Dynamics of Solid Fuel Rocket Engines: Exploring Physics and Feedback

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Abstract

Increased interest in science, technology, engineering, and math (STEM) curriculum opens the door to many non-linear and dynamically complex systems for study. Gaining a basic understanding of dynamic complexity can get lost in the detail complexity of the subject. This paper uses the dynamics of a solid fuel rocket engine to describe a modeling structure that allows three layers of exploration. The first exploration layer provides an interface for gaining an intuitive feel for the system through interactive experimentation. The second exploration layer provides an overview of the feedback structure of the major components of the system. Finally, the third exploration layer provides the mathematical and scientific details one component at a time for users who desire a more detailed understanding of rocket engine dynamics. It is proposed that the presented model structure could be used as a blue-print for describing other dynamically complex processes within a successful STEM curriculum.

Keywords: Rocket Engine, Solid Fuel, High Power Rocketry, Ideal Gas Law, Bates Grain, STEM

Introduction

Recent emphasis on science, technology, engineering, and math (STEM) curriculum has created a renewed interest in the associated fields of study, including rocket science. Highly publicized efforts to encourage the private pursuit of rocket science such as the X-Prize (www.xprize.org) and the Team America Rocketry Challenge (TARC: www.rocketcontest.org) have generated international attention and increased enthusiasm for model rocketry. As a result, membership in amateur rocket organizations such as The National Association of Rocketry (www.nar.org) has reached record levels.

While there are many scientific considerations that go into a successful rocket flight, this paper will focus on the high speed dynamics of solid-fuel propellants. These fuels must be self-oxidizing and must provide sufficient thrust to boost the rocket to the desired altitude. Amateur rockets range in weight from a few ounces to hundreds of pounds and can be successfully flown to altitudes of hundreds to thousands of feet. Without sacrificing power, solid rocket propellants must be safe to handle, ship, and store to make them practical for the amateur scientist.

Using generally available information, this paper introduces a system dynamics model containing the physics and feedback of how a rocket engine using safe solid fuel can generate the thrust required to achieve an exciting and successful rocket launch. The model uses three interactive layers to allow multiple levels of investigation. It is hoped that this layered approach will make teaching this science available to a wider range of students. Interesting rocket engine dynamics can be explored with or without exploring the most detailed layer within the model.

At the most abstract “interface” layer, the user is encouraged to change the physical dimensions of the solid fuel propellant and to turn on and off two significant physical effects, to gain an intuitive understanding of the physics and feedback of solid fuel propulsion. The next layer details a causal loop diagram showing the major components and relationships responsible for rocket propulsion. The third layer details the physics of each causal component exposing some of the science behind the dynamics. It is hoped that this model or one like it can be used in high school classrooms to introduce students to rocketry and the science making rocket flight possible.

The Model’s Interface Layer

At its most basic level, the solid fuel rocket engine model presents the geometry of a solid fuel propellant grain, input controls, and a graph pad of the resulting engine burn. The overall layout is shown in the figure below.

