

**IGNITION METHODS AND INITIATION STRATEGIES IN ROTATING
DETONATION ENGINES AT THE UNIVERSITY OF WASHINGTON**

Andrew Takacs

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science
in Aeronautics and Astronautics

University of Washington
2026

Supervisory Committee:
Carl Knowlen, Chair
Robert Breidenthal

Program Authorized to Offer Degree:
Department of Aeronautics and Astronautics

©Copyright 2026
Andrew Takacs

University of Washington

Abstract

**Ignition Methods and Initiation Strategies in Rotating Detonation Engines
at the University of Washington**

Andrew Takacs

Chair of the Supervisory Committee:
Carl Knowlen
Department of Aeronautics and Astronautics

Rotating detonation rocket engines (RDREs) have attracted sustained research interest for their potentially high thrust-to-weight ratio, compact size, and pressure-gain combustion. Successful operation of an RDRE depends on a detonation wave initiated inside the annulus. This thesis compiles a record of the experiments carried out at the University of Washington RDRE Laboratory across five engine scales: 6-inch, 3-inch, 2-inch, 1-inch, and 10 mm spanning different ignition sources such as single-spark, multi-plug wave generator, and pre-detonator tube initiation. For each engine scale, the ignition hardware and resulting initiation behavior are documented to establish reliability of RDRE ignition.

TABLE OF CONTENTS

Chapter 1: Introduction	1
1.1: Background and Motivation	1
1.2: Literature Review	3
1.2.1: Detonation Fundamentals	3
1.2.2: Ignition and Startup Transients	5
1.2.3: UW RDRE Ignition Approaches	5
1.2.4: RDRE Ignition Approaches Used Elsewhere	6
1.2.5: Ignition Studies	7
Chapter 2: Background and Methods	10
2.1: UW RDRE Laboratory	10
2.1.1: Gases	11
2.1.2: Backpressure and the Dump Tank	12
2.1.3: High-Speed Imaging	12
2.1.4: Flow Metering	13
2.2: Ignition Hardware	14
2.2.1: Wave Generator (Phased Multiple Spark)	14
2.2.2: Single-Spark Ignition	15
2.2.3: Pre-detonator Tube	15
2.3: Engine Hardware	16
2.3.1: 6-inch (154 mm) Engine	16
2.3.2: 3-inch (76 mm) Engine	18
2.3.3: 2-inch (51 mm) Engine	20
2.3.4: 1-inch (25 mm) Engine	21
2.3.5: 10-mm Engine	22
2.4: Data Sources	23
Chapter 3: Results: Historical Record of Ignition Experiments	24
3.1: 6-inch (154 mm) Engine	24
3.1.1: Wave Generator	24
3.1.2: Hydrogen-Oxygen Results	24
3.1.3: Methane-Oxygen Results and the Camera Campaign	24
3.2: 3-inch (76 mm) Engine	25
3.2.1: Startup Transient	25
3.2.2: Ignition Reliability and Failure Attribution	26

3.2.3: Operating Envelope	27
3.2.4: Steady State Operations	28
3.3: 2-inch Engine (51 mm)	29
3.3.1: Single-Spark Configurations	29
3.3.2: Pre-detonator	30
3.3.3: Results	31
3.4: 1-inch (25 mm) Engine	32
3.5: 10-mm Engine	36
3.5.1: Pre-detonator Performance with and without Cores	36
3.5.2: Cross-Geometry Reorientation: Spark Opposite Oxidizer	37
3.5.3: Spark-Location Effects on Plug Life	37
3.6: Cross-Cutting Findings	37
3.6.1: Operating Conditions as the Governing Parameters	37
3.6.2: Cross-Geometry Pre-detonator Reliability	38
Chapter 4: Discussion and Conclusion	39
4.1: Implications for Future RDRE Design	39
4.2: Recommendations for Future Work	39
4.3: Conclusion	40
Chapter 5: Bibliography	42

LIST OF FIGURES

Figure 1: Pressure-Volume Diagram Brayton vs. Humphrey Cycle	1
Figure 2: Pulse Detonation Engine.....	2
Figure 3: Rotating Detonation Rocket Engine	3
Figure 4: UW RDRE Ignition History	6
Figure 5: Current UW RDRE Laboratory	10
Figure 6: UW RDRE Propellant Diagram.....	11
Figure 7: Pre-detonator Flow Control System Diagram	15
Figure 8: 6-inch Engine (154 mm).....	16
Figure 9: 3-inch Engine (76 mm).....	18
Figure 10: 2-inch Engine (51 mm).....	20
Figure 11: 1-inch Engine (25 mm).....	21
Figure 12: 1-inch Engine (25 mm) Cores.....	21
Figure 13: 10 mm Engine CAD Cross Section	22
Figure 14: Ignition Methods Compared	25
Figure 15: Ignition Failure Comparison 3-inch.....	27
Figure 16: Test Matrix 3-Inch Engine	28
Figure 17: Engine 2-Inch (51 mm) All Runs.....	31
Figure 18: Run 125 Engine 2-Inch (51 mm).....	31
Figure 19: Run 120 Engine 2-Inch (51 mm).....	31
Figure 20: Run 120-121 Engine 2-Inch (51 mm).....	32
Figure 21: Engine 1-Inch (25 mm) All Runs.....	33
Figure 22: Comparison Between 1-inch Runs High-Speed Video.....	35
Figure 23: 10 mm Engine Ignition Outcomes	36

LIST OF TABLES

Table 1: Selected Ignition Approaches Reported	6
Table 2: Evolution of UW Facility	10
Table 3: 3-Inch Configurations.....	19
Table 4: 3-inch Ignition Probability	27
Table 5: 1-inch Outcome	34
Table 6: Comparison Between 1-inch Runs	34
Table 7: Comparison Between 1-inch Runs Timing	34

ACKNOWLEDGEMENTS

The data presented in this thesis were drawn from projects supported by the Air Force Office of Scientific Research and Office of Naval Research under the joint grant AFOSR FA9550-18-1-9-0076 and ONR funding document N0001417MP00398, and a 2014 Joint Center for Aerospace Technology Innovation (JCATI) grant. The high-speed camera used in this work was funded through the University of Washington Student Technology Fee.

NOMENCLATURE

Symbols

D_{CJ}	Chapman-Jouguet detonation velocity
L_{min}	minimum combustor core length for sustained detonation propagation
δ_{min}	minimum annulus gap width
λ	detonation cell size
ϕ	equivalence ratio

Abbreviations

AERB	Aerospace and Engineering Research Building
AFIT	Air Force Institute of Technology
AFRL	Air Force Research Laboratory
CAD	computer-aided design
CFN	critical flow nozzle
CJ	Chapman-Jouguet
CRDE	Cylindrical Rotating Detonation Engine
CTAP	capillary time-averaged pressure
DAQ	data acquisition
DDT	deflagration-to-detonation transition
ER	electronic regulator
FFT	fast Fourier transform
OFHC	oxygen-free high-conductivity (copper)
PDE	pulse detonation engine
PID	proportional-integral-derivative
RDRE	rotating detonation rocket engine
REFPROP	Reference Fluid Thermodynamic and Transport Properties Database (NIST)
UW	University of Washington
WG	wave generator

Chapter 1: Introduction

1.1: Background and Motivation

Most conventional rocket engines use deflagration, in which fuel and oxidizer release chemical energy and raise the gas temperature while the combustor pressure remains approximately constant or decreases slightly because of losses. In this cycle the combustor converts chemical energy primarily into thermal energy without producing a pressure rise across the reaction zone. Performance improvements therefore typically require higher chamber pressure, higher allowable combustion temperature, improved nozzle expansion, or reduced losses elsewhere in the engine system.

Detonation is a different mechanism than deflagration. A detonation consists of a shock coupled to a reaction zone, where exothermic chemical reactions release energy that sustains the shock, compressing the reactants to high pressure and temperature before combustion is completed. The result is a net pressure rise across the wave, in contrast to the slight pressure drop typical of deflagration. This behavior, known as pressure-gain combustion, provides the key thermodynamic advantage, producing work from a higher-pressure and thus a higher-temperature combustion process that increases efficiency. This is fundamentally the difference between the Brayton and Humphrey cycle seen in Figure 1.

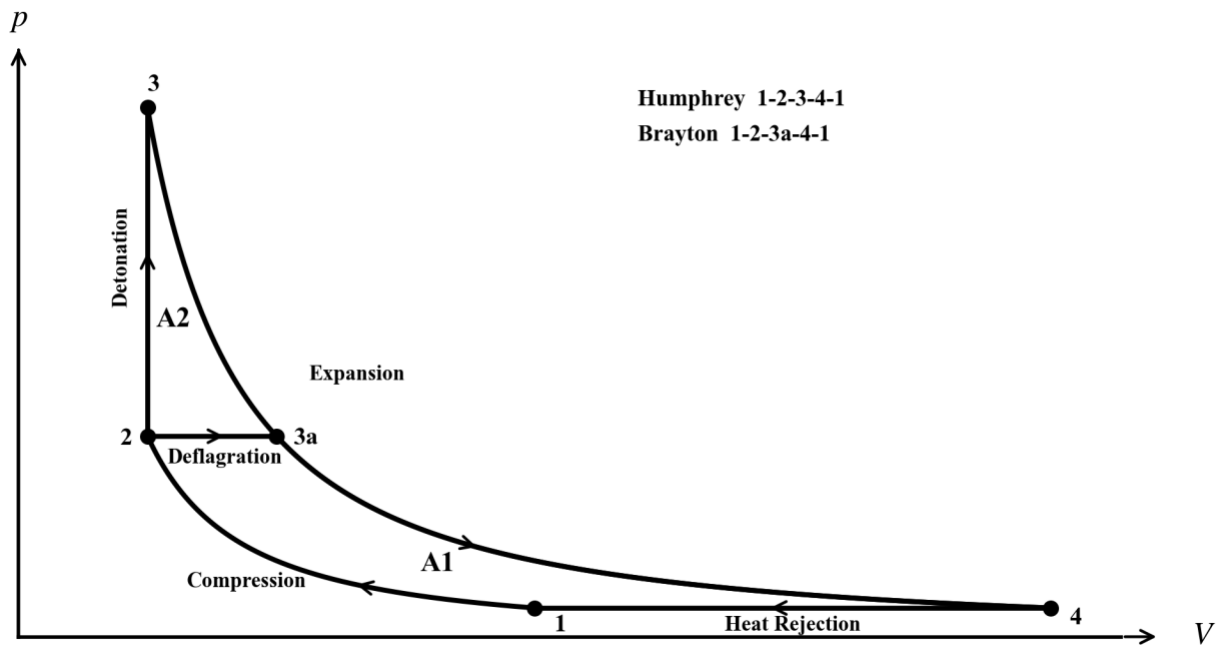


Figure 1: Pressure-Volume Diagram Brayton vs. Humphrey Cycle

Early efforts to harness pressure-gain combustion in a practical engine focused on the pulse detonation engine (PDE), in which a linear tube is repeatedly filled with reactants, ignited, and purged. Because a practical igniter deposits energy at deflagration scales, each cycle must traverse a deflagration-to-detonation transition (DDT) before a detonation is established, and the tube must be long enough to accommodate that transition - a geometric constraint that sets a floor on engine length and works against compact installation.

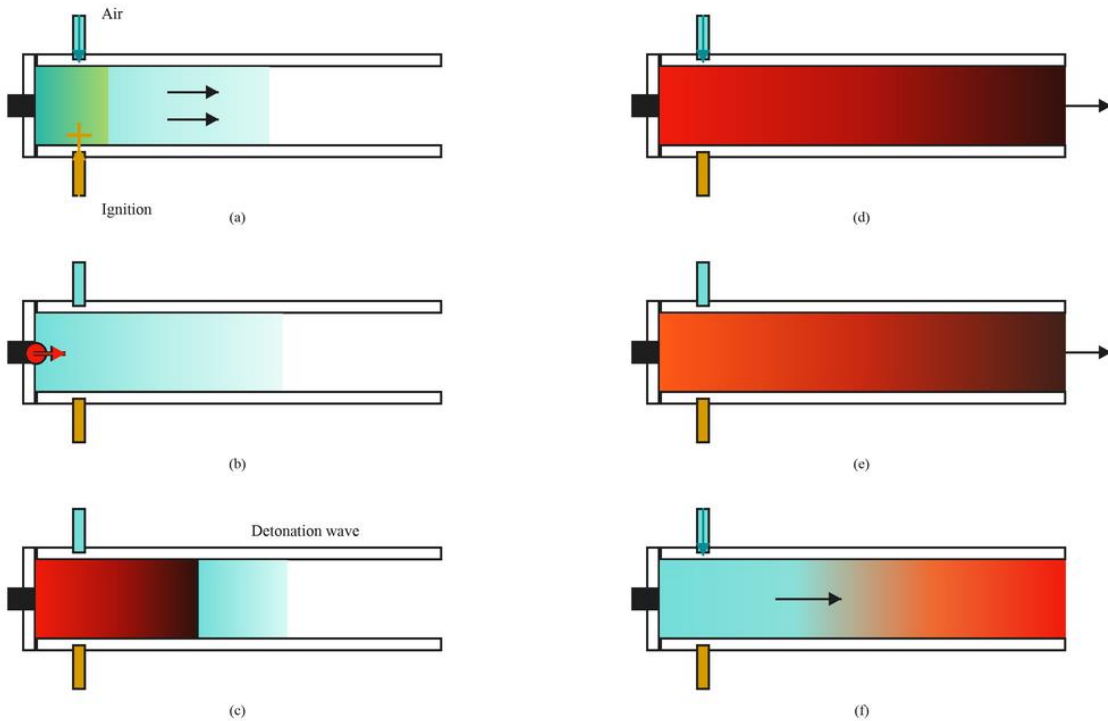


Figure 2: Pulse Detonation Engine

The pulse detonation engine operates through a repeating cycle illustrated across the six panels. In (a) the oxidizer and a fuel fill the detonation tube from the closed end, with the igniter at the bottom armed but not yet fired. In (b) the igniter fires, initiating a subsonic deflagration, a slow flame kernel at the head end. At (c) that flame accelerates and undergoes deflagration-to-detonation transition (DDT), forming a supersonic detonation wave that sweeps down the tube, marked by the sharp boundary between hot burned products behind it and unburned charge ahead. In (d) the detonation reaches the open end having consumed the full charge, leaving the tube filled with high-pressure, high-temperature combustion products that begin venting out the exit and producing the bulk of the thrust impulse. In (e) this blowdown continues as the products exhaust, cool, and depressurize back toward ambient. Finally, in (f) the fuel is re-added, and fresh fuel and oxidizer enter from the head end, purging the remaining hot residual gas out the exit to cool the tube and clear it for the next charge, returning the system to state (a). The complete loop, fill, ignite, transition to detonation, blowdown, and purge, repeats. The cycle time required to fill, fire, purge, and refill also caps operating frequency in the low hundreds of hertz, and because thrust is produced only during the brief detonation and blowdown portion of each cycle, the PDE delivers intermittent thrust with large pressure and momentum oscillations that complicate integration with nozzles, inlets, and turbomachinery [1].

The rotating detonation rocket engine (RDRE) addresses these limitations by sustaining one or more detonation waves continuously around an annular combustor fed at the head end through a distributed injector, as shown in Figure 3

Figure 3: Rotating Detonation Rocket Engine [2]

, rather than re-initiating a detonation on every cycle. The waves propagate transversely, and once a wave is established the fresh reactants injected behind it are consumed by the next passage of the wave, so DDT is not repeated in steady operation and the axial length of the device is no longer set by transition distance. Wave passage frequencies are typically in the kilohertz range, an order of magnitude above achievable PDE cycle rates, and because a wave is always present somewhere in the annulus, the engine produces quasi-steady thrust at the system level even though any given fluid element experiences an unsteady, shock-led process.

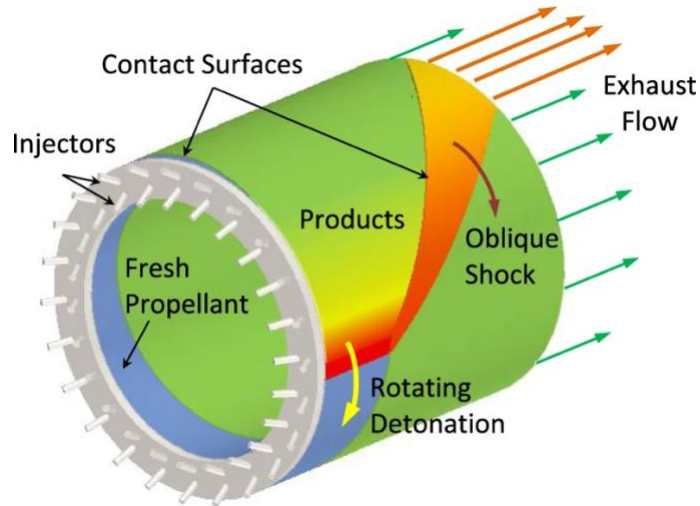


Figure 3: Rotating Detonation Rocket Engine [2]

Relative to pulse detonation engines, which repeatedly fill and fire a linear tube, the rotating geometry avoids cyclic purge-and-fill losses and produces a continuous exhaust. Relative to conventional constant-pressure combustors, the RDRE promises higher specific impulse at a given chamber pressure, a more compact combustor for a given heat-release rate, and a mechanically simple architecture with no moving parts in the combustion path.

Realizing the thermodynamic potential in hardware is another matter. Practical RDREs must establish and maintain one or more detonation waves in a confined annulus across a range of propellant flow rates, equivalence ratios, and backpressures. They must inject and mix reactants quickly enough that the wave encounters a detonable mixture on every revolution and survive the resulting thermal and mechanical environment. Among these challenges, this thesis focuses on the ignition of rotating detonation waves.

1.2: Literature Review

1.2.1: Detonation Fundamentals

A rotating detonation wave contains a shock-led reaction zone: the detonation is sustained by coupling between a leading shock and the chemical energy released immediately behind it [3]. Two general routes can lead to this state. In direct initiation, a large amount of energy is deposited into the mixture rapidly enough to launch a self-sustaining detonation immediately; the required energy is large and scales strongly with the detonation cell size of the mixture, making direct initiation impractical for most engine-scale combustors [3]. In deflagration-to-detonation transition (DDT), a weaker ignition source first establishes a deflagration that accelerates,

generates compression waves, and transitions to a detonation over a finite run-up distance. Practical RDRE ignition therefore commonly relies on weak ignition followed by a transition process either in the main annulus or in an auxiliary pre-detonator rather than direct initiation in the combustor.

