An experimental investigation of a dual-mode scramjet isolator is presented. A constant area isolator was fabricated and tested in conjunction with a Mach 2, hydrogen-air combustor operating at a simulated Mach 5 flight enthalpy. Predicted isolator performance was validated through pressure measurements obtained via low frequency pressure taps. These measurements demonstrated that the maximum pressure ratio measured in the combustor approached the design, and normal shock, limit of 4.5. The measurements also indicated that scramjet operability was improved. Mode transition from supersonic to subsonic combustion, without isolator-inlet interaction, was achieved for an equivalence ratio ($\phi$) range of 0.06-0.32, as opposed to 0.32-0.37 without the isolator. Shock train location repeatability was found to vary somewhat with $\phi$. Shock train leading edge detection techniques were also examined in this study using high frequency Kulite pressure measurements. Three criteria were defined to locate the leading edge of the shock train and analyzed: 1) 150% of the average pressure measurements upstream of the shock train leading edge, 2) 150% of the average pressure fluctuations upstream of the shock train leading edge, and 3) the maximum pressure fluctuation. The results indicated that the criterion of 150% of the average pressure fluctuations upstream of the shock train leading edge provided the earliest method of detecting the arrival of the shock train. Another method to detect the shock train leading edge utilized frequency decomposition of the pressure signal to examine the relationship between the shock train leading edge and dominant frequency components in the pressure signal. The results suggest that there may be dominant frequency components characteristic of the shock train leading edge.

### Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L$</td>
<td>isolator length</td>
</tr>
<tr>
<td>$h$</td>
<td>isolator duct height</td>
</tr>
<tr>
<td>$\theta$</td>
<td>momentum thickness</td>
</tr>
<tr>
<td>$Re_\theta$</td>
<td>momentum thickness based Reynolds number</td>
</tr>
<tr>
<td>$P$</td>
<td>pressure</td>
</tr>
<tr>
<td>$M$</td>
<td>Mach number</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>ratio of specific heat</td>
</tr>
<tr>
<td>$\phi$</td>
<td>equivalence ratio</td>
</tr>
<tr>
<td>$X$</td>
<td>scramjet axial location with origin at base of fuel injector</td>
</tr>
<tr>
<td>$H$</td>
<td>normal height of ramp fuel injector</td>
</tr>
<tr>
<td>$t$</td>
<td>time</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>standard deviation</td>
</tr>
<tr>
<td>$n$</td>
<td>number of traces</td>
</tr>
</tbody>
</table>

### Subscripts

- $ref$ = reference quantity at isolator inlet
- $avg$ = average value upstream of shock train leading edge

### I. Introduction

A dual-mode scramjet (DMSJ) is a fixed geometry air-breathing engine. A classical schematic of the DMSJ is shown in Figure 1. As shown in the figure, the DMSJ is composed of four main sections. The inlet captures the air-mass, the isolator separates combustion effects from the inlet, the combustor introduces, mixes, and burns the fuel-air mixture, and the exit nozzle expands the exhaust gases to produce vehicle thrust⁴. The DMSJ requires no mechanical compressor, but instead utilizes external and internal shock structures to achieve inlet air compression. This means that the DMSJ is only able to operate at supersonic speeds, which may be initially achieved via a rocket or turbine based systems.

The DMSJ is able to operate in two modes, hence its name. At low Mach numbers, $M \approx 3-4$, the DMSJ operates in ram-mode which is characterized by subsonic combustion. The flow is thermally choked by the heat release in the relatively low Mach number flow of the combustor. High back-pressure in the combustor generates a shock train in the...
isolator which provides inlet air-compression as well slowing the flow down to sonic conditions prior to combustor inlet\textsuperscript{1,2}. At higher Mach numbers, M=5-6, the DMSJ transitions from ram-mode to scram-mode\textsuperscript{1,2}. The flow is characterized by regions of subsonic and supersonic flows in the combustor. The DMSJ is also characterized by a shock train in the isolator. At still higher Mach numbers, M>7, the DMSJ operates in scram-mode, where the flow is characterized by supersonic combustion. At these high Mach flight speeds, it is not necessary to reduce to the flow speeds to sonic conditions. In fact, doing so decreases operational performance though pressure losses\textsuperscript{1,2}. Thus, the shock train in the isolator is non-existent during this mode of operation.

