# Mechanistic Model for Analysis of Pulse-Mode Engine Operation

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**A highly detailed time-dependent numerical model has been developed that is capable of quantitatively calculating the transient system processes occurring in a pulsed liquid rocket engine. The operational problems that can be analyzed include vacuum hypergolic ignition and the start transient, pulse-mode specific impulse, low frequency system instability, production of contaminant material in the plume as wall film, explosion pressures that can be obtained from chamber detonations, and engine response to off-nominal operating conditions. Good agreement with experiment has been obtained.**

## Introduction

THE combustion chamber processes important to large rocket engines have been modeled successfully for several years using the method introduced by R. J. Priem[1] and subsequently refined by others.[2] In these methods, numerical integration is used to calculate the trajectories and evaporation rates of the propellant droplets, assuming steady conditions in the chamber and one-dimensional flow of the gas and droplets. This same basic analysis has been extended to include the more complex events of importance in small pulse-modulated rocket engines.[3] However, small rocket engines differ from large engines in two important ways: first, the proximity of the injection points to the chamber wall, the larger surface-to-volume ratio of the chamber, and the widespread use of film-cooling make deposition and behavior of unburned propellant on the walls much more important in small engines; second, small rocket engines are typically used to control vehicle attitude or for minor trajectory corrections, where the firing duration is typically as short as 10 to 100 ms, thus the transient behavior of a small engine system is at least as important as the steady-state behavior. These aspects of pulse-mode operation have been emphasized in the present analysis.

## Method of Approach

The analytical technique and computer program described here constitute a time-dependent mechanistic analysis of the simultaneous and sequential processes that take place in the feed system, injector, combustor, and nozzle of a propulsion system in the reaction control system (RCS) size range. The computer program is called the Transient Combustion Chamber program.[4-10] The system modeled consists of a pressure-fed bipropellant feed system, an injector, a combustion chamber, and a nozzle (see Fig. 1).

The initial flow of propellant is calculated as the valves open, the fluids accelerate through the resistive-inertial feed lines, and the injector fills. If the vapor pressure of the first injected propellant is sufficiently above the initial chamber pressure, and the stream Weber number is sufficiently high, the atomization is calculated to take place by vacuum-flashing of the stream. If one stream is injected before the other and does not flash, it is calculated to undergo single-stream breakup if there is sufficient distance. Alternatively, it impinges upon the chamber wall, where part of it sticks as wall film and the rest is calculated to atomize by the wall impact. Later in the firing, atomization occurs by the impingement of the two unlike streams. The time-varying initial mean droplet size, the droplet size distribution, the initial droplet velocity vector, initial velocity distribution, and the distance traveled before the breakup process is completed are all calculated as time-varying functions of the injection and chamber parameters.

Two-dimensional trajectories of all of the droplets injected into the chamber are calculated with Reynolds-number-dependent drag coefficients recalculated for each droplet group at each time interval. The trajectories are followed until the droplets either burn completely, pass through the nozzle incompletely burned, or impact upon the wall. The normal bipropellant combustion rates of the droplets are based on droplet diameter and physical properties, droplet Reynolds number, combustion gas temperature and composition, and the presence or lack of ignition in the chamber. When a propellant constituent such as hydrazine has appreciable monopropellant character, this may also be modeled. The combustion rates are recalculated for each droplet group at each time interval to reflect the changing conditions in the chamber. The chamber gas properties are recalculated at each time interval, as is the chamber's velocity profile. The velocity profile is based on the axial distribution of contributions of vapor from burning droplets, igniter flows, vacuum flashing propellant streams, propellant burned off the wall film and propellant vacuum-evaporated from the wall film.

Hypergolic vacuum ignition is calculated in the vapor phase, based on global chemical kinetics.[11] Various locations are examined to determine where ignition will occur first, the well-mixed vapors in the chamber, the most recently formed vapor mixture from the flashing streams, the boundary layer around the fuel droplets, or the boundary layer around the oxidizer droplets. Once ignition occurs anywhere, the entire chamber contents are presumed to ignite and will continue to burn until the criterion for extinguishment is met. Before ignition, the values for the temperature, molecular weight, and specific heat of the chamber gas are calculated, assuming well mixed but unreacted fuel and oxidizer vapor. After ignition, properties appropriate for equilibrium combustion