A detonation front is not smooth but carries a three-dimensional cellular structure produced by the interaction of the lead shock with transverse shock waves sweeping across it. The characteristic transverse spacing of this structure is the detonation cell size, λ and it is the natural length scale of a detonable mixture. Physically, λ measures the distance over which the lead shock and the reaction zone repeatedly decouple and re-couple, so a mixture that is harder to detonate (slower chemistry, lower energy density) carries a larger cell size. Because λ sets this length scale, it provides a first-order criterion for the minimum geometry in which a detonation can propagate. Conventional detonation theory relates the minimum tube diameter d for sustained propagation to cell size as $\pi d \geq \lambda$ [3]. Bykovskii et al. adjusted this for annular geometry, correlating the minimum annulus diameter, fill height, gap width ($\delta_{\min} \approx 2.4\lambda$), and core length ($L_{\min} \approx 24\lambda$) with the propellant cell size [4]. Cell size depends strongly on mixture composition and pressure: for stoichiometric methane-oxygen near atmospheric pressure, reported cell widths are on the order of a few millimeters, with the California Institute of Technology Detonation Database giving approximately 2.4 to 3 mm near stoichiometric conditions [5], and λ decreases with increasing pre-detonation pressure following an approximately power-law trend [6].

The cell-size criterion is necessary but not sufficient, because annular confinement introduces a second geometric length scale: the inner radius of curvature. As a detonation propagates around the annulus it is curved around the inner body, which stretches the front and can weaken the shock-reaction coupling, so whether the wave sustains near-Chapman-Jouguet (CJ) speed, the ideal self-sustaining detonation velocity for the mixture, or degrades depends on the inner-radius-to-cell-size ratio, r_i/λ , rather than on λ alone. In the University of Washington (UW) scaled-combustor experiments, r_i/λ identified distinct regions of behavior, non-detonative operation below $r_i/\lambda \approx 6$, counter-rotating-wave activity below $r_i/\lambda \approx 26$, and stable co-rotating waves only above it, with the majority of observed wave speeds falling to 60-80% of D_{CJ} [7]. The same study found that cell size and chemical power flux dominated operating behavior at high mass flux, while curvature effects became significant only at low mass flux and at the most fuel-lean and fuel-rich conditions [7].

These dependencies define the UW RDRE scaling dilemma. As engine scale decreases, the combustor diameter, annular gap, and inner radius all shrink toward the mixture's detonation length scale, so both criteria, adequate gap, and diameter relative to λ , and adequate r_i/λ for a curvature-tolerant wave, become harder to satisfy at once. This makes ignition and sustained rotating-wave operation more restrictive at small scale, especially for methane-oxygen, whose cell size is larger than that of hydrogen-oxygen under comparable conditions.

The dependence of initiation on cell size also explains the three ignition approaches used at UW: single-spark ignition, phased multi-spark wave-generator ignition, and auxiliary pre-detonator ignition. In single-spark ignition the spark plug is the only ignition hardware, but the spark does not directly initiate a detonation; it deposits a small amount of energy that produces a

local flame or deflagration, which under favorable mixture, pressure, flow, and geometric conditions can strengthen in the confined annulus, generate compression waves, and transition into a rotating detonation. The wave generator extends this spark-based approach by distributing multiple weak sparks around the annulus and firing them in a phased sequence, attempting to impose a preferred circumferential direction and seed a rotating pressure disturbance rather than relying on a single local event. Frolov and coworkers demonstrated that a properly timed sequence of weak igniters can promote detonation initiation over a shorter distance than a single weak igniter [8]; the UW wave generator applies the same principle using spark plugs that individually deposit only millijoules of energy. The pre-detonator uses a different strategy: it establishes a detonation in a small, high-pressure auxiliary tube, where the cell size is reduced and the DDT run-up distance is shorter, then discharges the resulting detonation products into the main annulus.

1.2.2: Ignition and Startup Transients

While the fundamentals describe whether a detonation can be initiated and sustained, a separate body of work examines what happens during the startup transient of a rotating detonation engine: how the first waves form, how many waves appear, and how the engine settles into a steady operating mode. This transient is the subject most directly related to the present thesis.

Fotia, Hoke, and Schauer conducted direct-connect testing to identify the parameters governing the transition of an RDRE to steady detonating operation, focusing on the relationship between pre-detonation chamber pressure and the rate of pressure rise in the propellant feed manifolds [9]. They documented not only successful detonating ignition but also the special cases of acoustic operation and of partial or suppressed detonation, showing that the feed-system response during startup strongly influences whether a detonation is established at all. Their treatment of pre-detonation pressure and manifold pressurization rate as scaling parameters is directly relevant to an analysis of ignition behavior across engine scales.

The behavior of the detonation after initiation has also been studied. Burr and Yu unwrapped the RDRE annulus into a linear channel to visualize the detonation structure with crossflow present, and observed that an incident detonation can decouple into a blast wave on encountering reactive crossflow and, under certain injection conditions, reignite into a detonation [10]. This re-initiation behavior links the startup transient to steady operation because the same coupling and decoupling processes govern whether a wave, once established, survives each revolution of the annulus.

1.2.3: UW RDRE Ignition Approaches

The UW RDRE facility has employed a variety of ignition approaches across its engine development history. The earliest campaigns, conducted on the 6-inch (154 mm) engine, utilized a wave generator consisting of a phased array of circumferentially mounted spark plugs. As the program scaled down to the 3-inch (76 mm) engine, the wave generator was initially retained before a transitional period of single-plug spark ignition was explored during an axial injection configuration. Ultimately, the laboratory transitioned to pre-detonator tube ignition, a spark-

ignited CH₄-O₂ torch tube that fires a detonation wave radially into the combustor annulus, which became the standard ignition method for all subsequent engine sizes. All engines from the 2-inch through the 10 mm scale used the pre-detonator. The 3-inch engine was the exception in its final campaign, where the pre-detonator was operated together with a secondary annular spark plug. This progression is illustrated in the timeline in Figure 4. Specific ignition hardware is described in 2.2.:

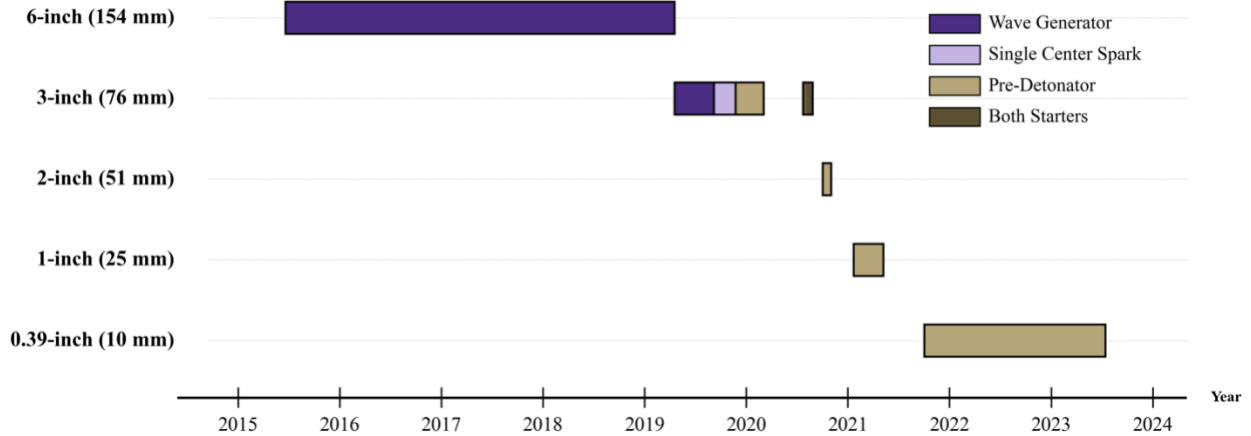


Figure 4: UW RDRE Ignition History

1.2.4: RDRE Ignition Approaches Used Elsewhere

A range of ignition and initiation approaches has been reported across RDRE programs. Table 1 summarizes selected examples from the literature, including pre-detonator, spark-based, hypergolic, electric-fuse, combustion-wave approaches. The table is intended as a representative comparison rather than an exhaustive survey of every RDRE facility. The selected literature shows that pre-detonator ignition is one of the most frequently reported RDRE initiation strategies, particularly in university-scale combustors. Spark-based systems, hypergolic ignition, pyrotechnic ignition, combustion-wave ignition, and piloted afterburner approaches have also been reported.

Table 1: Selected Ignition Approaches Reported

Program / Facility	Reported Initiation	Source
Purdue University Maurice J. Zucrow Laboratories, Indiana, USA	Hypergolic; pre-detonator	[11,12]
University of Central Florida Propulsion and Energy Research Laboratory, Florida, USA	Pre-detonator	[13,14]
University of Alabama in Huntsville Propulsion Research Center, Alabama, USA	Pre-detonator	[15]
University of Alabama, Agrawal group, Alabama, USA	Combustion-wave igniter	[16]
University of Cincinnati, Gutmark group, Ohio, USA	Pre-detonator	[17]

Peking University, Beijing, China	Pre-detonator	[18]
Nanjing University of Science and Technology, Nanjing, China	Spark; pre-detonator	[19]
Warsaw University of Technology Wolański- Kindracki group, Warsaw, Poland	Spark; pre-detonator	[20]
Nagoya University, Aichi, Japan	Pyrotechnic igniter	[21]
University of California Los Angeles, California, USA	Hypergolic	[22]
Northwestern Polytechnical University, Xi'an, China	Spark; pre-detonator	[23]
National University of Defense Technology, Changsha, China	Spark; pre-detonator	[24]
AFRL Edwards, California, USA	Pre-detonator	[25]

1.2.5: Ignition Studies

Beyond cataloging the ignition hardware used by individual facilities, a smaller set of studies has deliberately varied the ignition method within a fixed combustor. These comparisons provide the most direct evidence for what the igniter can and cannot control. Much of this work is concentrated in studies from the Nanjing University of Science and Technology, where ignition method is treated not only as a hardware choice but also as a variable affecting initiation dynamics. When the comparison is framed in terms of reliability, pre-detonator ignition is consistently favored. Kindracki et al. reported that a commercial spark plug initiated a methane-oxygen mixture with a success rate near 40%, whereas a pre-detonator tube exceeded 95% repeatability under otherwise identical conditions [20]. When the comparison is framed in terms of startup dynamics, deposited ignition energy becomes the dominant factor. Yang et al. compared an ordinary spark plug, a high-energy spark plug, and a hot jet in a hydrogen-air combustor and found that rotating-detonation-wave formation time decreased as ignition energy increased, reaching its minimum with the hot-jet igniter [19].

Xia et al. provided the most complete version of this comparison by testing a low-energy spark plug, approximately 50 mJ, a high-energy spark plug, approximately 2 J, and a hydrogen-oxygen pre-detonator tube in a plane-radial hydrogen-air engine, while also varying the radial ignition position [26]. They divided the initiation process into five stages: ignition, disordered deflagration, circumferential flame-wave propagation, unstable rotating detonation, and stable rotating detonation. Their results showed that higher ignition energy made the circumferential flame wave easier to establish, shortened the formation time, and substantially improved run-to-run consistency. The pre-detonator tube produced both the shortest mean formation time, approximately 2.8 ms, and the narrowest distribution. By contrast, the low-energy spark plug produced formation times scattered between roughly 1.5 and 6.7 ms [26]. Ignition position also affected the transient. An optimum location minimized formation time, while ignition near the combustor center promoted the formation of multiple wave heads during the initial transient. However, the most important result concerned what the igniter did not control. Under fixed injection conditions, neither ignition method nor ignition position appreciably changed the stabilized operating state. Stable frequency, wave speed, and peak pressure remained

approximately 4.6 kHz, 1465 m/s, and within about two percent across all three ignition methods and all four ignition positions [26].

Bai et al. reached the same conclusion in a different combustor architecture by comparing auto-initiation with pre-detonator tube ignition in an annular combustor [27]. In this case, auto-initiation refers to spontaneous combustion of high-temperature hydrogen-rich gas after contact with air. The two ignition methods produced clearly different startup transients. The pre-detonator established a stable wave in roughly 1 ms and did not require a distinct adjustment stage, while auto-initiation required approximately 3 ms and passed through a weak, unstable self-adjustment phase. Once the combustor stabilized, however, the two cases were nearly indistinguishable. Wave speeds were approximately 1486 and 1500 m/s, and dominant frequencies were 4302 and 4344 Hz, respectively [27]. The ignition method did affect the stable operating envelope. Although both methods produced rotating detonation over an equivalence-ratio range of 0.68 to 1.96, the higher-energy pre-detonator widened the range of stable single-wave operation and reduced variability in wave speed and peak pressure. Even so, the sequence of propagation modes observed as equivalence ratio increased was governed primarily by equivalence ratio, not by the ignition source [27]. Bai et al. also noted that the wave-travel direction was not prescribed by the igniter, but instead resulted from the chance survival of one wave after the initial two-wave collision.

Taken together, these comparative studies support a consistent interpretation: the ignition method strongly affects the startup transient, formation time, repeatability, initial wave count, and the width of the stable operating envelope. It has much weaker influence on the stabilized wave speed, frequency, and propagation mode, which are governed primarily by propellant chemistry, equivalence ratio, mass flux, and combustor flow conditions.

This same igniter-as-starter interpretation underlies the ignition hardware used throughout the Air Force Research Laboratory (AFRL) and Air Force Institute of Technology (AFIT) rotating-detonation programs, both of which favored pre-detonators over in-channel spark ignition. On the AFRL Rocket Propulsion Division 76 mm methane-oxygen engine, ignition was provided by a pre-detonator operating on gaseous methane and oxygen. A small, premixed volume was fed into a mixing chamber, ignited by a conventional automotive spark plug, and driven through deflagration-to-detonation transition in a tube before the resulting detonation was delivered into the annulus [25,28,29]. In this arrangement, the spark plug is located inside the pre-detonator rather than inside the detonation channel. For injector-response studies, AFRL extended this concept into a multiple-pre-detonator igniter. In that system, one spark source fed several DDT tubes with different lengths and radii of curvature, causing each tube to transition to detonation at a slightly different time. The result was up to four successive detonation waves spaced roughly 100 microseconds apart, with tube length and curvature setting the DDT timing [28].

The AFIT effort at Wright-Patterson, led by Schauer, examined the ignition choice most directly at the small-engine scale most relevant to the present work. On a 28 mm nitrous-oxide and ethylene micro-RDRE, earlier testing used an in-channel spark plug. However, the protruding electrode was found to anchor an unstable clapping-wave mode, burn away as a metal fire within a single run, and erode its insertion hole [30]. The investigators therefore replaced the

in-channel spark with a pre-detonator built by Innovative Scientific Solutions Inc. This system used a spark-initiated hydrogen-oxygen detonation delivered into the chamber through a one-eighth-inch detonation tube. The pre-detonator was selected specifically because it interfaced with the combustor through a small, flush hole, removing the protrusion that had destabilized the rotating wave. The pre-detonator entry was then redesigned to reduce erosion. The original one-eighth-inch hole, which experienced flame-holding, was reduced to one-sixteenth inch. At this smaller diameter, the hydrogen-oxygen detonation still propagated into the channel without quenching and without appreciable loss of ignition capability. The entry was also relocated to 5.5 mm above the injectors so that it remained within the roughly 8 mm fill height and was cooled by the unburned reactants, while the surrounding outer body was rebuilt in Inconel. A manual firing sequence allowed multiple ignition attempts when the first pre-detonator wave failed to light the engine, with the pre-detonator solenoid held open for approximately 70 ms to fill the tube before firing.

Across both the AFRL and the AFIT hardware, the ignition conclusion is consistent with the comparative literature reviewed above. A pre-detonator is preferred over an in-channel spark because a channel-intrusive igniter can perturb the flow, destabilize the rotating wave, and fail structurally during operation. A flush DDT-tube pre-detonator instead provides a reliable starting disturbance while minimizing direct interference with the stabilized operating mode.

The hot-jet ignition mechanism underlying these pre-detonator systems also has a documented upper operating limit. Bilgin, Keller, and Breidenthal studied ignition of propane-air mixtures by a rotating hot jet sweeping past a single simulated wave-engine cell and found that ignition behavior across nozzle diameters and sweep rates collapsed onto a single step function of a short-pulse Damköhler number, defined as the ratio of the rotation period of the critical vortex formed by the jet to the chemical time of the mixture, with ignition failing below a critical value of approximately 0.01 [31]. Sweeping the jet past the cell too quickly produced no ignition: a shorter passage time injects less hot mass into the vortex, lowering the mixed-gas temperature and lengthening the chemical time exponentially, an effect the authors found stronger than the competing influence of jet impulse on the vortex rotation period. The critical passage time scaled inversely with the square of the nozzle exit diameter, so each nozzle geometry carried a quantitative ignition boundary. Hot-jet ignition is therefore bounded from above as well as from below: the same hardware that ignites reliably at long passage times fails when the jet is delivered too briefly. Although the wave-rotor test cell is a different device from an RDRE, with discrete cells undergoing a fill-burn-purge cycle rather than supporting a continuously propagating wave, the criterion it established describes the jet-ignition event itself rather than the device surrounding it. The same competition between jet delivery time and chemical time arises whenever a transient hot jet must ignite a fresh propellant charge, making this result a quantitative framework directly applicable to the sizing and timing of pre-detonator jets in RDREs.

Chapter 2: Background and Methods

2.1: UW RDRE Laboratory

The University of Washington RDRE laboratory is housed in the Aerospace and Engineering Research Building (AERB). The facility has operated continuously since approximately 2015, supporting five distinct engine size scales. The shared infrastructure includes the dump-tank exhaust system, test location, and a centralized data acquisition architecture. While the core layout of the facility has remained consistent, the propellant handling system, flow metering, flow control, and optical access have each evolved over the course of the program. Table 2 summarizes how these elements changed across the major engine campaigns; the subsections below describe each in detail.