The DMSJ offers many advantages over conventional rocket or turbine based engines. The DMSJ is able to operate efficiently at high Mach numbers while turbine-based systems are limited to low Mach flight speeds due to compressor and turbine blade flow separation. Also, the fact that the DMSJ is an air-breathing engine offers a distinct advantage over the rocket based system. A rocket-based engine must store and supply its own oxidizer. The DMSJ is able to eliminate this need by utilizing the atmospheric air as oxidizer. This eliminates the mechanical complexities of oxidizer supply systems, the weight of the oxidizer storage tank, and reduces mission risk\textsuperscript{3}. However, the DMSJ offers its own unique set of design and operational challenges. As stated previously, the DMSJ must operate at supersonic speeds to achieve inlet air compression values, thus the DMSJ needs an external system to bring the vehicle to supersonic speeds\textsuperscript{5}. Also flow speeds in the DMSJ may reach values well above 1000m/s, thus poses a difficult challenge to introduce, mix and combust the fuel-air mixture prior to vehicle exhaust\textsuperscript{6}. In this study, isolator flow studies have been conducted to examine shock train behaviors and methods to detect and control its location.

Knowing the behavior and location of the shock train is of importance to DMSJ operation. During combustion, there is a sudden increase in pressure, which is considerably higher than the inlet pressure. The shock train thus allows a natural pressure rise to occur prior to combustion. The shock train exists as a means to equilibrate the inlet pressure with the combustor back pressure. Thus, the shock train exists as a response to the combustion back pressure. As the combustion back pressure increases, the shock train must increase in length to allow the combustor inlet pressure to rise sufficiently. However, the shock train length must be maintained such that it does not reach the inlet. If the shock train were to influence the inlet there would be a loss of air-mass capture, increased pressure and thermal loads, increased drag, and decreased thrust, which may result in mission and/or vehicle failure\textsuperscript{1,3}. This phenomenon is known as engine unstart. Also, an understanding of shock train behavior and location prediction methods may be used to optimize DMSJ operation by providing maximum compression values, i.e. maximum shock train length.

In this investigation, the shock train isolator flow physics and shock train location and detection techniques will be examined. First, an empirical isolator design model will be evaluated by examining the pressure rise predicted for an isolator, or equivalently, a shock train of a given length. Next, a study on the effect of an isolator on DMSJ operability will be studied. Following this, unsteady shock train behavior will be studied using low and high frequency pressure measurements. Shock train leading edge detection techniques will then be studied using the high frequency pressure measurements. Specifically, three definitions of shock train leading edge will be studied and signal frequency decomposition techniques will be utilized to search for dominant frequency components which may be characteristic of shock train leading edge.

II. Facility

This investigation was conducted at the University of Virginia's Aerospace Research Laboratory using the University of Virginia Supersonic Combustion Tunnel Facility. The facility along with the dual-mode scramjet, DMSJ, combustor is shown in Figure 2(a) and is fully described by Refs 4 - 6. The facility is vertically mounted, electrically heated supersonic combustion tunnel. The air supply comes from compressed room air source and passes down the outside of an annulus and travels up the electrical heaters. The flow then passes up through a ceramic flow straightener, and then passes through a Mach 2 nozzle before entering the DMSJ combustor. Figure 2(b) shows the DMSJ combustor prior to isolator installation. The DMSJ combustor was modified in 2004 to include a 10 inch isolator section and is shown in Figure 2(c). The isolator's main function is to isolate the combustion

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{figure1.png}
\caption{Schematic of Classical Dual-Mode Scramjet Configuration.}
\end{figure}
effects, i.e. shock train, from the combustor inlet while allowing the pressure to rise prior to combustion. Operating conditions are given in Table 1. Figure 3 is a schematic of the isolator instrumentation. The instrumentation includes 3 thermocouples (T) on each wall, 4 pressure taps (P) on each wall and 3 Kulite pressure transducers (K) on the observation and injection wall.

