

Peer Review Feedback for the CEV Aerosciences Project (CAP)

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Overview/Background

The NASA Engineering and Safety Center (NESC) peer review team is providing an independent, ongoing, and sustained review of the CAP team database development activities through critical design review (CDR) delivery, currently scheduled for 2008. The NESC-assembled peer review team met for a second CAP Peer Review session held on September 28-29, 2006, at the Langley Research Center (LaRC). The CAP team presented status, interim results, and future plans to the NESC Peer Review Team. The NESC Peer Review Team considered the information presented and herein provides feedback in the form of Findings and Recommendations. These findings and recommendations have been segregated into 5 groups: General, Database, Aerodynamic, Aerothermal, and Peer Review Process. The peer review team continues to be impressed by the level of skills and capabilities within the CAP and the combined team efforts to produce high quality deliverables. The peer review team believes the recommendations enclosed can help further these efforts.

It is requested that the CAP respond to each recommendation no later than 60 days after receipt. This response should include either an *accept* or *reject* statement (to include a justification) and a forward action plan for implementation of each accepted recommendation. Retroactively, the response should also address the initial CAP peer review findings and recommendations.

1. General Findings and Recommendations

Finding: Project plans and priorities are not fully justified by risk analysis, nor are the risk management processes sufficient to guide decision making.

Discussion: Top risks were identified under the CAP overview, but clear mitigation and a formal process for tracking each risk was not presented. Several of the risks were poorly characterized. In particular, consequences of potential events were not fully developed. It was not clear if the risks, mitigation plans, and the test and analysis plans were properly aligned with each other. Uncertainties and analysis deficiencies were not traced to system impacts. Tests were not directly linked as mitigation to identified risks. Given the stated CAP funding constraints, it was unclear that the current distribution of resources is optimally applied to address those risks deemed highest priority (e.g. compression pad impacts to aero, aerothermal; radiation estimation; Phenolic Impregnated Carbon Ablator (PICA) ablation – are these the highest priority risk areas?).

Recommendation (R-25)¹: Repeating a recommendation from the first peer review (February 6, 2006, see Attachment)², it is strongly suggested that the CAP manage risks in a standard NASA 5 x 5 matrix format (Likelihood versus Consequence), along with formal mitigation plans and progress tracking. This approach will enable the Crew Exploration Vehicle (CEV) Project to understand the history and track progress for each risk element over the CAP development lifecycle. Rank risks and align resources and tests consistent with the risk rankings. Identify Test-Like-You-Fly exceptions as anticipated residual risks assuming successful completion of CAP activities.

Finding: The integration of CAP plans, schedules, and products with the customer communities (Guidance, Navigation & Control (GN&C), Thermal Protection System (TPS), etc.) are not clearly evident.

Discussion: The CAP team discussed numerous test and analysis activities aimed at reduction of various aero/thermal uncertainties. While the objectives of these efforts are laudable, it appears that some of the technical challenges that the team is facing are being internalized, and impacts are not necessarily defined and communicated across the project. One example is the dynamic aerodynamic uncertainties. An effort is being made to reduce the uncertainties. However, it is not clear that GN&C has a plan for accommodating higher uncertainties if that is the outcome (or for that matter if reduced uncertainties are a significant benefit to GN&C?). Center-of-gravity (c.g.) location is a similar issue, as is TPS surface recession and resulting aero impacts.

Recommendation (R-26): Develop a product/customer list. Cross-populate the customer and CAP product development teams to ensure the focus for uncertainty reduction is prioritized appropriately. Understand the customer milestones and their impact on CAP activities. Ensure regular participation of customers (GN&C, Trajectory Design, TPS, Parachutes, etc.) in CAP activities, and their direct participation in major reviews (Database Reviews, Peer Reviews, TIMs, etc.). As an example, the GN&C team needs to be aware that the uncertainties may remain high, and they need to have an approach for accommodating the uncertainties. An integrated plan with options for different outcomes needs to be worked between the Aero and GN&C customers.

Finding: The CAP is currently organized by function (e.g. Aero computational fluid dynamics (CFD), Aero Testing, Aerodatabase, etc.) instead of by product (e.g. CEV Aerodynamics, Launch Abort Vehicle (LAV) Aerodynamics, etc.). This organization was very successful in setting up the teams and getting the capabilities up and running. However, current the organizational structure is not facilitating customer interfaces and deliverables. In addition, the current organization is overburdening the single team lead since all functional leads report to the single lead for all aero and aerothermal integration and all products.

¹Continuation of Recommendations from Peer Review #1

²Peer Review #1 (Rev. 2-23-06) Document No. RP-06-19

Recommendation (R-27): The team should be reorganized / restructured to provide product teams and leads. The CAP should identify a responsible individual to plan and coordinate the activities necessary to deliver each specific product and serve as the primary interface with the product's customer – GN&C, TPS, Structures, etc. Product team leads should report to the overall team lead. Product team leads should support customer interfaces and should be responsible for daily decisions for a given product.

