Design and Development of a 100km Nitrous Oxide/Paraffin Hybrid Rocket Vehicle

Conference Paper · July 2007

DOI: 10.2514/6.2007-5362

Jonathan Dyer
Muon space, inc

Eric Doran
SpaceX

Gregory G. Zilliac
National Aeronautics and Space Administration

Arif Karabeyoglu
Koc University

Design and Development of a 100 km Nitrous Oxide/Paraffin Hybrid Rocket Vehicle

Jonny Dyer,* Eric Doran,* Zach Dunn,* Kevin Lohner*
Cedric Bayart* and Andy Sadhwani*
Stanford University, Stanford, CA 94305, CA

Greg Zilliac†
NASA Ames Research Center, Moffett Field, CA

Professor Brian Cantwell‡
Stanford University, Stanford, CA 94305, CA

Arif Karabeyoglu§
Space Propulsion Group, Inc., Sunnyvale, CA

The Peregrine Sounding Rocket Program is a joint program of NASA Ames Research Center, NASA Wallops, Stanford University and the Space Propulsion Group, Inc. (SPG) to design, build, test and fly a liquefying fuel hybrid rocket vehicle to an altitude of 100 km. The program was kicked off in October of 2006 with initial ground testing of the propulsion system to begin in September 2007 and first flight to be conducted in July 2008. Two virtually identical vehicles capable of lofting a 5 kg payload will be constructed and flown out of the NASA Sounding Rocket Facility at Wallops Island. The propellants utilized will be nitrous oxide and SP1x01, a high regression rate, paraffin-based liquefying fuel initially developed by Dr. Arif Karabeyoglu at Stanford University. The goals of the Peregrine program include demonstrating the operational maturity of liquefying hybrid propulsion systems for space applications, utilizing a lean and efficient engineering team to keep cost down and progress on schedule, and paving the way for future large-scale hybrid propulsion work at Stanford University, NASA Ames and SPG. This paper is divided into sections describing project goals, programmatic details, initial vehicle design and progress to-date on the propulsion ground test phase of the program.

Nomenclature

D	Drag Force
I_ρ	Density Impulse
I_{sp}	Specific Impulse
O/F	Oxidizer to Fuel Ratio

I. Introduction

Hybrid rocket technology has long shown promise as a technology safer to operate and cheaper to develop than liquid rocket propulsion systems and safer to process and capable of higher performance than solid rocket propulsion systems. The perceived barriers to a high performance hybrid system are slowly falling as more is learned about the stability and efficiency characteristics of a hybrid rocket and the technology is scaled to larger and larger systems. The principle design barrier that has plagued hybrid systems of the past is the relatively low regression rate of most solid fuels which makes both performance and packaging problematic.

*Graduate Student, Mechanical Engineering, AIAA Member.
†Research Scientist, NASA Ames Research Center, AIAA Member.
‡Professor, Department Chair, Aeronautics and Astronautics Engineering, Stanford University, CA, AIAA Fellow.
§Research Scientist, CEO, Space Propulsion Group, AIAA Member.

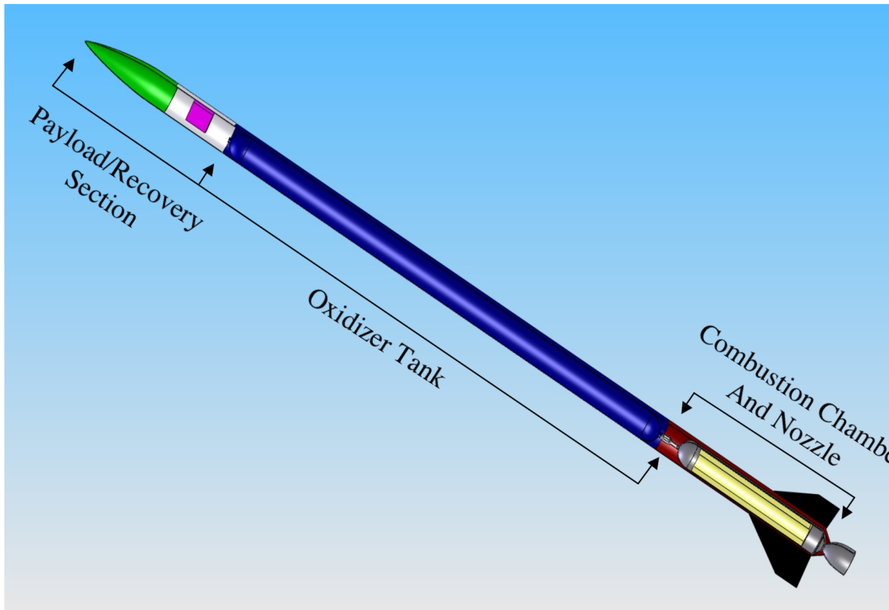


Figure 1. Conceptual configuration for early designs of the Peregrine Sounding Rocket

