

Aerothermodynamic Analysis of a Flexible Thermal Protection System under Reentry Loads

Zohar R. Hoter

Outpost Technologies Corporation, Playa Vista, CA, USA

Gabriel C. Nastac and Kevin E. Jacobson

NASA Langley Research Center, Hampton, VA, USA

Grant E. Palmer

AMA, Inc. at NASA Ames Research Center, Moffett Field, CA, USA

The Carryall Block 1 reentry vehicle being developed by Outpost Space utilizes a strut supported semi-rigid deployable heatshield. This consists of a flexible thermal protection system, a heat-resistant fabric stack, stretched over actuated spars. The advantages of a deployable heatshield include reduced heat loading and earlier deceleration in the trajectory. However, the nature of the flexible thermal protection system necessitates considering the loaded shape of the heat shield. The flexible thermal protection system will deflect under reentry loads leading to areas of higher heating rates as well as a reduced axial coefficient as compared to the nominal shape. The Carryall Block 1 is analyzed using NASA's FUN3D and DPLR CFD solvers with a deflected shape based on the catenary equations. The aerodynamic results are found to be within a percent for both solvers and both structured and unstructured mesh types. Fluid Structure Interaction (FSI) analysis is currently a work in progress, using file I/O to communicate between FUN3D and LS-DYNA, a commercial nonlinear structural solver. Challenges in deforming the geometry, mesh, and initial results are presented here.

I. Introduction

As the rate of annual launches and mass transferred to space increases, technologies to return mass to Earth, especially high value cargo and in space manufactured products, must be urgently developed. Deployable heat shields, a form of aerodynamic decelerator, work by increasing the frontal cross sectional area and thereby the drag per payload mass. The ratio of vehicle mass to drag is represented by the ballistic coefficient

$$BC = \frac{m}{C_d A}$$

where A is the frontal cross sectional area. This lowers the heat pulse of reentry significantly as the deceleration and kinetic energy is bled to lower density air higher in the atmosphere. Several low ballistic deployable heat shield concepts have been developed and some even tested.

NASA's Adaptable Deployable Entry and Placement Technology (ADEPT) program developed a strut supported fabric aeroshell. The program culminated in the SR-1 sounding rocket test of a 0.7 m vehicle which collected aerodynamic and GNC data on the configuration [Dutta, 2022]. The Low-Earth Orbit Flight Test of an Inflatable Decelerator (LOFTID) mission demonstrated a six-meter inflatable heat shield from orbital reentry velocities. The vehicle was successfully recovered along with its reconstructed trajectory and aerodynamic performance [Hollis, 2025]. Post flight data analysis from on-board cameras recorded a deflection of 2 in from the heatshield's nominal shape [Hughes, 2023].

Outpost Space is developing a strut supported flexible thermal protection system as part of the Carryall Block 1 vehicle shown in **Figure 1**. The Carryall Block 1 will return 200 kgs of payload sized to ISS double middeck locker standards to support scientific and in space economy missions. The deployable heat shield is a three meter flexible carbon-based fabric stretched over radial spars. A sphere cone angle of 70 degrees is considered in this paper. An octagonal satellite bus sits behind the shield with a center of gravity 0.16D of the shield diameter behind the tip of the nose. The analysis geometry has a cylindrical satellite bus.

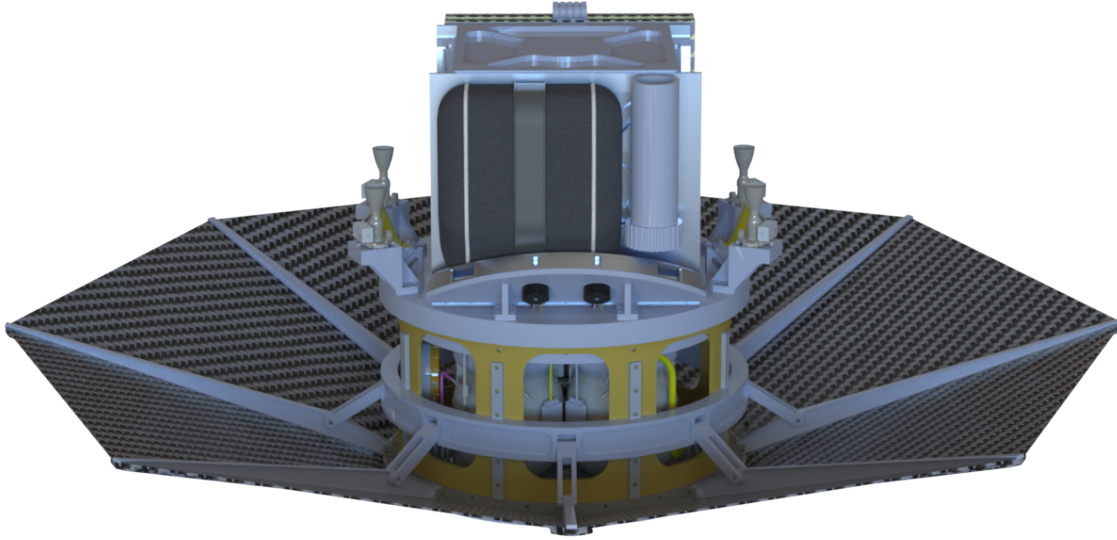


Fig. 1 The Outpost Space Carryall Block 1 Vehicle.

Both ADEPT and LOFTID spent considerable effort during the design phase considering the flexible thermal protection systems deflection under aerodynamic loading during reentry. The deflection of the flexible thermal protection system must be considered as the altered shape will decrease axial force coefficients impacting the vehicle trajectory. In a semi-rigid concept this deflection can also cause heating rates to rise in areas where there is a transition from rigid to flexible TPS. Geometries can become sharper as well as forward and backward facing steps exaggerated.

In this paper two methods of obtaining a deflected shape on the Carryall block 1 are considered: a catenary deflection assuming uniform loading, and an uncoupled Fluid Structure Interaction (FSI) approach using an external structural solver, LS-DYNA.

II. Analysis Methods

CFD analysis of the Carryall Block 1 is run using two solvers, NASA Fully Unstructured Navier-Stokes 3D (FUN3D) and NASA Data Parallel Line Relaxation algorithm (DPLR) to compare and cross verify results. The full trajectory detailed in [Hoter, 2026] is generated using FUN3D while solver-to-solver comparisons as well as mesh studies included DPLR. This current work analyzes a deflected geometry to determine differences compared to the nominal rigid geometry.

