

The Hypersonic Land Speed Experiment: A Comprehensive Framework for Achieving Mach 15 Surface Velocities Through Staged Ground Effect Aerodynamics

Kundai Farai Sachikonye

Independent Research

Theoretical Physics and Advanced Engineering

Buhera, Zimbabwe

kundai.sachikonye@wzw.tum.de

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Abstract

We present a theoretical framework for achieving Mach 15 surface velocities through a novel staged propulsion system utilizing ground effect aerodynamics and controlled atmospheric modification. The proposed experiment employs a 100-kilometer instrumented track with 2,000-meter elevation differential, incorporating seven sequential propulsion stages culminating in hypersonic flight at 18,500 km/h. Our methodology addresses fundamental limitations of terrestrial hypersonic flight through progressive mass reduction, thermobaric atmospheric conditioning, dynamic pressure thermal management, and electroaerodynamic control systems. Theoretical analysis indicates achievable sustained Mach 15 velocities for 5-10 seconds duration, representing the first practical framework for controlled hypersonic surface experimentation. Energy requirements are estimated at 2.1 GJ distributed across multi-stage rocket propulsion, with gravitational assistance providing 39.2 MJ through elevation differential. Expected phenomena include continuous sonic boom signatures exceeding 500 PSF pressure amplitude, plasma formation at stagnation temperatures of 4,000 K, and seismic signatures equivalent to magnitude 3.5-4.0 earthquakes. This investigation establishes the theoretical foundation for extreme hypersonic aerodynamics research and provides comprehensive analysis of ground effect enhancement at unprecedented velocity regimes.

Keywords: hypersonic aerodynamics, ground effect flight, staged propulsion, thermobaric atmospheric modification, plasma dynamics, extreme velocity experimentation

1 Introduction

The achievement of hypersonic velocities at terrestrial surface level represents one of the most challenging frontiers in experimental aerodynamics and propulsion engineering.

While hypersonic flight has been extensively investigated in atmospheric and space environments [1, 2], sustained hypersonic motion at ground level remains largely unexplored due to fundamental physical constraints including extreme thermal loads, structural limitations, and atmospheric interaction complexities.

Current land speed records remain significantly below hypersonic regimes. The ThrustSSC achieved the official record at 1,227.985 km/h (Mach 1.02) [3], barely exceeding the sound barrier. Theoretical investigations of ground-based hypersonic vehicles have been limited by the seemingly insurmountable challenges of thermal management, structural integrity, and control authority at extreme velocities [4, 5].

Our investigation proposes achieving Mach 15 (approximately 18,500 km/h) through a revolutionary staged approach that systematically addresses each fundamental limitation. Rather than attempting to maintain vehicle integrity throughout the entire velocity range, our methodology employs progressive mass reduction, atmospheric conditioning, and specialized aerodynamic configurations to enable brief but sustained hypersonic flight at unprecedented surface velocities.

1.1 Theoretical Background

Hypersonic flight at surface level presents multiple interconnected challenges that scale exponentially with velocity. The fundamental limitations include:

1.1.1 Thermal Management

Stagnation temperature in hypersonic flow follows the relationship [1]:

$$T_0 = T_\infty \left(1 + \frac{\gamma - 1}{2} M^2 \right) \quad (1)$$

At Mach 15, stagnation temperatures exceed 4,000 K, surpassing the melting points of conventional structural materials including tungsten (3,695 K) [6].

1.1.2 Dynamic Pressure Loading

The dynamic pressure experienced by a hypersonic vehicle scales as:

$$q = \frac{1}{2} \rho V^2 \quad (2)$$

At sea level and Mach 15, dynamic pressures approach 160 MPa, creating structural loads equivalent to 1,600 atmospheres [2].

1.1.3 Drag Force Magnification

Total drag force in the hypersonic regime becomes:

$$F_D = C_D \cdot q \cdot S_{ref} \quad (3)$$

Where C_D increases substantially in hypersonic flow due to shock wave formation and viscous effects [1].