Finding: There is not a clear definition of the roles and responsibilities of the CAP with the Prime Contractor (Lockheed Martin/Orbital), the CEV TPS Advanced Development Project (ADP), and Flight Test Office.

Recommendation (R-28): Formally describe the expectations, roles and responsibilities of the Prime Contractor team, including communication and feedback paths, and how they are integrated with the CAP processes. The roles and responsibilities with regards to aerothermodynamics data and models provided by the CAP to the TPS ADP, and any feedback paths back to the CAP, need to be clarified and explicitly stated.

Finding: No discussion was provided on the proposed flight test opportunities and what data could be obtained, and the required instrumentation to obtain the data.

Recommendation (R-29): The CAP should consider having a representative from the Flight Test Office participate in the development planning and ensure that appropriate instrumentation requirements are provided early and similarly for the TPS ADP efforts.

2. Database Findings and Recommendations

Finding: Database development will use both test and analysis results – which is appropriate – but a change from the initial strategy of a CFD-based product.

Recommendation (R-30): Ensure that the updated objectives of test and analyses requests are communicated clearly to the technical staff so that the activities can be designed and conducted appropriately.

Finding: The aerodynamic and aerothermodynamic databases, as currently constructed, are based on a nominal (“smooth”) outer mold line (OML) configuration. It is unclear how dynamic geometric changes (primarily due to material recession) will be incorporated into the analysis process, and consequently, how the database will be constructed to accommodate that process.

Discussion: As per the plans shown in the presentations, heatshield recession will be taken into account both for aerodynamics and aerothermodynamics via “deltas” to the nominal. Implicit in this plan is that the choice of heatshield TPS material is PICA. It is unclear how a dynamic (i.e., time-, material- and trajectory-dependent) phenomenon will be incorporated into a static database constructed in a design-space (parameterized by Mach number, dynamic pressure, and

angle-of-attack) paradigm, especially when surface recession will definitely change aerothermodynamic performance during the heating portion of the entry and the aerodynamic performance during the descent and landing portion. The effects are likely to be magnified in the presence of surface non-uniformities (compression pads, windows, etc.) and, perhaps, with trajectory dispersions.

Recommendation (R-31): A modest trajectory-based analysis effort should be undertaken to understand the system sensitivities to shape change (global recession and local effects). The results of this study would be the identification of requirements in accounting for shape change (both in terms of analysis process and database architecture). One suggestion is anchoring the CFD analysis process to the compression pad/tension tie experiment in the LaRC Mach 6 tunnel - an exercise that will hopefully provide a sense of “scale” on heating augmentation (i.e. see Finding associated with R-25 and manage this as a risk).

Finding: The aero/aerothermal databases are “square”.

Discussion: Square matrices lead to unrealistic (outside any anticipated trajectory) data points in the product, most likely defined through extrapolation of valid data from test and analysis.

Recommendation (R-32): Ensure that extrapolated points are clearly marked and that the boundaries for valid data are delineated. GN&C trajectory simulations should clearly flag when trajectories have violated these boundaries.

Finding: The definition of uncertainty in the aerodynamic database is not clear, thereby creating the potential for misapplication of the uncertainty data.

Discussion: Version 1 of the aerodynamic database is an estimate of the CEV aerodynamics based on extrapolation of the Apollo aerodynamics. The uncertainty estimates in the database are not an expression of the potential error in extrapolating from one geometry to another, but an estimate of the residual uncertainty after the CEV aerodynamics are measured experimentally and assessed computationally. The former uncertainty band is likely greater than the latter. Therefore, the current uncertainty bands are useful for designing a guidance algorithm to account for the eventual uncertainty, but may not fully encompass the possible range of nominal aerodynamic parameters when assessing the trajectory space.

Recommendation (R-33): Clearly define and communicate the uncertainty parameters in the aerodynamic database. Consult with data users as to the application of the uncertainty parameters and determine appropriateness of use. Do the same for the aerothermal database.

3. Aerodynamic Findings and Recommendations

Finding: It is unclear if the CAP is responsible for the aerodynamics under the parachutes (drogue & main) or the wake properties for which the chute designers will require.

Recommendation (R-34): Confirm addition of these responsibilities from the Orion Project Office.

Finding: It was stated that the CAP is expecting Launch Abort System (LAS)/LAV OML changes after the Pad Abort Test 1.

Recommendation (R-35): Estimate liens for additional aero test/requirements analysis beyond FY08.

Finding: It was noted that the potential change in the c.g. location could drive the test and analysis focus. This is a reactive posture.

Recommendation (R-36): Develop products that appropriately cover the range of c.g. to be considered plus some margin in a pro-active approach to developing a flexible and functional database.

Finding: Various test techniques and test data have resulted in large dynamic (damping) model data variability and uncertainties. It is not clear how the various dynamic data sets will be reconciled to derive nominal and uncertainty models.

