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APPLICATION OF THE RELIABILITY-DRIVEN DESIGN AND TEST METHODOLOGY TO NUCLEAR THERMAL PROPULSION SYSTEMS

Abstract

Due to the exorbitant costs and extensive schedules associated with full-scale ground testing of nuclear thermal propulsion (NTP) systems, today's programs are looking to minimize or even eliminate this step, instead going straight to flight demonstration. Regardless of the benefits that doing so may provide, the fact is that no rocket engine, nuclear or otherwise, has ever been flown without first undergoing an extensive ground test and qualification program.

While the safety consequences of an uncrewed, in-space nuclear failure may be minimal, the likely severity of the public, programmatic, and political response emphasizes prioritizing the probability of mission success, a.k.a. reliability, and confidence in this prediction. The following work presents a new methodology called Reliability-Driven Design and Test (ReDDT) with the goal of streamlining the test program through intentional design and test planning for a given NTP system-level reliability.

The ReDDT methodology's foundation is based on the United States' Nuclear Engine for Rocket Vehicle Applications (NERVA) project's approach to testing, which was the first to set reliability and safety as the most critical parameters. After 22 successful full-scale reactor and engine tests, program estimates suggest NERVA planned to need only 8 more ground tests, 30 total, to achieve flight qualification. 30 full-scale ground tests is significantly fewer than the hundreds traditionally required for rocket qualification; however, it is still more than desired for today's NTP programs.

Thus, NERVA's approach is further improved through introducing a qualitative failure mode analysis to identify which tests are necessary and maximize program efficiency. To verify the qualitative analysis, Shannon's Information Entropy theory and other modern uncertainty reduction techniques are applied to identify the test program that minimizes the system's technical uncertainty and thereby maximizes reliability.

The ReDDT methodology is then verified through a case study performed in partnership with the Ultra-Safe Nuclear Corporation. The results of applying ReDDT to a real industry NTP rocket engine design and impact on the overall test program will be measured and compared to the original predictions. The results of this study can be used as a foundational roadmap for all future space nuclear program test programs. In addition, while ReDDT was developed for the current NTP effort it has broader applicability to future chemical rocket engine and complex aerospace system developments and upgrades.