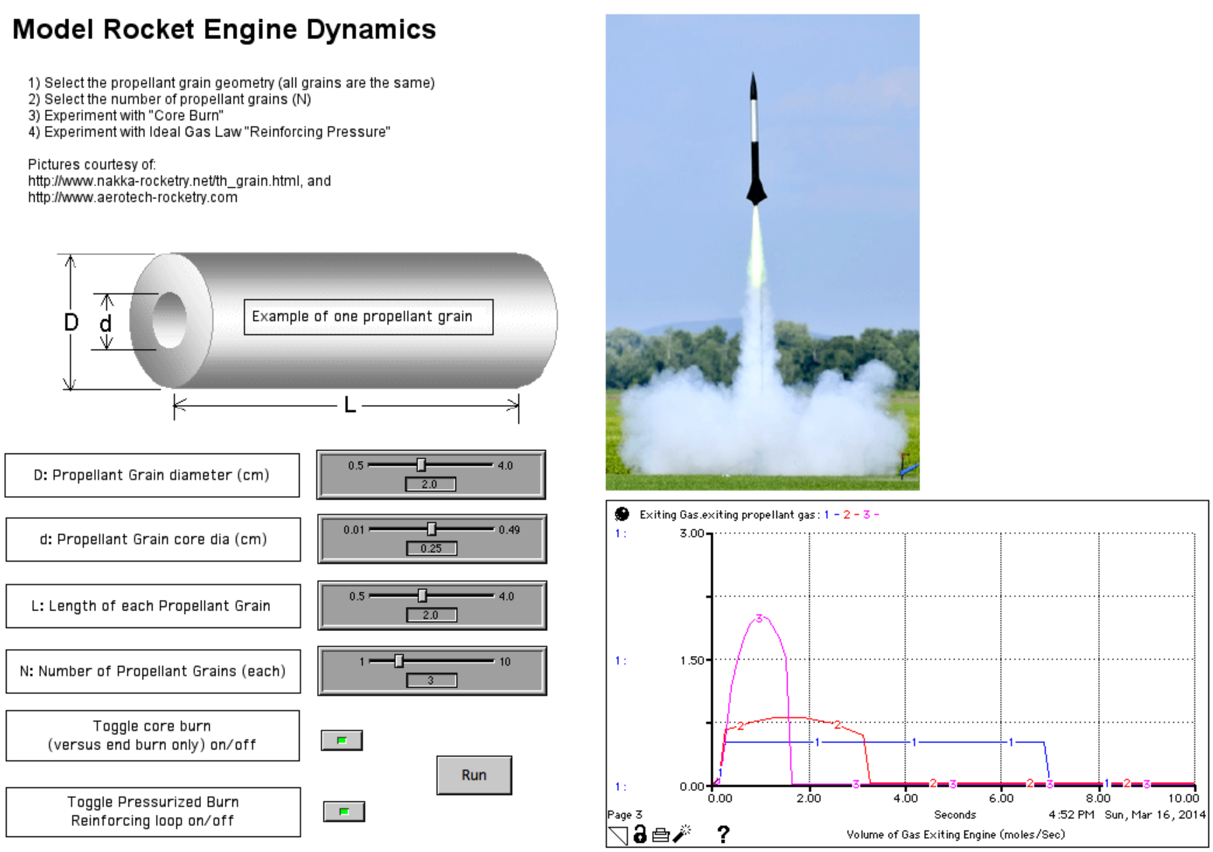


Figure 1: Model Interface Layer

Solid fuel model rocket engines are composed of one or more cylindrical propellant grains contained in an engine casing. The top end of the engine casing is plugged and the lower (aft or "business") end of the engine casing contains the nozzle through which hot exhaust gases pass to produce thrust. Propellant grains are cylindrical with a diameter (D) and a length (L). To increase the burring surface area, multiple propellant grains are used in place of one long grain. Because the grains burn from each end simultaneously, the more grain segments, the more end-burning surface area and the more thrust. A comparison of different propellant configurations is shown in figure 2a below.

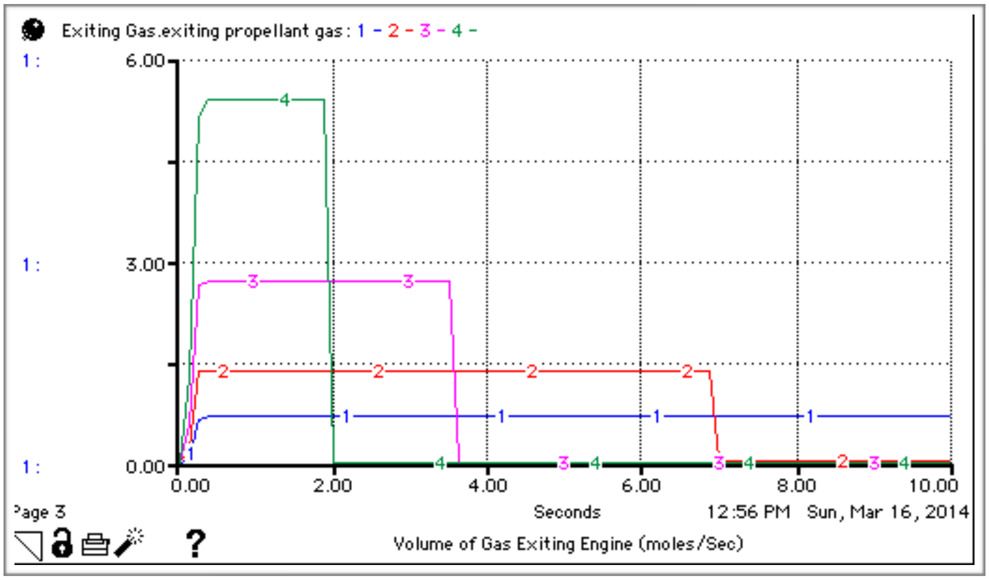


Figure 2a: Comparison of 1 to 8 Propellant grains in a 4 cm Engine without Core Burn

An engine of length four cm composed of a single grain burns two ends simultaneously (blue) causing the combustion gas to exit the engine's nozzle over a relatively long burn time (low thrust). Whereas an engine of length four cm composed of eight half cm grains burns 16 ends simultaneously (green) causing the combustion gas to exit the engine's nozzle over a relatively short burn time and producing relatively more thrust for the same volume of propellant.

In addition to burning from its ends, a propellant grain also burns from the inside core outwards. The experiment above ignored the core burn effect using the "Toggle Core Burn" switch. Burning a four cm two grain engine with and without the core burn effect is shown in figure 2b below. The addition of a core burn (red line) causes the propellant to be consumed non-linearly. More propellant burns sooner improving the rocket's ability to accelerate faster during lift-off. (Note: that the core burn effect is not dependent on the number of propellant grains.)

