SHARP-B2: Flight Test Objectives, Project Implementation, and Initial Results.

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Key words: SHARP, UHTC, Ultra-High Temperature Ceramics,

On September 28, 2000 the SHARP-B2 flight experiment was launched from Vandenberg Air Force Base, California. SHARP-B2 is the 2nd Ballistic flight test in the SHARP (Slender Hypervelocity Aerothermodynamic Research Probes) program which develops and tests new thermal protection materials and sharp body concepts.

The flight tested Ultra-High Temperature Ceramics (UHTCs), which may radically change the design and performance of future aerospace vehicles. The new designs may overturn an age-old tenet of aerodynamics: that blunt-body aerospace vehicles, but not those with sharp leading edges, can survive the searing temperatures created as the vehicles tear through the atmosphere. Sharp leading edges offer numerous advantages over the blunt-body design currently in use. They could allow a space shuttle or crew return vehicle to maneuver in space more like an airplane and potentially allow astronauts to return to Earth from anywhere on orbit. They may allow improved astronaut safety by decreasing the risk of aborting into the ocean. They may reduce the electromagnetic interference that causes the communications blackouts that plague reentering blunt-body space vehicles. Reducing the amount of drag could lead to a reduction in propulsion requirements. Planetary probes could make use of sharp-body technology for aerobraking and to maximize their maneuvering capability.

SHARP-B2 was a joint effort among NASA Ames, Sandia National Laboratories, the U.S. Air Force and the U.S. Army. It was funded by the Pathfinder Program at NASA's Marshall Space Flight Center. The SHARP-B2 payload was carried aboard a U.S. Air Force Minuteman III missile carrying a modified Mk 12A reentry vehicle (RV), which blasted off from Vandenberg Air Force Base near Lompoc, CA, at 3:01 a.m. PDT on Sept. 28. The RV was equipped with four 5.1-inch-long strakes, or sharp leading edges. Each strake contained three UHTCs: $ZrB_2/SiC/C$; ZrB_2/SiC; and HfB_2/SiC.

Once it reached an altitude of about 400 nautical miles, the RV was released, returning through Earth's atmosphere at speeds exceeding Mach 22. One pair of strakes was designed to retract just before reaching temperatures high enough to cause the material to begin ablating. The other pair was designed to retract shortly after ablation began, at an expected temperature of nearly 5,100 degrees Fahrenheit. Sensors in the strakes measured how closely performance matched pre-flight calculations, and data was successfully collected throughout the 23-minute flight. A parachute was deployed (but not fully inflated) and the RV splashed down in a lagoon at the Kwajalein missile range in the Pacific Ocean. Within 3 hours radar track analysis showed ocean entry to be precisely at the latitude/longitude coordinates estimated during pre-flight simulation. An hour later a ship was deployed by the Army to

recover the reentry vehicle, which was recovered in 165 feet of water, just 500 feet from its planned splashdown point. This is the first RV recovery in over a decade.

The RV impacted the ocean three times faster than expected, but this did not damage the strakes. All four strakes were intact. The four HfB_2/SiC aft-strake segments suffered similar, multiple fractures. Two of the four mid segments (ZrB_2/SiC) fractured, and the four front segments (ZrB_2/SiC/C) did not fracture. There was no physical evidence at all of severe heating on the strakes. Analysis of these results is still in progress, but initial findings are included below, subject to further clarification as analysis progresses.

To date only the aft-segments of the flight articles have been analyzed. Strength limiting defects, such as large grained, hafnium diboride-rich agglomerates were observed post-flight. Temperatures measured by the thermocouple sensors show that temperatures were drastically lower than expected, but the thermal gradient is much higher than expected. Radar data was analyzed and shows that the first fracture occurred at 14.5 seconds, just 2.2 seconds prior to strake retraction. Post flight analysis leads us to believe that rarefied flow effects may have delayed significant heating to lower altitudes, explaining the lower temperatures, higher thermal gradients and higher stresses, and causing fractures.

Complete analysis of the other SHARP-B2 strake segments is in progress. Work is underway with CFD codes (ASC and GASP) to resolve differences between aerothermal predictions and flight results, and to try and incorporate the rarefied flow effects. Detailed results will be published for the appropriate audience when available. Ames will continue efforts to improve the aerothermal predictive models and the thermostructural models. We also will continue to study the performance requirements for SHARP aerospace mission applications. Materials development will be continued on these and other UHTC materials. We plan to continue to our ground based testing in the arc jet facilities, as well as pursue additional flight test experiments. SHARP- B2 strongly reinforced the value added by recovering the flight hardware, and future experiments will be designed for material recovery as well.

