ASEE 2022 ANNUAL CONFERENCE
Excellence Through Diversity
MINNEAPOLIS, MINNESOTA, JUNE 26TH-29TH, 2022 ASEE

Paper ID #36443

Development of a Concept Hybrid Rocket Demonstrator

Dustin Scott Birch (Associate Professor - ME)

Dustin Birch possesses a Doctor of Philosophy in Systems Engineering from Colorado State University, a Master of Science in Mechanical Engineering from the University of Utah, a Bachelor of Science in Mechanical Engineering from the University of Utah, and an Associate of Science in Design and Drafting Engineering Technology from Ricks College. Dustin teaches in the Department of Mechanical Engineering at Weber State University in Ogden, Utah.

DEVELOPMENT OF A CONCEPT HYBRID ROCKET DEMONSTRATOR

Dustin Birch, P.E., Ph.D.
Department of Mechanical Engineering, Weber State University

1 Abstract

Most conventional rockets are of an either solid fuel or liquid fuel configuration. Nearly all production rocket motors produced throughout modern history are one of these two types. Conversely, a hybrid rocket utilizes a solid fuel grain and liquid oxidizer, thus capitalizing on the inherent advantages of both designs. A hybrid rocket exploits the power density (power per unit volume) of a solid fuel rocket, and the start-stop and throttling capability of a liquid fuel rocket. To date, only a few hybrid rocket designs have been developed to a production level configuration. This type of rocket motor technology remains largely in the experimental domain. [1]

The Concept Hybrid Rocket Demonstrator (CHRD) is a small scale, modular, low-cost hybrid rocket design, for use in hybrid rocket research as well as educational applications in senior capstone curriculum for an undergraduate Mechanical or Aerospace Engineering or Engineering Technology program. Basic research activities include investigations of rocket fuel types and fuel grain port configurations, ignition systems, oxidizer delivery systems, rocket nozzle materials and aerodynamics, instrumentation schemes, and analytic modeling of rocket performance using computational software.

The first generation of CHRD has been designed, fabricated, and tested successfully. A small rocket motor approximately two inches in diameter and ten inches long was fired multiple times during the spring of 2021, with preliminary results of rocket performance being documented. The current rocket prototype was the product of two consecutive academic years of senior capstone teams' efforts. The design, fabrication, and testing were supervised by a Mechanical Engineering faculty, who assumed the role of project manager and chief investigator.

2 Introduction

Numerous examples of student projects focused on hybrid fuel rocket motors and hybrid rocket motor powered flight vehicles are identified in the literature. The various efforts documented have focused on different fuel grain materials, fuel grain manufacturing approaches, ignition system design, and rocket housing structural considerations. Also, of particular interest in current hybrid rocket design efforts are the economic considerations, with low-cost solutions being evaluated. [2][3][4][5][6][7][8]

Unlike more conventional rocket designs that utilize a liquid fuel and liquid oxidizer (liquid fuel rocket motor) or a solid oxidizer entrained within a solid fuel grain (solid fuel rocket motor), a hybrid design typically incorporates a liquid oxidizer and a solid fuel grain. This configuration leverages the advantages of both the liquid fuel rocket, which is the ability to start and stop the motor as well as throttling the thrust level, and the solid fuel rocket, which is a higher thrust density for a given motor size. [1]

The Concept Hybrid Rocket Demonstrator (CHRD), as currently designed, was produced for under $3000 USD, and met most of the initial operational and performance goals. The current design includes a modular approach to fuel grain replacement, greatly simplifying and expediting the tasks related to multiple test firings in quick succession. Additionally, the design utilizes several Commercially Available Off-the-Shelf (COTS) components to simplify the design and reduce costs. The current configuration operates using Hydroxyl Terminated Polybutadiene (HTPB) as the solid fuel grain, and Nitrous Oxide (N_2O) as the liquid oxidizer. Both of these substances are individually inert, and safe, thus rendering the rocket components very safe for storage, transport, and handling, making this approach attractive for student involvement in an informal environment.

3 Background

As part of the two-semester senior capstone project required of all baccalaureate degree candidates, a Concept Hybrid Rocket Demonstrator (CHRD) design project has been implemented. A hybrid rocket was selected for a research effort for two reasons. First, hybrid rockets have not seen the level of development and design maturity that comparable liquid or solid fuel motor designs have undergone over the past few decades. Second, the liquid (oxidizer) and solid (fuel) constituents of the hybrid rocket designs are individually inert, and very safe to handle. Without an ignition source with sufficient heat addition, a sustained oxidizing reaction cannot be achieved. Therefore, the storage and handling of rocket materials is very safe. [1]

Commencing with the 2018-2019 academic year, a three-phase development program to design, produce, and test various hybrid rocket designs and associated technologies was specified. The three developmental phases are identified as:

- CHRD Phase I – Non-Thrusting Fuel, Oxidizer, and Ignition System Design and Testing
- CHRD Phase II – Thrusting Static Motor Demonstration
- CHRD Phase III – Fuel Grain Port Configuration and Alternate Fuel Grain Material Studies

For each of the three design phases, budgets, schedules, and anticipated technical milestones, with decision gates, were established. The student design teams assigned to the CHRD project performed all of the design and analysis activities, fabricated and assembled all test hardware, created all of the relevant documentation, provided budget and schedule management, and reported progress regularly to a faculty advisor.