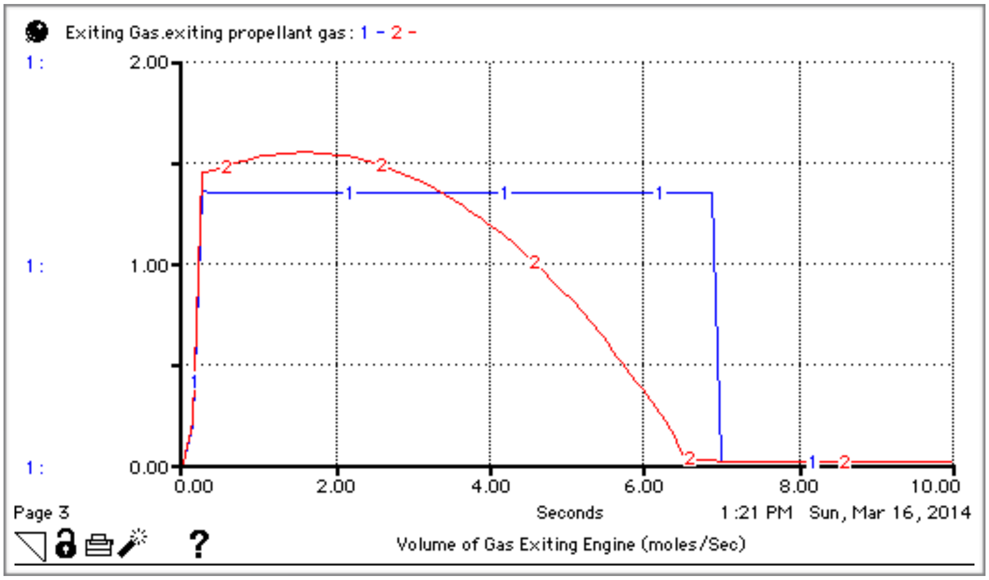


Figure 2b: Comparison of Linear Burn versus Core Burn in a 4 cm Engine with 2 Propellant grains

These first two simple experiments demonstrate significant differences in result and introduce non-linear behavior through the properties of propellant grain geometry alone. While these experiments do contain some feedback mechanisms (e.g. the propellant burn ends when the propellant is consumed), the primary reinforcing feedback loop is disabled using the "Pressurized Burn Reinforcing Loop" switch.

The Ideal Gas Law relates gas pressure to mass, temperature, and container volume. Because the propellant is contained in a rocket engine casing, the more gas created through conflagration, the more pressure there is inside the engine. Pressure is released as gas exits though the engine's nozzle. Higher engine pressure also causes the linear burn rate of the propellant to increase, causing more propellant to burn (feedback mechanisms will be described in more detail in the Causal Loop Layer section of this paper). Turning on the Pressurized Burn reinforcing loop adds the pink result in figure 3 below.

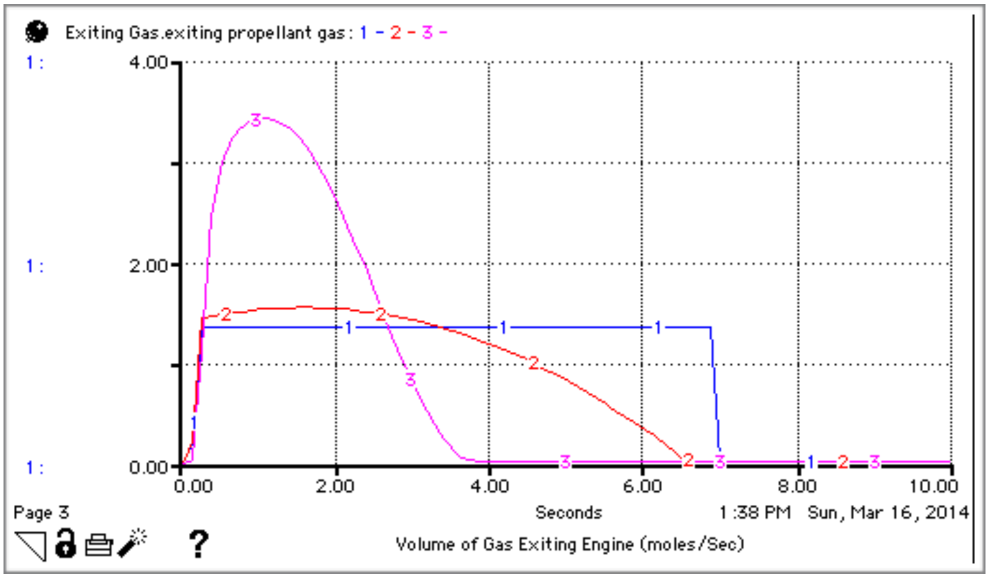


Figure 3: Comparison of Linear Burn versus Core Burn versus Core Burn with Pressurized Burn reinforcing feedback in a 4 cm Engine with 2 Propellant grains

The addition of this critical reinforcing feedback loop shows the true lift-off thrusting power of a rocket engine. The absence of this reinforcing feedback is also why solid fuel propellant is much safer when it is stored outside of the rocket engine casing. Without a container to cause pressure to build, the linear burn rate of the solid propellant is limited. In addition, without containment, solid propellant tends to burn from one end (whatever end is lit) and progress at its relatively slow nominal linear burn rate. It is for this reason that safety regulations require propellant grains to be stored in plastic bags (outside of their engine casings) and in groups of limited propellant mass. In this format, propellant grains can be safely handled, stored, and shipped.

In addition to the experiments described above many other scenarios can be developed using the input sliders available on the interface layer. Students could be encouraged to come to their own conclusions about what is happening by making calculated changes to these sliders one at a time while developing their own hypotheses about what causal mechanisms are effecting the outcome.

The Model's Causal Feedback Layer

At the model's next layer of detail, causal relationships can be explored. The model is broken up into seven modular components. Each module represents a core math or science concept that can be explored further with students by opening the corresponding module. By hiding the detail within each module, the overall model dynamics are easily explained as shown in figure 4 below. Green causal arrows indicate a positive relationship (for example: the more remaining propellant there is, the more burn volume there will be, all else being equal). Red causal arrows indicate an inverted relationship (for example: the faster the linear burn rate, the less remaining propellant there will be, all else being equal). The causal feedback layer shows four feedback loops: one powerful reinforcing loop and three balancing loops.