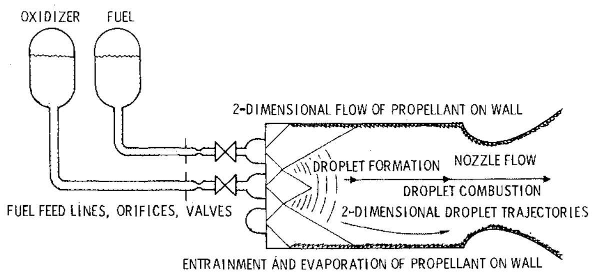


**Fig. 1 Rocket system diagram. Film-cooled unlike-impinging injector.**

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products are used. After extinguishment, a distinction is drawn between quenched combustion gas and newly formed propellant vapors, so as to properly calculate reignition, if it occurs.

The film of liquid that builds up on the wall flows in the axial and tangential direction, from its initial momentum, and under the influence of shear forces from the combustion gas and chamber wall. When the tangential velocity is appreciable, the effects of spin-generated forces are considered. The film is partially burned off by the heat transfer from the hot combustion gases flowing past it. When threshold levels for an entrainment parameter are exceeded, entrainment from the liquid film is calculated. The axial variation in the wall-deposited material is approximated by dividing the chamber wall into 100 discrete axial segments. The deposition, flow, burnoff, entrainment, and vacuum evaporation from each segment are treated separately, so as to give the film thickness and composition profile and to correctly reflect the influence of unevenly distributed propellant. If the amount and rate of flow of the material on the wall are sufficiently high, some of the wall film material will be carried through the throat and ejected (one form of contaminant production).

The rate of burnoff from each axial segment of the wall is calculated from a heat transfer coefficient based on the time-varying local Reynolds number, corrected for counter-current mass transfer and rippling of the surface. Entrainment from the surface is modeled based on the local film thickness and velocity, the local velocity and density of the combustion gas, and the local surface tension of the film.[12]

When the local chamber wall temperature is sufficiently above the boiling temperature of the propellant droplets (at the momentary chamber pressure) an impacting droplet will bounce off instead of sticking.[13] When wall-film flows onto an axial segment that is sufficiently hot to cause the transition to film-boiling, the film is detached from the surface, converted to a group of droplets, and entered into the ensemble of droplet groups in the chamber.

In calculating the axial and tangential velocities of the liquid material deposited on the wall, each axial element of fluid on the wall is treated at each time interval as an inertial free body being acted upon by shear from the wall, shear from the combustion gas, spin-induced forces, mass and momentum addition from the impinging droplets, mass and momentum loss from burnoff and entrainment, and, with convection of fuel and oxidizer mass, axial and angular momentum at the upstream and downstream boundaries. The axial and tangential shear forces at the gas-liquid and liquid-wall interfaces are calculated based on corrections with appropriate local Reynolds numbers. It is presumed that the material in each axial segment is well-mixed at each time interval. When a hydrazine-derivative fuel and nitrogen tetroxide oxidizer are mixed on a wall segment, the neutralization reaction is presumed to take place to form the hydrazinium nitrate salt plus a remainder of whichever reactant is in excess of the stoichiometric ratio. This time-varying two-component system is used to estimate the physical properties of the wall film at each segment.

The assumption is implicitly made that injected fuel or oxidizer will react to give thermochemical equilibrium combustion products only when it is vaporized from the surface of a stream, droplet, or liquid film and the vapors subsequently are mixed with a mass of hot, ignited, combustion product gases.

After the valves have closed, the pressure in the chamber decays, most of the droplets leave the chamber, and the combustion in the chamber is calculated to be extinguished as soon as the time-varying calculated quenching distance exceeds the chamber diameter.

If the chamber pressure falls below the vapor pressure of the propellant in the injector dribble volumes, this material will flow out of the injector. The same technique is used to compute flow rate, atomization, and droplet trajectory as was used during the rest of the firing; with the exception that injector vapor pressure is now used instead of tank pressure to produce flow, and the flow impedances of the injector orifices are used instead of the whole system flow impedances. This dribbled material will be calculated to burn, be expelled through the throat unburned, or be deposited on the chamber walls, depending on the injector and chamber conditions.