B. NASA FUN3D

NASA FUN3D is an unstructured finite-volume CFD flow solver developed at NASA Langley Research Center [Anderson, 2025]. The solver is widely used at NASA and across the US aerospace community for flows ranging from subsonic incompressible speeds to hypersonic speeds involving thermochemical nonequilibrium. The governing equations in FUN3D for thermochemical nonequilibrium flows are described in [Gnoffo, 1989].

A median-dual finite-volume approach is used for spatial discretization on general unstructured meshes containing tetrahedra, pyramids, prisms, and hexahedra. A dual-mesh is generated by bisecting every edge and connecting them to cell centroids to generate polyhedral control volumes. Inviscid fluxes are computed at each dual-face using an approximate Riemann solver, HLLE++ [Nastac, 2022] in this work, with second-order accuracy obtained using an unstructured Monotonic Upstream-centered Scheme for Conservation Laws (UMUSCL) reconstruction with unweighted least-squares gradients. Viscous fluxes are computed using a Galerkin-based approach. The equations are integrated in time implicitly.

The FUN3D simulations in this work are carried out on AMD and NVIDIA GPUs using the GPU-optimized approach described in [Nastac, 2021] and [Nastac, 2023]. The software is written in a thin abstraction over CUDA C++ which enables primarily single-source software capable of efficiently running on NVIDIA, AMD, and Intel GPUs as well as multicore CPUs. Performance is commensurate with memory bandwidth, which enables modern GPU nodes consisting of a few GPUs to be equivalent to thousands of CPU cores of performance, substantially reducing power and space requirements versus CPU-based systems.

The software is routinely being used to run hypersonic simulations of complex geometries using the hybrid adaptation approach described in [Nastac, 2025], where off-body tetrahedra adaptation captures features such as shocks and a thin-prismatic boundary-layer mesh is generated to accurately capture surface gradients. This paper utilizes pre-generated surface and boundary-layer meshes due to the deflected geometry creation process, although these can be both adapted in the future.

C. NASA DPLR

The NASA DPLR CFD flow solver [Wright, 2009] is a parallel, structured, multi-block finite volume software that solves the reacting Navier-Stokes flow equations including finite-rate chemical reactions and, if needed, thermal nonequilibrium. The DPLR solver has been one of the workhorse CFD solvers used by NASA, academic institutions, and industrial partners over the past 20 years and is well suited to generating flow solutions over spacecraft entering a planetary atmosphere. The Euler fluxes are evaluated using a low-dissipation form of Steger-Warming flux vector splitting with third-order spatial accuracy achieved with monotonic upstream schemes for conservation law (MUSCL) extrapolation [Wright, 2006]. The solver offers a wide variety of gas chemistry and turbulence models that can be applied to a given planetary entry simulation. DPLR is a structured solver, so the meshes consist of rectangular or hexahedral elements. In the present paper, the DPLR solver will be used to provide solver-to-solver comparisons of surface heating rates, pressures, and aerodynamic coefficients against FUN3D solutions.

III. Solver and Mesh Comparisons for Gore Deflection

A. Geometry

The amount of gore deflection is affected by the pressure loading on the surface, the material strength and elasticity, the amount of tension in the fabric before a pressure load is applied, and the heat loading. If the spacecraft is at a non-zero angle of attack, the pressure loading, and therefore deflection, may be higher on the windward surfaces than will be experienced by the leeward surfaces. For this initial assessment, a simplified deflected gore surface was modeled. A constant 5% deflection was imposed on the outer 2/3 of the gore surfaces as a function of the local width of the gore at that location. From the inner 2/3 of the gore surface to the nose cap, the gore deflection was linearly reduced from the 5% value to be zero at the outer boundary of the nose cap. An image of the deflected surface mesh using this simplified model is shown in **Figure 2**. Only the heatshield portions of the geometry are considered for the deflected gore simulations. Overall results are compared to previous results of the nominal non-deflected geometry simulated in [Hoter, 2026]. The deflection is performed directly on the nominal structured mesh. A geometry surrogate is generated with Fidelity Pointwise by exporting the 2D structured surface with bicubic interpolation to an IGES file. The geometry was simplified to be planar at the outflow as well. There are noticeable but minor artifacts at geometry interfaces using this bicubic approach; future approaches should deflect the geometry directly in a CAD software.

B. Mesh and Simulation Details

A comparison of structured and unstructured meshes and solvers is carried out. A hypersonic (Mach 24~) condition is considered. The wall is modeled as fully-catalytic and assumed to be in radiative equilibrium with a surface emissivity of 0.85 for conservative heat transfer and surface temperature predictions. A 5-species air Park gas model is employed. The flow is modeled as laminar due to low enough Reynolds number.

DPLR is first run with mesh adaptation to shock-fit the structured mesh. The surface forebody mesh for the DPLR CFD simulations is shown in **Figure 2** on the left. As the DPLR CFD solution progresses, the outer boundary is tailored to match the shape of the bow shock. The near wall cell spacing is also adjusted to reach a near wall cell Reynolds number of unity. The final adapted structured mesh is approximately 6.5 million hexahedra with approximately 40 thousand quads on the surface.

FUN3D is run on the final adapted structured mesh for a more one-to-one comparison. An unstructured mesh is generated with the geometry surrogate described earlier. A hybrid C2S process, where the surface is adapted dynamically, was carried out, but the CAD surrogate artifacts became exacerbated, so a fixed surface mesh with off-body adaptation was analyzed instead. The initial hybrid unstructured mesh is generated in HPCMP CREATE Capstone [Mestreau, 2019]. The unstructured surface mesh is shown in **Figure 2**. A general surface spacing of $0.01D$, where D is the vehicle diameter, is imposed. The nose cap has a finer spacing of $0.005D$. Surface edge boundary layers (three layers with $0.001D$ initial spacing) are imposed on the geometry edges. A prismatic boundary layer is extruded for 40 layers with a growth rate of 1.2, where the first layer matches the adapted structured mesh spacing. The surface mesh has approximately 50 thousand triangles and 25 thousand points. There are approximately 2 million prisms. The target mesh point count is set to 4 million. Twenty CFD/refinement cycles are carried out. The final mesh has 4.2 million points.

