Simulation for Prediction of Entry Article Demise (SPEAD): an Analysis Tool for Spacecraft Safety Analysis and Ascent/Reentry Risk Assessment

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ABSTRACT

For the purpose of performing safety analysis and risk assessment for a potential off-nominal atmospheric reentry resulting in vehicle breakup, a synthesis of trajectory propagation coupled with thermal analysis and the evaluation of node failure is required to predict the sequence of events, the timeline, and the progressive demise of spacecraft components. To provide this capability, the Simulation for Prediction of Entry Article Demise (SPEAD) analysis tool was developed. The software and methodology have been validated against actual flights, telemetry data, and validated software, and safety/risk analyses were performed for various programs using SPEAD. This report discusses the capabilities, modeling, validation, and application of the SPEAD analysis tool.

1. INTRODUCTION

In the pre-launch safety analysis of a potential off-nominal suborbital/orbital reentry, the response of the spacecraft to the environment and the outcome of the surviving debris are predicted in order to perform risk assessment and contingency planning. Vehicle safety/breakup analysis has also found application in the area of post-flight reconstruction of an off-nominal ascent/entry and in the design for debris disposal during a nominal reentry. Work devoted to these topics have been ongoing for decades and are well documented [1-3]. The objectives of these analyses include the determination of the sequence of progressive failure in the spacecraft components, the timeline of the breakup events, the debris survival, and the debris dispersion footprint. The basic functions required to perform vehicle breakup and burnup analysis consist of trajectory simulation, coupled with thermal analysis and influences, and the evaluation of component failure. To provide these capabilities without employing multiple software programs and lengthy analyses, the Simulation for Prediction of Entry Article Demise (SPEAD) analysis tool was developed, which allows the reentry trajectory with vehicle breakup and burnup to be propagated seamlessly in a single run.

The methodology used with the SPEAD software to perform vehicle breakup analysis has a long history of development and application since the 1970's. The functions from the legacy software have been implemented in SPEAD with additional capabilities for a wider application. The SPEAD software and methodology have been validated against actual flights, telemetry data, validated software, independent analyses by other organizations, and manual calculations. The SPEAD program has been used to perform breakup and burnup analysis for the Stardust's potential off-nominal Earth-return reentry; reconstruction of the Soyuz 14S and 15S ballistic reentries; the Origins, Spectral Interpretation, Resource Identification, Security, Regolith Explorer (OSIRIS-REx) potential off-nominal Earth-return reentry; suborbital reentry of the Falcon 9 Upper Stage with the Dragon capsule from a potential launch failure; and Boeing CST-100 service module's nominal reentry debris disposal analysis.

2. METHODOLOGY FOR PERFORMING VEHICLE BREAKUP ANALYSIS

The methodology for performing vehicle breakup analysis began its development in the 1970's at the Jet Propulsion Laboratory (JPL) to assess aerospace nuclear safety and environmental impact for space missions that used nuclear powered systems. The safety analysis addressed potential launch failures leading to inadvertent suborbital and orbital reentries for risk assessment, which was an imperative step for obtaining launch approval. The legacy software, also developed at JPL, performed three degrees-of-freedom (3-DOF) breakup analysis 4 and was employed over a span of three decades for missions including the Viking (1975), Galileo (1989), Ulysses (1990), Cassini (1997), Mars Exploration Rover (2003), New Horizons (2006), Mars Science Laboratory (2011), and Genesis (2001).

The SPEAD software program has implemented all the functions in the legacy software, as well as new capabilities to support missions that do not use nuclear powered systems. The notable new capabilities include 6-DOF trajectory propagation, functions for performing burnup analysis, the incorporation of a build-in database of material properties, debris footprint calculation and plotting on a world map, and the automation for updating the vehicle's mass and aerodynamic properties following a component failure.

The process for performing vehicle breakup analysis is summarized in the flowchart in Figure 1.