High regression-rate, liquifying hybrid fuels, discovered by Dr. Arif Karabeyoglu[1] at Stanford University, solve the regression rate issues as well making a large scale high performance hybrid systems imminently more feasable. Recent work performed at Stanford University, NASA Ames Research Center and Space Propulsion Group, Inc. has given a glimpse of the scalability and simplicity of large hybrid systems.

Demonstrating an operational vehicle capable of attaining 100 km of altitude is a key milestone in proving a new propulsion systems technological maturity for large scale development. The Peregrine Sounding Rocket project has set out with the goal of sending a 5 kg payload to 100 km and demonstrating both the maturity of liquifying hybrid propulsion and the effect its simplicity has on the cost and timeline of a significant propulsion project. This paper outlines the project at high level including the goals, the program structure, and progress made to-date towards the goal.

II. Background

The American Rocket Company (AMROC) lead the largest hybrid development program during the late 1980s and 1990s culminating in the design, testing and eventual unsuccessful flight of a 250 klb. thrust hybrid propulsion system. The state of the art in fuel technology at the time was hydroxyl terminated poly-butadiene (HTPB), borrowed from the solid rocket fuel industry. Its low regression rate in hybrid applications leads to inefficient and awkward grain geometries which has long been the Achilles heel of hybrid rocket propulsion systems (although was not the cause of the AMROC failure). More recent, smaller scale hybrid rocket development has been done by SpaceDev and Scaled Composites in support of SpaceShip I which recently won the X-Prize for manned spaceflight. Hybrids were selected for this propulsion system due to many of their inherent safety advantages in a manned flight

Figure 2. Sub-scale testing at Stanford University

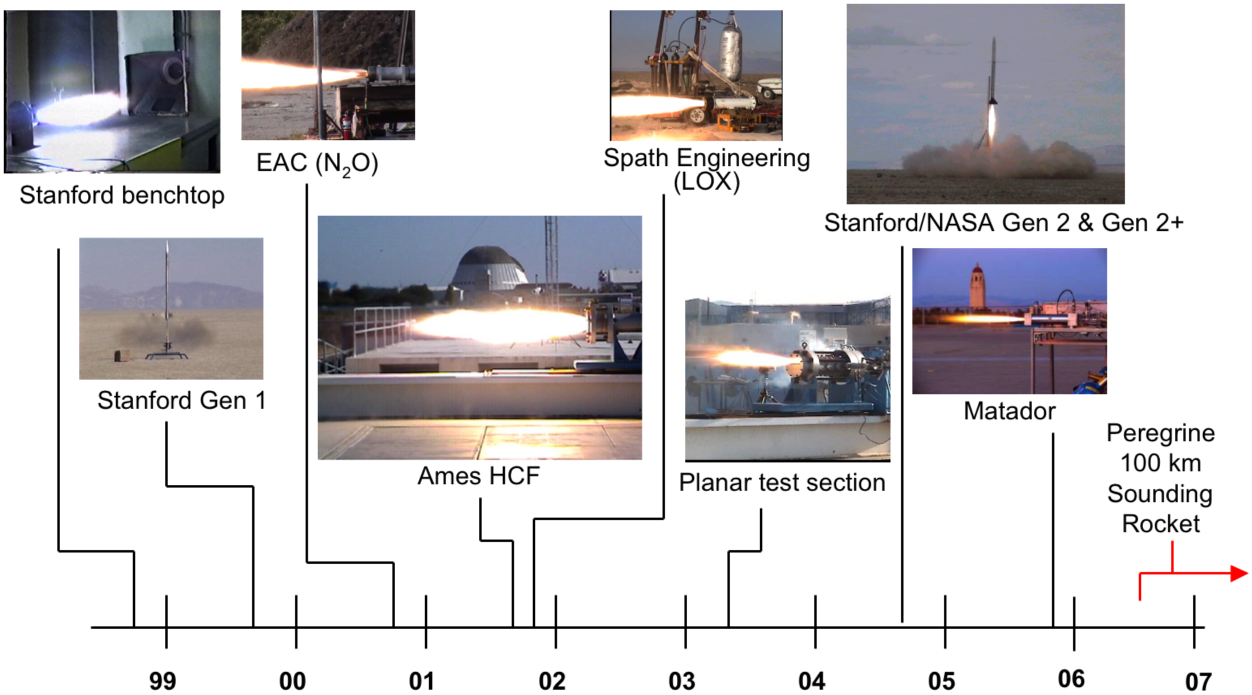


Figure 3. Historical Perspective on Hybrid Propulsion Development at Stanford University, NASA-Ames and the SPG