Recommendation (R-37): Use simulation capabilities to show how sensitive vehicle dynamics are to dynamic aero models and uncertainties; need to work closely with the GN&C customer to understand sensitivities in all 3 axes to guide model development strategy including uncertainty definition, and the need for additional testing. (i.e., see Finding associated with R-25 and manage this as a risk).

Finding: Due to budget cuts, 2007 Hypersonic Aerodynamics Testing is being delayed to 2009. The team plans to use CFD to generate the aerodynamics database.

Discussion: This issue may or may not be a concern. As suggested by the CAP team, if the CFD results compare well with the aerothermal testing data (i.e., good comparisons with heat transfer), then the predominately pressure-dominated aerodynamics should be well resolved for hypersonic flows. However, since the Apollo aero flight data is unreliable as a “truth model” (as discussed during CAP Peer Review #1), the team has limited confidence in the aero results and associated uncertainties until 2009. Furthermore, the impact of protuberances on the heatshield and the subsequent effect on the aerodynamics is unknown (see Finding associated with R-31).

Recommendation (R-38): The team needs to better address any risks associated with delaying the testing until 2009. Perhaps this improves their situation as the final smooth-OML and potential geometric changes due to ablation with the now selected PICA or protuberances will be better finalized. The team should also address how they will quantify their aerodynamic

uncertainties in the near-term without data for comparison. Assess this effect with the GNC customer.

Finding: Several RANS calculations were performed on the LAS to determine overall drag for various configurations over subsonic, transonic, and mildly supersonic Mach numbers.

Discussion: Drag predictions for unsteady turbulent flows for subsonic, transonic and low supersonic Mach numbers are rarely well predicted by unsteady RANS calculations, especially in regions of large flow separation and in wakes. In most cases, the unsteady RANS calculations will drastically under-predict the drag. It is not clear that even the proper trends can be predicted since the large turbulent scales are being averaged out. The effects could be even more pronounced in 3-D.

Recommendation (R-39): In addition to the unsteady RANS simulations, the team needs to assess the applicability of these results by using some unsteady hybrid RANS/LES methods. While certainly more computationally intensive, these methods do a much better job of predicting drag than unsteady RANS.

4. Aerothermal Findings and Recommendations

Finding: The activity of estimating aerothermodynamic heating due to radiation is on a success-driven schedule, i.e., 100 percent uncertainty in the radiation magnitude is assumed, and planned tests are intended to confirm that there are no “unknown-unknowns” that could cause heat rates to exceed the estimated uncertainty. It is not clear that there is requisite expertise on the team to resolve unexplained experimental findings if there are any.

Recommendation (R-40): If possible, front-load efforts in radiation modeling assessment to create time for contingency mitigation.

Finding: The primary concern in the radiative aspect of entry heating is the current lack of quantified uncertainties in: (1) radiative heating from wavelengths shorter than 200 nm, and (2) closure of the radiative heat pulse at low freestream densities (equivalently early entry). The “safe” route chosen by the analysis team is to assign an ad hoc 100 percent uncertainty on predicted radiative heat flux.

Discussion: Assuming the radiative heat pulse to be quite narrow, this uncertainty in heat rate will have little impact on the radiative heat load. However, the uncertainty in radiative heat pulse closure at early entry may have an influence on the heat load and will require closure scrutiny. As for short wavelength or vacuum ultraviolet radiation, there have been very few experiments conducted in ground-based facilities to characterize it, and all flight experiments (Fire-II, AS-501/502) have had instruments/windows that cut off radiation below 200 nm. While the current series of tests in the EAST are showing promise in obtaining data in the short wavelength region, contamination by carbon-bearing species (especially CN) will impose constraints on the

traceability of models employed in simulations of ground-based experiments to those employed for flight environment predictions. The data from a flight experiment flow on board the PAET might be of some value. The PAET experiment [ref. 1-3] was originally meant to aid in deducing the amount of atmospheric CO₂ through measurements of CN and N₂⁺ (1st negative) band systems. The experiment of Palumbo et al [ref. 4] in the early 1990's in the AHF at NASA Ames Research Center provided the first calibrated/quantitative measurements of atomic oxygen and nitrogen lines at 130 and 174 nm, respectively. Numerical simulations of this arcjet-based experiment will require addressing uncertainties in the thermochemical state of the nozzle gas mixture – an exercise that will be required, perhaps, for the planned CUBRC tests as well. Another guide towards quantification of uncertainties in vacuum ultraviolet (VUV) radiation is the work of Whiting and Park [ref. 5]. The impact of Voigt profiles of atomic lines in the VUV was carefully studied for the Aeroassist Flight Experiment (AFE) vehicle.

