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High-Temperature Materials Testing using a Hybrid Rocket Testbed

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HIGH TEMPERATURE MATERIALS TESTING USING A HYBRID ROCKET TESTBED

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1.0 ABSTRACT

The Concept Hybrid Rocket Demonstrator (CHRD), originally developed as a Senior Capstone design project in the Mechanical Engineering (ME) and Mechanical Engineering Technology (MET) programs at Weber State University (WSU), has been modified into an experimental testbed used in high temperature materials rapid screening testing **[1]**. This high temperature materials research is being directed by the WSU affiliated Miller Advanced Research and Solutions Center (MARS).

Utilizing a team of recently graduated ME and MET students as well as undergraduate student research assistants from various academic programs, the original basic rocket system was modified into an experimental testbed supporting high temperature materials research and numerous CBAM nozzles were produced for evaluation. The original phase of this effort included the development of a comprehensive instrumentation suite to measure rocket operational parameters for correlation to post-test evaluation of composite nozzle test articles and production of rapid prototype composite nozzles. Numerous test firings were conducted to evaluate both testbed performance and material behavior when exposed to the combustion product flow-field.

Consistent with the typical operational characteristics of a hybrid rocket, the CHRD system utilizes a solid fuel grain and fluid type oxidizer. The solid fuel grain is composed of Acrylonitrile Butadiene Styrene (ABS) plastic produced using simple 3D printing approaches and the oxidizer is gaseous Nitrous Oxide (N_2O) or Gaseous Oxygen (GOX / O_2). As a result of the conversion into a high temperature testing system, the baseline CHRD system, as developed in the undergraduate senior project series, has undergone modifications and upgrades to develop it into a testbed used to evaluate experimental high temperature materials produced by MARS on behalf of academic, government, and industrial partners. Of specific interest in the initial phase of the project were the testing of various Carbon-based Additive Manufacturing (CBAM) produced Converging-Diverging (CD) rocket nozzles. Rocket nozzle materials are typically exposed to severe environments of elevated temperature gas flowing at sonic speeds in the nozzle throat developing to supersonic speeds at the nozzle exit, thus they are excellent candidates for high temperature durability experimentation.

Promising results from the initial testing were realized such that additional funding has been committed for an ongoing development effort. Future activities will encompass upgrades and experimental qualifications of the rocket testbed operation, instrumentation, and control system. Follow-on materials testing will be conducted for both additional nozzle sections and planar impingement specimens fabricated using various composite fabrication techniques. Future work will again employ several recent graduates and undergraduate research assistants to plan and implement the experimental upgrades.

2.0 PROJECT EDUCATIONAL OBJECTIVES:

Many of the students at Weber State University (WSU) have full or part-time jobs off campus to help support themselves during their educational efforts. The majority of these jobs have little or no association with their field of study, and are simply a means to generate revenue during the students' university tenure. Employment opportunities for the students within The College of Engineering, Applied Science, and Technology (EAST), was recognized as a significant benefit to the students' immediate need to earn income as well as gain additional training and networking opportunities with the local and broader industrial community. The desired educational outcome was intended to fill six basic requirements for the associated students. These include:

1. Reinforce core concepts instructed in the various engineering and engineering technology curriculums.
2. Generate interest and persuade students to enroll in upper division technical elective coursework specialized in aerospace and closely related fields.
3. Develop comradery, collaboration, and teamwork skills among the students enrolled in the various traditional engineering and engineering technology programs. Of particular interest was the enhancement of networking and mutual respect among students enrolled in the traditional engineering and engineering technology programs, which do not share a significant amount of common curriculum.
4. Better recognize and appreciate the connection between theory and applied engineering.
5. Further develop and refine communication and formal presentation skills to the various project stakeholders. Particularly, enhancing the ability to understand the needs of a specific audience and generating communication tailored to the expectations of that group.
6. Gain an understanding of system lifecycle management concepts and requirements engineering.

All students at WSU, enrolled in engineering and engineering technology programs, are required to complete a senior capstone project. The proposal to develop the Concept Hybrid Rocket Demonstrator (CHRD) into the high temperature materials testbed was conceived of as a unique opportunity to engage students in engineering activities beyond what is possible to accomplish in a typical two semester, six credit hour capstone project. Members of the Mechanical Engineering faculty as well as the management team at Miller Advanced Research and Solutions Center (MARS) recognized that a much more immersive student experience than what is possible in the standard capstone curriculum, was possible in the development of the experimental testbed. For the undergraduate students involved, they will gain valuable experience and knowledge, and be much better prepared to engage effectively in their own capstone project when the time comes. For the graduate students involved, the testbed is an excellent opportunity to use and expand the skills learned during their own prior capstone experience.

Students recruited into the testbed project are typically employed at a competitive wage for the duration of their enrollment at WSU. As part of the testbed design team, each student research assistant will work a preset schedule weekly and report to a direct supervisor, simulating closely the work structure of a professional position in industry. The goal is that each student will recognize the long-term benefits of involvement in the project, and not require additional income from another job. As students work on the project, they gain valuable experience that will hopefully set them apart from other candidates when they graduate and seek their first industry position. Additionally, students involved in the testbed development project have been making valuable professional networking connections with influential academic, government, and industrial partners to assist them in their future career aspirations.

3.0 STUDENT COLLABORATION:

The students enrolled in degree programs available within the College of Engineering, Applied Science, and Technology (EAST) can typically choose between baccalaureate degrees in traditional engineering and engineering technology. As is commonly understood, traditional engineering is more conceptual and theory based, including the advanced mathematical background of the various subjects. Engineering technology takes a more applied "hands-on" approach to engineering instruction with an emphasis on the implementation of engineering principles to solve technical problems. Within the various degree programs at Weber State University (WSU), some interaction and collaboration opportunities inherently exist between the two programs of study. However, significant collaboration is not typical. The testbed development project has provided an opportunity for both engineering and engineering technology majors to work together closely, learn to appreciate each other's specific areas of expertise, and leverage that diversity to build stronger teams, and reach better overall outcomes. Associated faculty mentors typically instruct coursework in both the engineering and engineering technology programs and have developed a personal relationship with the students in both degree programs. They use this familiarity to foster teamwork and close collaboration between students in all of the various programs.

An additional asset to the project is the involvement of a limited number of graduate students enrolled in the Master of Science in Systems Engineering (MSSE) program. These students bring an added level of maturity and expertise to the project. They also possess a more advanced understanding of program and project management concepts as well as an understanding of engineering lifecycle management due to their specialized training. An additional benefit of having graduate and undergraduate students working together is the exposure of the undergraduate students to the MSSE program, and its potential future application to their own educational goals. This working relationship is an effective recruitment tool in inspiring current undergraduate students to pursue an advanced degree, particularly in the Systems Engineering program at WSU.

4.0 ACADEMIC CURRICULUM APPLICATION:

As noted, one of the educational objectives of the testbed development program is to leverage the Concept Hybrid Rocket Demonstrator (CHRD) / materials testbed system design activities to remind and reinforce the concepts taught in the undergraduate curriculum for both the engineering and engineering technology programs. Required coursework in the various curriculum instructs concepts that are applicable while performing design, analysis, fabrication, assembly, and testing of the testbed system. When applicable, faculty advisors point out and review with students where specific core concepts are applied within the design process. For students enrolled in the Mechanical Engineering (ME) program, examples of the coursework that contains relevant concepts for emphasis include:

- Mechanics of Materials
- Materials Science and Engineering
- Thermodynamics
- Fluid Mechanics
- Heat Transfer
- Sensors, Instrumentation, and Control Systems

For students enrolled in the Mechanical Engineering Technology (MET) program, examples of the coursework that contains relevant testbed design concepts for emphasis include:

- Engineering Technology Materials
- Mechanical Measurement and Instrumentation
- Mechanical Design with FEA
- Thermal Science

For students enrolled in the Manufacturing Systems Engineering (MSE) program, examples of the coursework that contains relevant testbed design concepts for emphasis include:

- Project Management for Engineers
- Manufacturing Processes and Materials
- Machining Principles
- Metal Forming, Casting and Welding
- Mechanics of Materials
- Manufacturing Processes and Materials
- Computer Numerical Control (CNC) in Manufacturing

As the student research assistants progress through their required curriculum, they are encouraged by the associated faculty advisors to take specific upper division technical elective credit with direct relevance to aerospace systems. Weber State University (WSU) offers several courses with direct application in the testbed system. These courses are:

- Finite Element Analysis
- Material Failure Analysis
- Compressible Fluid Flow
- Aerospace Propulsion
- Intermediate Thermal-Fluids

Graduate coursework within the Master of Science in Systems Engineering, also with direct application in the project include:

- Engineering Project and Program Management
- Requirements Engineering
- System Design and Operational Analysis

5.0 APPLIED LEARNING OPPORTUNITIES:

In addition to the reinforcement of learning for specific subjects taught in the core curriculum of the various degree programs, direct application of engineering principles to "real-world" problems are emphasized and practiced in the development of the testbed system. Students are accountable for the work that is completed, and are evaluated against budget, schedule, and system performance metrics during their employment on the project. They must effectively communicate their progress regularly to all project stakeholders and must employ professional project management approaches. They are also expected to learn and master specific skills related to their job responsibilities. These include:

- Interpretation, application, and tracking of engineering requirements.
- Schedule and budget management using commonly applied methods.
- Advanced Computer Aided Design (CAD) modeling.
- Geometric Dimensioning and Tolerancing (GD&T)
- MATLAB / Python coding.
- Conventional machining.
- Numerically Controlled (NC) machining.
- Composite material fabrication techniques.
- Utilization of rapid prototyping technologies.
- Coupled field (thermal/structural) Finite Element Analysis (FEA).
- Instrumentation and sensor design, development, and testing.
- Feedback control system design, implementation, and testing.
- LabVIEW coding.
- Application and operation of advanced imaging technologies such as Keyence microscopes and Scanning Electron Microscopes (SEM).
- Process control, repeatability, and reproducibility studies.
- Test plan writing.
- Test report writing.

Having advanced training in specific areas will always provide an advantage over their peers as they transition into the workplace. The Industrial Advisory Boards (IAB) representing the degree programs previously noted, have often voiced their desire for more specialized training in the areas noted, and this project is an excellent mechanism to accomplish that. The testbed project provides students an effective forum for learning these skills and mastering them at a professional level.