system but again the low regression rate of the HTPB based fuel resulted in sub-optimal performance and some structural mishaps. Another program aimed at demonstrating hybrid rocket propulsion as a technology was the Hybrid Sounding Rocket Project (HYSR),[2] a joint project of Lockheed Martin Co., NASA Ames, NASA Wallops and NASA Marshall. Designed-for performance was not achieved due to structural failure of the HTPB based grain, a result of the multi-port design and high aluminum loading required by the low regression rate fuels. Work by Dr. Arif Karabeyoglu and Professor Brian Cantwell of Stanford University and Greg Zilliac of NASA Ames in the late 1990s uncovered a new class of high regression rate liquefying hybrid rocket fuels. Karabeyoglu showed that anomalously high regression rates observed in tests with frozen Pentane performed by the United States Air Force could be explained by the formation of a low-viscosity unstable melt layer on the surface of the fuel grain which entrained liquid droplets in the port gas flow.[1] Development of models to predict this behavior led to the discovery of the long-chain paraffins as ideal candidates for room temperature liquefying hybrid rocket fuels. Extensive hot fire testing has not only proven the high regression rates of these fuels but also their insensitivity to unfavorable scaling effects normally seen with hybrid rocket motors.

Under the leadership of Professor Cantwell, the Stanford rocket propulsion group has amassed significant design, test and flight experience with hybrid rocket systems (Fig. 3). Recently, sub-scale testing conducted at Stanford (Fig. 2) to characterize the regression rate, stability and efficiency characteristics of a number of solid fuels has produced a large data set that can be drawn on for design purposes. See Doran[3] for this data. Continued research on liquefying fuel formulation conducted at SPG has cemented them as the leader in hybrid fuel grain processing. The Stanford University, SPG, NASA Ames partnership is a small, driven and efficient group of engineers and students capable of rapid design, development and testing.

III. Program Objectives and Structure

A. Program Objectives

The goal of the Peregrine project is to demonstrate the maturity of hybrid rocket propulsion by developing a space-capable propulsion system and flight vehicle in less than two years at a budget of $1.2 million. More specifically, the goal is to send a $5kg$ payload to an altitude of 100 km, the internationally recognized boundary of space, with a ground-launched sounding rocket at an initial flight angle of 85°. The project received initial funding in October of 2006 and initial flight testing is to be conducted in July 2008, less than two years after project inception (see Fig. 4). A secondary goal of the project is educational and as such the bulk of the engineering work has been and will continue to be performed by graduate students at Stanford University.

