ISSUES ASSOCIATED WITH A HYPERSONIC MAGLEV SLED

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INTRODUCTION

Magnetic levitation has been explored for application from motors to transportation. All of these applications have been at velocities where the physics of the air or operating fluids are fairly well known. Application of Maglev to hypersonic velocities (Mach > 5) presents many opportunities, but also issues that require understanding and resolution. Use of Maglev to upgrade the High Speed Test Track at Holloman Air Force Base in Alamogordo New Mexico is an actual hypersonic application that provides the opportunity to improve test capabilities. However, there are several design issues that require investigation. This paper presents an overview of the application of Maglev to the test track and the issues associated with developing a hypersonic Maglev sled. The focus of this paper is to address the issues with the Maglev sled design, rather than the issues with the development of superconducting magnets of the sled system.

CURRENT TESTING APPROACH

History of the test track

High speed test track facilities have been in operation for nearly half a century. The first track in the United States was commissioned in 1946 at the Naval Weapons Center in California. During the 50's, tracks were built in France and England and, in the early 60's in Russia.

The High Speed Test Track at Holloman AFB, New Mexico, became operational in 1950 when a 1,082 meter section of test track was constructed for operation as a Snark missile launching facility. The test track was extended to 1,546 meters in 1955 and to 10,690 meters in 1956. In 1972, the track was further extended to 15,480 meters in length. It is the longest and most precisely aligned track in the United States. The facility consists of two 171 lb/yd crane rails spaced 2.13 meters apart for its total length. In the northern 5,000 meters of the track, a third rail forms a 0.67 meter rail gauge with one of the other two rails. The rails are continuously welded and prestressed to remain under tension at temperatures below 60 degrees Centigrade. A south to north view of the Holloman test track is shown in Figure 1.

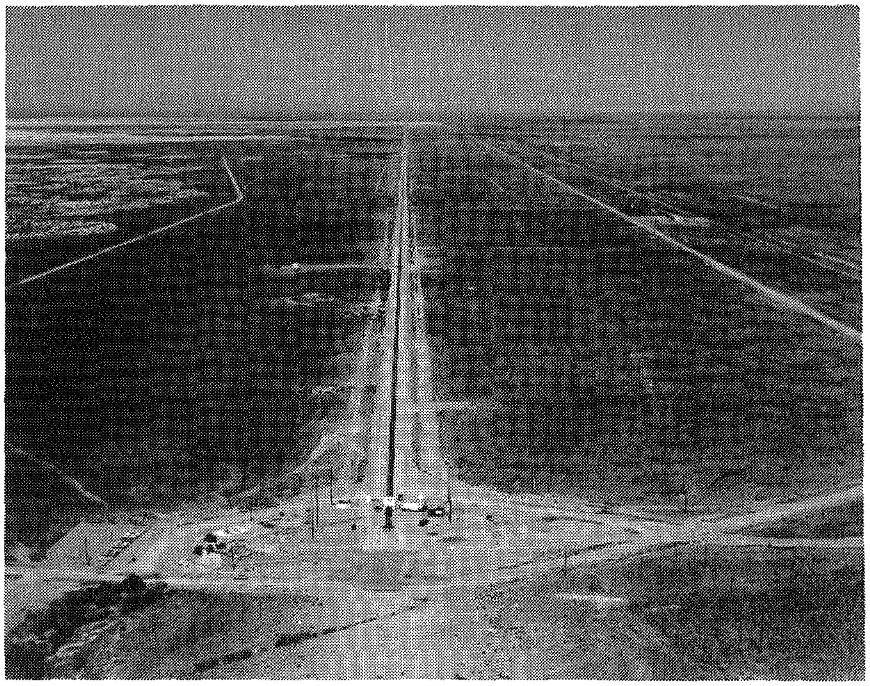


Figure 1. South-North View of the Holloman Track

High speed test tracks have been used to test a variety of aerospace hardware, such as guidance systems, crew escape systems, missile seekers and control systems, warheads, missile lethality and vulnerability, and rain erosion effects on radomes, just to name a few. Advancements in technology have created a need for higher and higher test velocities. Figure 2 is a collage of pictures showing a Theater Missile Defense interceptor impacting a simulated re-entry threat vehicle at hypersonic velocity after release from the test track.

High Speed Test Track System

The operation of vehicles in close proximity to the ground from low subsonic speeds up to hypersonic velocities produces aerodynamic ground interference effects which result in Mach number dependent lift loads and pitching moments. Therefore, it is necessary to control the biasing loads on sleds within certain limits to maintain captive flight. The means by which sled vehicles transfer loads to the rail and thus guide the vehicle are through structural hardware called slippers. Basically, the slippers are structural components fitted around the top flange of the rails with a maximum all around clearance of 1.524 mm, Figure 3. The rail gap is required because of small irregularities in rail alignment and rail surface imperfections. Due to the loads acting on the sled vehicles and the presence of the slipper gaps, sled vehicles translate through the slipper gap and the steel slippers impact the rail causing high vibration loads in the sled vehicles. The steel slippers also wear as they travel along the steel rail. This slipper wear allows excessive clearance at the slipper-rail interface and, along with the high vibration loading, can lead to catastrophic failure of the sleds.