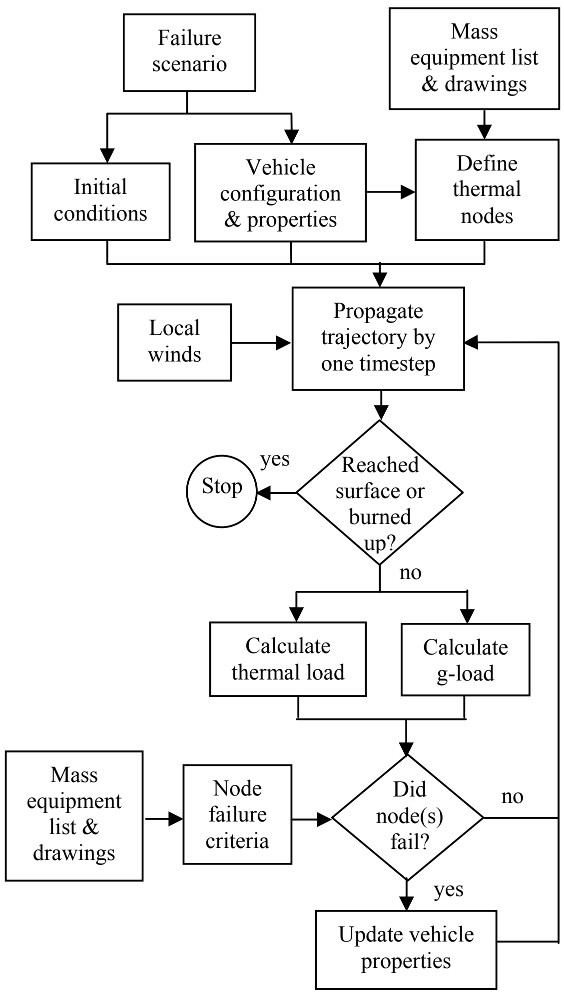

Figure 1. Process for Performing Vehicle Breakup Analysis

Given a failure scenario, the vehicle state and configuration are assumed known. From the detailed drawings and design information of the spacecraft, thermal nodes are selected which are typically components in which a failure will cause a significant alteration in the spacecraft configuration or a change to the exposure of other components to aeroheating. The thermal nodes are modeled as simple shapes; e.g. spheres, cylinders, or slabs. During the simulation, the node temperatures are calculated for the assessment of node failure, and g-loads are evaluated for structural failure when applicable. Following a node failure, the vehicle mass and aerodynamic properties may need to be updated, and the ablation of the node is simulated. Subsequently, the impact conditions of the surviving debris are determined, and the debris dispersion footprint calculated.

The 6-DOF analysis provides a notional case which is a good representation of the probable reentry with breakup. In addition, Monte Carlo and sensitivity analyses can be performed to help bound the problem, including 3-DOF simulations where the vehicle flies at face-on, side-on, and end-on fixed-orientations, and a tumbling case by averaging the end-over-end rotating motion. Note that all predictions of the vehicle breakup and impact conditions are valid only within the assumptions and engineering judgment made in the analysis.

3. MODELING AND CAPABILITIES

The SPEAD analysis tool is a synthesis of a 6-DOF trajectory propagator for the simulation of translational and rotational motion, with embedded heat transfer and structural models for the calculation of thermal and mechanical loads to evaluate spacecraft component failure. The modeling and capabilities of the software program are discussed in the following sections.

3.1 Trajectory Propagation

SPEAD is applicable for both Earth and Mars, with the option for 3- or 6-DOF trajectory propagation. The trajectory is propagated by integrating the coupled differential equations for the spacecraft translational and rotational motion using fourth-order Runge-Kutta. The dynamics consist of gravitation and aerodynamics from the environment, as well as thrust and control forces from actuation. The common g-load is calculated based on the non-gravitational, perturbing acceleration.

Static atmospheres are used in SPEAD where the atmospheric density, pressure, and temperature versus altitude profiles are provided in tables. Default planet-dependent atmospheres are available, with the option for user-supplied tables. Exponential interpolation is performed for the density, while the interpolations for the temperature and pressure are linear. The aerodynamics data are also supplied in tables, for linear interpolation of up to four independent variables. The synthetic wind profile is supplied in a table for linear interpolation. The effects of local winds produce both downrange and crossrange variations in the prediction of impact point and contribute to the aerodynamics calculations. The gravitation model can include up to twenty zonal harmonic coefficients.