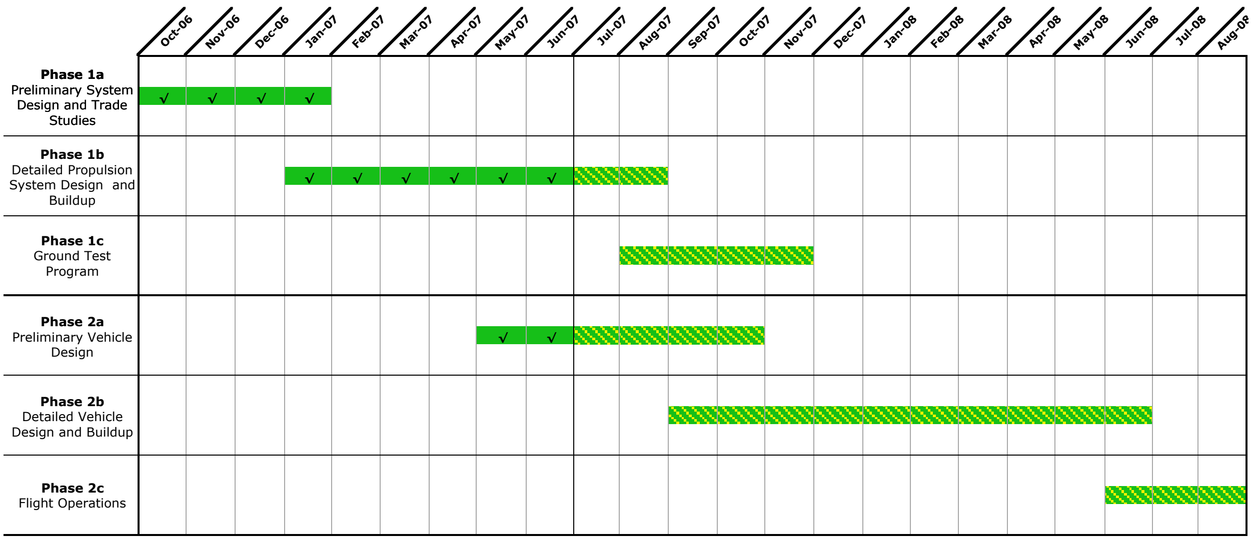


Figure 4. Project Timeline - Check marks indicate completed status.

B. Program Structure

The project is divided into two distinct phases and the engineering work is distributed between three entities: Stanford University, SPG and NASA-Ames. Greg Zilliac at NASA-Ames is the project lead and is responsible for schedule, budget and technical oversight. Fuel grains will be cast at SPG using their proprietary SP1x01 liquefying fuel formulation and sold to NASA-Ames through a sole source procurement. Five graduate students in Professor Cantwell's rocket propulsion group each take the lead on one aspect of project design and are responsible for the majority of the primary design and engineering work. They are supported through an academic grant awarded to Stanford University from the project's budget at NASA-Ames. Finally, students in the AA284 Advanced Rocket Propulsion Design course series at Stanford work under the five student leads in areas of interest to them.

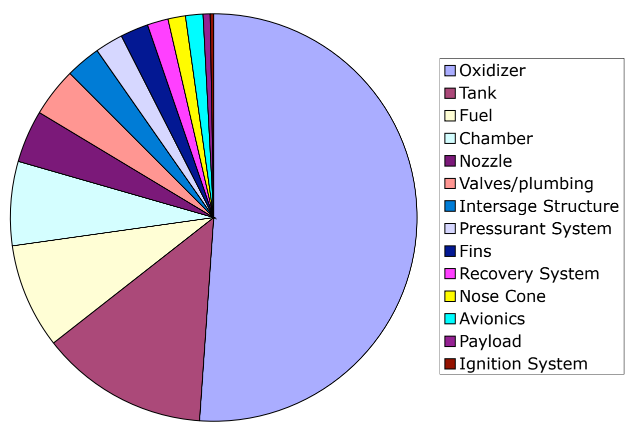


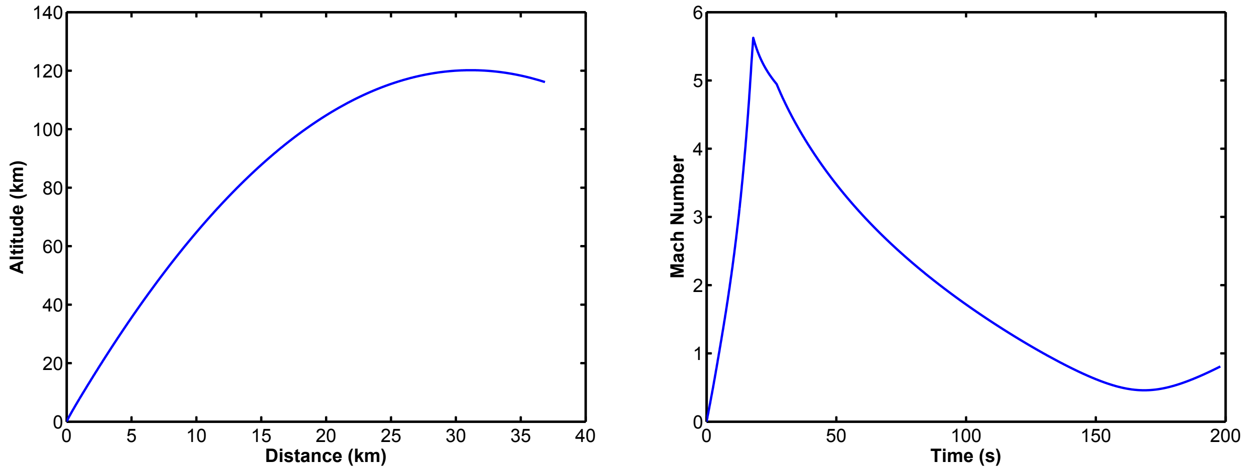
Figure 5. Mass breakdown for preliminary vehicle design

IV. Design Progress to date

As of May, 2007 a significant amount of work has been accomplished on this project. Fig. 4 shows an overview of the progress to date which includes a preliminary vehicle design including comprehensive mass accounting (Fig. 5), detailed propulsion and trajectory simulation, sensitivity studies for risk mitigation, detailed design on the propulsion system of the vehicle and design/buildup of the ground test facility at NASA-Ames. A short overview of the progress in each of these areas is provided below.

