Status Update Report for the Peregrine 100km Sounding Rocket Project

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The Peregrine Sounding Rocket Program is a joint basic research program of NASA Ames Research Center, NASA Wallops, Stanford University and the Space Propulsion Group, Inc. (SPG). The goal is to determine the applicability of liquifying hybrid technology to a small launch system. The approach is to design, build, test and fly a stable, efficient liquefying fuel hybrid rocket vehicle to an altitude of 100 km. The program was kicked off in October of 2006 and has seen considerable progress in the subsequent 18 months. Two virtually identical vehicles will be constructed and flown out of the NASA Sounding Rocket Facility at Wallops Island. This paper presents the current status of the project as of June 2008. For background on the project, the reader is referred to last year's paper.[1]

I. Introduction

The Peregrine Sounding Rocket Program was conceived of in late-2006 as a research program studying scaling of single-port high regression rate hybrid rockets. The project goal is to demonstrate the inherent cost and simplicity advantages of such hybrid systems in a real-world flight demonstration program. Aggressive performance goals have been set, targeting 100km in altitude (the edge of space) and a fairly compressed development schedule. The project team consists of a partnership between NASA Ames Research Center, Space Propulsion Group, Inc. and Stanford University. For a full background on the project, its scope and the parties involved, please see Dyer et. al.[1]The project has now been active for roughly 18 months and in that time significant progress has been made, including:

- Successfully completed Conceptual Design Review (CoDR), and Preliminary Design Review (PDR) for flight vehicle capable of 100km altitude
- Designed and fabricated flight-weight combustion chamber, main oxidizer valve, throttle system and thrust structure
- Successfully completed Conceptual Design Review (CoDR), preliminary design review (PDR), Critical Design Review (CDR) and Integrated Test Readiness Review (ITRR) for ground test facility at NASA Ames Research center

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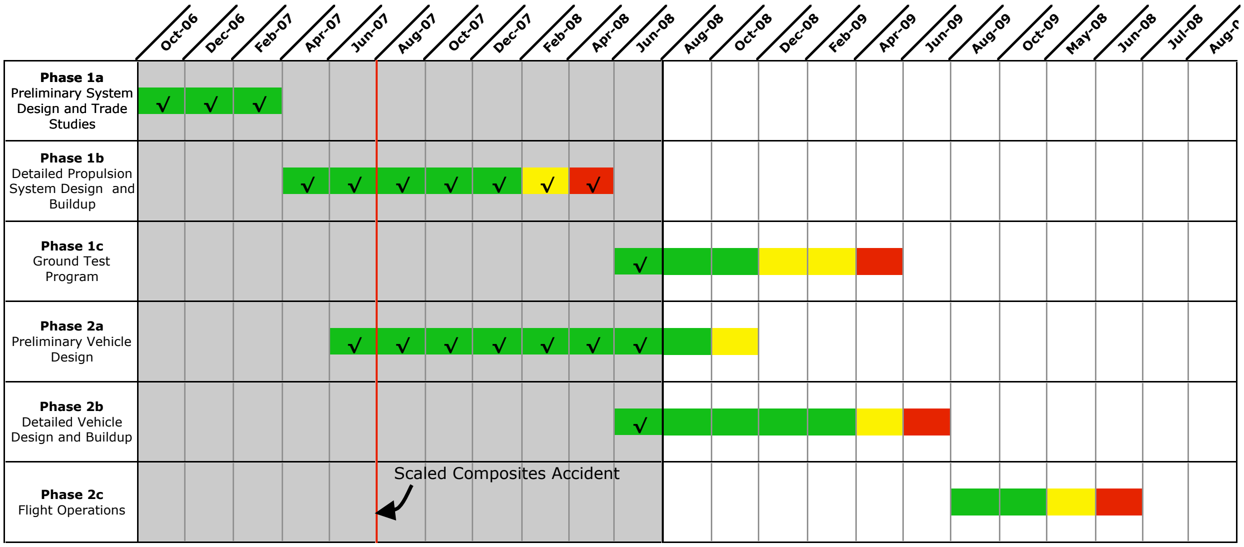

Figure 1. Updated Peregrine Timeline

- Completed subsystem testing for flight weight main oxidizer valve, throttle system, helium pressurization system, ignition system, and thrust structure
- Completed facility integrated test series including 5 cold-flow tests including two with live igniters, and 3 hot-fire tests.

