Practical APCP motor design for Amateur & High Power rocketry
What we will be covering:

• The basics & definitions
• Some other considerations
• The process to get the data to input into the BurnSim program
• Designing motor profiles in BurnSim
What we won’t be covering:

\[
\rho_p = \frac{1}{\frac{f_0}{\rho_a} + \frac{f_0}{\rho_b} + \frac{f_0}{\rho_c} + \ldots}
\]

\[
V_1 = \frac{V_p}{V_2} = \frac{I_0}{I_T \rho_p} \frac{1}{V_2}
\]

\[
\rho_{0c} = \frac{m_{0c} \rho_{0c}}{V_{0c}}
\]

Molar = \( \frac{\pi}{4} (D^2 - d^2) L \)

For a right cylindrical grain, where \( D \) = outer diameter, \( d \) = inner (circular) diameter, \( L \) = length of grain.

\[
\rho_p = \frac{1}{\frac{f_0}{\rho_0} - \frac{f}{\rho_T}}
\]

\[
W_f = \frac{D - d}{D} = \frac{2 \pi b}{D} \quad \frac{A_2}{A_1} = \frac{\pi D^2 (1 - V_1)}{L_1}
\]

\[
C_{12}H_{22}O_{11} + 6.29 \text{KNO}_3 \rightarrow 3.80 \text{CO}_2 + 5.21 \text{CO} + 7.79 \text{H}_2\text{O} + 3.07 \text{H}_2 + 3.14 \text{N}_2 + 3.00 \text{K}_2\text{CO}_3 + 0.27 \text{KOH}
\]

\[
2 \text{H}_2 + \text{O}_2 \leftrightarrow 2 \text{H}_2\text{O}
\]

\[
\begin{align*}
\nu_A A + \nu_B B & \Rightarrow \nu_C C + \nu_D D \\
K_c &= \frac{y_C^{\nu_C} y_D^{\nu_D}}{y_A^{\nu_A} y_B^{\nu_B}} \left( \frac{P}{P_i} \right)^{\nu_C \cdot \Delta \nu_C + \nu_D \cdot \Delta \nu_D}
\end{align*}
\]

\[
\begin{align*}
\sum_{i} n_i [n_i - \Delta n_i] & = \sum_{i} n_i [n_i + \Delta n_i]
\end{align*}
\]

\[
\begin{align*}
\text{H}_2\text{O} & \leftrightarrow \text{HO} + \frac{1}{2} \text{H}_2 \\
\text{O}_2 & \leftrightarrow 2 \text{O} \\
\text{H}_2 & \leftrightarrow 2 \text{H}
\end{align*}
\]
A solid rocket motor usually consists of a casing, nozzle, forward closure, a liner and a fuel grain.
Aluminum Motor case

• Aluminum strength rapidly decreases with increased temperature
• Liner material / heat protection
• Case bonding can be used for thermal protection
• The forward closure is a component of the case.
**Propellant**

The grain behaves like a solid mass, burning in a predictable fashion and producing exhaust gases. The nozzle dimensions are calculated to maintain a design chamber pressure, while producing thrust from the exhaust gases.
• The grain burns at a predictable rate, given its surface area and chamber pressure.
• The chamber pressure is determined by the nozzle orifice diameter and grain burn rate.
• Allowable chamber pressure is a function of casing design.
• The length of burn time is determined by the grain "web thickness".
Common modes of failure in solid rocket motors include fracture of the grain, failure of bonding to the casting tube or case bonding, and air pockets in the grain. All of these produce an instantaneous increase in burn surface area and a corresponding increase in exhaust gas production rate and pressure, which may rupture the casing.
Nozzle

- Directs and accelerate combustion gasses to high velocities. Provides Choked flow to prevent catastrophic erosive burning. (Going supersonic in the propellant core)
- Goal is maximum thrust coefficient with minimum nozzle weight.
- Nozzle throat area controls combustion chamber pressure and divergent angle controls thrust amplification through the coefficient of thrust.
Kn  (burning-area to throat-area ratio)
First, it is a general rule that long motors will be erosive. With a standard bates grain geometry, a large burning surface area means there will be a lot more combustion gases flowing, especially at the bottom grain. A general rule is if you have length/diameter of $\geq 8$ (measuring the propellant itself, not hardware) you should be concerned. With nominal bates grain geometries, this is a 5-grain motor.
Erosive Burning Motor Design Issues - 1

High Length-to-Diameter (L/D) Motors Increase Rocket Flight Performance.
Maximizes Total Impulse within a Given Frontal Area,
Minimizes Aerodynamic Drag in Minimum Diameter Rockets.