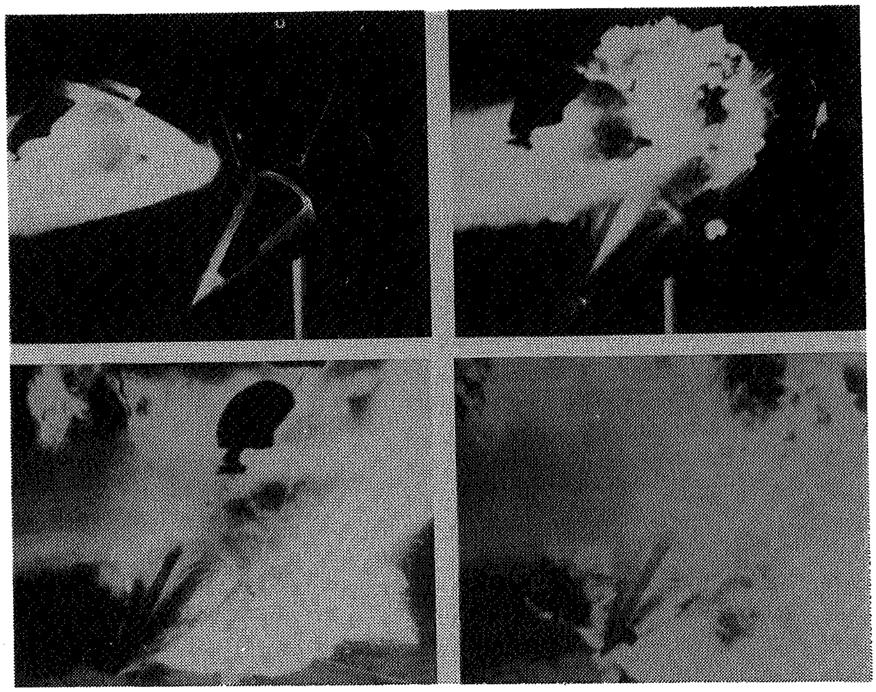


Figure 2. Impact of a Theater Missile Defense interceptor

Issues Associated with the Current Test Track

Currently, sled test velocities are theoretically limited by the combination of sled weight, drag, and thrust. With the present day techniques, the maximum theoretical velocity achievable on the Holloman test track is between 3.0 and 3.5 km/sec. In reality, sled velocities are limited by slipper wear and vibration environment along with weight, drag, and thrust resulting in theoretical velocities being impossible to achieve. To routinely obtain sled test velocities of 3.0 km/sec and higher, new ways of guiding sleds must be considered.

Aerodynamics also has a large effect on hypersonic monorail testing. The sled geometry is tailored to counteract aerodynamic lift loads, to minimize shock waves, and to prevent ram air at stagnation temperatures and pressures from entering the slipper rail gap. Structural materials and ablative or refractory coatings are selected to withstand the high enthalpy airflow encountered in the dense air at ground levels.

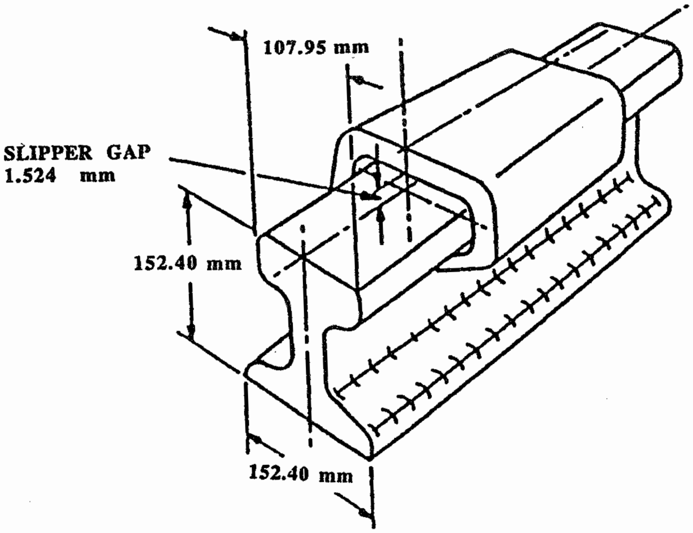


Figure 3. Test Track Slipper System

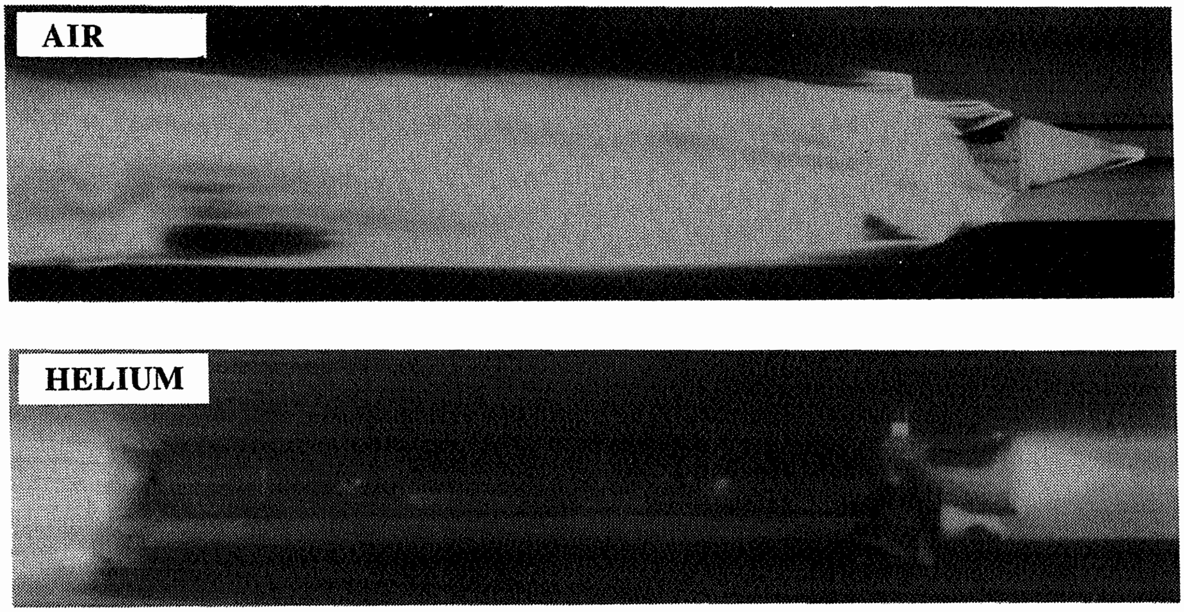
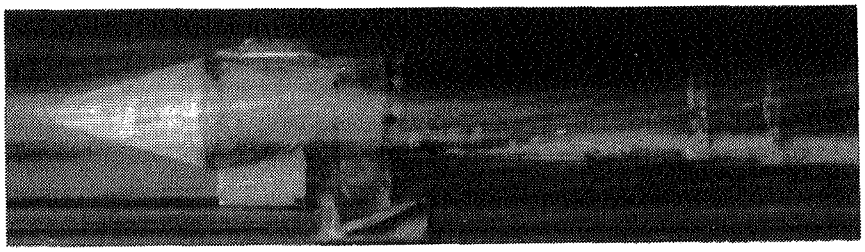


Figure 4. Image Motion Compensation Photograph of Sled in Helium Environment

Low-density operations, consisting of a helium tunnel encompassing a portion of the test rack, are also used to reduce the aerodynamic drag and aeroheating effects of hypervelocity testing. Figure 4 is an Image Motion Compensation photograph taken in a helium environment showing the cooling effect of the helium atmosphere. A slipper-rail impact can also be seen in Figure 5. It can clearly be seen in the bottom photograph that the slipper sheared from the sled bulkhead, causing a catastrophic failure. This was due to the previously discussed vibration environment.

