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RESUME

Ce document décrit un programme d'ordinateur, appelé REGUN, qui sert à analyser la balistique intérieure des fusils sans recul, et présente ses diverses fonctions. Ce programme utilise la technique numérique des différences finies pour intégrer l'ensemble des équations différentielles partielles. On explique en détail les aspects pratiques de sa réutilisation et on donne en appendice quelques références générales dans ce domaine. (NC)

ABSTRACT

A computer code, called REGUN, for analysing the interior ballistics of recoilless rifles is described and its capabilities are presented. This code uses a finite-difference numerical technique to integrate the full partial-differential equations. The practical aspects of using REGUN are fully described and an appendix provides general references in this area. (U)

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NOMENCLATURE

A	barrel bore area (in^2)
A^*	nozzle throat area (in^2)
$A_{surface}$	barrel surface area (in^2)
B	propellant gas co-volume (in^3/b_m)
C_{er}	erosive burning-rate coefficient (s/in)
C	speed of sound (ft/s)
D	web thickness (in)
E	specific total energy ($\text{ft-lb}_f/\text{lb}_m$)
e	specific internal energy ($\text{ft-lb}_f/\text{lb}_m$)
F	propellant force constant ($\text{ft-lb}_f/\text{lb}_m$)
h	heat-transfer coefficient ($\text{ft-lb}_f/\text{ft}^2\text{-s}$)
K_{frict}	barrel friction coefficient
M	Mach number
M_{proj}	projectile mass (lb_m)
m	mass flow rate through nozzle (lb_m/s)
P	gas pressure (psi)
P_{amb}	ambient pressure (psi)
P_{base}	projectile base pressure (psi)
P_{exit}	nozzle exit pressure (psi)
q_{loss}	heat loss to barrel (ft-lb_f)
R	barrel radius (in)
r	burning rate (in/s)
T_{barrel}	barrel temperature (^{o}R)
T_{gas}	propellant-gas temperature (^{o}R)

T	temperature (^{o}R)
U	gas velocity (ft/s)
U_{proj}	projectile velocity (ft/s)
U_{throat}	gas velocity at throat (ft/s)
V_{ch}	combustion chamber volume (in^3)
V_{gas}	volume occupied by propellant gases (in^3)
W	initial propellant charge (lb_m)
X_{proj}	projectile travel (in)
Z	burnt fraction of propellant
Z_o	initial burnt fraction of propellant
α	burning rate exponent
β	burning-rate coefficient ((in/s)/psi$^{\alpha}$)
γ	ratio of specific heats for propellant gas
ρ	density ($slugs/ft^3$)
ρ_{prop}	propellant density ($slugs/ft^3$)
ρ_{gas}	propellant gas density ($slugs/ft^3$)

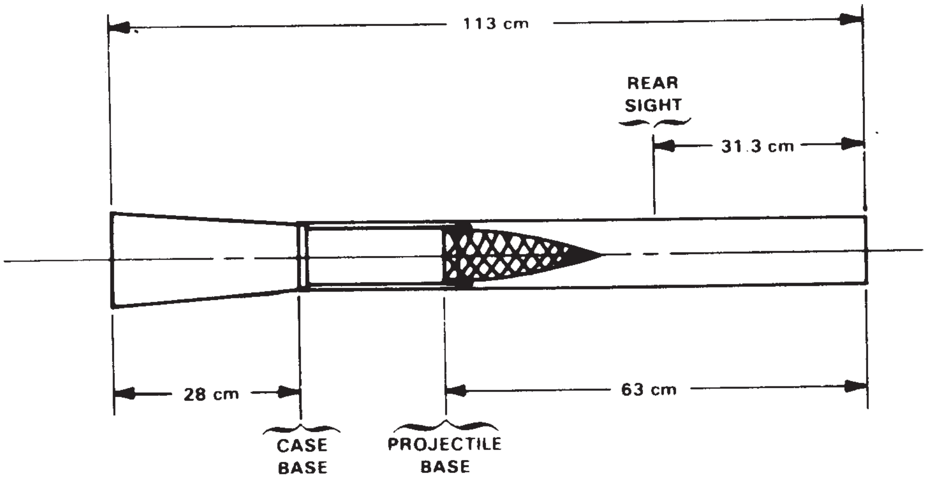


FIGURE 1 - Schematic diagram of Carl Gustaf recoilless rifle

1.0 INTRODUCTION

In this report, the development of a recoilless gun interior ballistics computer-code based on the full partial-differential equations will be described, along with a brief survey of recoilless weapon operation. The code (called REGUN) was originally developed by Computing Devices of Canada (CDC) as part of a general program involving the development of computer codes for the analysis of the interior ballistics of guns. This report will deal with the theoretical basis, input requirements, and capabilities of the current code, which incorporates several modifications to the CDC product. The work was performed under PCN 21R05, Interior Ballistics of Tube Weapons, between January 1978 and February 1981.

1.1 Operation of a Recoilless Gun

Figure 1 illustrates the major elements of a typical recoilless gun. The most notable feature is the open venturi to the rear of the cartridge case. The throat area, an important design parameter, is chosen to ensure that the momentum of the rearward escaping gases is equal to that of the projectile. The net momentum (or recoil) of the weapon will then be zero, thus allowing a relatively large projectile to be fired from a shoulder-held weapon.