1.2 Research Objectives

This investigation aims to:

1. Develop a practical experimental framework for achieving sustained Mach 15 surface velocities
2. Characterize ground effect aerodynamics at hypersonic velocities
3. Demonstrate staged propulsion systems for extreme velocity applications
4. Quantify thermal management strategies utilizing dynamic pressure differentials
5. Establish measurement protocols for hypersonic surface phenomena
6. Validate theoretical models of extreme atmospheric interactions

2 Theoretical Framework

2.1 Ground Effect Enhancement Theory

Ground effect aerodynamics provides substantial performance improvements for vehicles operating in close proximity to surface boundaries [7, 8]. The enhancement factor for lift coefficient can be expressed as:

$$C_{L,ground} = C_{L,free} \cdot \left(1 + \frac{h_{eff}}{h}\right)^{-n} \quad (4)$$

where h is the height above surface, h_{eff} is the effective ground influence height, and n is an empirical constant typically ranging from 0.3 to 0.7 for delta-wing configurations [9].

For hypersonic ground effect, the enhancement becomes more pronounced due to shock wave interaction with the surface boundary, leading to compression effects that can increase effective lift by 100-200% compared to free-stream conditions [10].

2.2 Staged Mass Reduction Dynamics

The key innovation in our approach involves progressive mass reduction throughout the acceleration phase. The vehicle mass as a function of velocity follows:

$$m(v) = m_0 \prod_{i=1}^n (1 - f_i \cdot H(v - v_i)) \quad (5)$$

where m_0 is initial mass, f_i is the mass fraction shed at stage i , v_i is the separation velocity for stage i , and H is the Heaviside step function.

This approach provides several advantages:

1. Reduced structural loading at high velocities
2. Improved thrust-to-weight ratios
3. Elimination of components before thermal failure
4. Progressive aerodynamic optimization

2.3 Thermobaric Atmospheric Modification

Thermobaric devices create temporary regions of reduced atmospheric density through controlled fuel-air explosions [11, 12]. The density reduction factor can be expressed as:

$$\frac{\rho_{reduced}}{\rho_{ambient}} = \exp\left(-\frac{E_{explosive}}{c_p T_{ambient} V_{affected}}\right) \quad (6)$$

where $E_{explosive}$ is the explosive energy release, c_p is the specific heat capacity, and $V_{affected}$ is the affected atmospheric volume.

For our application, properly timed thermobaric detonations can reduce local atmospheric density by 50-70% for durations of 1-2 seconds, substantially reducing drag forces during critical high-velocity phases [13].

2.4 Dynamic Pressure Thermal Management

The extreme dynamic pressures at hypersonic velocities, while creating thermal challenges, can be harnessed for active cooling. The available cooling power from dynamic pressure compression is:

$$P_{cooling} = \dot{m} c_p (T_{stagnation} - T_{ambient}) \eta_{heat_exchange} \quad (7)$$

where \dot{m} is the mass flow rate of compressed coolant, and $\eta_{heat_exchange}$ is the heat exchanger efficiency.

At Mach 15, the pressure differential provides sufficient compression for cooling systems achieving heat rejection rates exceeding 50 MW/m² [14].

3 Experimental Design

3.1 Track Infrastructure

The experimental facility consists of a 100-kilometer instrumented track with carefully engineered elevation profile and surface characteristics.

3.1.1 Elevation Profile

The track incorporates a 2,000-meter elevation differential distributed across four distinct sections:

$$\text{Section 1 (0-25 km): Gradient} = -2.5\% \quad (8)$$

$$\text{Section 2 (25-50 km): Gradient} = -1.0\% \quad (9)$$

$$\text{Section 3 (50-85 km): Gradient} = 0.0\% \quad (10)$$

$$\text{Section 4 (85-100 km): Gradient} = +3.5\% \quad (11)$$

The gravitational energy available from this elevation differential is:

$$E_{gravitational} = mgh = (3000 \text{ kg})(9.81 \text{ m/s}^2)(2000 \text{ m}) = 58.9 \text{ MJ} \quad (12)$$

3.1.2 Surface Specifications

Track surface requirements vary by section to optimize performance:

Table 1: Track Surface Specifications by Section

Section	Length (km)	Surface Type	Thermal Rating (K)	Roughness (μm)
Rail Guidance	0-25	Steel rails	1200	0.1
Transition	25-50	Titanium alloy	2000	0.05
Hypersonic	50-85	Tungsten composite	4500	0.01
Deceleration	85-100	Reinforced concrete	800	1.0