Currently, the world land speed record of 2.71 km/sec is held by the Holloman High Speed Test Track. Sled tests in excess of 1.8 km/sec are routinely conducted and tests in excess of 2.5 km/sec are occasionally conducted with limited success, primarily due to the high vibration environment and slipper wear problems.

A promising approach to achieving the higher velocity, reducing vibration, and eliminating slipper wear is provided by magnetic levitation.



Prior to Failure

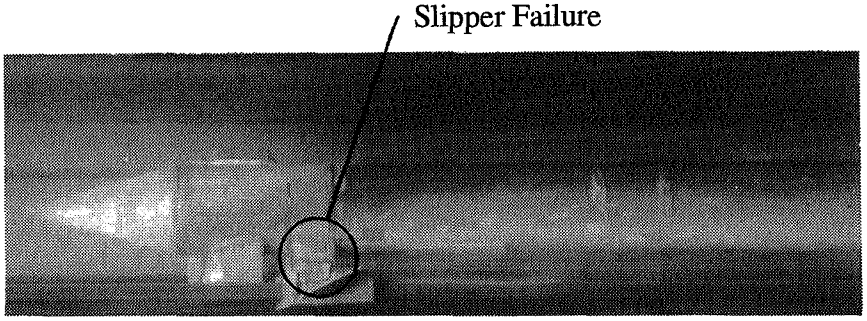


Figure 5. Slipper-Rail Impact and Slipper Failure

MAGLEV SLED APPROACH

Goal of the Maglev System

The overall goal of the Maglev sled system for the High Speed Test track is two fold. First to provide a capability for the Department of Defense, DoD, to conduct realistic hypersonic testing of warhead lethality and propulsion systems at an affordable price.

Second, to provide a capability to non DoD users, such as the Federal Railroad Administration, to test superconducting magnetic designs and fabrication, and to verify computer codes which predict dynamic magnetic fields for commercial transportation.

To achieve these goals the Holloman High Speed Test Track is being upgraded to provide magnetic levitation of payloads from 1000 kg to 25 kg with velocities ranging from subsonic to hypersonic speeds. This upgrade is required to provide higher test velocities than are achievable with the current system and to reduce the level of vibration during test. The near term approach is to accomplish this using magnetic levitation with solid rocket propulsion boosters. However, electromagnetic propulsion will be demonstrated during the upgrade. The upgraded capability will also provide magnetic braking capability.

Maglev Concept

The hypersonic Maglev sled used as a focal point of this paper is being developed under a Phase 1 contract led by General Atomics for Holloman Air Force. The Maglev sled design will continue to evolve under the Phase 2 Air Force contract, however this Phase 1 concept provides a mechanism to discuss the associated sled issues.

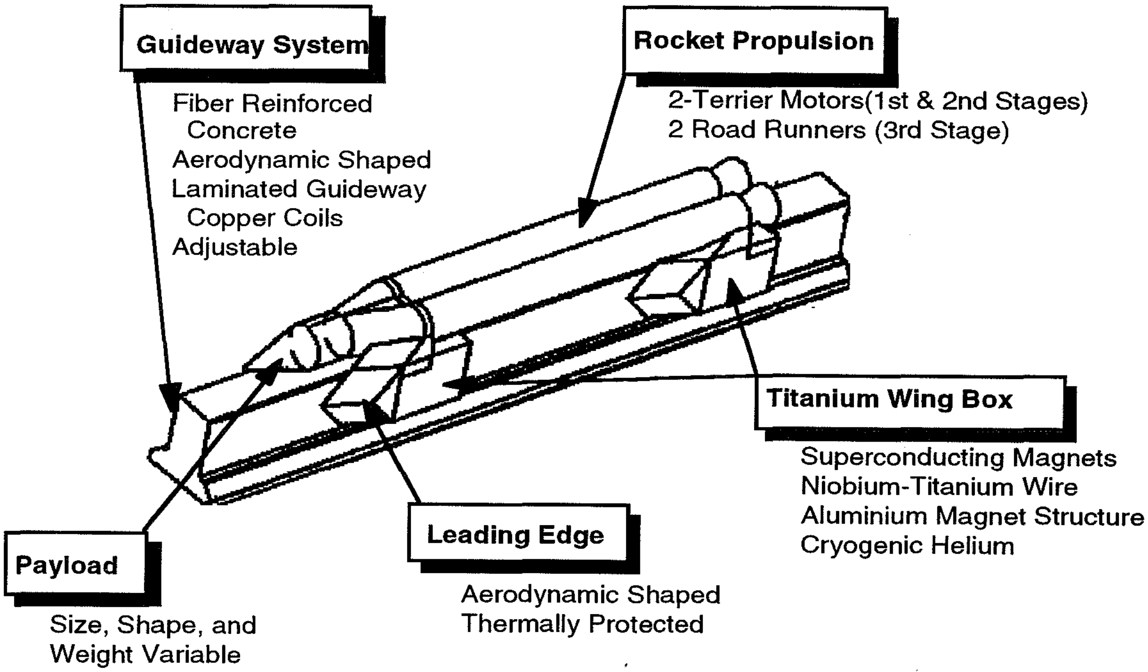


Figure 6. Phase 1 Sled Concept

The concept for a hypersonic sled is to magnetically levitate the sled by use of superconducting magnets and propel the sled along the test track using expendable solid rocket motors. Essentially, the steel slippers of the existing system are replaced with magnetic slippers. Figure 6 illustrates the Phase 1 sled concept. The sled is comprised of rocket motors, a payload for the final stage, sled-wing attachment structure, and wings. The wings are made up of a wing box that houses the magnetic system and a leading edge fairing. The left and right wing boxes, leading edges, and wing-rocket attachment structure comprise a wing assembly. Each sled has a forward and aft wing assembly. Three stages are used to propel the payload to the hypersonic test velocities. The sled is levitated over a concrete guideway which contains copper coils to transmit the fluxes generated by the superconducting magnets and allow the restoring forces which control the sled. The Phase 1 sled-guideway Maglev system is depicted in Figure 7.

The ability to achieve hypersonic maglev testing with rocket propulsion is a systems design study involving rocket thrust (thrust to weight); the magnetic system's weight and its capability to generate the required forces; and the sled's weight and its generated lift and drag forces.