6.0 STUDENT OUTCOMES

One of the primary goals of the initial phase of the Hybrid Rocket and High-Temperature materials testing project was to assess the effectiveness of research engagement strategies and long-term employment opportunities for students on the research teams. Of particular interest is how this model worked for complex engineering and research activities related to aerospace systems. Considering the Primarily Undergraduate Institution (PUI) emphasis of Weber State University (WSU), significant numbers of graduate students, with associated long-term funding options, are not as common when compared to an R1 type university. Thus, to satisfy local demand for fundamental research and encourage academic-government-industry partnerships, the project model described in this paper was instituted. As currently assessed, the outcome of this initial effort is mostly positive, with favorable feedback received from students and faculty advisors alike. To assess student perception and their overall satisfaction in the outcomes, a Qualtrics survey was completed by student research assistants following the initial phase of the project. The survey consisted of a series of six questions with a typical Likert scale response provided for each inquiry. The questions were structured such that higher Likert scores indicate positive responses, and lower scores indicate the opposite. Seven students from the original research teams responded to the voluntary survey. The possible responses to each question with their respective points used for scoring are presented in **Table 1**.

Table 1 - Likert Scale Scoring

SURVEY RESPONSES	POINTS
STRONGLY AGREE	4
SOMEWHAT AGREE	3
NEITHER AGREE NOR DISAGREE	2
SOMEWHAT DISAGREE	1
STRONGLY DISAGREE	0

The six questions posed, as well as the composite average of responses are presented in **Table 2**.

Table 2 - Student Questions and Composite Scoring of Responses

QUESTION #	QUESTION	COMPOSITE AVERAGE
1	Working as a research assistant on the Concept Hybrid Rocket Demonstrator (CHRD) project increased my understanding of rocket propulsion and materials theory, analysis, and design.	4.0
2	Working as a research assistant on the Concept Hybrid Rocket Demonstrator (CHRD) improved my understanding of the application of engineering theory to engineering practice and the design of actual systems.	4.0
3	The collaboration between Weber State University (WSU) and the Miller Advanced Research and Solutions (MARS) center was effective and provided a unique learning experience in both rocket theory and materials research.	3.7
4	My participation in the Concept Hybrid Rocket Demonstrator (CHRD) / high temperature materials testing project has increased my interest in the aerospace industry and inspired me to possibly pursue a career in this area.	3.9
5	The Concept Hybrid Rocket Demonstrator (CHRD) / high temperature materials testing project has increased public and industry awareness of the capabilities of Weber State University (WSU) and the Miller Advanced Research and Solutions (MARS) center.	3.9
6	If a multi-year opportunity to work part-time as a research assistant in my area of study was available, I would be interested in this instead of other employment opportunities outside of the university.	3.0

The composite averages noted for each question indicate that the students were generally happy with their project involvement and the knowledge, skills and experience acquired were beneficial to them. It also indicates that their understanding and interest in the aerospace sector was enhanced. Due to the technical success of the initial phase of the project in conjunction with student satisfaction, additional funding has been provided by the Miller Advanced Research and Solutions Center (MARS) to continue the project on an ongoing basis.

It is also noteworthy that as word-of-mouth discussions regarding the project spread throughout the student body in the various engineering majors, two additional students were added to the research teams working on strictly a voluntary basis as all available funding for salaries had been allocated. These students have remained contributing team members of the project. As a result, one of these volunteers has been added to the project as a paid employee, with the other slated to join as an official employee beginning in Summer 2024.

7.0 CONCEPT HYBRID ROCKET DEMONSTRATOR (CHRD) SYSTEM OVERVIEW

Traditional rocket motors typically are classified into two categories. First, liquid fuel rocket motors that utilize a liquid fuel and oxidizer that are mixed in a combustion chamber producing the expanding high temperature gas resulting in a rocket thrust. This type of motor can be throttled up or down as well as started and stopped upon command. Second, solid fuel rocket motors that incorporate the oxidizer in a single solid fuel grain. The fuel grain containing the oxidizer is ignited in the combustion chamber and burns until completely consumed. A solid fuel motor cannot be throttled and is very difficult to stop once ignited. A hybrid rocket motor is fundamentally different from traditional motors in that it typically utilizes a solid fuel grain and a liquid oxidizer. Thus, it exploits the thrust control of a liquid fuel type motor with the fuel density advantages of a solid fuel type motor **[1]**.

The Concept Hybrid Rocket Demonstrator (CHRD) is a small hybrid rocket motor developed over several years at Weber State University (WSU) as a senior capstone project in the undergraduate Mechanical Engineering (ME) and Mechanical Engineering Technology (MET) programs **[1]**. WSU is a large Primarily Undergraduate Institution (PUI) based in Ogden, Utah. During the successive capstone project efforts, numerous groups of students took part in developing and improving the basic rocket motor design during their year-long (two semester) experience. In Spring 2020, the baseline rocket configuration now used was established and test fired numerous times. A CAD model representation of the overall baseline CHRD system, a cut-away view of the hybrid rocket motor assembly, and photographs of the baseline CHRD configuration are presented in **Figure 1**, **Figure 2**, **Figure 3** and **Figure 4** respectively.

