SIMULATION OF GUN BARREL EROSION IN ADVANCED CONTINUOUS SIMULATION LANGUAGE (ACSL)

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INTRODUCTION

The bore erosion process in a gun barrel has been simulated using the Advanced Continuous Simulation Language (ACSL). The validity of this model has been proven through comparison with actual firing range data. Data representative of the class of gun, but not associated with any particular weapon, is used in this paper.

The class of gun being considered is a rapid-fire cannon in the 20-40 mm range typically used as an antiaircraft weapon. The barrel is a limited resource similar to ammunition and must be resupplied the same way. In the field, therefore, it is important to know how much life remains in a barrel before it becomes unusable.

The simulation, in showing how the bore erosion is affected by the firing duty cycle, makes it possible to incorporate consideration of gun barrel life as well as ammunition supply into the firing doctrine. The model could also serve as the basis for an algorithm in the actual fire control computer to show moment by moment during battle the amount of barrel life remaining.

The end of the life of a barrel is sharply defined. Erosion begins at the breech and proceeds forward, the projectile experiencing increasingly long free flight before engaging the uneroded lands. Eventually the round receives so little spin from the rifling remaining that it tumbles upon emerging from the muzzle. Interestingly, dispersion is virtually constant until near the end of barrel life, but then deteriorates very sharply.

Although in reality the depth of erosion depends on the distance from the breech, the model implicitly treats the barrel as being uniform along its length. The assumption has proven reasonable; results show less than five percent difference between the life predicted by the model and that actually observed from firing range data.

The simulation consists of three models: 1) a firing profile model, which determines when each round is fired; 2) a heat flow model, which determines the bore temperature when the round passes through; and 3) an erosion model, which first determines the bore material loss caused by each round and then sums it with that previously lost to show the total loss.

The firing profile model accepts any firing rate and any periodic or aperiodic firing duty cycle as inputs.

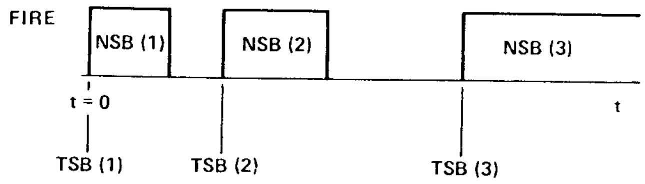
The heat flow model comprises three submodels simulating 1) heat input, 2) heat distribution, and 3) heat rejection. The heat input model injects an impulse of thermal energy into the bore wall each time a round is fired. The heat distribution model simulates the conduction of heat radially outward from the bore to the outer surface of the barrel. The heat rejection model simulates the transfer of heat from the outer surface into the atmosphere.

The amount of erosion (i. e., the number of grams of bore material removed) by each round as it passes through depends only on the temperature of the bore at the moment the round is fired. The erosion model contains a table of this function.

Plot outputs of the simulation include temperature versus time at different points along the radius from bore to outer surface, and cumulative erosion versus number of rounds fired.

FIRING PROFILE MODEL

The firing profile is controlled by the user through the input constants illustrated in Figure 1.



TSB (i) = TIME OF START OF BURST (i) (s)
NSB (i) = NUMBER OF SHOTS PER BURST (i) (ROUNDS)

ND = FIRING RATE (RND/s) (SAME FOR ALL BURSTS)

Figure 1 - Terminology of Firing Profile Model

Firing is done in bursts. The firing rate is established by the design of the recoil mechanism and is input to the program as the constant ND.

The starting time and duration of each burst are controlled by the two input arrays TSB (time of start of burst) and NSB (number of shots per burst). Each array is currently 50 elements long, so as many as 50 bursts can be simulated in a run. The times can be set to be periodic or aperiodic, and NSB can be set to any integers.

Cannon in the class being considered are usually fired in bursts to allow the bore to cool periodically. These brief cooling periods significantly extend the barrel life, but at the same time decrease the fire power (average rounds per second). Deciding on the optimum firing profile is a complex trade-off of barrel life versus fire power, and the simulation provides a means of generating the trade-off data without costly firing range tests.