While this is significant progress by any measure, the project suffered a schedule setbacks due to the July 2007 explosion at the Scaled Composites test site involving nitrous oxide (see Fig. 1). A thorough review of the system design and nitrous oxide operational procedures was undertaken and several changes have been implemented to increase human safety. The work of Karabeyoglu et al.[2] presents much of the theory surrounding nitrous oxide decomposition kinetics and flame propagation. These results were instrumental in performing the system safety assessment for the Peregrine system and are recommended reading for anyone designing or operating nitrous oxide based systems. Despite slippage of approximately 8 months due to these changes, the project is at full force and progressing well towards the stated goals. An updated timeline is included in Fig. 1.

II. Background

Our research group began studying liquifying hybrid rocket fuel technology more than a decade ago. The overall goal of the research is to gain a better understanding of the fundamental physics of the liquid layer entrainment process responsible for the large increase in regression rate observed in these fuels, and to demonstrate the effect of increased regression rate on hybrid rocket motor performance. To date we have carried out more than 400 motor tests with a variety of oxidizers (N2O, GOx, LOx) at ever increasing scales with thrust levels from 5 to over 5,000 pounds in order to move this technology from the laboratory to practical applications.

The Peregrine program is the natural next step in this development. We have flown a number of small sounding rockets with diameters of 3, 4 and 6 inches but Peregrine at a diameter of 15 inches and 14,000 pounds thrust is by far the largest system we have ever attempted and will be one of the largest hybrids ever flown. Successful Peregrine flights will set the stage for a wide range of applications of this technology. The metrics of the program are

1. Demonstrate satisfactory motor performance in ground test.
2. Demonstrate motor throttling in ground test.

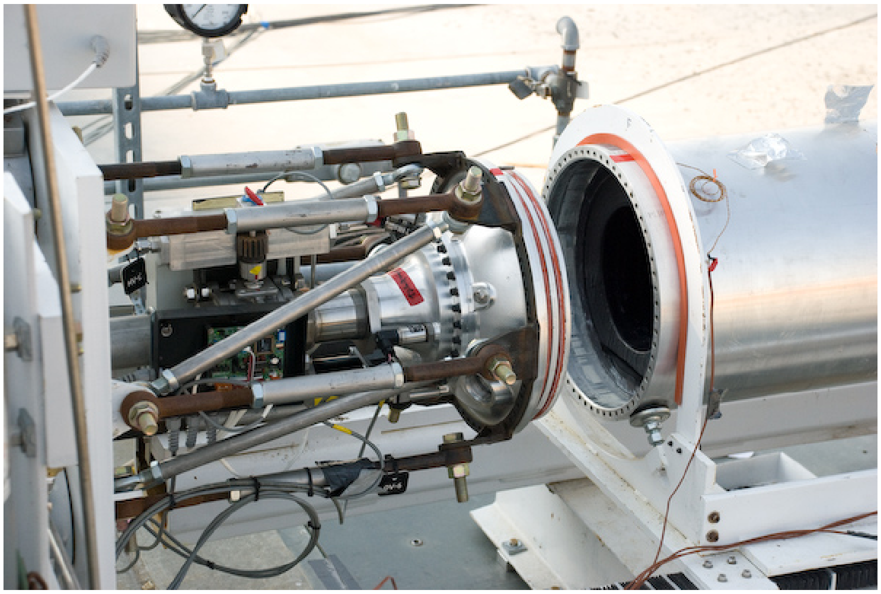

Figure 3. Flight weight fore-end

3. Fabricate the sounding rocket system, transport it to the NASA Wallops facility and and launch a payloadt to 100km using paraffin and $N_2 0$ as the propellants.