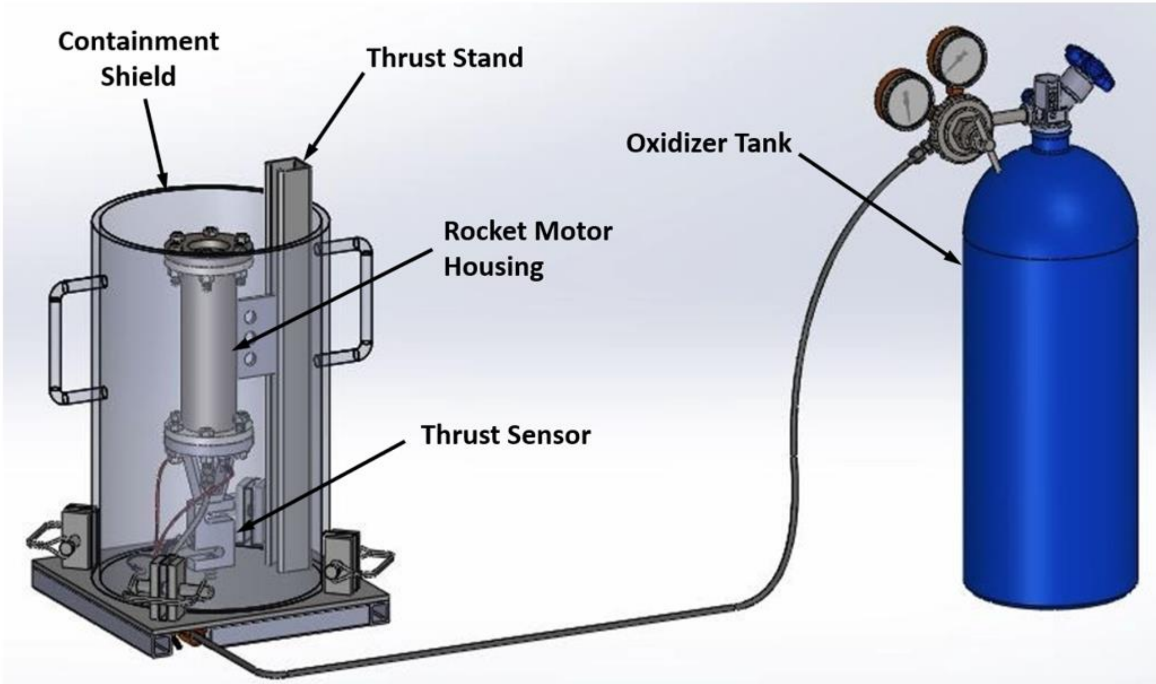

Figure 1 – Baseline Concept Hybrid Rocket Demonstrator (CHRD) Assembly

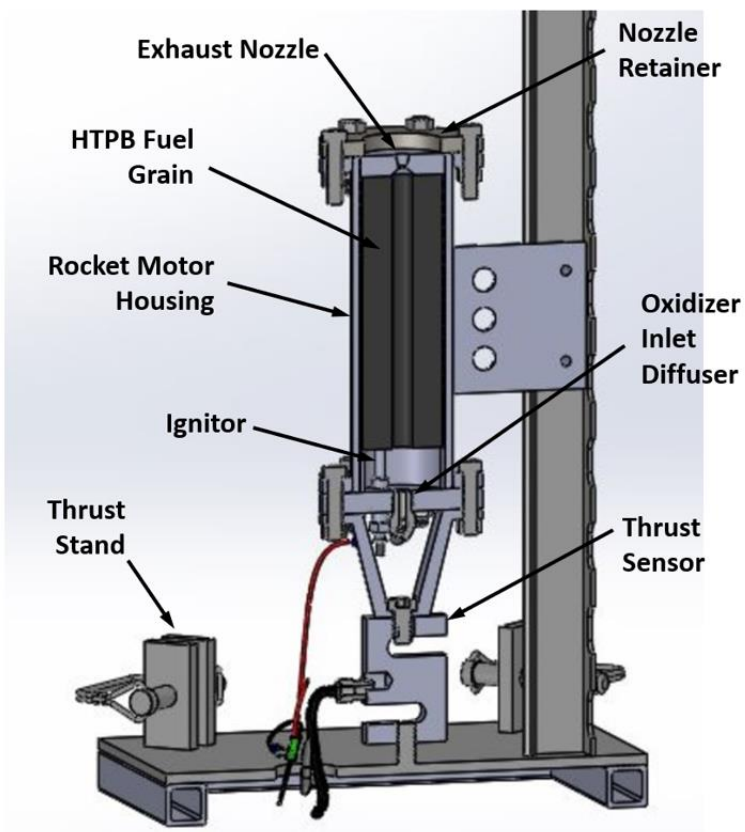

Figure 2 – Rocket Motor Cut-Away Assembly

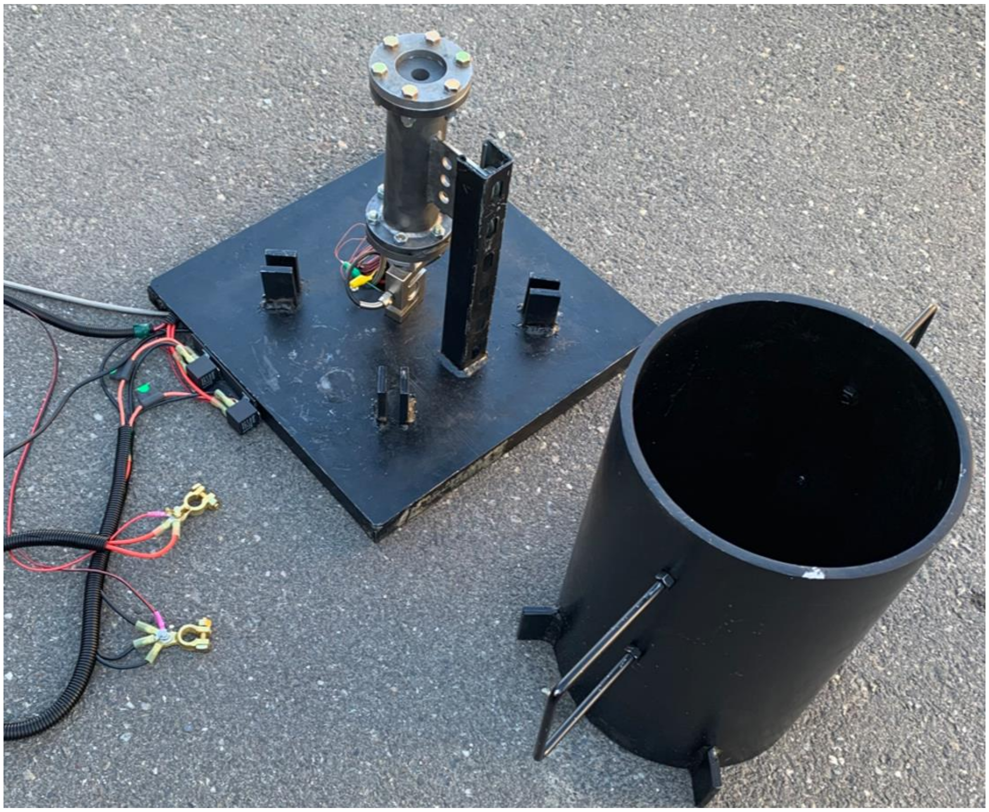

Figure 3 – Pre-Test Rocket Assembly (Containment Shield Removed)

Figure 4 – Pre-Test Rocket Assembly (Containment Shield Installed)

As noted above, several test firings of the baseline CHRD have occurred. Various rocket performance data have been collected and analyzed from each test firing. A photograph of the CHRD system during a static test firing is presented in **Figure 5**.

Figure 5 – Concept Hybrid Rocket Demonstrator Exhaust Plume During a Test Firing

Since the end of World War II, northern Utah has seen steady growth in its aerospace industry. Hill Air Force base and a large number of supporting contractor companies are located in the area and employ many thousands of engineers and technicians. The Air Force base and associated companies conduct many large defense and space launch related programs. As such, they have an ongoing interest in advanced high temperature materials research and development, particularly in the areas of high-speed flight and propulsion systems.

Recently, the CHRD system has been converted into a testbed for the evaluation of high temperature materials being produced and evaluated by the Miller Advanced Research and Solutions Center (MARS). One goal of this effort is to become a project partner with the local aerospace industry and support high temperature materials development projects. As part of this initiative, two Mechanical Engineering faculty members at WSU were asked to assemble research teams to concurrently develop the CHRD into a reliable and repeatable research testbed and support the design, fabrication, and testing of high temperature materials. Of specific interest was the development and testing of rocket nozzles. The erosion characteristics of various low-cost Carbon-Based Additive Manufacturing (CBAM) prototypes was to be initially investigated. Future applications identified include using the CHRD rocket plume as the heat and mass flow source for material evaluation undergoing high temperature impingement testing.

The research teams were recruited from a group of recent graduates and current students in the Mechanical Engineering (ME), Mechanical Engineering Technology (MET), Manufacturing Systems Engineering (MSE), and Master of Science in Systems Engineering (MSSE) programs. Beginning in May 2023, the teams commenced work on the project. A laboratory / project space was established in the Noorda Building on the WSU main campus where the CHRD development team began development of the enhanced instrumentation and control suite as well as various design and functional upgrades to the rocket motor hardware. The materials development team worked in conjunction with the engineering and technical staff at MARS, located approximately 10 miles from the WSU main campus, to produce the required test articles. Multiple test firings of the rocket during this development phase were conducted at both the WSU main campus and at MARS.

8.0 STUDENT ENGAGEMENT AND PROJECT ACCOMPLISHMENTS

As noted above, two separate student research teams were tasked with Concept Hybrid Rocket Demonstrator (CHRD) upgrades and modifications as well as design and fabrication of test articles, specifically rocket nozzles samples for high temperature evaluation. Some development focus areas for the students were:

Fuel Grain Development:

The initial fuel grain specified for rocket use was fabricated from cast Hydroxyl Terminated Polybutadiene (HTPB) **[1]**. The HTPB manufacturing process entailed a multi-part mixture of rubber, solidifying agent, and catalyst, being cast to fuel grain shape using a mold and mandrel. The material was inherently difficult to procure, relatively expensive, and difficult to fabricate with a reasonable yield of usable fuel grains. Additionally, the ignition properties of the HTPB were such that it was not reliable. A reliability rate of approximately 30% was realized for commanded rocket firings fueled by HTPB. To address these limitations, the student team developed 3-D printed fuel grains using Acrylonitrile Butadiene Styrene (ABS). The fuel grains produced using this method are more dimensionally consistent, and the yield is near 100%. Commanded ignition reliability was also greatly improved over the HTPB alternative. A photograph of the fuel grain fabrication process is presented in **Figure 6**.

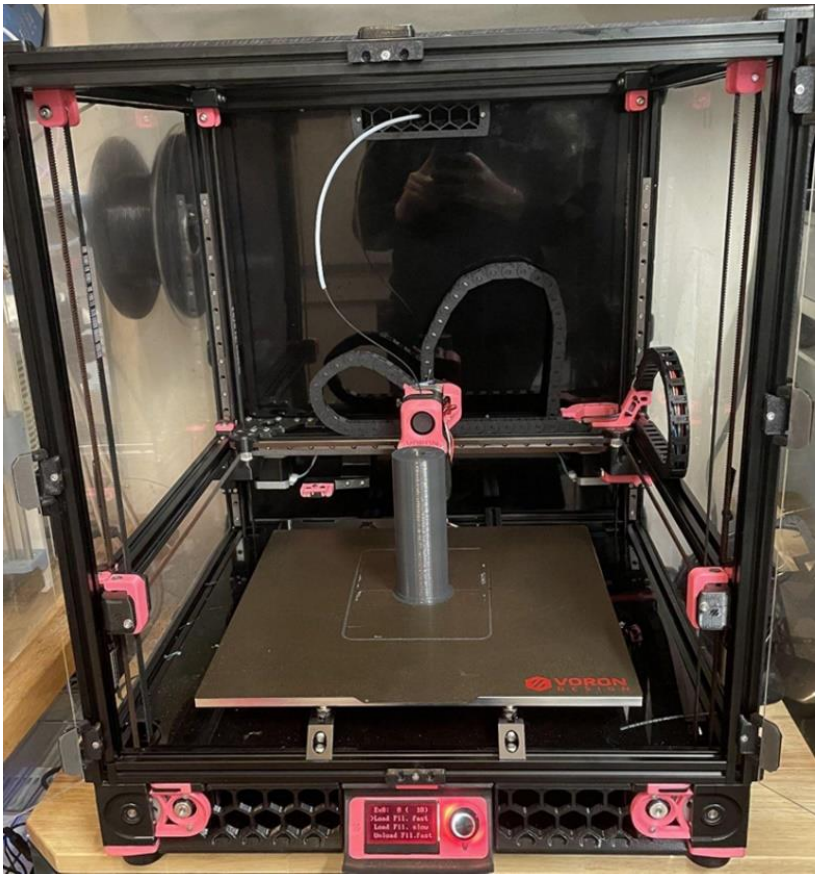

Figure 6 – ABS Fuel Grain Fabrication (3-D Printing)

<u>Rocket Nozzle Development:</u>

For the initial material testing activities related to the Concept Hybrid Rocket Demonstrator (CHRD), the exhaust nozzle, and particularly its durability characteristics, were the key point of interest in the study. The baseline nozzle used in rocket development activities was machined using conventual methods from a solid graphite bar. Subsequent test articles were produced using Carbon-based Additive Manufacturing (CBAM) techniques. Students were involved in both the development and fabrication of both types of nozzles working at the Miller Advanced Research and Solutions Center (MARS) supporting their engineering and manufacturing. A photograph of a completed graphite and CBAM nozzle are presented in **Figure 7**.

Figure 7 – Graphite (Left) and CBAM (Right) Exhaust Nozzle Test Articles

Numerous tests of the CBAM type nozzle were conducted during rocket development activities. Of particular interest was the nozzle degradation characteristics when exposed to the very high temperatures and mass flow exiting the rocket combustion chamber. Nozzle throat erosion rates were categorized and compared post-test.

Rocket Motor Instrumentation and Control System Development:

In its original incarnation as a student senior project, the Concept Hybrid Rocket Demonstrator (CHRD) had minimal instrumentation present. Instrumentation active during a typical test included only a thrust measurement generated by the load cell attached to the rocket motor. Various attempts had been made over its various design iterations to capture combustion chamber temperature, pressure, as well as oxidizer flow rates. However, repeatable and reliable measurements were not accomplished on a regular basis, and the development of this functionality was very much a work in progress.

Once the CHRD was allocated as a testbed by MARS for high-temperature materials testing, a concerted effort was planned to evolve and develop the instrumentation and control capabilities of the system. Additional funding of the project allowed a dedicated student-based research team to be hired. This funding also provided for the purchase of more sophisticated hardware and electronics used to refine the overall instrumentation and control capabilities of the rocket motor.

The planned materials testing requirements include a specification for two basic modes of rocket motor operation. The first mode of operation specifies holding the rocket combustion chamber pressure constant by varying oxidizer mass flow during a test firing. The second mode of operation specifies holding the oxidizer mass flow rate constant during a test firing. To accomplish these operational modes, a system for measuring rocket combustion chamber pressure and oxidizer mass flow rate in conjunction with integration of an automatic throttle (flow control system) is required. The student team assigned to the rocket development effort assisted in the conceptual design, detail design, construction, and testing of these system elements.