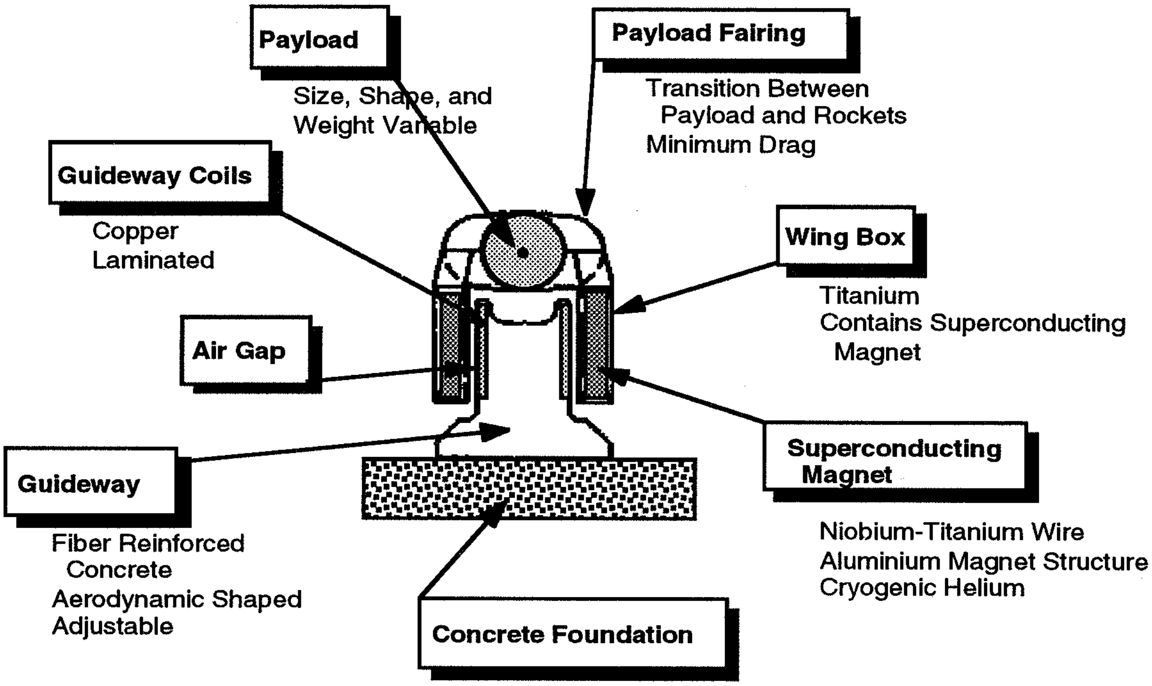


Figure 7. Maglev System

Issues Associated with Maglev Sled Development

In developing a Maglev system, optimization must occur at the system level rather than at the component level. The interplay between the component weights and the component associated forces require a careful balance to achieve an efficient system. In fact, it is require to achieve a successful system. If the sled is viewed as one of the overall Maglev system components there are several issues that have to be investigated and understood so they can be part of the overall system design.

Evolving from a captive sled (steel slipper to rail) system to a free flying system at hypersonic speeds presents unique challenges to the sled design and development, Figure 8. These challenges or issues can be categorized in broad groups such as: Aerodynamics, Flow Field definition, Stability & Control, Aeroheating, Thermal Management, Structural Design, and Integration (guideway and superconducting magnet). Each of these broad categories are composed of a subset of factors that need to be studied. The remainder of this paper will discuss these categories and the accompanying factors. System Integration/Guideway Integration by its very nature is discussed in several sections.

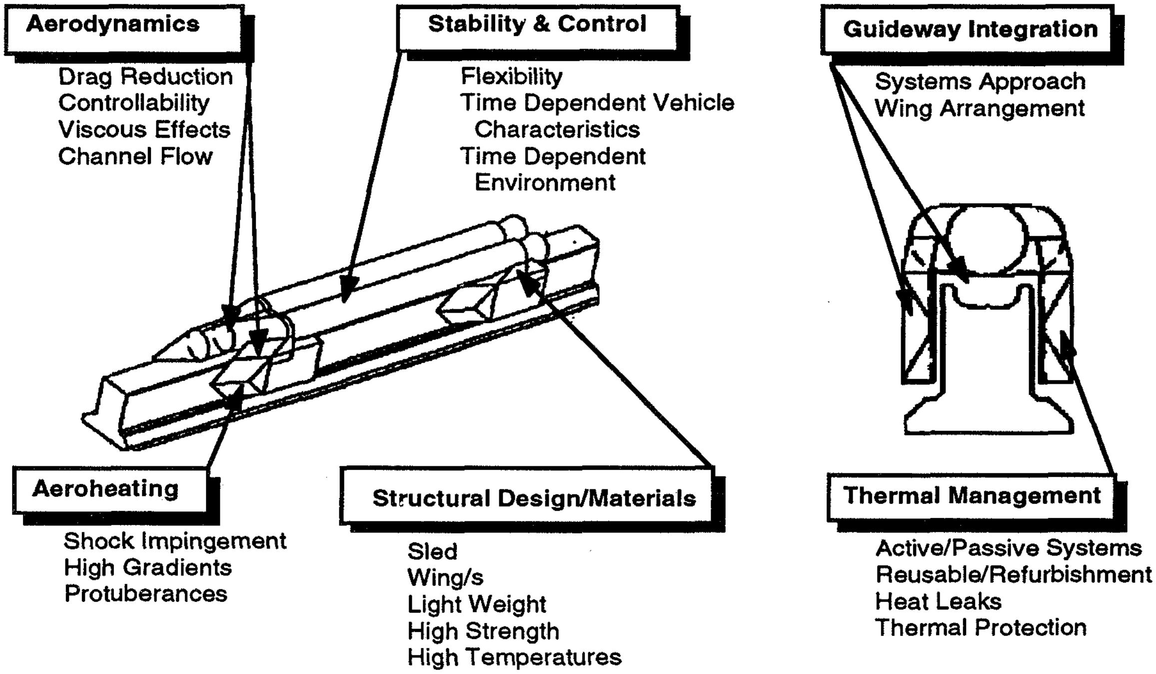


Figure 8. High Speed Sled Design Issues

Aerodynamics. In developing a hypersonic sled with magnetic levitation properties two major sled design issues are in the forefront; weight and drag. Aerodynamic design and analysis plays a major role in developing a successful system. There are several aerodynamic issues involved in sled design as shown in Figure 9, of which the major aerodynamic influence is that of sled drag. The more drag, the more propulsion power required or the less maximum speed that is achievable. Lift is also another major driver in that it imparts moments that must be resolved by the magnet system. Sled shaping is one way to reduce aerodynamic drag. Optimizing the payload to rocket fairing concept as well as how the wings attach to the sled are extremely important. Drag control and reduction also impacts the shape, radius, and sweep of the wing leading edges.