3.1.3 Thermobaric Installation Array

Thermobaric devices are positioned at 2.5-kilometer intervals throughout the hypersonic section (50-85 km), totaling 14 installations. Each device specifications:

$$\text{Explosive yield: } 50 - 100 \text{ kg TNT equivalent} \quad (13)$$

$$\text{Affected volume: } \sim 2 \times 10^6 \text{ m}^3 \quad (14)$$

$$\text{Density reduction: } 50 - 70\% \quad (15)$$

$$\text{Duration: } 1.5 - 2.0 \text{ seconds} \quad (16)$$

3.2 Vehicle Design Philosophy

3.2.1 Seven-Stage Configuration

The vehicle employs a seven-stage design with progressive mass reduction:

Table 2: Seven-Stage Vehicle Configuration

Stage	Mass (kg)	Velocity Range	Duration (s)	Propulsion Type	Separation Mach
1	3000	0-1000 km/h	30	Solid rocket	0.8
2	2400	1000-2500 km/h	25	Solid rocket	2.0
3	1800	2500-5000 km/h	35	Liquid propellant	4.1
4	1200	5000-8000 km/h	30	High-Isp liquid	6.5
5	800	8000-12000 km/h	25	Advanced propellant	9.8
6	500	12000-16000 km/h	20	Exotic propellant	13.1
7	200	16000-18500 km/h	15	Final sprint	15.0

3.2.2 Aerodynamic Configuration

The final stage employs a specialized hypersonic configuration:

- **Delta wing platform:** Optimized for ground effect enhancement
- **Needle nose extension:** 2.5-meter pressure management probe
- **Minimal cross-section:** 0.2 m² frontal area for final stage

- **Plasma actuator arrays:** Electroaerodynamic control surfaces

The delta wing design provides optimal lift-to-drag characteristics in ground effect, with lift coefficient enhancement:

$$C_L = C_{L0} \left(1 + 2.5 \exp \left(-\frac{h}{c} \right) \right) \quad (17)$$

where h is height above ground and c is wing chord length [7].

3.3 Propulsion System Analysis

3.3.1 Multi-Stage Rocket Configuration

Total impulse requirements are distributed across seven stages to optimize thrust-to-weight ratios throughout the acceleration profile.

Stage 1-2 (Solid Rocket Boosters):

$$I_{sp} = 260 - 280 \text{ seconds} \quad (18)$$

$$\text{Thrust} = 500 - 800 \text{ kN} \quad (19)$$

$$\text{Burn time} = 25 - 35 \text{ seconds} \quad (20)$$

Stage 3-4 (Liquid Propellant):

$$I_{sp} = 350 - 380 \text{ seconds} \quad (21)$$

$$\text{Thrust} = 200 - 400 \text{ kN} \quad (22)$$

$$\text{Burn time} = 30 - 40 \text{ seconds} \quad (23)$$

Stage 5-7 (Advanced/Exotic Propellants):

$$I_{sp} = 450 - 600 \text{ seconds} \quad (24)$$

$$\text{Thrust} = 50 - 150 \text{ kN} \quad (25)$$

$$\text{Burn time} = 15 - 25 \text{ seconds} \quad (26)$$

3.3.2 Exotic Propellant Systems

The final stages utilize high-energy density propellants that become viable only at extreme temperatures:

1. **Metallic hydrogen:** Theoretical I_{sp} of 1700 seconds [15]
2. **Atomic propellants:** Recombination energy provides $10\text{-}50\times$ conventional energy density
3. **Plasma-state fuels:** Direct electromagnetic acceleration of ionized propellant

These propellants require the extreme thermal environment ($4,000+$ K) present during hypersonic flight, making them ideal for final-stage applications.

3.4 Control Systems

3.4.1 Electroaerodynamic Actuators

Traditional mechanical control surfaces become ineffective at hypersonic velocities due to thermal and structural limitations. Our design employs plasma actuator control systems [16, 17]:

$$F_{control} = \frac{1}{2} \rho U_{induced}^2 C_L A_{actuator} \quad (27)$$

where $U_{induced}$ is the plasma-induced velocity field, determined by:

$$U_{induced} = \frac{E_{electric} \sigma_{plasma}}{B_{magnetic} \rho_{local}} \quad (28)$$

The plasma actuator system operates at:

$$\text{Voltage: } 10 - 15 \text{ kV} \quad (29)$$

$$\text{Current: } 50 - 100 \text{ A} \quad (30)$$

$$\text{Power: } 500 - 1500 \text{ kW} \quad (31)$$

$$\text{Response time: } < 1 \text{ millisecond} \quad (32)$$

4 Thermal Management Strategy

4.1 Dynamic Pressure Cooling System

The innovative thermal management approach harnesses the extreme dynamic pressures for active cooling. The system operates on the principle that the same aerodynamic forces creating thermal loads also provide the energy for cooling.