III. Research Summary
The addition of the isolator allowed the opportunity to conduct studies which examined the isolator’s ability to allow the necessary pressure rise without shock-inlet interaction. The isolator was designed using an empirical model given by EQ. (1). Based on desired operational conditions, the shock train length, or equivalently, the isolator length can be modeled. The isolator length was modeled based on results gathered in previous investigations conducted by Goyne et. al. These results are shown in Figure 4. The figure provides an axial distribution of the normalized pressure throughout the DMSJ combustor for various equivalence ratios, Φ, and a schematic of the DMSJ combustor is superposed to provide physical reference to the reader. The figure shows DMSJ mode transition from scram-mode to ram-mode operation. At Φ = 0.0 (at fuel-off), the flow in the DMSJ is fully supersonic and pressure fluctuations are due to reflecting shock and expansion waves. At Φ = 0.32, the flow is still supersonic during combustion. However, there is no upstream influence due to combustion as can be seen by the coincidence of the pressure levels on the face of the ramp at x = -4.8H for Φ = 0.0 & Φ = 0.32. At Φ

Table 1 - Nominal Test Conditions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Air</th>
<th>Fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stagnation Pressure, kPa</td>
<td>331</td>
<td>224-1093</td>
</tr>
<tr>
<td>Stagnation Temperature, K</td>
<td>1020</td>
<td>300</td>
</tr>
<tr>
<td>Mach Numbera</td>
<td>2.03</td>
<td>1.7</td>
</tr>
<tr>
<td>Static Pressure', kPa</td>
<td>41</td>
<td>45-221</td>
</tr>
<tr>
<td>Static Temperature', K</td>
<td>600</td>
<td>190</td>
</tr>
<tr>
<td>Velocity', m/s</td>
<td>977</td>
<td>1781</td>
</tr>
<tr>
<td>Equivalence Ratio</td>
<td>-</td>
<td>0.06 - 0.34</td>
</tr>
</tbody>
</table>

*a Precombustion property at nozzle exit, calculated using area ratio of nozzle and assuming isentropic flow.

Figure 3. Schematic of isolator instrumentation locations. K1-K6 = high frequency pressure transducers, P1-P16 = low frequency pressure taps, and T1-T12 = Type K thermocouples.

Figure 2. Schematic of: (a) University of Virginia Supersonic Combustion Facility, (b) Pre-existing dual-mode scramjet combustor without isolator modification, and (c) dual-mode scramjet combustor with isolator modification.
Sufficient pressure rise without shock-inlet interaction is an important aspect from the figure. The pressure rise at X = -7.1H indicates that the shock train has moved up into the facility nozzle. Thus, the results indicate that the isolator allows the pressure to rise upstream of to fuel injection. The pressure rise measured at X = -7.1H indicated that the shock train has traveled upstream into the facility nozzle.

In comparison, Figure 5 shows that for $\Phi = 0.31$ the pressure rise is also approximately 4.2 prior to combustion. However, there is no pressure rise measured at X = -44.8H, which indicates that the shock train has not traveled upstream past this location. The maximum pressure rise that can be achieved in a supersonic flow is that from a normal shock. Compressible flow theory states that for a Mach 2 flow, the maximum pressure rise across a shock train is equal to that of a normal shock. This value is given as $P_2/P_1 = 4.5^8$. This value is depicted in Figure 6. This figure shows the maximum pressure achieved in the isolator at for various values of $\Phi$. As seen in this figure, the maximum pressure rise tends towards the theoretical design value of 4.5. Thus, the results indicate that the isolator allows sufficient pressure rise without shock-inlet interaction during mode transition.

$$\frac{P_3}{P_1} = 1 + \frac{\gamma M_2^2}{1 + \gamma M_2^2}$$

The second conclusion can be made pertaining to the DMSJ operability. Operability refers to the ability of the DMSJ to operate over a wide range of fuel conditions. The DMSJ, without the isolator addition, was able to operate for $\Phi =$
However, with the isolator addition, the DMSJ was able to operate for $\Phi = 0.08-0.31$. Thus, in this case, the isolator addition effectively increases the DMSJ operability by 360%.

Shock train unsteadiness was also examined in Figure 7 & Figure 8. Figure 7 examines the repeatability of the shock train location within the isolator. This figure utilizes low frequency pressure measurements and plots the pressure distribution in the isolator at various values of $\Phi$, where $n$ indicates the number of distributions plotted. The variability in the repeatability of the pressure distribution varies for different values of $\Phi$, which suggests that the shock train location is somewhat sensitive to $\Phi$. Figure 8 examines the transient fluctuations of the shock-train. Time-resolved measurements are combined with the low-frequency pressure tap measurements to indicate the level of pressure fluctuations. The results suggest that the shock-train is relatively steady, where pressure fluctuations seem to be within one standard deviation of the low-frequency pressure distribution.

