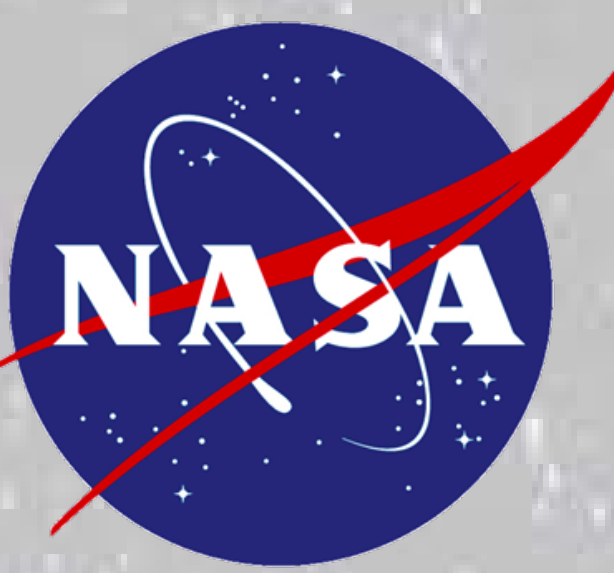


# TUFROC Thermal Protection System

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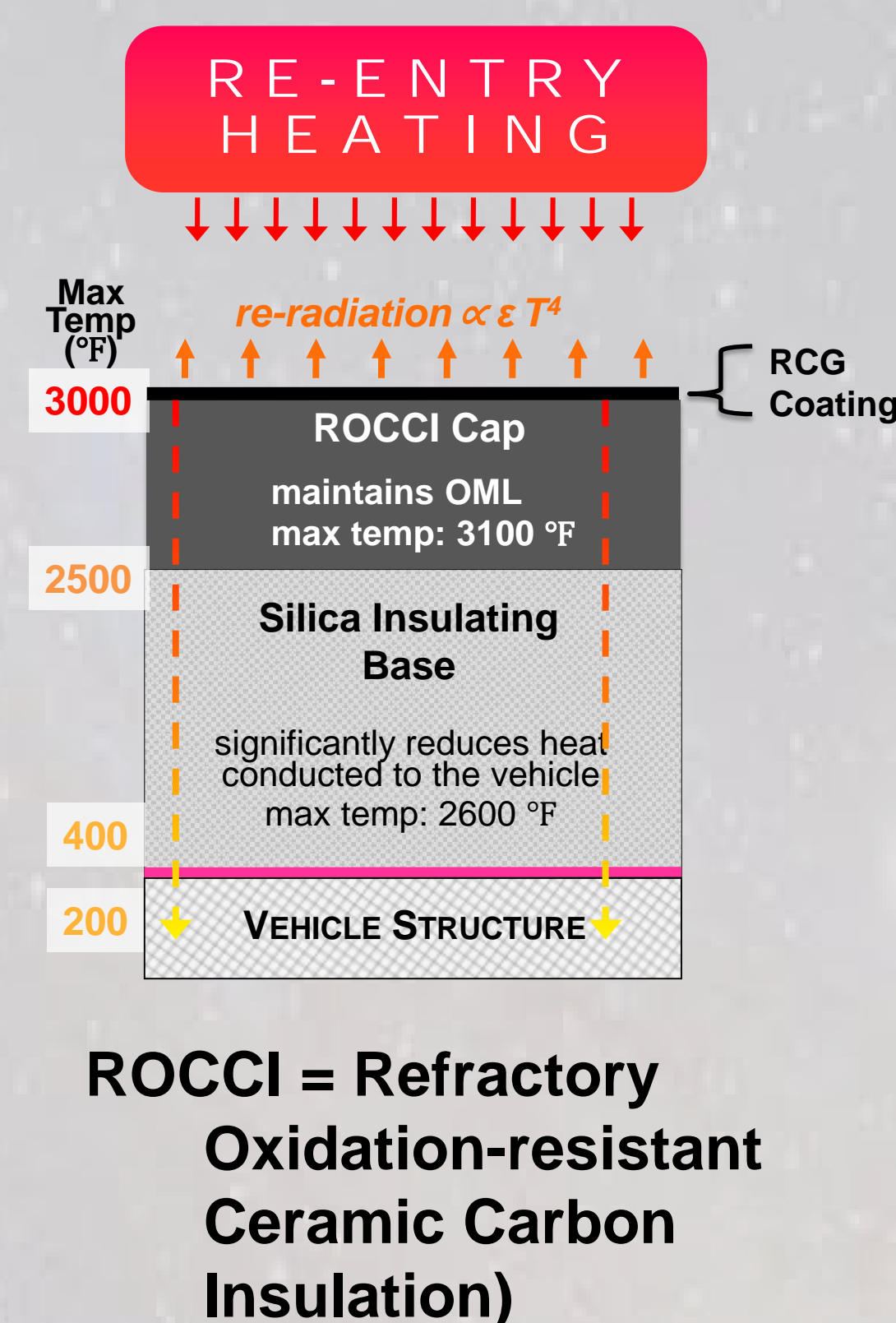
## Introduction

- Toughened Unipiece Fibrous Reinforced Oxidation-resistant Composite (TUFROC) is a tiled Thermal Protection System (TPS) suitable for reusable entry heating at 2900+ ° F and with single use potential up to at least 3600 ° F
- TUFROC was initially developed for NASA's X-37 project and ultimately resulted in use on the Air Force X-37B as the wing leading edge (WLE) of the vehicle
- TUFROC has similar high temperature capability compared with carbon/carbon, but is manufactured at an order of magnitude lower cost & faster schedule