- (1) Seiff, Al, Reese, D. E., Sommer, S. C., Kirk, D. B., Whiting, E. E., and Niemann, H. B., "PAET, An Entry Probe Experiment in the Earth's Atmosphere," ICARUS, Vol. 18, pp.525-562, 1973.
- (2) Whiting, E. E., Arnold, J. O., Page, W. A., and Reynolds, R. M., "Composition of the Earth's Atmosphere by Shock-Layer Radiometry During the PAET Entry Probe Experiment," J. Quant. Spectrosc. Radiat. Transfer, Vol. 13, pp. 837-859, 1973.
- (3) Arnold, J. O. and Whiting, E. E., "Nonequilibrium Effects on Shock-Layer Radiometry During Earth Entry," J. Quant. Spectrosc. Radiat. Transfer, Vol. 13, pp. 861-870, 1973.
- (4) Palumbo, G., Craig, R. A., Whiting, E. E., and Park, C., "Measured Specific Intensity from 130 To 900 nm at the Stagnation Point of a Model in an Arcjet Flow of 7.8 km/sec," J. Quant. Spectrosc. Radiat. Transfer, Vol. 57 (2), pp. 207-236, 1997.
- (5) Whiting, E. E., and Park, C., "Radiative Heating at the Stagnation Point of the AFE Vehicle," NASA TM 102829, Nov. 1990.

One final thought on radiative heating – predictions are only as good as the thermophysical models/assumptions used in the flow simulations. Radiative transition data (dipole transition moments, Franck-Condon factors, etc.) are accurately known, and "errors" in integrating the radiative transport equation are also well quantified. The main sources of uncertainty are then in population distributions, temperature(s), and, to some extent, coupling of radiation and matter.

Recommendation (R-41): The following simulations (both flow and radiation) must be performed (listed in order of priority).

1. Study impact of Voigt profiles on atomic line shapes using the methodology of Whiting and Park as a guide.
2. Determine sensitivity of radiative heating at low freestream densities to establish closure of the radiative heat pulse.
3. Simulate arcjet experiment of Palumbo et al. This exercise might require a sensitivity analysis to account for freestream uncertainty.
4. Simulate PAET flight environments (trajectory-based) to account for CN influence (indirectly CO₂ contamination). A requisite in the simulation is a reaction mechanism for a flow medium containing air and CO₂.

Finding: The benefit of proposed wall blowing tests is not clear.

Discussion: Blowing tests will be conducted at CUBRC and LaRC to validate coupled ablation simulations and to assess transition criteria. It is not clear how relevant this data will be. It will likely be valuable in validating blowing boundary conditions in the code, but it will not by any means be representative of the flow and surface interactions that will take place in flight. Material thermal response codes (i.e., FIAT or CMA) can provide representative blowing rates, but it is unclear how the team will ultimately use this data to validate their coupled ablation codes or assess transition criteria in a cold and noisy facility. How will they deal with variations in porosity? What about chemistry between flow and products of ablation?

Recommendation (R-42): The team needs to better address the overall usefulness of this data, especially since the team is sizing the heatshield for fully turbulent flow. Since PICA is the TPS of choice, there needs to be some assessment of which effect is more important, surface roughness or blowing. If Holden data suggests rough surface will increase heating above smooth-OML turbulent values and that small blowing rates will decrease this value, this money may be better spent examining roughness issues, if that will be a problem for PICA. Timely reduction of Stardust data will be required. The team needs to better articulate the cost-benefit of this series of tests (i.e., see Finding associated with R-25 and manage this as a risk).

5. Review Process Findings and Recommendations

Finding: Excellent aerothermal CFD and aerothermal testing progress was shown. The team was concerned that their time to present was cut short. A detailed aerothermal environments plan was not presented, possibly due to time on agenda? As a result it is not clear that the analyses and testing that is taking place have been prioritized.

Recommendation (R-43): Reformat peer review to ensure adequate time for Aerothermal team. Either two separate reviews/panels, or sharp cut-off for whichever team is first on the agenda. If only one review is scheduled next time, the Aerothermal team should be scheduled to go first.

Recommendation (R-44): In addition to the altitude-velocity map showing the design space, it would be good to see a design space map in terms of Reynolds and Mach number with operating envelopes of ground-based facilities and numerical tools overlaid. Such a map will give a good idea of “coverage” provided by both experimental and numerical methods.

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Approval and Document Revision History

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1.0	Initial Release	NESC Discipline Expert, JSC	

Attachment

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Overview

The NASA Engineering and Safety Center (NESC) assembled a peer review team who met for the first time with the Crew Exploration Vehicle (CEV) Aerosciences Project (CAP) on February 7, 2006. The objective of this initial review was to assess the CAP development plans for CEV Aerodynamics and Aerothermodynamics for technical completeness, to identify any shortcomings in the development plan, and to provide recommendations. The meeting was conducted via presentations from the CAP team leads to the NESC-assembled peer review team and allowed for questions and answers. The full day meeting also allowed a complete coverage of the presentation materials.