The integration step size in the simulation is variable. It is set at a low minimum at the beginning of each burst and is allowed to increase during long pauses (as a function of the temperature gradient) to a set maximum. The process assures sufficiently fine calculation where required, at the same time allowing cost savings when running the program over long cooling periods.

HEAT FLOW MODEL

The purpose of the heat flow model is to determine the bore temperature at the time of erosion. Heat is introduced into the bore wall by the passage of each round. It then flows radially outward to the outer surface where it is rejected into the atmosphere.

The gun barrel can be approximated as a hollow right circular cylinder. In the simulation, it is modelled as a series of concentric cylinders. Figure 2 shows how the cylinder radii increase so that approximately equal temperature drops will be experienced across each cylinder. The

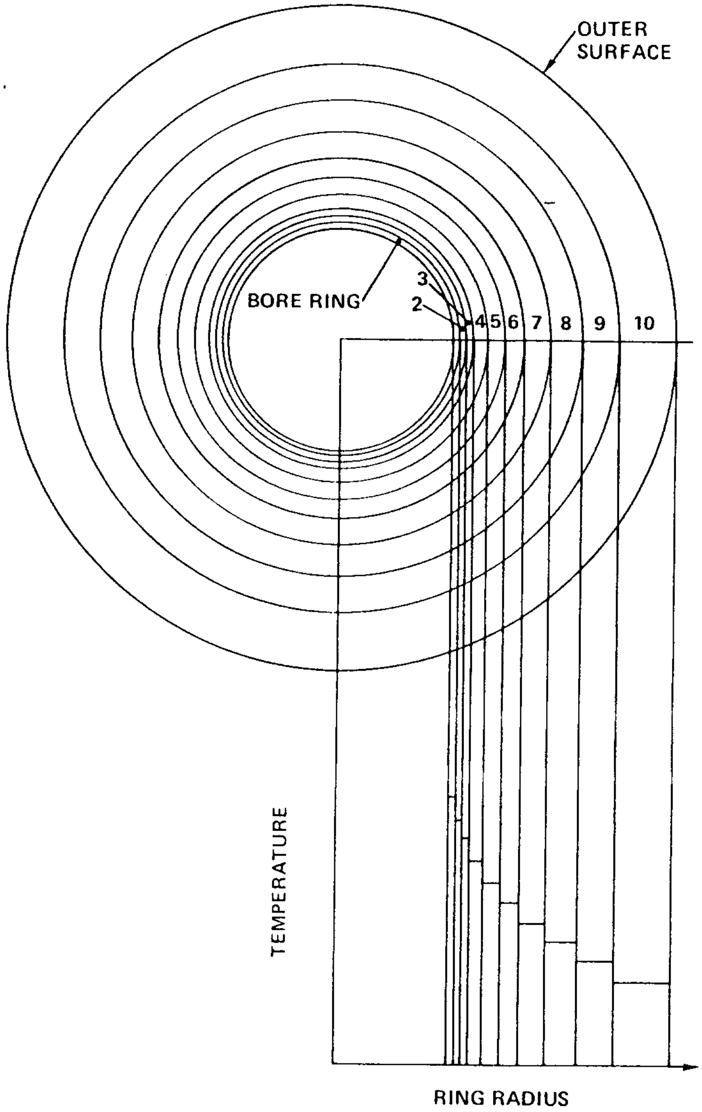


Figure 2 - Temperature Drops Across Barrel Rings

division of the barrel into these annuli, or rings, allows the heat flow to be modelled in lumped fashion. The thermal capacity and resistance of each ring are thought of as residing at an infinitesimally small ring at its outer surface, while no temperature drop occurs across the ring itself. The model uses ten rings, which was found to be a good compromise between cost and accuracy.

The ACSL language is structured into four major sections: 1) INITIAL, where initial conditions and other items are calculated once at the beginning; 2) DERIVATIVE, the simulation model with variables updated each integration step; 3) DYNAMIC, data-logging; and 4) TERMINAL, for final calculations done only once (1).

