ABSTRACT
This paper presents a dynamic model of the interior ballistics of an experimental liquid propellant-powered rifle. The liquid propellant-powered rifle described utilizes a mixture of Hydroxyl Ammonium Nitrate (HAN) and hydrocarbon fuel to replace gunpowder typically used in such firearms. The motivation for such a development is to discard the need for a shell casing whereby carrying only propellant and bullets will reduce both the mass and volume per shot carried by the soldier. A first-principles dynamic model of the interior ballistics is derived as a compressible fluid power problem with the chemical liberation of heat within the chamber modeled via a condensed-phase reaction rate law. The model is used to predict the overall performance in terms of ballistic kinetic energy as well as draw design insight regarding the role of friction, chamber geometry, and the profile of chamber pressure with respect to time. Simulation results are presented as well as preliminary experimental results from a proof-of-concept device.

1.0 INTRODUCTION
The motivation for this work is primarily to dispense of the brass shell casing that houses gunpowder in firearms such as the M16-A2 military rifle in order to lighten the ammunition load of foot soldiers. The proposed mechanism for achieving this is to replace the conventional solid propellant (gunpowder) with a liquid propellant that is a stable mixture of fuel (hydrocarbon fuel) and oxidizer (Hydroxyl Ammonium Nitrate). This paper outlines the potential advantages of this approach and formulates a dynamic model of the interior ballistics used to offer design insight and predictions regarding performance. Experimental results and observations are used to validate the model.

A conventional rifle is shown in Figure 1. An impact primer ignites a mixture of sulfur, charcoal, and potassium nitrate or some similar mixture that is contained in a brass case. These solid pellets of propellant begin to burn rapidly, creating a high-pressure gas that pushes the bullet down the barrel. A liquid propellant approach uses the same basic concept regarding the generation of a high-pressure gas to propel a bullet, yet allows a number of potential advantages. Among these are the following: 1) a reduction in the total mass carried per shot given that the brass casing is no longer necessary, 2) a reduction in the mass of propellant per shot given that the liquid propellant can be formulated to be more energy dense that the solid propellant, 3) the capacity to carry more rounds per clip given that only the bullets need to occupy the clip, 4) a weapon less prone to jamming given that no ejection port or mechanism is required, 5) the potential for variable selectable muzzle velocity (non-lethal to high-power) by injecting variable amounts of liquid propellant into the combustion chamber, and 6) safer logistics given the transport of non-explosive liquid containers.

Figure 1: M16-A2 Rifle

Previous work regarding liquid propellant powered weapons includes a broad research effort by the U.S. military to employ liquid propellants for large scale artillery guns. The Crusader or “Advanced Field Artillery System” (AFAS) was a large-scale artillery gun (Figure 2) that was to replace the solid propellant powered M109A6 Paladin howitzer and older M109A2/A3 howitzer in service since 1960. There were, however, numerous problems with its design and the program was cancelled in 2002. One of the largest problems with the Crusader was the rapid reaction rate of the propellants, if bulk loaded, would...
cause a pressure spike leading to catastrophic failure of the gun. The Crusader therefore employed a so-called regenerative system that would inject propellant into the chamber as the reaction preceded in order to slow the rate of pressure build-up. This requirement led to various design complications and a complex overall system. The Crusader program was cancelled in 2002.

As shown by the dynamic model presented here, the application of a liquid propellant powered weapon system on a smaller scale avoids the difficulties of over-pressurization and allows a simple bulk-loaded design. Smaller caliber weapons, such as the M16, are promising application domains given the appropriate scaling of the coupled chemical reaction rate dynamics and inertial dynamics of the projectile. Specifically, the inertia of the projectile is more appropriately matched such that the reaction rate dynamics of the bulk-loaded propellant is of an appropriate time scale to produce a pressure profile with peak pressures capable of being contained with conventional materials.

2.0 MERITS OF THE PROPOSED SYSTEM
The most compelling motivation for looking into small-scale liquid propellant powered weapons is their distinct advantage over conventional propellant guns in ammunition mass that must be carried, volume occupied by the ammunition, and deliverable energy stored in the propellant.