The NESC peer review team has considered the information presented and provided the feedback in the form of Observation and/or Finding with a follow-on Recommendation. These have been segregated into general, aerodynamic or aerothermodynamic, as well as experimental, computational or flight test groupings. The purpose of the present report is to articulate those concerns, and provide several recommendations. It is requested that the CAP respond to each recommendation no later than 30 days prior to the next scheduled peer review session. The NESC peer review team will provide for an independent, ongoing, and sustained review process and follow along with the CAP team database development activities through a critical design review (CDR) delivery, currently scheduled for 2008. It is anticipated that the next scheduled Peer Review session will be held in the Summer of 2006.

Overall Summary

Overall, the CAP presentations were well-delivered, informative, and provided an excellent basis of understanding for the CEV aerodynamic and aerothermodynamic database development activities. The CAP team appears to be well integrated across the three primary centers: Johnson Space Center (JSC) (lead), Ames Research Center (ARC), and Langley Research Center (LaRC). Project organizations currently consist of NASA personnel only. The team assembled from across the Agency is well qualified to complete the development plan. Contractor personnel will be integrated once the selection of a prime CEV contractor is made. It is recognized that because of the lack of maturity and pending decisions on the final CEV geometry and trajectories, very little actual data has been generated to date. Therefore, this review focused primarily on the proposed development plans, including experimental facilities and computational tools and methods, and current “best practices” development efforts. Plans to meet schedule and technical challenges were addressed cogently. As stated earlier, the focus of the review was largely

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concentrated on the smooth Outer Mold Line (OML) of the Command/Crew Module (CM), the absence of details regarding the other configurations must be noted. In general, the Launch Abort System (LAS) and Service Module (SM) configurations involve more complex geometries, as well as plume interactions from Reaction Control System (RCS) and abort motors, entailing complex modeling conditions and configurations. Sufficient planning details on these other configurations, in particular the LAS, need to be established as soon as practical to ensure the CAP team resources are adequately scoped and can support the intended CEV Project Office (CEVPO) development schedule. It is strongly recommended that this be given additional priority in the near-term planning efforts.

The nature of peer reviews is typically to help identify shortcomings (as per the stated objective above). As such, the general tone of this document should not be misconstrued as an overly negative assessment of the CAP. It is the opinion of the peer review team, that the CAP has assembled a team of top quality personnel with the necessary skill mix and proficiencies in the tools and the identified facilities to produce high quality deliverables as defined. However, the peer review panel feels that in some areas greater definition/clarity is necessary.

Note: Number of diamonds (◇◇◇) provides relative importance of finding/recommendation

General Findings/Observations/Recommendations

◇◇◇ **Observation:** Top risks were identified under the CAP overview but clear mitigation and a formal process for tracking each risk was not presented, although mitigation plans were discussed at an informal level. Discussion of some specific risk elements for the aerodynamic and aerothermal database development also occurred during the course of the review, but again no formal mitigation and tracking plan was presented.

Recommendation (R-1): It is strongly suggested that for future reviews and tracking the CAP present top risks in a standard NASA 5x5 risk matrix (likelihood vs. consequences) format, along with formal mitigation plans and progress. This will enable the review panel (and the CEV Project) to understand the history and to track progress for each risk element over the CAP development life-cycle.

◇◇◇ **Finding:** While the current state of flux in the dimensions of the OML was noted, it was not apparent that the potential impact had been clearly or fully addressed by the CAP team.

Observation: Changes in the OML can (and should) be expected in the design analysis cycles. There does not appear to be sufficient margin in the schedule or sufficient flexibility in the plan to adequately address these changes.

Recommendation (R-2): The CAP team should develop a plan/strategy to address changes to the OML in the database development sequence. In cases where the geometry is photographically scaled (i.e., the most recent change, the current OML, 18.05-ft diameter, is a photographically scaled version of the original OML, 16.5-ft diameter, except for the aft corner radius, reduced from 10.83 inches to 2 inches), scaling laws should be considered for determining the new initial heat shield and windward aerothermal environments from the environments for the original geometry. Additionally, a proactive study on backshell angle

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sensitivity should be considered as direct CAP support to the CEVPO OML configuration control board.

◇◇◇ **Observation:** Documentation is an extremely important part of any project. For a fast paced development program such as the CEV, it is critical to tightly integrate documentation efforts into the overall technical effort. Although the CAP has outlined plans for configuration control for data products, it is not clear whether test and analysis documentation is part of this plan, and if sufficient resources are allocated to it.

Recommendation (R-3): Ensure that each and every test and computational solution set is thoroughly documented, and that all documentation is formally reviewed and placed under configuration control with revision tracking. Every data point in the substantiation document should be traceable back to the original source. Test facility and experimental setup (including balance calibration information, check loads, computational grids and inputs, etc.) should be fully documented.

◇◇ **Finding:** The CAP development plan has been established without inputs from the Prime Contractor (to be selected).

Observation: The selection and introduction of the Prime Contractor into the CAP process will be a significant event and should be planned for with an identified approach/strategy. This could be particularly acute at interfaces with contractor developed systems (e.g. Thermal Protection System (TPS), Guidance, Navigation & Control (GN&C), etc.).