4 CHRD Phase I – Fuel, Oxidizer, and Ignition System Design and Testing

The Phase I design efforts related to the Concept Hybrid Rocket Demonstrator (CHRD), were focused on fuel grain, oxidizer delivery, and ignition system development and testing. The initial design objectives, that drove engineering specifications, were focused on using as many Commercial Off-The Shelf (COTS) components as possible, to simplify the design, and keep development costs to a minimum. The initial rocket housing for this phase of development did not incorporate a flow restricting nozzle. Hence, it was not intended to be back-pressured during rocket firing, resulting stresses in the housing that were very low. For this reason, the initial test articles were fabricated using standard piping components that were threaded together.

The fuel grain used during this phase was composed of repurposed rubber from a scrap automotive tire. The chemical composition of the rubber is very close to the Hydroxyl Terminated Polybutadiene (HTPB), and would be a reasonable facsimile for development testing. A representative fuel grain was fabricated from a tire, and installed within the test apparatus.

The selected oxidizer system was adapted from a commercial Nitrous Oxide System (NOS) used in automotive racing applications. The pressurized NOS tank is filled with gaseous Nitrous Oxide (N_2O) that is subsequently released through a standard needle valve that is manually actuated by a test engineer. The oxidizer is delivered to the combustion chamber via a braided hose typical of a commercial NOS unit into a diffuser located near the upstream end of the fuel grain port.

To initiate combustion, the oxygen must be broken free of the nitrogen in the Nitrous Oxide molecule. Sufficient heat must be present in the gas for this to occur. A commercial glow plug used in a typical diesel truck engine was selected to accomplish this. The glow plug was positioned within the combustion chamber near the oxidizer inlet diffuser and fuel grain center port surface. Prior to rocket motor ignition, the glow plug was energized using a standard 12 Volt automotive battery. Once the fuel and air present in the motor housing was heated sufficiently, the oxidizer flow was initiated. Once stable ignition was confirmed visually, the glow plug is de-energized, and oxidizer flow was increased until the observed exhaust flame stabilized and reached a maximum intensity. To cease combustion and stop the rocket firing, the oxidizer flow valve was closed. Within a few seconds of oxidizer cessation, the motor combustion would terminate. The fuel grain would smolder for a few seconds, and then begin to cool down. This ignition process could be repeated to re-light the motor successively for several test firings.

A photograph of the initial developmental CHRD prototype is presented in **Figure 1**.

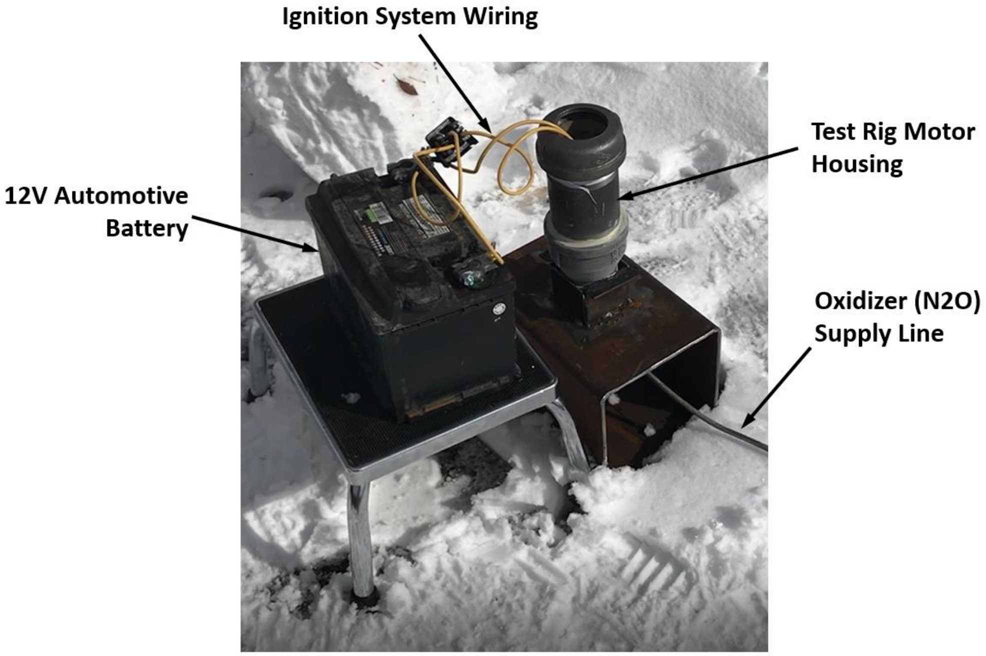


Figure 1 – CHRD System Developmental Test Hardware

Initial testing confirmed that the fuel grain, oxidizer system, and ignition system were viable, and would perform satisfactorily in the static configuration planned for the fully functional CHRD prototype. The demonstrator indicated that repeated firings of the rocket motor would be possible using the basic design specified.