When the chamber pressure falls below the vapor pressure of the material on the walls, it starts to evaporate, absorbing heat from the chamber walls. The rate of evaporation from each segment of chamber length is calculated separately, based on simultaneous solution of the Knudsen-Langmuir evaporation law and the heat transfer through the liquid film. At any time, the propellant valves may be reopened to initiate a second pulse of firing. The propellant dribbled from the injector following the first pulse will constitute the injector void volume that must be filled to prime the injector for the second pulse; the propellant buildup on the walls will continue from the values attained during the vacuum evaporation following the first pulse, etc.

The general introduction to the mathematical treatment of rocket engine transient behavior may be found in Ref. 4. The general mathematical treatment of the unlike impinging injector, ignition, and wall processes may be found in Ref. 7. A highly detailed description of all the mathematical approximations, the numerical methods, and the program operating instructions may be found in Ref 8. A detailed description of the application of the method to solve a particular problem may be found in Ref. 9.

## Comparison with Experiment

There has been no separate effort explicitly directed toward experimental confirmation of the model. However, comparisons have been attempted whenever suitable experimental data became available with sufficient documentation to permit precise modeling.

### Low-Frequency Combustion Instability

The Transient Combustion Chamber (TCC) program calculations were first tested by comparison with high-amplitude, low-frequency combustion instability produced in a small experimental engine.[14] The engine was operated with a family of four injectors, which differed only in impingement distance. The input to the program consisted of blueprint values for the engine and literature values for the propellant physical parameters, with no fitted coefficients of any kind. The calculated and experimental frequencies differed by no more than 7% while the amplitudes agreed within 5% for the entire family of injectors.[4,5]

Figure 2 shows the calculated chamber pressure for one of the injectors. It agrees in waveform with the experiment. The rate of rise is two to three times faster than the rate of fall, and it is cusped at the minimum points. The calculated fuel feed line flow rate was interesting in that it periodically assumed negative values, i.e., reverse flow. The integral of the reverse flow with time predicted a maximum back-flow bubble volume of 0.4 cc. The back side of the injector was observed with high-speed motion picture photography through a transparent window, and the observed bubble size was in agreement with the calculations.

### Vacuum Hypergolic Start Transients

Figure 3 illustrates a McDonnell Aircraft Co. research engine that has been fired to investigate vacuum hypergolic start transients and pulse-mode behavior.[15] Figure 4 shows a comparison of an experimental 25-msec duration pulse and a corresponding computed value. The two curves show surprisingly good agreement, especially in the prediction of events. The injector priming delay, the ignition delay, the initial

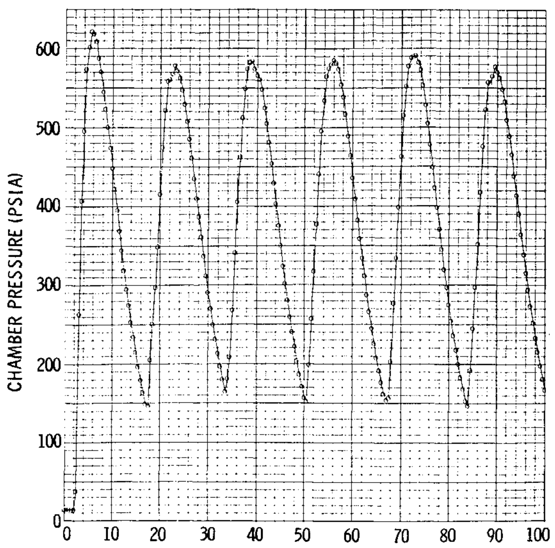


**Fig. 2 Calculated chamber pressure vs time during low-frequency combustion instability.**

surge from flash-atomized fuel, the succeeding pressure trough, the second pressure surge, the steady-state chamber pressure, and the cutoff delay are all in good agreement. The residual differences between the curves are associated with pressure waves in the experimental engine feed system, which was equipped with very long propellant lines. Pressure waves are not modeled by the lumped-parameter flow algorithm of the TCC program.

## Contaminant Production

Contamination from a conventional bipropellant RCS engine takes one or more of three forms: reacted or unreacted propellant vapor; incompletely burned droplets expelled through the throat; and unburned propellant that impinges upon the chamber wall and is eventually ejected from the nozzle lip.