Recommendation (R-4): The Prime Contractor should be required to provide both a management and technical skill base interface with the CAP in order to ensure buy in for the delivered CAP products. Revisit other Government-furnished equipment (GFE) contractor/government relationships to obtain lessons learned on appropriate structure for these relationships.

◇ **Observation:** The risk of using team members to support both the CEV and Space Shuttle Programs (SSP) is not adequately addressed, especially should CEV milestones coincide with Space Shuttle missions.

Recommendation (R-5): While it was reported that this risk is recognized by the CEVPO and the CAP, a more proactive approach to address the risk should be considered. For example, to account for some unexpected disruption of work either gain full commitment of CAP team members or identify back up personnel for key responsibilities known to be at risk for SSP support.

Database Development Findings/Observations/Recommendations

◇◇◇ **Observation:** A formal process for independent review and documentation of all aerodynamics and aerothermodynamic model inputs and mapping to database software routines was not presented.

Recommendation (R-6): The CAP should develop a formal independent review process to ensure all data (wind tunnel and computational, including uncertainty models) are independently

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reviewed and the mapping into database models are independently validated. A suggested approach would be to independently “reverse engineer” the database by mapping data points back to the original source (wind tunnel or computational) and ensuring data falls within stated uncertainties. A formal document should also be developed with a standard set of model input/output check cases to be conducted by all users of the database subroutines (Government/Prime Contractor GN&C, simulations, structural loads, etc).

◇◇◇ **Observation:** A plan for uncertainty model development, including experimental, computational, and ground-to-flight scaling, was not discussed in detail. Typically, the experimental measurement uncertainties are well understood and documented, but computational and ground-to-flight scaling uncertainties are difficult to assess and require significant engineering judgment and reasoning.

Recommendation (R-7): The CAP team should form an uncertainty modeling group with representation from the experiment and computational groups. It is suggested that a thorough review of the Apollo pre-flight data versus flight data, and assessment of the Apollo uncertainty models be conducted and utilized to guide the development of appropriate uncertainties for CEV flight articles. This review should include nonlinear and linear aero models, aero loads, and aerothermodynamic models.

◇◇ **Observation:** The methodology for development of an aerodynamics database has not been formally documented. While it is agreed with the general principles stated in the presentation charts, there is no substitute like a written process document (“white paper”) with all the mathematical details.

Recommendation (R-8): Formally document the aerodynamic and aerothermal database development methodologies. This will help crystallize and communicate the process, while adding precision to the broader statements in the presentation charts (e.g. method for combining, selecting or excluding data from multiple sources). This is likely a living document along the lines of the Aerothermal “Best Practices” for computer fluid dynamics (CFD) analysis document. The process of supplying the aerodynamic and aerothermal databases to the GN&C and TPS teams needs to be exercised early on to ensure the relevant information is provided to these users.

Aerodynamic Findings/Observations/Recommendations

◇◇◇ **Observation:** The requirement for the CEV minimum hypersonic lift-to-drag (L/D) is not clear. Several times it was stated and presented as 0.4 and at other points as 0.35.

Recommendation (R-9): The CEV project should identify a minimum L/D requirement and the CAP team should document trim alpha and L/D performance towards this requirement. Clearly identify issues and impacts associated with attaining this requirement. Impacts of potential CEV backshell angle change and associated aftbody afterbody heating and resultant TPS requirements should be clearly defined and documented to the CEVPO by the CAP team.

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◇◇◇ **Finding:** Given that the OML is in a state of flux, the initial theoretical analysis has been appropriately focused, as stated by the CAP, on verifying/validating/calibrating tools and methodologies that can then be applied with confidence to the actual capsule shape(s). As presented, aero validation using Apollo flight data will not be performed due to uncertainty in the vehicle shape during flight tests. The CAP intends to only use wind tunnel data.

Observation: Doctoral work by Basil Hassan (see references^{1,2}) showed that chemistry effects are important to Apollo trim angle. Early flights were of low enough velocity that significant ablation did not occur.

Recommendation (R-10): Revisit the Apollo flight data for validation of aerodynamics. While the initial investment may seem large and somewhat disconnected from the actual CEV shape, the lessons learned should be of immense value in accelerating the analysis process for the CEV shape.

◇◇◇ **Finding:** To the best of our knowledge and based on CAP comments, Aero/RCS data on Apollo are not available.

Observation: Below is an excerpt from a briefing to Mars Science Laboratory (MSL) 20 April 05 by Takashima, Dyakanov, and Scallion describing the historical information on Aero/RCS interaction found for MSL. (Shuttle information was included on the chart as well).