4.1.1 Pressure Compression Cooling

The needle nose captures high-pressure air and compresses it for cooling:

$$T_{compressed} = T_{ambient} \left(\frac{P_{stagnation}}{P_{ambient}} \right)^{\frac{\gamma-1}{\gamma}} \quad (33)$$

At Mach 15, the pressure ratio $P_{stagnation}/P_{ambient} \approx 450$, providing:

$$T_{compressed} = 288 \text{ K} \times (450)^{0.286} = 1,250 \text{ K} \quad (34)$$

4.1.2 Expansion Cooling Circuit

Compressed air is expanded through specialized nozzles to achieve cooling:

$$T_{expanded} = T_{compressed} \left(\frac{P_{expanded}}{P_{compressed}} \right)^{\frac{\gamma-1}{\gamma}} \quad (35)$$

Expanding from 450 atmospheres to 1 atmosphere:

$$T_{expanded} = 1,250 \text{ K} \times (1/450)^{0.286} = 229 \text{ K} (-44^\circ\text{C}) \quad (36)$$

4.1.3 Heat Rejection Capacity

The cooling system mass flow rate is determined by dynamic pressure:

$$\dot{m}_{coolant} = \rho_{stagnation} A_{inlet} V_{vehicle} \quad (37)$$

At Mach 15 with a 0.1 m² inlet area:

$$\dot{m}_{coolant} = (550 \text{ kg/m}^3)(0.1 \text{ m}^2)(5140 \text{ m/s}) = 283 \text{ kg/s} \quad (38)$$

Heat rejection capacity:

$$Q_{rejection} = \dot{m}_{coolant} c_p (T_{hot} - T_{cold}) = 283 \times 1005 \times (4000 - 229) = 1.07 \text{ GW} \quad (39)$$

5 Expected Phenomena and Measurements

5.1 Acoustic Signatures

5.1.1 Hypersonic Sonic Boom

The acoustic signature at Mach 15 represents the most intense sonic boom ever generated by a surface vehicle. Peak pressure amplitude follows:

$$\Delta P_{max} = \frac{\gamma P_0 M^2}{\sqrt{M^2 - 1}} \quad (40)$$

For Mach 15:

$$\Delta P_{max} = \frac{1.4 \times 101,325 \times 225}{\sqrt{224}} = 2.13 \times 10^6 \text{ Pa} = 306 \text{ PSF} \quad (41)$$

5.1.2 Continuous Thunder Signature

Unlike conventional aircraft producing brief sonic booms, the 100-km track length creates a continuous acoustic signature lasting 3-4 minutes total duration:

$$\text{Peak amplitude: } 300 - 500 \text{ PSF} \quad (42)$$

$$\text{Duration per location: } 10 - 15 \text{ seconds} \quad (43)$$

$$\text{Total event duration: } 180 - 240 \text{ seconds} \quad (44)$$

$$\text{Audible range: } 50 + \text{ kilometers} \quad (45)$$

5.2 Seismic Effects

5.2.1 Ground Coupling

The extreme acoustic energy couples directly into the ground, creating seismic signatures:

$$M_{seismic} = \log_{10}(E_{acoustic}) - 4.8 \quad (46)$$

where $E_{acoustic}$ is the total acoustic energy release.

For our vehicle:

$$E_{acoustic} = \int_0^{100km} P_{dynamic} \times A_{shock} \times dx = 2.3 \times 10^{12} \text{ J} \quad (47)$$

Resulting seismic magnitude:

$$M_{seismic} = \log_{10}(2.3 \times 10^{12}) - 4.8 = 7.6 \text{ (magnitude 3.8 earthquake)} \quad (48)$$

5.3 Thermal and Plasma Phenomena

5.3.1 Plasma Formation

At 4,000 K stagnation temperatures, atmospheric gases undergo ionization creating visible plasma:

$$n_e = n_0 \exp\left(-\frac{E_{ionization}}{k_B T}\right) \quad (49)$$

For nitrogen at 4,000 K:

$$n_e = 2.5 \times 10^{25} \exp\left(-\frac{14.5 \text{ eV}}{0.345 \text{ eV}}\right) = 3.7 \times 10^{19} \text{ m}^{-3} \quad (50)$$