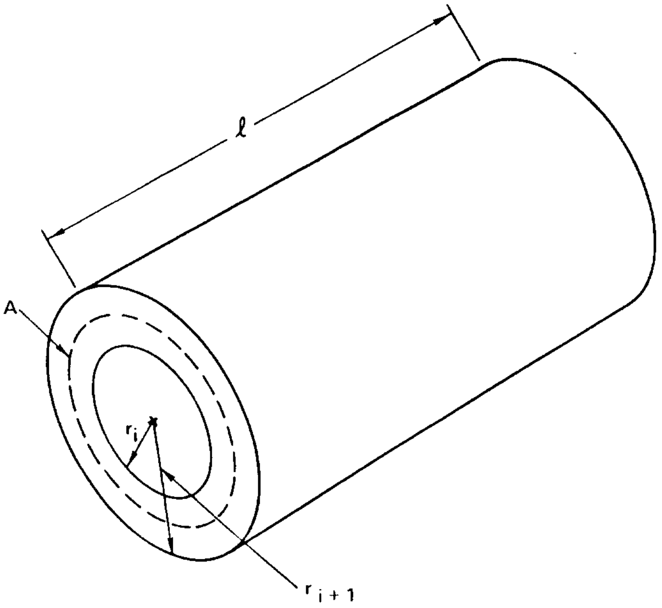
The heat content, Q, of each ring is a state variable, and its initial condition, Q_{IC} is determined in the INITIAL section. First, given user-specified values for the ring radii (r), length of barrel (ℓ), and density (ρ) and thermal capacity (c_p) of the barrel metal, the thermal mass of each ring is calculated:

$$M_{c_p}(i) = c_p \rho \ell \left[(r_{i+1})^2 - (r_i)^2 \right]$$

Then, assuming all rings to begin at some user-specified ambient temperature (T_∞), the initial heat content (Q_{IC}) is calculated:

$$Q_{IC}(i) = M_{c_p}(i)\ T_\infty$$

Also computed in the INITIAL section is a constant of average area to thickness for each ring (see Figure 3). This constant is used in the DERIVATIVE section, together with thermal conductivity (which is temperature dependent), to find the thermal conductance of each ring interface.



i = INDEX NUMBER OF RING

A = AVERAGE AREA OF RING = $\dfrac{2\pi r_{i+1}\ell + 2\pi r_i \ell}{2}$

L = THICKNESS OF RING = $r_{i+1} - r_i$

Figure 3 - Dimensions of Simulated Rings

$$\frac{A}{L}(i) = \frac{\pi (r_{i+1} + r_i)}{(r_{i+1} - r_i)}$$

The area of the outside of the barrel, used in calculating the convection and radiation coefficients for that surface, includes a factor for fluting in addition to the area based on the radius.

Heat Input

The heat impulse (ΔQ_F) introduced into the bore ring when a round passes depends on the difference between the flame temperature (T_F) and the bore temperature (T_1), and on the flame-to-bore heat transfer coefficient (K_{FB}), which is determined from range temperature measurements of the barrel before and after a round has been fired and the heat distributed throughout the barrel.

$$\Delta Q_F = K_{FB} (T_F - T_1)$$

This quantity is used in the heat distribution model.

Figure 4 shows how Δt and ΔQ_F are determined. The area under the actual curve, taken from (2), is approximated by the area under the assumed pulse of finite time Δt and height T_F, which is known from range measurements.