SHARP-B2

Flight Test Objectives, Project Implementation, and Initial Results

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January 22, 2001

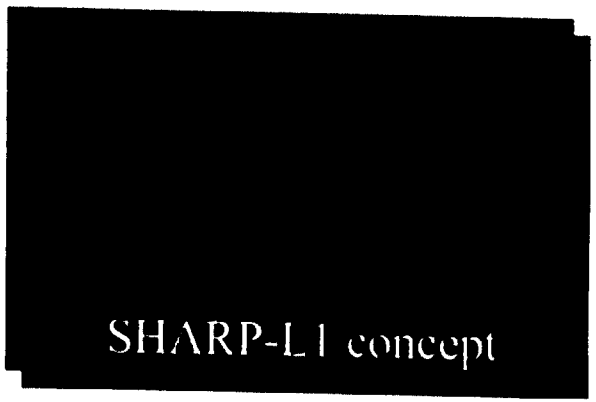
SHARP-B2 Presentation Outline

SHARP: *Slender Hypervelocity Aerothermodynamic Research Probe*

- Purpose of the SHARP Program
  - SHARP Program - goals, progress, & selected benefit: impact on crew safety
  - Flight Objectives for B2
- SHARP-B2 Flight Experiment: Project Implementation
  - Hardware Design
  - Mission Scenario
- Initial Results
  - Launch & Recovery Highlights
  - Analysis to date
- Key Lessons Learned
- Next Steps

SHARP Program Goals

- Develop and validate thermal protection systems for a new class of Reusable Launch Vehicles (RLV), Crew Transfer Vehicles (CTV), & planetary exploration vehicles.
  - Volume optimized sharp body hypersonic vehicles. Break through the blunt body design limitations imposed by TPS.
  - Increase safety and performance
    - Increase maneuverability
    - Increase time for safe abort to orbit*
    - Triple out-of-orbit cross range
    - Reduce propulsion requirements by lowering drag
    - Limit the electromagnetic interference that causes the communications blackouts on re-entry