FUN3D is run with adaptive CFL control (max local CFL of 100) and automated solver termination when integrated convective heat transfer changes by less than 0.01% in 100 nominal steps. The unstructured adapted simulation is run on NVIDIA A100 GPUs. The structured mesh FUN3D simulation takes 15 minutes on 16 NVIDIA A100s (4 NVIDIA A100 hours). The unstructured mesh simulation process (with twenty cycles) takes 2 hours; CFD takes 1 hour on 16 NVIDIA A100 GPUs and refinement takes 1 hour on 4 AMD EPYC 7763 CPUs. The structured mesh is already adapted from DPLR; further structured mesh cycles would be needed for a closer performance cost comparison. The last ten adapted cycles are faster than the first ten; CFD normally runs for the minimum steps for the latter cycles due to converged heat transfer and refinement also converges and occurs more quickly once shock features are well adapted.

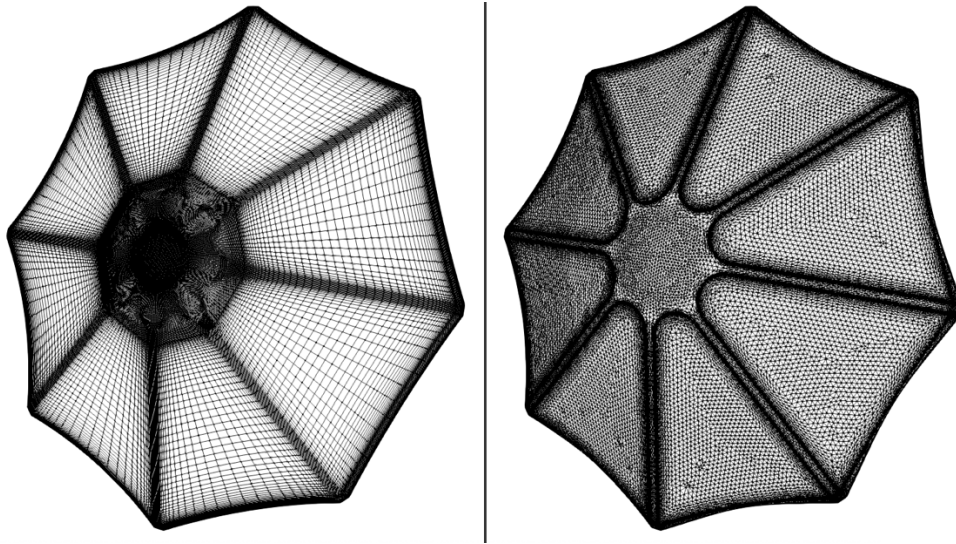


Fig. 2 Left: Structured Forebody Mesh. Right: Unstructured Forebody Mesh.

C. Simulation Results

Stagnation line pressure and temperature profiles are plotted in **Figure 3**. Stagnation pressures differ by less than 0.1% between all results. Peak temperature differences are less than 0.1% between structured mesh results; the unstructured mesh temperature is about 1% higher and is better resolved at the peak. Stagnation mass fractions are plotted in **Figure 4**. Molecular oxygen completely dissociates post-shock and molecular nitrogen partially dissociates. There is a few percent of nitric oxide present. Mass fraction results between both solvers and mesh approaches are indistinguishable.

Figure 5 plots surface contours of pressures, heat transfer, and shear stress. **Figure 6** plots quantities through the y-axis whereas **Figure 7** plots through a 22.5-degree rotation about the x-axis. **Figure 8** plots quantities through an x-slice roughly at the midpoint of the nose and shoulder. Pressure and shear stress predictions are in excellent agreement between all cases. Heat transfer predictions are also in good agreement overall; only the stagnation region is not entirely smooth for the unstructured mesh result, but the expected magnitudes are similar. Further mesh adaptation should improve smoothness of results near the nose. Surface temperatures are also in good agreement – the structured mesh FUN3D simulation underpredicts temperature by about 20 K versus the unstructured FUN3D and structured DPLR simulations. This minor difference in temperature is likely attributed to FUN3D’s shock capturing which employs a stronger limiter than DPLR; the stronger limiting is required when running with anisotropic tetrahedra. For the x-slice results, the peaks at the rib-gore interfaces are more sharply captured with the unstructured mesh. The structured mesh should be further refined at this interface. Overall, all three surface results are comparable from an engineering accuracy point of view.

Centerline y-slice contours near the nose of the mesh, temperature, Mach number, and nitric oxide mass fraction are plotted in **Figure 9** comparing FUN3D on structured and unstructured meshes. DPLR and FUN3D comparisons are plotted for the whole y-slice in **Figure 10**. Results between the structured and unstructured meshes are visually identical for all solvers and mesh approaches.

Drag coefficient result differences are shown in Table 1. The structured results agree to within 0.1%. The unstructured result predicts about 0.3% lower drag versus the structured meshes. For the ten degree angle of attack condition, axial coefficients between FUN3D and DPLR on the structured mesh agree within 0.2%.

Solver and Mesh	Drag Coefficient Error (%)
DPLR Structured	0.0
FUN3D Structured	+0.06%
FUN3D Unstructured	-0.32%

Table 1 Errors in drag coefficient at 0 degrees angle of attack. Error is computed with DPLR as the baseline.