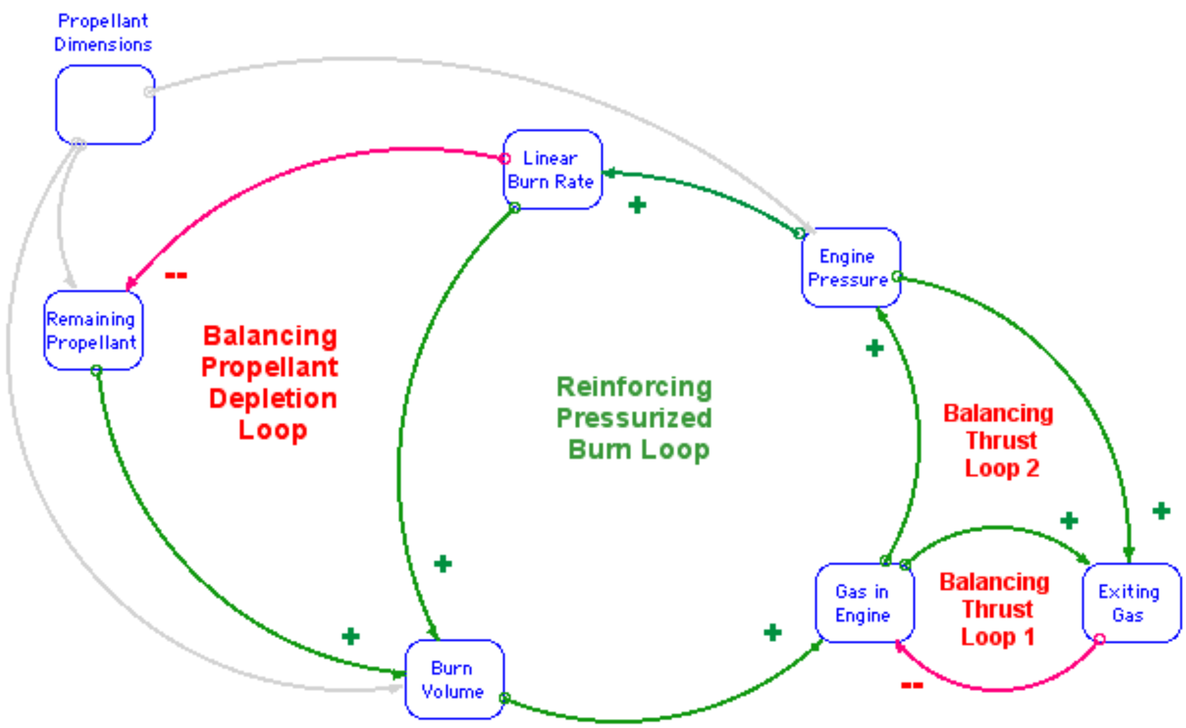


Figure 4: Model Causal Feedback Layer

The reinforcing loop involves the relationship between pressure in the engine and the linear burn rate of the propellant. Starting with the Burn Volume: the more volume of burring propellant, the more gas will be in the engine; the more gas in the engine, the more pressure in the engine container; the more pressure in the engine container, the faster the linear burn rate of the propellant (at the “conflagration face” of the burring solid propellant); the faster the propellant burns, the more volume of burring propellant, and so on around the feedback loop. This is the reinforcing feedback that can be turned on and off by the “Pressurized Burn” toggle switch on the interface layer.

In a similar fashion, the balancing feedback loops can be traced out. There are two primary balancing processes in the model. First, the more propellant is burning, the less propellant that remains. Thus the propellant burn is limited by the availability of propellant fuel (Balancing Propellant Depletion Loop). And second, the more gas present in the engine container, the more gas exiting the engine container (primarily due to increased pressure - Balancing Thrust Loops 1 & 2). Thus the pressure in the engine container is limited by gas exiting the engine nozzle. In absence of this balancing feedback, engine pressure would continue to build until the engine container exploded. (While this can be quite exciting, it is not what a rocket scientist amateur or professional is hoping to achieve.)

In this manner, the model's causal feedback layer can be easily used to describe non-linear interactions between the burning solid propellant, the changing linear burn rate, the changing pressure in the engine chamber, and the developing thrust over time. Using these causal arguments, students can gain a deeper understanding of the causes of the dynamic behavior of the experiments they performed using the model's interface layer. Students could be asked to sketch their dynamic hypotheses of causal mechanisms for the observed interface layer behavior before viewing the causal layer of the model. Comparing the student's dynamic hypotheses with the causal mechanisms built into the model could add to the learning experience.

The Model's Detail Layer

The final layer of model details lie within each of the component modules. The underlying model structure answers such questions as: "How is linear burn rate related to pressure?;" "What causes the engine pressure to increase?;" and "How is the volume of burring propellant calculated?" For brevity, three of the component modules will be described in this paper, leaving the remaining four modules for the curious reader to explore (iThink model file accompanies this paper).

Figure 5 below shows the details of the "Propellant Dimensions" module. A graphic of propellant grains with their measured dimensions clearly shows the information being used to capture propellant geometry. In addition, calculated fields such as "total propellant length" and "engine volume" are shown. Clicking into either of these calculated fields will reveal their relatively simple formulas.