4. Demonstrate operational efficiency at the Wallops launch site.

III. Ground Test Hardware

One of the goals of the ground test program was to test as much of the flight weight hardware as early as possible. All of the chamber components are in their flight configuration except that the wall thickness on the main chamber section was left thicker for initial testing. The entire main valve and throttling assemblies consist of the actual flight hardware.

Figure 2. Assembled combustion chamber on the test stand at NASA Ames

A. Combustion Chamber

The combustion chamber components are all complete and proof-pressure tested. No major revisions were needed between Critical Design and manufacture. The assembled combustion chamber on the ground test stand is depicted in Fig. 2.

B. Flight Weight Main Valve

The flight-weight main valve, actuator and control system has been manufactured, assembled, tested and run in live tests. The assembly consists of an off-the-shelf lightweight ball valve, a custom designed light-weight high pressure pneumatic actuator, four off the shelf solenoids and a flight-weight solid-state valve controller board. The partially disassembled fore-end of the motor is depicted in Fig. 3.

C. Facility Plumbing, Control and Instrumentation

All major plumbing has been hydrotested. The control system, developed for Peregrine, is almost identical in hardware and software to that which will be used for the flight ground support equipment and has successfully completed a rigorous test program (Fig. 4). All sensors in the instrumentation system are calibrated.

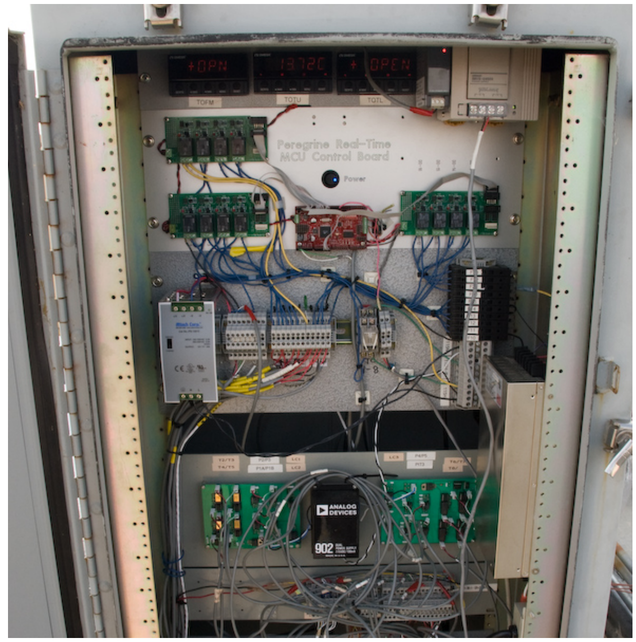

Figure 4. Peregrine control system

IV. Pre-Hot Fire Testing

A. Cold-flow Tests

A total of three cold flow tests were run to verify system flow capability. A flow model for the entire supercharged nitrous oxide tank and feed system was built in order to predict flowrates. A two-phase injector model was used for injector design.[3] For the first cold flow, the injector was left with approximately 12% of its design open area unused to hedge against lower than expected flowrate. The measured flowrates and system pressures confirmed the flow system and injector model and the injector was opened to its final area. Fig. 6 shows a cold flow test. Fig. 5 illustrates the agreement between model and measurements.

B. Cold All-up Tests

Two "all-up" tests were performed. These tests were essentially dry rehearsals for the hot-fire test, consisting of live igniters and cold flow. The first test used one igniter and the second all three. In both tests the flowrate was as expected and the igniter timing was deemed acceptable. Fig. 7 shows "all up" test $A5$ prior to oxidizer flow the "all-up" tests.

V. Hot Fire Tests

The hot-fire phase of the test program is the most important to the success of the Peregrine program moving forward. During the hot-fire test program, all major flight subsystems will be tested in an integrated manor, except for recovery. Proving that the propulsion system meets its design objectives is critical both to the detailed design of the flight vehicle and to range safety at NASA Wallops.

