# Phase I Project Summary

**Firm:** CFD Research Corporation
**Contract Number:** NNX10CD76P
**Project Title:** Software for Automated Generation of Reduced Thermal Models for Spacecraft Thermal Control

**Identification and Significance of Innovation:**
Accurate, efficient thermal analysis is well-recognized as a challenge for precise spacecraft design and control. Current thermal analysis relies on either full-scale, high-fidelity computations or simplified analytical models. These approaches are either computationally prohibitive (such as the STOP-G analysis of LISA in a single model topology) or inadequate in accuracy, and require a significant level of expertise from spacecraft design engineers, leading to substantial cost overruns and delays in spacecraft development. Therefore, there is a clear and unmet need for a software tool that can automate the generation of mathematically rigorous, reduced thermal models to enable order-of-magnitude savings in computational resources and time leading to efficient spacecraft design. The integrated Model Order Reduction (MOR) tool developed in the Phase I specifically addresses such computational challenges. Key innovations that mark this effort include:

- ***Mathematically proven, projection-based, nonlinear MOR*** approaches to enable automated generation of reduced models and to address strong nonlinear thermal effects in spacecrafts
- A verification module to automate the comparison of reduced thermal models against large models
- ***A modular software framework*** to seamlessly integrate the entire process of MOR, reduced model computation, and verification against the large model analysis

Our MOR software will deliver NASA engineers a valuable tool to perform rational and computationally affordable analysis, develop reliable thermal control strategies for spacecrafts, and greatly reduce the development cycle times and costs.

**Technical Objectives and Work Plan:**
The overall objective of the project is to develop robust model order reduction (MOR) algorithms and software to significantly and automatically reduce the computational orders of large thermal models for precise thermal analysis/design of delicate instruments and spacecrafts. Specific Phase I technical objectives and work plan are:

- Select appropriate MOR methods and formulate the MOR algorithms
- Develop a solver module for the reduced thermal models
- Develop data export interfaces to export the large-dimensional model and analysis data
- Develop a verification module to compare results of reduced models and large models
- Design a software environment to streamline the above processes
- Demonstrate the software by performing case studies of NASA interest

**Technical Accomplishments:**
***All Phase I goals were successfully accomplished or exceeded***, including:

1. Various linear and nonlinear projection-based MOR methods were investigated with respect to multiple criteria (such as accuracy, stability, and computational cost). Proper orthogonal decomposition (POD)-MOR and trajectory piecewise linear (TPWL)MOR, including its constituent Krylov-subspace linear MOR, algorithms and engines were developed to efficiently reduce the computational orders of the large spacecraft thermal models.
2. A solver module harnessing Matlab built-in Differential-Algebraic Equation (DAE) integrators was developed to efficiently simulate the reduced order models.
3. Two sets of data exchange interfaces were developed to export the definitive information of the full-scale model and analysis data from NASA-relevant thermal analysis tool (SINDA/FLUINT) and CFDRC-developed high fidelity computational tool (CFD-ACE+).
4. A verification module was developed to compare reduced order model results against the full scale model results.
5. A modular simulation architecture was designed and established to integrate the aforementioned key components and streamline the entire process.
6. Finally, the utility of our MOR software to NASA applications was demonstrated by performing ***whole-satellite*** thermal analysis (LISA model). The study demonstrated that our MOR software can achieve orders-of-magnitude (***10–500X***) reduction in computational times/costs while retaining excellent accuracy (average relative error ***<0.3%)*** relative to the full-scale models.

Phase I study provided critical evidence that ***reduced thermal models can be used for unprecedented speed-up and accuracy of thermal analysis and spacecraft design being actively pursued by NASA researchers***.

**NASA Application(s):**
Based on the challenges identified in the original solicitation, the NASA applications of our MOR software are evident. The NASA Vision for Space Exploration and Earth Science calls for the development of sophisticated thermal control technology to address the harsh space environment and the increasingly demanding operational requirements of spacecrafts during exploration. Therefore, it is essential to develop a MOR framework capable of automatically generating accurate, reduced thermal models that can be consistently used for engineering of spacecrafts at every stage including design, test, ground-operation simulation, and controller development. The developed MOR algorithm and software will deliver NASA engineers a valuable tool to (1) perform rapid and computationally affordable thermal analysis for better understanding of design spaces, (2) develop advanced, reliable

thermal control strategies for spacecrafts and instruments, and (3) arrange test procedures for rational use of instruments and facilities. The success in the research will markedly reduce the development cycles of spacecrafts.

**Non-NASA Commercial Application(s):**
The non-NASA markets and customers of our MOR technology are varied and include various government and commercial applications. For instance, among government customers, Air Force Research Laboratory (AFRL) is seeking a flexible, module thermal control management methodology for Operationally Responsive Space (ORS) Satellites. In the commercial sector, applications exist in semiconductor industry, combustion, power and aerodynamics industry, chemical plants, biomedical companies, micro-electro-mechanical systems (MEMS) and microfluidics manufacturers. This spans diverse applications such as rapid thermal processing (RTP) systems, combustion and propulsion devices, structure design and fatigue analysis, distributed reacting systems (e.g., chemical vapor deposition), and biochip devices. The effort would directly contribute to these vital areas by providing a powerful tool to generate fast reduced order models, which can be extensively used to (1) analyze the industrial processes for fault diagnostics and optimized design (e.g., more effective utilization of existing technologies and the development of new technologies); and (2) develop advanced controller strategies for online process monitoring and control.

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