The chamber pressure measuring system was designed with a capillary line to isolate the sensors (thermocouple and pressure transducer) away from the extremely hot gas (greater than 4000 degrees Fahrenheit) generated during the fuel combustion process. The pressure transducer monitors rocket chamber pressure during motor operation. Motor operation is terminated prior to the mixing and migration of hot gasses up the capillary line sparing the transducer damage due to excessive temperature. Note that the associated thermocouple is not intended to measure chamber temperature, it is added as a safeguard to monitor temperature of the gas near the pressure transducer. Following evaluations during several rocket tests, the combustion chamber pressure measurement system was found to perform as designed. A photo of the capillary chamber pressure measurement system is presented in **Figure 8**.

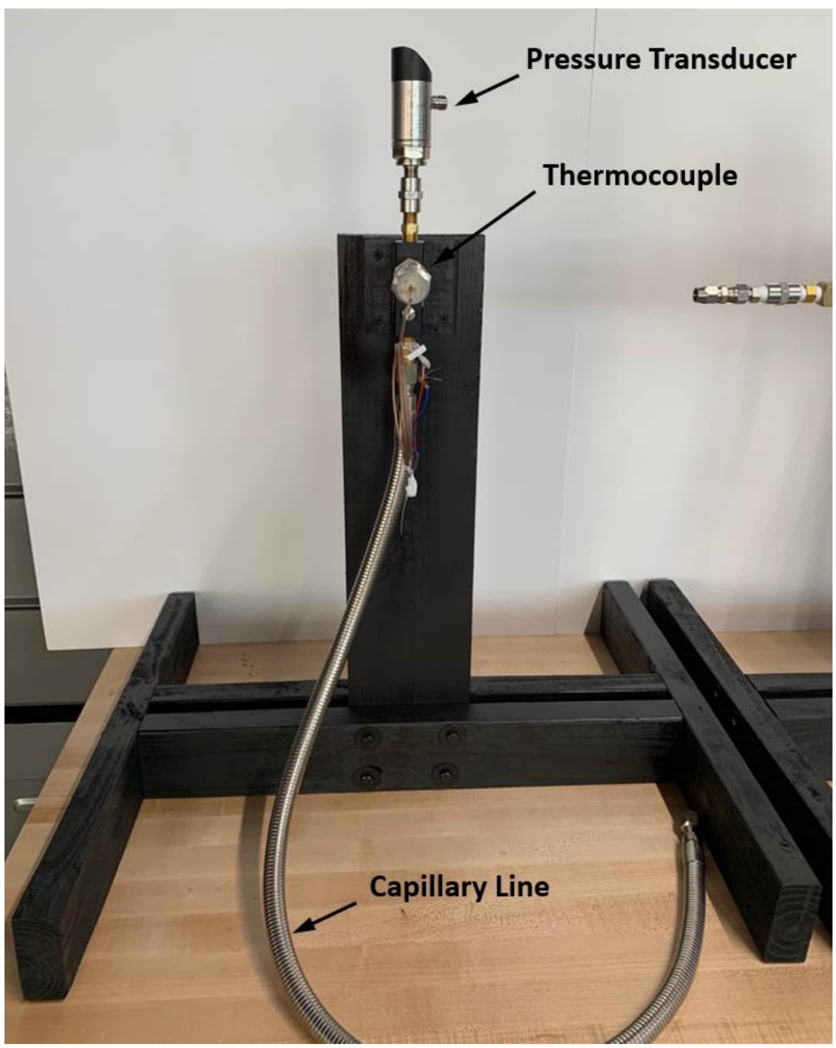

Figure 8 – Capillary Combustion Chamber Pressure Measurement System

An upgraded system that measures oxidizer flow has been implemented and is undergoing continued development. The current configuration of the oxidizer flow measuring system, including the pressure transducer, thermocouple and integrated flow rate sensor are presented in **Figure 9**.

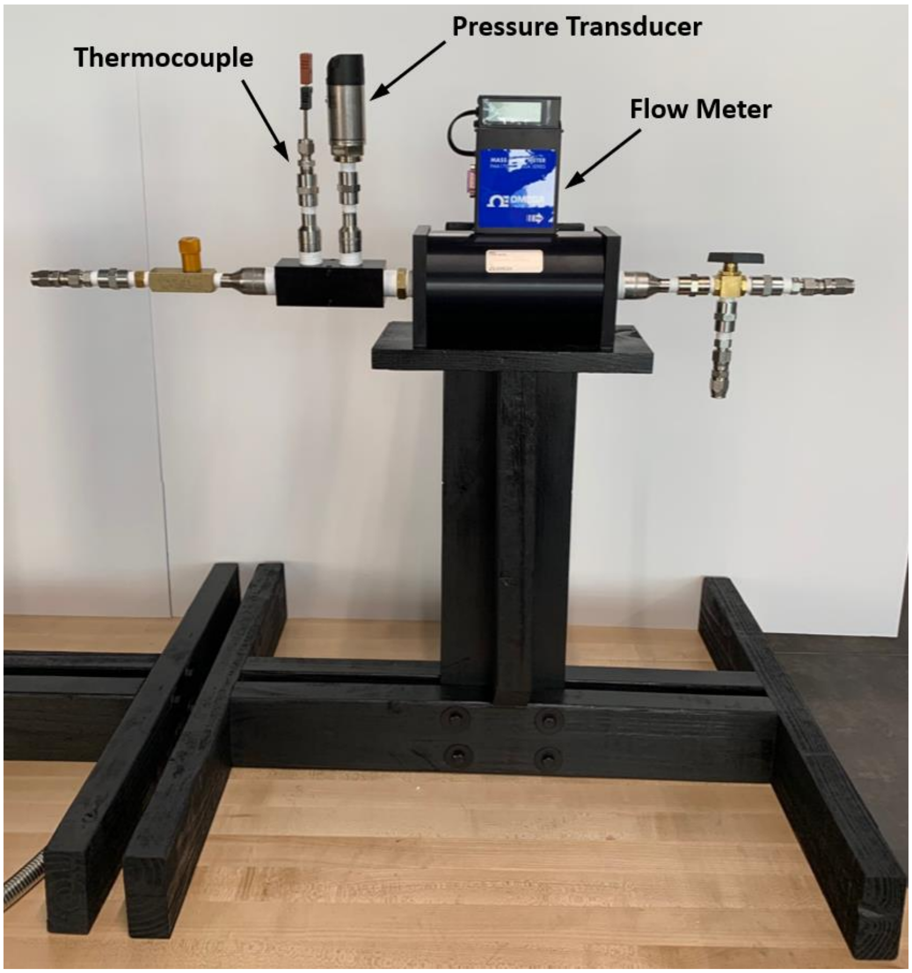

Figure 9 - Oxidizer Flow Measurement System

All of the signals generated by the rocket system instrumentation are collected using Emerson / National Instruments (NI) Data Acquisition (DAQ) hardware. Instrumentation signals are processed and interpreted using Laboratory Virtual Instrument Engineering Workbench (LabVIEW) software also supplied by NI. Programs were written by students to record the signal received from the various instruments monitoring the rocket motor.

The current oxidizer system design, as well as a required feedback control system to throttle oxidizer flow, is currently in development and testing. Faculty advisors and student research assistants have been refining designs with the objective of providing a reliable and repeatable control loop to generate stated operational characteristics. There are currently two throttling devices under consideration. Preliminary designs of these systems include a servo motor driven ball valve **[2][3]**. This design would utilize Commercial Off-the-Shelf (COTS) components as well as custom fabricated elements, specifically the gearing and a machine frame. An assembly view of the current Computer-Aided Design (CAD) model is presented in **Figure 10**.

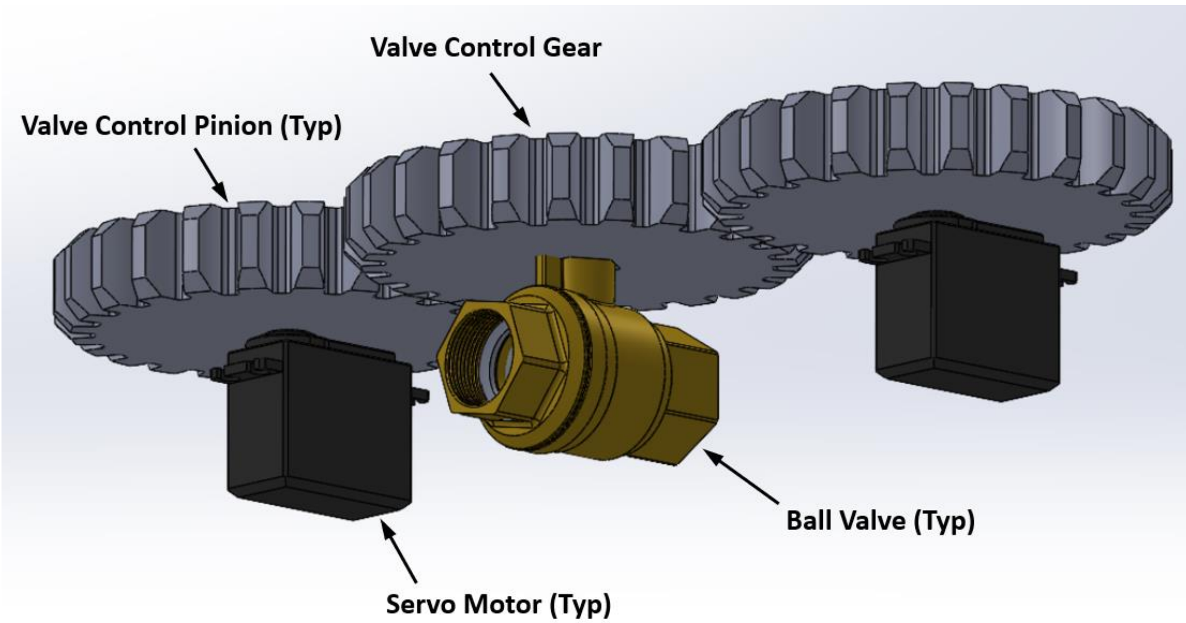

Figure 10 - Servo Ball Valve Flow Control Valve (Preliminary)

The second flow control device under consideration is a multi-port solenoid digital flow control valve **[2][3]**. This design also utilized COTS components in its configuration. A partial assembly view of the digital control is presented in **Figure 11**.