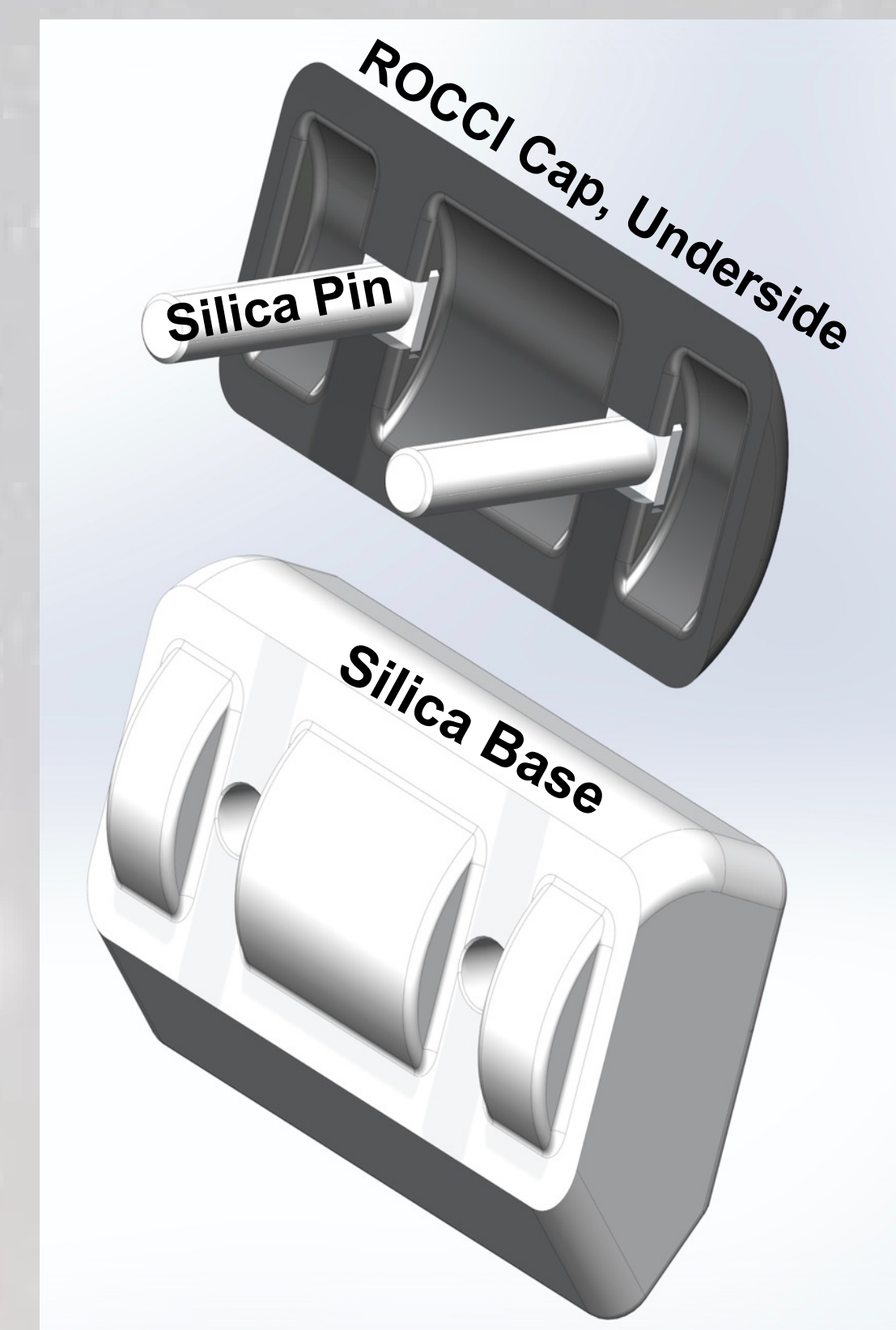
## TUFROC System Design

- The ROCCI cap consists of a carbon fiber preform with a silicon oxycarbide (SiOC) matrix for oxidation resistance
- ROCCI receives surface treatments to control thermal-expansion followed by a Reaction Cured Glass (RCG) coating to control emissivity and reduce oxygen diffusion into ROCCI
- The ROCCI cap is mechanically and adhesively attached to a silica tile base, typically Alumina Enhanced Thermal Barrier (AETB)
- AETB provides enhanced insulative performance
- The resulting system looks and behaves like a black Shuttle tile with increased temperature capability