Another major aerodynamic issue is the interaction of the sled flow field with the guideway and ground plane. Flow between the wing and guideway can result in a strong shock system and choke the flow resulting in increases both in pressure and heat transfer.

In addition, reflected shocks from the guideway or ground plane can reflect back onto the sled creating forces and moments that are difficult for the magnetic system to restore. A careful system analysis of the sled and guideway is required to properly establish the correct aerodynamic configuration and how the sled should integrate with the guideway.

In evaluating this interaction, consideration must be given to whether the wings will be inside the guideway as investigated in earlier studies, or whether the wings will be outside of the guideway as selected for the Phase 1 concept. This selection has a direct impact on channel flow and magnetic performance. The orientation of the wings to the guideway; vertical, horizontal, or somewhere in between needs to be traded. In addition, the distance between the wing and guideway must be studied. All of these studies trade performance against aerodynamic forces.

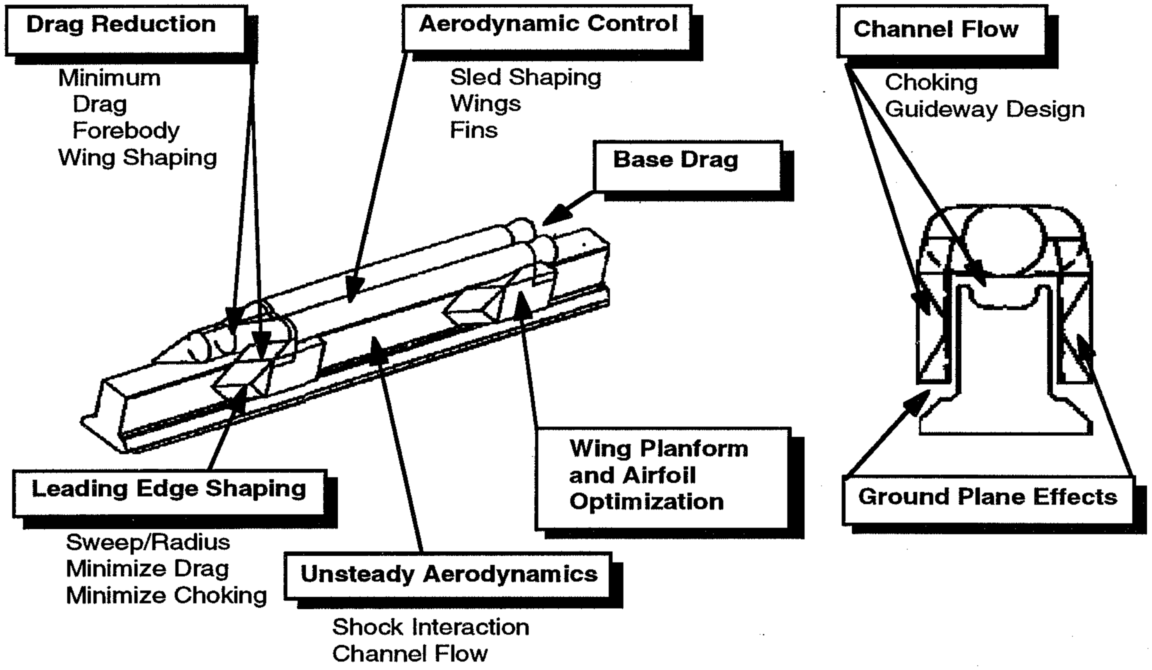


Figure 9. Aerodynamic Design and Modeling Issues

To model the resultant flow fields and capture the physics of the high speed flow requires tools other than conventional aerodynamic engineering codes. Computational Fluid Dynamics (CFD) is required to model the complex flow interactions between the sled, guideway, and ground plane. This is critical because the forces generated by reflected shocks or the viscous effects in the guideway gap can drive magnetic power requirements. These issues and requirements are indicated in Figure 10.

Computational Fluid Dynamics must be able to capture both the basic three dimensional structure of the flow around the sled which requires the ability to simulate multi-bodies, but it also must capture the viscous effects of the flow field. A computational fluid dynamics code must be able to analyze the sled from subsonic to hypersonic speeds. Also, solutions must crisply capture shock patterns and impingement including separated flow effects and heat transfer. In developing CFD solutions advanced gridding techniques will be required to capture not only the basic sled geometry, but to be able to model geometric details and the flow between the wing and the guideway. A reliable, versatile, and accurate CFD tool is a necessity for the Maglev sled design.

The importance of this capability is depicted in the flow field solution of the General Atomics feasibility study concept where the wings are located inside a guideway channel, Figure 11. This inviscid CFD solution presents the pressure flow field about the sled at 3400 m/s in an atmosphere of helium. Several features of the basic flow are evident such as the shock generated by the payload forebody and the subsequent expansion fan aft of the payload. Close inspection of the wing (with the guideway removed) shows a pressure rise associated with subsonic flow resulting from choked channel flow due to shock interactions. Also evident, though not as obvious, is the varying flow field along the wing. To correctly model the aerodynamic forces and moments of the sled in the presence of the guideway obviously requires the application of CFD.