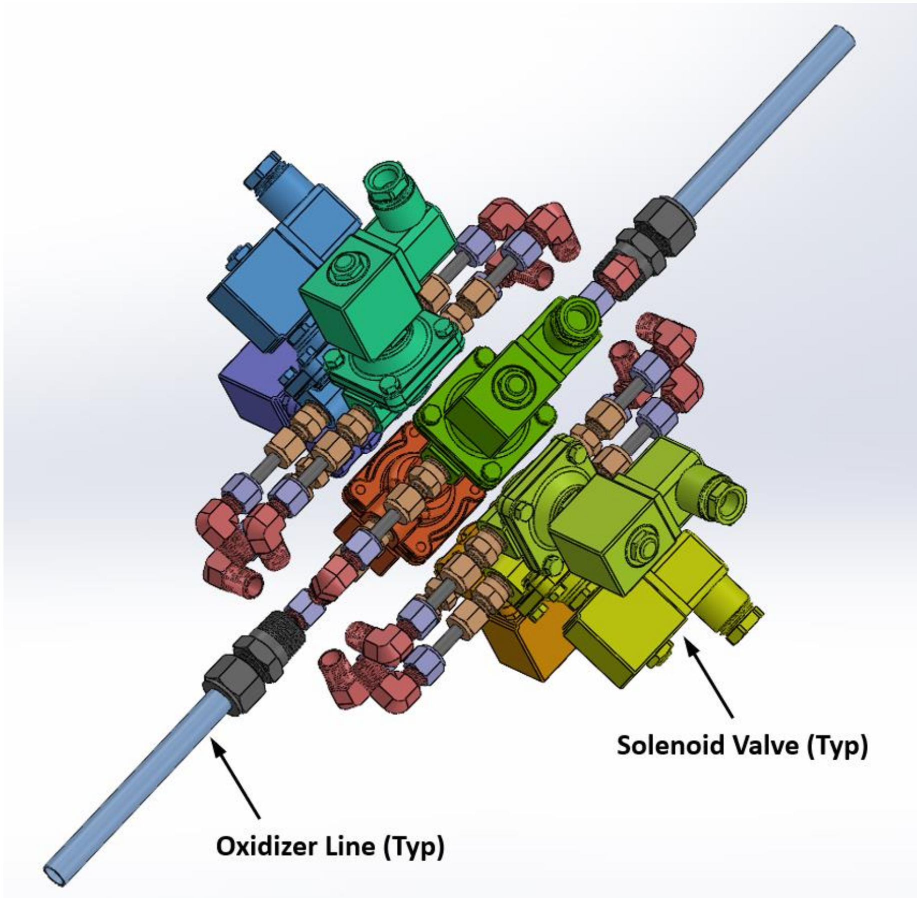

Figure 11 - Multi-Port Solenoid Digital Flow Control

In addition to the flow control system, an improved mass flow measurement system is also under consideration. An orifice plate mass flow measurement system is being designed that will expand the range of measurement for oxidizer flow **[4]**. A cut-away view of the CAD model is presented in **Figure 12**.

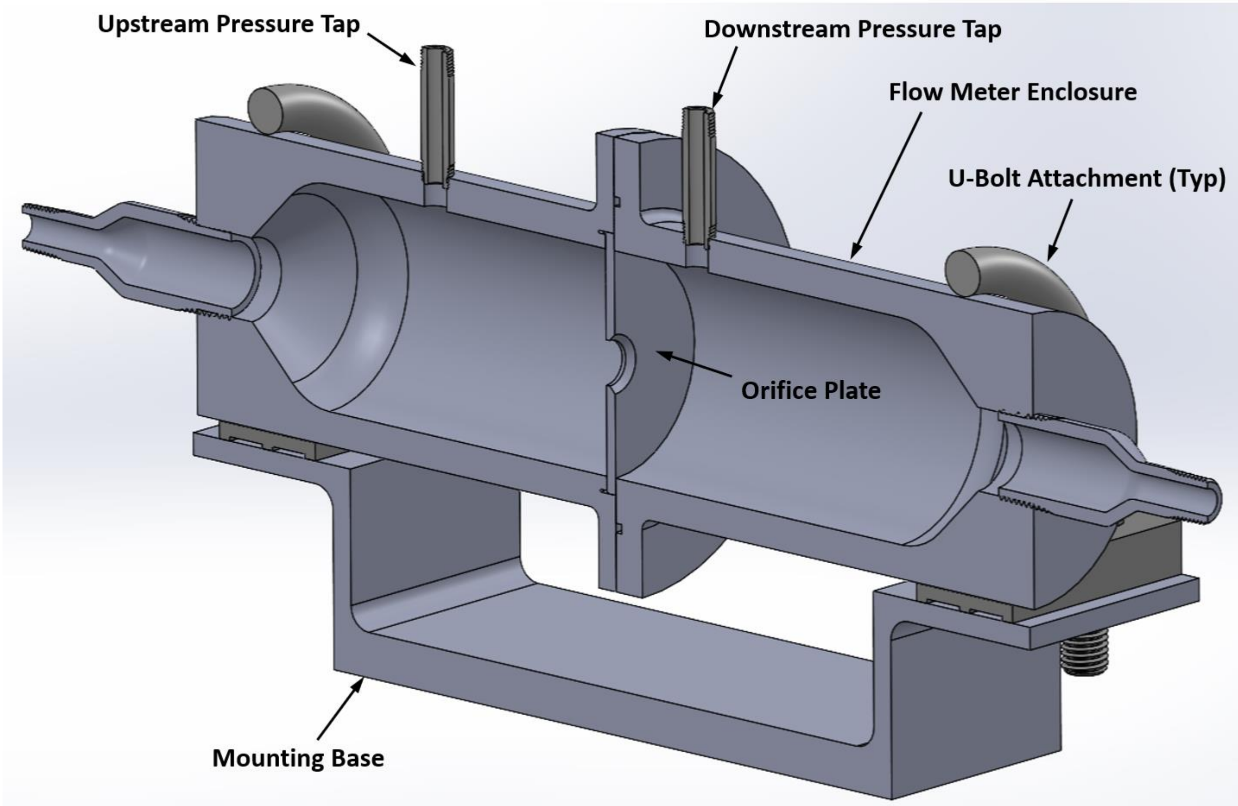

Figure 12 - Orifice Plate Flow Meter

Rocket Assembly and Test Engineering Support:

Throughout the spring and summer of 2023, the student research team assisted in the fabrication of the required test articles and other consumables used in the Concept Hybrid Rocket Demonstrator (CHRD) system. This included the rocket motor fuel grains and rocket nozzles. They were also responsible to help coordinate project management and supply chain activities such as procuring various vendor supplied components and materials, including rocket ignitors and the supply of compressed Nitrous Oxide and Oxygen used for testing.

To perform a static firing of the CHRD system, the student team was responsible for assembling the rocket motor system and performing readiness checks prior to beginning the test interval. These checks would include continuity checks of associate electrical systems, oxidizer system, instrumentation and data collection system readiness. Additionally, the students would locate and assemble the rocket testbed system at the designated outdoor test location, and assist in its operation during a test. Photographs of the student team assembling a rocket prior to test as well as the testbed system setup are presented in **Figure 13** and **Figure 14**.

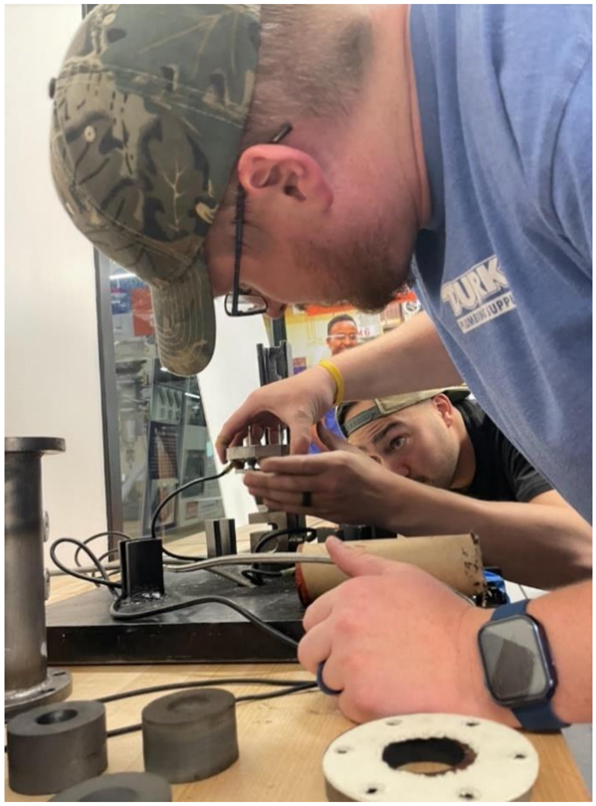

Figure 13 - Rocket Motor Build Being Performed by Student Research Assistants

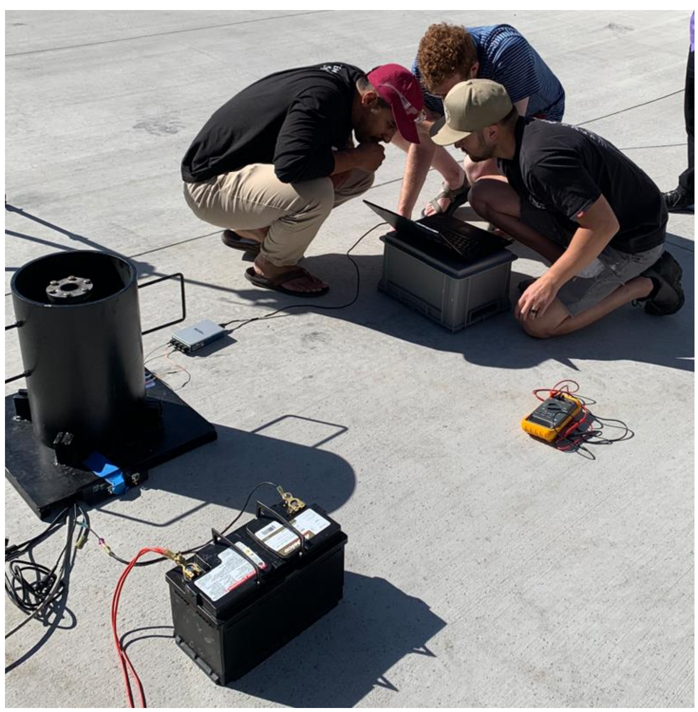

Figure 14 - CHRD System Setup and Configuration Performed by Student Research Assistants

During the first phase of the project over the summer of 2023, the team performed a static firing of the rocket motor approximately every two weeks to evaluate the rapid prototyped nozzle material characteristics as well as evaluate rocket system performance and development. Over time, as the learning curve progressed, the students were capable of assembling a test ready CHRD system quickly and efficiently which allowed for a higher volume of tests to be performed in a given test interval.