### TUFROC Design

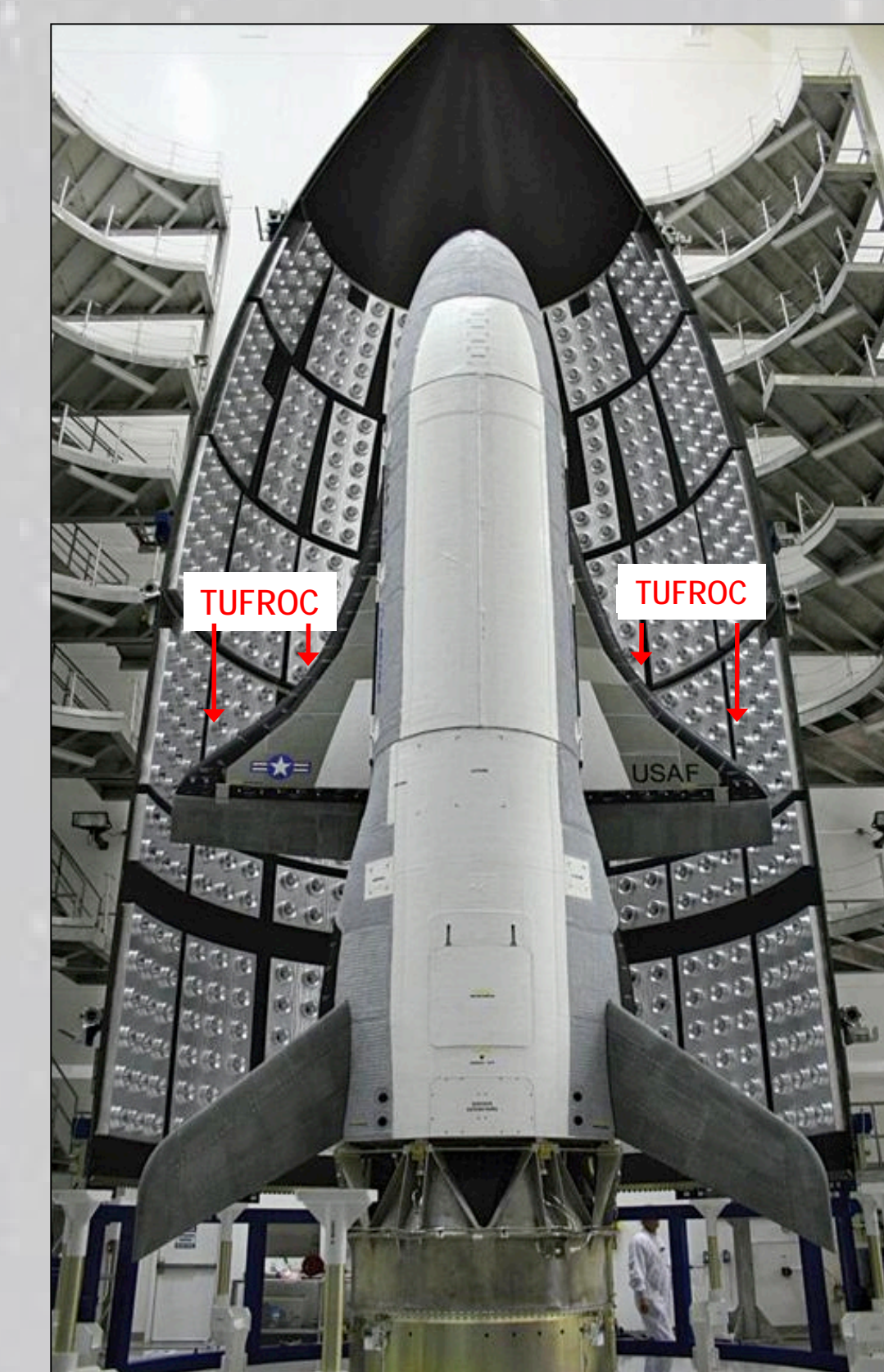


### WLE Tile Example

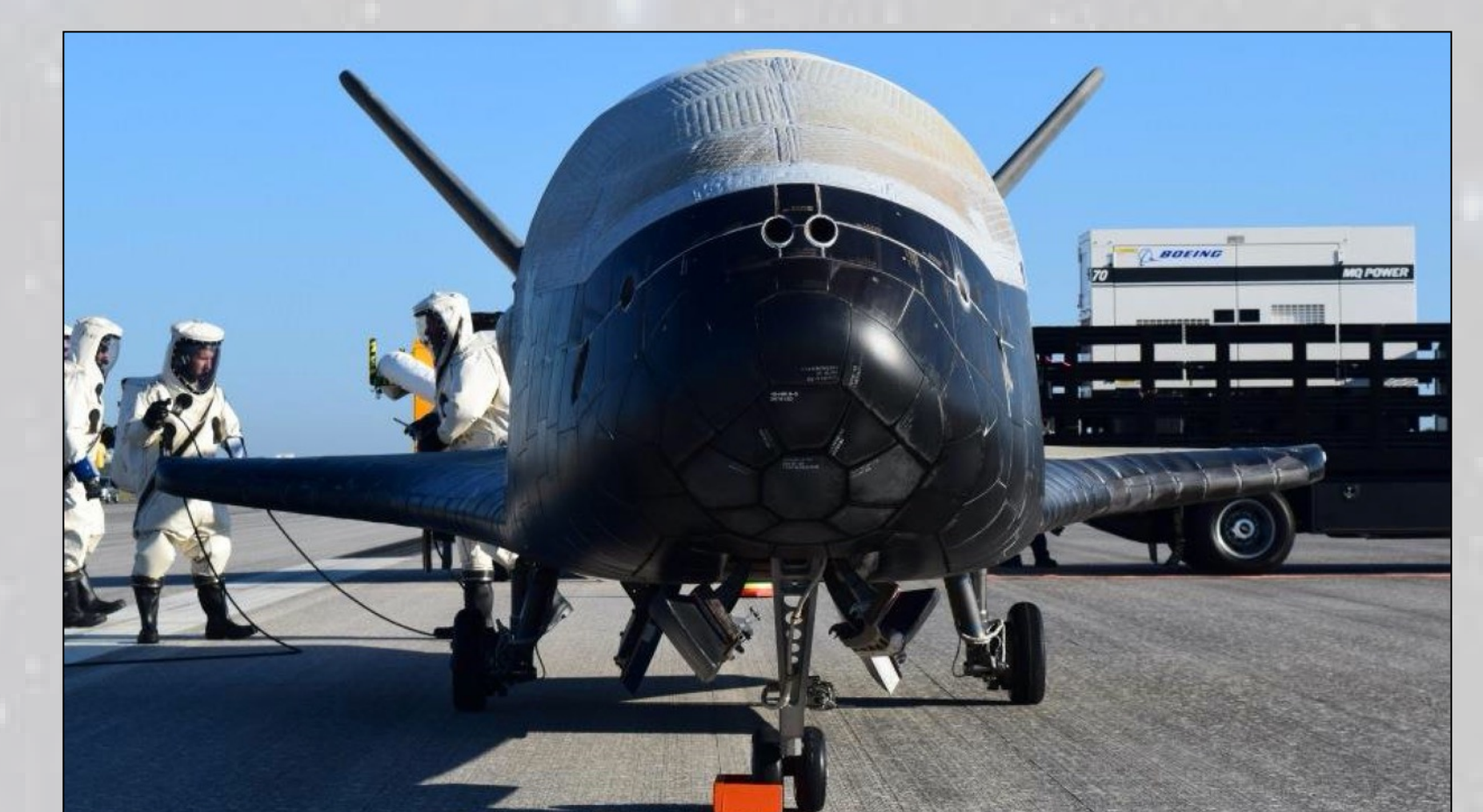


## Flight Proven TPS

The TUFROC wing leading edge has successfully flown and re-entered on four missions with X37B, with a fifth flight currently underway