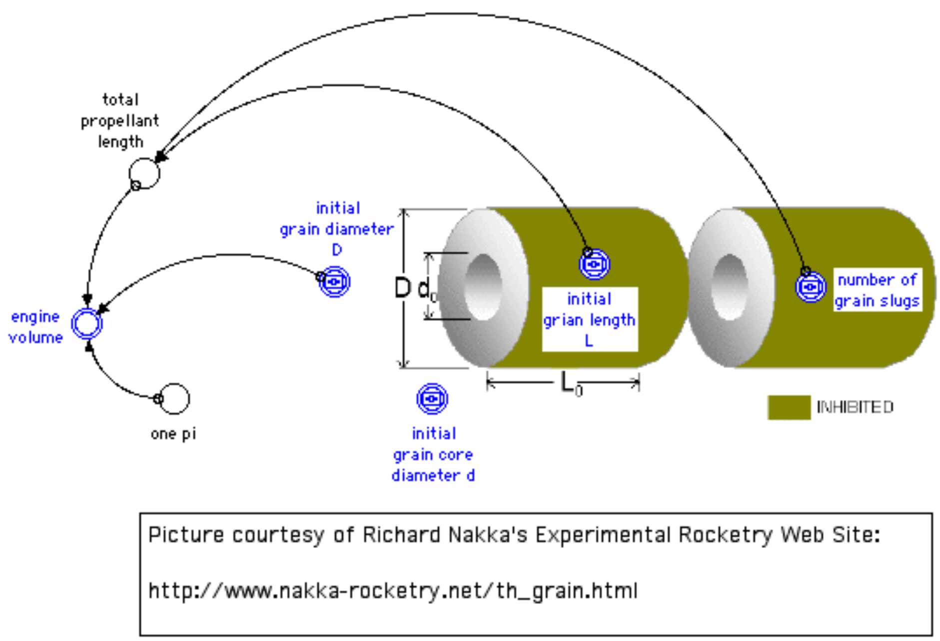


Figure 5: Details of the Propellant Dimensions Module

As can be seen in the causal feedback layer, the Propellant Dimensions module does not have any inputs and therefore does not participate in any feedback loops. This module is included to provide required setup information to the remaining modules as needed. Five of the module variables are available as outputs to other modules. The output variables are shown in blue and have a double wall circle symbol. The variables shown with a small slider symbol inside their circle are available as slider inputs on the model's interface layer.