Table 2: Evolution of UW Facility

	6-inch Early	6-inch Late	3-inch Early	3-inch Late	2-inch	1-inch	10 mm
Propellant	H ₂ -O ₂ CH ₄ -O ₂	CH ₄ -O ₂	CH ₄ -O ₂	CH ₄ -O ₂	CH ₄ -O ₂	CH ₄ -O ₂	CH ₄ -O ₂ H ₂ -O ₂
Flow Metering	Venturi	Venturi	Venturi	CFN	CFN	CFN	CFN
Flow Control	Manual Regulator	Manual Regulator	Manual Regulator	ER5000	ER5000	ER5000	ER5000
Back Pressure	Butterfly Valve	Butterfly Valve	Dump Tank	Dump Tank	Dump Tank	Dump Tank	Dump Tank
Optical Access	None	Wye	Wye	Wye	Wye	Wye	Wye
Ignition Method	WG	WG	WG Pre-det	Pre-det Big Spark	Pre-det Spark	Pre-det	Pre-det

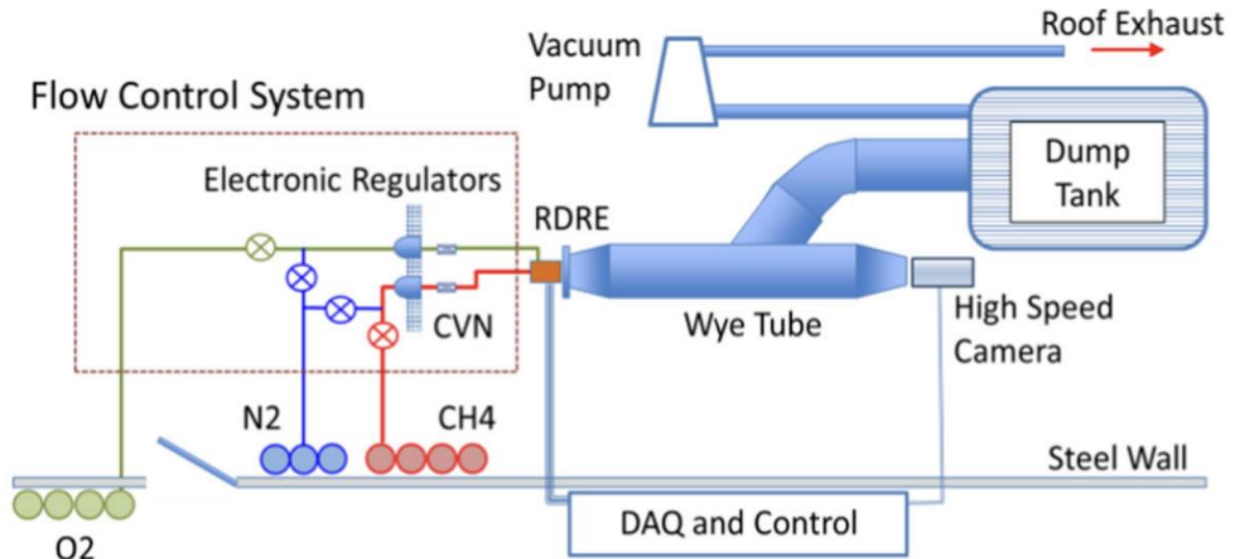


Figure 5: Current UW RDRE Laboratory [32]

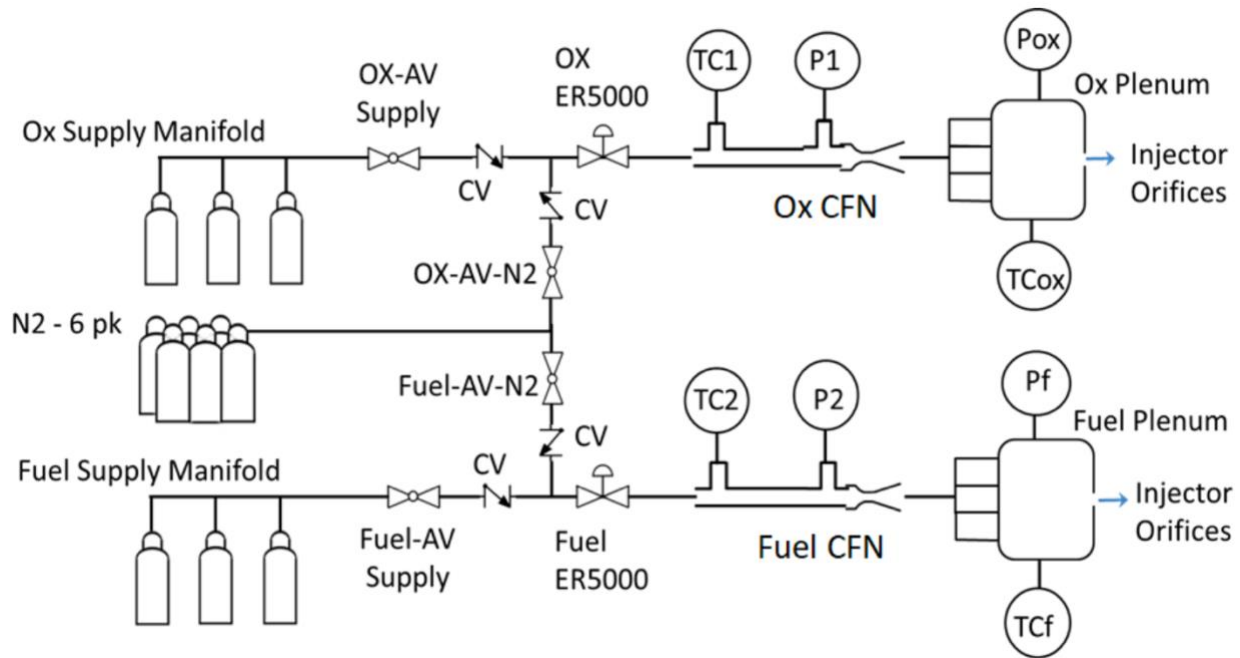


Figure 6: UW RDRE Propellant Diagram [32]

2.1.1: Gases

Fuel and oxidizer are provided via commercial high-pressure gas cylinders manifolded together in pairs for each propellant, with separate independent delivery lines for fuel and oxidizer routed through the manifolds, regulators, flow metering, and run valves. The propellant streams meet only inside the combustor annulus. As shown in Figure 5, the fuel and oxidizer supply cylinders are separated from the test area by a structural steel wall.

The primary propellant combination used was gaseous methane (CH_4) and oxygen (O_2). The 6-inch (154 mm) engine was the exception. Its initial campaign operated on hydrogen–oxygen ($\text{H}_2\text{--O}_2$) and transitioned to methane–oxygen ($\text{CH}_4\text{--O}_2$) in January 2018. The 10 mm engine was also tested with $\text{H}_2\text{--O}_2$ in a separate campaign beginning in March 2023, in addition to its methane–oxygen work. All other engines, the 3-inch, 2-inch, and 1-inch, to date have been operated with $\text{CH}_4\text{--O}_2$.

Nitrogen (N_2) is plumbed into both the fuel and oxidizer lines independently and serves as an inert purge, conditioning, and flow-control gas throughout all engine campaigns, though its role evolved as the propellant handling system was upgraded. In the 6-inch engine era, nitrogen was used as a pre-run and post-run purge gas. A pre-purge of approximately one second cleared residual air, overcame regulator start-up inertia, and helped establish stable regulator behavior before the lines were switched to propellant flow [33]. This was especially important because the engines exhausted into a dump tank rather than venting directly to atmosphere: unlike an atmospheric facility, the UW system had to limit the total amount of gas admitted to the tank and avoid accumulating unburned fuel or oxidizer during regulator transients. A post-purge of comparable duration diluted and displaced combustion products before the dump tank was evacuated [2,34].

When the facility transitioned to electronically controlled regulators, this same pre-run diluent flow took on regulator conditioning as its explicitly documented purpose: a brief nitrogen flow ahead of propellant settled the electronic regulator setpoints, controlled the initial pressure transient, and cleared the plenum before test gas was introduced during the initial seconds of each run [35]. This pre-flow was standard in the 3-inch and 2-inch campaigns. The smallest engines were the exceptions: in both the 1-inch and 10 mm combustors, the low mass flow rates required made the plenum take excessively long to purge, so the nitrogen pre-flow was omitted and propellant was introduced directly from the start of each run [7].

Where pre-detonator tube ignition was employed, on the 3-inch engine and smaller, a dedicated CH₄ and O₂ supply independent of the main propellant circuit fed the pre-detonator. This consisted of small high-pressure accumulators (Swagelok 304L-HDF4-1000) that provided a brief co-flow of methane and oxygen into the 350 mm pre-detonator tube approximately 300 ms before each run's main propellant valves opened. The pre-detonator supply was exhausted in a single firing per run and recharged between runs from the main cylinder supply. The diagram for the pre-detonator can be found in the Pre-detonator Tube section.

2.1.2: Backpressure and the Dump Tank

The lab is split between a control room and an experiment room separated by a structural wall, with all engine operation performed remotely from the control room. The dump-tank exhaust system has been continuous across all five engine campaigns. The engine mounts directly to a stainless-steel transitional piping section that routes combustion products into a 4 m³ dump tank which is rated from vacuum to several hundred kPa working pressure. A Kinney KT-300 oil-sealed rotary-vane vacuum pump performs three roles, evacuating the dump tank between runs to clear products and unburned reactants, setting the initial backpressure prior to each hot fire when sub-atmospheric conditions are desired, and drawing down the dump-tank contents through the building's external exhaust stack in the event of a no-ignition run. The vacuum pump can set initial dump-tank pressures as low as approximately 2 kPa absolute. At UW the dump-tank pressure downstream of the engine exit is the engine's backpressure and can be controlled deterministically rather than being atmospheric. The exhaust duct is 0.25 m inner-diameter stainless steel and incorporates a wye section between the engine and the dump tank. The wye's straight branch terminates in a polycarbonate viewport that provides line-of-sight optical access aft through the combustor exit, with the engine centerline offset from the dump-volume centerline specifically to allow this geometry to work. The wye section is the structural enabler for the lab's high-speed imaging capability. It was introduced late in the 6-inch campaign as part of a 2019 facility refit, where it replaced the original butterfly-valve dump-tank entrance, and it was carried forward to the 3-inch engine and all later configurations.

2.1.3: High-Speed Imaging

Optical access to the operating UW RDRE was not available across all facility iterations. The original 154 mm, or 6-inch, engine exhausted directly into stainless-steel piping leading to the dump tank, with no axial observation path through the combustor. Hot-fire diagnostics in this era were therefore based primarily on embedded measurements, including PCB piezoelectric pressure transducers, static-pressure transducers, and thermocouples. Although Heath's 2015

work used a high-speed Phantom camera, that imaging was performed in a separate non-reacting plastic annular duct and did not image the operating stainless-steel engine.

The diagnostic suite expanded with the transition to the 76 mm engine. Washington's 2019 work introduced capillary time-averaged pressure (CTAP) probes and ionization probes into the UW RDRE lineage, with the full CTAP, PCB, ionization-probe, and thermocouple package implemented on the 76 mm engine to better localize the detonation zone. The older 154 mm engine incorporated CTAP measurements in this period; the wye section arrived only for its final runs, and systematic through-engine imaging began with the 76 mm engine.

Direct high-speed imaging of detonation-wave dynamics became available with the later 76 mm engine configuration and wye-section exhaust geometry. Koch's 2020 Ph.D. work documents and uses this optical path, in which the 76 mm engine centerline was offset from the dump-volume centerline to provide a clear axial view through the combustor exit. This enabled direct recording of the spatiotemporal evolution of the rotating waves, supporting analysis of wave nucleation, mode locking, modulation, and transient mode behavior.

In the present work, the Phantom V1211 camera is operated through the wye-section optical viewport. Post-processing maps a polar mesh onto the imaged annulus, constructs a space-time intensity matrix from integrated luminosity, and uses this matrix for FFT-based wave-count and frequency extraction. The same imaging framework also provides the basis for the transient wave-identification methods used in the present ignition analysis. Thus, the present ignition-transient imaging approach is inherited from the 76 mm/wye-section diagnostic architecture, rather than from the original 154 mm facility configuration.

2.1.4: Flow Metering

In the earlier 6-inch (154 mm) and early 3-inch (76 mm) campaigns, mass-flow rates were found using Venturi flow meters installed downstream of the supply-line pressure regulators. The setup used Badger Meter VBR-series brass Venturis on both the fuel and oxidizer lines, with a 1/2-inch unit on the fuel line and a 3/4 inch unit on the oxidizer line, instrumented with Omega differential-pressure transducers (PX419-500DDU5V) and absolute-pressure transducers (PX319-1KA5V). These Venturis acted as differential-pressure meters rather than choked metering devices, allowing high flow rates to be measured at modest supply pressures but leaving the inferred flow rate sensitive to upstream and downstream line conditions. This sensitivity motivated the facility's transition away from Venturi-based metering, through an intermediate orifice-metering configuration, to the present critical-flow-nozzle system. Gas-property and critical-flow quantities are evaluated using real-gas thermodynamic properties from REFPROP. Upstream supply pressures are commanded using TESCOM ER5000 electro-pneumatic controllers with TESCOM 44-4000-series electronic pressure regulators. The ER5000 controllers communicate with the run-control computer through RS-485 over USB, and their PID gains are tuned during commissioning using TESCOM's ERTune software. This arrangement provides repeatable digitally commanded pressure regulation and faster settling during the short startup transient before operation.

Flow metering evolved substantially over the 76 mm campaign. The engine began with true (non-choked) Venturi meters, which were used from the start of the campaign through approximately Run 654, when the log entry “CHOKING ORIFICES REMOVED, Predet, CAMERA WHITE OUT” confirms that an intermediate set of choking orifices (on the order of twenty to thirty runs in duration) had been bridging the venturi and final critical-flow-nozzle eras. The facility then settled on Flow-Dyne sonic (critical-flow) nozzles for both fuel (CFN N080050-SA, N0800110-SA) and oxidizer (CFN N120086-SA, N1200165-SA), with a quoted per-nozzle uncertainty of $\pm 0.5\%$. The distinction matters physically: a critical-flow nozzle chokes at its throat, so the metered mass flow is fixed by the upstream conditions and is insensitive to downstream pressure fluctuations, whereas a Venturi does not choke and leaves the inferred flow rate sensitive to line conditions during the startup transient. The transition to choked metering therefore improved flux control and run-to-run repeatability. The combined ER5000 regulator and sonic-nozzle upgrade is marked in the log at Run 668 (July 2, 2020), and the finalized “Both Starters” (pre-detonator plus annular Big Spark) configuration became the standard from Run 814 (July 22, 2020) onward.

The choked-metering era also coincided with the late-campaign DAQ expansion (channel 28 was added at Run 911) and with the last logged hardware changes to the 76 mm engine: an engine disassembly and fuel-injector debris removal at Run 893 (August 13, 2020) and new pre-detonator valves and new starter plugs at Run 897.

2.2: Ignition Hardware

Every rotating detonation wave reported in this thesis was started by an electrical spark. What distinguished one ignition system from another was not the spark itself but where that spark energy was deposited and where the deflagration-to-detonation transition (DDT) was allowed to develop, directly in the main annulus, or in a separate auxiliary tube whose products were then injected into the annulus. This section describes the Wave Generator, the single-point spark, and the pre-detonator tube. The chronological record of which engine used which system, and how well each performed, is given in Chapter 3:

2.2.1: Wave Generator (Phased Multiple Spark)

The Wave Generator (WG) served as the ignition system throughout the 6-inch engine campaign and during the initial phase of the 3-inch engine campaign. The system used an azimuthal array of NGK BUHW-2 button-style coaxial-electrode spark plugs mounted flush with the inner surface of the outer combustor wall. Spark timing was supplied through wave-controller electronics and individual spark-control boxes driven by an external signal source. Two generations of drive electronics served these arrays. The 6-inch twelve-plug system delivered a nominal 8 mJ per spark, adjustable from 4 to 16 mJ, with a per-plug hardware ceiling of approximately 8 to 10 kHz. In operation, each plug fired below this ceiling at the rate required to track the imposed rotating-wave sequence [2]. A dedicated six-plug exciter unit, associated with the later six-plug array, was a substantially higher-energy design, delivering approximately 0.15 J per spark at up to 14 kV through surface-gap plugs, with six-spark sequences re-triggerable at up to 10 Hz [34]. In both configurations, the plugs were energized in a programmable phased sequence intended to seed a circumferential transverse pressure pulse,

promote DDT in the propellant-filled annulus, and initiate co-rotating detonation-wave operation in the direction prescribed by the firing sequence.

Boeing's original conceptual design for the 6-inch engine used six spark plugs, but the final implementation was scaled to twelve plugs at 30° intervals, allowing programmed 1-, 2-, 3-, and 4-wave driving configurations. Wheeler later showed that a reduced six-plug configuration was as reliable as the original twelve-plug array, and subsequent 6-inch campaigns, including Washington's radial-injector-mixing studies, used only six of the twelve installed plugs [36,37]. The 3-inch engine retained a six-plug spark-based ignition arrangement consistent with the WG approach, with programmable driving frequency, wave-driving number, and azimuthal direction.

2.2.2: Single-Spark Ignition

The simplest ignition hardware used was a single spark plug mounted in the combustor wall. The plug was the same NGK BUHW-2 button-style plug used on the WG, a flush center-post plug with no protruding hook electrode so that no hardware intruded into the detonation-swept annular flow. The plug produced a local deflagration that had to undergo DDT within the annulus under suitable mixture, pressure, and flow conditions. Single-point spark ignition was used on the 3-inch engine after the WG was removed, and on the 2-inch engine as the initial ignition method before the pre-detonator was retrofitted.

2.2.3: Pre-detonator Tube

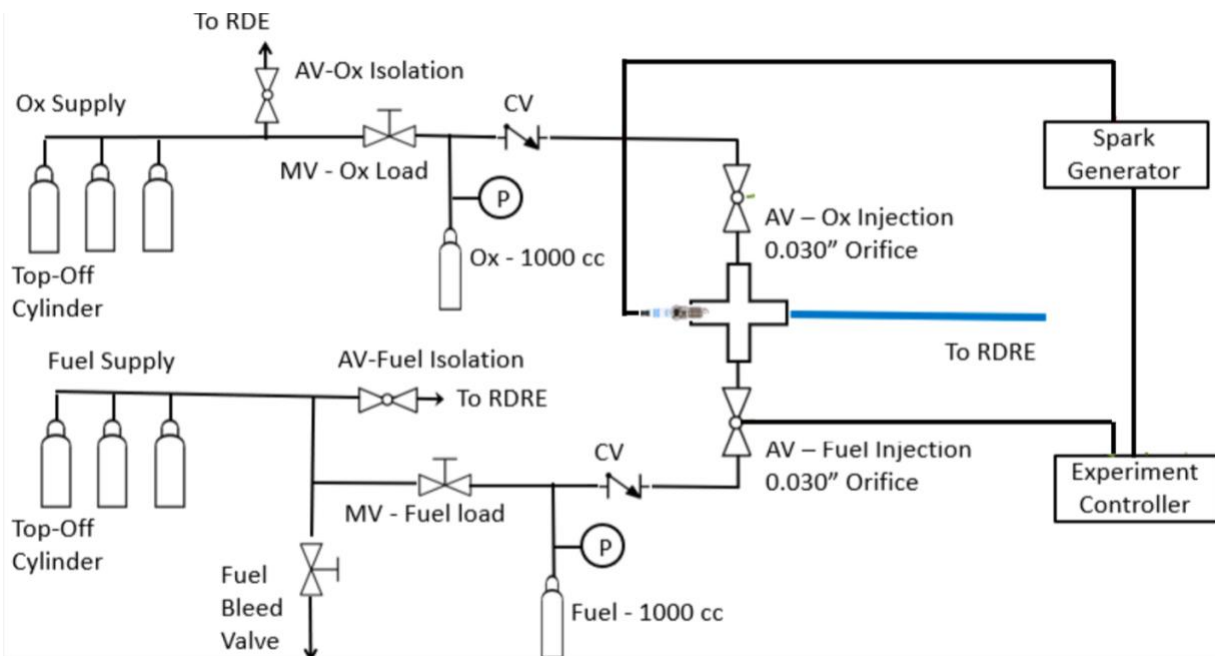


Figure 7: Pre-detonator Flow Control System Diagram [38]

The pre-detonator ignites stoichiometric $\text{CH}_4\text{--O}_2$ in a small auxiliary chamber, allows DDT to occur in a connecting tube, and discharges the resulting detonation wave into the main combustor through a dedicated port. The current UW implementation consists of two auxiliary 1000 cc fill cylinders (one for CH_4 filled to nominally 1380 kPa, one for O_2 at 4140 kPa, sized for many runs between refills); matched Parker Series 9 miniature calibrant valves that inject the auxiliary CH_4 and O_2 into opposing ends of a stainless steel cross; a 6.4 mm diameter stainless steel tube with a length-to-inner-diameter ratio of 50 connecting the cross to a radial port in the combustor, which provides the run-up length for DDT; and a co-annular gap spark plug installed in the cross. The standard cross geometry has fuel and oxidizer ports impinging across the cross, the spark plug perpendicular to that axis, and the pre-detonator tube opposite the spark plug.