The modeling of a single motor is available and can be adapted to multiple motors. Correction for the ambient pressure is made for the vacuum thrust. The time rate of change in the vehicle mass could be from propellant consumption and/or node ablation, and is one of the governing equations propagated by the integrator. Note that the separation of a component from the spacecraft due to node failure is modeled as an instantaneous change in the vehicle mass. A separated component flies independently and is assumed to tumble randomly. Since the aeroheating on the separated node flying alone is no longer dependent on body orientation, the software automatically reverts to 3-DOF simulation for the separated node. Thus, the software generates multiple trajectories in a single run: 6-DOF for the main vehicle and 3-DOF for all the separated nodes.

The footprint for the nominal impact points of the surviving debris in the notional case is calculated and plotted on a world map. An example is given in Figure 2. To generate the footprint for bounding a piece of debris' impact points due to uncertainties in the environment, vehicle properties, and winds, a Monte Carlo analysis can be performed where the dispersions are modeled with normal or uniform distributions. A scheduler is available to set up user-defined events. Through the scheduler, the user can specify and automate the change in the vehicle configuration following a node failure. Given the new vehicle configuration, the software will then update the vehicle mass and aerodynamic properties. The software architecture consists of modularized functions designed to allow quick incorporation of guidance, navigation, control, aerodynamics, and mechanical models.

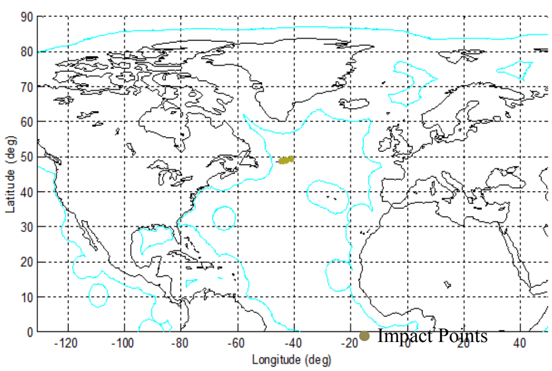

Figure 2. Footprint Plot on World Map

3.2 Thermal Models

The thermal node temperature is calculated by modeling the applicable convective, radiative, and conductive heat transfer. The free-molecular and continuum convective heating are calculated, and the transition is assumed to occur approximately where the two curves intersect. Thus, the lower value of the free-molecular and continuum heating is used for the reference convective heating. In a 6-DOF simulation, the local convective heating on a node is dependent on 1) the location of the node in the spacecraft and its orientation to the flow modeled by an exposure factor, and 2) the geometries of the spacecraft and the node modeled by a heating factor and convective area. The exposure factor ranges from zero to one; zero for complete shielding from the flow and one for direct exposure to the flow. The aerodynamic radiative heating is considered only for reentries at high speeds; e.g. greater than 9 km/s in the Earth atmosphere. The black-body radiative cooling is determined by the Stefan-Boltzman law. One-dimensional conductive heat transfer between adjacent nodes is approximated based on the Fourier's law of heat conduction.

Once a node reaches its melting temperature, node ablation is initiated. The node ablation simulates the decreasing mass; the decreasing convective, radiative, and reference areas; and variable heating factor. Analyses have shown that the simulation of the decreasing mass and areas can affect the ablation of the node significantly. Without considering the decreasing mass and areas, the node will go through more ablation, resulting in fewer surviving debris. Towards the end of the heat pulse during the reentry, the radiative cooling begins to exceed the convective heating and could leave a node only partially ablated. In general, the effect of radiative cooling on node temperature is not negligible. During the simulation, a thermal node is in one of three phases: heating, melting, or cooling phase. Without the modeling of radiative cooling, the thermal node would have only the heating and melting phases.

A built-in database provides the thermo-mechanical properties of common spacecraft materials and propellants. For solids, the material properties include the density, specific heat, thermal conductivity, emissivity, melting temperature, and heat of fusion. For materials that tanks are commonly constructed of, the percent of room temperature yield strength versus temperature are also provided in the database. For liquid propellants, the properties include the enthalpy of vaporization, density of saturated vapor, surface tension of liquid-vapor, density of saturated liquid, specific heat at constant volume, and the coefficients for the vapor pressure equation. Currently, there are over fifty material types and less than ten propellants in the database. Typically, the specific heat, emissivity, and thermal conductivity are modeled as constants in the analysis, but an option exists for modeling these properties as a function of node temperature from the database. The software also provides an option for the user to specify additional materials and properties not found in the database.