A photograph of the CHRD prototype during a successful ignition test is presented in **Figure 2**.

Figure 2 – CHRD Ignition Test Result

5 CHRD Phase II – Thrusting Static Motor Demonstration

Following the subsystem developmental testing in Phase I, the complete Concept Hybrid Rocket Demonstrator (CHRD) prototype was designed and analyzed for repeated static firings. Sub-Assemblies and Components tested and qualified in Phase I were retained in the updated design. Specifically, the oxidizer delivery system and ignition system were incorporated into the final design. During the design phase, an analytical model used to predict rocket motor performance was developed by the engineering team. This predictive model was established using MS Excel as the computational basis. The model accepts basic operational parameters related to the rocket characteristics as well as environmental factors. These values are then used to determine expected rocket performance characteristics. [9][10][11][12][1]

An example of the user interface of the CHRD predictive model is presented in **Table 1**.

Constants		
UNIVERSAL GAS CONSTANT	8.314	$J/MOL^{-1}*K^{-1}$
APPROXIMATE SPECIFIC HEAT RATIO FOR CALCULATIONS (γ)	1.4	
MOLAR MASS OF AIR	0.029	KG/MOL
ATMOSPHERIC PRESSURE (P_a)	12.6	PSI
ATMOSPHERIC TEMPERATURE (°F)	35	°F
LOCAL SPEED OF SOUND	1089.623884	fps
MACH NUMBER AT THROAT	1	Ma
ALTITUDE (OGDEN)	4300	feet above sea level

ARBITRARY CONSTANTS		
A_e/A^* FOR ON DESIGN NOZZLE	3	ratio
T/T_0	0.415886879	ratio
P/P_0	0.046388814	ratio
ρ/ρ_0	0.111541902	ratio
MACH NUMBER AT EXIT (M_{ne})	2.65	ratio
CONE ANGLE FOR 98% EFFICIENCY	15	°
NOZZLE THROAT DIAMETER	0.205	in
FUEL DENSITY (ρ_f) OF HTPB	0.033237108	lb/in^3
OXIDIZER DENSITY (ρ_o) OF N_2O (AT BOILING POINT)	0.0440753	lb/in^3
FUEL GRAIN LENGTH	7.5	in
FUEL GRAIN CENTER HOLE DIAMETER	0.5	in
a FOR HTPB	0.1	unitless
n FOR HTPB	0.6	unitless
COMBUSTION EFFICIENCY (ξ)	0.93	unitless
MOLECULAR WEIGHT OF COMBUSTION PRODUCTS (M)	26.88	g/mol
COMBUSTION CHAMBER TEMPERATURE (T_c)	1900	K°

PREVIOUS BUILD GOALS		
GOAL CHAMBER PRESSURE	400	psi
GOAL THRUST	75	LBS

CALCULATIONS		
AREAS		
EXIT DIAMETER	0.355070416	in
NOZZLE EXIT AREA (A_{ne})	0.099019073	in^2
LENGTH FROM THROAT TO EXIT	0.280035208	in
NOZZLE THROAT AREA (A_{nt})	0.033006358	in^2
FUEL BURN AREA (A_b)	11.78097245	in^2
FUEL PORT CROSS SECTIONAL AREA (A_c)	0.196349541	in^2
RATES		
SOLID FUEL REGRESSION RATE {r}	0.045059262	in/sec
OXIDIZER MASS FLUX (G_0)	0.264833825	lb/in^2s
FUEL MASS FLOW RATE ($\dot{m}_f$)	0.01764365	lb/sec
OXIDIZER MASS FLOW RATE ($\dot{m}_o$)	0.052	lb/sec
PROPELLANT MASS FLOW RATE ($\dot{m}_{prop}$)	0.06964365	lb/sec
OXIDIZER FUEL RATIO (φ)	2.947235928	unitless
CHARACTERISTIC VELOCITY OF EXHAUST GASSES (C^*)	799.68484	m/s
COEFFICIENT OF THRUST (C_f)	1.718808722	unitless
COMBUSTION CHAMBER PRESSURE (P_c)	1186112.519	Pa
NOZZLE EXIT PRESSURE (P_{ne})	55022.35251	Pa
THRUST (F_y)	130.2388638	N
IMPULSE (I_{sp})	4123.515833	s

CURRENT EXPECTED RESULTS		
CHAMBER PRESSURE	172.0313876	psi
THRUST (F_y)	27.22934791	LBS

Table 1 – CHRD Predictive Model User Interface

Using the analytical model as a design guide, the basic sizing and configuration of the rocket motor and associated components was determined. Also identified at this phase was a preferred instrumentation suite required to measure rocket performance as well as verify the accuracy of the initial performance characteristics determined by the predictive model. Specifying a baseline maximum thrust of 75 pounds force for a duration of 10 seconds, a fuel grain size 2.0 in OD x 0.5 in ID x 6.5 in long fuel grain was established. All of the resulting motor hardware was designed around these basic dimensions. It is of note that the fuel grain was cast in liquid form within a cardboard sleeve, then cured and solidified for easy installation and removal across multiple motor firings. If it was not designed this way, the rubber would need to be cast inside of the metal motor housing, greatly complicating motor change over for subsequent tests. A commercially available thrust sensor was acquired to measure rocket thrust in situ during test firings. The motor housing in a free state, is constrained vertically with respect to the thrust stand via the thrust sensor.