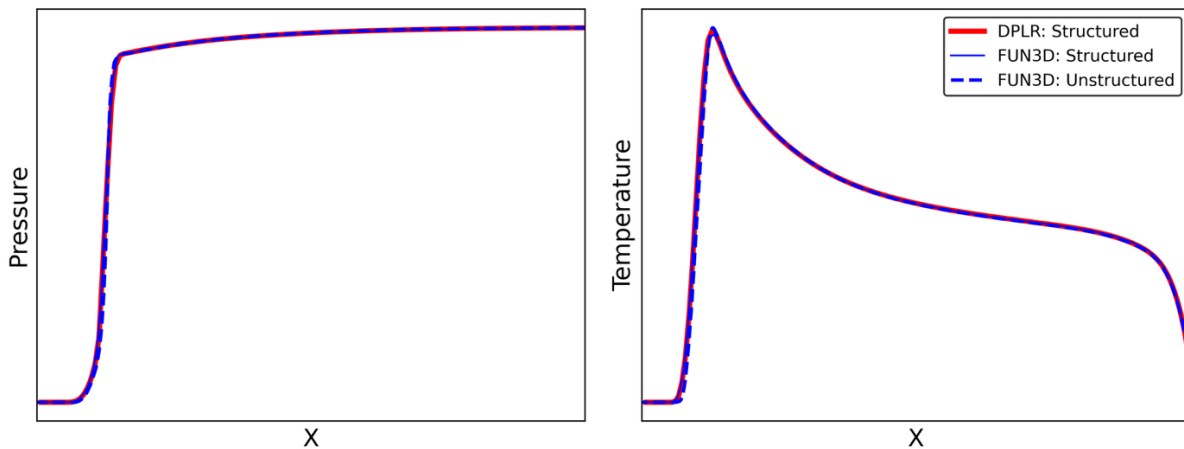


Fig. 3 Stagnation line pressure and temperature. Vehicle stagnation point is on the right.

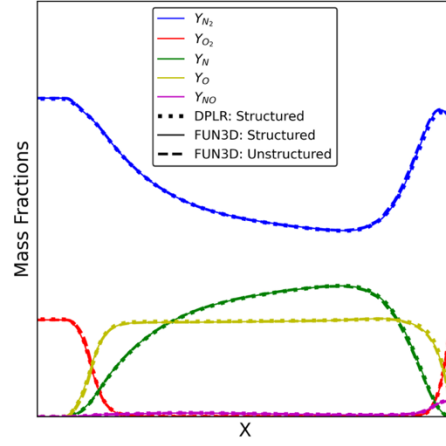


Fig. 4 Stagnation line mass fractions. Vehicle stagnation point is on the right.

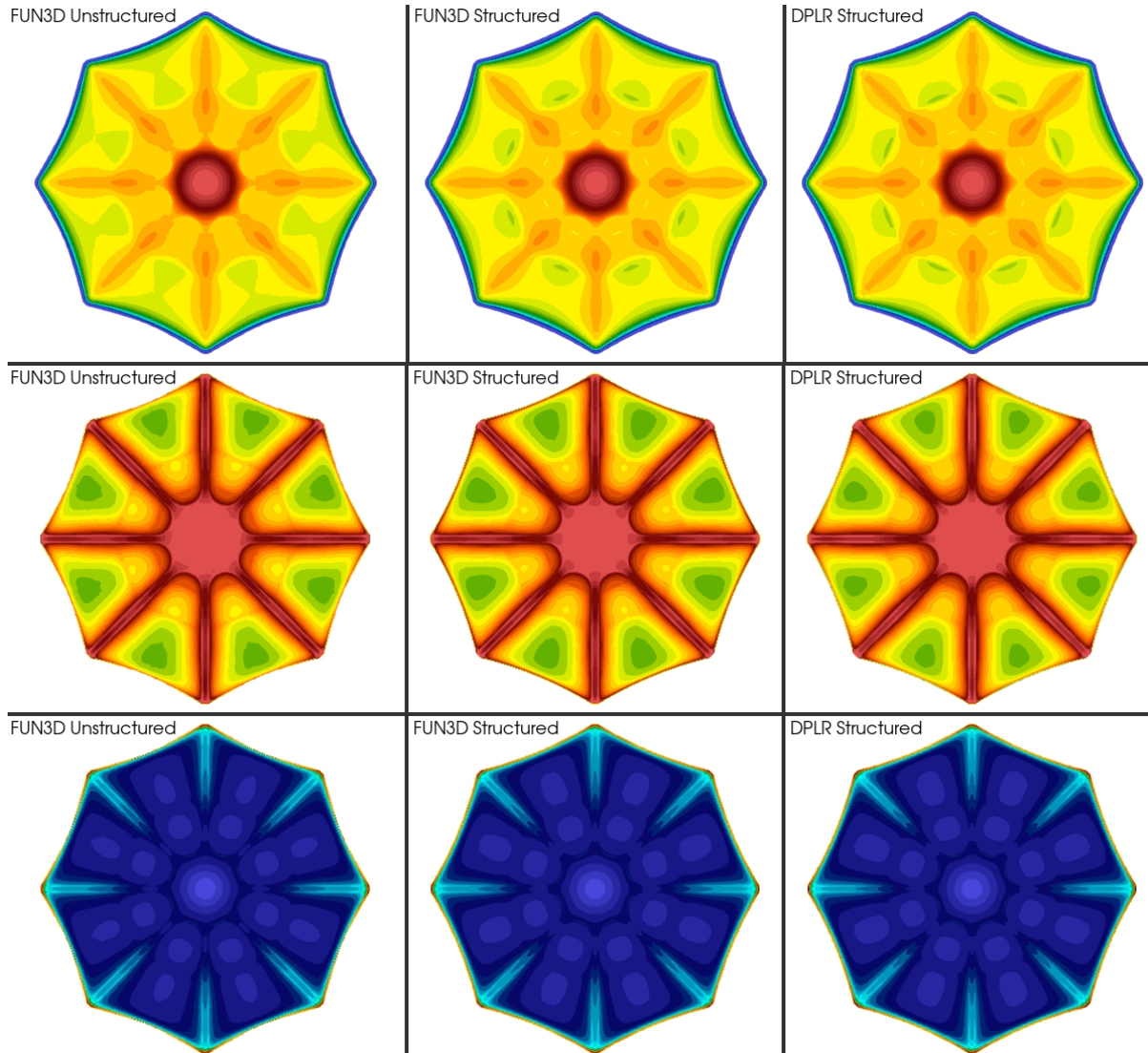


Fig. 5 Top: Surface Pressure. Middle: Surface Heating. Bottom: Surface Shear Stress.