3.3 Node Failure Evaluation

Node failure is typically evaluated based on the material melting temperature. However, the g-load and the differential pressure are also considered if the failure criteria were provided by the project. The differential pressure is the differential force along the direction of deceleration applied on a support connecting two components of different masses. An option exists in SPEAD to evaluate the failure of a pyrotechnic by specifying the auto-ignition temperature. This feature is rarely used since the pyrotechnic is usually buried in the spacecraft and shielded from aeroheating, and therefore not selected as a thermal node.

Three different modes of failure are evaluated for a liquid propellant tank. First, the tank could fail by reaching the melting temperature. The liquid propellant in a propellant tank acts as a heat sink and is considered in the calculation of tank temperature. The second mode of failure is to burn through when the burnout flux is exceeded. The convective heat flux applied to the tank is transferred to the liquid propellant by nucleate boiling. As the external heat flux rises and the nucleate boiling limit is exceeded, the liquid can no longer serve as a heat sink in transition boiling. Thus, heating is absorbed by the tank wall, and subsequently tank failure can occur in the film-boiling region due to stagnation point flux on a sphere or stagnation line flux on a cylinder. The third mode of failure for a tank is to rupture from excessive internal pressure. This occurs when the total internal pressure from the liquid vapor pressure of the liquid propellant and the pressure of the gas exceeds the tank burst pressure. The pressure of the gas is a function of the current tank temperature, the operating temperature, and the operating pressure. Once the tank failure occurs, the liquid propellant is assumed to escape. The chemical reaction of the liquid propellants is not modeled in SPEAD.

4. SOFTWARE VALIDATION

The 3-DOF trajectory propagation in SPEAD was validated against the Simulation and Optimization of Rocket Trajectories (SORT) program, which is a 3-DOF legacy software at the NASA Johnson Space Center. The co-plots of the altitude, relative velocity, relative flightpath angle, and ground track are given in Figure 3 - Figure 6. The 3-DOF trajectory propagation and g-load calculation in SPEAD were also validated against the AeroCAPture Simulation (ACAPS) software, which was validated against the Pathfinder Mars entry and Stardust Earth return post-flight reconstructions, and against the ATRAJ2 software tool.