In addition to the oxidizer and ignition components noted above, specific motor hardware and related subsystems were designed with appropriate engineering analysis applied. A partial list of these subsystems and components include:

- Motor Housing
- Exhaust Nozzle
- Retaining Hardware
- Plumbing and Electrical System
- Thrust Stand with Motor Attachment Bracket and Containment Shield

A Computer Aided Design (CAD) assembly and cross-section view of the CHRD design is presented in **Figure 3** and **Figure 4**.

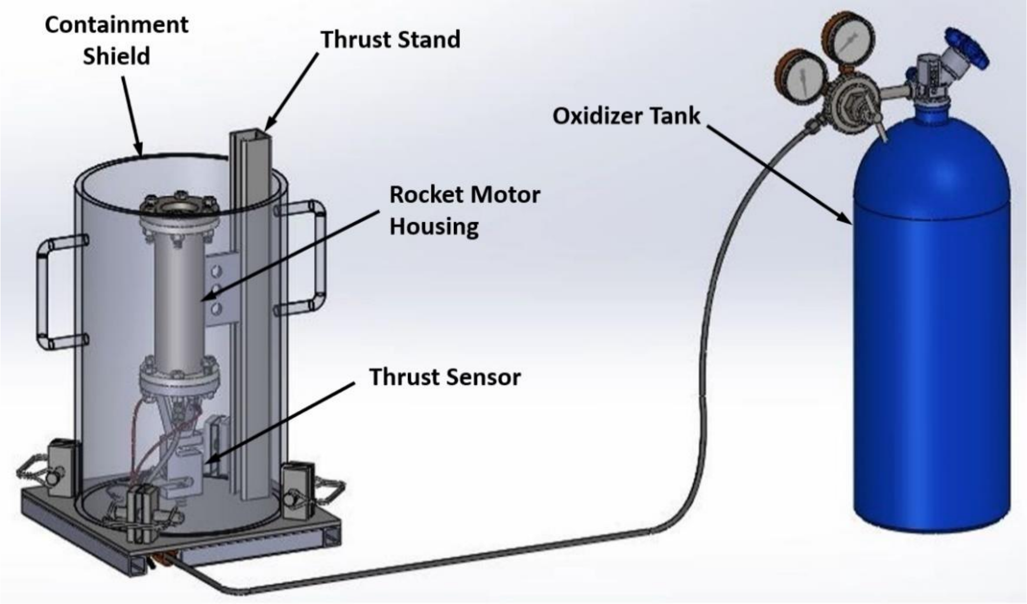


Figure 3 – CHRD Assembly CAD Model

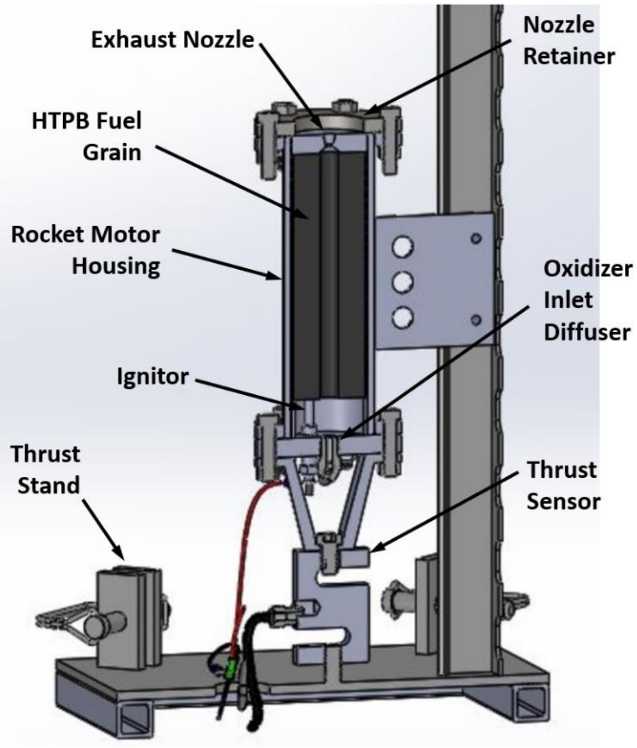


Figure 4 – CHRD Assembly CAD Cross-Section Model

Once the final design was completed, all of the components required by the CHRD assembly were either purchased, or fabricated. During the manufacturing process, all components were inspected per blueprint requirements, to ensure they met all dimensional and workmanship requirements. All of the associated instrumentation was integrated and assembled as needed to measure desired motor performance parameters. The individual signals generated, were transmitted to a Data Acquisition Device (DAQ), and then processed using LabVIEW software. Both the DAQ and LabVIEW software were supplied provided by National Instruments (NI).