Post Test Materials Evaluation:

Following each rocket firing, the rocket nozzle was extracted from the housing and its post-test condition was examined using various methods. These techniques included:

- Visual inspection of the component.
- Scanning Electron Microscopy (SEM).
- Inspection under high magnification (Keyence Digital Microscope)

A photograph of a sectioned post-test nozzle is presented in **Figure *15***.

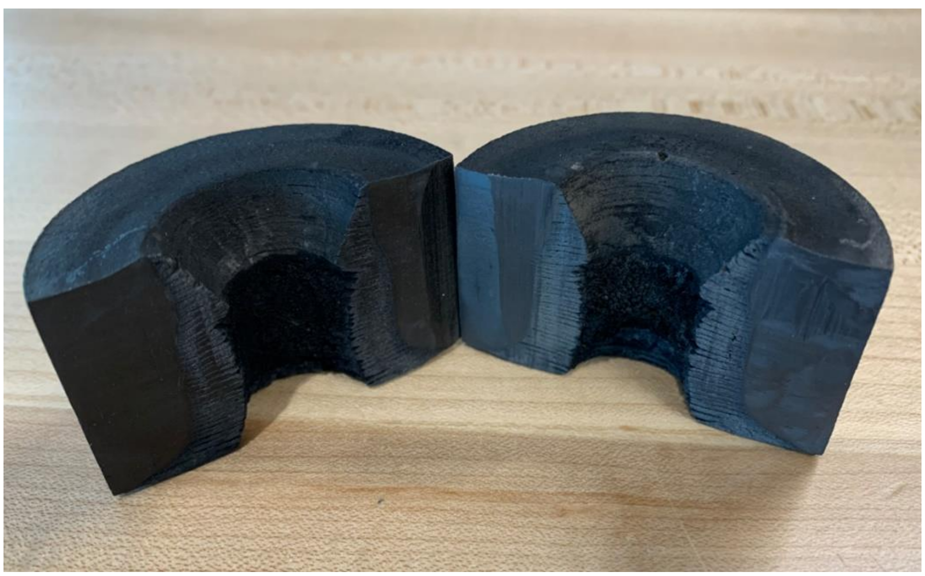

Figure 15 – Post Test CBAM Nozzle (Sectioned)

Evident in the photograph of the sectioned post-test nozzle is the throat erosion, char, and heat affected zone including evidence of partial delamination of fabrication layers.

A SEM image of a post-test nozzle is presented in **Figure *16***.

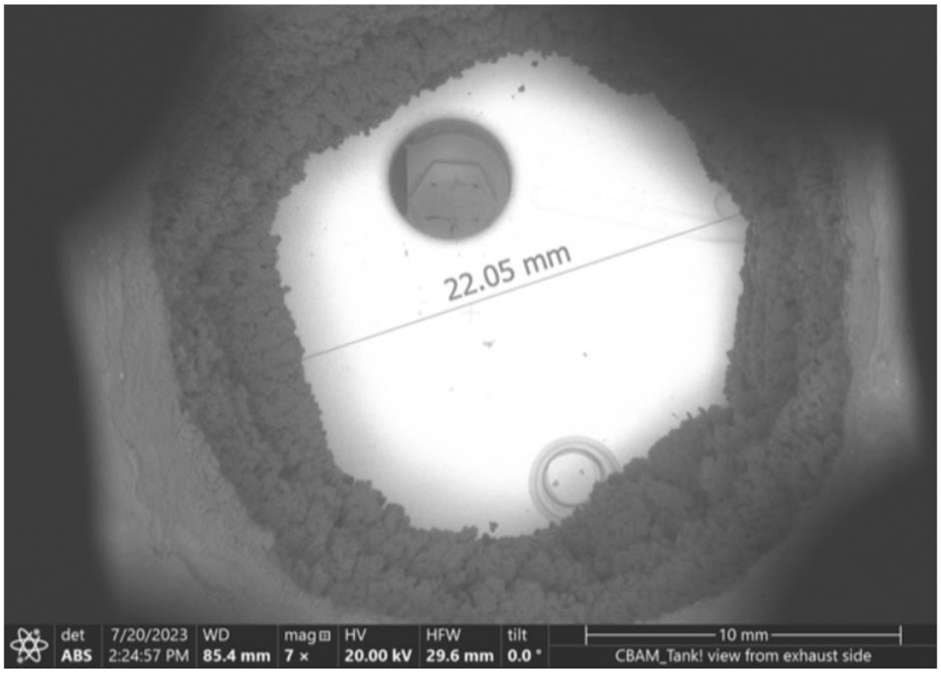

Figure 16 - Post Test CBAM Nozzle Throat (SEM Image)

Visible in the SEM image is the charred remnants of the CBAM material and ABS fuel residue at the nozzle throat.

The student research assistants were also utilized in these subsequent materials evaluations. They assisted by helping prepare the specimens for examination and assisting in the inspection process. They were trained in the basics of using the various inspection technologies.

As noted, the goal of the testing program is to evaluate and categorize the various high-temperature materials. Identification of materials exhibiting the highest temperature tolerance (minimal thermal damage) is the main priority of the test activities. In the future, other material types are being considered for evaluation. Additionally, impingement testing of materials external to the rocket but located within direct influence of the exhaust plume are being considered for application of the Concept Hybrid Rocket Demonstrator (CHRD) system.

Rocket Performance Analysis:

Several engineering activities have also been undertaken to provide predictive insight into rocket motor behavior without requiring an actual rocket test. A student created and maintained analytical model of the rocket has been developed and iteratively enhanced for use in fundamental rocket sizing and performance prediction. Basic operational characteristics are input into the model, and resulting output parameters are calculated. Inputs include:

- Oxidizer mass flow rate.
- Oxidizer thermodynamic properties.
- Solid Fuel port geometry.
- Solid Fuel mass properties.
- Exhaust nozzle area ratio.
- Atmospheric back pressure.

Resulting outputs include:

- Combustion products overall mass flow rate.
- Solid Fuel regression rate.
- Exit flow Mach Number.
- Rocket thrust.
- Rocket specific impulse.

For added insight into the overall durability of the materials of construction as well as the thermal characteristics of the nozzle test articles, a transient thermal Finite Element Analysis (FEA) simulation of the rocket test cycle has been developed using SolidWorks Simulation. The FEA simulation performs a time-step iteration of an entire test firing of the rocket and predicts component temperatures throughout the duration of the event. As empirical data are collected from actual rocket tests, boundary condition values in the FEA are adjusted, such that simulation results converge to match test results. Eventually, as alignment between the model and actual rocket performance are correlated, the FEA model may possibly be used to establish material performance predictions for certain types of materials without the requirement of an actual rocket test. A contour plot showing the final timestep in a test firing simulation by the FEA is presented in **Figure *17***.

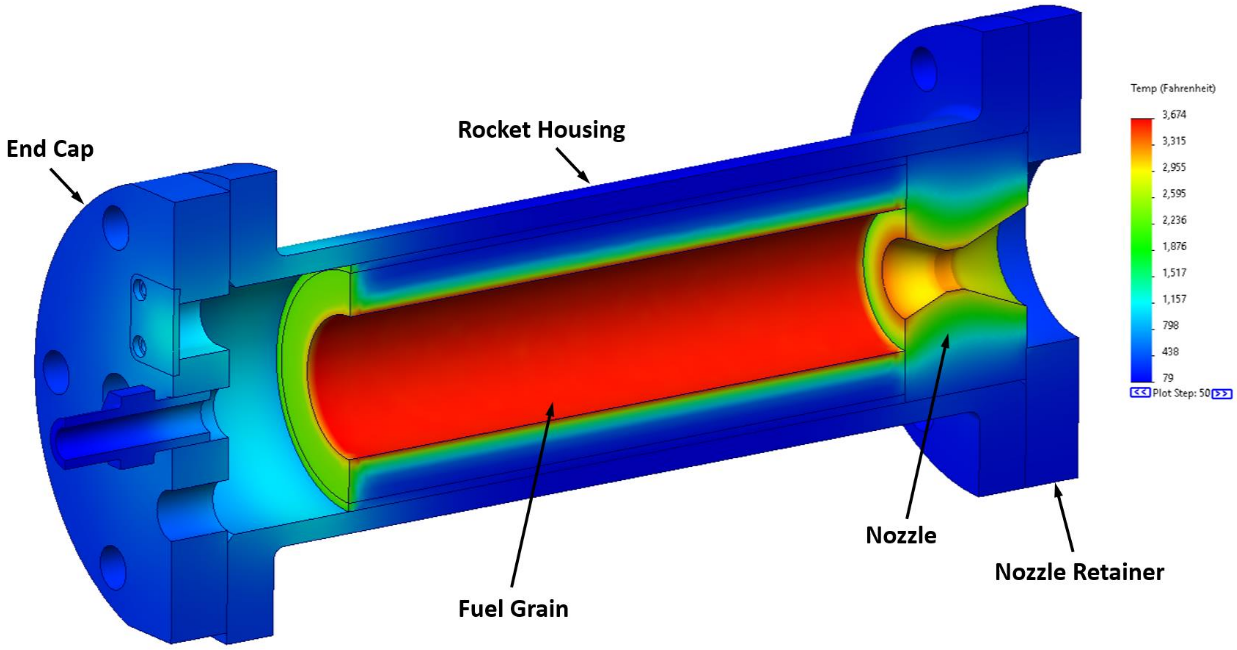

Figure 17 - CHRD Assembly Transient Thermal FEA (Final Time Step)

Future engineering activities are also being proposed to model the rocket combustion process and resulting exhaust flow using Computational Fluid Dynamics (CFD) codes to better understand fundamental combustion chemical reactions and fluid mechanics characteristics during rocket operation. These CFD results will also likely have application in better aligning the FEA simulation using a coupled-field approach to establishing system boundary conditions. The initial CFD activities are planned as a collaborative approach with a neighboring university. Further development of the resulting analytical approaches and simulation models will eventually become the responsibility of Weber State University (WSU) faculty advisors and student research assistants.