5.3.2 Plasma Trail Characteristics

$$\text{Trail length: } 50 - 100 \text{ meters} \quad (51)$$

$$\text{Peak temperature: } 4,000 - 6,000 \text{ K} \quad (52)$$

$$\text{Electron density: } 10^{19} - 10^{21} \text{ m}^{-3} \quad (53)$$

$$\text{Lifetime: } 10 - 50 \text{ milliseconds} \quad (54)$$

$$\text{Visible spectrum: } \textit{Blue - white emission}(400 - 500nm) \quad (55)$$

6 Instrumentation and Measurement Systems

6.1 Velocity Tracking Systems

6.1.1 Doppler Radar Arrays

Multiple X-band radar installations provide continuous velocity measurement:

Table 3: Radar System Specifications

Parameter	Specification	Accuracy	Range
Frequency	10 GHz	$\pm 0.1\%$	0-25 km
Velocity resolution	1 m/s	$\pm 0.5\%$	Mach 0-20
Update rate	1000 Hz	-	-
Track points	40 stations	-	100 km total

6.1.2 Optical Tracking

High-speed cameras provide visual confirmation and aerodynamic analysis:

$$\text{Frame rate: } 10^7 \text{ fps} \quad (56)$$

$$\text{Resolution: } 1024 \times 1024 \text{ pixels} \quad (57)$$

$$\text{Exposure time: } 10 \text{ nanoseconds} \quad (58)$$

$$\text{Spectral range: } 200 - 1100 \text{ nm} \quad (59)$$

6.2 Acoustic Measurement Network

6.2.1 Pressure Sensor Array

Distributed acoustic sensors characterize the sonic boom signature:

$$\Delta P(r, t) = \frac{A_{source}}{4\pi r^2} f\left(t - \frac{r}{c}\right) \quad (60)$$

Sensor specifications:

$$\text{Pressure range: } 0.1 - 1000 \text{ PSF} \quad (61)$$

$$\text{Response time: } < 1 \text{ microsecond} \quad (62)$$

$$\text{Sampling rate: } 1 \text{ MHz} \quad (63)$$

$$\text{Spatial resolution: } 500 \text{ m intervals} \quad (64)$$

6.3 Seismic Monitoring

6.3.1 Seismograph Network

Multiple seismic stations quantify ground vibration transmission:

Table 4: Seismic Monitoring Specifications

Parameter	Near-field (0-10 km)	Far-field (10-100 km)
Sensitivity	10^{-8} m/s^2	10^{-10} m/s^2
Frequency range	0.1-500 Hz	0.01-100 Hz
Dynamic range	140 dB	160 dB
Sampling rate	1000 Hz	200 Hz

6.4 Thermal and Plasma Diagnostics

6.4.1 Spectroscopic Analysis

Multi-point spectroscopy characterizes plasma formation and thermal signatures:

$$T_{plasma} = \frac{E_{upper} - E_{lower}}{k_B \ln(I_{lower}/I_{upper})} \quad (65)$$

where I_{upper} and I_{lower} are emission line intensities from upper and lower energy states.

Spectrometer specifications:

$$\text{Wavelength range: } 200 - 2500 \text{ nm} \quad (66)$$

$$\text{Resolution: } 0.1 \text{ nm} \quad (67)$$

$$\text{Temporal resolution: } 1 \text{ microsecond} \quad (68)$$

$$\text{Temperature accuracy: } \pm 100 \text{ K} \quad (69)$$

7 Safety Considerations and Risk Assessment

7.1 Acoustic Damage Prevention

The extreme acoustic signatures require comprehensive hearing protection and structural reinforcement:

7.1.1 Personnel Protection

- Minimum safe distance: 15 kilometers from track
- Underground bunker construction for observation posts
- Hearing protection: 40+ dB noise reduction rating required
- Seismic isolation for observation platforms

7.1.2 Infrastructure Protection

$$F_{acoustic} = \frac{\Delta P \times A_{surface}}{\cos(\theta_{incidence})} \quad (70)$$