A. Test A6

Upon successful completion of the cold flow and "all-up" tests, the decision was made to proceed with initial hot-fire testing. Because the system consists of flight weight components, including the chamber itself, it was deemed prudent to build up flowrate and chamber pressure slowly to the design goals. For this reason, the first two hot-fire tests utilized a nozzle with roughly $2x$ the design throat area. Furthermore, the first test was executed at 60% throttle, reducing the mass flowrate in the system. Test $A6$ successfully demonstrated all stated goals including

- Successful and smooth ignition with no pressure overshoot
- Verify the physical integrity of chamber, nozzle and fuel grain under combustion conditions
- Further validation of injector model including back-pressure

Fig. 8 shows test $A6$.

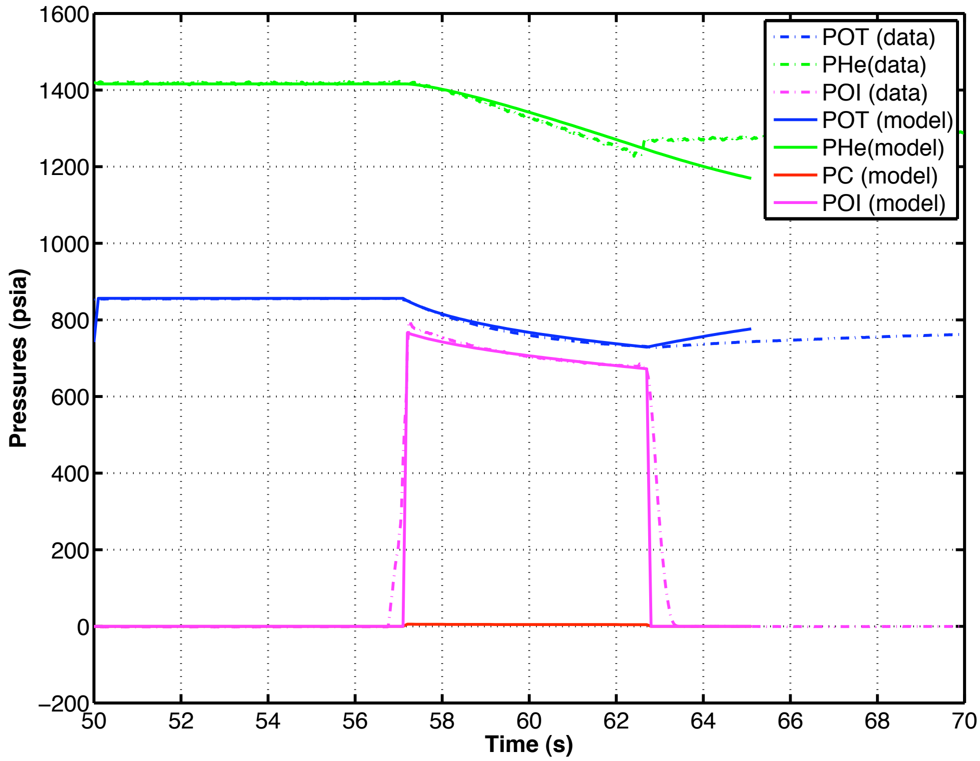

Figure 5. System model results agree with cold flow very well

Figure 6. Cold Flow - Test A3

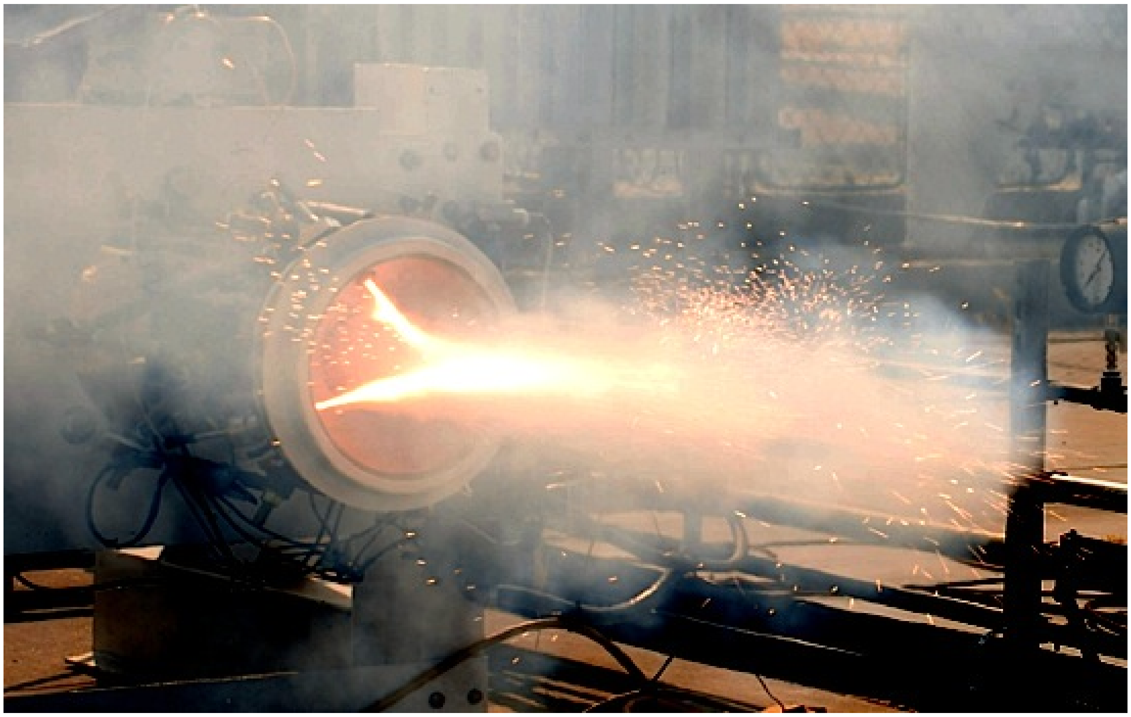

Figure 7. "All-up" with three igniters - Test A5 - prior to oxidizer flow

Figure 8. Test A6 - First hot fire test at 60% throttle and $2x$ throat area

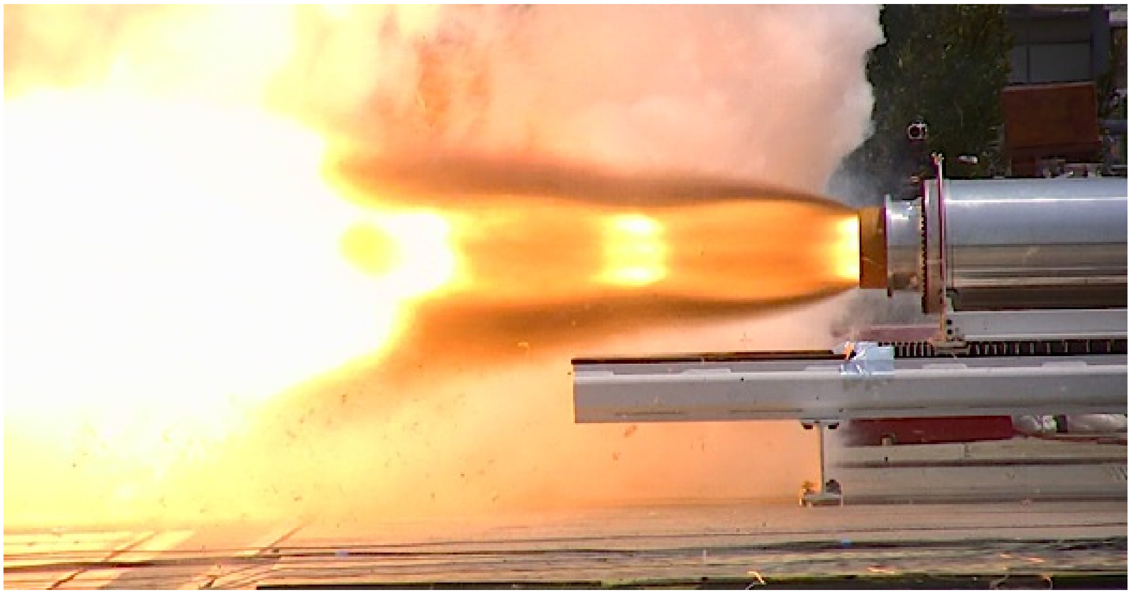

Figure 9. Test A7 - Second hot fire test at 100% throttle and $2x$ throat area

B. Test A7

Test $A7$ was identical to Test $A6$ except that the throttle was set to 100% delivering the full $30kg/s$ mass flowrate of oxidizer to the chamber. The test successfully demonstrated ignition at full oxidizer mass flowrate and further verified the structural and thermal integrity of the chamber, nozzle and fuel grain. Fig. 9 depicts Test $A7$ roughly 1 second into the burn.