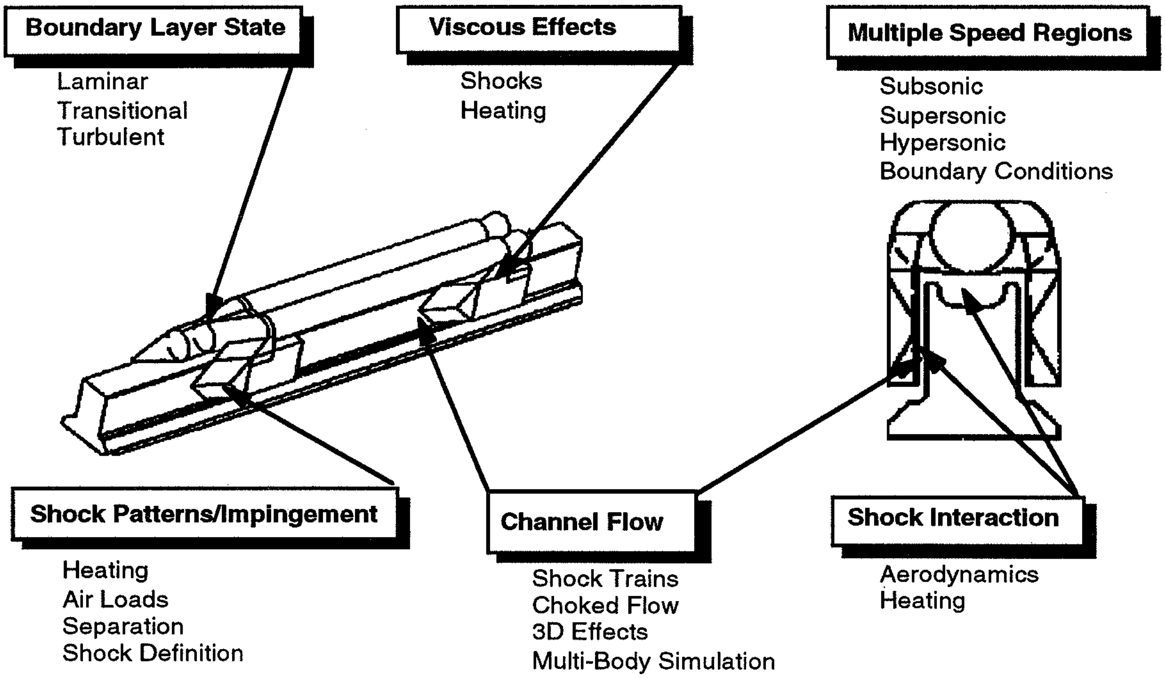


Figure 10. Flow Field Issues Associated with Sled Design

Stability & Control. Maintaining the sled in level and controllable flight with a passive (magnetic) control system while flying within an inch of a concrete guideway at hypersonic speeds is a major challenge. The only variables for the designer are aerodynamic shaping of the sled and the magnetic restoring forces.

To achieve stable and controllable flight requires definition of all the induced forces and moments due to aerodynamics, rocket propulsion, magnetic levitation, and external environments, Figure 12. In addition, transient effects such as entering and exiting a helium bag with a significantly different atmosphere, including ignition and burnout of the rocket motors must be included in the simulation model. The effects of the interaction of the sled with the guideway and ground plane must be considered.

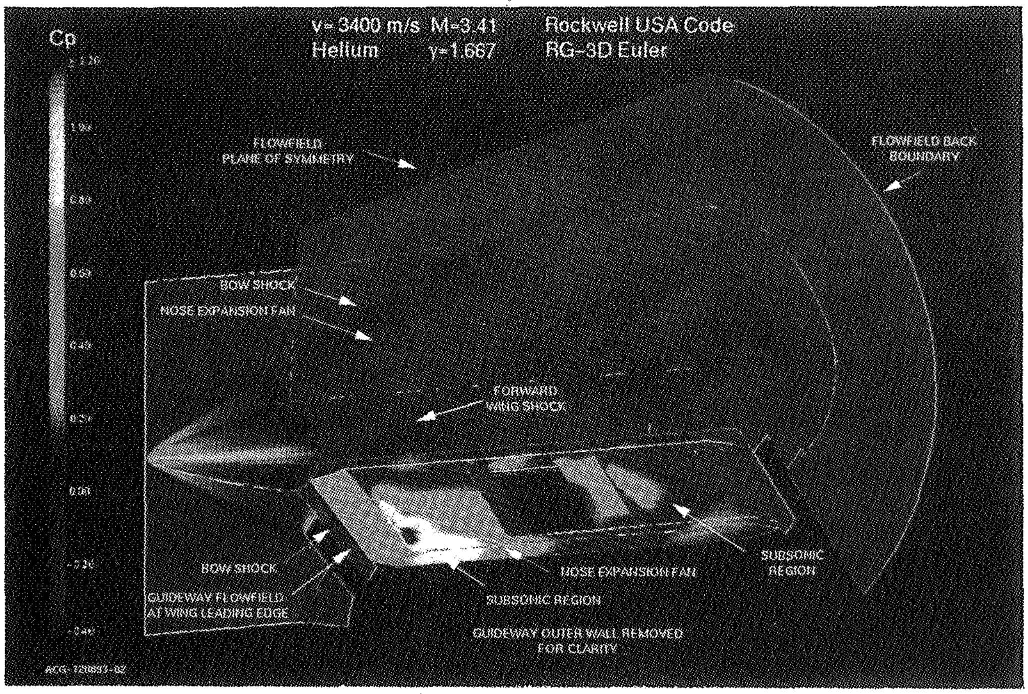


Figure 11. Pressure Flow Fields of a Sled with Guideway Effects

Time variation in forces and moments must be modeled as well as changes in overall sled weight due to expending solid rocket propellant. Simulation of these features requires a six degree-of-freedom simulator to accurately model and verify sled stability. If the sled isn't stable, changes will be required in the aerodynamic design, the sled-guideway arrangement, and/or in the magnetic power.

Aeroheating. As the speed of the sled increases into the hypersonic velocity range, heat transfer due to boundary layer forces/friction and shock impingement become an important design consideration. This requires the accurate prediction of heat transfer rates and the location and magnitude of impinging shocks. Sled design trades can be conducted to reduce heating effects by considering such design parameters as wing leading edge sweep and radius, guideway integration (guideway shaping and the wing-guideway gap), and structural attachments to the rocket motors, Figure 13. As the sled design matures, aerodynamic heating impacts due to system penetrations and protuberances associated with the superconducting magnetic system must be considered. Use of another atmosphere such as the helium tunnel at Holloman provides a reduction in both aerodynamic heating rates and aerodynamic forces. The heating rate estimates impact where and how much thermal protection is required on the sled and have a direct impact on the overall system weight.

