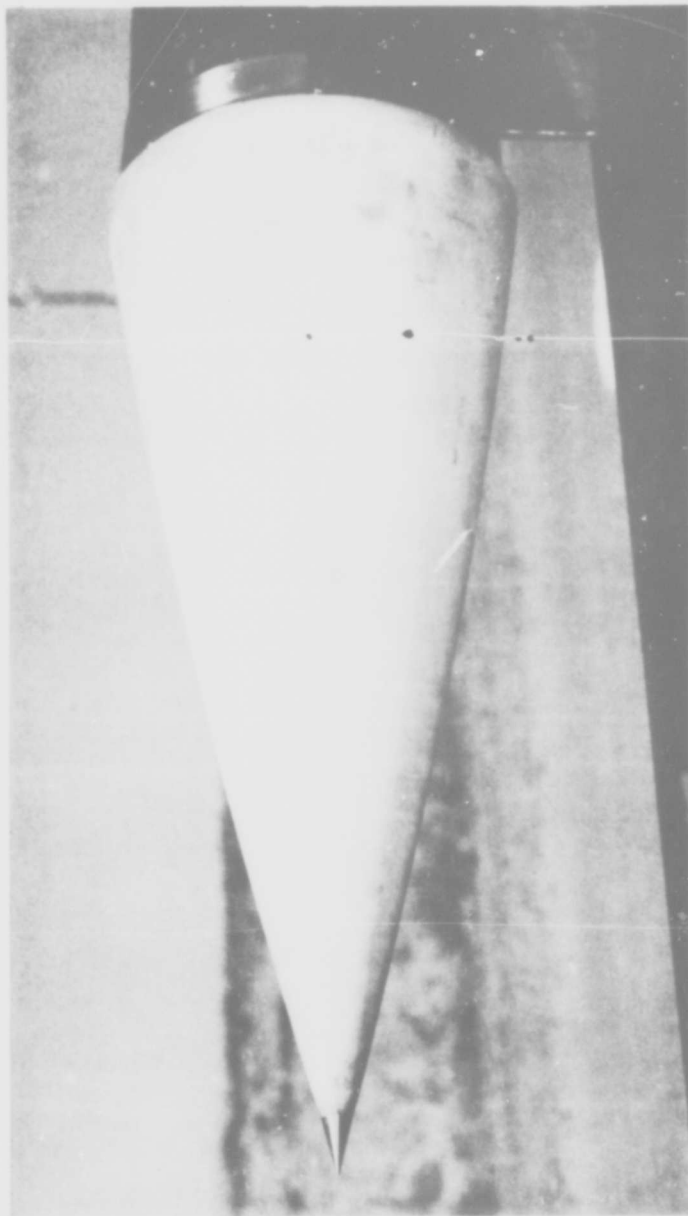


FIGURE 2-A EXTERNALLY MOUNTED THIRTY FOUR POUND TEST CONE

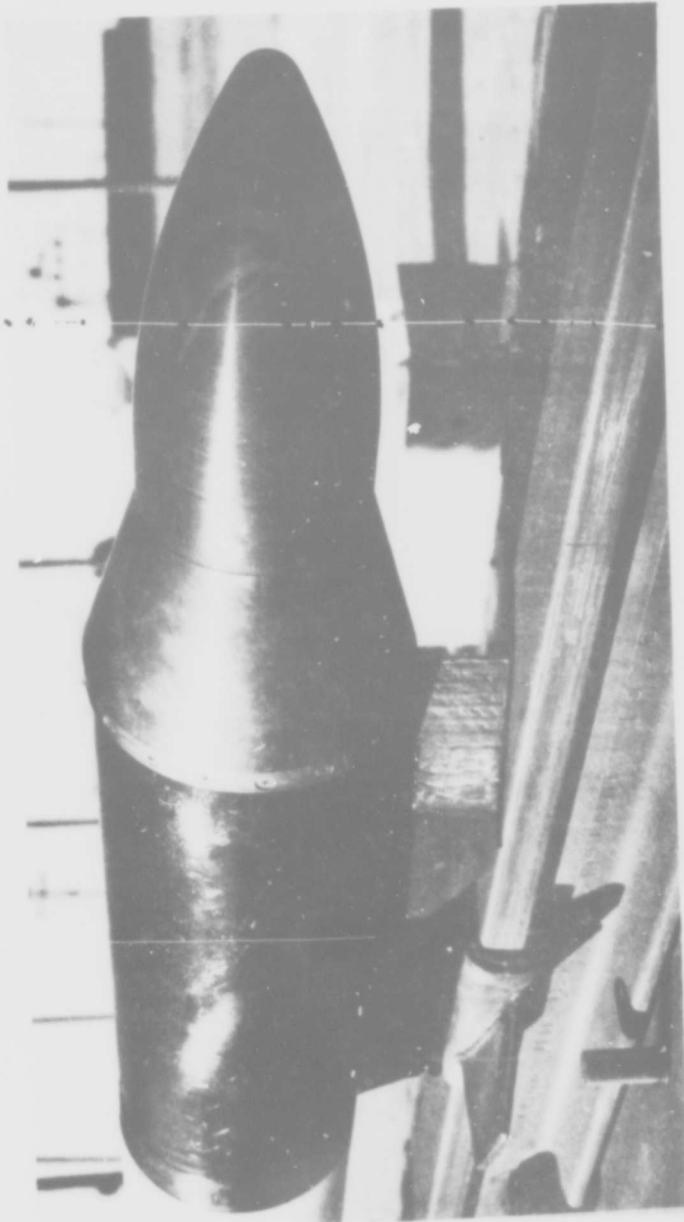


FIGURE 3-A EXTERNALLY MOUNTED TEST ITEM ON RUN SERIES 3-C



FIGURE 4 - A SLED CONFIGURATION FOR RUN SERIES 6 - I

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13. ABSTRACT <p>A nine inch diameter monorail rocket sled was designed, fabricated and tested at Holloman Air Force Base. The vehicle was designed to allow easy replacement of appendages which were subject to severe aerodynamic heating and/or high wear rates. The monorail vehicle as described was shown to be capable of reaching 6200 feet per second and of being recovered with water brake entrance velocities up to 2000 feet per second. Drag coefficients up to Mach 5 were obtained and are presented in this report.</p>		

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