X-37b preparing for first launch, 2010

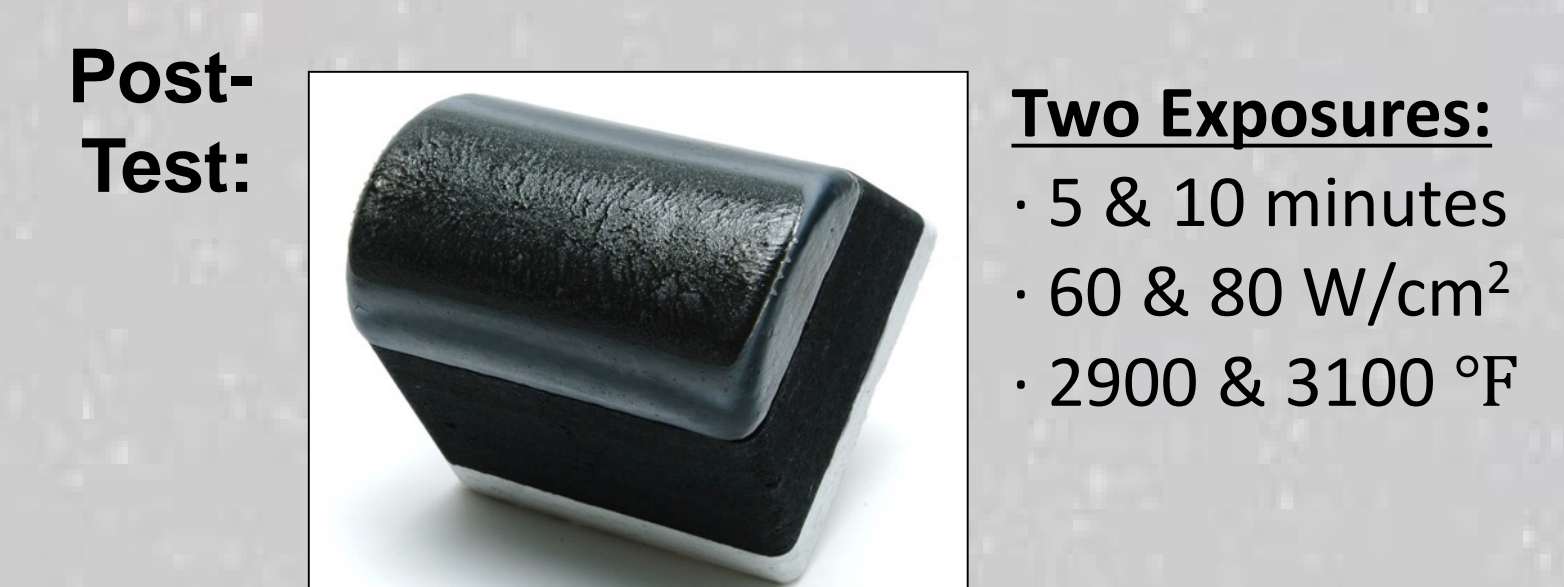
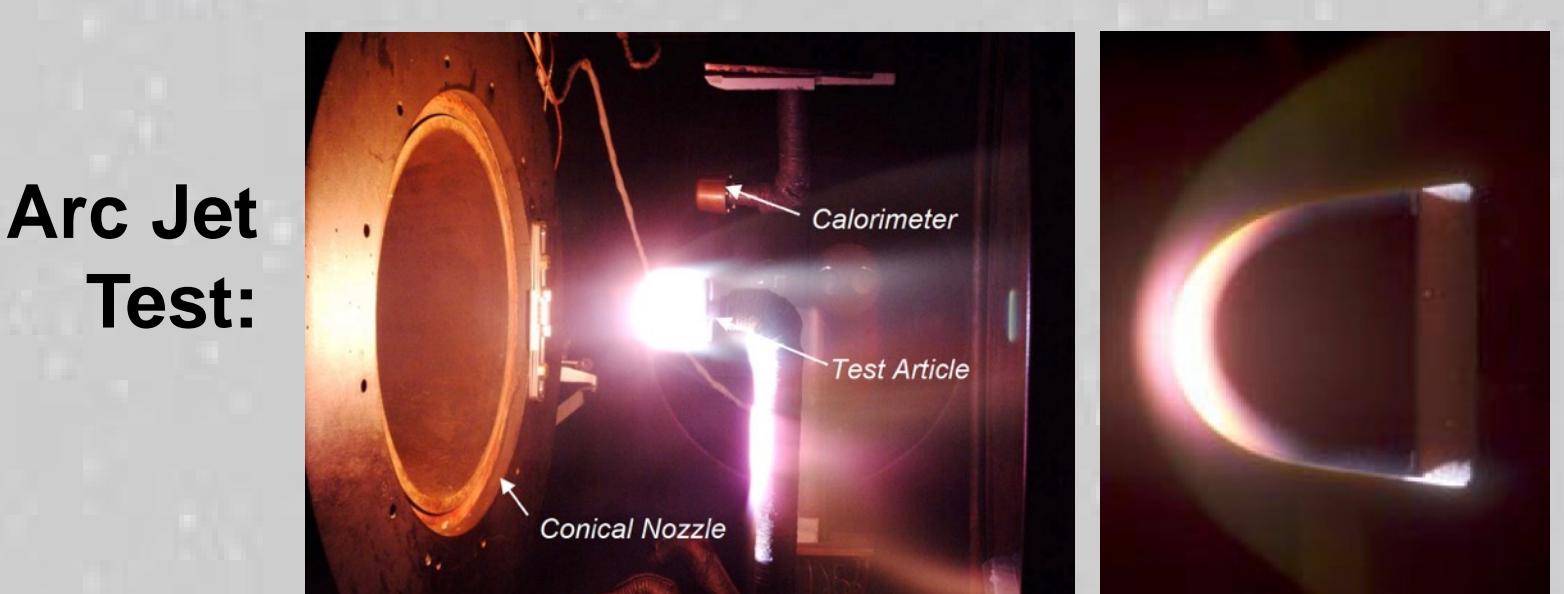
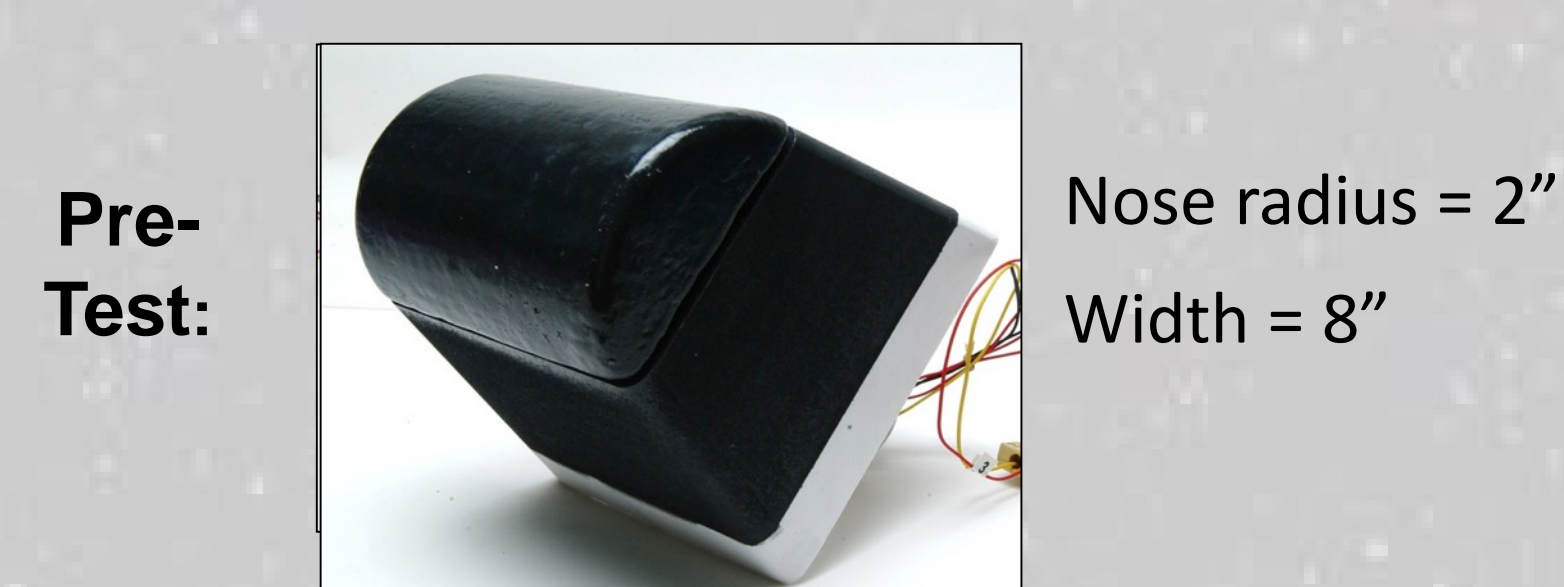