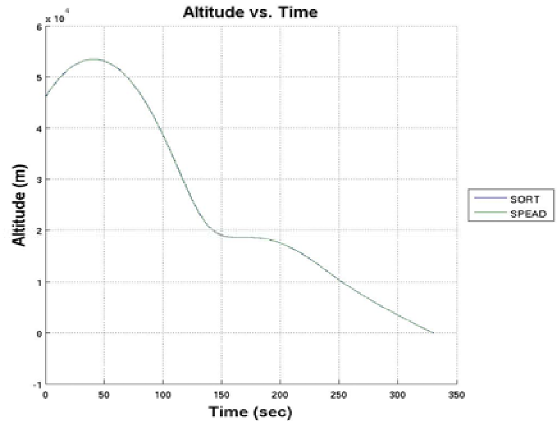

Figure 3. Altitude Co-plot for Validation Against SORT

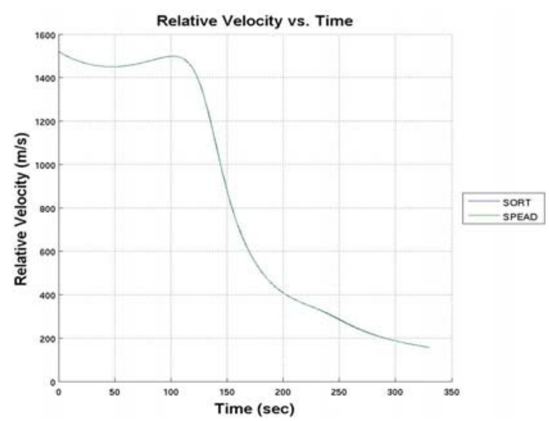

Figure 4. Relative Velocity Co-plot for Validation Against SORT

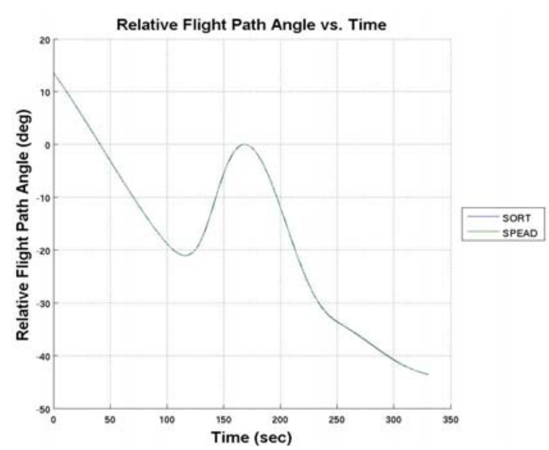

Figure 5. Relative Flightpath Angle Co-plot for Validation Against SORT

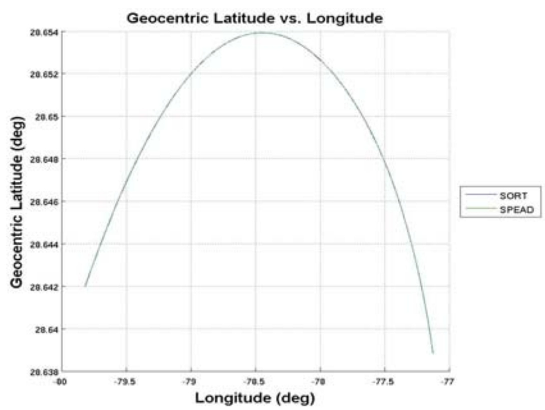

Figure 6. Ground Track Co-plot for Validation Against SORT

The 6-DOF trajectory propagation in SPEAD was validated against the Jaffe code. It is a 6-DOF legacy software developed at JPL for an axi-symmetric body, which does not require the calculation of vehicle bank angle. The Jaffe code was validated against flight data obtained from ballistic range, free-flight range, and drop tests. The co-plots of the altitude, total angle-of-attack, roll, pitch, and yaw are given in Figure 7 - Figure 11.