A. Initial Vehicle Performance Simulation and Design

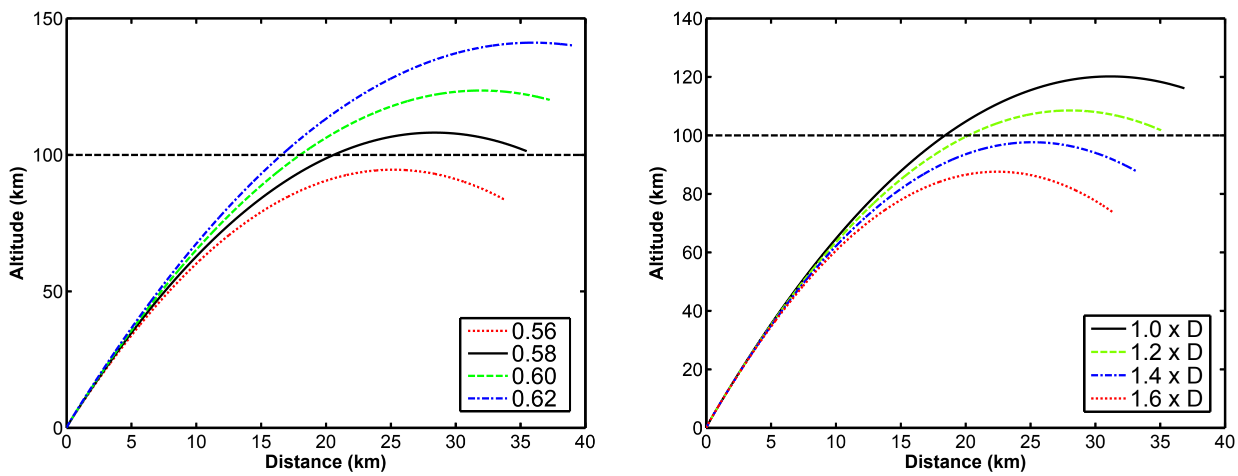
Any rocket vehicle design project is inherently multi-disciplinary and involves many iterations before a final configuration is obtained. A propellant trade study is first carried out to narrow down the fuel and oxidizer options after which some assumptions regarding propulsion performance can be made. The motor configuration can then be determined for a given burn time and its trajectory integrated to evaluate apogee. Iteration continued until the estimated mass properties converged to those calculated by the simulation. This led to a vehicle approximately 30 feet in length and 16 inches in diameter with a gross lift-off weight of 1,874 lbs and average thrust of 14,034 lbf. The resulting trajectory and Mach number history are plotted in Figure 6.



(a) Ballistic Trajectory (b) Mach History of Flight

Figure 6. Initial Trajectory and Speed of Flight Vehicle

Sensitivity studies were carried out on critical design parameters to ensure sufficient margin for revisions of the initial design. These parameters included drag, dry mass fraction, combustion efficiency, nozzle erosion rate, and chamber pressure. It was found that mass fraction and drag impacted the performance of the vehicle most, thus requiring the most attention.



(a) Mass Fraction Sensitivity (b) Drag Sensitivity

Figure 7. Sensitivity Analyses on Critical Parameters

The mass fraction of the baseline design is around 59% and changes in trajectory based on deviations from this value are shown in Figure 7a. It can be seen that a 2% decrease in mass fraction and the rocket will fail to meet its target.

The program Missile DATCOM was used to compute a baseline drag polar based on the initial vehicle dimensions. A multiplication factor was then applied to the entire drag polar to determine the effect of increased drag over the entire trajectory. It can be seen from Figure 7b that almost a 40% margin exists over the estimated drag.