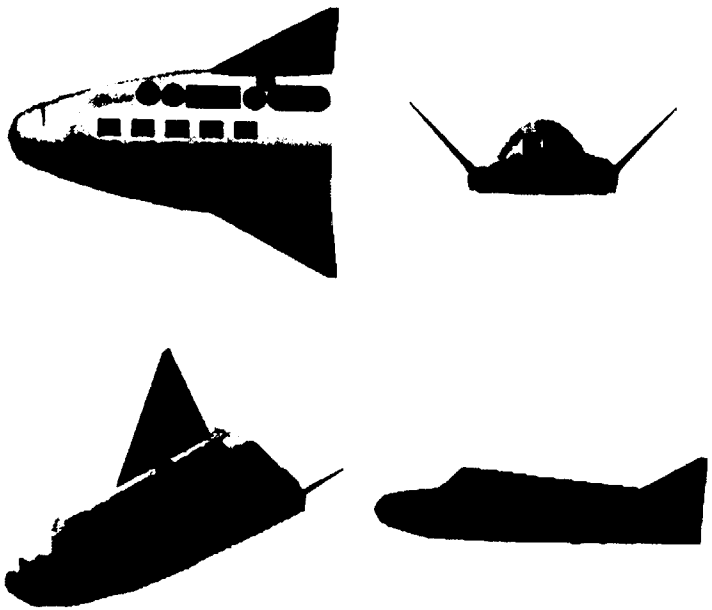
SHARP-L1 concept

Progress in SHARP Program to date

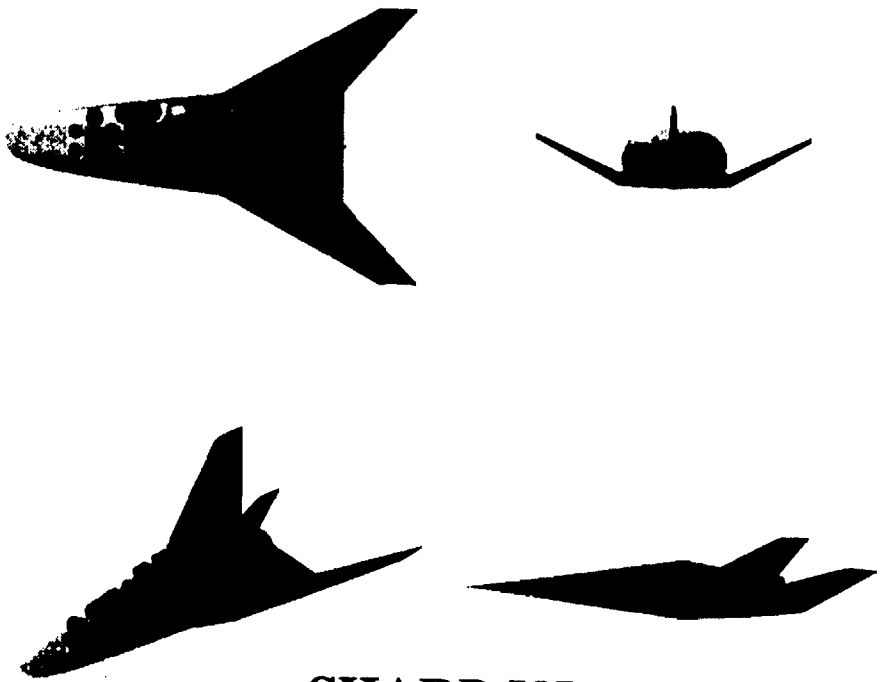
- Early 90's - present:
  - Ground based research: computer modeling, material development and initial characterization, Arc Jet testing
- 1997: SHARP-B1 (1st Ballistic Flight)
- 1999 - present: SHARP-L1 (1st Lifting Flight) Advanced Concept Development
- 2000: SHARP-B2 (2nd Ballistic Flight) and SHARP Crew Transfer Vehicle Systems Analysis