The fill-spark sequence is: calibrant valves open for 200 ms to fill the cross and tube with stoichiometric pre-detonator mixture; valves close; 5 ms after closing, the spark plug is fired at 500 Hz for 100 ms. The 200 ms fill ensures complete mixing, the 5 ms post-close delay prevents the spark from firing while the fill valves are still moving, and the 100 ms sparking window provides multiple sparking events to ensure successful initiation. The DDT proceeds in the long stainless tube, and the resulting detonation wave enters the main combustor through the pre-detonator port. The pre-detonator is effectively a one-shot device per run - by contrast, pulse testing in the lab's history was performed only with the spark-based systems, never with the pre-detonator.

2.3: Engine Hardware

2.3.1: 6-inch (154 mm) Engine

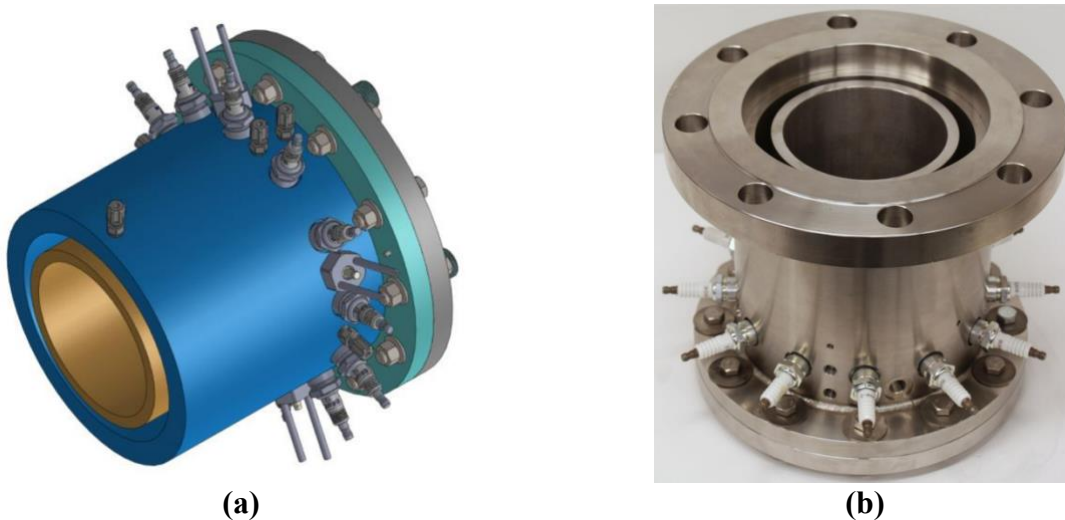


Figure 8: 6-inch Engine (154 mm)

(a) CAD Cross Section (b) Photograph Assembled [39]

The 6-inch (154 mm) RDRE was the original and largest annular rotating detonation engine developed in the UW RDRE laboratory. In earlier UW literature, this engine is referred to as the

Cylindrical Rotating Detonation Engine (CRDE); in the present work it is identified as the 6-inch RDRE. The engine was designed and machined in-house from 304L stainless steel and operated as a passively cooled heat-sink device, with run duration limited by thermal soak to approximately 1-2 s. Unlike the smaller copper engines, the 154 mm RDRE was tested with both gaseous hydrogen–oxygen and methane–oxygen propellants, making it one of the two UW engines which were operated on more than one propellant chemistry.

The “6-inch” designation refers to the combustor flow path outer diameter of 154.0 mm. The center-body outer diameter is 131.6 mm, producing an 11.2 mm annular gap and a mean annulus diameter of 142.8 mm. The combustor length is taken here as 182.0 mm from the front-end wall to the exit. Propellant injection is radial, with fuel injected outward from the center body and oxidizer injected inward from the outer wall through staggered rings of 24 orifices each. This radial injection layout leaves the front-end wall available for instrumentation and distinguishes the 154 mm RDRE from later axially injected engines.

Ignition on the 154 mm RDRE was provided by the UW Wave Generator, an azimuthal spark-plug ignition system developed for this engine. The canonical configuration used twelve flush-mounted NGK BUHW-2 spark plugs spaced around the outer wall, although later testing showed that six plugs could provide comparable ignition reliability. The Wave Generator fired the plugs in a phased sequence intended to seed a circumferential pressure disturbance and initiate deflagration-to-detonation transition in the annulus. No single-spark or pre-detonator ignition configuration was tested on the 154 mm RDRE.

Instrumentation on the 154 mm RDRE included dynamic pressure transducers, mean static pressure transducers, capillary time-averaged pressure measurements, thermocouples, and plenum pressure measurements. Because the injector was radial rather than axial, pressure ports could be distributed along the combustor and around the front-end region without competing with an injector face. The engine exhausted through a conical nozzle into downstream piping and a dump volume, with later facility configurations enabling limited back-pressure sensitivity studies.

2.3.2: 3-inch (76 mm) Engine

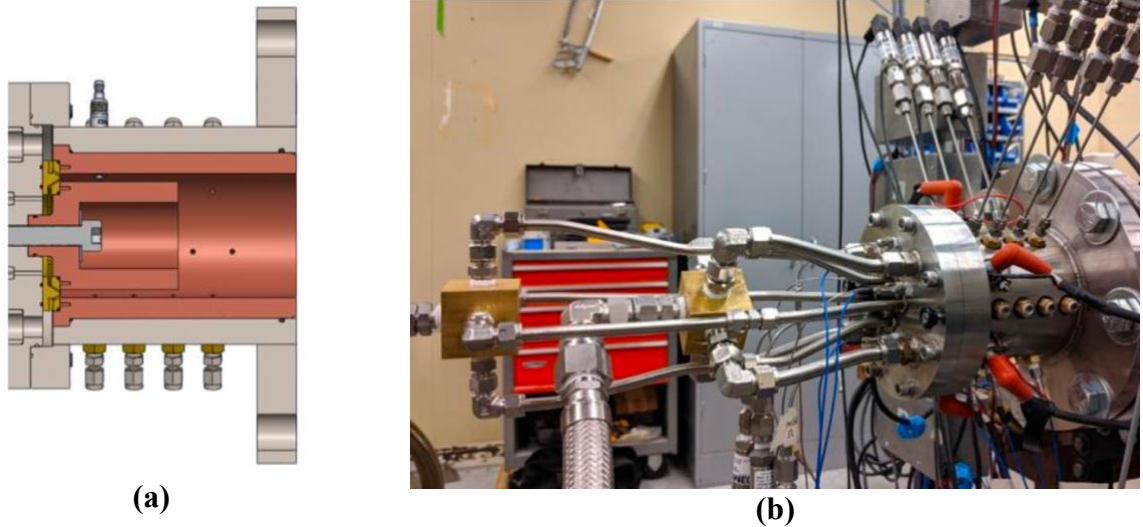


Figure 9: 3-inch Engine (76 mm)

(a) CAD Cross Section (b) Photograph Assembled [32]

The 3-inch (76 mm) RDRE was the most extensively tested combustor in the UW RDRE laboratory and served as the primary platform for direct ignition-method comparison. The engine was designed for both reconfigurability and high-mass-flux operation. It consisted of a 304L stainless-steel outer shell sleeved with an oxygen-free, high-conductivity (OFHC) copper liner. The copper liner conducted heat away from the annular flow path, allowing high-mass-flux operation without active cooling, while the surrounding stainless-steel shell carried the structural and pressure-containment loads (AIAA 2019-4038; AIAA 2019-4131). The engine was operated exclusively on gaseous methane and oxygen.

The “3-inch” designation refers to the combustor flow-path outer diameter of 76.2 mm. In its nominal configuration, the center-body outer diameter was 66.2 mm, producing a 5.0 mm annular gap and a mean annulus diameter of 71.2 mm (AIAA 2019-4038). The engine hardware allowed the annular gap to be reset to 3 mm or 7 mm by replacing the inner core (AIAA 2023-0354), but all logged runs used the nominal 5.0 mm gap. The nominal annular cross-sectional area was approximately 1120 mm². Four interchangeable core lengths were used over the campaign: 152 mm and 102 mm cores during the Wave-Generator era (AIAA 2019-4038), a 12.7 mm stub core tested briefly, and a 76.2 mm core, equal in length to the flow-path outer diameter, which was installed for the single-spark, pre-detonator, and Both Starters eras and underlies most of the dataset (AIAA 2023-1104).

The engine’s modular construction allowed the combustor length, injector-to-annulus area ratio, and injection scheme to be changed without rebuilding the combustor. In its radial-injection configuration, fuel was injected outward from the center body and oxidizer was injected inward from the outer wall through discrete injector rings containing 36 orifices each. These rings were exchanged to set injector-to-annulus area ratios of 0.135, 0.188, and 0.240 (AIAA 2019-4038; AIAA 2019-4131). The engine could also accept transverse and axial injection hardware, including a drop-in 72-element impinging injector (AIAA 2023-1104). In the axial-

injection configuration, propellant was introduced from the injector end of the combustor rather than through opposed radial injection rings, moving the initial mixing and heat-release region toward the front of the engine.

The combustor carried 24 instrumentation ports arranged as three axial rows of eight stations, providing co-located static pressure and temperature measurements at 12.5 mm axial resolution. Additional ports were located on the front-end wall and in the propellant plenums (AIAA 2019-4038; AIAA 2023-1104). Fast-response piezoelectric pressure transducers were used to monitor detonation-wave dynamics in the combustor, along the front-end wall, and within the plenums. The engine exhausted through its rear flange, a standard 6-inch steam flange, into the test-cell dump volume. Over the course of the campaign, the flow-metering hardware evolved from venturis to orifices and finally to critical-flow nozzles, as discussed in §2.1.

Table 3: 3-Inch Configurations

Configuration	Runs	Injection	Igniter	Flow metering
Wave Generator	4–257	radial	six-plug spark array	venturi
Single spark	258–412	axial	one NGK plug, plus dump-zone flare-off	venturi (relocated, Run 257)
Pre-detonator only	551–635	radial (Dist-A restored, Run 521)	pre-detonator torch	metering orifice
Both Starters	636–991	radial	pre-detonator plus annulus spark	orifice; sonic nozzle and ER5000 from Run 668

The 3-inch RDRE is the only UW engine on which all three laboratory ignition systems were used. Under radial injection, ignition was provided by a six-plug spark array operated in Wave-Generator fashion (Boening et al., 2018; see §2.2). With six plugs, the array could drive one-, two-, and three-wave ignition sequences, but not the four-wave sequence available on the twelve-plug 154 mm engine (Boening et al., 2018). After the transition to axial injection, the Wave Generator was replaced by a single in-chamber spark plug, supported by a downstream flare-off spark located in the dump zone and fired on the same spark circuit. A pre-detonator torch later replaced the in-chamber spark plug and became the standard ignition system for the remainder of the campaign; this torch entered the combustor radially (AIAA 2023-0354; AIAA 2023-1104). In the final configuration, the engine was operated with the pre-detonator and a separately commanded high-energy spark, the “Big Spark,” fired downstream of the annulus exit (AIAA 2023-0354; AIAA 2023-1104). The Big Spark carried on the dump-tank function of the earlier flare-off spark and was an ignition source, on occasion producing the engine’s initial ignition, as shown in Chapter 3. This dual-ignition configuration was referred to as “Both Starters,” a fourth ignition configuration assembled from two of the three systems.

The 76 mm campaign comprised nearly one thousand logged runs, from Run 4 through Run 991, beginning in April 2019. Hot-fire testing concluded in mid-September 2020, and the log closes with calibration cold flows. Across this campaign, the engine operated through three injector area-ratio settings, four core-length configurations, three flow-metering generations, and

the full ignition progression from Wave Generator to single-spark ignition, pre-detonator ignition, and finally dual-ignition operation. The tested operating envelope spanned equivalence ratios from roughly 0.4 to 2.4 and mass fluxes up to roughly $370 \text{ kg/m}^2\text{-s}$. The era boundaries and associated hardware changes are summarized in Table 3.

Because each ignition configuration occupied a distinct contiguous block of the campaign, the igniter never changed in isolation. The single-spark ignition era was also the axial-injection era, and the Both Starters era was also the sonic-nozzle metering era. The ignition-method comparisons of Chapter 3 are therefore drawn at matched operating conditions within fixed injector configurations wherever possible. Any comparison that crosses an injection, geometry, or metering change is identified as such.

2.3.3: 2-inch (51 mm) Engine

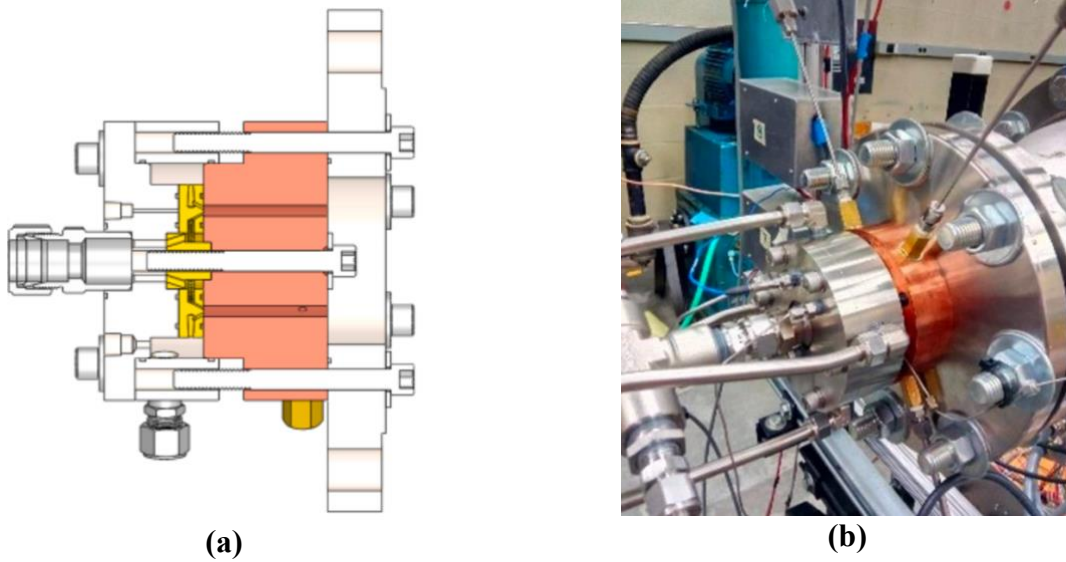


Figure 10: 2-inch Engine (51 mm)

(a) CAD Cross Section (b) Photograph Assembled [32]

The 2-inch (50.8 mm) RDRE was designed not as a geometric scaling of the 76 mm engine but as a deliberate departure from it: the combustor length was reduced from 76.2 mm to 50.8 mm, while the annular gap was held fixed at 5.0 mm rather than scaled to the ≈ 3.3 mm that geometric similarity would require. Holding the gap fixed while shrinking the diameter decouples the inner radius from the gap width, allowing the inner-radius-to-cell-size ratio to be varied independently of the gap. Unlike the 3-inch engine, the 2-inch engine's copper combustor walls are thick enough (≥ 19 mm minimum) that no outer stainless containment sleeve is required. The oxidizer plenum is radially fed through four 9.5 mm distributor lines, and the fuel plenum is axially fed through a single 25 mm weld-port fitting. A brass injector bushing aligns the centerlines of the injector and inner core with the outer wall to ± 0.025 mm. Instrumentation is deliberately restricted to three axial combustor pressure stations (versus the 76 mm engine's eight) to minimize port-induced disturbance of wave dynamics: a center, front, and back pressure tap.

Ignition on the 2-inch engine used both single-spark and pre-detonator configurations, but never a Wave Generator. The original installation used a single spark plug mounted opposite the center pressure tap, together with a downstream exit spark that acted as a flare-off igniter. Pre-detonator ignition was subsequently retrofitted by converting instrument-port holes into pre-detonator ports. The spark-ignited $\text{CH}_4\text{-O}_2$ pre-detonator was mounted radially in an instrument port of the combustor, in either the middle or the exit position [7]. It was first installed in the last (exit) instrument port, which left only two combustor pressure measurements, and was later relocated to the spark-plug port near the middle of the combustor; this freed an instrument port so that static pressure could be collected at three axial locations rather than two [7].