C. Test A8

Test A8 was completed literally days before this report was submitted so all of the data has not been thoroughly reviewed. This was the first test to use the as-designed nozzle area leading to a chamber pressure very close to the designed value. Though the test data reduction continues, the preliminary results indicate combustion efficiency well in excess of 90%. In addition, the liquifying paraffin based grains have survived the full chamber pressure structurally intact. These results are very encouraging.

VI. Flight Vehicle Design Status

Much of the design work has been completed on the flight vehicle. The bulk of the detailed design effort went into the combustion chamber and associated components. The main factors that are being considered now are

- System multi-disciplinary optimization
- Stability, aerodynamics and fin design
- Tank detailed design and manufacturability
- Recovery system design
- Ground support equipment design

The systems optimization code has been built but the actual study is pending completion of the hot-fire test series. A fair amount of effort will go into ground support equipment design, build-up and testing in the hope of streamlining operations at NASA Wallops as much as possible. A snapshot of the current detailed design is shown in Fig. 10.

Table 1. Test Matrix

Test No.	Chamber Installed	Duration	Ignitors	Target Flowrate	Achieved Flowrate	Notes
A1	No	3 s	0	20.5 kg/s	21.5 kg/s	12% of injector design open area left undrilled for first test
A2	No	3 s	0	18.9 kg/s	18.5 kg/s	Throttle set at 60%Injector area opened by 20%
A3	No	7 s	0	25.5 kg/s	22.5 kg/s	Regulator droop led to lower than expected flowrate
A4	No	3 s	1	31.1 kg/s	31 kg/s	Igniter timing test
A5	No	6 s	3	31.6 kg/s	31 kg/s	Three igniter timing test
A6	Yes	4 s	2	18 kg/s	17.8 kg/s	First hot-fire test. Successful ignition, test proceeded for full duration without incident
A7	Yes	4 s	2	29 kg/s	29.5 kg/s	First 100% hot-fire test. Successful ignition, test proceeded for full duration without incident
A8	Yes	4 s	2	25 kg/s	22.5 kg/s	Nominal nozzle throat area. Small throttle system anomaly resulted in low flowrate. Combustion efficiency very high.

Figure 10. Current flight vehicle design in-progress

VII. Future Direction and Conclusion

The Peregrine project is proceeding rapidly towards a flight in 2009 from NASA Wallops. In the next 3-4 months, there will be intense testing activity at NASA Ames as the team slowly continues to do basic research on the stability and efficiency characteristics of this motor. Once the motor is well characterized, 2 full duration tests will be run to satisfy NASA Wallops mission requirements. An additional set of testing will be performed after this to demonstrate throttling which will not be utilized until Flight 2. Concurrently, the team will be working on vehicle detailed design using actual performance numbers from ground test. Initial vehicle fabrication and ground support equipment buildup will begin in January of 2009 leading to a projected flight in the second half of 2009.

References

[1]Dyer, J., Doran, E., Dunn, Z., and Lohner, K., "Design and Development of a 100 km Nitrous Oxide/Paraffin Hybrid Rocket Vehicle," *Joint Propulsion Conference and Exhibit*, July 2007.

[2]Karabeyoglu, A., Dyer, J., Stevens, J., and Cantwell, B., "Modeling of N2O Decomposition Events," *Joint Propulsion Conference and Exhibit*, 2008.

[3]Dyer, J. and Doran, E., "Modeling Feed System Flow Physics for Self-Pressurizing Propellants," *Joint Propulsion Conference and Exhibit*, July 2007.

Acknowledgments

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