SHARP-B2

Selected Benefits of SHARP vehicle - CTV study



HL-20

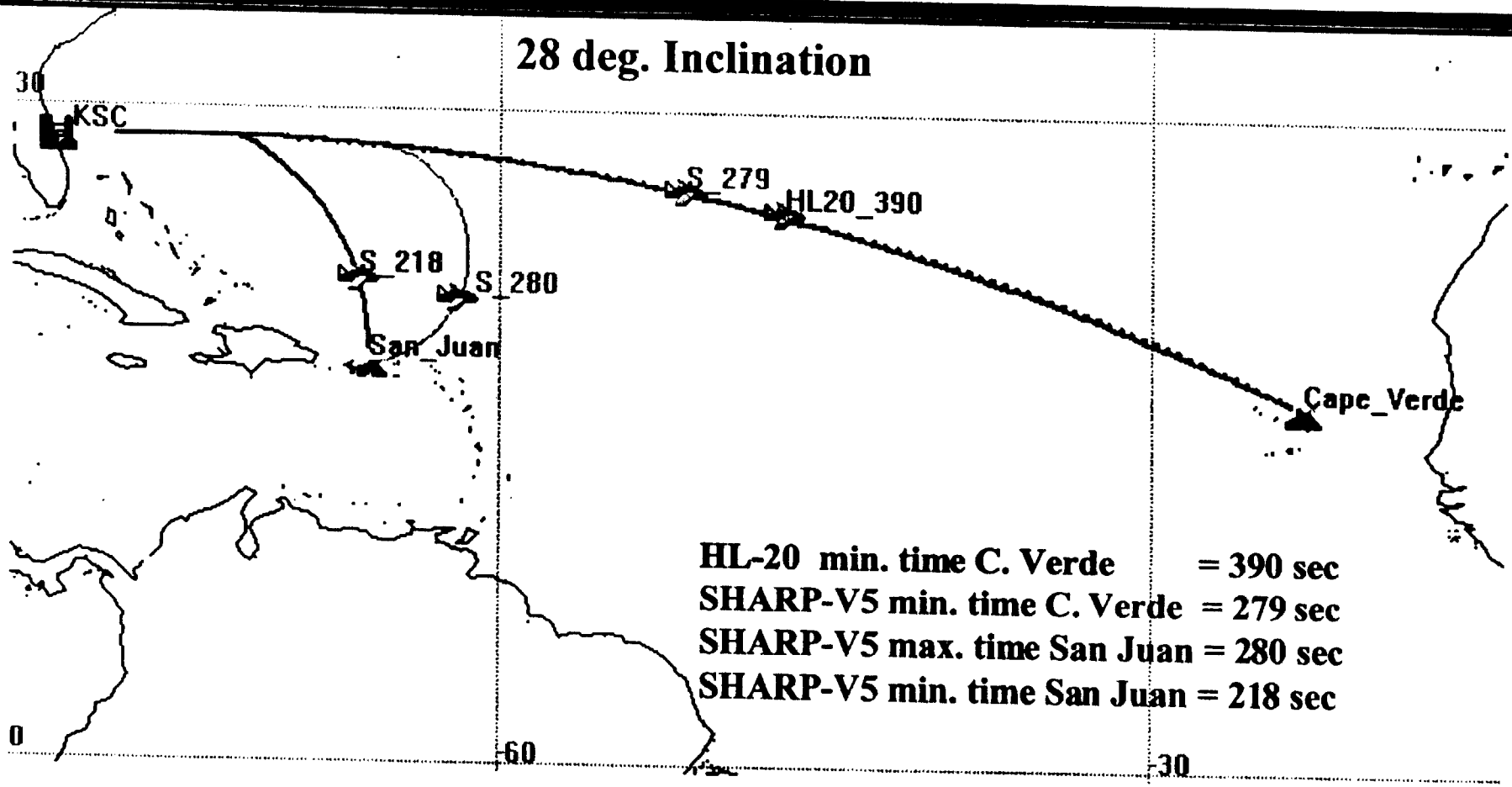


SHARP-V5

Ames has performed a systems analysis study comparing the features of a SHARP CTV to HL-20, (LaRC 1993 publication). Publications pending, Reuther, Kinney et. al.

SHARP-B2

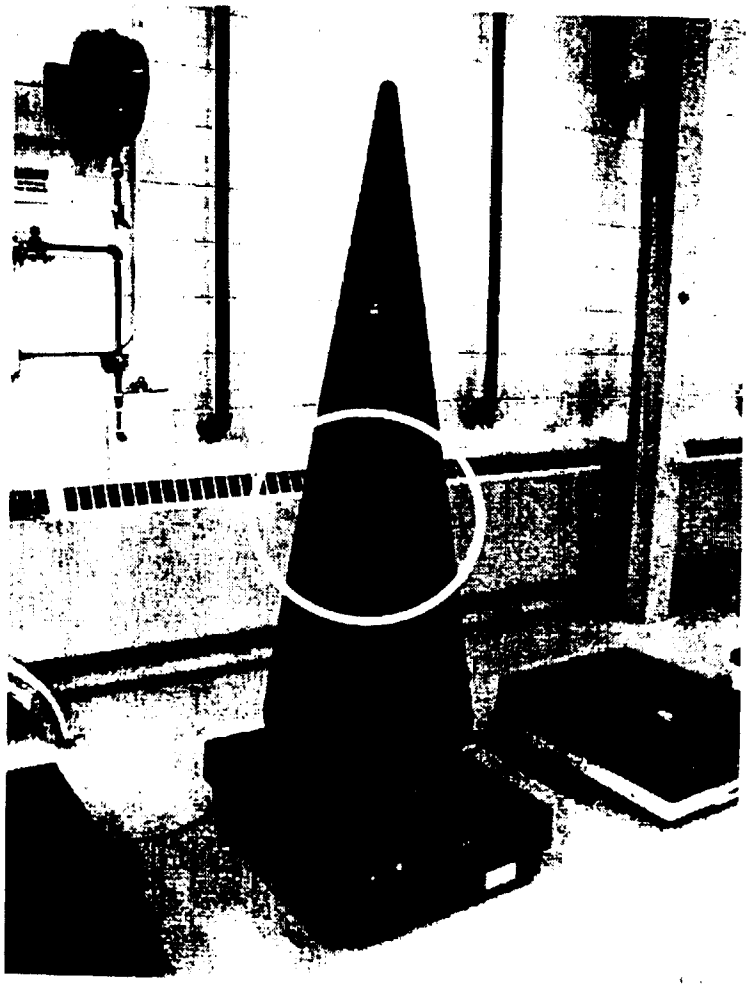
Potential Benefit - Impact On Crew Safety



SHARP CTV increases capability of landing on a runway in the event of a failure during launch. 390 - 218 = 172 seconds improvement. The results of the CTV study show the potential of minimizing the need to abort into the ocean.