B. Propulsion System Trades and Design Decisions

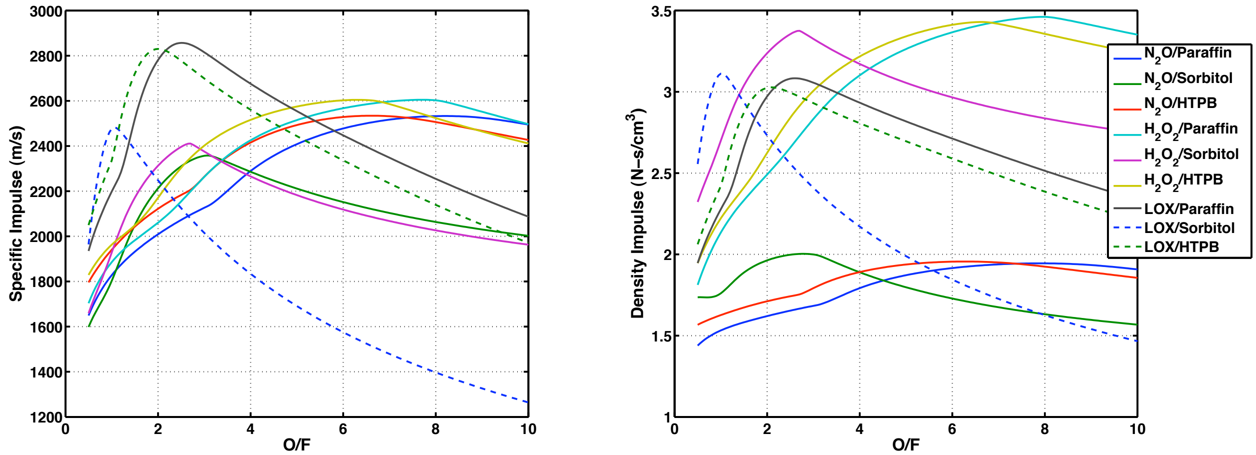


Figure 8. Propellant trade-study example: Specific Impulse and Density Impulse

The project started with a wide-open space for propellant selection and propulsion system design with the only constraint being that it must be a hybrid system and that the propellants must be essentially non-toxic. A series of propellant trade studies were conducted in order to choose a propellant combination that would meet the performance requirement and was also attractive from a systems standpoint. For instance density impulse, I_{rho} was shown to be very important in early trajectory simulations as described above, and a trade study showed that there were cases where a higher I_{sp} propellant had a significantly lower density impulse than a lower I_{sp} alternative that may have originally seemed attractive (Fig. 8). Systemic factors were also weighed heavily and properties such as the high vapor pressure of nitrous oxide (N_2O) were taken into consideration. Less quantitative factors were considered as well including perceived ease of handling and the team's experience base. In the end, nitrous oxide was chosen as the oxidizer because of its high vapor pressure (which makes pressurization much less problematic), ease of handling and track record at Stanford even though its performance wasn't as high as some of the other oxidizers.

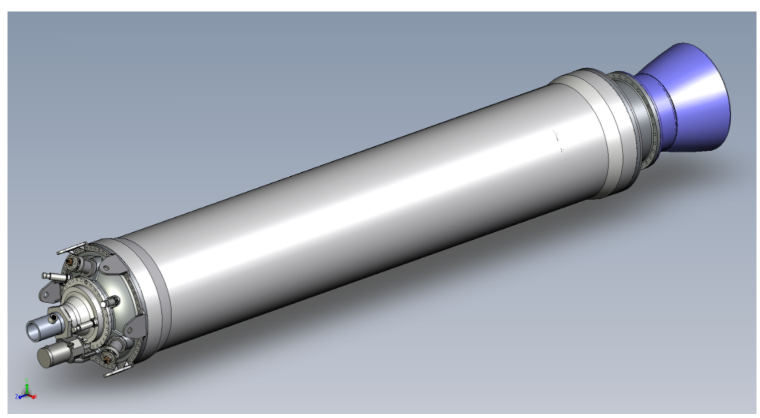


Figure 9. Flight-weight combustion chamber

Fuel choice was handled in a similar fashion except that regression rate and experience base were seen as the overriding factors. Paraffin came out as the clear winner on regression rate and experience base and was also one of the best fuels from a performance standpoint. Metal additives were briefly considered for performance reasons but due to the unknowns surrounding their effect on regression rate and the structural integrity issues with metalized grains, they were dropped.

In the final configuration, the nitrous oxide is slightly super-charged above its vapor pressure in order to prevent cavitation in the feed system. Composite combustion chamber cases were considered for weight reasons but reusability and cost were deemed to be significant unknowns so a lightweight machined aluminum combustion chamber was chosen.

C. Ground Test Facility

In order to validate the design and characterize the performance of the Peregrine system, a Ground Test Facility (GTF) is being built at NASA Ames. The site is adapted from a legacy hybrid rocket testing facility, and much of the preexisting support infrastructure such as oxidizer storage tanks and feed lines are able to be reutilized in the support of Peregrine. The layout of the updated Peregrine GTF is captured in Fig. 10 below.