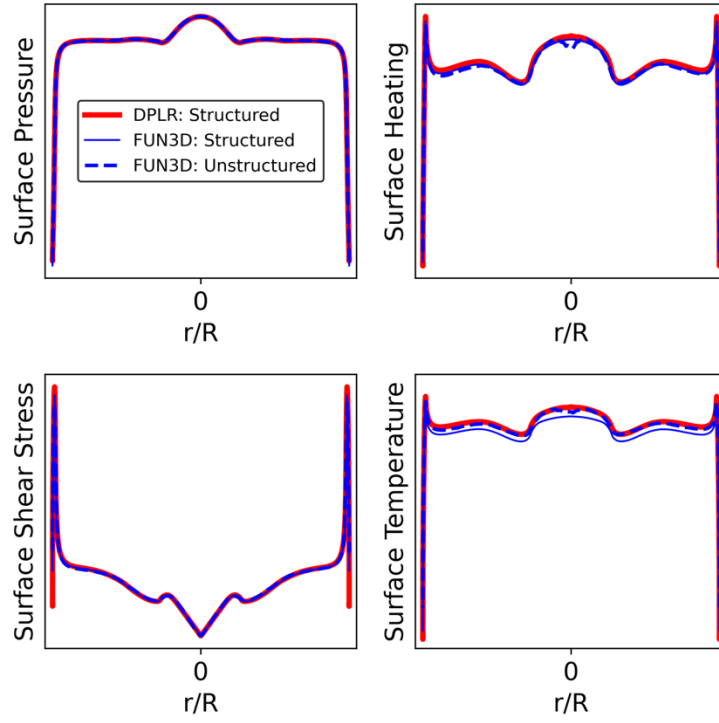


Fig. 6 Centerline surface pressure, heat transfer, shear stress, and temperature along the y-axis.

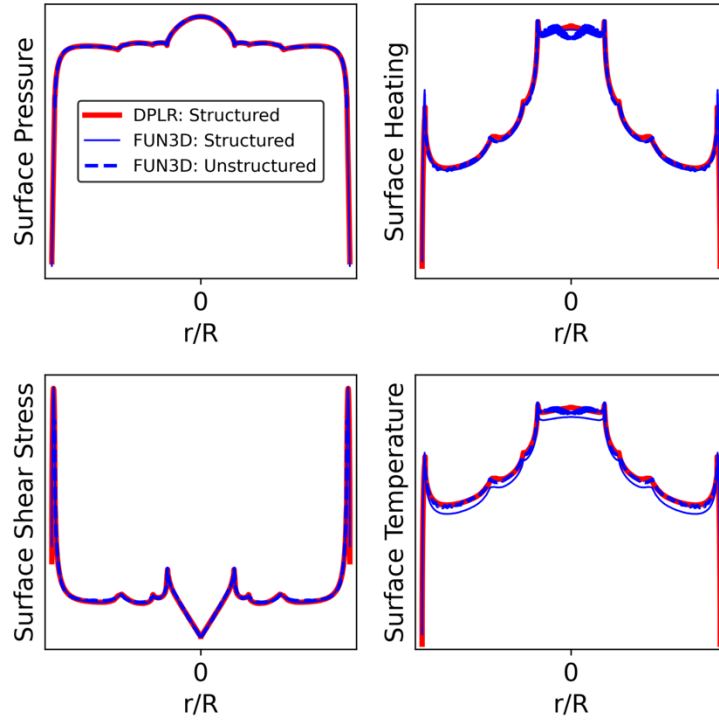


Fig. 7 Line surface pressure, heat transfer, shear stress, and temperature along a 22.5-degree rotation about the x-axis.

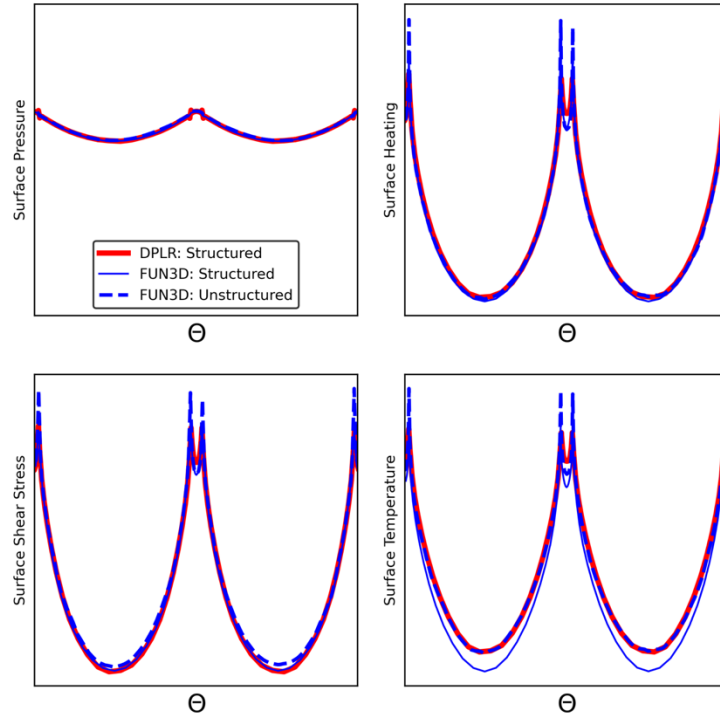


Fig. 8 Surface pressure, heat transfer, shear stress, and temperature along an x-slice at about the midpoint of the vehicle. The x-axis is angle about the x-axis – 90 degrees are plotted.