2.3.4: 1-inch (25 mm) Engine

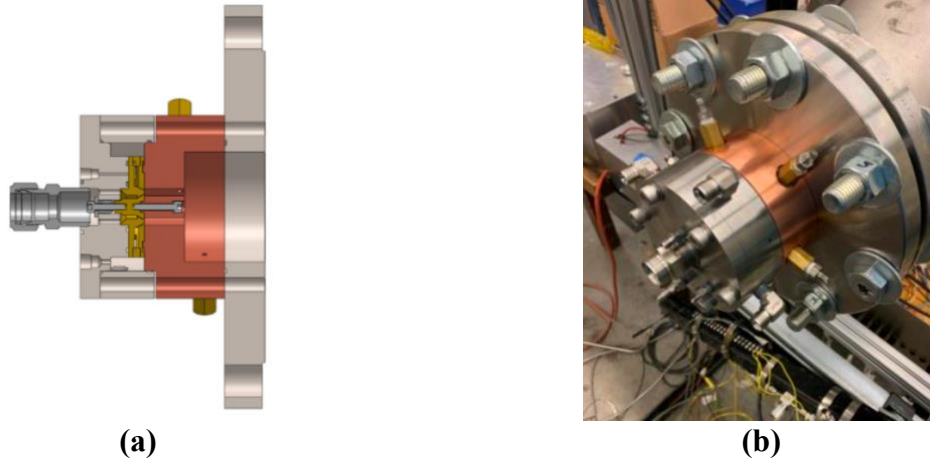


Figure 11: 1-inch Engine (25 mm)

(a) CAD Cross Section (b) Photograph Assembled [32]

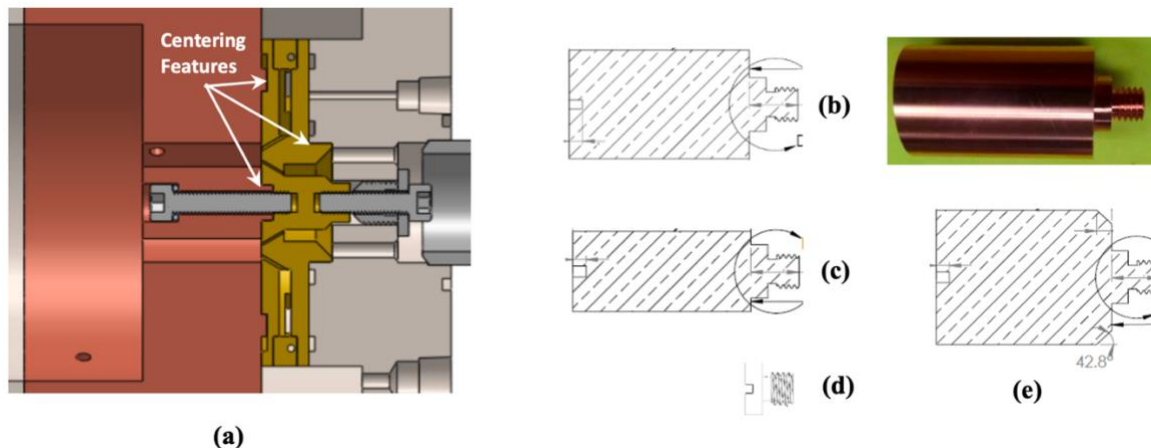


Figure 12: 1-inch Engine (25 mm) Cores

(a) 1-inch Engine (25 mm) Section View (b) 15.4 mm Core with Photo (c) 11.4 mm Core (d) Recess Plug for Coreless Testing (e) 19.4mm Core [32]

The 1-inch (25.4 mm) engine has a combustor length 25.4 mm and uses oxygen-free high-thermal-conductivity (OFHC) copper construction for the combustor, a brass injector, and an OFHC copper core plug. The engine had a modular design enabling various inner cores to be swapped producing annular gaps of 3, 5, or 7 mm, or coreless cylindrical operation when the core plug is replaced with a threaded blank that creates a flush injector face. To reduce part count and machining cost, the engine reuses the front endplate, oxidizer ring, and mounting flange of the 2-inch engine; the injector was redesigned to fit the smaller bore and bolts directly to the internal fuel-distributor section of the endplate. Manufactured tolerances are ± 0.013 mm for the injector and ± 0.025 mm for the inner cores. Instrumentation comprises four sidewall pressure ports plus one in the 76.2 mm exit section that joins the engine to the dump-tank piping, plus one dedicated pre-detonator port at the rear. Ignition was tested only with the pre-detonator; no spark system was installed on the 1-inch engine. The pre-detonator hardware uses the standard cross-shaped geometry described in 2.2.3: fuel and oxidizer ports impinging, a spark plug perpendicular to that axis, and the pre-detonator tube opposite the spark. Operation has been on $\text{CH}_4\text{-O}_2$ only. Multiple center-core geometries and core lengths have been tested in the engine; the pre-detonator port location remained fixed across these variations.

2.3.5: 10-mm Engine

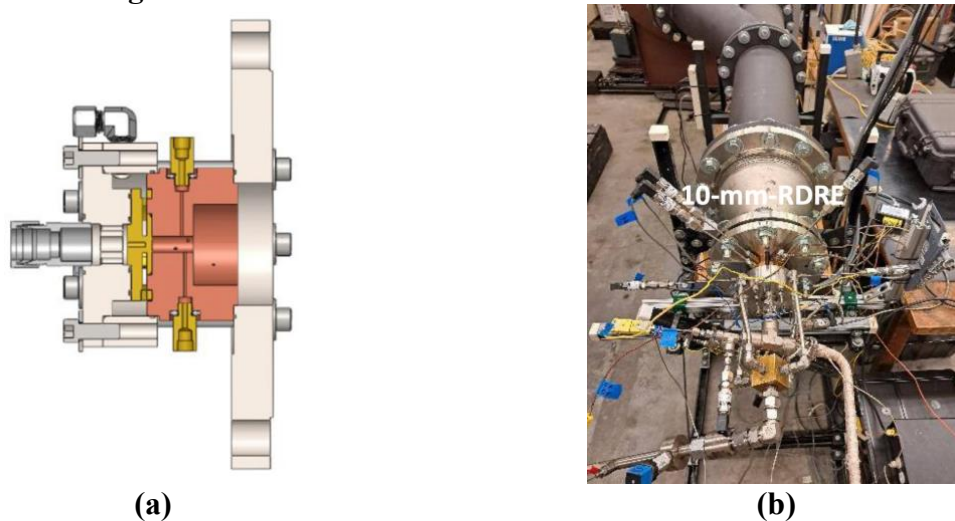


Figure 13: 10 mm Engine CAD Cross Section

(a) CAD Cross Section (b) Photograph Assembled [40]

The 10 mm RDRE is the smallest engine at UW and sits near the predicted lower size limit for sustained rotating-detonation operation, where the detonation cell width becomes comparable to the combustor's radius of curvature and gap. It is a cylindrical, heat-sink combustor operated without active cooling, and has been run primarily in a coreless configuration. A cored variant, formed by inserting a 6 mm center body to create a 2 mm gap, was attempted but proved impractical at this scale: the intense heat flux eroded copper and molybdenum cores within roughly 500 ms, and a tungsten core survived only a single test. Like the 154 mm engine, the 10 mm RDRE was tested on both methane–oxygen and hydrogen–oxygen. It is the only UW engine tested with heated propellant.

The combustor has an outer diameter of 10 mm, with an overall combustor length of 20 mm. In its primary coreless form, the combustor is a full-bore cylinder with no center body; the optional cored configuration produces the 2 mm annular gap noted above. Propellant is introduced at the head end through a single flat-faced impinging injector comprising twelve fuel-oxidizer doublets, with fuel orifices of 0.51 mm and oxidizer orifices of 0.81 mm, giving an oxidizer-to-fuel injector area ratio of about 2.56 and an injector-to-combustor area ratio of 0.11. This head-end impinging scheme, rather than the wall-mounted radial injection of the 154 mm engine, reflects the engine's small scale and its role in the laboratory's geometric-scaling program.

Ignition on the 10 mm RDRE was provided exclusively by a pre-detonator, with a tangential pre-detonator port placed near the exit of the core at the rear of the combustor. No spark-array or single-spark ignition was used at this scale. The reorientation of the cross-shaped pre-detonator geometry, placing the spark opposite the oxidizer inlet rather than opposite the pre-detonator tube, was developed and demonstrated on this engine, and raised ignition reliability to approximately 99%.

Instrumentation comprises nine sidewall pressure ports clustered at axial stations between 9 and 17 mm from the injector face, a back-pressure measurement port in the 51 mm exit section, and the pre-detonator port at the rear of the combustor; fast-response piezoelectric transducers resolve the spinning-wave dynamics. The heated-propellant system replaces the standard fuel line with a 0.61 m stainless steel tube wrapped in 200 W heat tape and PID-controlled to a 360 to 400 K wall temperature, raising the fuel exit temperature to approximately 330 K to aid methane–oxygen operation.

2.4: Data Sources

The primary data source for this work is the laboratory's historical run log, a shot-by-shot record that has been maintained continuously across the lab's engine campaigns. Each engine has its own run log, and the logs share a common structure. Every hot fire is assigned a sequential run number and recorded with its date, pre-run wall temperature, backpressure, and propellant supply conditions (bottle pressures and, in later campaigns, electronic regulator or orifice settings), together with the computed total mass flow rate and equivalence ratio, the ignition configuration used, and the combustion outcome, classified as detonation, deflagration, or no combustion. Where the diagnostics allow, the detonation frequency, wave count, and ignition time are also tabulated. A free-text notes field captures per-run changes such as hardware swaps, timing adjustments, and anomalies. High-speed video, recorded through the wye-section viewport with a Phantom v1211 camera, served as a source for investigating the startup transient and wave count.

Chapter 3: Results: Historical Record of Ignition Experiments

3.1: 6-inch (154 mm) Engine

All ignition testing on the 154 mm engine used the twelve-plug Wave Generator. Injection was radial throughout, and no major configuration change was made to the engine across the campaign, although an early tail cone was present in some test series. Both $\text{H}_2\text{-O}_2$ and $\text{CH}_4\text{-O}_2$ were run, spanning fuel-lean to fuel-rich, which makes the 154 mm engine-together with the 10 mm engine-one of only two UW engines tested on more than one propellant chemistry. The earliest run preserved in the present experiment logs is Run 476 (January 12th, 2018); the preceding runs belong to the Heath, Boening, and Wheeler campaigns and are documented in those theses rather than in these logs.

3.1.1: Wave Generator

3.1.2: Hydrogen-Oxygen Results

Hydrogen-oxygen operation was characterized across a range of equivalence ratios from fuel-lean to fuel-rich. Hydrogen-oxygen detonation was established on this engine very early in its operating history, within roughly the first ten runs of the campaign. The earliest $\text{H}_2\text{-O}_2$ run preserved in the available logs is Run 511 (February 13th 2018); the substantial number of preceding runs were not retained in these logs, so Run 511 marks the start of the recovered record rather than the first successful hydrogen detonation. The high-speed camera was not installed during the 154 mm campaign, so wave-direction interpretation rested entirely on high-frequency pressure-transducer data; for $\text{H}_2\text{-O}_2$ these data indicated that the rotating wave propagated in directional agreement with the prescribed spark sequence.

Several hardware milestones bracketed the hydrogen campaign. The first hydrogen run with a downstream spark plug was logged at Run 512 (February 21st 2018), and a single-spark configuration was attempted at Run 517 (February 26th 2018), but produced no combustion, with detonation recovered at Run 518 once the firing arrangement was restored. The Wave Generator was returned to service after a repair at Run 523 (March 29th 2018), where the reported equivalence ratio and mass flow were noted as anomalously high. Across these runs the driving frequency was held near 14.4 kHz at supply voltages of roughly 178-198 V, which together with the four-wave firing pattern set the seeding conditions for hydrogen detonation.

3.1.3: Methane-Oxygen Results and the Camera Campaign

Methane-oxygen was first run on this engine at Run 476 (January 12th 2018), the earliest run in the available logs and roughly fifteen months before the 76 mm engine's first hot fire. When a high-speed camera was later brought to bear during the $\text{CH}_4\text{-O}_2$ campaign, it revealed that the rotating detonation wave frequently initiated and then stabilized in the direction opposite to the spark-sequence direction. Wave direction is thus effectively decoupled from spark direction in $\text{CH}_4\text{-O}_2$ -a conclusion that the pressure-transducer data alone could not have supplied, and one that revised the earlier directional interpretation drawn from the $\text{H}_2\text{-O}_2$ runs. A short-lived hydrogen pre-detonator was also tested alongside the Wave Generator beginning at Run 524 (March 29th 2018), and coaxial ionization probes were introduced into the diagnostic suite over Runs 529-568 during this period.

3.2: 3-inch (76 mm) Engine

Section 2.3.2 established the four ignition configurations of the 76 mm engine and the central caveat that the igniter never changed alone. This section reports the results: how the engine started, how reliably each configuration ignited, where the engine operated, and what state it reached once running. Detonation outcomes are verified by measured wave speed wherever camera records exist; the Wave-Generator era predates the wave-speed records and enters the steady-state comparison only through imaging.

3.2.1: Startup Transient

The violence of a delayed ignition made the startup transient an operational concern from the first month of testing. An early radial-injection run logged a late ignition whose pressure spike registered plenum pressures roughly an order of magnitude above the steady operating value; the immediate response was a ten-hertz spark-pulse cadence and a shift of the spark timing by a tenth of a second to bracket the transient.

The ignition method determined how the engine started but not where it ran. High-speed imaging at matched conditions (equivalence ratios of 1.09 to 1.18, mass fluxes of roughly 160 to 210 kg/m²-s) shows two distinct startup paths, presented in Figure 14. With the Wave Generator, combustion luminosity built throughout the annulus before detonation appeared: the spark array fired continuously while the annulus filled, igniting a deflagration that subsequently accelerated to detonation. The single in-chamber spark followed the same deflagration-first pattern. With the pre-detonator, the annulus remained dark until detonation appeared directly: a single pulse delivered into an already filled annulus initiated the wave with no visible deflagration phase. In the dual-starter configuration either source could produce the initial ignition. The commanded sequences show the Big Spark firing tens of milliseconds before the pre-detonator; in a sample of ten dual-starter detonations, nine ignited off the pre-detonator and one ignited off the Big Spark, with combustion onset 32 ms before the pre-detonator fired. A quantitative deflagration-to-detonation time could not be extracted reliably from the imagery, since luminosity does not distinguish deflagration from detonation and the startup frames saturate, so the difference in startup path is reported qualitatively. Whether these different paths lead to different operating states is quantified in Section 3.2.4.

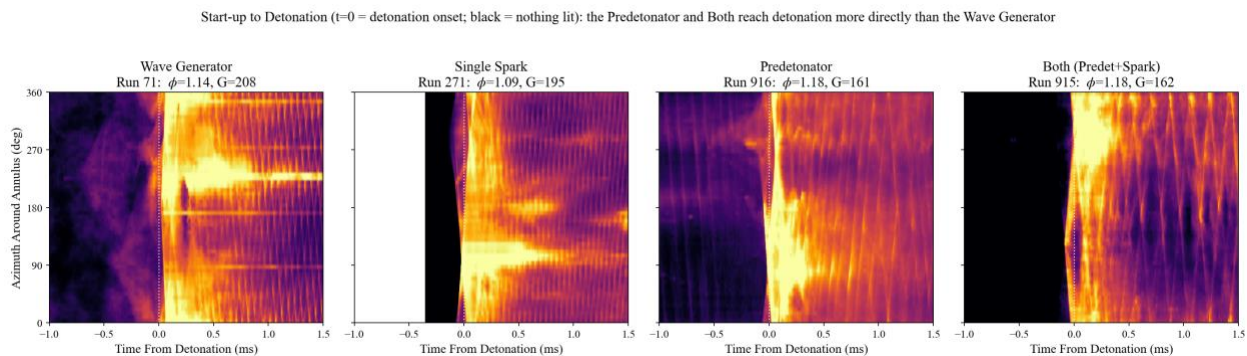


Figure 14: Ignition Methods Compared

3.2.2: Ignition Reliability and Failure Attribution

The switch to axial injection moved the mixing-completion point, and with it the detonation zone, to the front of the engine, where it sat directly on the spark plugs and consumed them. The log records repeated plug replacements throughout the single-spark era. Plug burnout, not an inability to ignite the mixture, was the era's defining reliability problem, and it directly motivated the move to pre-detonator ignition.

Raw ignition percentages overstate the differences between igniters because the no-ignition record mixes genuine igniter misfires with failures that have nothing to do with the igniter. Every no-ignition run in the campaign, 61 in total, was therefore classified individually against the operator notes, against the configuration's own demonstrated operating envelope, and against a twin test: a no-ignition was attributed to the igniter only when another run with the same igniter detonated at closely matched equivalence ratio, mass flux, and backpressure, so that the only meaningful difference within the pair was whether the igniter caught. Figure 15 presents representative pairs. The top row shows stochastic igniter misfires, each with a detonating twin at matched conditions; the bottom row shows condition-edge failures, for which no twin exists because the surrounding operating region fails regardless of igniter.

Of the 61 no-ignitions, only 10 are attributable to the igniter itself: 5 single-spark failures during the plug-burnout era and 5 isolated stochastic misfires across all other configurations combined. The remainder are 29 equipment and commissioning blocks, 13 condition-edge runs, 4 timing errors, 3 invalid records, and 2 deliberate tests of the Big Spark alone. Defining the true ignition rate as ignitions divided by ignitions plus genuine igniter misfires, the raw and true rates are: Wave Generator 95% raw, 99% true; single spark 85% raw, 96% true; pre-detonator 87% raw, 100% true; Both Starters 88% raw, 99% true. The pre-detonator never failed to light an ignitable mixture in 97 attempts. Critically, every burnout-era spark misfire had a detonating twin: the same operating point detonated on a spark run when the plug was healthy. Ignition reliability on this engine therefore reduces to igniter hardware durability rather than to any difference in what the methods could ignite.