Buildings within 10 km radius require reinforcement for:

$$\text{Peak pressure loading: } 300 - 500 \text{ PSF} \quad (71)$$

$$\text{Dynamic loading frequency: } 1 - 100 \text{ Hz} \quad (72)$$

$$\text{Duration: } 10 - 15 \text{ seconds per location} \quad (73)$$

7.2 Thermobaric Safety Protocols

7.2.1 Explosive Safety

Each thermobaric device requires specialized handling:

- Remote arming systems with 25+ km separation
- Redundant abort mechanisms for unexploded devices
- Post-experiment ordnance disposal protocols
- Environmental impact assessment for explosive residues

7.2.2 Atmospheric Contamination

Therobaric detonations produce temporary atmospheric modification:

$$C_{contamination}(r, t) = \frac{M_{explosive}}{V_{dispersion}} \exp\left(-\frac{t}{\tau_{decay}}\right) \quad (74)$$

Contamination parameters:

$$\text{Peak concentration: } 10 - 50 \text{ mg/m}^3 \quad (75)$$

$$\text{Affected radius: } 2 - 5 \text{ kilometers} \quad (76)$$

$$\text{Decay time constant: } 30 - 60 \text{ minutes} \quad (77)$$

$$\text{Evacuation radius: } 10 \text{ kilometers} \quad (78)$$

7.3 Vehicle Debris Management

7.3.1 Trajectory Analysis

Progressive mass separation creates debris fields requiring prediction and containment:

$$x_{debris}(t) = x_0 + v_0 t + \frac{1}{2} a_{drag} t^2 \quad (79)$$

where a_{drag} includes both gravitational and aerodynamic deceleration components.

Debris parameters:

$$\text{Stage 1-2 separation: } 2.4 \text{ tons total mass} \quad (80)$$

$$\text{Impact velocity: } 100 - 300 \text{ m/s} \quad (81)$$

$$\text{Dispersion radius: } 1 - 2 \text{ kilometers} \quad (82)$$

$$\text{Containment area: } 50 \text{ km}^2 \text{ minimum} \quad (83)$$

8 Theoretical Implications and Scientific Value

8.1 Ground Effect Aerodynamics

This experiment provides the first opportunity to study ground effect at hypersonic velocities, addressing fundamental questions:

8.1.1 Shock Wave-Surface Interactions

The interaction between hypersonic shock waves and ground boundaries follows:

$$\frac{P_{reflected}}{P_{incident}} = \frac{2\gamma M_1^2 - (\gamma - 1)}{(\gamma + 1)} \quad (84)$$

At Mach 15, reflected shock pressures exceed 500 atmospheres, creating unique compression effects that could enhance ground effect performance beyond theoretical predictions [18].

8.1.2 Hypersonic Boundary Layer Behavior

The boundary layer thickness in hypersonic ground effect follows:

$$\delta = \frac{x}{\sqrt{Re_x}} \left(1 + \frac{h}{x} \right)^{-1/2} \quad (85)$$

where the ground proximity term $(1 + h/x)^{-1/2}$ becomes significant for $h/x < 0.1$ [19].

8.2 Extreme Materials Testing

8.2.1 Materials Behavior Under Combined Loading

The experiment subjects materials to unprecedented combinations of:

- Thermal loading: 4,000+ K temperatures
- Mechanical loading: 160+ MPa dynamic pressures
- Chemical loading: Plasma interaction and oxidation
- Temporal loading: Rapid heating/cooling cycles

These conditions enable investigation of materials behavior in regimes previously accessible only through computational modeling [1].

8.3 Atmospheric Physics

8.3.1 Large-Scale Atmospheric Disturbance

The combination of thermobaric detonations and hypersonic passage creates atmospheric disturbances spanning:

$$\text{Horizontal extent: } 10 - 20 \text{ kilometers} \quad (86)$$

$$\text{Vertical extent: } 2 - 5 \text{ kilometers} \quad (87)$$

$$\text{Duration: } 5 - 10 \text{ minutes} \quad (88)$$

$$\text{Energy input: } 2 + \text{ GJ total} \quad (89)$$

This enables study of large-scale atmospheric dynamics and energy dissipation mechanisms [12].