The vapors of fuel, oxidizer, or combustion products emitted during preignition, ignition, steady-state, or postcutoff dribble periods will form plumes that can impinge on various surfaces with the possibility of deposition and in-situ reaction. Contamination from this source usually takes the form of a hazy deposit of smokelike particles (fairly uniform in size, 1 to $2\mu$).[16]

The fuel and oxidizer droplets, which are too large to burn completely in the chamber and which are centrally directed, will pass through the nozzle throat. These particles will be accelerated by aerodynamic forces both upstream and downstream of the throat, and can attain quite high velocities, which gives this class of particles the capability of doing considerable damage by abrasion.[17]

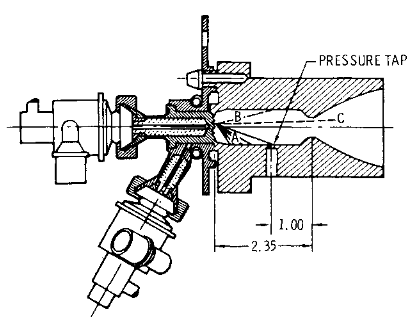


**Fig. 3 Research rocket engine. Chamber characteristics: throat diameter 0.417 in., contraction ratio 4.1, characteristic length 8.35 in., nominal pressure 100 psia.**

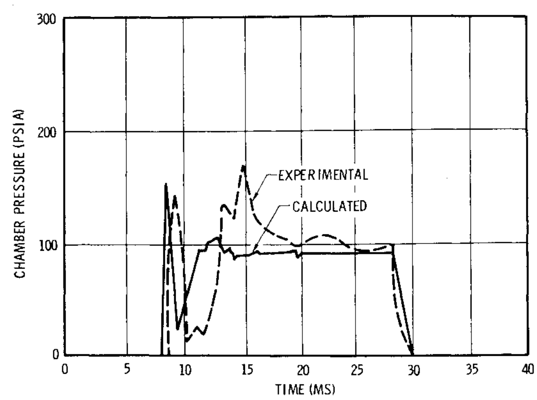


**Fig. 4 Comparison of experimental and calculated pulse mode firing.**

The third form of contamination is the propellant that impinges on the chamber wall and is then dragged downstream under the influence of shear forces from the combustion product gases. If this wall-film material is able to move to the nozzle lip without being thermally destroyed, it will be thrown off as large droplets in directions roughly normal to the axis of the chamber. This material is generally dark colored and shows the effects of thermal decomposition.

Quantitative experimental data on contaminant production are still rather scarce. However, two papers have been published describing contaminant production from pulse-mode firings of the 22-lb Marquardt R1-E engine.[18,19] This engine is similar in design but larger than the 5-lb Marquardt R6-C engine, which has been thoroughly parametrically analyzed using the TCC program. Many aspects of the experimental firings of the R1-E engine agree with the trends calculated for the R6-C engine.

Martinkovic[18] found that contaminant production was a function of injector temperature. His measurements for the temperature trend of the R1-E engine show good agreement with our calculations for the R6-C engine as shown in Fig. 5. The absolute values for contaminant expelled as wall film were also in good agreement. The Martinkovic 22-lb R1-E engine experimentally produced 0.772 mg of wall film per 17-msec pulse at 75°F; i.e., about one part per thousand of total injected propellant ended up as wall film contaminant. Our calculations for the 5-lb R6-C engine indicated that 0.33 mg of wall film would be produced per 17-msec pulse at 70°F; i.e., about two parts per thousand of total injected propellant. This is in agreement with the well-known trend toward increased contaminant production with decreased engine size.

## Chamber Explosion Amplitude

Since the spatial distribution of unburned propellant in the form of streams, droplets, unreacted wall-film, or

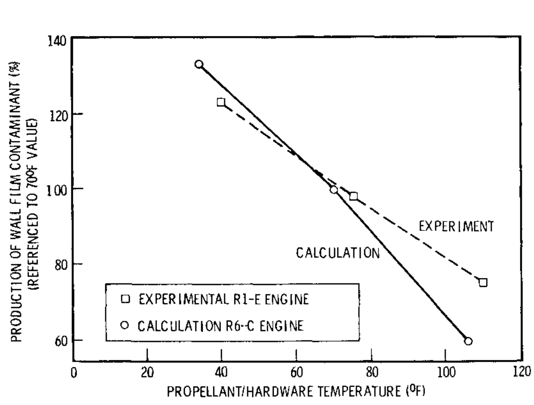


**Fig. 5 Comparison of experimental and calculated wall-film contaminant production as a function of propellant/hardware temperature.**

hydrazinium-nitrate deposits is known in a time-dependent manner, it is possible to calculate the mean chamber pressure that could be produced at any instant by the explosive combustion of this material. The term popping is often used to describe the moderate amplitude explosions of the droplets and streams that may be periodically initiated by explosive reactions of the fuel and oxidizer streams near the impingement point. The stream hydraulic conditions and chamber conditions that can produce impingement point explosions, and the conditions necessary for such an initiating explosion to propagate a detonation through the droplet spray contained in the chamber have been discussed in a number of publications.[20-23]