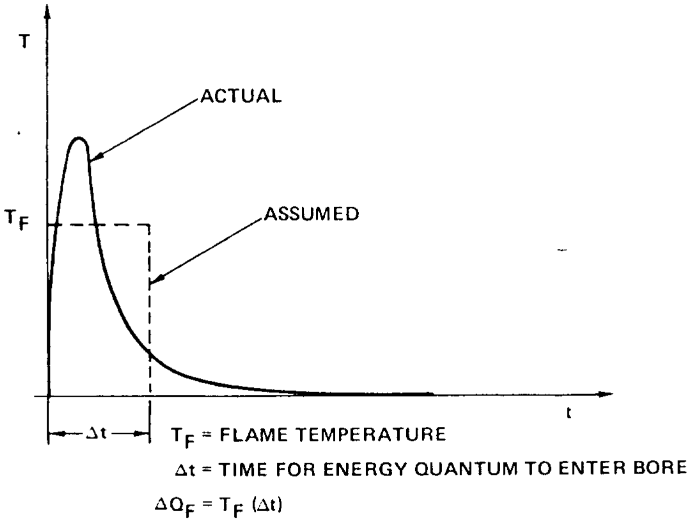


Figure 4 - Flame Temperature versus Time at a Given Position Along Bore

Heat Distribution

After the heat from a projectile enters ring 1, it begins to flow through the insulating interface into ring 2, from there into ring 3, and so on.

The thermal conductivity of each ring is a function of its temperature. Thermal conductivity (K) as a function of temperature is entered as a table on the basis of handbook or manufacturer's data.

The heat flux ($\dot{Q}_I$) into a given ring is calculated by multiplying thermal conductivity (K) and area over thickness (A/L, calculated in the INITIAL section) by the difference between its temperature and that of its immediate inner (i.e., hotter) neighbor. The heat flux out of a ring is simply the heat flux into the next larger ring. $\dot{Q}$, the net rate of change of heat content of a ring, is the heat rate input from its inner neighbor minus the neat rate output to its outer neighbor.

Ring 1, having no inner neighbor, takes its heat input from ΔQ_F, calculated in the heat input model, and its output from the negative of the input to ring 2 ($-\dot{Q}_2$). The total heat content of ring 1 (Q_1) is calculated by summing ΔQ_F, integrating $-\dot{Q}_2$, and adding both to the initial condition, Q_{1IC}. This procedure is necessary because the continuous simulation integration algorithm does not integrate impulses (1).

The heat content (Q) of the other rings is found by integrating $\dot{Q}$, with Q_{IC} being the initial condition. Q is then divided by the thermal mass ($M c_p$) to find the temperature (T) for all rings.

Heat Rejection

After travelling through the metal of the barrel, the heat is rejected from the barrel outer surface into the atmosphere by means of convection and radiation.

$$\dot{Q}_\infty = UA(T_{10} - T_\infty) + \sigma\epsilon A(T_{10}^{4} - T_\infty^{4})$$

where U = convection coefficient

A = area of outer surface

T_{10} = temperature of barrel outermost ring

T_∞ = ambient temperature

σ = Boltzmann's constant

ϵ = emissivity of the barrel surface

$\dot{Q}_\infty$ is used in the heat distribution model as the heat output from ring 10.

EROSION MODEL

The incremental erosion, α_N (expressed as a percent of the total grams of bore material removed at the end of barrel life), caused by a particular round depends only on the effective bore temperature at the instant the erosion takes place ($T_{1\alpha}$). The relationship characteristically displays a sharp knee as shown in Figure 5. The relationship of α_N to $T_{1\alpha}$ is stored as a table of log (α_N)-vs-$T_{1\alpha}$ in order to reproduce the sharp rise more accurately.