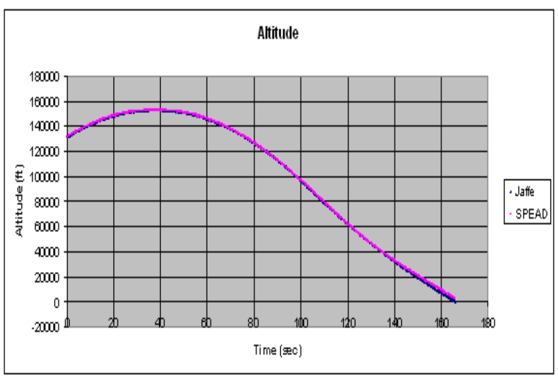

Figure 7. Altitude Co-plot for Validation Against the Jaffe Code

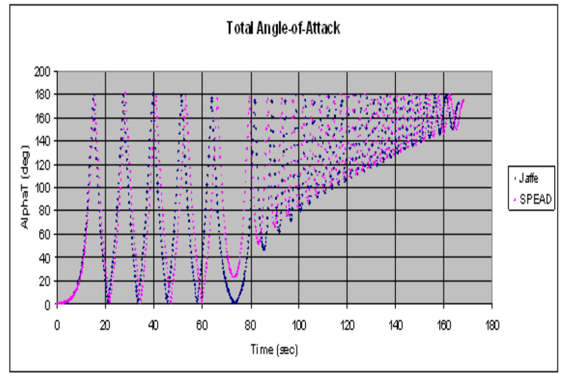

Figure 8. Total Angle-of-Attack Co-plot for Validation Against the Jaffe Code

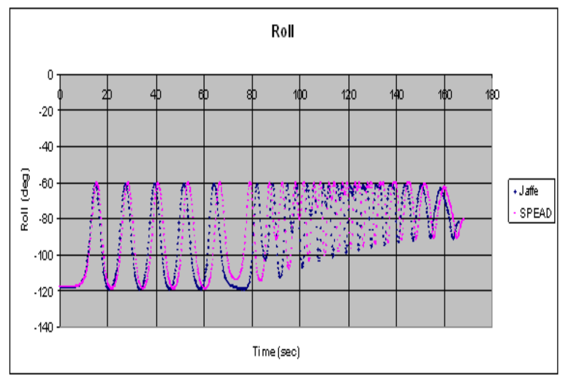

Figure 9. Roll Co-plot for Validation Against the Jaffe Code

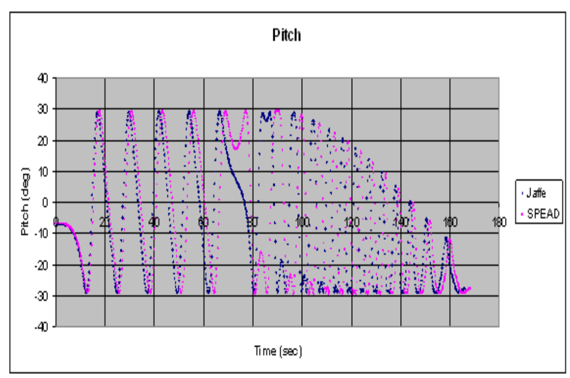

Figure 10. Pitch Co-plot for Validation Against the Jaffe Code

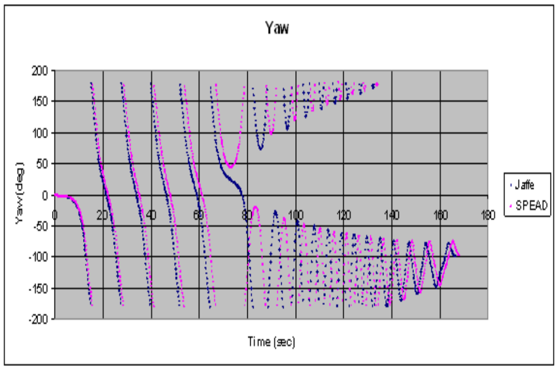

Figure 11. Yaw Co-plot for Validation Against the Jaffe Code

The node temperature from convective heating calculated in SPEAD was validated against the legacy software for breakup analysis as shown in Figure 12. The calculation of the convective heating and convective area over a sphere was validated against hypersonic, shock-tube data. The remainder functions in the software were verified by manual calculations, including the free-molecular convective heating, continuum reference convective heating, aerodynamic radiative heating, integrated heating, radiative cooling, conductive heat transfer between adjacent nodes, and node ablation.

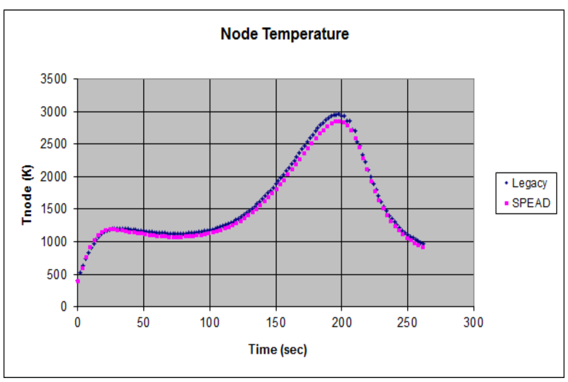

Figure 12. Node Temperature Co-plot for Validation Against Legacy Software for Breakup Analysis

5. VALIDATION AND APPLICATION OF METHODOLOGY

The SPEAD analysis tool was used to provide vehicle safety or breakup analysis for various missions. These included the Stardust's probable off-nominal Earth-return reentry [5]; the reconstruction of the Soyuz 14S and 15S ballistic reentries [6]; OSIRIS-REx's probable off-nominal Earth-return reentry; the suborbital reentry of the Falcon 9 Upper Stage with the Dragon capsule from potential launch failure [7]; and the Boeing CST-100 Service Module's nominal reentry breakup analysis.

Coincidentally, the studies on the Stardust's off-nominal Earth-return and the Soyuz' ballistic reentries are also suitable references for the validation of the software and methodology for performing breakup analysis. These two cases are discussed in further detail in the following sections. Note that previous studies to validate the methodology had been performed by other analysts but are not discussed in this report.

5.1 Case 1: Stardust Potential Off-Nominal Earth Return

In compliance with the NASA guidelines and requirements, independent breakup and burnup analyses were performed by Lockheed Martin (LMA) and JPL prior to the 2006 Earth-return of Stardust to determine, in the event of an off-nominal reentry, if any spacecraft component could survive to reach the ground, resulting in a higher risk of human casualty. Both the bus and the sample return capsule of the Stardust spacecraft were analyzed, as illustrated in Figure 13. In the JPL analysis, an early version of the SPEAD program was used to perform the burnup analysis.