9.0 SYSTEM SAFETY CONSIDERATIONS

Due to the pressurized rocket housing, oxidizer system, and very high-temperature energy release during a test firing, safety is paramount in the design and operational procedures related to the testbed. The students working with the system are relatively inexperienced working with a rocket motor system and the potential for mishap is certainly not nonexistent. Thus, a detailed safety plan related to rocket design and test activities has been developed.

As noted, the Concept Hybrid Rocket Demonstrator (CHRD) operates using cast Hydroxyl Terminated Polybutadiene (HTPB) or 3-D printed Acrylonitrile Butadiene Styrene (ABS) as the solid fuel grain, and Nitrous Oxide (N_2O) or Gaseous Oxygen (GOX – O_2) as the oxidizer **[1]**. Both the HTPB and ABS fuel types are not inherently reactive or energetic individually. Both of the fuel types and oxidizers are reasonably non-toxic. They are not sensitive to moisture, shock loading, electrical discharges, minor temperature changes, or other environmental conditions, thus rendering the rocket materials safe for storage, transport, and handling. The typically safer nature of these types of rocket fuel and oxidizer make the hybrid rocket approach attractive for student involvement in an undergraduate project environment.

Further oxidizer safety analysis indicates that, lacking a sustained high-temperature ignition source of over 1,000 degrees Fahrenheit, exothermic Nitrous Oxide decomposition will not occur, and a sustained reaction cannot be achieved. To further safeguard the system, the oxidizer tank is never close-coupled to the rocket motor housing. Typically, the oxidizer tank is located 20 to 30 feet away during a test. During hybrid rocket operation, If the oxidizer flow is suspended following ignition, the reaction will cease, and the combustion is terminated almost immediately and the energy release ceases.

Beginning in the fall of 2023, GOX was added as a suitable oxidizer type due to cost and availability. Using GOX will eliminate the decomposition risk for the oxidizer, however, oxygen does increase flammability concerns at room temperature. This is recognized, and precautions in the storage and handling have been implemented accordingly for all rocket test activities.

The CHRD was designed as a ground-based static test device. The motor was not sized or designed for flight in any type of vehicle. As such, the rocket housing was designed with a significant Factor of Safety (FS). Any FS in excess of 1.0 indicates that there is structural margin relative to the predicted burst pressure of the housing. As the rocket motor is firing, the internal pressure of the housing increases due to the combustion of fuel in the presence of the oxidizer. Per the analytical model developed to predict motor performance, the maximum possible chamber pressure, assuming the oxidizer is flowing at its peak rate, is approximately 400 psia. Note that the rocket typically operates at pressures at or less than 200 psi based on operational experience.

A Finite Element Analysis (FEA) was performed on the primary structural elements associated with the rocket motor housing. These components include:

- Cylindrical Housing
- Oxidizer End Cap
- End Cap Strain Gauge Plate
- Nozzle Retainer

The Cylindrical Housing is a pressure vessel with flanges welded to each end. The Oxidizer End Cap and Nozzle Retainer attach to the Cylindrical Housing to seal the housing during rocket operation. Assuming a maximum operating pressure of 400 psia, the peak stress in the cylinder wall is predicted to be no greater than 2,791 psi. It is important to note that the target operating pressure of the rocket housing was approximately 200 psi, so a design factor of approximately 2 based on loading was established in the analysis. Assuming a minimum material yield strength of 36,000 psi, the resulting factor of safety for this component is determined to be greater than 12. The Von-Mises stress contour plot associated with this analysis is presented below in **Figure 18**.

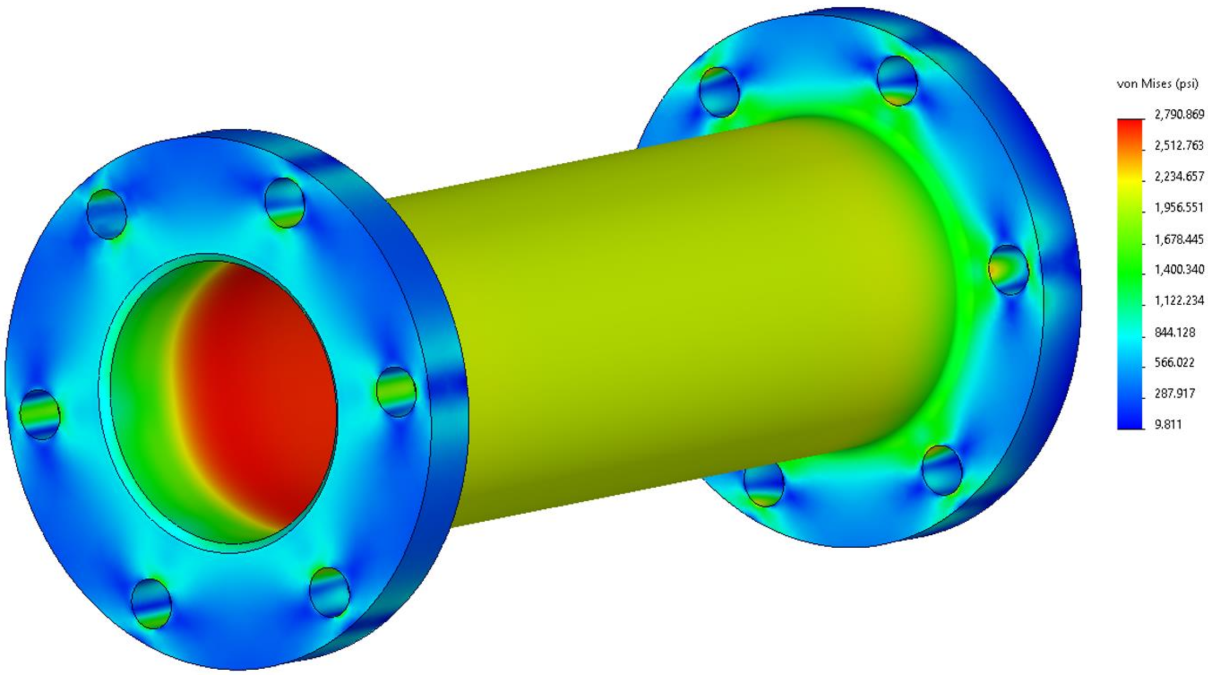

Figure 18 – Rocket Housing Finite Element Analysis (FEA) Von-Mises Stress Result (High Pressure Operation)

The Oxidizer End Cap includes ports for the oxidizer delivery line, glow plug igniter, chamber pressure tap, and a strain gauge mounting plate. The Oxidizer End Cap is connected to the Cylindrical Housing via 6 threaded fasteners. Assuming a maximum operating pressure of 400 psia, the peak stress in the Oxidizer End Cap is predicted to be no greater than 5,618 psi. However, this stress is highly concentrated in a port bore. The average bulk stress present in the cap is approximately 3,400 psi. Assuming a minimum material yield strength of 36,000 psi, the resulting factor of safety for this component is determined to be between 6 and 10. The Von-Mises stress contour plot associated with this analysis is presented below in **Figure 19**.

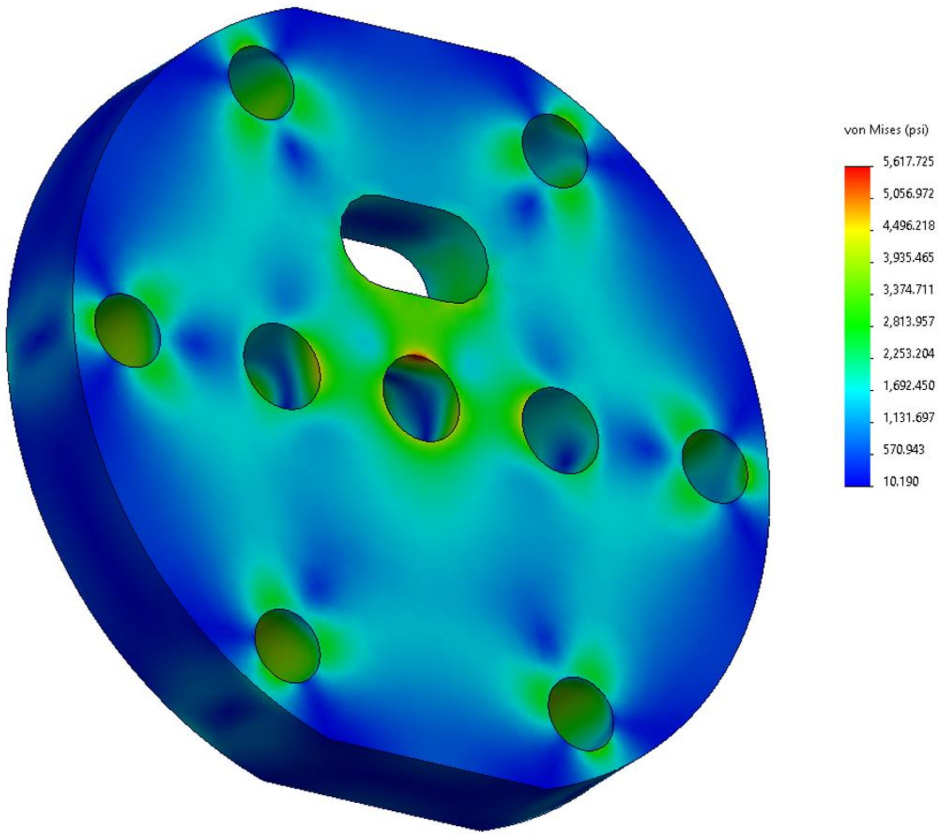

Figure 19 – Oxidizer End Cap Finite Element Analysis (FEA) Von-Mises Stress Result (High Pressure Operation)

The Nozzle Retainer constrains the exhaust nozzle within the Cylindrical Housing. The Nozzle Retainer is connected to the Cylindrical Housing via six (6) threaded fasteners. Assuming a maximum operating pressure of 400 psia, the peak stress in the Nozzle Retainer is predicted to be no greater than 5,568 psi. If the concentrated stress in the bolt holes is disregarded, the predicted stress is approximately 2,500 psi. Assuming a minimum material yield strength of 36,000 psi, the resulting factor of safety for this component is determined to be between 6 and 14. The Von-Mises stress contour plot associated with this analysis is presented below in **Figure 20**.