SHARP-B2 Flight Hardware

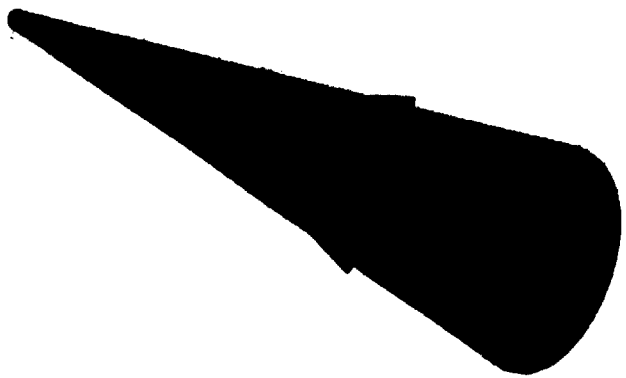
SHARP-B1 May 21, 1997



SHARP-B2 Sept. 28, 2000

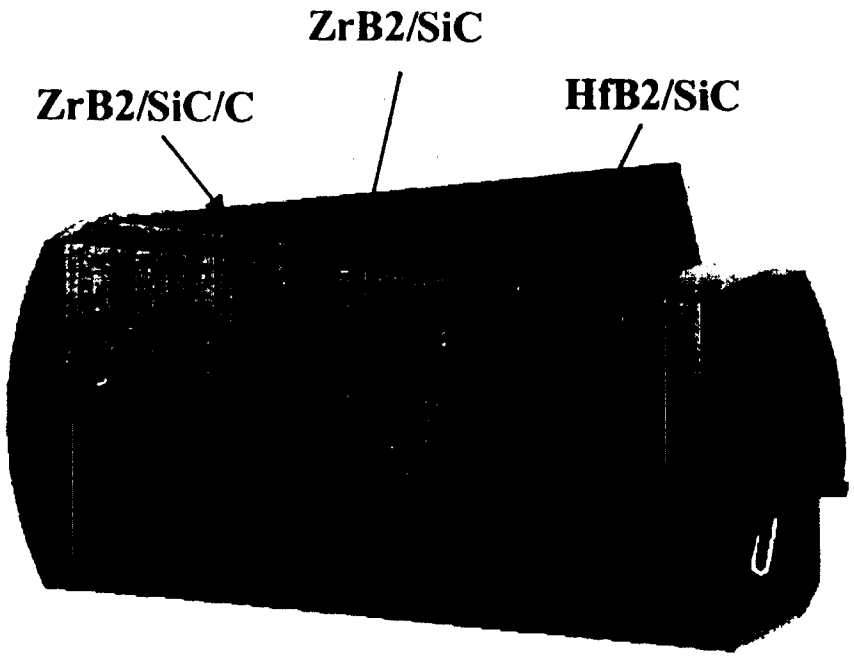
SHARP-B2 B2 Project Flight Objectives

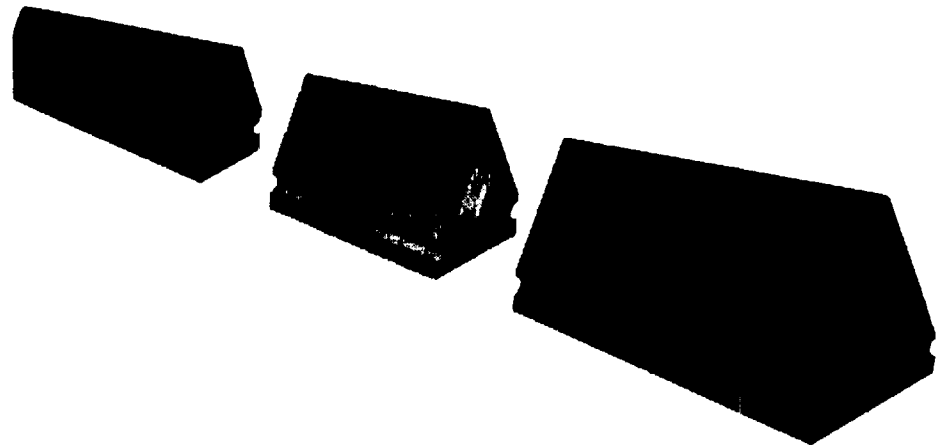
- Primary : Demonstrate the material performance of a UHTC sharp (1 mm radius) leading edge and attachment structure near the strake aerothermal performance constraint.
- Secondary: Validate thermal structural analytical models with flight and post-flight results to advance UHTC TRL's.