Photographs of the CHRD test hardware, as deployed for a static test during Phase II, are presented in **Figure 5** and **Figure 6**.

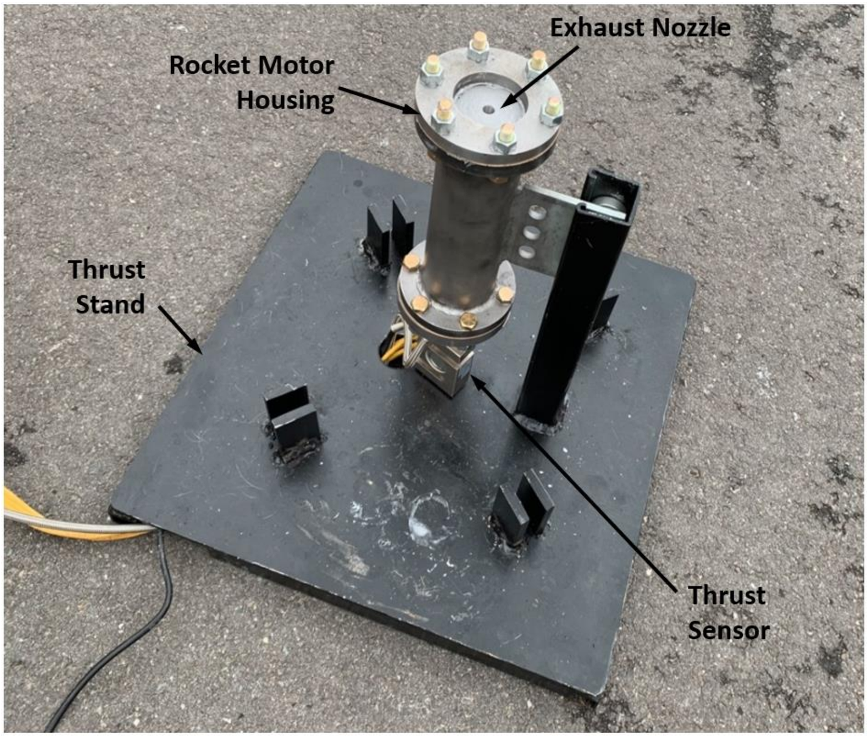


Figure 5 – CHRD Motor and Thrust Stand

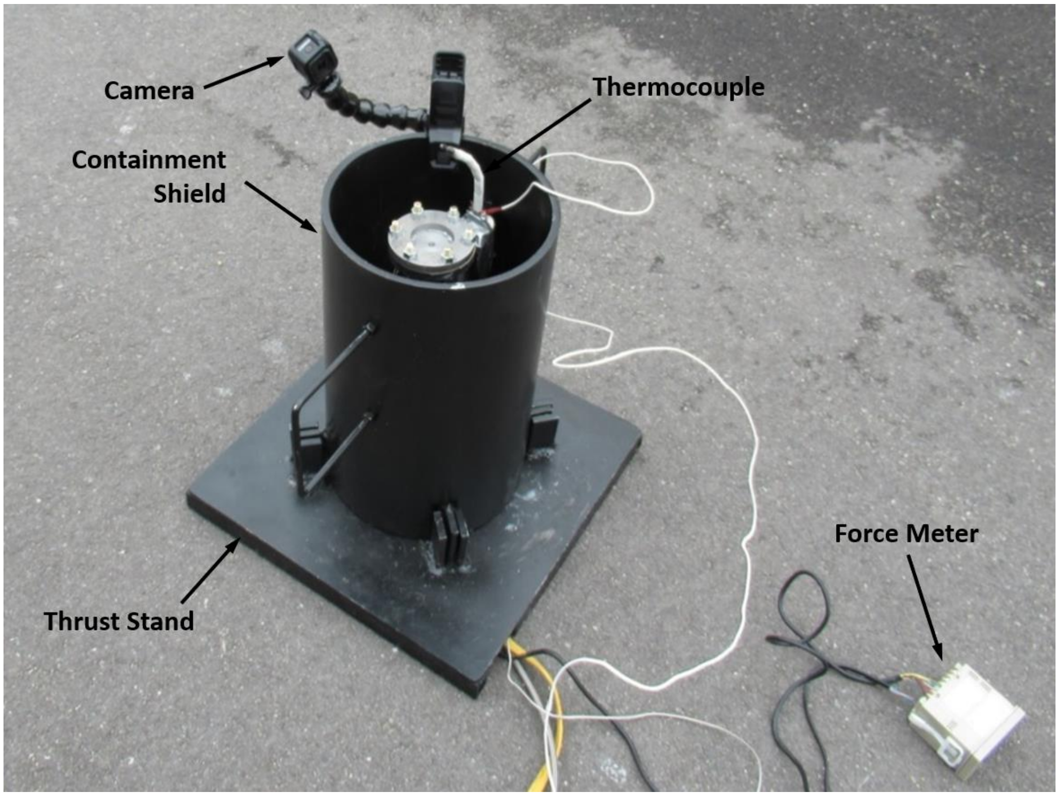


Figure 6 – CHRD Assembly Prior to Motor Firing

During the spring of 2021, several static firings of the CHRD were successfully accomplished. During each motor firing, engine performance data was collected and analyzed. During these tests, a peak motor thrust of approximately 30 lbf was measured. As future testing progresses, the prototype will be run to higher thrust values by increasing the oxidizer flow rate. A future testing goal is to determine the maximum motor thrust, and compare that to the theoretical values produced by the theoretical model.