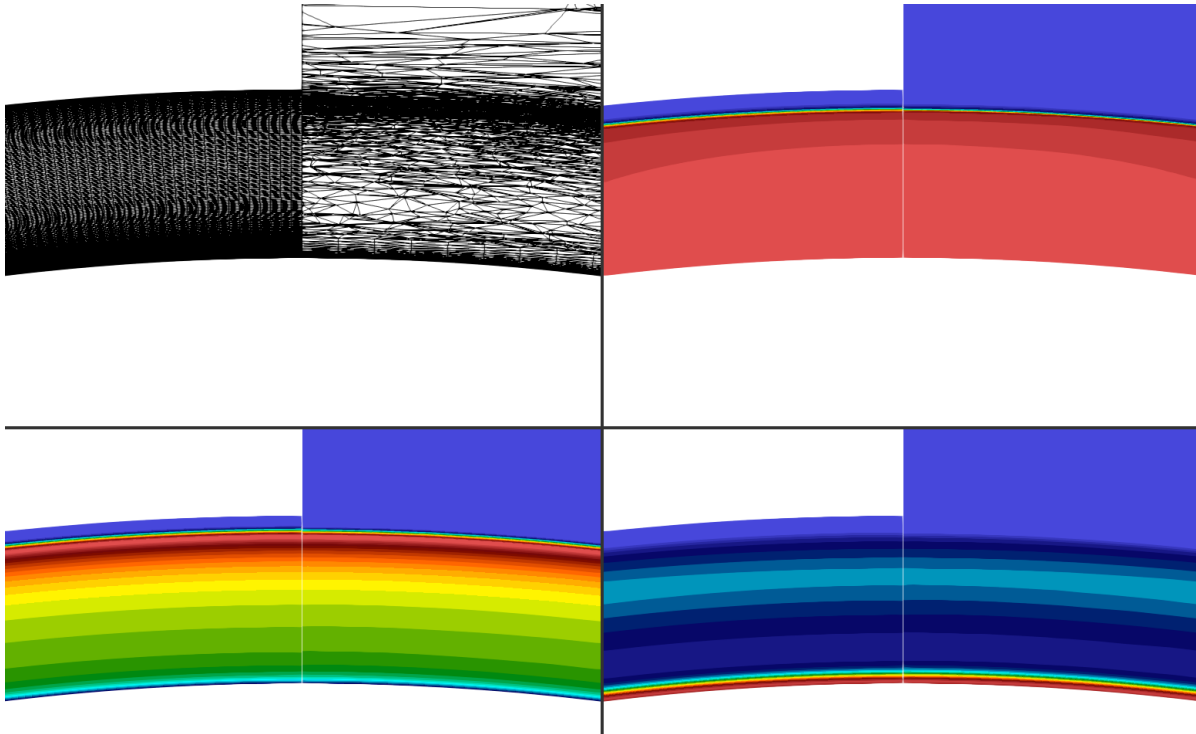


Fig. 9 Centerline y-slice near the nose of the vehicle. Left: FUN3D structured. Right: FUN3D unstructured. Top Left: Mesh. Top Right: Pressure. Bottom Left: Temperature. Bottom Right: Nitric Oxide Mass Fraction.

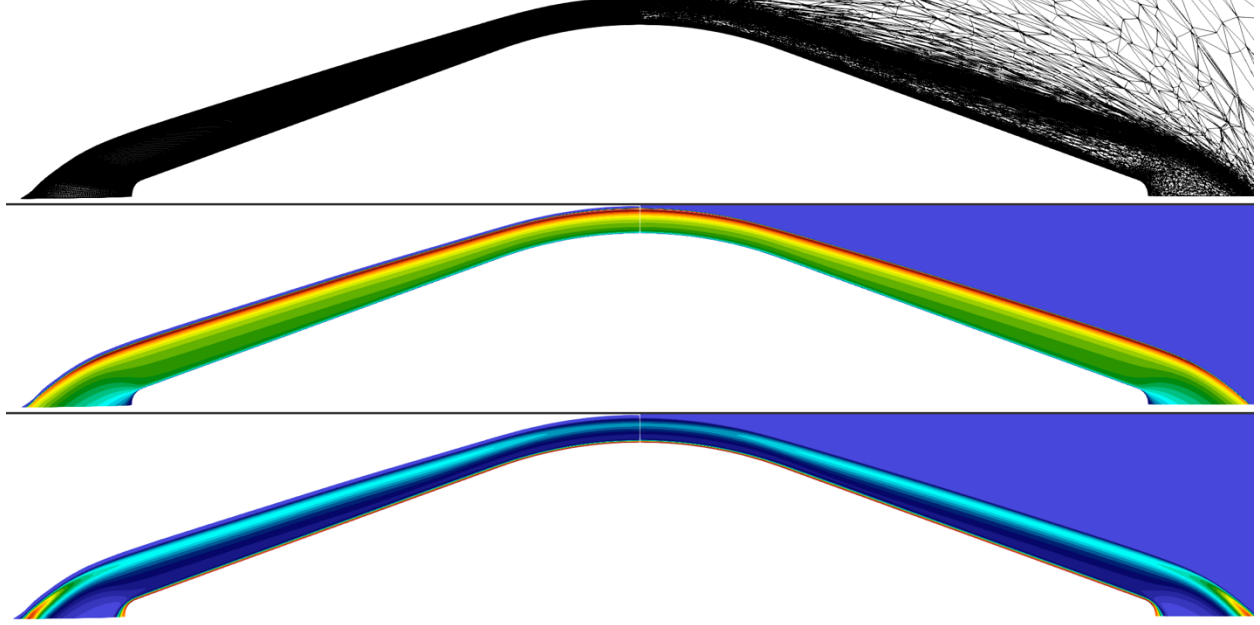


Fig. 10 Centerline y-slice. Left: DPLR structured. Right: FUN3D unstructured. Top: Mesh. Middle: Temperature. Bottom: Nitric Oxide Mass Fraction.

D. Comparisons to Nominal Geometry

Results of the nominal geometry were carried out in [Hoter, 2026]. For the zero angle of attack condition, there is about a 10% decrease in surface heating rate in the center of the gores, because the deflection has created a light concavity in the surface. Closer to the nose cap on the gores and on the nose cap itself, there is a slight increase in heating rate due to gore deflection. A more significant change in heating rates occurs along the rib-gore interface, where the heating rates for the deflected gore geometry increase up to 30%. The way the deflection was modeled, the rib surfaces do not change location, so when the gores deflect the edge at the rib-gore interface becomes sharper, and sharper edges generate higher heating rates. The gore deflection decreases the axial coefficient and increases the side coefficient at angles of attack. A small number of cases were run at nonzero angle of attack and uniform deflections where the pitching moment also increases compared to nominal.

IV. Static Fluid Structure Interaction

Pressure distributions from the nominally shaped cases in [Hoter, 2026] were applied in the non-linear structural solver LS-DYNA [Ansys, 2025]. As at zero angle of attach the pressure distributions are similar on each gore, a single gore model was developed to reduce computational complexity, and the deflection was applied to each gore. The spars are assumed rigid and rotate through the tensioning phase of the heat shield deployment to provide a realistic baseline before the pressure load is applied. Radial basis functions are created using the deflections at each node in the coarser structural grid and then applied to each of the gores through appropriate rotations. The root of the gore was enforced in mapping to have no deflection to ensure a smooth transition from the nosecone to the gore. FUN3D is able to modify input grids through both rigid grid motion and elastic grid deformation around a changing boundary, or a combination of both. For this analysis only the elastic deformation about the moving fabric gores is used. **Figure 10** shows results of the initial structural analysis.