Keeping the Core Diameter the Same,
Motor Propellant Grain Length is Increased.

How Much Can Motor Length Be Increased
For a Given Motor Diameter?

For Velocity-Based Erosive Burning:
1) Increased Propellant Grain Length
   Increases Propellant Surface Area.
2) For Same $K_c$, Increased Propellant Surface
   Area Requires Increase in Throat Area ($A_{th}$).
3) Increased Throat Area Approaches
   Port Area ($A_p$, the Core Cross-Sectional Area).
   Port-to-Throat Area Ratio ($A_p/A_{th}$) Decreases,
   Core Mach Number Increases, Increased
   Velocity-Based Erosive Burning.

For Mass Flux-Based Erosive Burning:
1) Increased Propellant Grain Length Increases
   Propellant Surface Area.
2) Increased Propellant Surface Area Increases
   Mass Flow Rate Down Core.
3) With Same Core Diameter, Port Area (Core Cross-
   Sectional Area) Remains the Same.
   Increased Core Mass Flow Rate through Same
   Core Cross-Sectional Area Results in
   Increased Core Mass Flux, Increased Mass
   Flux-Based Erosive Burning.

Figure 1. Erosive Burning Motor Design Issues - 1.
Constant Core Mass Flux Core Design

Core Mach Number and Core Mass Flux Design Point Conditions are at Motor Ignition

Core Mass Flux Values Based on Non-Erosive Propellant Burn Rate

Core Diameter Increased Past This Point to Maintain Constant Core Mass Flux

Provides Maximum Motor Length, Minimum Motor Core Diameter, Maximum Propellant Loading for a Given Level (Design Point) of Erosive Burning

Design Point Core Mass Flux Achieved

Design Point Core Mass Flux (Recommended Values)

Non-Erosive: $p_c = 400-600$ psia

Core Mass Flux $\leq 1.0$ lb/sec-in

$p_c = 800$ psia

Core Mass Flux $\leq 1.75$ lb/sec-in

$p_c = 1400$ psia

Core Mass Flux $\leq 2.0$ lb/sec-in

Max Erosive: $p_c = 400$ psia

Core Mass Flux $= 2.0$ lb/sec-in

$p_c = 600$ psia

Core Mass Flux $= 2.5$ lb/sec-in

$p_c \geq 800$ psia

Core Mass Flux $= 3.0$ lb/sec-in

Initial Core Diameter Based On Design Point Core Mach Number

Non-Erosive; $M_a = 0.50$

$\gamma = 1.2; \frac{A_p}{A_{th}} = 1.36$

Max Erosive; $M_a = 0.70$

$\gamma = 1.2; \frac{A_p}{A_{th}} = 1.10$

Figure 9. Constant Core Mass Flux Core Design.
My motor design process from the start to finish

Using PROPEL20 spreadsheet workbook, ProPep3, and BurnSim
Select Propellant formula for characteristics desired

- Simple formula to start
- Colored flame
- Smoke or no smoke
- Fast burn / High thrust / High performance
- Slow burn / Long burning / Long length to diameter motors
- Packable or pourable
Select the motor size (Impulse, motor case to be used, etc.)
  • Test motor grain size x multiple burns for mix batch amount
The ‘Batch’ sheet for mixing your propellant
Mixing the propellant

- HTPB / Binder – fuel
- Plasticizer
  - DOA (Dioctyl adipate)
  - IDP (Isodecyl Pelargonate)
- Cross linking agent
  - Castor Oil
- Bonding Agent
  - Tepanol or HX-878
- Surfactant (Surface Acting Agent)
  - Lecithin
  - Silicon Oil
Metals are fuel (Powdered Aluminum, Magnesium, Zinc)

- Increases combustion temperature
- Dampens combustion instability
- Magnesium reported to improve low pressure burning
Burn Rate Modifiers

- Catalyst
  - Transition Metal Oxides 0.05% to 1% such as red Iron Oxide, manganese dioxide, cupric oxide, chromium oxide, etc.
- Burn Rate Suppressant
  - oxamide, ammonium chloride, calcium carbonate, etc.
Opacifier if needed

Ammonium Perchlorate Oxidizer (AP)
  • 90 micron, 200 micron, 400 micron

Curatives (Diisocyanates)
  • MDI, IPDI, DDI, HDI, TDI, E744

Vacuum Processing
Cast Propellant & Cure time
Area for propellant properties tab in the BurnSim program
Values for $C^*$, $(a)$, $(n)$, Density, Heat Ratio & Molar Mass are found in the steps on the following slides. These are needed to run motor sims.