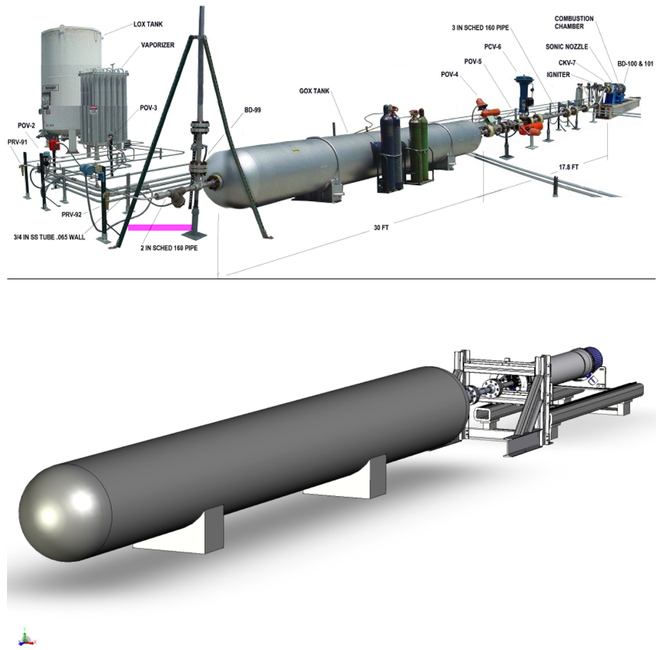


Figure 10. The Outdoor Ames Rocket Facility as it appeared in 2001 and as it will appear for Peregrine testing

Peregrine's GTF can be broken down into 3 major subsystems: plumbing, instrumentation and control. In designing these subsystems, personnel and hardware safety were of utmost concern. For example, each trapped gas volume in the plumbing system is fitted with a manual pressure gage so that site workers do not have to rely on pressure transducers before cracking a fitting. The control system will only allow a test to be conducted if stringent hardware and personnel conditions are met. Critical data from the instrumentation is continually checked, and if data are out of pre-determined ranges, the test will be terminated.

Further breakdown of the plumbing subsystem can lead to examination of fluid handling for the 3 working fluids used with the Peregrine GTF: nitrous oxide, helium, and shop air. Nitrous oxide serves as the oxidizer for peregrine, and the GTF oxidizer storage and handling components have the purpose of delivering the nitrous oxide to the combustion chamber at the appropriate flow rate, pressure and temperature. Helium has multiple uses, the primary of which is to pressurize the nitrous oxide beyond its vapor pressure to prevent cavitation in oxidizer feedline between the run tank and the combustion chamber. It also serves as a combustion chamber purge, quenching combustion after a test or in the event of a test abort, and finally it is used to actuate the main oxidizer valve. Shop air is used to actuate all other site ball valves and it is the third working fluid of the plumbing system.

Fig. 11 below is a Plumbing and Instrumentation Diagram (P&ID) for the Peregrine GTF and will help to clarify the system for the reader. For a detailed discussion of the Peregrine GTF refer to Dunn[4] et al.

V. Future Direction and Conclusion

Team members are currently busy building up the test facility at NASA Ames and providing oversight to the Ames machine shop as they fabricate the first test article. Initial system checkout is slated to start in August and initial hot-fire testing will be conducted in September. The team will be doing detailed design on the flight vehicle itself in parallel with ground testing in order to feed test results into design decision.

When flown in 2008, the Peregrine Sounding Rocket will be the highest performing rocket ever developed in a University setting. It will also be one of the shortest and least expensive programs ever to have designed, ground tested, built and flown a vehicle of this scale and performance.