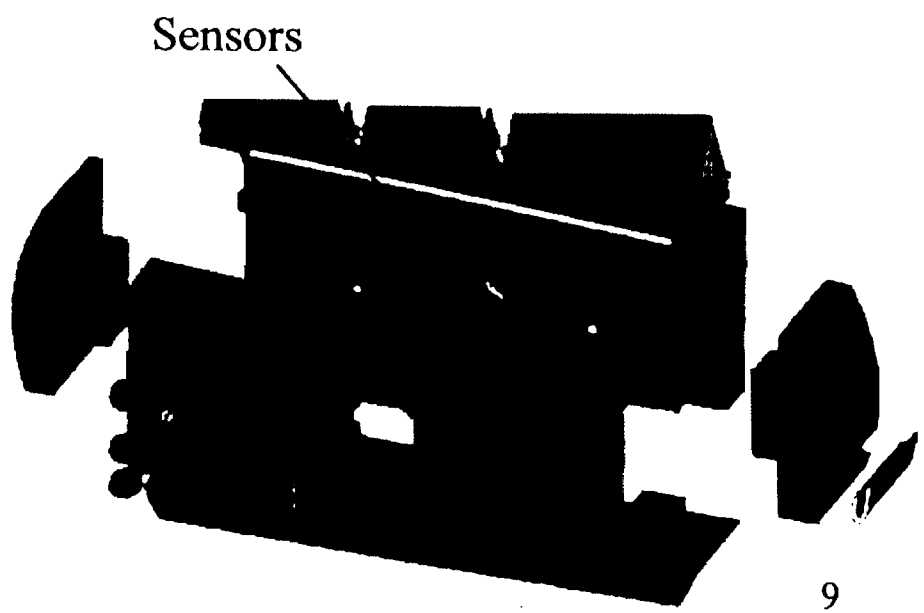


SHARP-B2

Strake Design

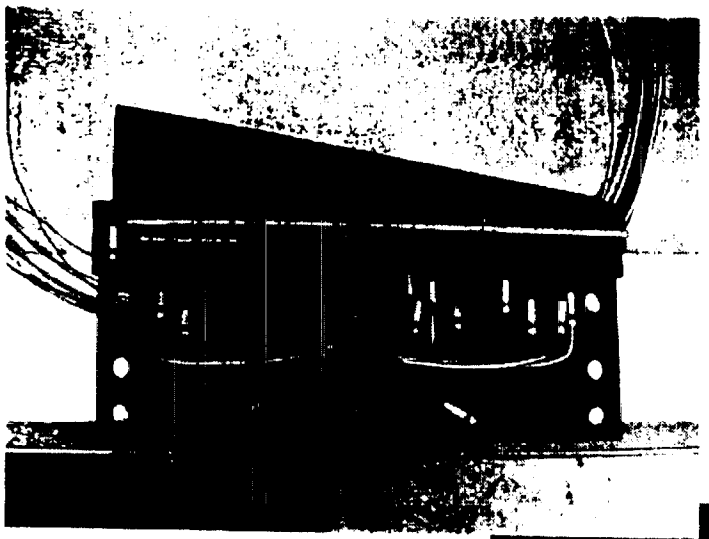


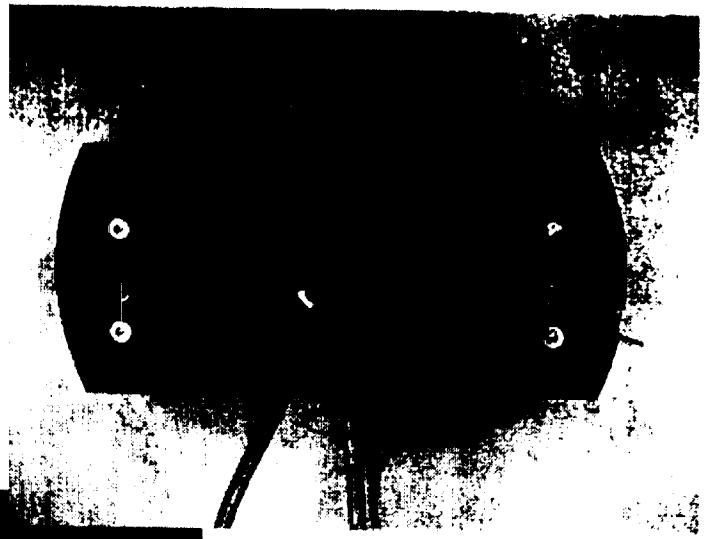


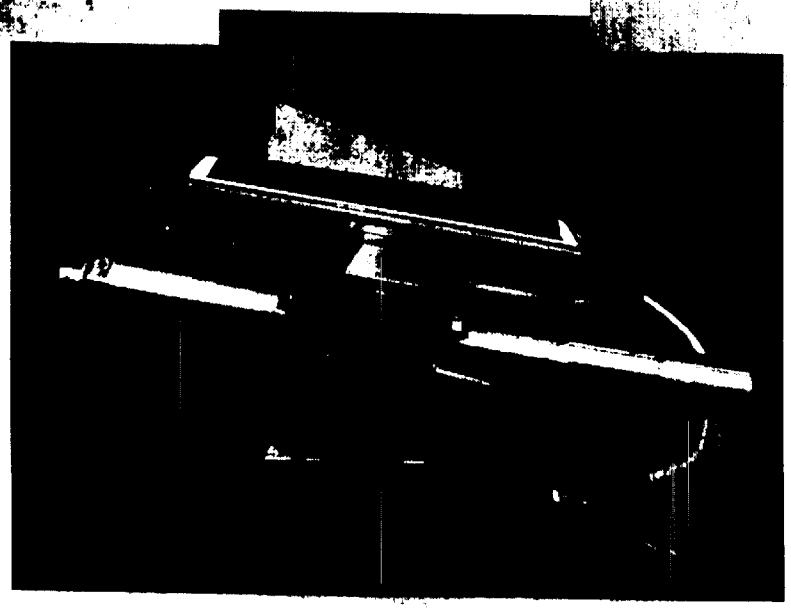


SHARP-B2

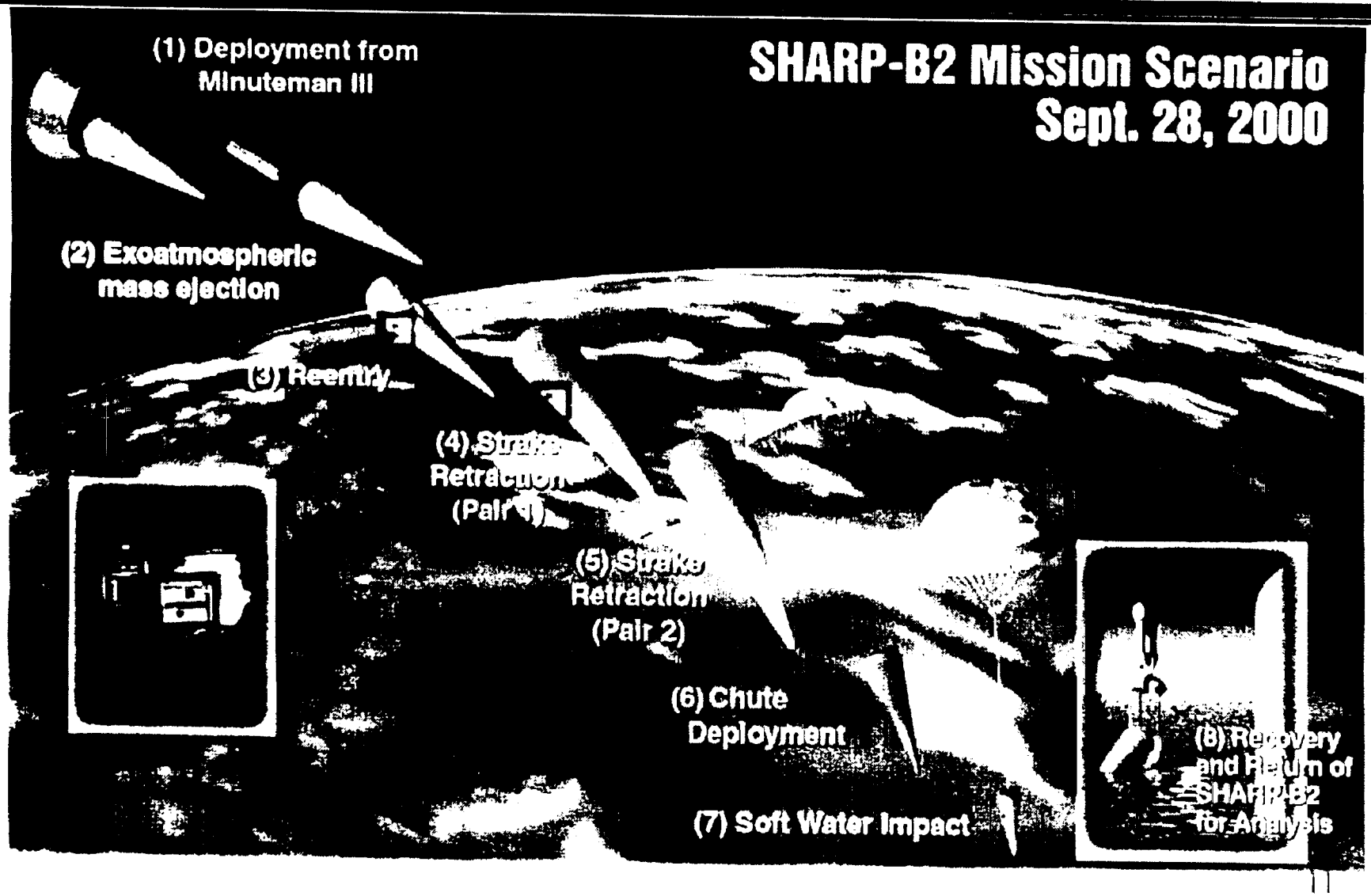
Strake Hardware







SHARP-B2


SHARP-B2 Mission Scenario
Sept. 28, 2000
(1) Deployment from Minuteman III
(2) Exoatmospheric mass ejection
(3) Reentry
(4) Strake Retraction (Pair 1)
(5) Strake Retraction (Pair 2)
(6) Chute Deployment
(7) Soft Water Impact
(8) Recovery and Return of SHARP-B2 for Analysis