Following each test, the aft retaining cap was removed, and the fuel grain cartridge was replaced. The nozzle was also visually inspected for thermal erosion. If noticeable erosion to the converging-diverging (CD) section was observed, a spare nozzle was substituted into the assembly for the next test. It was common to observe significant nozzle throat degradation following a single test firing. Of additional concern was the possible migration of combustion gasses around the outside of the cartridge style fuel grain or out through the end cap flange assemblies. This risk was mitigated using various design safeguards. The fuel grain and nozzle axial stack was designed to stand approximately 0.060 – 0.100 inches proud of the motor housing in a free state. The HTPB material used in the fuel grain is highly compliant, and will elastically deform under compressive load. When the nozzle retainer is installed, and tightened to the required assembly load, the fuel grain would slightly compress and form a tight interface between it and the nozzle. Additionally, in areas suspected to be susceptible to gas leakage, a high temperature gasket sealant was used to provide a barrier to leakage. The rocket assembly end caps utilize high temperature automotive gaskets with high temperature sealant applied to further safeguard against gas migration under bolted load.

All visual inspections of post-test hardware revealed excellent durability, with no evidence of thermal damage or other issues. Following a number of test firings, the inside wall of the motor housing has shown no indications of combustion gas leakage around the fuel grain cartridge, and the end caps are free of evidence of leakage. This supports a conclusion that no significant unexpected hot gas leak paths are present in the assembly. A photograph of a typical CHRD test firing is presented in **Figure 7**.

Figure 7 – CHRD Test Firing at Full Thrust (April 2021)

Despite the successful motor firings, instrumentation limitations were identified during the initial testing. For ongoing testing planned in the spring of 2022, an improved instrumentation suite is designed to better capture data related to oxidizer flow rates, combustion chamber temperature, and combustion chamber pressure. An additional design upgrade planned for next testing cycle includes an improved exhaust nozzle and ignition system. The initial nozzle was fabricated from coated steel, and was found to erode quickly, requiring replacement between engine firings. The next generation nozzle has been designed, and will be fabricated from graphite for improved temperature resistance and durability. The ignition system will be incorporating a secondary system to provide a short burst of heat at the point of oxidizer introduction into the combustion chamber. This is intended to improve reliability and repeatability of the ignition. Current reliability rates of the ignition system indicate approximately 1 failed light-off per 3 attempts. The design revisions are intended to improve the success rate to over 90% (1 fail in 10 attempts).

6 Planned CHRD Phase III – Fuel Grain Port Configuration and Alternate Fuel Grain Material Studies

Following the completion of all Phase II testing planned for the spring 2022, a third phase development program is planned and currently funded for the 2022-2023 academic year. Two primary design objectives are identified for the third, and most likely final phase of development. The first objective is to experiment and evaluate various fuel grain port geometries. The current port design, which is considered the baseline configuration, is a simple cylindrical port along the centerline axis of the grain. Different port geometries are being planned for evaluation. The goal is to determine fuel regression rates, and thrust versus time profiles, as they relate to the fuel grain port cross-section shape and size.

A diagram illustrating the baseline fuel grain cross-section port shape, with conceptual alternative shapes, are presented in **Figure 8**.

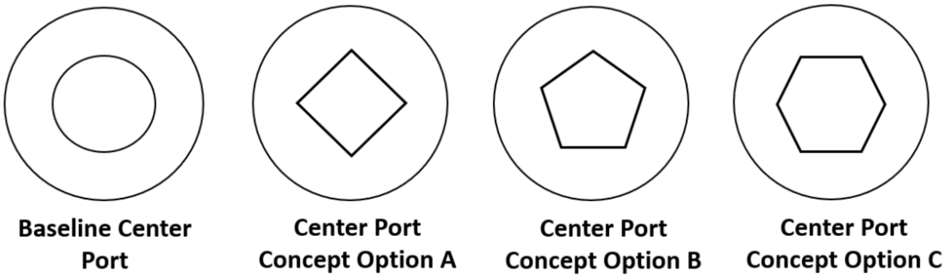


Figure 8 – Baseline and Conceptual Fuel Grain Port Geometries

In addition to the various fuel grain port geometry evaluations, alternate fuel grain material types and manufacturing methods are planned to be studied. Using rapid prototyping technology (3D Printing), fuel grains composed of Acrylonitrile Butadiene Styrene (ABS) have been identified as a candidate substitute for the currently utilized Hydroxyl Terminated Polybutadiene (HTPB) material. The various port geometries can be generated using the prototyping technology, which will eliminate the need for specialized casting tooling (form and mandrel) currently used to produce the fuel grain. Thrust and performance data comparing the ABS and HTPB fuels would be evaluated.