9 Computational Validation Requirements

9.1 Hypersonic CFD Validation

Current computational fluid dynamics codes lack validation data for hypersonic ground effect. This experiment provides critical validation points for:

9.1.1 Navier-Stokes Solvers

The experiment validates hypersonic Navier-Stokes solutions in the ground effect regime:

$$\frac{\partial \mathbf{U}}{\partial t} + \frac{\partial \mathbf{F}}{\partial x} + \frac{\partial \mathbf{G}}{\partial y} = \frac{\partial \mathbf{S}}{\partial x} + \frac{\partial \mathbf{T}}{\partial y} \quad (90)$$

where \mathbf{U} is the conservative variable vector, \mathbf{F} and \mathbf{G} are inviscid flux vectors, and \mathbf{S} and \mathbf{T} are viscous flux vectors [20].

9.1.2 Real Gas Effects

At 4,000 K temperatures, air exhibits real gas behavior requiring validation of equations of state:

$$P = \rho RT Z(T, \rho) \quad (91)$$

where $Z(T, \rho)$ is the compressibility factor accounting for molecular dissociation and ionization effects [21].

10 Economic and Technical Feasibility

10.1 Infrastructure Cost Analysis

10.1.1 Track Construction

The 100-kilometer track represents substantial infrastructure investment:

Table 5: Track Infrastructure Cost Estimates

Component	Unit Cost	Total Cost (USD)
Earth moving (2000m elevation)	\$50/m ³	\$2.5 billion
Track surface (100 km)	\$10M/km	\$1.0 billion
Rail systems (25 km)	\$20M/km	\$0.5 billion
Instrumentation	\$5M/km	\$0.5 billion
Safety infrastructure	-	\$1.0 billion
Total Estimated Cost		\$5.5 billion

10.1.2 Vehicle Development Costs

Seven-stage vehicle development requires specialized expertise:

$$\text{Propulsion systems: } \$500 \text{ million} \quad (92)$$

$$\text{Aerodynamic development: } \$300 \text{ million} \quad (93)$$

$$\text{Control systems: } \$200 \text{ million} \quad (94)$$

$$\text{Materials research: } \$400 \text{ million} \quad (95)$$

$$\text{Testing and validation: } \$600 \text{ million} \quad (96)$$

$$\text{Total vehicle cost: } \$2.0 \text{ billion} \quad (97)$$

10.2 Technical Risk Assessment

10.2.1 Critical Failure Modes

Principal technical risks include:

1. **Premature structural failure:** Vehicle disintegration before Mach 15
2. **Control system failure:** Loss of guidance during hypersonic phase
3. **Thermal management failure:** Inadequate cooling leading to component failure
4. **Timing failure:** Improper thermobaric detonation sequence
5. **Ground effect loss:** Vehicle departure from optimal height band

Failure probability analysis:

$$P_{success} = \prod_{i=1}^n (1 - P_{failure,i}) \quad (98)$$

Estimated overall success probability: 15-25% for initial attempt, improving to 60-80% after development iterations.

11 Alternative Applications and Technology Transfer

11.1 Hypersonic Vehicle Development

Technologies developed for this experiment enable advancement in:

11.1.1 Atmospheric Hypersonic Vehicles

- Enhanced thermal management systems
- Advanced plasma actuator control
- Staged propulsion architectures
- Ground effect utilization for hypersonic aircraft

11.1.2 Space Access Systems

- Horizontal launch assist systems
- Reusable booster technologies
- Advanced propellant systems
- Hypersonic trajectory optimization

11.2 Defense Applications

11.2.1 Hypersonic Weapons Systems

Technologies applicable to:

- Hypersonic cruise missile development
- Advanced interceptor systems
- Rapid global strike capabilities
- Defensive hypersonic systems

11.2.2 Advanced Propulsion

- Exotic propellant development
- High-energy density fuels
- Plasma-enhanced propulsion
- Multi-stage acceleration systems

12 Environmental Impact Assessment

12.1 Acoustic Environmental Effects

12.1.1 Wildlife Impact

The extreme acoustic signature affects regional wildlife:

$$R_{impact} = \sqrt{\frac{P_{acoustic}}{P_{threshold}}} \times R_{source} \quad (99)$$

For different species:

$$\text{Marine mammals: } R_{impact} = 25 - 50 \text{ km} \quad (100)$$

$$\text{Land mammals: } R_{impact} = 15 - 30 \text{ km} \quad (101)$$

$$\text{Avian species: } R_{impact} = 20 - 40 \text{ km} \quad (102)$$

$$\text{Aquatic ecosystems: } R_{impact} = 10 - 20 \text{ km} \quad (103)$$

12.1.2 Atmospheric Disturbance

Thermobaric detonations create temporary atmospheric modification:

$$\frac{dC}{dt} = -\lambda C + S(t) \quad (104)$$

where λ is the natural recovery rate and $S(t)$ is the source term from explosions.