There has been a considerable amount of work done in studying the merits of various HAN-based liquid propellants for various applications. HAN has been stoichiometrically mixed with fuels such as methanol, ethanol, 1-propanol, 2-propanol, 1-butanol, HEHN, and glycine. Various candidates have their advantages and disadvantages. Glycine, for example, has very safe propellant properties, however, its energy content is relatively low when compared with other fuels, and additionally is not very soluble in HAN. A HAN/methanol mix has much higher energy per unit mass, is a stable mixture, and is very soluble in HAN. However, methanol can be toxic if ingested or absorbed through the skin. A HAN/ethanol mixture has somewhat more energy than does HAN/methanol, is very soluble in HAN, is somewhat more stable than HAN/methanol, and is non-toxic. The comparisons, dynamic model, simulation results and experimental results presented in this paper are based on a stoichiometric mixture of 13 molar HAN and ethanol.

A mass based comparison of the proposed HAN/ethanol liquid propellant powered system reveals a significant advantage over a conventional M16A2 system. The most obvious way that the mass reduction will occur is through elimination of the shell casing due to the fact that the propellant can be injected directly into the chamber. The casing amounts to nearly half of the mass of a round of ammunition in the conventional M16A2 system. Mass savings are further enhanced when considering the high mass specific energy density of the liquid propellant over powder. Experimental firing data yields a maximum value of 2205 kJ of delivered kinetic projectile energy per kilogram of propellant, as compared to 1215 kJ/kg for powder in a conventional M16A2 weapon. As summarized in Table 1, this implies that the mass per round for an equal kinetic energy shot with the liquid propellant system is 42% of that for the conventional M16A2 system.

<table>
<thead>
<tr>
<th>M855/SS109 (M16A2)</th>
<th>Mass</th>
<th>Liquid Propellant Mass System</th>
</tr>
</thead>
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<tr>
<td>Case</td>
<td>6.2 g</td>
<td>Case</td>
</tr>
<tr>
<td>Bullet</td>
<td>4.0 g</td>
<td>Bullet</td>
</tr>
<tr>
<td>Powder</td>
<td>1.6 g</td>
<td>Propellant</td>
</tr>
<tr>
<td>Total</td>
<td>11.8 g</td>
<td>Total</td>
</tr>
</tbody>
</table>

Table 1: Mass-based comparison for equal muzzle velocity.

A volumetric comparison also yields benefits with regard to the number of bullets that can be carried in a magazine (clip), as well as the reduced volume occupied by the propellant. Seven times the number of bullets can be placed in a magazine because of the elimination of the shell casings. Figure 3 shows a pictorial representation of this increase. Dispensing of the shell casings requires that the propellant must be housed somewhere in the weapon. Candidate locations for storage of the propellant include the hollow spaces in the handle or the stock, or both (see Figure 1). Based on experimental data, the volumetric energy density of the proposed system is 3.05 kJ/ml (projectile kinetic energy per milliliter of propellant) versus 1.04 kJ/ml for the conventional M16A2 system. This implies a volumetric requirement per shot of the proposed system that is 34% of that for the conventional system.

Figure 3: Shows the number of shots capable of being stored in an M16 magazine with (left) and without (right) shell casings.
Additional merits of the proposed system include: a weapon less prone to jamming given that no ejection port or ejection mechanism is required, the potential for variable selectable muzzle velocity (non-lethal to high-power) by injecting variable amounts of liquid propellant into the combustion chamber, and safer logistics given the transport of non-explosive liquid containers.

3.0 DYNAMIC MODEL
As shown in the model presented below, the reaction rate of HAN-based combustion reactions is proportional to the area of the barrel as well as the temperature of the reaction product gases. Simulations of a bulk-loaded system show that the inertia and length scales of an M16 result in reasonable and appropriate pressure profiles, and thereby support the notion of applying the liquid propellant concept to small-scale arms.