Figure 6 illustrates the calculated maximum volume-mean popping amplitude as a function of time for a particular 50-msec engine firing. Experimental bombings of this engine during the steady-state portions of the firing produced experimental chamber pressure amplitudes that had a mean value within 14% (or 1.2 experimental standard deviations) of the calculated value.

The time-dependent volume-mean chamber pressure amplitude that could result from a detonation of hydrazinium-nitrate deposits on the chamber walls is calculated in a similar way. Such detonations, often called spikes, have been observed in a number of engines and can be quite destructive. Large transient accumulations of hydrazinium-nitrate have been calculated for two engines which experimentally are known to produce spikes or spike-like behavior under certain conditions.

One of these engines is the McDonnell Aircraft Company research engine illustrated in Fig. 3.[24] When this engine is operated in pulse-mode, the difference in the initial voidage of the dribble volumes and the inertial imbalance of the feed systems during the start transient (Fig. 7) causes flash-atomized fuel to be deposited on the walls for the first 8 msec after valve opening (A in Fig. 3). The resultant-angle from the unlike-impinging injector is directed strongly outward for approximately the next 10 msec (B in Fig. 3), before equilibrating to the steady-state design value (C in Fig. ). This is long enough to deposit 272 mg of mixed fuel and oxidizer on the wall (Fig. 8). This material can be burned off completely in an additional 60 msec of steady operation. However, if it detonates at the worst possible time, a volume-mean chamber pressure of 2000 to 3000 psi is produced, depending on whether the unburned droplets and streams contained in the chamber are detonated also.

This is in general agreement with experiment, which gave local measured peak pressures as high as 7,000 psi, with

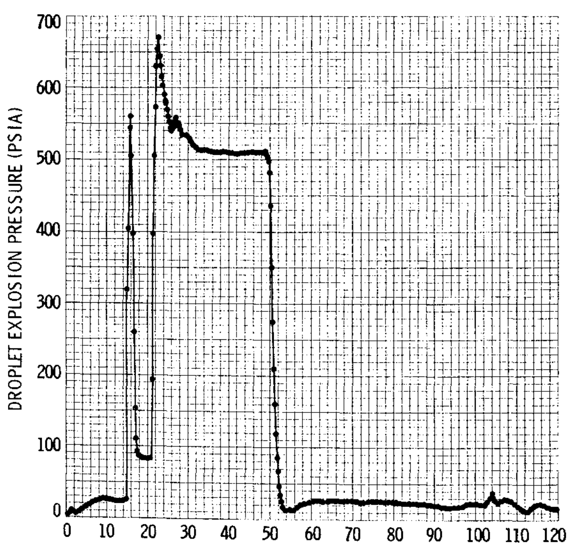


**Fig. 6 Calculated popping amplitude vs time.**

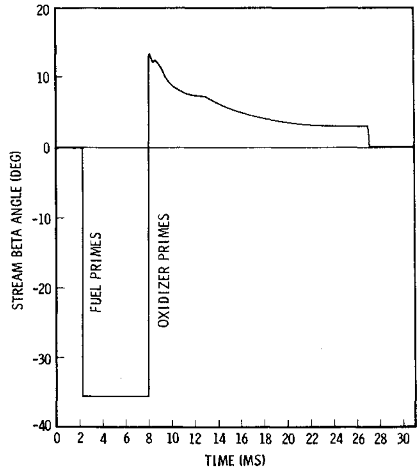


**Fig. 7 Calculated resultant stream angle vs time.**

volume-mean chamber pressures on the order of 1,500 to 3,000 psi. The other engine, for which calculations have been made, only exhibits spikelike behavior when it is run cold and in short pulses. Both of these conditions contribute to the accumulation of detonable material. Again, reasonable agreement between calculated and measured over-pressures are obtained.[10,25]

Figures 9 and 10 show the results of closely spaced repetitive firings of another small RCS engine. This engine will burn its walls clean in only 13 msec of steady firing after a start transient; however, with closely spaced firings shorter than this, the wall-deposited propellant builds up over a series of pulses. The maximum accumulation of unburned propellant during the first pulse could produce a 650-psia explosion. while the maximum accumulation during the second pulse corresponds to 1400 psia. For some unknown reason, this engine does not initiate chamber detonations, but rather expels a film of unburned MMH-nitrate mixture from the nozzle lip when it is operated under adverse duty cycles.