3-inch run-by-run twin test: TOP — igniter misfires (X) have a matched same-igniter twin that detonated at the same ϕ , G , back pressure and temperature → attributable to ignition; BOTTOM — condition-edge failures sit alone (no twin)

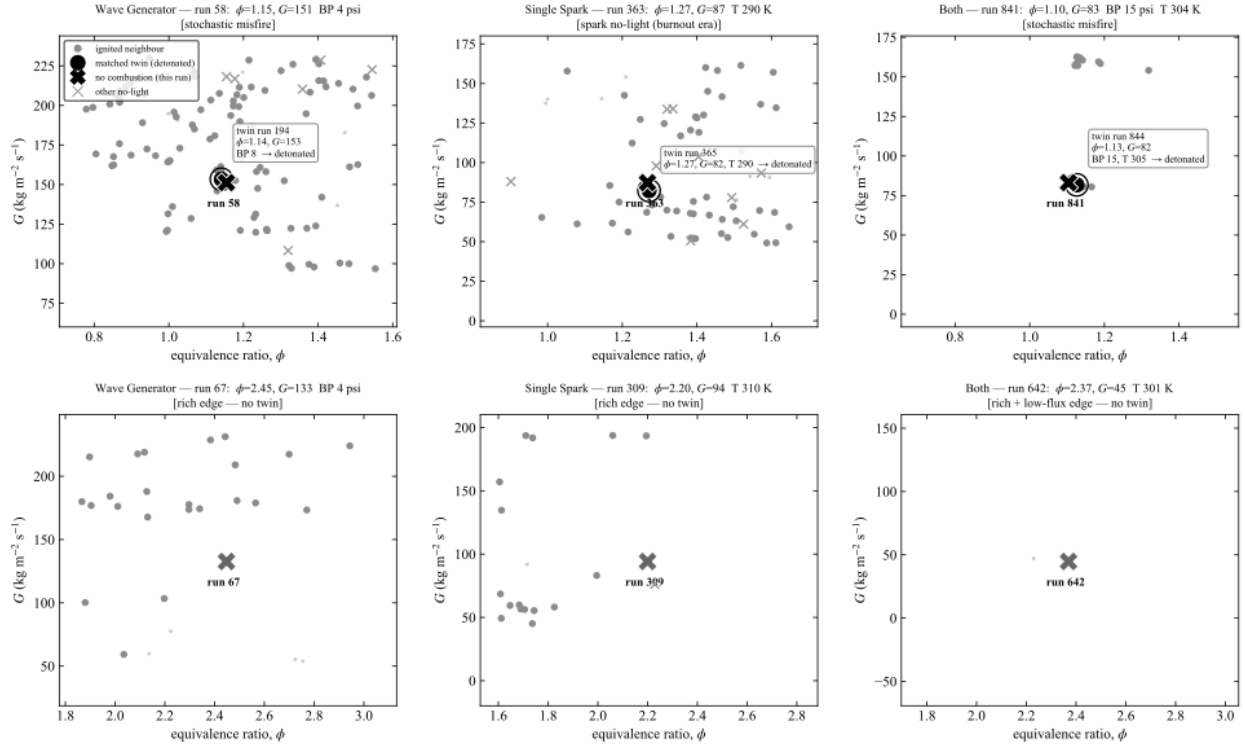


Figure 15: Ignition Failure Comparison 3-inch

Table 4: 3-inch Ignition Probability

Configuration	Scored hot fires	Raw ignition	No-ignitions (all causes)	Attributable to igniter	True ignition
Wave Generator	229	95%	12	2	99%
Single spark	149	85%	23	5 (burnout)	96%
Pre-detonator	97	87%	13	0	100%
Both Starters	94	88%	11	1	99%

3.2.3: Operating Envelope

Figure 16 maps every scored hot fire in equivalence-ratio and mass-flux space for the four ignition configurations: 229 Wave Generator runs, 149 single-spark runs, 97 pre-detonator runs, and 94 Both Starters runs (Table 4). The three radial-injection configurations detonate across the same window, roughly equivalence ratios of 0.5 to 1.5 and mass fluxes of 100 to 250 $\text{kg/m}^2\text{-s}$, with failures only at the lean, rich, and low-flux edges. The single-spark panel is the most scattered, but its successful runs span the same region (its own lit envelope reaches down to an equivalence ratio of about 0.43 and a mass flux of about 45 $\text{kg/m}^2\text{-s}$): the scatter is the plug-burnout record of the axial era, not evidence of a narrower ignitable envelope. Equivalence ratio bounded the envelope on both ends; mass flux bounded it only from below, with no upper flux limit encountered up to the roughly 380 $\text{kg/m}^2\text{-s}$ maximum tested. The operating boundary is set by the conditions, and no ignition method moved it.

Aggregated rates can disguise this. The block of runs that straddled the flow-choking-orifice experiment averaged 56% ignition, which splits into 8% (1 of 12) while the orifices throttled the feed to the low-flux edge and 100% (13 of 13) once they were removed. None of those failures is an igniter misfire at a normal operating point: where the conditions were ignitable, the igniters lit every run.

Backpressure completes the picture. A dedicated backpressure sweep at 200 g/s early in the Wave-Generator era found operation insensitive across the swept range, and dump-tank initial-pressure sweeps recur through the pre-detonator eras. At the end of the campaign the engine ran a sustained block of pre-detonator and Both Starters detonations at dump-tank pressures of 5 to 12 psia, extending the demonstrated envelope to low backpressure under the mature ignition configuration.

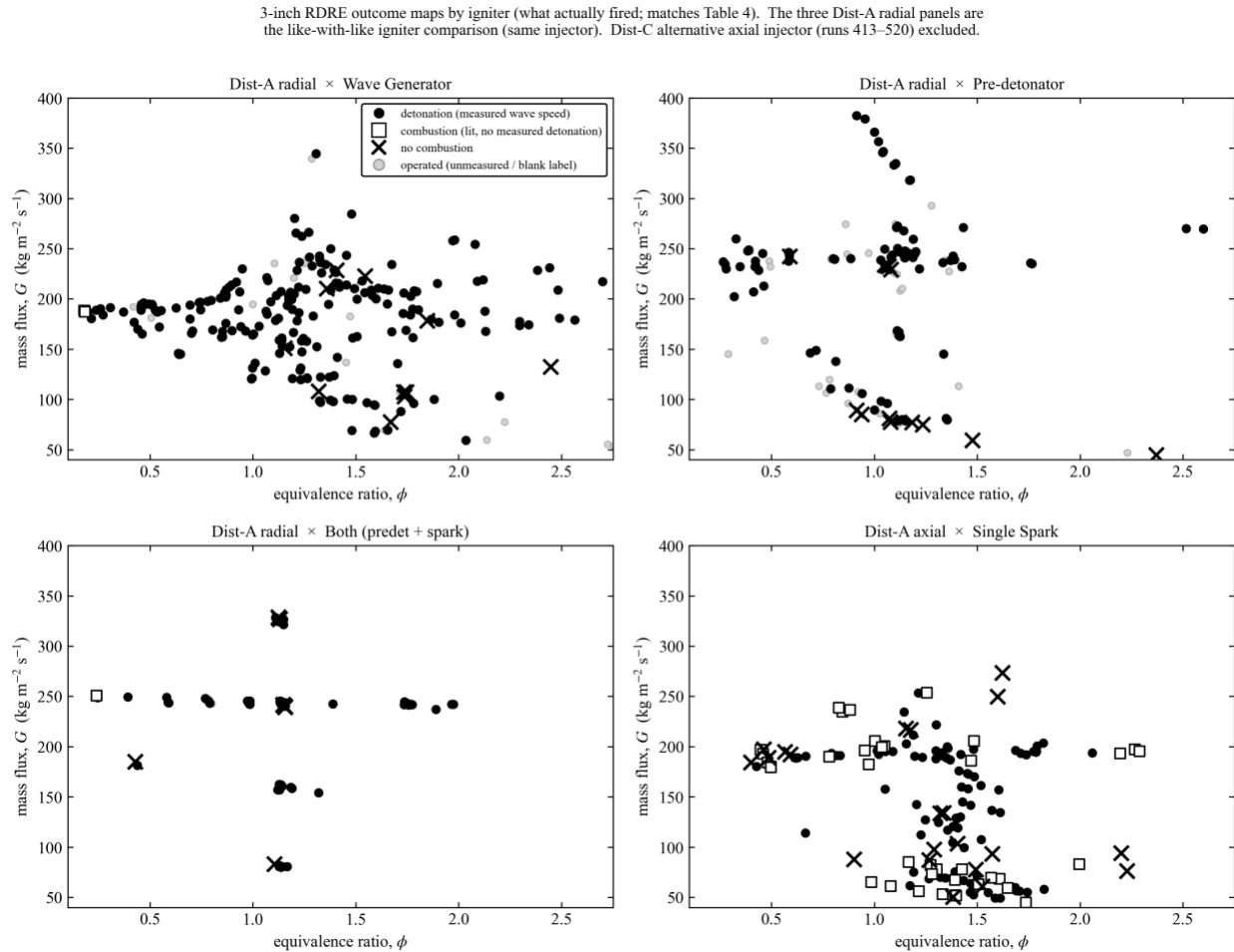


Figure 16: Test Matrix 3-Inch Engine

3.2.4: Steady State Operations

The startup differences of Section 3.2.1 do not carry into steady operation. The cleanest available igniter contrast is single spark against pre-detonator, the one comparison that does not

cross the orifice-to-sonic metering upgrade. At matched equivalence ratio, mass flux, and backpressure, that contrast is null on both observables: the fraction of Chapman-Jouguet speed differs by -0.007 in matched twin pairs ($p = 0.43$) and by +0.006 in regression ($p = 0.62$), and the wave count differs by +0.06 waves ($p = 0.33$), despite the comparison also spanning the axial-to-radial injection change. In a regression over the same data, the ignition-method term is not significant after equivalence ratio and mass flux are controlled ($p = 0.36$ for wave speed, $p = 0.31$ for wave count), while equivalence ratio dominates: each unit of equivalence ratio lowers the speed fraction by roughly 0.10 ($p < 1e-20$). Wave count follows mass flux through the same two-to-three-wave staircase near 220 kg/m²-s for every igniter, and below 120 kg/m²-s every igniter ran exactly two waves ($p = 0.37$). The remaining contrasts, single spark or pre-detonator against Both Starters, cross the sonic-nozzle metering upgrade, shift wave speed and wave count together in the signature of a flux-measurement change, and are partly explained by a measurement-radius convention between data reductions (periphery versus median radius, a ratio of 1.07); they are reported as era and measurement artifacts, not ignition effects.

Matched-condition imaging confirms the statistical result. At equivalence ratios near 1.18 on the radial injector, Wave Generator, pre-detonator, and Both Starters runs all establish the same two-wave co-rotating mode; a single-spark run at higher backpressure ran three waves, consistent with the smaller detonation cell at higher pressure rather than with any igniter effect. The Big Spark provides the final piece: fired alone in its original downstream position it did not ignite the engine on either attempt, but after relocation to the annulus exit the log attributes one detonation directly to it (Run 662), at 0.72 of Chapman-Jouguet speed on the same equivalence-ratio trend as the pre-detonator detonations. Two different starters, and two different start paths within the dual configuration, delivered the engine to the same steady state: the igniter starts the engine, and the propellant conditions and geometry determine what it becomes.

3.3: 2-inch Engine (51 mm)

The 2-inch engine was run exclusively on CH₄-O₂ and, after its first hot fire, a pre-detonator. It was deliberately designed for minimum flow perturbation, carrying only three combustor pressure taps, one center, one front, and one back, out of a concern that additional taps might disturb the wave dynamics. The campaign was the most compact in the UW record: 133 logged runs over roughly one month, from the first hot fire at Run 14 through Run 133 all in a single injector and core geometry. Run 1 was a dry run whose hot-fire timings were copied wholesale from the 76 mm engine at Run 974, giving the campaign a direct inheritance from the immediately preceding engine. Runs 2 through 13 the same day were cold flow checks of the oxidizer and fuel circuits, and the first hot fire followed at Run 14.

3.3.1: Single-Spark Configurations

Consistent with the minimum-perturbation design, the engine's first igniter was a single spark plug in the chamber sidewall opposite the center pressure tap, the least intrusive ignition option and one that, unlike a pre-detonator, required no dedicated injection port. A second spark at the downstream exit served as a flare-off igniter to consume unburned propellant before it reached the dump tank. The first hot fire, Run 14, used the annular spark alone and produced no combustion, although the plug fired and the sparks were visible in the high-speed video. The

propellant flow, regulator setpoints, and run timing had been copied from the 76 mm engine at Run 974, a pre-detonator-ignited run.

This was the only spark-only hot fire of the campaign. A single attempt is not a controlled test of spark ignition at this scale and Run 14 should not be read as establishing that the spark is incapable of igniting the engine; it establishes only that the spark-only configuration did not ignite on this one occasion. On the very next run a sidewall pressure port was repurposed for a pre-detonator, and the engine ran on the pre-detonator for the remainder of the campaign.

3.3.2: Pre-detonator

Combustion was first achieved with the pre-detonator at Run 15, the run immediately following the single spark attempt, and pre-detonator ignition was used for every subsequent hot fire. The run notes for Run 15 record that the pre-detonator was installed, the last axial capillary-tap probe was sacrificed to make room for the pre-detonator port, and the timing was copied from the 76 mm engine at Run 974. Once in place, ignition was effectively immediate, and the engine ran combustion runs essentially every test day thereafter. Because the spark was attempted only once before the switch, the campaign is best read as an engine that briefly tried spark ignition and then adopted the pre-detonator, not as a controlled comparison between the two methods; it was the pre-detonator's established reliability on the preceding 76 mm engine, not a head-to-head test, that motivated the change.

The published 25- and 51-mm results report that the pre-detonator was first installed in the last instrument port, at the combustor exit, and later relocated to the spark-plug port near the middle of the combustor; the move freed an instrument port so that static pressure could be collected at three axial locations rather than two, and repeat tests showed that it did not affect the wave dynamics [7]. This engine change is not recorded in the run log: neither the two configurations nor the run at which the igniter was relocated appears in the logged data, so the timing of the move and the detail of the two geometries survive only in the published account. It is a gap in the primary record. What the log does establish is that the change had no effect on ignition, which remained reliable on the pre-detonator both before and after the move.

Run 46 was the first major maintenance event, a full disassembly in which the inner-core seals were replaced, and the injector and core were cleaned of residue. The fuel pre-purge was removed at Run 126, and the campaign closed at Run 133.

3.3.3: Results

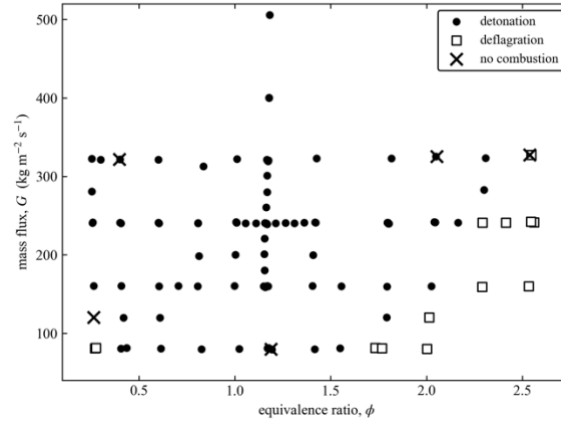


Figure 17: Engine 2-Inch (51 mm) All Runs

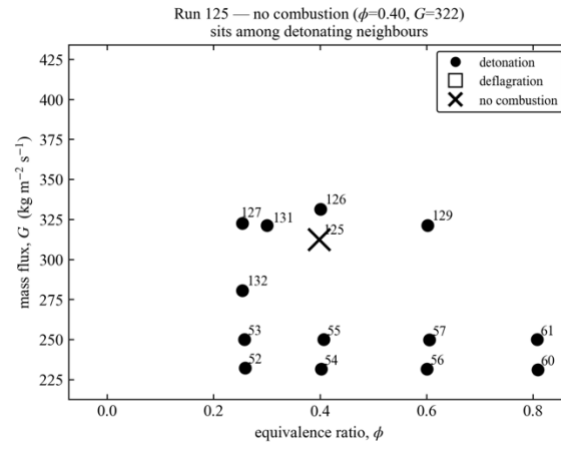


Figure 18: Run 125 Engine 2-Inch (51 mm)

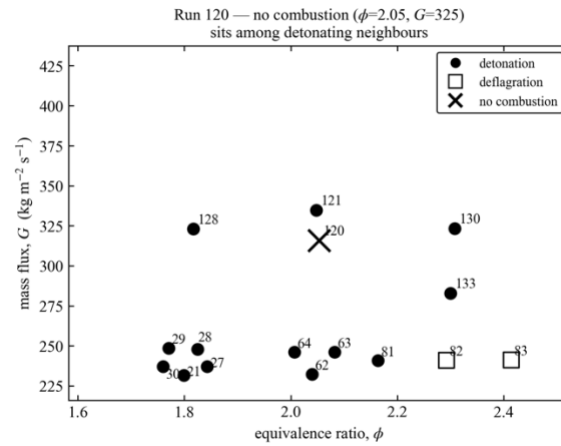


Figure 19: Run 120 Engine 2-Inch (51 mm)

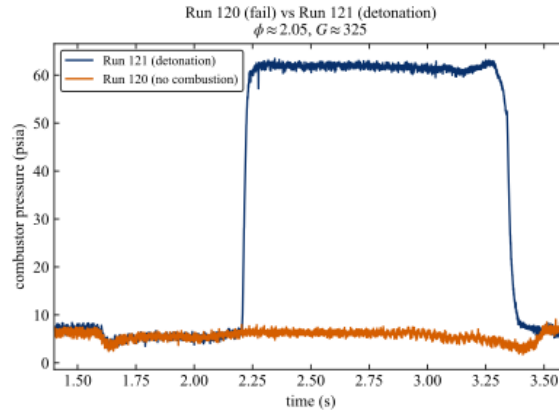


Figure 20: Run 120-121 Engine 2-Inch (51 mm)

The 51 mm engine primarily only used one geometry and one igniter, the pre-detonator, which makes it the cleanest case in the program for separating the role of the igniter from that of the operating conditions.

Of the 112 pre-detonator hot fires, 94 detonated, 13 deflagrated, and 5 did not ignite, so the engine ignited on 107 of 112 attempts (96 percent) and detonated on 94 of 112 (84 percent). Detonation occurred from an equivalence ratio of about 0.25 to about 2.4 wherever the mass flux was sufficient, and deflagration appeared only at the rich limit above about 2.4 and at the extreme-lean, low-flux corner. The boundary between detonation and deflagration was set by the fueling conditions, not by the igniter, which was identical for every run.

The five non-ignitions are the central result. Each occurred where neighboring runs at the same equivalence ratio and mass flux ignited normally, and three have a detonating companion at essentially identical conditions: Runs 39 and 40, Runs 125 and 126 (Figure 18), and Runs 120 and 121 (Figure 19). A failure surrounded by successes at the same operating point cannot be attributed to that point. Back pressure, wall temperature, and plenum pressure matched within each failure-and-neighbor pair, and the pre-detonator firing time does not predict failure, since firing early was the normal practice and ignited the engine about 95 percent of the time. The clearest case is Runs 120 and 121: identical equivalence ratio, mass flux, back pressure, and both plenum pressures, yet one produced no combustion and the other a strong detonation, with the combustor pressure staying at its cold-fill value in the non-ignition and rising sharply in the detonation seen in Figure 20. The failures are therefore isolated, condition-independent misfires of the igniter.

3.4: 1-inch (25 mm) Engine

The 25.4 mm engine was run exclusively on CH₄-O₂. Ignition was entirely by pre-detonator-no spark system was ever installed on this engine, so it represents the lab's first fully pre-detonator-only engine from its first hot fire. The engine carried more pressure taps than the smaller engines, and the available log runs from the first hot fire at Run 16 January 20th, 2021, through Run 438 on May 7th, 2021.