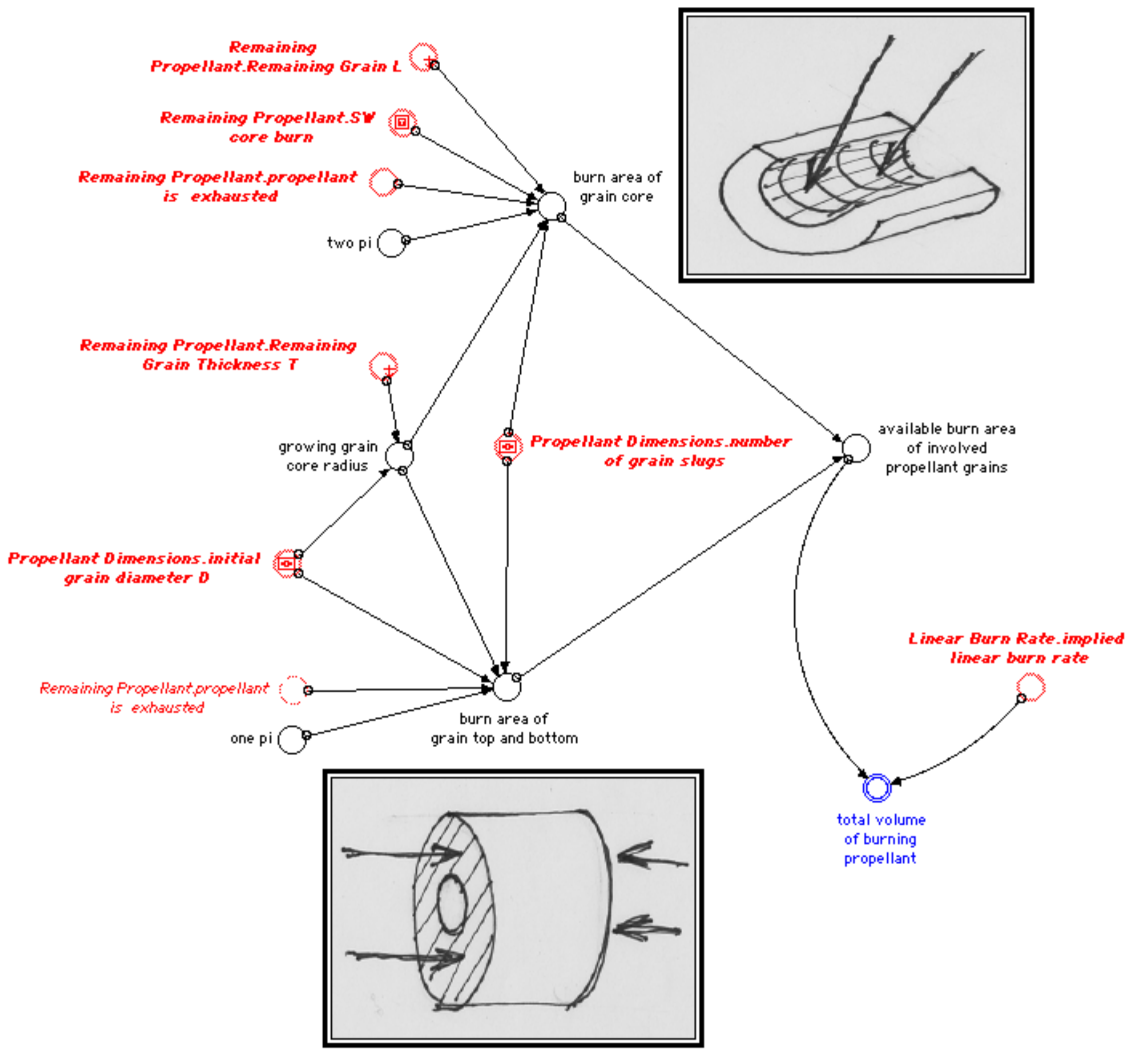


Figure 6: Details of the Burn Volume Module

Figure 6 above shows the details of the "Burn Volume" module. Again pictures are included to help explain the calculations. In this module burning propellant occurs either on each end of the propellant grain ("burn area of top and bottom" at the bottom of figure 6), or in the core of each grain ("burn area of grain core" at the top of figure 6). This module has seven inputs (shown in red). Six of the input variables provide propellant dimensions from the Remaining Propellant and Propellant Dimensions modules. The remaining input variable is the “implied linear burn rate” from the Linear Burn Rate module.

The Burn Volume module provides one output (shown in blue) which is the “total volume of burning propellant”. The volume of burning propellant is a rate (cubic cm/sec) equal to the “available burn area” (square cm) times the current “implied linear burn rate” (cm/sec). While this module may have several details, the calculations generally build from left to right.

Figure 7 below shows the details of the “Engine Pressure” module. This module uses the Ideal Gas Law to compute the “pressure in engine chamber P” using the “engine volume” and the “Moles of Propellant Gas n” inside the engine (for simplification, a constant temperature is assumed). A text box is included to remind the user of the Ideal Gas Law formula. Inputs from other modules are shown in red and this modules output is shown in blue.

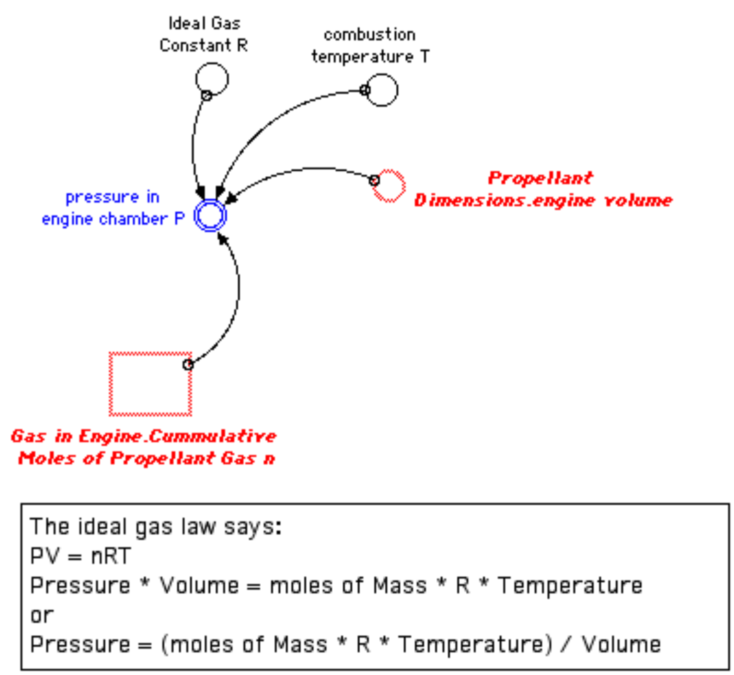


Figure 7: Details of the Engine Pressure Module

Exploring all of the component modules provides a high level of detail contained in the model. Exploration of all of the detail is not required to create a meaningful learning experience. One of the primary goals in creating this model was to create the opportunity to interact and explore with an interesting real physical phenomenon at different levels of explanation. A model with realistic behavior must include the detailed equations that may not be of interest to some. But permanently hiding important details makes the model a frustrating “black box” experience for those who want to know more. This model was structured to provide both summary and detailed experiences as the model user chooses. Figures 8 through 11 below show the details of the remaining four model component modules. Inputs to each module are shown in red, outputs are shown in blue.