The dynamics of the interior ballistics of the liquid propellant powered rifle can be cast as a lumped parameter model consisting of the motion dynamics of the bullet and remaining liquid propellant, the chemical combustion rate dynamics, and an energetically-based fluid power model relating the rates of change of pressure of the combustion gases to the work done by the gases. The literature contains various models and assumptions regarding the combustion of liquid propellants in guns. As was assumed in [1] and [2], it will be assumed here that the process results in a pocket of high-pressure combustion gases that forces the remaining quantity of propellant up against the bullet. This assumption results in a gas/liquid interface. The formation of such an interface, along with the assumption of an incompressible liquid propellant, allows the bulk representation of the slug of liquid propellant as a rigid body with variable mass. The combustion rate dynamics can then be expressed in terms of the area of the gas/liquid interface and the temperature at the interface surface. An energetic balance of a control volume drawn around the gas relates the enthalpy of the reaction, the pressure and temperature of the gas, and the work rate. Figure 4 shows a schematic of the process and the nomenclature used.

![Figure 4: Schematic of the liquid propellant model.](image)

3.1 Dynamics of Motion
A free body diagram of the bullet relates the acceleration of the bullet $\ddot{v}_b$, the mass of the bullet $m_b$, and the mass of the remaining propellant $m_l$, to the frictional force, $F_{f\text{ic}}$, produced between the bullet and the barrel, the pressure $P$ in the gas CV that is transmitted through the propellant and pushes on the area of the bullet $A_b$, the force from atmospheric pressure $P_{\text{atm}}$ applied to the front area of the bullet, and the force from the rate of change of the propellant $\dot{m}_l$ multiplied by $v_p$, the velocity of combustion products of the propellant as it enters the gas CV relative to the velocity of the fluid at the interface:

$$ (m_b + m_l)\ddot{v}_b = PA_b - P_{\text{atm}}A_b - F_{f\text{ic}} - \dot{m}_l v_p $$

In Equation (1) it will be assumed that the relative velocity of the mass departing from the liquid is equal to the velocity of the slug of liquid propellant; this is equivalent to assuming that the liquid “deposits” gas behind the gas/liquid interface as the reaction proceeds. The velocity of the fluid particles at the gas/liquid interface can be obtained from an assumption of incompressible flow by equating volumetric flow rates near the bullet and near the interface: $A_b v_p = A_h v_b$. Therefore $v_p = v_b$, as expected. The dynamics of the bullet are therefore specified by:

$$ (m_b + m_l)\ddot{v}_b = (P - P_{\text{atm}})A_h - F_{f\text{ic}} - \dot{m}_l v_b $$

Assuming an incompressible liquid propellant, the position of the bullet and interface can be related to the mass of propellant:

$$ m_l = \rho_A A_h (x_b - x_{\text{int}}) $$

Differentiation and rearrangement of Equation (3) leads to the following expression for the velocity of the gas/liquid interface:

$$ v_{\text{int}} = \frac{\rho_A A_h v_b - \dot{m}_l}{P_A A_h} $$

Substitution of $\dot{V} = A_h v_{\text{int}}$ leads to an expression for $\dot{V}$, which will be needed in the compressible fluid power model of the gas CV.

3.2 Combustion Rate Dynamics
Use of Equation (2) requires that the mass consumption rates of the propellant and the pressure of the combustion gases be related to the motion dynamics of the bullet. The combustion of the propellant (a stoichiometric mixture of HAN and ethanol) can be written as the following two-step reaction:

$$ \text{NH}_2\text{OHNO}_3 + \phi \text{H}_2\text{O} \rightarrow \text{N}_2 + (\phi + 2)\text{H}_2\text{O} + \text{O}_2 $$

$$ \frac{4}{3}\text{C}_2\text{H}_5\text{OH} + \text{O}_2 \rightarrow \frac{4}{3}\text{CO}_2 + \text{H}_2\text{O} $$