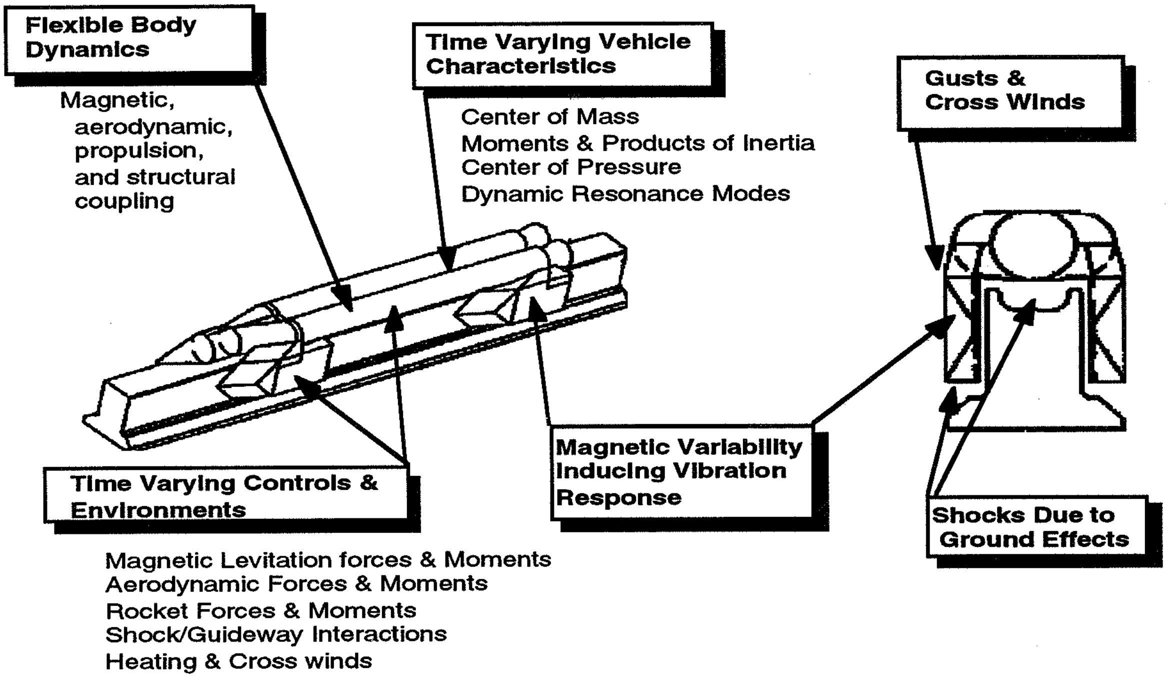


Figure 12. Stability & Control Sled Issues

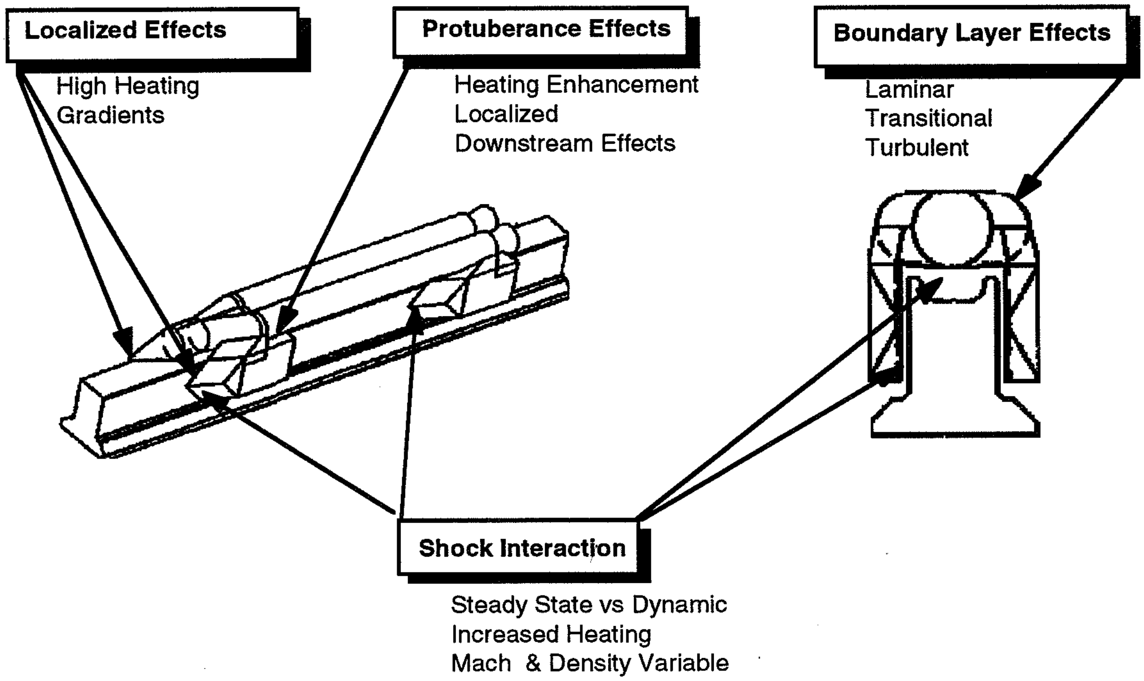


Figure 13. Aerodynamic Heating Issues

Thermal Management. Induced heating rates and loads must be accommodated to protect the basic sled structure as well as the superconducting magnets. Gradients due to shocks and the cryogenic liquids need to be included in the thermal modeling. Thermal management is challenged to protect the structure and components while minimizing the impact on the overall system weight and system refurbishment time and cost, Figure 14.

Thermal analysis must consider the transient nature of the problem where essentially the sled is in equilibrium prior to flight (Alamogordo temperature environments and cryostat temperatures) and then in a matter of seconds peak temperatures are reached. A metallic surface could see a rise of 900 °F on the side of the wing box, or a 2200°F rise on the wing leading edge in just 6 seconds. The sled must be able to withstand not only the peak temperatures, but the soak back while coasting to a stop or finally at rest.

For system operability, the desire is to maximize the use of unprotected metals by using materials such as titanium. However, leading edges and regions of high heat transfer require thermal protection. In these regions trades are required on density, reusability (ablator and susceptibility to damage), refurbishment capability (repair and replacement time), ability to attach to the structure, and material costs. Thermal analysis will require not only one and two-dimensional modeling, but possible three dimensional modeling in areas of severe thermal gradients.