Char. ISP value is automatically filled in when you enter the $C^*$ value.
Measure the actual density of your mixed & cast propellant
## DETERMINATION OF DENSITY OF PROPELLANT

To determine density, fill a graduated cylinder about half full of water. Record the volume. Weigh several pieces of propellant that will fit easily in the cylinder. Record the total weight. Carefully drop (without splashing) the pieces of propellant in the water. Record the new volume.

<table>
<thead>
<tr>
<th>Volume of water initially</th>
<th>7.2 milliliters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight of propellant added to cylinder</td>
<td>25.5 grams</td>
</tr>
<tr>
<td>New volume of propellant and water together</td>
<td>24.8 milliliters</td>
</tr>
</tbody>
</table>

### Density

<table>
<thead>
<tr>
<th>Density</th>
<th>1.4489 grams/mL</th>
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<tbody>
<tr>
<td></td>
<td>0.05234 lb/cu.in</td>
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</table>

Or you can get a fair value for density by weighing a given propellant grain. You must also know the weight of an empty casting tube (it doesn’t have to be the same length as your grain)

<table>
<thead>
<tr>
<th>Length of paper casting tube</th>
<th>21 inches</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight of paper casting tube</td>
<td>77.5 grams</td>
</tr>
<tr>
<td>O.D. of propellant (i.d. of tube)</td>
<td>2.536 inches</td>
</tr>
<tr>
<td>Diameter of core</td>
<td>0.875</td>
</tr>
<tr>
<td>Length of grain</td>
<td>21</td>
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<tr>
<td>Weight of grain</td>
<td>2515.2 grams</td>
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### Density

<table>
<thead>
<tr>
<th>Density</th>
<th>1.592 grams/mL</th>
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<tr>
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<td>0.05756 lb/cu.in</td>
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</table>
Run propellant chemical composition in ProPep
Enter formula data here

Value for heat ratio

Display Results gives next slide data

(C Star) value

Molar Mass

Value for heat ratio
<table>
<thead>
<tr>
<th>Ingredient</th>
<th>C* Value for Small Motors</th>
<th>C* Value for Large Motors</th>
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<tbody>
<tr>
<td>Ammonium Perchlorate</td>
<td>0.8564</td>
<td>0.864</td>
</tr>
<tr>
<td>Ammonium Chloride</td>
<td>0.8564</td>
<td>0.864</td>
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<tr>
<td>Zinc</td>
<td>0.8564</td>
<td>0.864</td>
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<tr>
<td>Calcium Carbonate (CaCO3)</td>
<td>0.8564</td>
<td>0.864</td>
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<tr>
<td>HTP (H-45N)</td>
<td>0.8564</td>
<td>0.864</td>
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<tr>
<td>Dinitroxydinitrotoluene (DNX)</td>
<td>0.8564</td>
<td>0.864</td>
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<tr>
<td>MDA (Per 9H)</td>
<td>0.8564</td>
<td>0.864</td>
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</tbody>
</table>

**The Propellant Density is:** 0.55974 lb/cu-in or 1.636 g/cc
**The Total Propellant Weight is:** 104.2400 lbs

**Number of Granules of Each Element Present in Ingredients:**

<table>
<thead>
<tr>
<th>Element</th>
<th>Number</th>
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<tbody>
<tr>
<td>H</td>
<td>4.72146</td>
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<tr>
<td>O</td>
<td>1.37623</td>
</tr>
<tr>
<td>N</td>
<td>4.68054</td>
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<tr>
<td>C</td>
<td>7.3730</td>
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<tr>
<td>CL</td>
<td>0.66995</td>
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<tr>
<td>CN</td>
<td>0.00059</td>
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**Specific Heat (Molal) of Gas and Total:**