Reaction (5) is the deflagration of HAN and is the limiter to the overall reaction rate. Reaction (5) yields oxygen, which is assumed to be instantly consumed (relative to the time scale of the deflagration) by its combustion with ethanol in Reaction (6). The overall reaction can be written as:

$$ \text{NH}_2\text{OHNO}_3 + \phi \text{H}_2\text{O} + \frac{4}{3}\text{C}_2\text{H}_5\text{OH} \rightarrow \text{N}_2 + (\phi + 3)\text{H}_2\text{O} + \frac{4}{3}\text{CO}_2 $$

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where in Reactions (5) and (7), $\phi$ is dependent on the molarity of HAN used. As stated in [1], the rate of deflagration is dependent on the area of propellant surface and the temperature at the surface. Following from the model given in [1], Equation (8) below relates the mass consumption rate of the propellant, $\dot{m}_i$, to the area of the gas/liquid interface $A_b$ through a number of known constants:

$$
\dot{m}_i = -A_b \sqrt{\frac{2\rho_l RB \lambda T^2 e^{-E/RT}}{EqY_0}}
$$

where $\rho_l$ is the density of the liquid propellant mixture, $R$ is the universal gas constant, $B$ is a pre-exponential factor in units of sec$^{-1}$, $\lambda$ is the thermal conductivity of the mixture, $T$ is the temperature at the gas/liquid interface, $E$ is the activation energy in units of J/mol, $q$ is the heat of combustion per unit mass of HAN (J/kg), and $Y_0$ is the mass fraction of HAN in the mixture.

### 3.3 Compressible Fluid Power Model

A power balance performed on the gas CV relates the storage rate of energy to the power across the CV boundary,

$$
\dot{U} + \dot{E} = \dot{H} + \dot{Q} - \dot{W}
$$

where $\dot{U}$ is the rate of internal energy storage in the gas (energy storage in the form of heat), $\dot{E}$ is the rate of change of kinetic energy of the gas (energy storage in the form of kinetic energy), $\dot{H}$ is the enthalpy crossing the CV boundary due to the liquid propellant being converted into gas and entering the gas CV, $\dot{Q}$ is the rate of heat entering the CV, and $\dot{W}$ is the work rate of the CV on the external environment. In keeping with the assumption of the reaction “depositing” gas as the reaction proceeds (see Equation (2)), it is assumed that the kinetic energy of the gas is zero, and therefore that $\dot{E}$ is zero. For the analysis presented here, it is also assumed that the heat losses of the system can be neglected ($\dot{Q} = 0$). The rate of internal thermal energy storage can be written as:

$$
\dot{U} = \dot{P}V + \dot{P}'V
$$

where $P$ and $V$ is the pressure and volume of the gas CV respectively, and $\gamma$ is the ratio of specific heats of the products of reaction. The enthalpy rate is given by the mass flow rate of gas entering the CV, $\dot{m}$, the HAN mass specific heat of combustion, $q$, and the mass fraction of HAN in the propellant mixture $Y_0$:

$$
\dot{H} = \dot{m}qY_0
$$

Applying mass conservation, the rate of change of gas in the CV is due purely to the rate of change of the liquid propellant:

$$
\dot{m} = -\dot{m}_i
$$

The work rate of the gas CV is given by:

$$
\dot{W} = PV
$$

Combining Equations (9-13), the pressure dynamics of the gas CV may be written as:

$$
\dot{P} = \frac{(\gamma - 1)\dot{m}_i q Y_0 - \gamma P\dot{V}}{V}
$$

Using the ideal gas law, the temperature of the gas CV is given by:

$$
T = \frac{PV}{\overline{m}R}
$$

where $\overline{R}$ is the gas constant of the products in units of J/(kg·K).