X-37b after 717 days in orbit, 2017

## Standard TUFROC Arc Jet Testing (1998 – 2005)

- Initial arc jet testing included blunt cones, sharp & blunt WLE articles, an 8-inch long two-tile pylon designed to subject TUFROC to combined heat flux & shear conditions in a gapped tile configuration

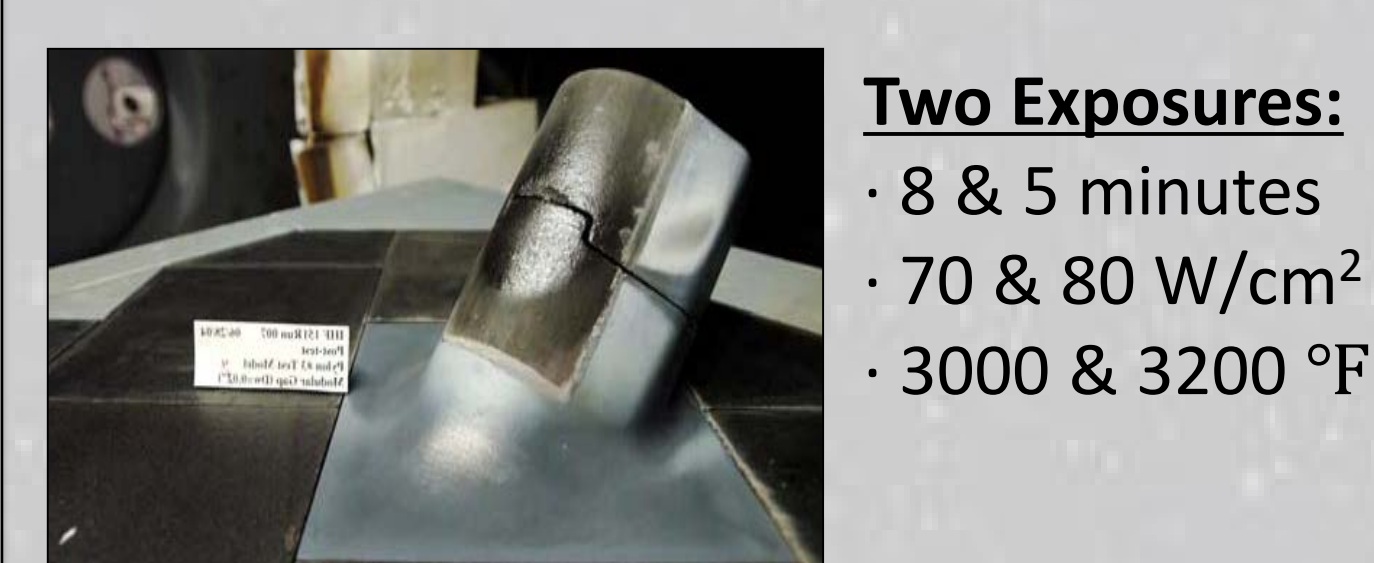
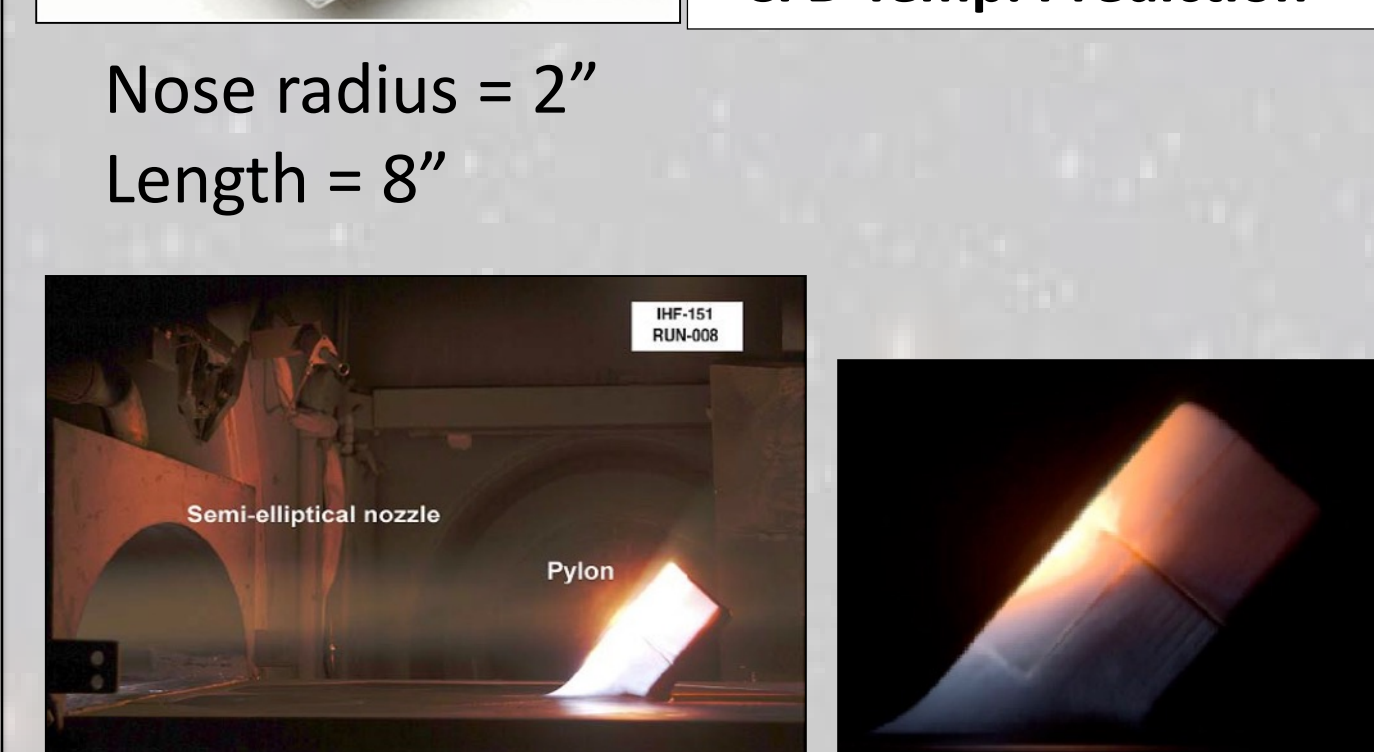
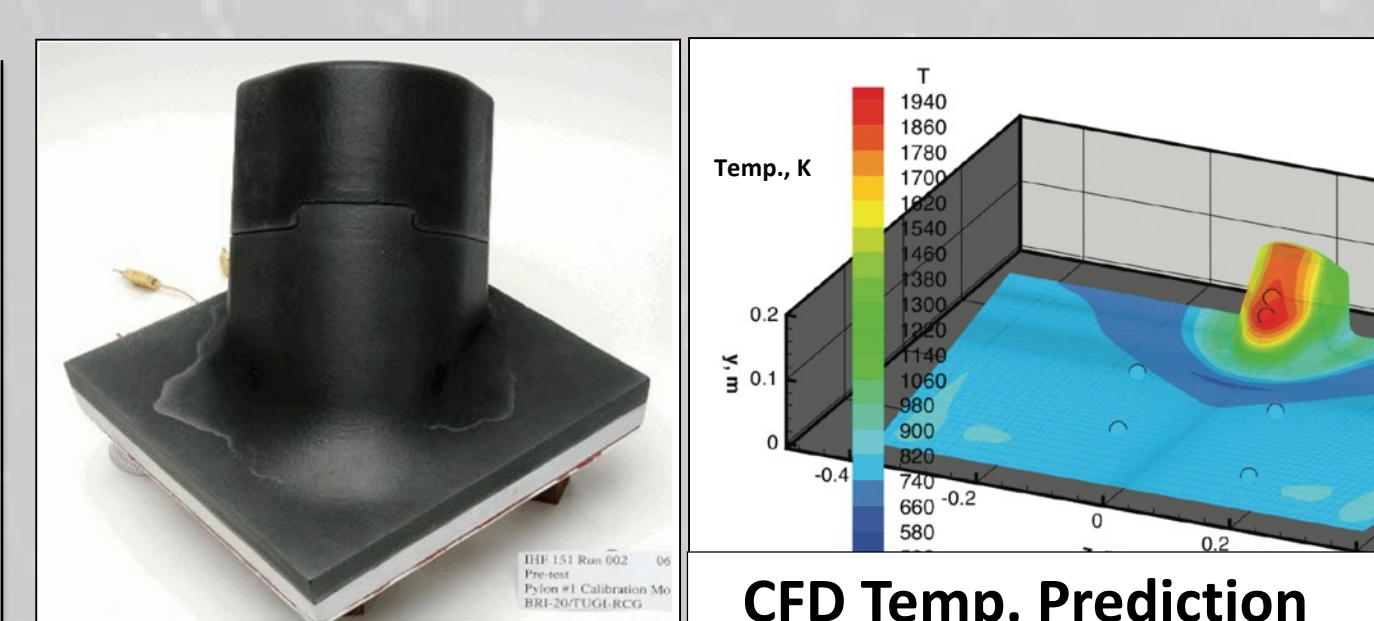
### Blunt WLE