Shock-train location methods were also examined in this research. As stated above, it is of importance to be able to monitor and control the location of the shock train to avoid and prevent unstart conditions from developing. The results presented in this section will examine several shock train leading edge detection methods using high frequency pressure measurements. Shock train leading edge detection techniques will be presented which utilize normalized pressure measurements, pressure fluctuations (i.e. standard deviation of the pressure measurements), and pressure signal frequency decomposition analysis. Two methods were developed to determine the location of the shock train.

The first three methods examined the shock train leading edge via three defined criteria: 1) 150% of the average pressure measurements upstream of the shock train leading edge, 2) 150% of the average standard deviation of the pressure measurements upstream of the shock train leading edge, and 3) the location of the maximum standard deviation of the pressure measurements.

The pressure measurements from one Kulite pressure transducer are shown in Figure 9 and will be examined to illustrate the effectiveness of each criterion to locate the shock train leading edge. This figure shows the (a) pressure measurements, (b) standard deviation, and (c) equivalence ratio recorded at axial position, $X=-48H$ for Kulite K3 versus time. The standards by which the shock train leading edge can be defined have been developed and are compared in Figure 9. Each method utilizes only the pressure measurements from the high frequency Kulite transducers. These are further explained below.

The first method utilizes the pressure measurements directly. The measured pressure upstream of the shock train is averaged, $P_{avg}$, and a criteria of 150% of $P_{avg}$ is defined. As the pressure levels rise and meet this criterion, the signal is determined and the time and equivalence ratio is recorded. This value is shown in Figure 9 as the dotted line. This allows a direct method of defining the shock train leading edge.

Another method used to define the shock train leading edge detection utilizes the pressure fluctuations, or equivalently the standard deviation of the pressure measurements over a running time-average window of 0.05 second. The average
pressure fluctuations, $P_{\text{avg}}$, upstream of the shock train are measured and 150% of $P_{\text{avg}}$ is defined as the criterion for this method. The location at which the pressure fluctuations reach this value is determined and recorded. This value is shown in Figure 9 and is represented as the dash-dot line.

A third method to define the shock train leading edge utilizes the maximum value of the pressure fluctuations, or equivalently the standard deviation of the pressure measurements in (a). (c) Equivalence ratio vs. time.

From Figure 9 it can be seen that the criteria of 150% of the upstream pressure fluctuations provide the earliest detection of the shock train leading edge. The results are generalized over 9 cases and are shown in Figure 10. The error bars indicate that the equivalence ratio detected by each method may vary slightly. However, in a case by case analysis, the method using 150% $P_{\text{avg}}$ consistently provides the earliest method of shock train leading edge detection. However, a combination of these techniques may be utilized to develop a propulsion system controller (PSC) to monitor and control the location of the shock train leading edge.

Another method for shock train detection was studied decomposed the signal into its frequency components utilizing Fourier signal decomposition. The decomposed signal was then analyzed using a power spectrum analysis. The pressure signals utilized in the illustration of this method is shown in Figure 11. Here, the pressure rise over only one axial location will be examined. The shock train is located between the intermediate and most upstream Kulite locations (-47H $\leq$ X $\leq$ -37H). This will allow a detailed examination of the shock train leading edge as it progresses upstream towards the Kulite transducer. Four power spectra are shown in Figure 12 which corresponds to four time intervals. The time intervals represent four locations of the shock train leading edge. At $t = 4.2$ sec., the shock train is well downstream of the Kulite position. This represents the power spectrum during steady flow upstream of the shock train. As indicated in Figure 12(a), the signal is mainly composed of low (DC) frequencies. However, at $t = 7.0$ sec., the shock train has initial influences on the Kulite transducer, indicating that the shock train is approaching the Kulite transducer axial location. The power spectrum for $t = 7.0$ sec. is shown in Figure 12(b). This figure shows that the signal has increased in frequency components with particular distinct characteristic frequencies. At $t = 7.4$ sec., the maximum shock train pressure fluctuations occur. The power spectrum for the corresponding pressure signal is shown in Figure 12(c). This figure indicates that the power of the frequencies has increased and larger frequencies are present in the signal. However, the distinct frequencies as shown in Figure 12(b) are not as obvious. At $t = 9.9$ sec., the shock train leading edge has moved upstream of the Kulite transducer and the corresponding power spectrum is shown in Figure 12(d). This figure shows that there are no distinguishable dominant frequencies.
IV. Conclusion & Continuing Research Goals