### 4.0 SIMULATION RESULTS

The dynamic model of the interior ballistics presented above was simulated numerically. The states of the dynamic system are given by $v_b$, $P$, and $V$, each evolving according to Equations (2) and (14) and (4) (where $\dot{V} = A_b v_{int}$). These state equations are summarized below for convenience:

$$
(m_b + \dot{m}_i)v_b = (P - P_{\infty})A_b - F_{fisc} - \dot{m}_i v_b
$$

$$
\dot{P} = \frac{(\gamma - 1)\dot{m}_i q Y_0 - \gamma P\dot{V}}{V}
$$

$$
\dot{V} = \frac{\rho_l A_b v_b - \dot{m}_i}{\rho_l}
$$

A number of auxiliary equations are also necessary to relate the states of the system to more convenient variables. These auxiliary equations are summarized below for convenience:

$$
\dot{m}_i = -\rho_l \sqrt{\frac{2\rho_l RB \lambda T^2 e^{-E/RT}}{EqY_0}}
$$

$$
\dot{m} = -\dot{m}_i
$$

$$
T = \frac{PV}{\overline{m}R}
$$

It should be noted that it is necessary to numerically integrate Equation (8) to obtain $\dot{m}_i$. It should also be noted that Equation (8) is a function of the states. The mass of gas $m$ used in Equation (15) is found by numerically integrating Equation
where is it necessary to initialize the integration with a small initial value of gas $m_0$ to avoid singularities.

### Table 2: Parameter values used in the dynamic simulation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>$m_b$</td>
<td>Bullet mass</td>
<td>5.5 g</td>
</tr>
<tr>
<td>$l_b$</td>
<td>Barrel length</td>
<td>0.53 m</td>
</tr>
<tr>
<td>$A_b$</td>
<td>Cross section of Barrel</td>
<td>24.63 cm$^2$</td>
</tr>
<tr>
<td>$m_{i0}$</td>
<td>Initial propellant mass</td>
<td>2.63 g</td>
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<tr>
<td>$\rho_l$</td>
<td>Propellant density</td>
<td>1384 kg/m$^3$</td>
</tr>
<tr>
<td>$B$</td>
<td>Pre-exponential factor</td>
<td>$3.1 \times 10^{10}$ sec$^{-1}$</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Propellant thermal conductivity</td>
<td>0.51 W/(m K)</td>
</tr>
<tr>
<td>$E$</td>
<td>Activation energy</td>
<td>7.165 kJ/mol</td>
</tr>
<tr>
<td>$q$</td>
<td>Heat of combustion</td>
<td>5892 kJ/kg</td>
</tr>
<tr>
<td>$Y_0$</td>
<td>HAN mass fraction</td>
<td>0.7484</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Ratio of specific heats</td>
<td>1.33</td>
</tr>
</tbody>
</table>

Table 2 shows the values of the parameters used in the simulation. The simulation was initiated by introducing an initial temperature and pressure in the initial quantity of gas $m_0$ to start the combustion. This initial temperature and pressure effectively model the primer. The friction was initially modeled to match the experimental setup where the lead bullet was required to extrude slightly through the bullet seat. The simulation was very insensitive to the magnitude of this friction modeling and it was subsequently neglected. Figure 5 shows the pressure in the chamber as a function of time. It should be noted that although the pressure reaches a higher pressure than a conventional M16A2 weapon, it is still within reasonable bounds for standard gun materials. Figure 6 shows the temperature as a function of time, and Figure 7 shows the velocity of the bullet and the velocity of the interface as a function of time. Figure 8 shows the mass of the propellant as it reacts. Simulation results yielded a mass specific energy density of 1770 kJ/kg of propellant and a volumetric energy density of 2.45 kJ/ml of propellant.

### 5.0 EXPERIMENTAL RESULTS

An experimental prototype of a liquid propellant powered rifle was constructed and tested. A stoichiometric mixture of 13
molar HAN and ethanol was used as the propellant mixture, and all physical parameters were matched by the simulation such that a comparison could be made. Figure 9 shows a photograph of the disassembled prototype. The prototype has a rifled 0.22 inch diameter, 18 inch long barrel similar to that used in an M16A2. The barrel, the bullet seat, and the combustion chamber carrier assemble together, using the barrel flange and the assembly collar, with chamfered surfaces to promote adequate sealing. The top of the combustion chamber carrier contains a seat for a standard small rifle primer that is initiated by a firing pin that is spring loaded in the firing/trigger mechanism.