Apollo

- *Entry Vehicle Control, NASA SP-8028, November 1969.*
 - *Apollo 7 reentry: "considerable pitch and yaw control activity in the transonic region during the final 2 min before drogue deployment", from simulation they concluded that this was a result of "thrust jet interaction with flow around the vehicle and strong winds."*
- *NASA TM-X-1063, R. Jones, J. Hunt, Effects of cavities, protuberances, and reaction control jets on heat transfer to the Apollo Command Module*
 - *Mention of interference patterns on aftbody caused by RCS jets*

Viking

- *Blake, W. W., Polutchko, R. J., "Hypersonic Experimental Aerodynamic Characteristics of Viking Lander Capsule," Martin Marietta Corporation, TR-3709012, May 8, 1970*
- *Aero/RCS interaction estimated in wind tunnel tests at M=20 using solid bodies to represent thruster plumes*
- *The data were inconclusive due to insufficient accuracy of the low AOA data*
- *The recommendation was to use a balance designed to measure small CN and Cm, and large CA to minimize data uncertainties, but this apparently was never accomplished for Viking.*

Recommendation (R-11): Update the chart (page. 20 – Aero Development Overview) that shows where there are or are not Apollo data, and confirm for each box. The transonic regime will likely not be included in the MSL aero/RCS tests. This regime should be included in Apollo aero/RCS interaction testing. NASA SP-8028 should be reviewed by the team.

◇◇ **Observation:** It was stated that the GN&C group will be responsible for the development of any linear aerodynamic models (using the non-linear 6 degree-of-freedom (DOF) databases) for control system design.

¹ Hassan, B, Candler, G V, and Olynick, D R, "Thermo-Chemical Nonequilibrium Effects on the Aerothermodynamics of Aerobraking Vehicles," *Journal of Spacecraft and Rockets*, Vol. 30, No. 6, Nov. - Dec. 1993, pp. 647-655.

² Hassan, B, Candler, G V, and Olynick, D R, "The Effect of Thermo-Chemical Nonequilibrium on the Aerodynamics of Aerobraking Vehicles," AIAA Paper No. 92-2877, July 1992.

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Recommendation (R-12): The Aerodynamics group should develop and provide the linear models and validated computer linear aero model subroutines, including linear model uncertainties, to the GN&C group. The aerodynamics team should be more familiar with the data models and would recognize and be responsible for understanding any peculiarities and nonlinearities in the 6DOF model used to develop linear data for control law design and validation. This would have the added benefit of forcing the aero and GN&C designers to effectively communicate and work closely together to ensure consistent and appropriate linear model implementation.

◇◇ **Observation:** Communication and coordination between the aerodynamics and GN&C groups (and the Government and Prime Contractor teams) will be paramount to the CEV development and mission success.

Recommendation (R-13): Ensure that appropriate communication (formal and informal) between Aero, GN&C, and simulation group occurs, including Government and Prime Contractor team personnel. Historically, the aero and the GN&C do not communicate effectively, and the added complexity of giving the Government responsibility for the aerodynamic and aerothermodynamic databases (GFE) and the Prime Contractor team leading the GN&C and primary simulation efforts will make this particular issue worthy of extra close attention. It is suggested that formal aerosciences and GN&C panels be established with representation from all groups (aero, aerothermal, flight dynamics, and GN&C teams) to ensure effective communication across formal discipline lines.

Aerothermodynamics Findings/Observations/Recommendations

◇◇ **Finding:** Shape change/ablation issues on aero/aerothermal.

Observation: It is unclear how ablation and shape change issues are to be considered. Shape change is directly tied to the choice of TPS material, and progress on selecting the final material is not expected before Summer of 2006.

Recommendation (R-14): The CAP Aerothermal group must be tightly integrated with the TPS group to ensure the broadest understanding of this sensitivity. This combined team needs to quantify ablation/shape change effects for representative trajectories. Assess whether or not fully coupled solutions are really necessary. The current approach is based on an assumption that ablation recession is insignificant and can be covered by uncertainty alone. The overall CAP plan needs more flexibility to adjust for the potential.

Computational Findings/Observations/Recommendations

◇◇◇ **Finding:** No definitive plan on how CFD analysis error quantification will be performed.

Observation: More than ever before in crewed flight vehicle development, CFD analysis will be relied upon for a significant part of the aero and aerothermal database for a majority of the flight environment and flight configurations. Uncertainty quantification and grid convergence were not discussed or provided in detail.

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Recommendation (R-15): A plan for determining "error bars" on CFD solutions and quantifying the error on the grids used should be defined. At a minimum, an approach such as Richardson extrapolation (solutions on 3 grids) should be considered for application on selected cases to assess potential CFD errors. A strategy to address modeling differences and uncertainties between the various codes should be defined.

◇◇◇ **Observation:** The current development plan for aero- and aerothermal databases calls for very heavy use of computational tools/methodologies, especially in flight regimes for which ground-based test facilities might not be well suited. Given the schedule constraints and limited computational resources (identified as risk) available to the team, it will be worth re-examining the strategies in developing the databases. The particular use of Active Directory Services Interface (ADSI) methodology to address computational resource issues is to be applauded.