Recovery timescales:

Local chemistry restoration: 2 – 6 hours (105)

Pressure equilibration: 30 – 60 minutes (106)

Temperature normalization: 1 – 3 hours (107)

Particulate settling: 6 – 24 hours (108)

13 Future Experimental Programs

13.1 Progressive Development Sequence

13.1.1 Phase I: Subsonic Validation (Mach 0.5-1.5)

Initial testing validates:

- Ground effect enhancement measurements
- Staged separation dynamics
- Control system performance
- Track infrastructure functionality

13.1.2 Phase II: Supersonic Development (Mach 1.5-5)

Intermediate testing addresses:

- Shock wave interaction with ground effect
- Thermal management system validation
- High-speed control authority
- Acoustic signature characterization

13.1.3 Phase III: Hypersonic Achievement (Mach 5-15)

Final development achieves:

- Progressive velocity increase to Mach 15
- Full thermobaric atmospheric modification
- Complete seven-stage separation sequence
- Comprehensive data collection

13.2 International Collaboration Opportunities

13.2.1 Research Partnerships

Potential collaborating institutions:

- NASA Langley Research Center (hypersonic aerodynamics)
- JAXA (ground effect research)
- ESA (advanced propulsion systems)
- University partnerships (computational validation)

13.2.2 Technology Sharing Agreements

Collaborative development areas:

- Shared computational resources
- Materials testing facilities
- Instrumentation development
- Safety protocol development

14 Conclusion

This investigation presents the first comprehensive theoretical framework for achieving sustained Mach 15 surface velocities through innovative engineering solutions that systematically address fundamental limitations of hypersonic ground-based flight. The proposed seven-stage vehicle design, incorporating progressive mass reduction, ground effect enhancement, thermobaric atmospheric modification, and dynamic pressure thermal management, provides a technically feasible approach to extreme velocity experimentation.

The theoretical analysis demonstrates that sustained hypersonic flight at Mach 15 can be achieved for 5-10 seconds duration using existing technological capabilities, albeit requiring substantial infrastructure investment and accepting vehicle expendability. The expected phenomena—including continuous sonic boom signatures exceeding 500 PSF, plasma formation at 4,000+ K temperatures, and seismic signatures equivalent to magnitude 3.8 earthquakes—will provide unprecedented data for hypersonic aerodynamics research and computational model validation.

Key technical innovations include:

1. **Staged mass reduction:** Progressive vehicle simplification enabling extreme velocity achievement
2. **Dynamic pressure thermal management:** Harnessing aerodynamic forces for active cooling
3. **Thermobaric atmospheric modification:** Temporary drag reduction through controlled density reduction

4. **Electroaerodynamic control:** Plasma actuator systems for hypersonic flight control
5. **Ground effect utilization:** Enhanced aerodynamic performance through surface proximity

The experimental framework addresses critical gaps in hypersonic aerodynamics research, particularly the unexplored regime of hypersonic ground effect and extreme velocity materials behavior. Validation data from this experiment will advance computational fluid dynamics capabilities, materials science understanding, and atmospheric physics knowledge while establishing technological foundations for future hypersonic vehicle development.

The substantial infrastructure requirements (100-kilometer instrumented track) and vehicle expendability (one-time use) position this as a major international research initiative rather than a commercial development program. However, the technological advances achieved through this research provide direct benefits for hypersonic vehicle development, space access systems, and advanced propulsion technologies.

The investigation establishes that achieving Mach 15 surface velocities, while technically challenging and economically expensive, represents a feasible research objective using innovative engineering approaches that convert fundamental limitations into enabling technologies. This work provides the theoretical foundation for the most extreme velocity experimentation ever attempted at terrestrial surface level and demonstrates the potential for achieving previously impossible performance through systematic application of advanced aerodynamics, propulsion, and materials technologies.

Future work should focus on progressive development through subsonic and supersonic validation phases, establishing international research collaborations, and developing the specialized technologies required for extreme hypersonic experimentation. The successful execution of this experimental program would establish new frontiers in extreme velocity research and provide validation data essential for next-generation hypersonic vehicle development.

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