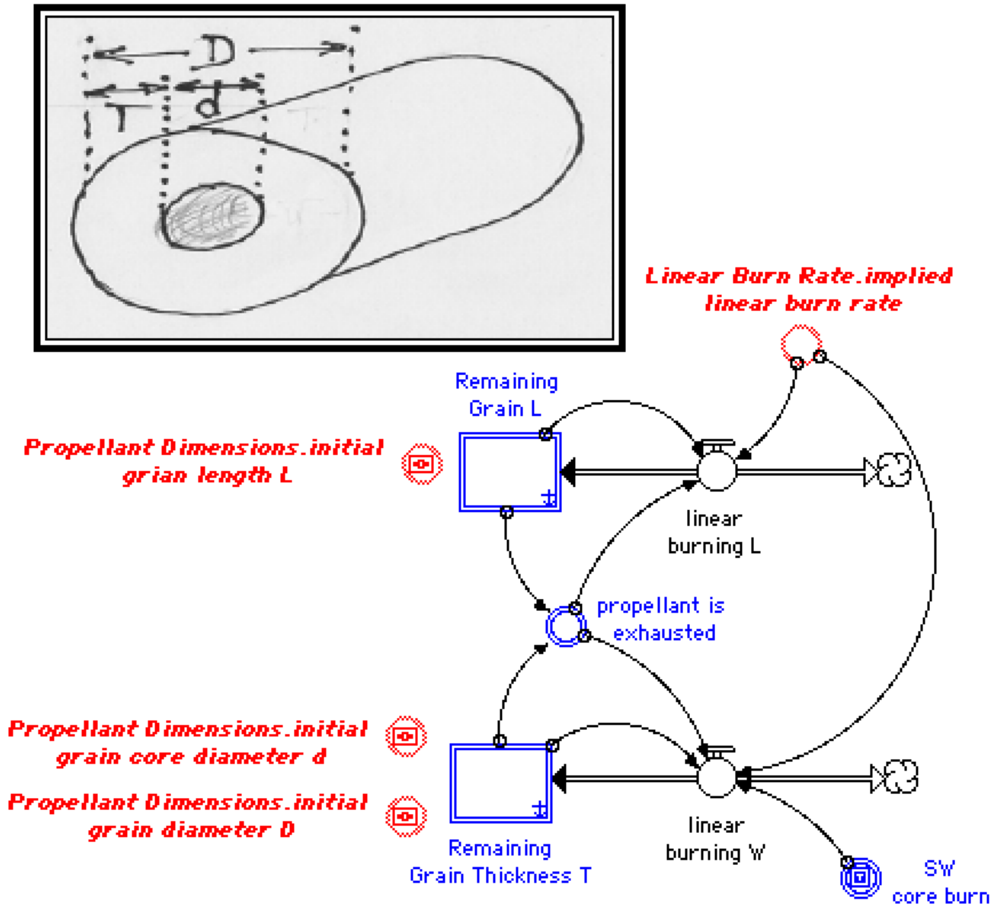
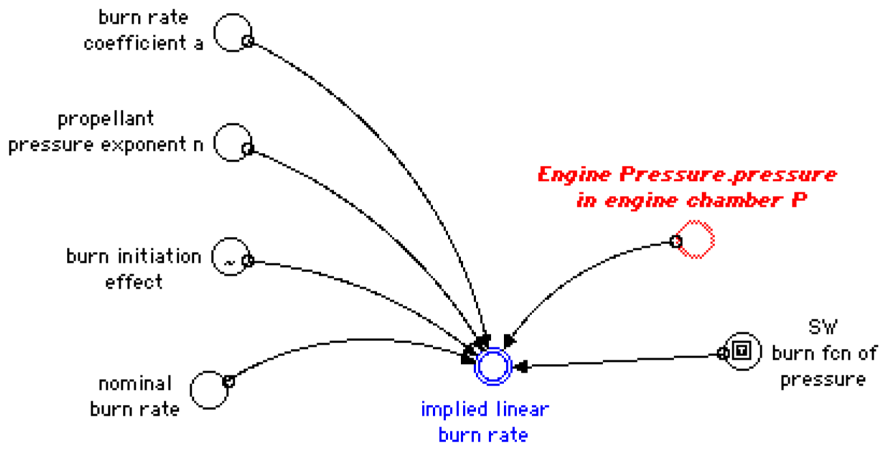


Figure 8: Details of the Remaining Propellant Module



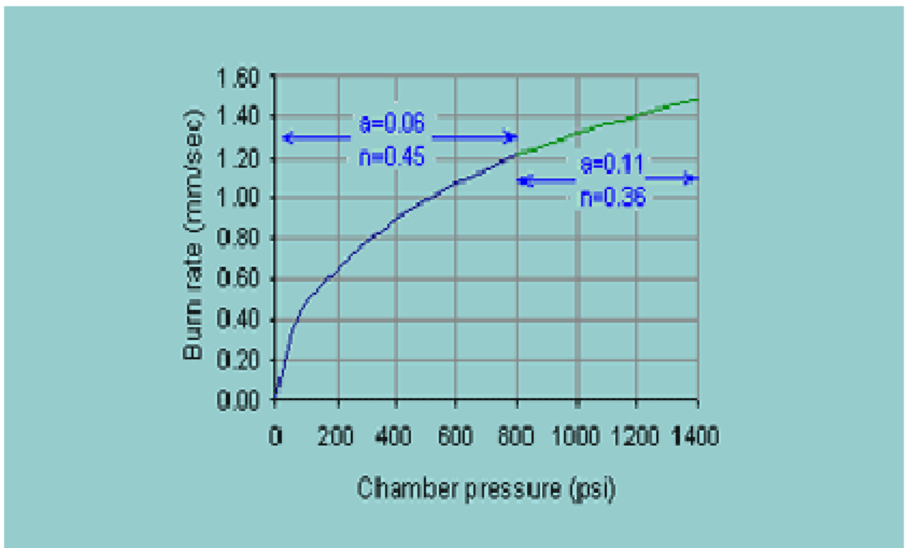
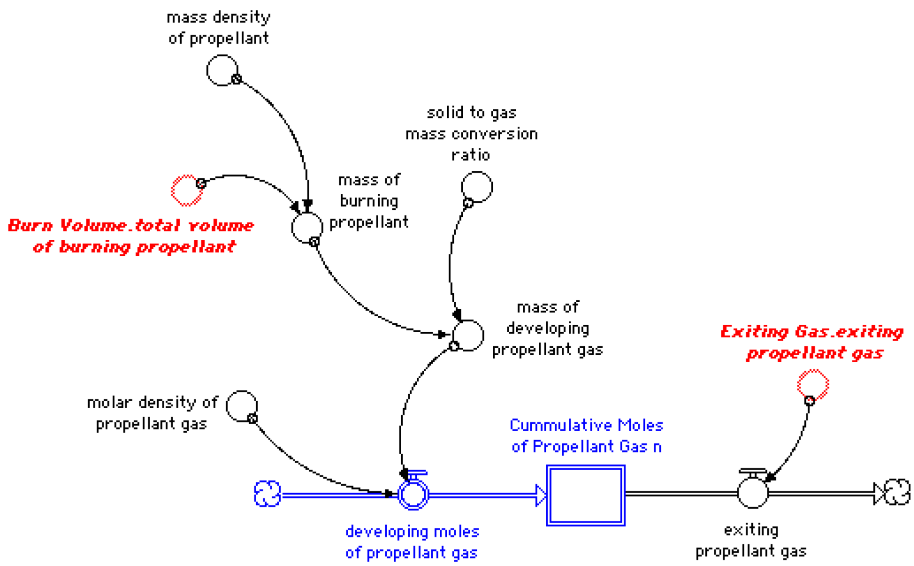