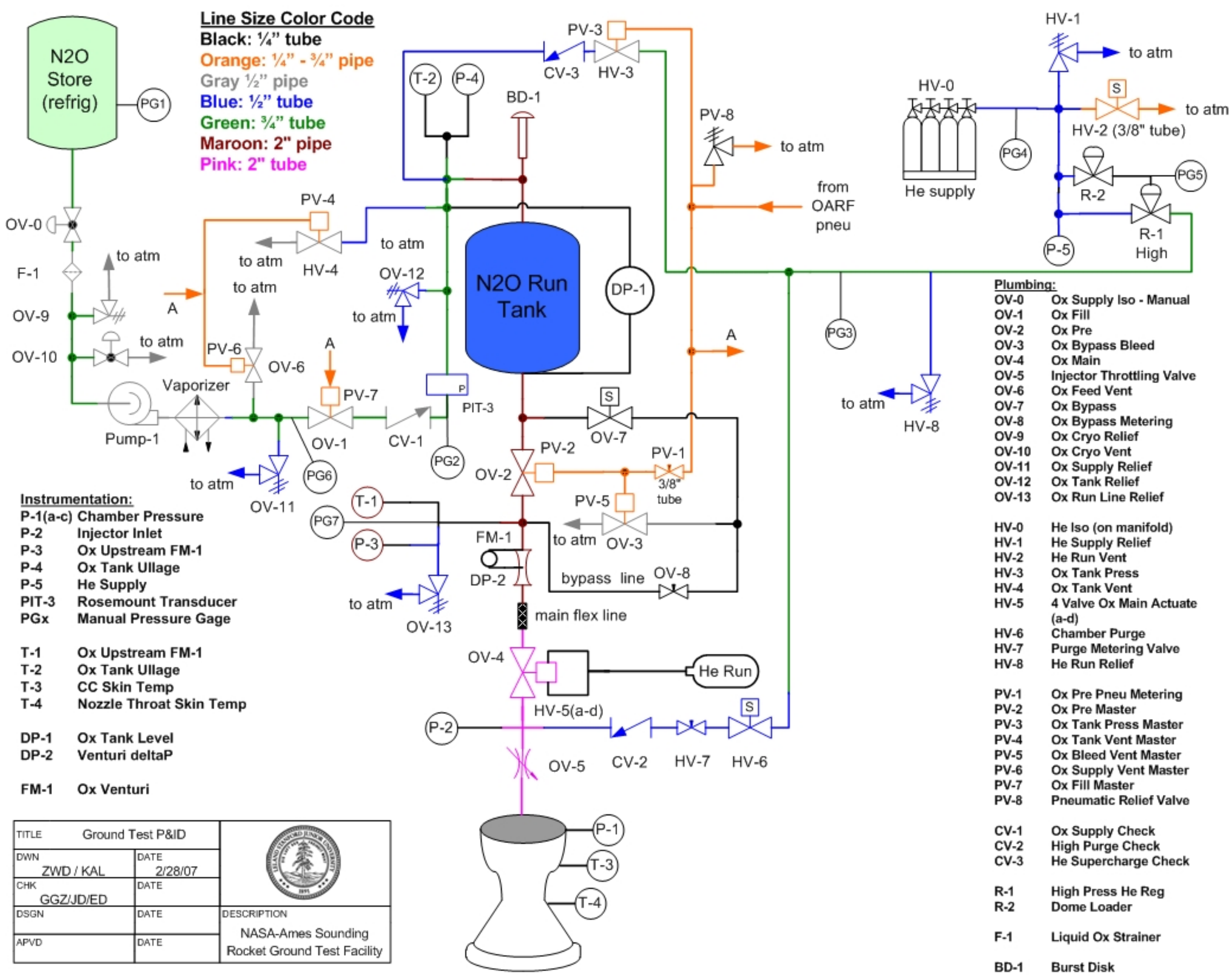


Figure 11. Peregrine Ground Test Facility Plumbing and Instrumentation Diagram

References

[1]Karabeyoglu, M. A., Altman, D., and Cantwell, B. J., "Combustion of Liquefying Hybrid Propellants: Part 1, General Theory," *Journal of Propulsion and Power*, Vol. 18, No. 3, May-June 2002, pp. 610–620.

[2]Arves, J., Gnau, M., Joiner, K., Kearney, D., McNeal, C., and Murbach, M., "OVERVIEW OF THE HYBRID SOUNDING ROCKET (HYSR) PROJECT," *Joint Propulsion Conference and Exhibit*, July 2003.

[3]Doran, E., Dyer, J., Lohner, K., and Dunn, Z., "Nitrous Oxide Hybrid Rocket Motor Fuel Regression Rate Characterization," *Joint Propulsion Conference and Exhibit*, July 2007.

[4]Dunn, Z., Dyer, J., Lohner, K., Doran, E., Bayart, C., Sadhwani, A., Karabeyoglu, A., and Cantwell, B., "Test Facility Development for the 15,000 lb Thrust Peregrine Hybrid Sounding Rocket," *Joint Propulsion Conference and Exhibit*, July 2007.

Acknowledgments

The authors would like to thank the NASA Ames Research Center Peregrine Review board for their support and advice. Thanks also go to NASA Ames Research Center for funding the project under Cooperative Agreement No. NNX07AD11A and Chuck Brodell at NASA Wallops Flight Facility for technical oversight and project management assistance.