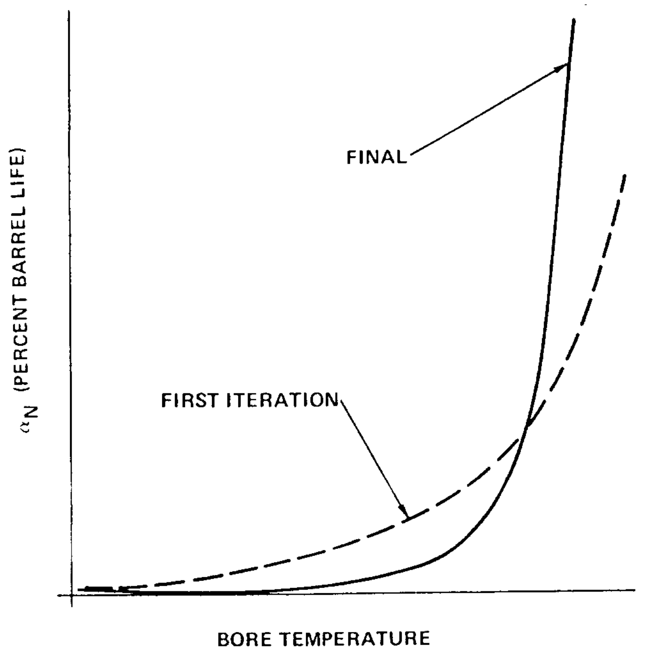


Figure 5 - Erosion Per Round versus Bore Temperature

Each time a round is fired, $T_{1\alpha}$ is determined; then, finding log (α_N) from the table, the antilog is taken and the resulting α_N added to the previous total erosion, α.

Several factors enter into the determination of $T_{1\alpha}$. Erosion results not so much from the friction of the round as from the turbulance of the propulsive particles moving immediately behind the projectile at high velocity. Figure 4 shows how temperature varies with time at a particular point along the bore. Assuming the particulate velocity to follow the same profile, the maximum rate of erosion -- and hence the effective instantaneous erosion -- will occur when the function peaks. At that moment, the temperature has risen to thirty percent of its final value, so that $T_{1\alpha}$ is calculated as T_1 (just before the round is fired) plus .3ΔT.

CALIBRATION

The α_N-vs-$T_{1\alpha}$ function is determined empirically from firing range data showing barrel life under various firing duty cycles; e.g., continuous firing (which erodes the bore most quickly), and cycles of short bursts followed by complete cooling (which require many rounds to be fired over a long time before the barrel is completely worn).

An initial α_N-vs-$T_{1\alpha}$ curve, smooth and monotonically rising, is assumed in the program, as, for example, the dashed line in Figure 5. The firing profiles used in the range tests are run in the simulation and the results compared to the firing range data. In Figure 6 the tests have been arranged in order of ascending erosion for a specified number of rounds fired. Since higher temperatures are encountered during the tests with higher erosion, it is clear that for the first simulation results in the example, the α_N-vs-$T_{1\alpha}$ curve must be adjusted to allow for greater erosion at higher temperatures and less at lower. Iteration continues until the simulation results are sufficiently close to the firing range data.

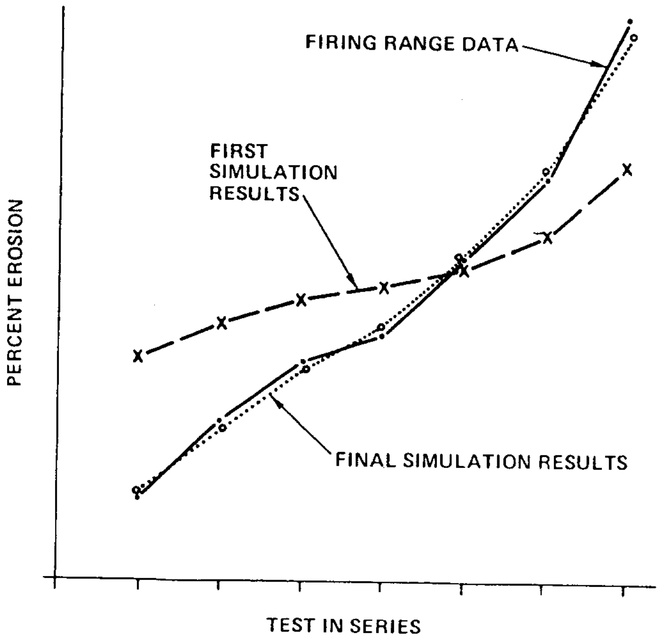


Figure 6 - Comparison of Simulation Results with Firing Range Data for Calibration

The curve is primarily a property of the bore material (alloy, heat treatment, nitriding, etc.) and the ammunition type and quantity of propulsive charge). It can therefore be used for any gun similar in these respects and regardless of calibre, firing rate, external cooling, or other factors.