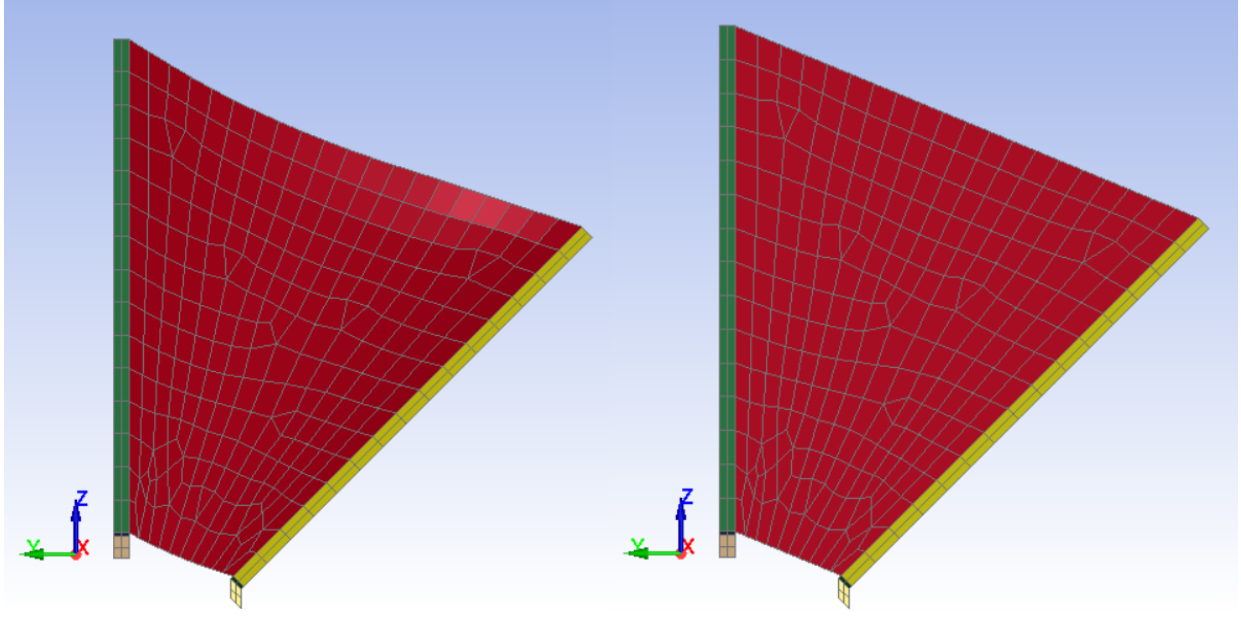


Fig 10. The deflected (left) and undeflected (right) states of the structural model of the gore. A single gore is modelled where the spars are assumed rigid.

Using the FUN3D utility MASSOUD, the unrefined mesh from the nominal geometry is deformed to the new surface curvatures. Due to the extremely small height of the first cell this proved challenging, however through increasing the number of deflection steps for the grid and adjustment of the elasticity function exponent, a successful deflection was obtained. CFD analysis then continued as before with adaptations as necessary.

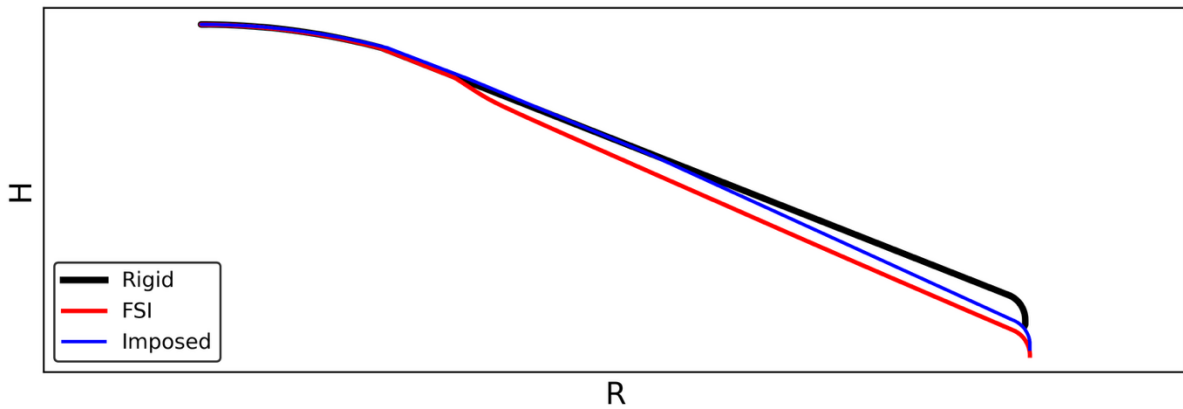


Fig 11. Slice of the geometry through the centerline of a gore for the rigid and deflected conditions.

The geometry deflection for a gore is shown in **Figure 11**. The initial FSI iteration deflection is similar at the trailing edge to the imposed deflection. The gore root deflection is noticeably larger for the FSI simulation. Artifacts from the mesh deformation can be seen in the contours of the deflected geometry, especially near the gore root and along the spar. The transition from the rigid nosecone to flexible fabric is uneven and a striping effect spanwise across each gore can be observed. These appear to be a direct result of the differing densities between the coarser CFD mesh and the coarser structural mesh. Tuning of the radial basis function and its application to the CFD surface points could likely improve these artifacts, as well as thoughtful choice of which structural points to include. Overall heating

magnitudes are similar to those in the catenary deflections discussed in Section III. The axial force coefficient is also reduced similarly.

The results are overall suitable for engineering use and vehicle development; however, improvements are identified. Specifically, tuning of the radial basis function to smooth the deflection between the coarser structural grid and finer CFD grid as well as thoughtful selection of the points to be included in the deflection to improve the transition from rigid nosecone to gore. Validation of the structural results will be conducted through testing of flight representative fabric under representative environmental and tension loads which will further improve confidence in the results of the overall analysis. Finally, the trajectory and uncertainties will be updated according to the axial coefficients using the deflected gore shapes.