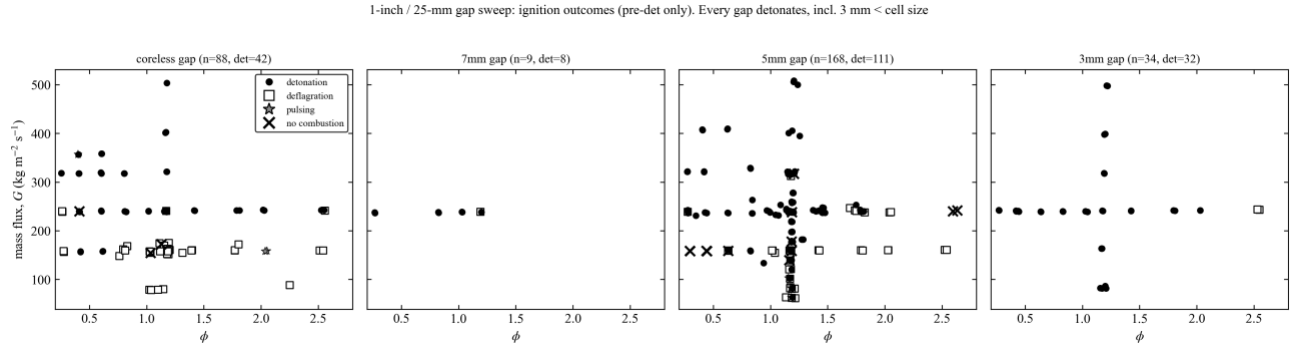


Figure 21: Engine 1-Inch (25 mm) All Runs

During 1-inch testing it was devoted to testing different center cores, core lengths, and annular gaps-including 3 mm, 5 mm, and 7 mm gaps as well as coreless configurations-while the pre-detonator igniter remained at the same location throughout. The tests for mass flux vs equivalence ratio for each gap size can be seen in Figure 21. The pre-detonator ignited reliably across all these core variations, but the cores themselves did not survive: every center core eventually burned up in service.

The analysis began by reducing the full 438-run log to a scorable set. Of the 438 logged runs, 131 were cold-flow or dry checks of the propellant lines that involved no combustion, and a further eight were hot-fire attempts whose equivalence ratio, mass flow, or outcome was not recorded, both groups were set aside. This resulted in 299 scored hot fires. Each of the 299 was assigned to the gap it ran under from the configuration sections marked in the log, and its mass flux was computed with the annular area of that gap, since the flow area changes with the core size. The hot fires split across the four geometries as 168 at the 5 mm gap, 88 coreless, 34 at the 3 mm gap, and 9 at the 7 mm gap, reflecting how long each configuration was held before its core was changed or burned up. By outcome, 193 of the 299 produced a rotating detonation, 91 produced a deflagration or an axial pulsing mode without a steady rotating wave, and 15 did not ignite at all.

The fifteen non-ignitions were the focus of the analysis, because the question for an ignition study is whether a no-light reflects a failure of the igniter or a limit of the operating conditions. To separate the two, each non-ignition was compared against the runs that did light at the same gap. For every failed run the analysis searched for a twin, a run at the same gap and nearly the same equivalence ratio, mass flux, and back pressure that nonetheless detonated. A failure with such a twin cannot be blamed on the conditions, since a nearly identical run lit, and is attributed to the igniter; a failure with no twin sits alone at the edge of the operating envelope, where the mixture or flow was too lean, too rich, or too sparse to burn, and is attributed to the condition. Detonation itself was confirmed from the measured wave speed where high-speed video was available, on 151 of the 193 detonations, rather than from the run-log text alone, and each failure's run note was read to catch causes a neighbor comparison alone would miss, such as a deliberately disabled igniter or an altered flow timing. By this procedure the fifteen non-ignitions split into two groups. Seven are genuine pre-detonator misfires, in which a near-identical run detonated, so the igniter is at fault. The other eight are not the igniter at all: six are condition-limited, meaning the mixture was too lean or too rich, or the flow too sparse, for any igniter to light it; one was caused by a change to the flow timing; and one was the deliberate pre-detonator-

disable test. Removing those eight non-igniter cases from the failure count is what raises the raw ignition rate to the true rate reported.

The attribution of a non-ignition to the conditions rather than to the igniter can be checked directly because the runs surrounding each failure carry their own evidence. The procedure is deliberately conservative toward the igniter: a no-light is charged to the igniter whenever a near-identical run detonated, and to the conditions only when no such run exists, so the seven misfires are an upper bound on igniter failures at points that were demonstrably ignitable. The condition-limited failures then rest on positive evidence rather than on the absence of a twin. At the rich edge of the 5 mm gap the outcome decays smoothly as the mixture is enriched: by an equivalence ratio of about two the engine had stopped detonating and only deflagrated, so the two non-ignitions near 2.6 are the far end of a continuous chemical degradation that every run followed, not isolated misses among detonations. At the lean edge the failures occur specifically at low mass flux, and the same pre-detonator is seen to light the engine both at the same lean equivalence ratio when the flux is higher and at the same low flux when the mixture is richer, so it is the combination of a lean mixture and a low flux that fails, a property of the combustion envelope and not of the igniter. The two remaining non-igniter cases are documented in the run notes rather than inferred, one recording a change to the flow timing and the other the deliberate disabling of the pre-detonator.

Table 5: 1-inch Outcome

Gap	Misfires
3 mm	0
5 mm	5
7 mm	0
coreless	2

Table 6: Comparison Between 1-inch Runs

Run	Gap (mm)	ϕ	Mass flux (kg m ⁻² s ⁻¹)	Backpressure (psi)	Wall Temp. (K)	Outcome
216	5	1.16	180	0.5	296	No combustion
220	5	1.16	179	0.5	296	Detonation

Table 7: Comparison Between 1-inch Runs Timing

Sequence Parameter	Run 216 (no comb.)	Run 220 (detonation)
Fuel valve on / off	1.70 / 2.80	1.70 / 2.80
Ox valve on / off	1.75 / 2.80	1.75 / 2.80
Pre-detonator fuel trigger on / off	1.795 / 2.095	1.795 / 2.095
Pre-detonator ox trigger on / off	1.795 / 2.095	1.795 / 2.095
Spark on / off	2.10 / 2.30	2.10 / 2.30
ER fuel / ox on	1.80 / 1.8	1.80 / 1.8
Run duration	5	5

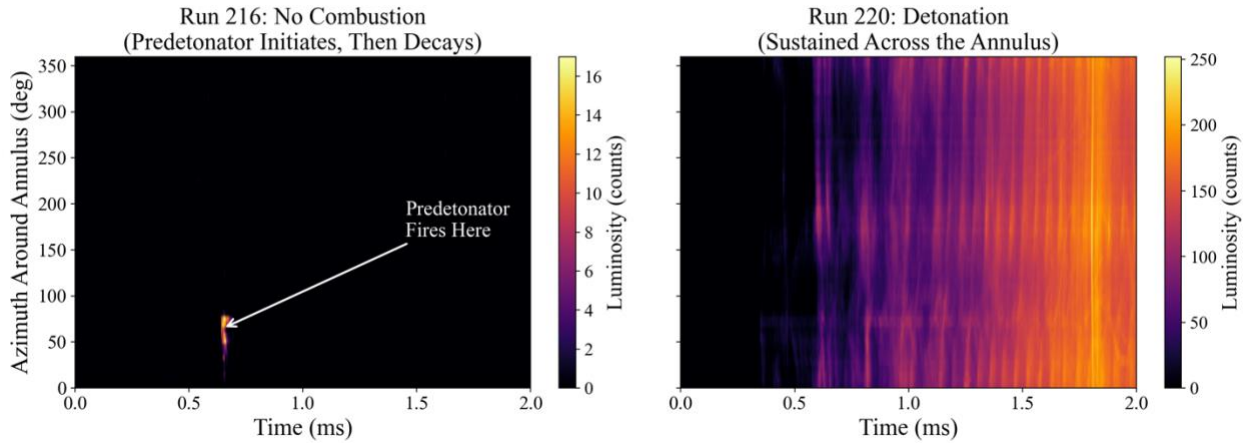


Figure 22: Comparison Between 1-inch Runs High-Speed Video

The strongest single demonstration that the misfires are the igniter, and not an unrecorded operating difference, is a matched pair at the 5 mm gap. Run 216 produced no combustion while run 220, a few runs later, detonated, and the two are identical not only in equivalence ratio (1.16), mass flux (about $180 \text{ kg m}^{-2} \text{ s}^{-1}$), back pressure (0.5 psia), and wall temperature (296 K), but in their entire commanded ignition sequence: as Table 7 shows, the fuel and oxidizer valve times, the pre-detonator fuel and oxidizer triggers, the spark window, and the run duration are identical.

High-speed video of the two runs, unwrapped around the annulus into the azimuth-versus-time maps of Figure 22, shows what differed. In each map the engine's annular channel is unrolled into a straight line: the vertical axis is azimuthal position around the annulus ($0\text{--}360^\circ$), the horizontal axis is time, and color encodes the local combustion luminosity, so a rotating detonation appears as bright bands sweeping diagonally across the map while a failed ignition appears as an isolated bright spot that fades. On run 220 the luminosity rises across the whole annulus and sustains. On run 216 the pre-detonator fires, producing a brief localized flash at its injection port, but the disturbance never spreads around the annulus and decays within a fraction of a millisecond, leaving the combustor dark for the rest of the run. The pre-detonator initiated; the detonation failed to transition into a sustained rotating wave.

This also locates where, and why, the pre-detonator misfires. The seven genuine misfires do not fall in the bulk of the engine's operation but on the low-pressure boundary of its envelope: four of the seven, including run 216, sit in the lowest few percent of back pressure recorded, near the near-vacuum dump-tank limit, and the remainder at low mass flux or lean mixtures. Each of these lowers the combustor pressure and so enlarges the methane-oxygen detonation cell size, pushing the smallest engine in the program closest to its detonability limit, the same limit the 3 mm-gap result showed it runs against. At that margin the pre-detonator wave must still diffract out of its 6.4 mm tube into the much larger annulus and re-establish a detonation, and whether it succeeds depends on the instantaneous state of the propellant at the port, the local mixedness and the microsecond-scale fill and wave timing, none of which the bulk equivalence ratio, mass flux, back pressure, or commanded sequence record. Run 220 met that margin and locked in; run 216,

at the same recorded conditions, did not. The misfire is therefore not true randomness but the signature of an engine operating at the edge of detonability, where the outcome turns on an unrecorded micro-state. Away from that edge of detonability, in the bulk of the envelope, the pre-detonator lit every run.

3.5: 10-mm Engine

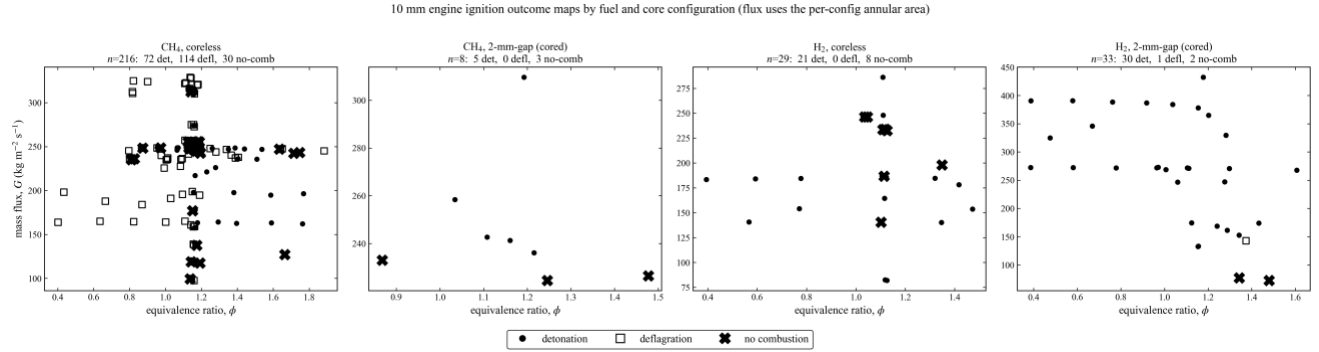


Figure 23: 10 mm Engine Ignition Outcomes

The 10 mm engine used pre-detonator ignition exclusively, with a tangential pre-detonator port located at the exit of the core. It was run on both H₂-O₂ and CH₄-O₂ and in both cored and coreless configurations, which-together with the 154 mm engine-makes it one of only two UW engines tested on more than one propellant chemistry. The pre-detonator was exercised extensively on this engine, and that volume of testing produced the clearest evidence in the UW program on how pre-detonator cross-geometry governs ignition reliability.

The 10 mm engine is the smallest engine in the UW series and the most recent. Its campaign was conducted by Shipman (2025) and does not have a public hot-fire log in the same form as the 3-inch, 2-inch, and 1-inch engines; the runs are described in Shipman's thesis and the body of evidence cited here is consistent with that source. The engine retained the same closed dump-tank exhaust, ER5000 pressure regulation, and critical-flow-nozzle metering used on the smaller engines, so the only first-order changes between this campaign and the 25.4 mm campaign were the engine's physical scale, the propellant heating, and the pre-detonator cross geometry.

3.5.1: Pre-detonator Performance with and without Cores

Both cored and coreless configurations were ignited reliably by the pre-detonator across H₂-O₂ and CH₄-O₂. As on the 25.4 mm engine, core survival was the limiting consideration rather than ignitability: at the 6 mm core / 2 mm gap geometry, copper and molybdenum cores both failed thermally and only a tungsten core survived a single test, so most operation was conducted coreless. The pre-detonator ignited the engine across these configurations, but before the geometry change described below-the reliability in CH₄-O₂ was inconsistent enough to warrant investigation.

The core-failure pattern at 10 mm is consistent with the 25.4 mm result: the heat flux into a centerbody at this scale is high enough that a solid copper core does not survive long enough to

characterize the engine, and even molybdenum—which has a substantially higher melting point and lower thermal conductivity than copper—did not survive either. The single tungsten test that did survive one run established that the failure mode is melting rather than something more exotic such as a chemical attack of the center body, but tungsten cores are not a routine option for this engine. Coreless operation therefore became the standard for the 10 mm campaign, exactly as the 25.4 mm engine progressed toward coreless operation across most of its later sections. To support sustained operation at this scale, the propellant feed to the engine was heated: a 0.61 m stainless-steel tube wrapped with a 200 W heat tape and PID-controlled to a 360–400 K wall temperature delivered fuel to the injector at roughly 330 K, which helped keep the smaller injector orifices clear of condensation and stabilized inlet conditions across runs.

3.5.2: Cross-Geometry Reorientation: Spark Opposite Oxidizer

The inconsistent ignition was traced to a flow asymmetry inside the cross-shaped pre-detonator. In the original cross, the fuel and oxidizer streams impinged head-on, and the spark sat centered between them. At near-stoichiometric conditions in $\text{CH}_4\text{-O}_2$ the oxidizer stream appeared to dominate the impinging flow and to displace the well-mixed region toward one side of the cross, so the centered spark was not reliably sitting in the combustible mixture. Reorienting the geometry corrected this: the fuel and oxidizer ports were placed at ninety degrees to one another, and the spark plug was moved to sit opposite the oxidizer port rather than centered between the streams. With the spark relocated into the region where the displaced mixture collected, ignition reliability rose to roughly ninety-nine out of one hundred attempts—a major improvement over the centered arrangement. This cross-geometry reorientation has not been reported in the existing UW publications and is a primary contribution of this thesis.

3.5.3: Spark-Location Effects on Plug Life

Relocating the spark plug as part of the cross reorientation produced a second practical benefit: it greatly reduced spark-plug burnout. In the earlier opposing-jet configuration, the spark plug had to be replaced frequently because the spark was required to bridge a relatively long distance, often of 0.5 to 1 inch, before reaching a sufficiently mixed fuel-oxidizer region. As the plug eroded and the spark energy degraded, even small changes in the effective spark gap could prevent reliable ignition. After the cross was reoriented, the oxidizer and fuel streams were directed across the spark-plug tip, placing the spark directly in the mixed region rather than forcing it to jump into that region. This change allowed the same spark plug to be used for hundreds of runs, even as its nominal spark strength degraded.

3.6: Cross-Cutting Findings

3.6.1: Operating Conditions as the Governing Parameters

Across all five engine scales, the steady operating state, was governed by the prevailing operating conditions rather than by how the engine was ignited. Mass flux, equivalence ratio, backpressure, and annular geometry each defined a detonability margin, and the igniter determined only how quickly the engine reached whatever state those conditions supported.

Mass flux set the operating threshold across every engine scale tested. Below a minimum flux level, detonation could not be established or sustained regardless of engine size, fuel, or ignition method; the igniter was simply unable to overcome a detonability margin that the flow conditions did not support. As flux increased above that threshold, ignition reliability improved consistently. No upper flux bound was encountered across the UW experimental envelope. In this sense, mass flux defined the floor of operability, and the igniter's role was to start the engine once the flow conditions cleared that floor, not to determine where the floor sat.

Equivalence ratio defined how much chemical energy was available to the detonation wave and carried both a lower and an upper bound. Operation near stoichiometric consistently produced the most reliable detonation, while both very lean and very rich mixtures moved the operating point toward deflagration or no-ignition regardless of engine scale or ignition method.

Backpressure also influenced the detonability margin. Higher backpressure raised the combustor pressure, which reduced the detonation cell size and improved ignition reliability. This effect was consistent across engines and aligned with the broader observation that conditions which increase combustor pressure tend to widen the margin toward reliable detonation.

Detonation cell size is the physical mechanism that unifies all four governing parameters. Equivalence ratio and combustor pressure, the latter set jointly by mass flux and backpressure, determine the cell size for a given fuel and mixture state. Whether that cell fits within the annular gap is a function of engine geometry. Larger engines with wider annular gaps accommodate more cells across their width and consequently operate with greater margin; smaller or coreless configurations that place the cell size close to the channel width sit near the detonability limit regardless of ignition method. The igniter can only start what the flow conditions and geometry can sustain.

3.6.2: Cross-Geometry Pre-detonator Reliability

Swapping the pre-detonator hardware from the original arrangement, where the spark plug was located opposite the fuel-oxidizer interaction region, to the revised arrangement, where the spark plug was placed opposite the oxidizer jet while fuel entered along the main passage, produced a clear improvement in ignition operability. The result suggests that ignition was not limited simply by spark energy, but by whether the spark plug was supplied with a locally flammable mixture. In the revised orientation, the higher oxidizer flow likely penetrated the fuel stream, drove local shear and entrainment, and routed mixed reactants toward the sparkplug before the flow was swept downstream into the pre-detonator tube. In contrast, the original configuration allowed fuel and oxidizer to mix near the central jet interaction region, but the spark location was less directly connected to that mixed flow. This configuration change therefore indicates that spark placement relative to the local fuel-oxidizer transport field was a controlling factor in pre-detonator ignition reliability.