SIMULATION OUTPUT

The simulation can be used to evaluate the effect of changing various parameters on the life of the barrel or to determine the life of an existing system under various firing duty cycles. The primary outputs are the bore erosion and temperature data in either printout or plots. They provide insight into the effects of continuous firing and of cooling times.

Figure 7 shows the temperature history of the different rings for a duty cycle of 1 second on - 1 second off - 10 seconds pause. The effectiveness of the cooling periods can be seen. Further, the relative unimportance of the heat rejection can be seen from the slow rise of the temperature of ring 10; the more important heat sink is the thermal mass of the barrel metal.

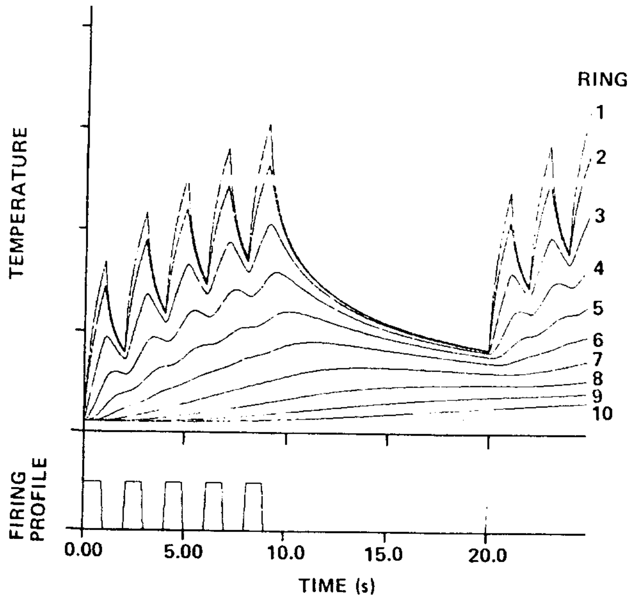


Figure 7 - Temperature History of Rings

Figure 8 shows a comparison of barrel life under three different firing duty cycles. Each curve reaches 100 percent erosion (and of barrel life), with the continuous firing duty cycle resulting in the steepest erosion slope.

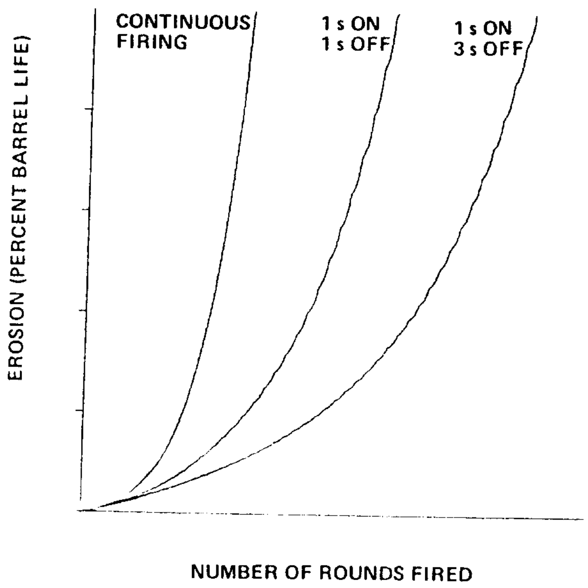


Figure 8 - Comparison of Erosion for Three Different Firing Duty Cycles

CONCLUSION

The barrel wear simulation provides a practical means of evaluating cannon firing duty cycles in terms of barrel life. A small number of firing range tests suffice to calibrate the simulation, which can then be used to provide extensive data to optimize firing doctrine and eventually be incorporated into the fire control computer algorithms. This systems level approach is believed to be unique.

ACKNOWLEDGEMENT

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REFERENCES

1) Mitchell and Gauthier Associates, "Advanced Continuous Simulation Language: User's Guide/Reference Manual," second edition, Mitchell and Gauthier Associates, Inc., Concord, Massachusetts, 1975.

2) Shelton, Si, et al, Technical Report AFATL-TR-73-69 "Study of Heat Transfer and Erosion in Gun Barrels", Georgia Institute of Technology, March 1973.