<table>
<thead>
<tr>
<th>Compound</th>
<th>Specific Heat (Molal)</th>
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<tbody>
<tr>
<td>M2</td>
<td>5.55656 x 10^3</td>
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</table>

**Specific Heat (Molal) of Gas and Total:**

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<th>Compound</th>
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<tbody>
<tr>
<td>M2</td>
<td>5.55656 x 10^3</td>
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</table>

**Number of Mols Gas and Condensed:**

<table>
<thead>
<tr>
<th>Mols Gas</th>
<th>Mols Condensed</th>
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<tbody>
<tr>
<td>4.419</td>
<td>0.031</td>
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</table>

**The Molecular Weight of the Mixture is:** 23.425

**Specific Heat (Molal) of Gas and Total:**

<table>
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<th>Compound</th>
<th>Specific Heat (Molal)</th>
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</thead>
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<tr>
<td>M3</td>
<td>5.55656 x 10^3</td>
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**Specific Heat (Molal) of Gas and Total:**

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<th>Compound</th>
<th>Specific Heat (Molal)</th>
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<tr>
<td>M3</td>
<td>5.55656 x 10^3</td>
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**Number of Mols Gas and Condensed:**

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<tr>
<th>Mols Gas</th>
<th>Mols Condensed</th>
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<tr>
<td>4.380</td>
<td>0.060</td>
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**The Molecular Weight of the Mixture is:** 23.477

**Performance:**

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<tr>
<th>Impulse</th>
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<th>P</th>
<th>C*</th>
<th>ISP*</th>
<th>OPT-ISP</th>
<th>D-ISP</th>
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<th>EX-T</th>
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<tr>
<td>198.6</td>
<td>1.2718</td>
<td>1781</td>
<td>26.22</td>
<td>748.6</td>
<td>6.07</td>
<td>318.4</td>
<td>0.1067</td>
<td>866</td>
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<td>201.9</td>
<td>1.2337</td>
<td>1814</td>
<td>26.51</td>
<td>742.5</td>
<td>6.48</td>
<td>333.9</td>
<td>0.1875</td>
<td>866</td>
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</table>
Do test burns & get time / pressure values with different $Kn$
(Propellant surface area to Nozzle throat area ratio)
Use this sheet to find your Kn ratios

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Note: you don’t have to fill in every box. Multiple boxes are given to allow you to see differences in Kn/nozzle throat with different dimensions.
Test burns to get burn times with different nozzle throat diameters (Kn)
Two burns times can get you a basic ‘a’ (BR-coefficient) and ‘n’ (BR-exponent)
Multiple burn times gives more accuracy

With the last of these values you can now start to model motors in the BurnSim program.

**Regression Output:**
- Constant: -1.92678
- Std Err of Y Est: 0.002525
- R Squared: 0.989382
- No. of Observations: 6
- Degrees of Freedom: 4

- X Coefficient(s): 0.481303
- Std Err of Coef: 0.016705

**Burn Rate Coefficient:** 0.011836
**Burn Rate Exponent:** 0.481303
Note the yellow warning of approaching erosion.

Insert nozzle values here.

Insert grain size values here, click on ‘add’ to add grains into simulation.
Cutting the top grain almost in half, and drilling the bottom core larger gets rid of the erosion warning.
Having no expansion on the nozzle shows the difference having no thrust coefficient. It goes from 38% L motor to 19% L.
Progressive fast burn
Neutral burn profile
On a Moon burner the core diameter determines initial thrust, the core offset determines the peak pressure.

Progressive/regressive long burn
This motor will overpressure on start up because of erosion.
Larger core on ‘C slot’ and it will run well. The flow of hot gasses along the outside of the motor makes it harder to protect the case from burn-thru.
Long motor design with progressive grains using a slow propellant. Notice the larger cores on the bottom two grains.
Core is a little small on this slide, the next shows a better sized core.
High thrust short burn
Under the ‘Action’ menu you can have the program run simulations to determine the most efficient exit diameter on the nozzle.
References

• Experimental Composite Propellant by Dr. Terry W. McCreary, Ph.D.
• Richard Nakka
• Defense Technical Information Center – Naval Weapons Center papers
• Wikipedia
• Charles E. Rogers
• John S. DeMar