Notes:

- Minimal shape change despite high condition, long exposure
- 2900 °F assessed as max temp. for stable, smooth OML

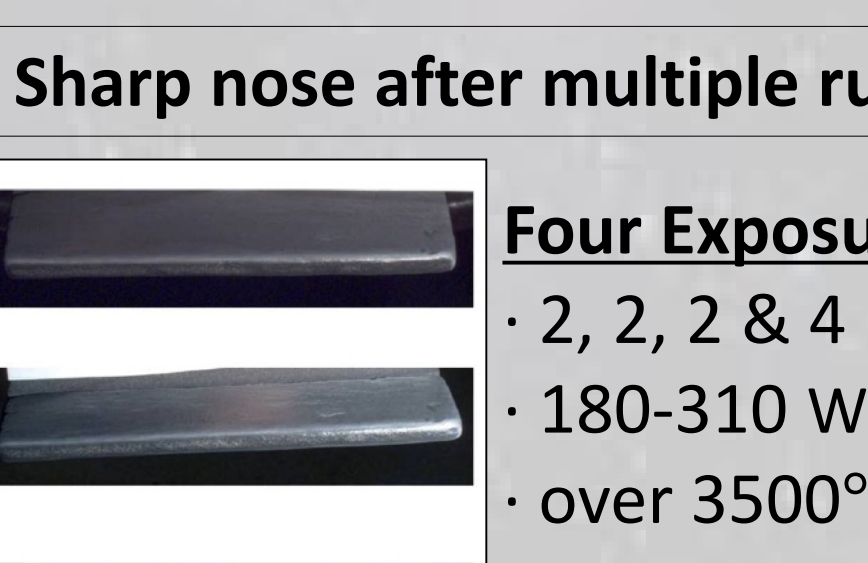
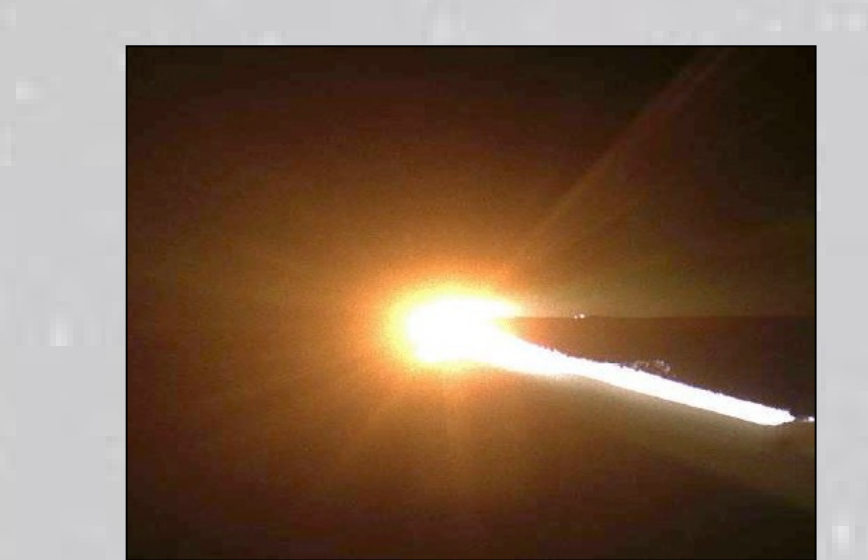
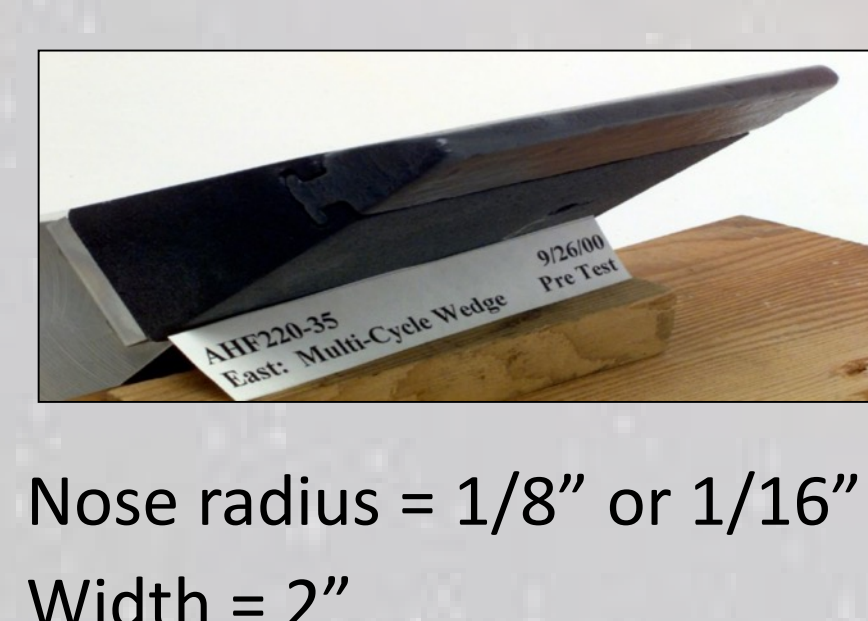
### Pylon



Notes:

- Qualification for X-37 WLE gapped tile configuration via combined high heat flux & shear environments

### Sharp WLE



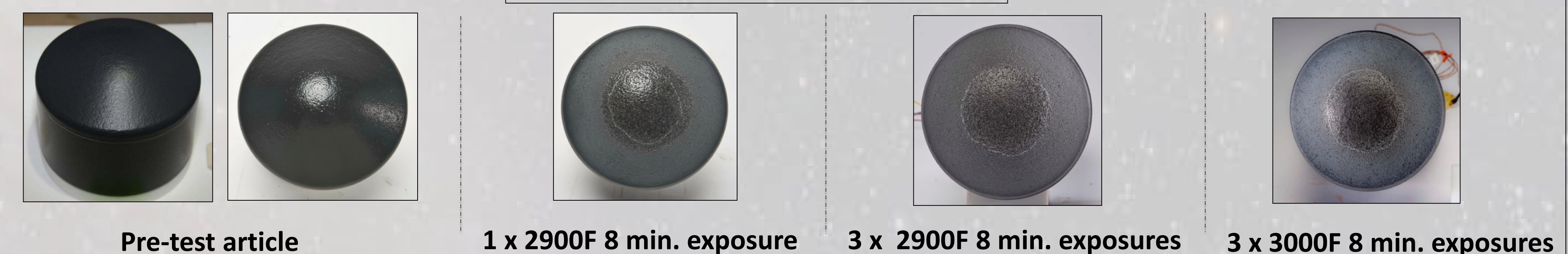
Notes:

