Phase 2 Project Summary

Firm:	**CFD Research Corporation**
Contract Number:	**NNK08EB52C**
Project Title:	**Numerical Simulation of Rocket Exhaust Interaction With Lunar Soil**

Identification and Significance of Innovation: (Limit 200 words or 2,000 characters whichever is less)

The liberation of dust and debris caused by spacecraft landing on the dusty lunar soil threatens to be one of the highest risks facing lunar exploration system architectures. There is currently no multidisciplinary analysis tool available in the NASA modeling and simulation arsenal that can perform lunar vertical take-off and landing simulations coupled with soil debris lofting and dispersion modeling. The disciplines of in-space rocket plume fluid dynamics, granular soil flow, and particle kinetics must be integrated into one unified simulation environment.

A simulation tool that combines the diverse disciplines of rocket plume aerodynamics, granular soil flow, and particle kinetics into one unified simulation system is required. CFD Research Corporation and the University of Florida have collaborated to achieve the objectives of this STTR project in developing such a simulation tool. The particular physical aspects to be included are the following:

- Spacecraft rocket plume impingement flow under lunar environment resulting in a mixed continuum-rarefied flowfield
- Modeling lunar soil characteristics to capture soil-specific effects of particle size and shape composition, soil layer cohesion and granular flow physics
- Accurate tracking of soil particles beginning with aerodynamically driven motion inside the plume to purely ballistic motion in lunar conditions

Technical Objectives and Work Plan: (Limit 200 words or 2,000 characters whichever is less)

The objectives of this Phase II STTR were to integrate innovative, multi-disciplinary simulation system in order to provide lunar exploration development with a unique tool that enables the screening of a wide array of scenarios, including: (a) identification of dust and debris transport footprint to aid in designing lunar settlement layout, (b) prediction of level of erosion and cratering as a function of local soil properties, (c) locations and kinetic energy of debris impact, (d) minimization of debris environment (e) optimization of landing approach flight path, (f) aid in designing dust and debris impact mitigation measures such as berms, deflectors, electro-statically charged fences, etc.

The specific objectives of Phase II research and development effort are the following:

- Establish a catalog of lunar region soil composition
- Extend fluid-soil interaction modeling capabilities to lunar soil compositions and conditions
- Formulate soil particle release models based on fluid-soil modeling
- Implement Lagrangian debris particle tracking module compatible with UFS
- Integrate UFS solver, erosion model, and particle tracking model into coherent toolset
- Develop post-processing framework visualizing simulation results
- Prepare detailed theory, application manuals, sample applications and tutorials, and provide application training to NASA and industry personnel.

Technical Accomplishments: (Limit 200 words or 2,000 characters whichever is less)

The Phase II work involved detailed formulations of the viscous soil erosion model, development of a Lagrangian particle transport solver and integration in the UFS framework and demonstrations of the multi-disciplinary simulation techniques for gas and granular flow physics under the peculiar conditions of the lunar environment:

1. Development of a Lagrangian debris transport model and integration with the UFS adaptive mesh refinement framework. Development and validation of a particle-particle collision model.
2. Development of a new frictional soil erosion model with good prediction quality in agreement with experiments.
3. Analysis of frictional stress model predictions with model parameters, computational geometry and mesh density, flow turbulence modeling, gas species, and time marching steps.
4. Three-dimensional demonstrations/analysis of UFS for Apollo LEM and Altair lander plume flows with detailed 3D lander configurations.

5. Three-dimensional demonstration/analysis of UFS for Apollo LEM plume impingement with surface craters and demonstration of particle transport.
6. Three-dimensional demonstration of plume induced particle transport with berm near the landing site.
7. Post-processing and visualization of combined flow and particle simulation results.

NASA Application(s): (Limit 100 words or 1,000 characters whichever is less)

The debris simulation tool will be of first order importance to the Space Exploration program for lunar robotic and human mission architecture definition. The tool will be equally applicable to follow-on Mars robotic and human missions. The developed technology will also be applicable for analysis of solid propulsion systems with embedded solid particle.

Non-NASA Commercial Application(s): (Limit 200 words or 2,000 characters whichever is less)

Many potential non-NASA commercial applications exist in civil and military industries. Dust, sand and snow stir-up during helicopter landing and take-off in a desert or arctic environment result in severe visibility impairment (brown-out), windshield abrasion and danger of debris ingestion. Civil engineering and environmental engineering applications include wind-borne landscape erosion and dust transport to populated areas.

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