![Prototype Photograph](Image)

Figure 9: Exploded view of the experimental prototype showing (from left to right) the barrel, the barrel flange, the bullet seat, the assembly collar, the combustion chamber carrier, and the firing/trigger mechanism.

The prototype was loaded with a 5.5 g lead bullet and 2.6 g of HAN/ethanol propellant mixture and fired several times. The muzzle velocity was measured with a chronometer. Table 3 shows the firing data obtained from the prototype.

<table>
<thead>
<tr>
<th>Shot #</th>
<th>Velocity (ft/s)</th>
<th>Velocity (m/s)</th>
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<tr>
<td>1</td>
<td>4761</td>
<td>1451.2</td>
</tr>
<tr>
<td>2</td>
<td>2879</td>
<td>877.5</td>
</tr>
<tr>
<td>3</td>
<td>1799</td>
<td>548.3</td>
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<tr>
<td>4</td>
<td>2275</td>
<td>693.4</td>
</tr>
<tr>
<td>5</td>
<td>2196</td>
<td>669.3</td>
</tr>
<tr>
<td>6</td>
<td>2275</td>
<td>693.4</td>
</tr>
<tr>
<td>7</td>
<td>1450</td>
<td>442.0</td>
</tr>
<tr>
<td>8</td>
<td>4678</td>
<td>1425.9</td>
</tr>
<tr>
<td>9</td>
<td>3555</td>
<td>1083.6</td>
</tr>
</tbody>
</table>

Table 3: Firing data from the experimental prototype.

Although the experimental prototype fired every time it was loaded, the measured muzzle velocities were inconsistent. It was observed that for the lower velocity shots, a small amount of liquid propellant residue remained in the firing chamber. For the highest velocity shots, the firing chamber was dry and clear of any propellant residue. One possible cause of this variation is inconsistent sealing of the chamfered pieces. Other possible causes include inaccuracy in the mixture, given the small amount used, or inaccurate measurement due to muzzle gasses possibly interfering with the chronometer. In fact, Table 3 shows only those shots that registered a measurement on the chronometer; four shots did not register a reading.

The muzzle velocity obtained from the simulation was 1300 m/s, which was in good agreement with the two highest muzzle velocities obtained with the experimental prototype. Based on the highest muzzle velocity measured (1451.2 m/s), the experimental setup exhibited a mass specific energy density of 2205 kJ/kg and a volumetric energy density of 3.05 kJ/ml.

6.0 CONCLUSIONS

A first principles dynamic model of a liquid propellant powered rifle was presented. This model incorporates a deflagration rate model of HAN-based reactions and treats the problem as a dynamic compressible fluid power problem. A simulation of this model was performed and compared with firing data from an experimental prototype that was constructed. The experimental setup showed significant variation in the muzzle velocity, but did fire reliably. The higher experimentally measured muzzle velocities agreed well with the simulated dynamic model and support the merits of such a propellant powered rifle over a conventional M16A2 rifle. These merits include: 1) a reduction in the total mass carried per shot, 2) a reduction in the mass of propellant per, 3) the capacity to carry more rounds per clip, 4) a weapon potentially less prone to jamming, 5) the potential for variable selectable muzzle velocity (non-lethal to high-power), and 6) safer logistics given the transport of non-explosive liquid components.

The dynamic model can additionally be used to draw design insights regarding the liquid propellant powered rifle design. Given that the deflagration rate controls the combustion rate and is a function of the cross sectional area of the combustion chamber, the dynamic model suggests that an area profile (i.e. not a constant as a function of $x$) could be designed to better control the combustion rate and therefore the pressure profile in the gun. The dynamic model also allows the investigation of other fuel candidates to be mixed with HAN, such as the nearly universal U.S. military fuel JP-8.

ACKNOWLEDGMENTS

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REFERENCES