- Very Good sharp WLE performance

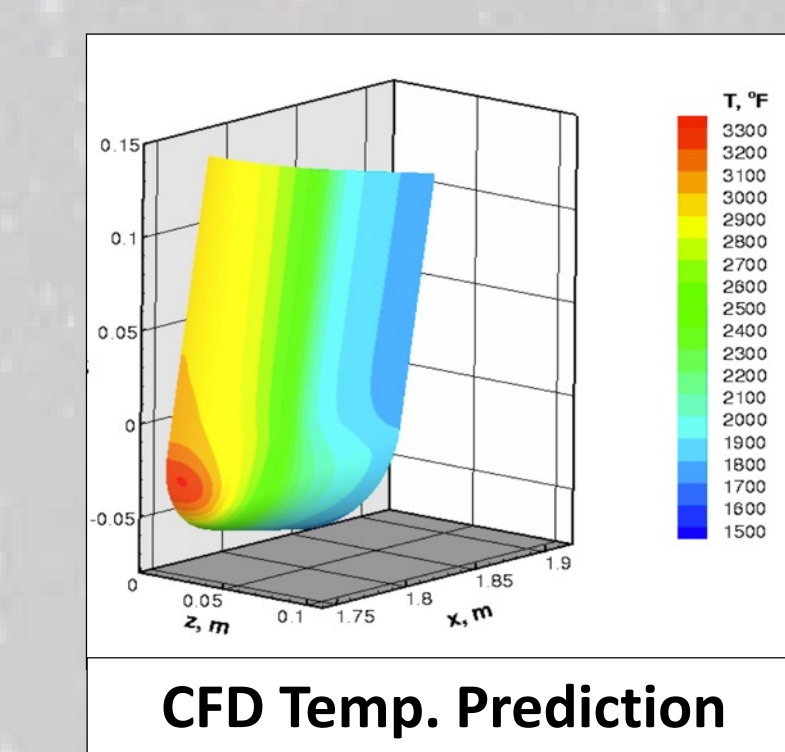
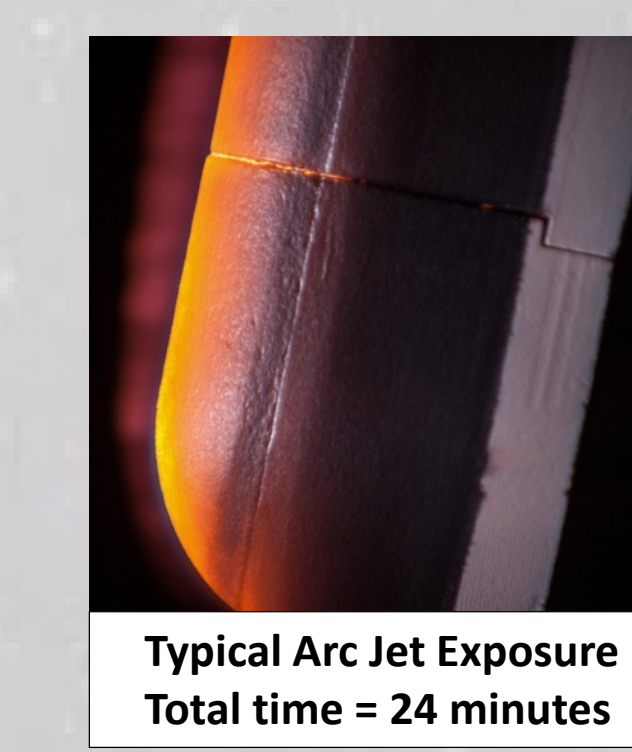
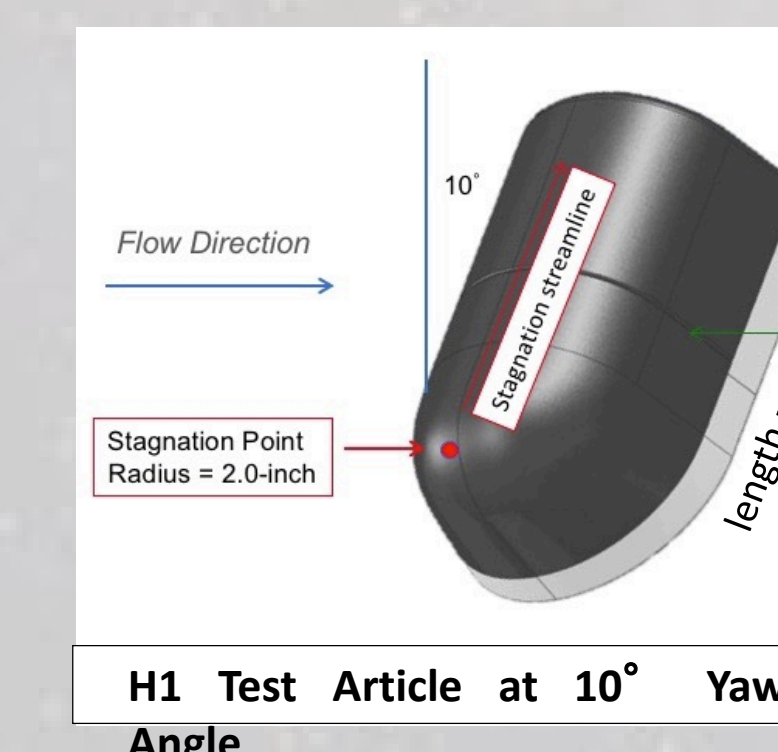
## Advanced TUFROC TPS & Test Articles (2006 – 2019)

- NASA Ames advanced the TUFROC formulation and processing to improve high-temperature performance

### 4" diameter blunt cone arc jet testing

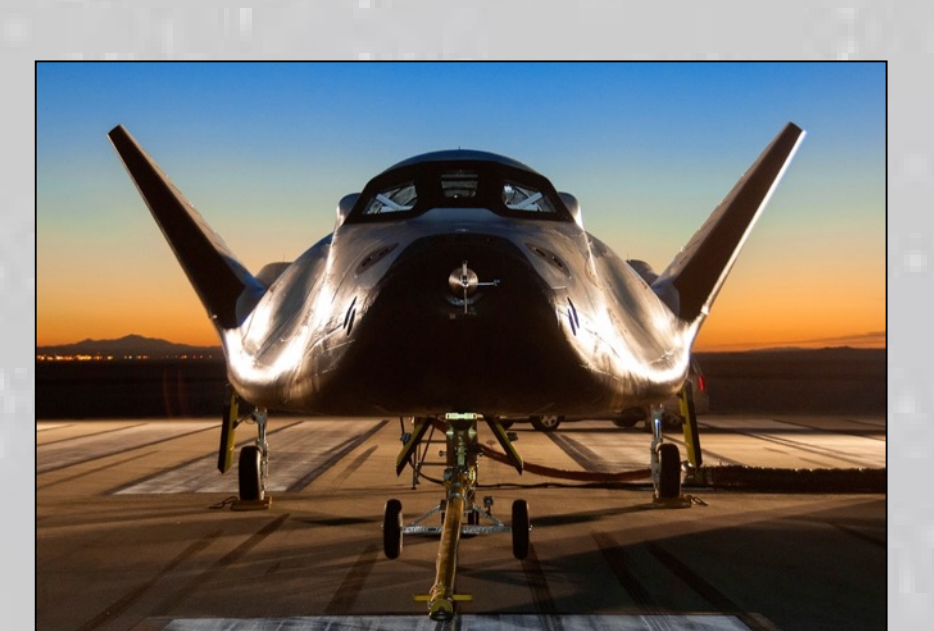


- The "H1" article was designed to expose gapped TUFROC tiles to combined heat flux and shear conditions at significantly lower cost compared with the pylon article used in X-37 qualification



- NASA licensed TUFROC to Sierra Nevada Corporation & is working with SNC in support of the Dream Chaser vehicle

- An 18-inch diameter TUFROC nose engineering unit was produced and provided to SNC for testing



## Future Directions

- We are interested in assessing TUFROC for applications in sharp WLE applications for hypersonic vehicles and are seeking opportunities for testing
- TUFROC is being assessed for several additional aerospace applications / missions where advanced thermal protection is required

**Acknowledgements:** Thanks to the NASA Ames Arc Jet Facility personnel for their help supporting testing, the Ames STAR labs for machining & assembling arc jet models, and Joe Conley of ARC for helpful conversations and graphics materials.