## Pulse-Mode Specific Impulse

The calculations of time-varying thrust and time-integrated specific impulse are at present a rather uneven mixture of sophistication and over-simplification. The fully transient, two-dimensional treatment of the droplets, and the very detailed treatment of the wall-film behavior implies that the predicted variation of delivered specific impulse with pulse width or with fraction of total used as film-coolant should be accurate, and this has been verified by comparison with experiment.

The most important simplifying assumptions are 1) treating the combustion gases in the chamber as being well-mixed, 2) ignoring wall-film evaporation from axial heat conduction in the chamber wall, 3) ignoring secondary breakup of the droplets, and 4) using equilibrium thrust coefficients. The

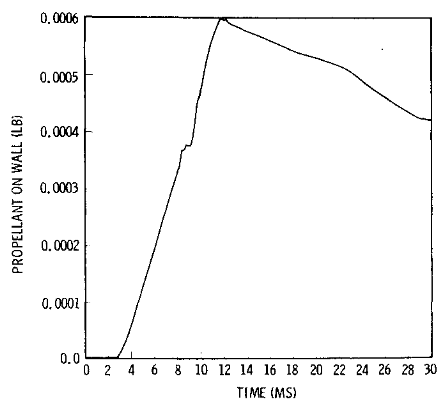


**Fig. 8 Accumulation of propellants on chamber wall vs time.**

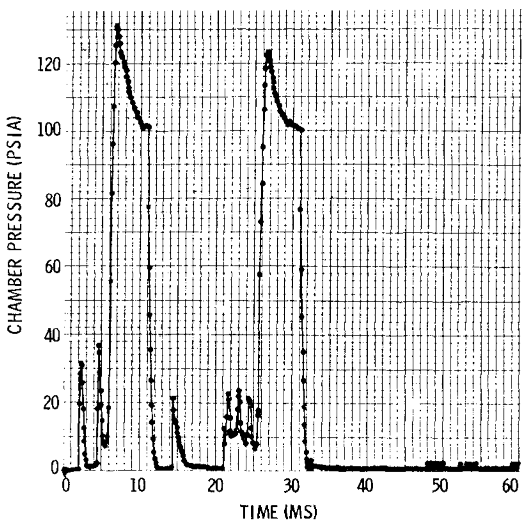


**Fig. 9 Calculated chamber pressure for two short closely spaced pulses.**

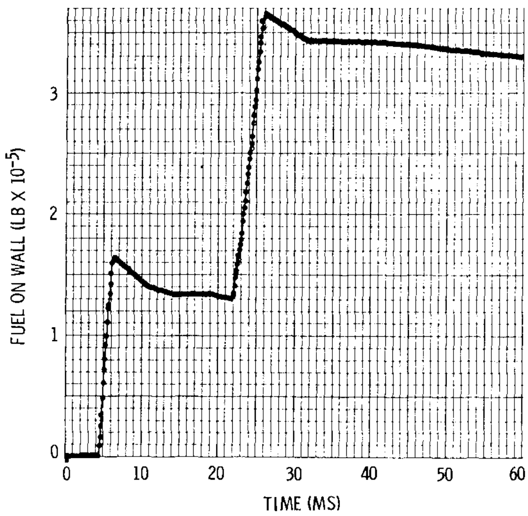


**Fig. 10 Progressive buildup of fuel on wall over two short closely spaced pulses.**

result of these simplifying assumptions is that the characteristic velocity is calculated a few percent too low, while the thrust coefficient is calculated a few percent too high. It is pleasant but fortuitous that the absolute values of calculated specific impulse have been almost identical with the corresponding experimental values.

## Conclusion

A mechanistic mathematical model of the combustion chamber and propulsion system has been developed that is capable of quantitatively calculating vacuum hypergolic ignition and the start transient, low-frequency system instability, production of contaminant material in the plume and as wall-film, mean chamber pressure amplitude of pops and spikes, the effects of off-nominal engine operation, and the effects of pulse-mode operation and film-cooling on delivered specific impulse.

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