7 Student Team Composition and Outcomes

The successive groups of students that comprise the two original capstone design teams involved in the CHRD project totaled eight people. The first group consisted of three students, and the second team consisted of five students. Each group was assigned to the project from the pool of students registered for the senior design series for that particular academic year. They were not recruited or selected specifically for the rocket project, but were assigned to a design team based on faculty manpower needs for an established project.

Most students involved in the CHRD have communicated excitement for the project, and have worked very hard to make it a success. Some anonymous comments collected from the course evaluations submitted by the students include the following input:

“The subject of the project is a challenging and very interesting one. A great introduction to rocket science.”

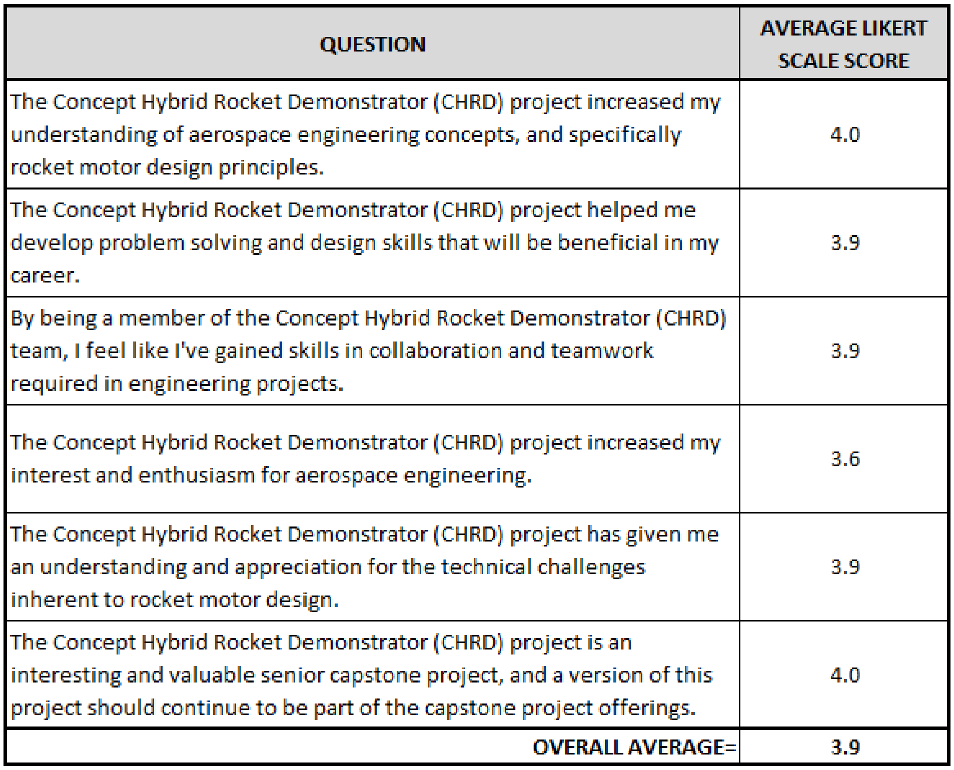
“I was so thankful I was able to get in a project that felt worthwhile for the time put in. The X and Y projects my friends were in seemed like they were just done because they needed a senior project to graduate and they were just filler projects to meet the requirement. Our project collected data and accomplished something that will be built on and I'm glad I was able to be a part of it.”

“I liked that the project was difficult at times and feel like I learned a lot from it.”

“I Thought this was a great senior project and felt like I learned more from this than I would have with any of the other projects going on at the time.”

A third capstone team consisting of seven students is currently working on continued development of the rocket for the 2021-2022 academic year. Their enthusiasm level is very high, and they are working hard to further the development of the rocket motor. Development activities currently underway are detailed in the summary and conclusions section below.

A survey soliciting student feedback regarding the CHRD project was submitted to former and current students. A series of five question regarding student satisfaction and perception of the project was answered by the survey recipients. A total of nine students responded to the survey. Scoring of the survey is a standard Likert scale where 0 would correlate to a strong disagreement to a particular question, and a 4 would correlate to a strong agreement to a particular question. A score of 2 would indicate a neutral opinion. A summary of all survey respondents to the survey is presented in **Table 1**.