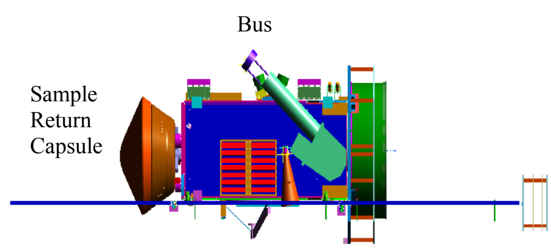

Figure 13. Stardust Spacecraft

The independent analyses produced mostly the same results. For the bus, the two analyses were in agreement and showed complete demise of the bus components with no surviving debris. For the capsule, the analyses determined complete demise of most of the capsule components, but differed in the results for two components: the nose ballast and the deck ballast. LMA showed full demise for the two ballasts, while JPL showed survival of the nose ballast with no ablation and partial to full demise of the deck ballast. The differences in the results for the two ballasts could be from differences in the models used. The decreasing mass and areas of the node during ablation was modeled in the JPL analysis but not in the LMA's.

The deck ballast was eventually removed from further consideration since the small surviving fragment would not exert enough kinetic energy at ground impact to be a source of risk to the population or property. However, the nose ballast was considered in the risk analysis, as well as the heatshield which both LMA and JPL determined would survive.

Although there was close agreement between the two analyses in predicting the same outcome for most of the spacecraft components, it could not be considered as validation. However, the agreement contributed to the credibility of the methodology and analysis tool.

5.2 Case 2: Soyuz 14S and 15S Ballistic Reentries

The Soyuz 14S reentry in 2007 and the 15S reentry in 2008 were ballistic due to a failure in the separation between the descent module (DM) and the service module (ПАО) prior to atmospheric entry. The two modules eventually separated during the reentry following the failure of the modules' interface from aeroheating, and the DM landed safely.

In the post-flight analysis for trajectory reconstruction, the truss in the DM─ПАО interface, the hatch antenna, and the chute cover were three of the thermal nodes modeled for temperature calculation and failure evaluation. A notional 6-DOF trajectory was generated, providing a time history of events and the motion of the spacecraft. The data available for the validation of the analysis and models included photographs of the DM taken after the landing, accounts from the astronauts onboard, and limited telemetry data. Note that the telemetry data were obtained after the analysis had already been performed and presented. Therefore, the models and simulation could not be manipulated intentionally to match the telemetry data.

The simulation from the analysis produced a maximum g-load and rotational motion for the reentry that were consistent with the astronaut's onboard observation. The predicted time and altitude of the truss failure leading to the separation of the modules and the subsequent tumbling motion of the DM until the vehicle trimmed showed a close match with the telemetry data. The predicted temperature of the hatch antenna which resembled a circular disk indicated that it reached the melting temperature during the reentry. It was verified by the photographs showing that most of the hatch antenna had melted away. The predicted temperature of the parachute cover showed that the outer surface of the cover got close to its melting temperature, but the aluminum frame beneath the cover had only a small increase in temperature through conductive heat transfer. Photographs of the parachute cover verified that the outer surface was charred, but the aluminum frame underneath remained pristine.

The Soyuz analysis resulted in the validation of both the software and the methodology. The 6-DOF trajectory simulation and thermal models in SPEAD were validated, as well as the methodology in predicting node temperature and node failure.

6. CONCLUSIONS

The SPEAD analysis tool provides a synthesis of models for trajectory propagation, thermal analysis, and the evaluation of spacecraft component failure to perform a complete vehicle breakup and burnup analysis in a single run. The methodology to perform the breakup analysis predicts the sequence of events, the timeline, and the progressive demise of spacecraft components.

The validation of the software and methodology have shown favorable comparisons against actual flights, telemetry data, validated software, independent analyses by other organizations, and manual calculations. The SPEAD analysis tool has been used to perform breakup and burnup analysis for pre-launch risk assessment and contingency planning, post-flight trajectory reconstruction, and in the design of debris disposal during nominal reentry. Future work includes the continuation of the validation of the SPEAD software and the methodology, and expanding the built-in database of material properties.

7. REFERENCES

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