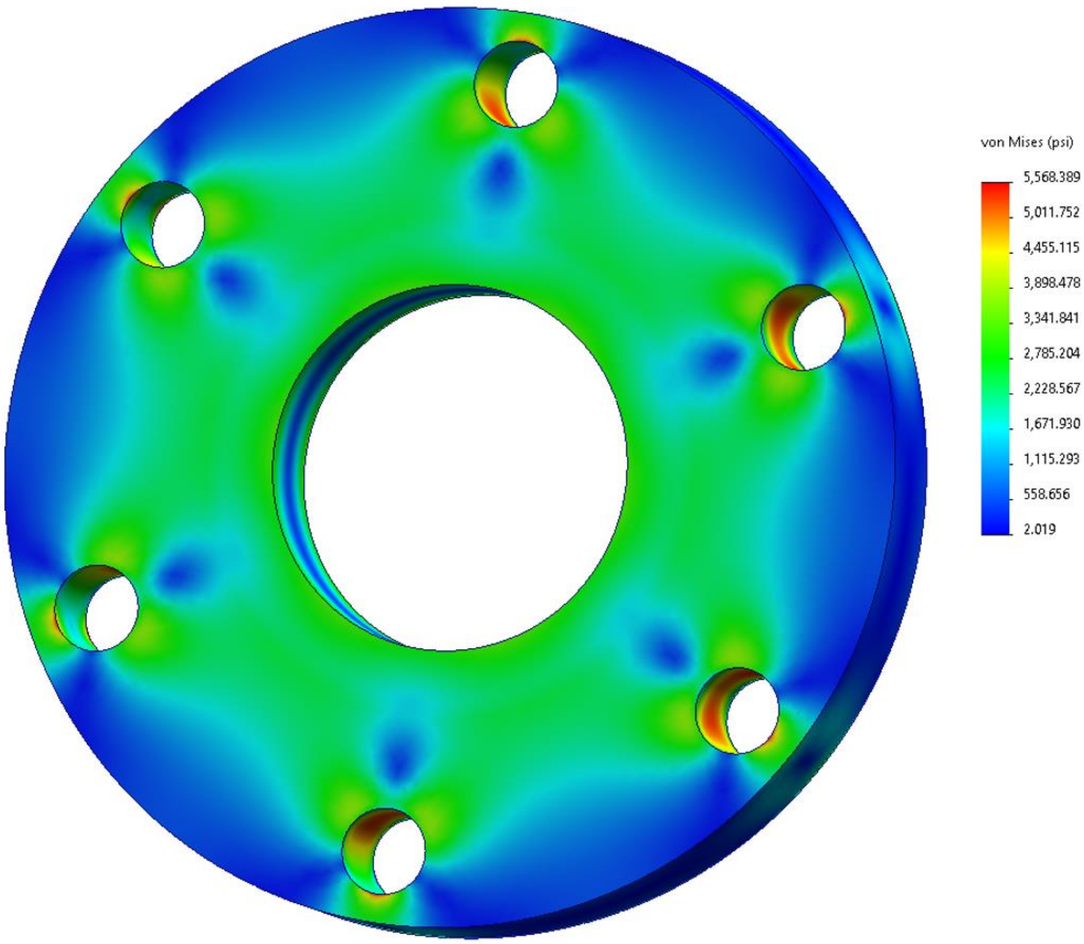

Figure 20 - Nozzle Retainer Finite Element Analysis (FEA) Von-Mises Stress Result (High Pressure Operation)

Oxidizer system components (fittings, gauges, valves, flowmeters, thermocouples, etc.) are all rated for pressures at, or in excess of those predicted during standard rocket operations. All hoses are of a braided stainless steel construction and rated for operational pressures greater than those predicted during rocket operation. The capillary line used for combustion chamber pressure measurements is rated in excess of the operational pressures and temperatures anticipated during rocket operation.

A cylindrical steel containment shield with a wall thickness of 0.375 inches is placed around the rocket housing during operation for an added level of safety. In the event the rocket housing experiences a structural failure during operation and a fragment or fragments are released, the containment shield is designed to contain the fragment(s), reducing the risk of damage or injury. The containment shield in place on the test stand is illustrated above in **Figure 4**.

A fundamental safety feature, inherent to the design, is that the rocket motor thrusts downward during operation. This is to ensure that if it were to become uncoupled from the test stand, the rocket will not become kinetic in an upward or sideways direction, thus posing a potential hazard to its surroundings. A schematic of this inverted thrust direction is presented below in **Figure 21**.

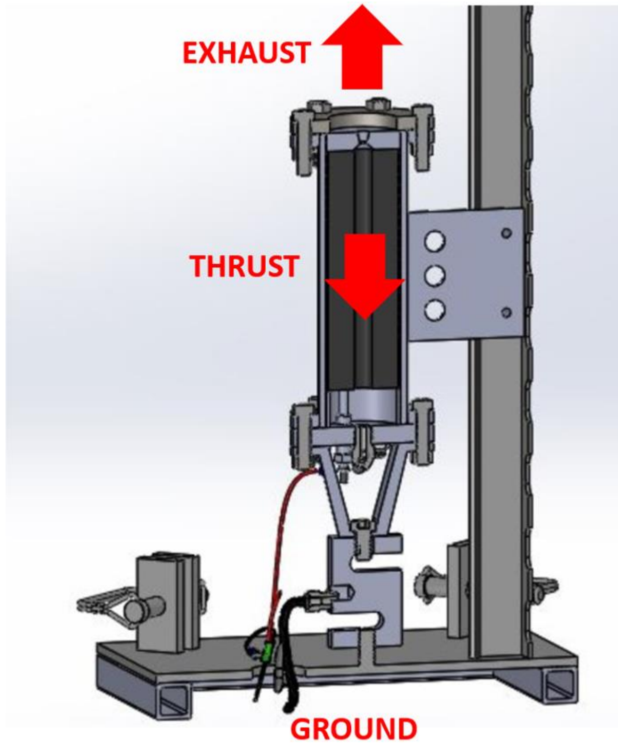

Figure 21 – Rocket Thrust Vector Diagram

Additionally, several safety countermeasures are employed during rocket operations. These include:

- During every test firing, a team member is assigned as the "fire watch". They have a fire extinguisher in hand and are prepared to address any unexpected fires that may result from the testing activities.
- All non-participating spectators are required to stand at least 30 feet from the rocket test. They must personally ensure that they have no line of sight to the rocket housing and can only see the containment shield in their field of vision.
- The rocket is only test fired out of doors.
- During a test firing, the rocket is placed at least 20 feet laterally from any other objects (buildings, vehicles, etc.)
- During a test firing, the rocket must have no obstacles vertically above it at any height. There must be no foliage, structures, etc. above it during a test.
- Following a test, the rocket is not to be touched or handled for at least 30 minutes to allow it to cool to levels that will not cause burns when touched.

Additionally, all hybrid rocket team participants and spectators must use Personal Protective Equipment (PPE) during rocket operations. These include:

- Hearing protection. Either in-ear or over-ear earplugs or earmuffs.

- Vision protection. Shatter proof safety glasses. Preferably, these will be tinted to reduce the light intensity of the rocket plume during rocket firing.
- Heat resistant gloves.

10.0 CONCLUSIONS

The Concept Hybrid Rocket Demonstrator (CHRD) and High-Temperature Materials Testing activities conducted through the summer of 2023 were deemed a success by faculty, students, and project partners alike. Student engagement in the engineering, manufacturing, testing, and evaluation, gave them a broader perspective in the areas of aerospace propulsion systems, high-temperature materials design and fabrication, instrumentation and control system design, experimentation, process control, and test engineering. As detailed in the Student Outcomes section above, the experiences of the students appear to be very positive, with many gaining a desire to explore future career opportunities in the aerospace arena. The project also gained exposure in several press releases, furthering local and national interest in the project, and its potential to assist various companies with their high-temperature materials qualifications **[5][6][7]**.

Building on the success of this initial phase of using the CHRD system to perform high temperature materials research, indefinite funding for further system development has been approved by Weber State University (WSU) and the Miller Advanced Research and Solutions Center (MARS) leadership. The goal of the follow-on development is to further mature the system into a materials testbed that is reliable and repeatable enough to generate publishable data for future publications as well as support possible research contracts for materials qualification in the aerospace industry at large. Project enhancements and other project updates under consideration for future development included:

- Rigorous process control repeatability and reproducibility (R&R) studies to quantify overall system accuracy and performance to specification requirements.
- Development of an experimental apparatus for external materials testing through plume impingement.
- Increased involvement of industry partners and stakeholders.
- Rocket motor control modes to support alternate operational characteristics (variable thrust, chamber pressure, and oxidizer flow profiles, constant oxidative potential of the fuel grain, etc.)
- Integration of the research program into future graduate studies programs being proposed at WSU.

11.0 REFERENCES

1. D. Birch. *Development of a Concept Hybrid Rocket Demonstrator*, ASEE Annual Conference, 2022

2. S.A. Whitmore, Z.W. Peterson, S.D. Eilers, *Closed-Loop Precision Throttling of a Hybrid Rocket Motor*, Journal of Propulsion and Power, 2014
3. T.J. Velthuysen, Closed-Loop Throttle Control of a Hybrid Rocket Motor, M.S. Thesis, University of KwaZulu-Natal, 2018
4. F.M. White, Fluid Mechanics, 7th Ed, McGraw-Hill, 2010
5. M. Tullis, *Weber State's MARS Center Hosts US Space Command*, https://www.techbuzz.news/u-s-space-command-visits-weber-state-s-mars-center
6. G. Nehls, *Weber State Students Showcase Composite Rocket Nozzle Studies*, https://www.compositesworld.com/news/weber-state-students-showcase-composite-rocket-nozzle-studies
7. B. Magana, *U.S. Space Command Gets Taste of Weber State's Role in Aerospace Innovation*, https://www.weber.edu/WSUToday/062823-MARS-aerospace-innovation.html?_gl=1*85tz4g*_ga*MTgzNTQ2OTcyNy4xNjU4NjE2MDM2*_ga_NBZY81HSZM*MTY4Nzk4NTUyMi4zMjMuMS4xNjg3OTg2OTA4LjAuMC4w