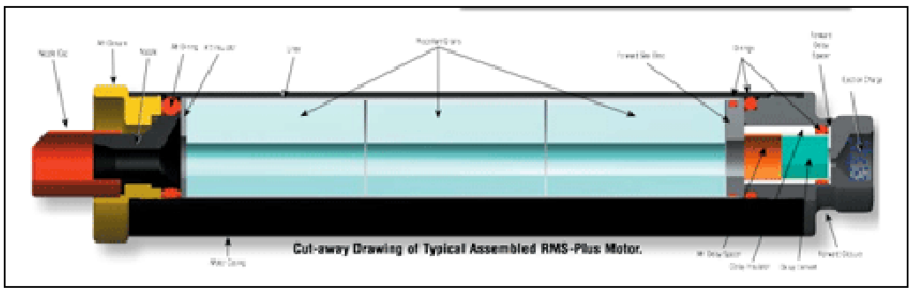
Figure 2 -- Saint Robert's model of burn rate v.s. pressure (example)

Burn Rate chart courtesy of Richard Nakka:

http://www.nakka-rocketry.net

Figure 9: Details of the Linear Burn Rate Module

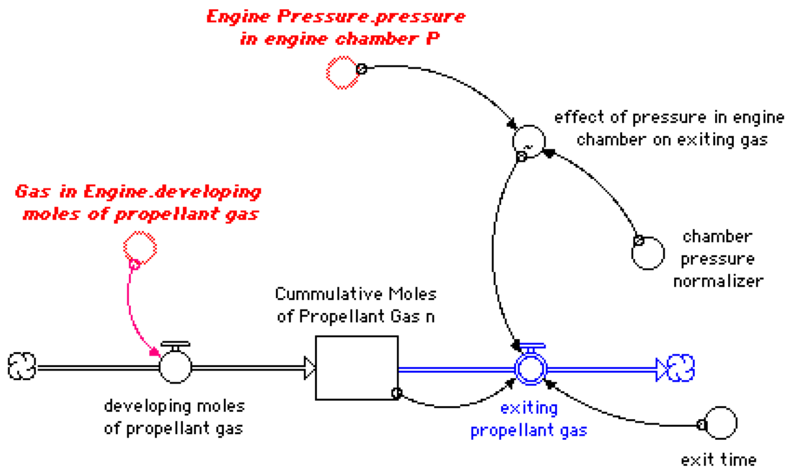




Picture curtesy of Aerotech Consumer Aerospace:

http://www.aerotech-rocketry.com/products.aspx

Figure 10: Details of the Gas in Engine Module



Picture curtesy of Aerotech Consumer Aerospace:

http://www.aerotech-rocketry.com/gallery.aspx

Figure 11: Details of the Exiting Gas Module

Summary and Future Work

The model presented in this paper provides an interactive environment for exploring the dynamics of solid fuel rocket engines. An effort was made to structure the model so that a causal user can gain an intuitive feel for these dynamics by experimenting while a more interested user can dig deeper through two additional layers of details to learn more about the system's feedback structure as well as the underlying calculations. Using this model structure additional details could be added to refine the calculations and/or feedback dynamics. While a single user could explore the model unguided, the model was built with the intent that it be used in a guided classroom type setting.

The model structure presented here is not limited to rocket science. Many other dynamic physical or chemical processes could be captured in the same model structure. Dynamic non-linear processes such as the rocket engine dynamics described herein are particularly hard to capture and explain. Because the proposed model structure is based on System Dynamics (an accepted and proven dynamic modeling tool), it is well suited to capturing and explaining dynamic systems. In addition, the multi-layer approach provides an easier experiential entry into understanding dynamic complexity. With this in mind, it is believed that this same modeling approach could be successfully used in many different classroom settings.

Acknowledgements

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Biography

Warren Farr received his Master of Science in System Dynamics from Worcester Polytechnic Institute in 2011. He has been working in the heating, ventilating, air conditioning, and refrigeration industry as a wholesaler since 1993. Prior to learning to operate a wholesale business, Warren worked in the computer industry developing and marketing network control products, and as a contractor to the military developing communication and targeting systems. He has a Bachelor of Science degree from Duke University and a Master of Business Administration also from Duke.