Recommendation (R-16): We encourage further investigation into the feasibility of using Design of Experiment (DoE) to aid in the "intelligent" selection of database points. The paper of Tang, Gee, and Lawrence entitled "Generation of Aerodynamic Data using a Design of Experiment and Data Fusion Approach", American Institute of Aeronautics and Astronautics (AIAA) Paper 2005-1137 is a useful reference. However, DoE-type approaches need to be used with understanding of their limitations, particularly in identifying and resolving non-linearities. Also, focusing attention on flight regimes where different physical phenomena (such as internal mode excitations, species dissociation, and ionization) manifest themselves will prove to be useful. Apart from reducing the number of solutions to be computed, the time savings will not only allow for more thorough interrogation of solutions and learning from them, but also will maximize flexibility in the process.

◇◇ **Observation:** The large, distributed nature of the CAP team, and the diversity of the CFD codes add benefit to enabling positive results and add challenges to ensure that the team is coordinated. Adding to the challenge are the large number of configurations (CM, Lifting Ascent Vehicle (LAV), etc.), design trajectories, flight conditions, types of solutions (comparison to tunnel, loads, RCS, separation, databases, etc), the fluid design, and the possible impact of ablation shape change.

Recommendation (R-17): If not already completed, it would be useful to put together a working matrix near-term that partitions off the work needed by Program phase at one level of detail more than presented in the review package. For example, for the preliminary design review (PDR), a matrix could list the number of CFD solutions as a function of (configuration, code, center, flight conditions, grid, solution type, OML). The CAP should generate a matrix of work versus CEV Project milestones for use in task and resource planning. This would allow iteration and communication with those completing the CFD, databases and wind tunnel tests and help coordinate resource planning.

◇◇ **Observation:** The "Best Practices" documents for aero and aerothermodynamics are a good attempt to standardize approaches that have been proven to yield the best results, based in part on the ongoing validation. It is probably apparent to the team, however, that particularly in the areas of aerothermodynamics (turbulence, radiation, aftbody) and some aerodynamics (separation, aero/RCS) that the "best practices" will need to evolve as the flowfields are understood.

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Recommendation (R-18): Describe the “best practices” as a living document for specific areas that require that flexibility. Establish a formal method of communication for these “best practices” to the entire team on a regular basis. Realize that as the Prime Contractor is integrated into the team, they will likely want to augment this document with their own “best practices.”

Experimental Findings/Observations/Recommendations

◇◇ **Observation:** The CAP plan calls for the use of multiple test facilities being used for similar test objectives.

Recommendation (R-19): Understand the overlap in test conditions and determine how these results complement one another. This is essential when interpreting the results for database development. The CAP should generate a table comparing the similarities and differences between facilities.

◇◇ **Observation:** As mentioned earlier, focused computational studies can help in developing the initial test matrix for experiments. While Tetrafluoromethane (CF₄) has been demonstrated as a viable test medium to obtain “real-gas” effects on aerodynamics, its application as a medium for aerothermal “real gas” effects is not as well established.

Recommendation (R-20): Clarify the role of CF₄ testing in the aerothermal database development.

◇◇ **Observation:** While the Picosecond Laser Induced Fluorescence (PLIF) technique does provide knowledge of flow structures, the presentation is not clear on how quantitative information can be extracted from the pictures.

Recommendation (R-21): Before relying on and investing in this technique, establish the application of the results. Also, if quantitative data is expected, establish the method for extracting this data.

Flight Test Findings/Observations/Recommendations

◇◇◇ **Finding:** Flight test requirements, detailed plans, flight vehicle development and the necessary support from the CAP team were not sufficiently identified.

Observation: Past experience indicates the tendency for a flight test program to overwhelm the same team dedicated to vehicle development with flight test-specific test and analysis that is not directly applicable to the basic vehicle development. Flight test requirements must be clearly understood.

Recommendation (R-22): Flight test plan and the CAP use of flight test needs a significant amount of further development — perhaps an entirely different plan and a separate peer review. Recognize this tendency and plan for this reality in any CAP resources dedicated to the CEVPO flight test programs.

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◇◇ **Finding:** The CAP team has not currently identified Flight Test Coordinators for either aero or aerothermal.

Observation: Both CAP aerodynamics and aerothermodynamics intend to take advantage of, or fully utilize, flight testing in their database development and verification activities.

Recommendation (R-23): Given the key role flight testing is to play in the CAP database development process, these Flight Test Coordinator positions should be filled without further delay.

◇◇ **Observation:** The plans/objectives for a larger Fire-II test are not clear, other than a broad statement on radiative heating.

Recommendation (R-24): Confirm the need for radiative heating to be quantified only through a large-scale vehicle flight test. Otherwise, consider a sub-scale model instrumented to study shock-layer radiative signature (a la PAET) as sufficient to characterize the thermochemical state of the shock-layer gas.

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