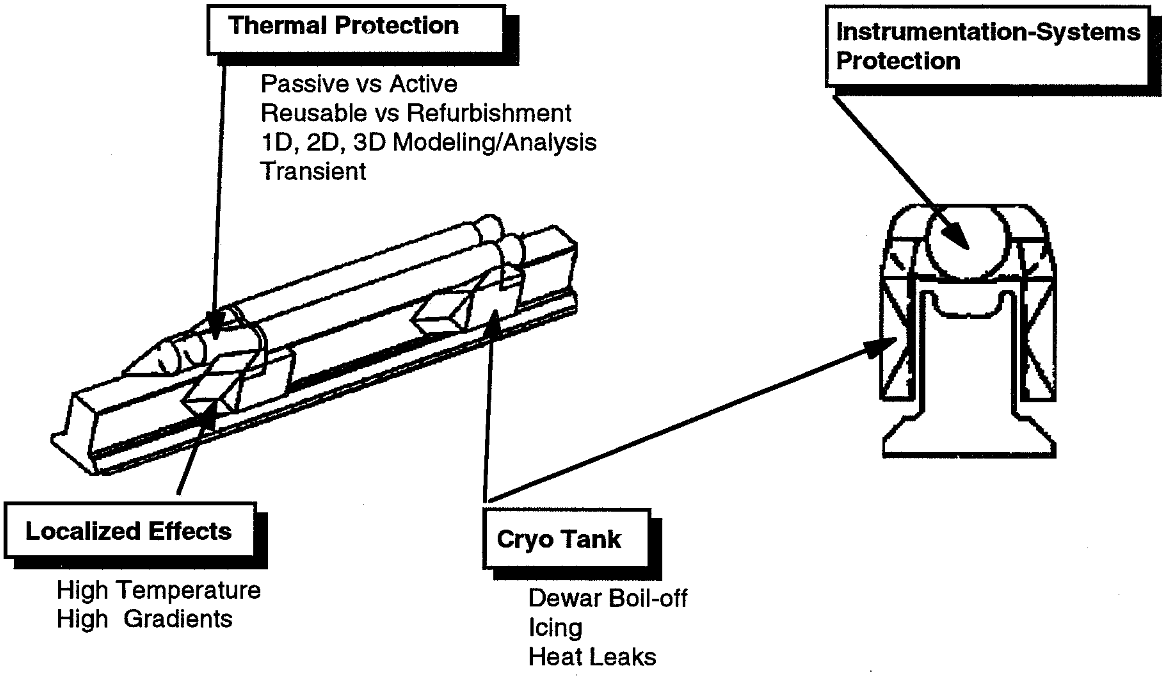


Figure 14. Thermal Management Issues

Structural Design. As mentioned in the aerodynamics discussion, weight and drag are two major design drivers. However, weight has a stronger influence on system performance (maximum velocity). The structural design or concept must strive to have the lightest weight system. Structural design and analysis must deal with some system unique issues, Figure 15. Basic construction needs to utilize non-magnetic materials which possess high strength, high temperature capability, and low density. Structural design is continually challenged to accommodate the system loads while accomplishing this with the minimum weight system. Loads from the magnet restoring forces must be transmitted from the magnets into the wing box and into the wing-rocket attachment structure to finally arrive at the rocket motor casing. Structural analysis must include all of the aerodynamic, propulsion, and magnetic forces and moments to define the total loads that the superconducting magnets must be able to restore. Stress analysis needs to trade the strength of the structural design and surface deflection limits against weight growth. In a system that is driven to obtain the lowest possible weight, care must be exercised in developing a robust but light weight design. Basic approaches of just increasing material thickness may not be the appropriate solution. Dynamic structural analysis of the sled system is required to consider the transient nature of these forces and to determine any fatigue issues. The sled experiences vibration from both aerodynamic and propulsion inputs. The long term effects of this environment has to be understood and included in the structural design. The structural design must also consider interfacing with the magnetic system so that tolerance build-up does not result in a loose magnetic installation or a crush condition. Design drawings must provide enough details to allow for quality products from both in-house and out-source manufacturing. In developing the sled design, high quality, low cost manufacturing must be achieved.

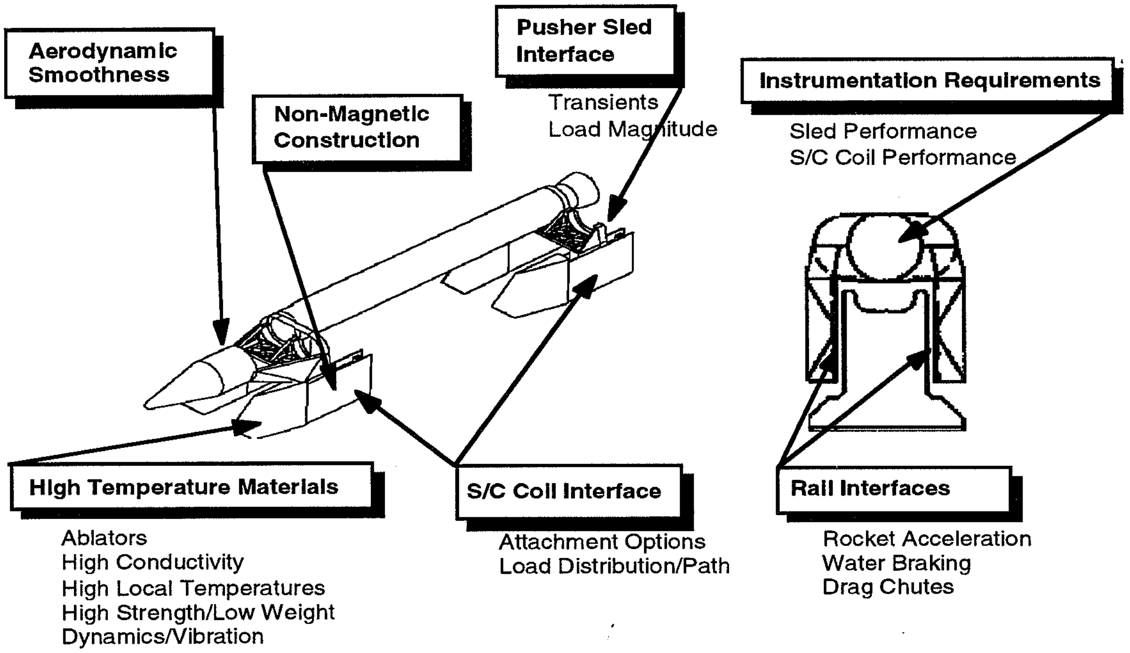


Figure 15. Structural Design Issues

SUMMARY

The Holloman High Speed Test Track has a 45 year history rich in high speed testing activities. This capability is being enhanced by the incorporation of magnetic levitation providing higher test velocities and reduced vibration. However, in the development of the hypersonic maglev sled there are several design and modeling issues that need to be addressed and understood. These issues associated with aerodynamics, flow fields, stability and control, aeroheating, thermal management, and structures/materials have been highlighted. As the Maglev sled design evolves and matures, these issues will be addressed and accommodated in the sled design.