The research presented in this investigation explores the isolator flow physics in a dual-mode scramjet (DMSJ) combustor. Previous investigations conducted by Goyne et al. found that shock-inlet interactions occurred during mode transition studies. Thus, an isolator was designed using an empirical model and expected performance parameters. The pressure distribution in the DMSJ combustor with and without an isolator was compared. It was found the isolator allowed comparable increase in pressure in the combustor without shock-inlet interactions. Also it was found that the maximum pressure rise in the isolator tended towards the theoretical maximum and design pressure rise of 4.5. The results also showed that the DMSJ operability was significantly increased with the addition of the isolator. Shock train unsteadiness was analyzed using low and high frequency pressure measurements. The results showed that the shock train leading edge may vary somewhat at the same Φ and that the transient pressure fluctuations were relatively low with fluctuations within 1 standard deviation of the low frequency pressure measurements. Shock train leading edge detection methods were developed using shock train leading definitions and pressure signal frequency decomposition. The shock train leading edge definition of 150% of the average pressure fluctuations, i.e. standard deviation of the pressure measurements, upstream of the shock train leading edge provided the earliest method of detection. However, a combination of the three definitions may be used to develop a propulsion system controller. Pressure signal frequency decomposition was analyzed using power spectra. The results indicated that there may be some dominant frequency components characteristic of the shock train leading edge.

Future research will continue to explore DMSJ isolator flow studies. Further experiments will seek to validate the results presented in this investigation. Specifically, shock train leading edge detection methods will be explored further. A propulsion system controller may be developed to

Figure 11. Typical time-resolved measurements of: (a) wall pressure for low rate of equivalence ratio change, and (b) equivalence ratio. $P_{ref} = 40$ kPa.

Figure 12. Power spectra of time-resolved pressure measurements for K1 in Fig. 11. Spectra determined for a time window of 0.16 sec. and centered on: (a) t=4.2 sec., (b) t=7.0 sec., (c) t=7.4 sec., and (d) t=9.9 sec.
utilize the shock train leading edge definitions to
detect and control shock train leading location.
Further studies will also be conducted to examine if
dominant frequency components may be related to
shock train leading edge to further support the
development of a propulsion system controller.

Acknowledgements
The authors appreciate the financial support
of the National Institute of Aerospace under NIA
Project 3002-VA., A.H. Auslender of NASA Langley
Research Center served as technical monitor.
Discussions with K.E. Rock of NASA Langley
Research Center are also appreciated. Testing was
also supported by NASA under grant NAG-1-02019
with C.R. McClinton and D.E. Reubush of NASA
Langley Research Center as technical monitors. The
authors also appreciate the contribution of J.C.
McDaniel and R.H. Krauss for technical support.

References
9, No. 4, 1993, pp. 499-514.
Airbreathing Propulsion, AIAA Education Series,
3. Cockrell, C.E., Jr., Auslender, A.H., Guy,
R.W., McClinton, C.R., and Welch, S.S.,
“Technology Roadmap for Dual-Mode Scramjet
Propulsion to Support Space-Access Vision Vehicle
Air Continuous Flow Propulsion Facility,” AIAA
5. Krauss, R.H., McDaniel, J.C., Jr., Scott, J.E.,
Jr., Whitehurst, R.B., III, Sega, C., Mahoney, G.T.,
and Childers, J.M., “Unique, Clean-Air, Continuous-
Flow, High-Stagnation-Temperature Facility for
Supersonic Combustion Research,” AIAA Paper 88-
W.B., and Goyne, C.P., “Test Gas Vitiation Effects in
a Dual-Mode Combustor,” AIAA Paper 2003-6960,
2003.
7. Goyne, C.P., McDaniel, J.C., Quagliaroli,
T.M., Krauss, R.H., and Day, S.W., “Dual-Mode
Combustion of Hydrogen in a Mach 5, Continuous-
Flow Facility,” Journal of Propulsion and Power,
8. Anderson, J.D., Jr., Modern Compressible
Flow With Historical Perspective, McGraw Hill,
Boston, 1990.
Transition in a Scramjet Combustor,” Journal of
Propulsion and Power, Vol. 9, No. 4, pp. 515-520.