SHARP-B2

Launch & Recovery Highlights

- Launched September 28, 2000 3:01 a.m. from VAFB.
- Tracked with 3 radar systems.
- Full retraction on strake #4 took longer than expected.
- Main chute malfunction caused vehicle to impact nearly 3X faster than expected, but minimal damage to strakes.
- 100% data collection on 140 channels.
- Vehicle recovered from a depth of 165 feet, approximately 500 feet from predicted impact point on October 1, 2000.

SHARP-B2

Recovery

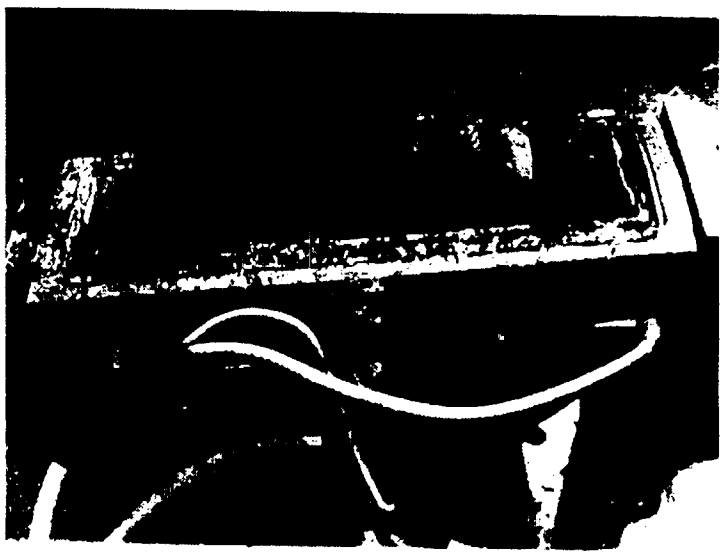
SHARP-B2 Initial Results

- Recovered flight hardware shows us that:
  - All four aft-strake segments (HfB2/SiC) suffered similar, multiple fractures. First fracture at 14.5 seconds, retractions at 16.7 seconds and 18.4 seconds.
  - 2 mid segments (ZrB2/SiC) fractured (2nd retraction).
  - 4 front segments (ZrB2/SiC/C) did not fracture.
- No evidence of severe heating damage (e.g. ablation, spallation or burning) was observed.
- Actual temperatures measured by TC's in strakes were 41% to 121% lower than expected.
- Heat flux 60% less than expected.
- Thermal gradient on aft strake higher than expected.

SHARP-B2 Post-Flight Strake Inspection

Pair 1 (47.9 km)

Pair 2 (43.3 km)



Initial Analysis - Work in Progress

- HfB2/SiC strake segments analyzed first.
  - The most likely cause of fracture is over-stress of material, with numerous flaws including large grained, hafnium diboride-rich agglomerates.
  - These strength-limiting defects in material lot are present on fracture surface.
  - Strakes with sensors fractured first.
  - Fracture patterns are consistent with predicted volumes of high stress.
- Rarefied flow effects may delay significant heating to lower altitudes, which may explain lower temperatures and produce higher thermal gradients and stresses.

Key Lessons Learned

- Recovery of materials much more valuable than we knew. Hardware tells you so much more than sensors alone.
- Quick Project cycle (1/99 - 1/01) allows for quick product development cycle - improve it and move on.
- Flight data is critical for advancing new technology development efforts because it tests our analytical and design assumptions.
- "Pure success results from mediocre goals" NASA Administrator, Dan Goldin, 1/11/01. We pushed it.

Next Steps

- Complete SHARP-B2 Post-Flight Analysis
  - Analyze other strake segments
  - Resolve differences between aerothermal predictions and flight results
  - Understand stresses experienced in flight
  - Publish results
- Continue SHARP Program
  - Improve aerothermal predictive models & thermostructural models
  - Understand performance requirements for SHARP aerospace applications (lifting vs. ballistic…)
  - Continue materials development
  - Arc Jet facility modifications
- Test, test, test, both ground and flight