V. Conclusions and Future Work

Analysis of the deflection of the Carryall Block 1 heatshield was conducted using both FUN3D and DPLR. Structured and unstructured mesh adaptation approaches were compared. Overall, differences between the two solvers are less than 1% and values for heating, surface pressure, and aerodynamic coefficients are adequate for engineering analysis.

As vehicle development progresses, further aerodynamic databases and analyses will be conducted. Increasing mesh density through more adaptation cycles and improving adaptation through increased iterations will be used to improve database heat transfer prediction. Also, a hybrid C2S approach will be considered in future solutions rather than a fixed surface mesh and boundary layer.

Through static FSI analysis introduced in section IV, the structure will be linearized about the nonlinear equilibrium condition to compute mode shapes. Flutter analysis will then be performed with FUN3D's internal modal solver to help determine if the edges of the flexible TPS are at risk of damage or damaging the structure through flutter.

The first reentry of a Carryall Block 1 is expected in late 2027 and will be instrumented to validate the aerodynamic coefficients as well as the surface heating rates and pressures.

References

Anderson, W.K., et. Al. FUN3D Manual 14.2, NASA TM 20250002308, 2025.

Ansys, Inc. *Ansys LS-DYNA User's Guide*, Release 2025 R1. Canonsburg, PA: ANSYS, Inc., 2025.

Biedron R.T., Thomas, J.L., "Recent Enhancements to the FUN3D Flow Solver for Moving-Mesh Applications" AIAA Paper 2009-1360, 2009. <https://doi.org/10.2514/6.2009-1360>

Coblish, J.J., Smith, M.S., Hand, T., Candler, G.V., and Nompelis, I., "Double-Cone Experiment and Numerical Analysis at AEDC Hypervelocity Wind Tunnel No. 9," AIAA Paper 2005-0902, 2005, <https://doi.org/10.2514/6.2005-902>

Dutta, S., Karlgaard, C., Korzun, A., Green, J., Tynis, J., Williams, J., Yount, B., Cassel, A., Wercinski, P. "Adaptable Deployable Entry and Placement Technology Sounding Rocket One Modeling and Reconstruction", *Journal of Spacecraft and Rockets*, 2022, 59(1), 236-259.

Fidelity Pointwise. Cadence, 2026.

Gnoffo, P.A., Gupta, R. N., and Shinn, J.L. "Conservation Equations and Physical Models for Hypersonic Air Flows in Thermal and Chemical Nonequilibrium" NASA TP-2867, 1989.

Hollis, B., Wise, A., Liechty, D., Korzun, A., Thompson, K., Rodrigues, N., Rieken, E. "Aerothermodynamic Analyses for the LOFTID Technology Demonstration Mission," *Journal of Spacecraft and Rockets*, 2026, 63:1, 113-133, <https://doi.org/10.2514/1.A36009>

Hughes, S., Swanson G.T., Cheatwood, F.M., Dinunno, J.M., Johnson, R.K., “Low-Earth Flight Test of an Inflatable Decelerator (LOFTID) Aeroshell Flight Performance”, 20th International Planetary Probe Workshop (IPPW), Marseilles FR, 2023.

Kessler, D., Hess, A., Obenschain, K., Eder, D., Koniges, A., Roe, K. McDaniel, D., Bond, R., Nielsen, E., Walden, A. Nastac, G., Jacobson, K., Knutson, A., Candler, G., Johnson, H., “Performance of Coupled Physics Solvers for Multidisciplinary Hypersonic Flow Simulations on Several Classes of Computer Architectures”, AIAA Paper 2022-0973, 2022, <https://doi.org/10.2514/6.2022-0973>

Mestreau, E., Aubry, R., Dey, S., and Richardson, M., “CREATE-MG Capstone Design, Architecture, & Feature Modeling Improvements”, AIAA Paper 2019-1716, 2019, <https://doi.org/10.2514/6.2025-0642>

Nastac, G., Forrest, M., Schneider, D., et Al., “Toward Adaptive Mixed-Element Unstructured Grids for Simulations of Viscous Flows”, AIAA Paper 2025-0642, 2025, <https://doi.org/10.2514/6.2025-0642>

Nastac, G., Nielsen E., and Tramel R., “Improved Heat Transfer Prediction for High-Speed Flows over Blunt Bodies using Adaptive Mixed-Element Unstructured Grids,” AIAA Paper 2022-0111, 2022, <https://doi.org/10.2514/6.2022-0111>

Nastac, G., Walden, A., et Al., “A Multi-Architecture Approach for Implicit Computational Fluid Dynamics on Unstructured Grids,” AIAA Paper 2023-1226, 2023, <https://doi.org/10.2514/6.2023-1226>

Nastac, G., Walden, A., Nielsen, E., and Frendi, A., “Implicit Thermochemical Nonequilibrium Flow Simulations on Unstructured Grids using GPUs,” AIAA Paper 2021-0159, 2021, <https://doi.org/10.2514/6.2021-0159>

Wright, M. W., White, T., and Mangini, N., "Data Parallel Line Relaxation (DPLR) Code User Manual Acadia – Version 4.01.1," NASA/TM-2009-215388, October 2009.

Wright, M.J., Milos, F.S., and Tran, P., “Afterbody Aeroheating Flight Data for Planetary Probe Thermal Protection System Design,” *Journal of Spacecraft and Rockets*, Vol. 43, No. 5, May 2006, pp. 929-943, <https://doi.org/10.2514/1.17703>

Wright, M.J., Olejniczak, J., Brown, J.L, Hornung, H.G, and Edquist, K.T., “Computational Modeling of T5 Laminar and Turbulent Heating Data on Blunt Cones, Part 2: Mars Applications,” AIAA Paper 2005-0177, January 2005, <https://doi.org/10.2514/6.2005-177>

Wright, M.J., Prabhu, D.K., and Martinez, E.R., “Analysis of Apollo Command Module Afterbody Heating Part I: AS-202,” *Journal of Thermophysics and Heat Transfer*, vol. 20, no. 1, 2006, pp. 16-30, <https://doi.org/10.2514/1.15873>

Hoter, Z., Nastac, G., Jacobson, K., Palmer, G., “Aerodynamic Analysis and Database Development of a Deployable Heatshield Reentry Vehicle,” AIAA Paper 2026-3816, 2026, <https://doi.org/10.2514/6.2026-3816>