Chapter 4: Discussion and Conclusion

4.1: Implications for Future RDRE Design

The UW RDRE ignition history demonstrates that multiple ignition methods can achieve reliable startup when the engine operates within a detonable envelope. The Wave Generator, single-spark ignition, and pre-detonator ignition all produced sustained rotating detonation under favorable conditions. This indicates that the ignition source itself is rarely the limiting factor once the mixture composition, pressure, mass flux, backpressure, and combustor geometry are sufficient to support detonation. An effective RDRE starter must deliver energy into a locally detonable mixture, but the engine must first provide conditions that allow this disturbance to develop into a sustained rotating wave.

The practical differences between ignition methods remain important. Both the single-spark and Wave Generator configurations demonstrated that direct ignition in the annulus can initiate rotating detonation, so spark-based ignition should not be dismissed as ineffective. However, in-channel spark hardware is exposed to the combustor environment, making plug erosion, burnout, and local flow disturbance important design considerations. If these effects are understood and acceptable for the intended operating duration, spark-based ignition remains a viable starting approach.

Pre-detonators offer a practical advantage by relocating the spark event from the main annulus to a separate tube. This reduces the need to place spark hardware directly in the detonation channel and helps isolate the ignition system from the sustained annular detonation environment. However, the UW results also show that pre-detonator reliability depends strongly on proper mixture preparation within the tube. The small-engine cross-geometry change demonstrated that reliable operation required a combustible fuel-oxidizer mixture to exist at the spark gap when the plug fired, not merely that fuel, oxidizer, and spark energy were all present.

The broader design implication is that RDRE ignition hardware should be selected after the combustor detonability margin is understood. Cell size, annular gap, radius of curvature, pressure, equivalence ratio, mass flux, and backpressure determine whether the engine can capture and sustain a rotating detonation. If the engine operates near this limit, changing the igniter alone may not yield reliable performance. Once adequate geometric and operating margin is established, the ignition method should be chosen based on practical requirements such as durability, packaging, repeatability, flow disturbance, and required number of starts.

4.2: Recommendations for Future Work

The observed improvement from the revised pre-detonator orientation suggests a useful future project for another student in the UW RDRE laboratory. In this work, the hardware change was evaluated through engine-level ignition reliability, but the local flow mechanism responsible for the improvement was not directly measured. A focused follow-up study could use the existing UW pre-detonator geometry to examine how the relative placement of the fuel inlet, oxidizer inlet, and spark plug controls mixture delivery to the spark gap. In addition to comparing geometry, it would be useful to vary the fuel and oxidizer injection velocities or momentum-flux ratio, since these parameters affect jet penetration, shear mixing, and the resulting mixture

quality at the spark gap. Although this effect was not tested in the present work, it provides a plausible mechanism by which the revised orientation could have improved ignition.

Another mechanism worth future investigation is the effect of pre-detonator entry angle into the RDRE chamber. In the UW hardware, larger engines used radial entry while the 10-mm engine used tangential entry. Although the present work suggests that steady RDRE operation is governed primarily by operating conditions such as mass flux, equivalence ratio, and backpressure, the pre-detonator entry angle may still influence the startup transient by changing how products, impulse, and momentum are deposited into the combustor. A tangential entry could add azimuthal momentum and potentially bias the initial rotating-wave direction. In contrast, a radial entry bifurcates the initial wave into two counter-rotating fronts, leaving the eventual wave direction determined by conditions rather than geometry [34]. This question could be examined in both cored and coreless RDRE geometries while holding annular gap width, mass flux, equivalence ratio, and backpressure fixed. Such a controlled comparison was not possible with the current UW dataset.

A third mechanism worth future investigation is the sensitivity of pre-detonator ignition to injection impulse. Bilgin, Keller, and Breidenthal [31] showed that hot-jet ignition of a combustible mixture is governed by a short-pulse Damköhler number, defined as the ratio of the vortex rotation time to the chemical ignition delay time. Injection impulse has competing roles in this framework: increasing impulse enlarges the vortex and extends the rotation time, raising the Damköhler number, while also promoting deeper penetration and dilution of the hot products, which lowers the effective ignition temperature and extends the chemical delay. It was found that temperature effects dominate through the exponential dependence of chemistry on temperature. Together these suggest an optimal injection impulse range may exist, motivating systematic variation of pre-detonator fill pressure as a future study parameter. A systematic variation of pre-detonator injection impulse was not performed in the present work. Therefore, a focused follow-on study could vary pre-detonator fill pressure while holding engine conditions fixed and connect RDRE pre-detonator ignition to the Damköhler framework.

4.3: Conclusion

The present results suggest that the ignition method has little measurable effect on the steady operation of the engine once a rotating detonation has been established. Operating frequency and sustained wave behavior appear to be governed primarily by the engine operating condition rather than by whether ignition was provided by a pre-detonator, Wave Generator, or spark system. The pre-detonator may produce a slightly faster startup transient, likely because the deflagration-to-detonation transition occurs more directly within the annulus, but this effect does not appear to persist into steady operation.

A second major finding is that many runs originally classified in the logs as ignition failures were not true ignition-system failures. The data indicate that failed or poor starts were usually associated with operating conditions that made detonation difficult, especially low mass flux, low equivalence ratio, or low back pressure. These parameters all influence mixture sensitivity and effective detonation cell size, which suggests that the observed failures were more often caused by unfavorable detonation conditions than by the igniter itself. This conclusion is

supported by comparisons between runs with similar timing, mass flux, equivalence ratio, and back pressure, where the ignition system alone did not explain the outcome.

The more meaningful difference between ignition systems was therefore practical reliability rather than steady-state engine performance. The pre-detonator was more robust in operation because it avoided the spark-plug degradation and burnout problems observed with direct spark ignition in the annulus. Future work could investigate spark-based ignition systems better suited to the high-pressure and high-temperature combustor environment, particularly designs that protect the electrode while still depositing energy into the mixed region.

The overall conclusion is that the engine can be successfully ignited by several different methods, and the ignition method itself is not the dominant factor controlling whether sustained detonation occurs. Instead, ignition reliability is strongly coupled to the operating condition of the engine. Future experiments should therefore focus on the detonation boundary at low mass flux, low equivalence ratio, and low back pressure, where failures were most common. A more systematic study of this boundary would help identify the conditions under which cell size becomes too large, mixture sensitivity becomes too low, or annular DDT becomes unreliable. One limitation of the current data set is that many high-speed videos from non-detonating runs were unavailable, deleted, or cropped around successful detonation events, which limits the ability to reconstruct failed startup behavior in detail.

Chapter 5: Bibliography

- [1] Lu, F. K., and Braun, E. M., “Rotating Detonation Wave Propulsion: Experimental Challenges, Modeling, and Engine Concepts,” *Journal of Propulsion and Power*, Vol. 30, No. 5, 2014, pp. 1125–1142. <https://doi.org/10.2514/1.B34802>
- [2] Koch, J., “Nonlinear Dynamics of Rotating Detonation Waves,” Ph.D. Dissertation. William E. Boeing Dept. of Aeronautics and Astronautics, University of Washington, Seattle, WA, 2020.
- [3] Lee, J. H. S., “The Detonation Phenomenon,” Cambridge University Press, 2008. <https://doi.org/10.1017/CBO9780511754708>
- [4] Bykovskii, F. A., Zhdan, S. A., and Vedernikov, E. F., “Continuous Spin Detonations,” *Journal of Propulsion and Power*, Vol. 22, No. 6, 2006, pp. 1204–1216. <https://doi.org/10.2514/1.17656>
- [5] Kaneshige, M., and Shepherd, J. E., “Detonation Database,” 1997. <https://doi.org/10.7907/G3GS-4Y69>
- [6] Schumaker, S. A., Knisely, A. M., Hoke, J. L., and Rein, K. D., “Methane–Oxygen Detonation Characteristics at Elevated Pre-Detonation Pressures,” *Proceedings of the Combustion Institute*, Vol. 38, No. 3, 2021, pp. 3623–3632. <https://doi.org/10.1016/j.proci.2020.07.066>
- [7] Mundt, T., Knowlen, C., and Kurosaka, M., “Scale Effects on Rotating Detonation Rocket Engine Operation,” *Applications in Energy and Combustion Science*, Vol. 19, 2024, p. 100282. <https://doi.org/10.1016/j.jaecs.2024.100282>
- [8] Frolov, S. M., Basevich, V. Y., Aksenov, V. S., and Polikhov, S. A., “Detonation Initiation by Controlled Triggering of Electric Discharges,” *Journal of Propulsion and Power*, Vol. 19, No. 4, 2003, pp. 573–580. <https://doi.org/10.2514/2.6168>
- [9] Fotia, M., Hoke, J., and Schauer, F. R., “Experimental Study of the Ignition Process in Rotating Detonation Engines,” presented at the 55th AIAA Aerospace Sciences Meeting, 2017. <https://doi.org/10.2514/6.2017-1928>
- [10] Burr, J. R., and Yu, K. H., “Detonation Reignition within a Rotating Detonation Engine,” presented at the 54th AIAA Aerospace Sciences Meeting, 2016. <https://doi.org/10.2514/6.2016-1202>
- [11] Anderson, W. S., Heister, S. D., Kan, B., and Hartsfield, C., “Experimental Study of a Hypergolically Ignited Liquid Bipropellant Rotating Detonation Rocket Engine,” *Journal of Propulsion and Power*, Vol. 36, No. 6, 2020, pp. 851–861. <https://doi.org/10.2514/1.B37666>
- [12] Walters, I. V., Journell, C. L., Lemcherfi, A., Gejji, R. M., Heister, S. D., and Slabaugh, C. D., “Operability of a Natural Gas–Air Rotating Detonation Engine,” *Journal of Propulsion and Power*, Vol. 36, No. 3, 2020, pp. 453–464. <https://doi.org/10.2514/1.B37735>
- [13] Malik, V., “On Liquid Rotating Detonation Rocket Engines Characterization and Performance,” Ph.D. Dissertation. University of Central Florida, Orlando, FL, 2023.
- [14] Burke, R., “Characteristics of Rotating Detonation Engines for Propulsion and Power Generation,” Ph.D. Dissertation. University of Central Florida, Orlando, FL, 2022.
- [15] Unruh, E. C., Venters, J. P., Hemming, M., Lineberry, D. M., Xu, K. G., and Frederick, R. A., “Experimental Study of a Racetrack-Type Rotating Detonation Rocket Engine with Shear-Coaxial Injectors Run on Gaseous Methane and Oxygen,” presented at the AIAA Propulsion and Energy 2021 Forum, 2021. <https://doi.org/10.2514/6.2021-3683>

- [16] Welch, C. H., “Experimental Investigation of Detonation Wave Speed Fluctuations in a Rotating Detonation Combustor,” Master’s Thesis. Department of Mechanical Engineering, The University of Alabama, Tuscaloosa, AL, 2018.
- [17] St. George, A., Randall, S., Anand, V., Driscoll, R., and Gutmark, E., “Characterization of Initiator Dynamics in a Rotating Detonation Combustor,” *Experimental Thermal and Fluid Science*, Vol. 72, 2016, pp. 171–181.
<https://doi.org/10.1016/j.expthermflusci.2015.11.002>
- [18] Ma, Z., Zhang, S., Luan, M., Yao, S., Xia, Z., and Wang, J., “Experimental Research on Ignition, Quenching, Reinitiation and the Stabilization Process in Rotating Detonation Engine,” *International Journal of Hydrogen Energy*, Vol. 43, No. 39, 2018, pp. 18521–18529. <https://doi.org/10.1016/j.ijhydene.2018.08.064>
- [19] Yang, C., Wu, X., Ma, H., Peng, L., and Gao, J., “Experimental Research on Initiation Characteristics of a Rotating Detonation Engine,” *Experimental Thermal and Fluid Science*, Vol. 71, 2016, pp. 154–163. <https://doi.org/10.1016/j.expthermflusci.2015.10.019>
- [20] Kindracki, J., Wolański, P., and Gut, Z., “Experimental Research on the Rotating Detonation in Gaseous Fuels–Oxygen Mixtures,” *Shock Waves*, Vol. 21, No. 2, 2011, pp. 75–84. <https://doi.org/10.1007/s00193-011-0298-y>
- [21] Goto, K., Matsuoka, K., Matsuyama, K., Kawasaki, A., Watanabe, H., Itouyama, N., Ishihara, K., Buyakofu, V., Noda, T., Kasahara, J., Matsuo, A., Funaki, I., Nakata, D., Uchiumi, M., Habu, H., Takeuchi, S., Arakawa, S., Masuda, J., Machara, K., Nakao, T., and Yamada, K., “Space Flight Demonstration of Rotating Detonation Engine Using Sounding Rocket S-520-31,” *Journal of Spacecraft and Rockets*, Vol. 60, No. 1, 2023, pp. 273–285. <https://doi.org/10.2514/1.A35401>
- [22] Nair, A. P., Keller, A. R., Morrow, D. S., Lima, A. B., Mitchell Spearrin, R., and Pineda, D. I., “Hypergolic Continuous Detonation with Space-Storable Propellants and Additively Manufactured Injector Design,” *Journal of Spacecraft and Rockets*, Vol. 59, No. 4, 2022, pp. 1332–1341. <https://doi.org/10.2514/1.A35272>
- [23] Zhao, M., Wang, K., Wang, Z., Zhu, Y., Yu, X., and Fan, F., “Effects of Ignition on Initiation Characteristics of Hollow Rotating Detonation Combustor,” *Acta Aeronautica et Astronautica Sinica*, Vol. 43, 2022. <https://doi.org/10.7527/S1000-6893.2020.24870>
- [24] Fan, W., Peng, H., Liu, S., Sun, M., Yuan, X., Zhang, H., and Liu, W., “Initiation Process of Non-Premixed Continuous Rotating Detonation Wave through Schlieren Visualization,” *Combustion and Flame*, Vol. 265, 2024, p. 113437.
<https://doi.org/10.1016/j.combustflame.2024.113437>
- [25] Bennewitz, J. W., Burr, J. R., Bigler, B. R., Burke, R. F., Lemcherfi, A., Mundt, T., Rezzag, T., Plaehn, E. W., Sosa, J., Walters, I. V., Schumaker, S. A., Ahmed, K. A., Slabaugh, C. D., Knowlen, C., and Hargus, W. A., “Experimental Validation of Rotating Detonation for Rocket Propulsion,” *Scientific Reports*, Vol. 13, No. 1, 2023, p. 14204.
<https://doi.org/10.1038/s41598-023-40156-y>
- [26] Xia, Z., Ma, H., Ge, G., and Zhou, C., “Effects of Ignition Condition on the Initiation Characteristics of Rotating Detonation Wave in Plane-Radial Structure,” *Acta Astronautica*, Vol. 175, 2020, pp. 79–89. <https://doi.org/10.1016/j.actaastro.2020.05.052>
- [27] Bai, Q., Han, J., Qiu, H., Zhang, S., and Weng, C., “Study on Initiation Characteristics of Rotating Detonation by Auto-Initiation and Pre-Detonation Method with High-Temperature Hydrogen Gas,” *International Journal of Hydrogen Energy*, Vol. 49, 2024, pp. 450–461. <https://doi.org/10.1016/j.ijhydene.2023.08.138>

- [28] Hargus, W. A., Schumaker, S. A., and Paulson, E. J., “Air Force Research Laboratory Rotating Detonation Rocket Engine Development,” presented at the 2018 Joint Propulsion Conference, 2018. <https://doi.org/10.2514/6.2018-4876>
- [29] Bigler, B. R., Bennowitz, J. W., Danczyk, S. A., and Hargus, W. A., “Rotating Detonation Rocket Engine Operability Under Varied Pressure Drop Injection,” *Journal of Spacecraft and Rockets*, Vol. 58, No. 2, 2021, pp. 316–325. <https://doi.org/10.2514/1.A34763>
- [30] Fiorino, N. T., Schauer, F. R., Polanka, M. D., Schumaker, S. A., and Sell, B. C., “Use of a Partially Pre-Mixed Injection Scheme and Pre-Detonator in a Small Scale Rotating Detonation Engine,” presented at the AIAA Propulsion and Energy 2021 Forum, 2021. <https://doi.org/10.2514/6.2021-3656>
- [31] Bilgin, M., Keller, J., and Breidenthal, R., “Ignition and Flame Propagation Process with Rotating Hot Jets in a Simulated Wave Engine Test Cell,” presented at the 34th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 1998. <https://doi.org/10.2514/6.1998-3399>
- [32] Knowlen, C., Mundt, T. J., and Kurosaka, M., “Experimental Results for Geometrically Scaled Rotating Detonation Rocket Engines,” presented at the AIAA SCITECH 2023 Forum, 2023. <https://doi.org/10.2514/6.2023-0354>
- [33] Boening, J. A., Wheeler, E. A., Heath, J. D., Koch, J. V., Mattick, A. T., Breidenthal, R. E., Knowlen, C., and Kurosaka, M., “Rotating Detonation Engine Using a Wave Generator and Controlled Mixing,” *Journal of Propulsion and Power*, Vol. 34, No. 6, 2018, pp. 1364–1375. <https://doi.org/10.2514/1.B36603>
- [34] Boening, J. A., “Initiation of Orderly Spinning Detonation Waves via Phased Sparking,” Master’s Thesis. William E. Boeing Dept. of Aeronautics and Astronautics, University of Washington, Seattle, WA, 2016.
- [35] Mundt, T. J., Chang, L., Ikeda, M., Menn, D., Knowlen, C., and Kurosaka, M., “Operating Characteristics of a 76-Mm Rotating Detonation Rocket Engine,” presented at the AIAA SCITECH 2023 Forum, 2023. <https://doi.org/10.2514/6.2023-1104>
- [36] Washington, M. R., “Radial Injector Mixing Effects on Detonation Zone Position in Rotating Detonation Engine,” Master’s Thesis. William E. Boeing Dept. of Aeronautics and Astronautics, University of Washington, Seattle, WA, 2019.
- [37] Wheeler, E., “Experimental Investigation of Throatless Supersonic Exhaust on a Rotating Detonation Engine,” Master’s Thesis. William E. Boeing Dept. of Aeronautics and Astronautics, University of Washington, Seattle, WA, 2017.
- [38] Shipman, H., “Acoustic Analysis in Small-Scale Rotating Detonation Engines,” Master’s Thesis. William E. Boeing Dept. of Aeronautics and Astronautics, University of Washington, Seattle, WA, 2025.
- [39] Heath, J. D., “Generating Detonation Waves in an Annulus via Phased Adiabatic Shocks,” Master’s Thesis. William E. Boeing Dept. of Aeronautics and Astronautics, University of Washington, Seattle, WA, 2015.
- [40] Knowlen, C., Mundt, T. J., Roberts, Q., Hamza, A., Menn, D., and Kurosaka, M., “Operating Characteristics of a 10-Mm Rotating Detonation Rocket Engine,” presented at the AIAA SCITECH 2024 Forum, 2024. <https://doi.org/10.2514/6.2024-2610>