QUESTION	AVERAGE LIKERT SCALE SCORE
The Concept Hybrid Rocket Demonstrator (CHRD) project increased my understanding of aerospace engineering concepts, and specifically rocket motor design principles.	4.0
The Concept Hybrid Rocket Demonstrator (CHRD) project helped me develop problem solving and design skills that will be beneficial in my career.	3.9
By being a member of the Concept Hybrid Rocket Demonstrator (CHRD) team, I feel like I've gained skills in collaboration and teamwork required in engineering projects.	3.9
The Concept Hybrid Rocket Demonstrator (CHRD) project increased my interest and enthusiasm for aerospace engineering.	3.6
The Concept Hybrid Rocket Demonstrator (CHRD) project has given me an understanding and appreciation for the technical challenges inherent to rocket motor design.	3.9
The Concept Hybrid Rocket Demonstrator (CHRD) project is an interesting and valuable senior capstone project, and a version of this project should continue to be part of the capstone project offerings.	4.0
OVERALL AVERAGE=	3.9

Table 2 – Student Survey Likert Scale Results

It also interesting to note that two of the former team members moved on into career positions in the aerospace industry. A current team member (2021-2022 academic year) has also decided to pursue a career track position at a local aerospace company as well.

8 Summary and Conclusions

The initial design and testing efforts related to the Concept Hybrid Rocket Demonstrator (CHRD) have been successful. Thus far, all of the project objectives, as defined in the design specification and schedule, have been met. A rocket motor capable of being lit, with thrust control, successful shutdown, and subsequent relight was repeatedly demonstrated. Additionally, operational data during test firings was collected and analyzed.

As noted above, a measured thrust of approximately 30 lbf was demonstrated during motor testing. Future testing planned in the near term (spring 2022) will attempt to push rocket performance as close as possible to the maximum thrust value of 75 lbf as documented in the baseline analytical predictive model. With planned instrumentation improvements as well as an improved exhaust nozzle design, it is anticipated that motor performance can be improved, and data can be better correlated to theoretical calculations.

As noted, In the current design, the exhaust nozzle does not provide durability or reusability consistent with project goals. The current design effort involves an improved nozzle design both in aerodynamic performance and materials development to provide a nozzle that will deliver optimal thrust as a well as be usable over several test firings.

Additionally, the rocket motor instrumentation has demonstrated durability and reliability concerns. Therefore, additional upcoming research and development efforts will be focused on improving the instrumentation as well. The goal is to design and implement an instrumentation suite that accurately measures exhaust gas temperature, oxidizer flow rate, chamber pressure, and rocket housing temperature.

With the improvements noted above, anticipated to be competed during 2022, the rocket development effort is expected to progress into Phase III as forecast. With the commencement of Phase III, specific research and testing will be dedicated to the investigation of rapid prototyped fuel grain structures consisting of varied materials on port geometries. This will also include investigation of alternate types of fuel, and evaluation of their performance characteristics as compared the original HTPB fuel.

9 References

[1] G.P. Sutton, *Rocket Propulsion Elements: An Introduction to the Engineering of Rockets*, Wiley & Sons, 6th Edition, 1992

[2] M.J. Degges, P. Taraschi, J. Syphers, D. Armold, E. Boyer, K. K. Kuo, *Student Investigation of Rapid Prototyping Technology for Hybrid Rocket Motor Fuel Grains*, 49th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, 2013

[3] M. Kobald, U. Fischer, K. Tomilin, A. Petrarolo, P. Kysela, C. Schmierer, A. Pahler, J. Gauger, J. Breitinger, F. Hertel, B. Hochheimer, *Sounding Rocket "HEROS" – A Low-Cost Hybrid Rocket Technology Demonstrator*, 53rd AIAA/SAE/ASEE Joint Propulsion Conference, 2017

[4] M. Kobald, U. Fischer, K. Tomilin, A. Petrarolo, C. Schmierer, *Hybrid Experimental Rocket Stuttgart: A Low-Cost Technology Demonstrator*, Journal of Spacecraft and Rockets, Vol. 55, No. 2, 2018

[5] K. Schuttauf, A. Stamminger, *Operation of Solid Rockets in Comparison with Hybrid Rockets During the STERN Project*, SpaceOps Conference, 2016

[6] F. Heeg, L. Kilzer, R. Seitz, E. Stoll, *Design and Test of a Student Hybrid Rocket Engine with an External Carbon Fiber Composite Structure*, Aerospace, Vol. 7, Issue 5, 2020

[7] M. Kobald, C. Schmierer, U. Fischer, K. Tomilin, A. Petrarolo, M. Rehberger, *The HyEnD STERN Hybrid Sounding Rocket Project*, Progress in Propulsion Physics, Vol.11, 2019

[8] S.D. Mathias, S.A. Whitmore, R. Harvey, *High Voltage Breakdown and Arc-Tracking Mechanism of Thermoplastics with Applications to Hybrid Rocket Arc-Ignition*, 53rd AIAA/SAE/ASEE Joint Propulsion Conference, 2017

[9] J.K. Bowen, D. Birch, *Development of an Analytical Prototype for Hybrid Rocket Motor Design,* American Institute of Aeronautics and Astronautics, AIAA Region VI Student Conference, 1997

[10] P. Hill, C. Peterson, *Mechanics and Thermodynamics of Propulsion*, Pearson, 2nd Edition, 1991

[11] F. White, *Fluid Mechanics*, McGraw-Hill, 7th Edition, 2010

[12] J.D. Anderson, *Fundamentals of Aerodynamics*, McGraw-Hill, 5th Edition, 2010