The operation of the gun illustrated is straightforward. The propellant in the cartridge is ignited with a rapid rise in gas pressure inside the cartridge ensuing. When the shot-start pressure is reached, the projectile begins accelerating down the barrel. The shot-start pressure depends on the means used to connect the projectile to the cartridge and the force needed to engrave the band, i.e. engage the projectile in the rifled grooves of the barrel. At about the same time a diaphragm blocking the throat bursts, allowing hot gases to escape rearward. Despite this loss, the pressure behind the projectile continues to increase until a maximum is reached, then declines until the projectile clears the muzzle. The maximum pressure reached in the combustion chamber is termed the peak pressure and is, as might be expected, an important design parameter since it determines the design strength of the weapon. The shot-start pressure also influences the weapon design because of the significant axial force which the combustion chamber wall and breech must resist before the diaphragm bursts and projectile travel starts.

The description given above is broadly true for any recoilless gun and not just for the Swedish 84-mm Carl Gustaf illustrated in Fig. 1.

American recoilless guns generally have wide combustion chambers in which rounds with perforated cartridges are placed. The 106-mm and 90-mm recoilless guns are typical U.S. designs.

Closely related to the true recoilless guns in both purpose and performance are the in-tube burning rocket systems which, essentially, are tubes through which a rocket-powered projectile is fired. The best known of the class is the U.S. 2.36-in bazooka of World War II fame. The Canadian Hellers A and B (described in the following section) were in this class as is the U.S. 66-mm M72 LAW (Light Anti-Tank Weapon).

The remainder of this report will describe the theoretical and numerical bases of the REGUN code. Those interested in delving further into the interior ballistics of recoilless guns should consult the references surveyed in Appendix A. A survey of previous DREV work in this area will be given in another report.

2.0 THEORETICAL BASIS OF REGUN

2.1 Fundamental Equations

In order to obtain the pressure history within the weapon and the projectile muzzle velocity, the three basic equations of fluid dynamics-continuity, momentum, and energy must be solved, along with an equation of state which takes into account the nonperfect nature (or co-volume) of the gases within the weapon and an empirical propellant burning-rate law.

Assuming one-dimensional, inviscid flow, the continuity equation is, using the Eulerian system:

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial x} = 0 \qquad [1]$$

The momentum equation, under the same conditions, is:

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} = \frac{-1}{\rho} \frac{\partial p}{\partial x} \qquad [2]$$

while the energy equation is:

$$\frac{\partial e}{\partial t} + u \frac{\partial e}{\partial x} + q_{loss} = \frac{-p}{\rho} \frac{\partial u}{\partial x} \qquad [3]$$

q_{loss} being the heat lost to the barrel from the hot propellant gases.

Using standard heat-transfer practice, we may write the relation:

$$q_{loss} = h\, A_{surface} (T_{gas} - T_{barrel}) \qquad [4]$$

T_{gas} is simply the internal energy of the gas divided by C_v while T_{barrel} may safely be assumed to remain at 530 °R, given the short times involved. The relation:

$$h = (7.11 \times 10^5)\ (\rho u)^{0.8}/R^{0.2} \qquad [5]$$

is used to determine h, (with h in ft-lb_f/ft^2-s, ρ in slugs/ft^3, u in ft/s, and R in inches) it being based on a textbook relation for forced convection heat transfer whose coefficient has been adjusted to fit experimental data. It should be noted that although q_{loss} can be of the same order as the kinetic energy imparted to the projectile, large variations in the value assumed result in negligible changes in the interior ballistics, the dominant energy term being the total energy of the propellant gases.

Rewriting eqs. 1 to 3 in the conservative (homogeneous) form gives:

$$\frac{\partial \rho}{\partial t} = \frac{-\partial(\rho u)}{\partial x} \qquad [6]$$

$$\frac{\partial(\rho u)}{\partial t} = -\frac{\partial}{\partial x}(\rho u^2 + P) \qquad [7]$$

and

$$\frac{\partial(\rho E)}{\partial t} = -\frac{\partial}{\partial x}(\rho E u + P u) - \rho q_{loss}) \qquad [8]$$

with $E = e + \frac{1}{2u}2$

Generalizing to the variable-area case, eqs. 4 to 6 may be rewritten to give the versions of the continuity, momentum and energy equations which will be used in our computer model.

$$\frac{\partial \rho}{\partial t} = - \frac{\partial}{\partial x} (\partial u) - \frac{\partial u}{A} \frac{\partial A}{\partial x} \qquad [9]$$

$$\frac{\partial}{\partial t} (\rho u) = - \frac{\partial}{\partial x} (\rho u^2 + P) - \frac{\rho u^2}{A} \frac{\partial A}{\partial x} \qquad [10]$$

and

$$\frac{\partial}{\partial t} (\rho E) = \frac{\partial}{\partial x} (\rho u E + \rho u) - \frac{(\rho u E + P u)}{A} \frac{\partial A}{\partial x} - q_{loss} \qquad [11]$$

P, T and ρ are related using the Clausius or Noble-Abel equation of state:

$$P(\frac{1}{\rho} - B) = RT \qquad [12]$$

where B is the co-volume of the propellant gas. Equation 10 can be written in terms of e, the internal energy, to give:

$$P = \frac{e\ (\gamma-1)}{\frac{1}{\rho} - B} \qquad [13]$$

where γ is the ratio of the specific heats (C_p/C_v) of the propellant gas.

The burning rate, r, is given by (with the units of velocity)

$$r = \beta\ P^{\alpha}\ (1 + C_{er}\ |u|) \qquad [14]$$

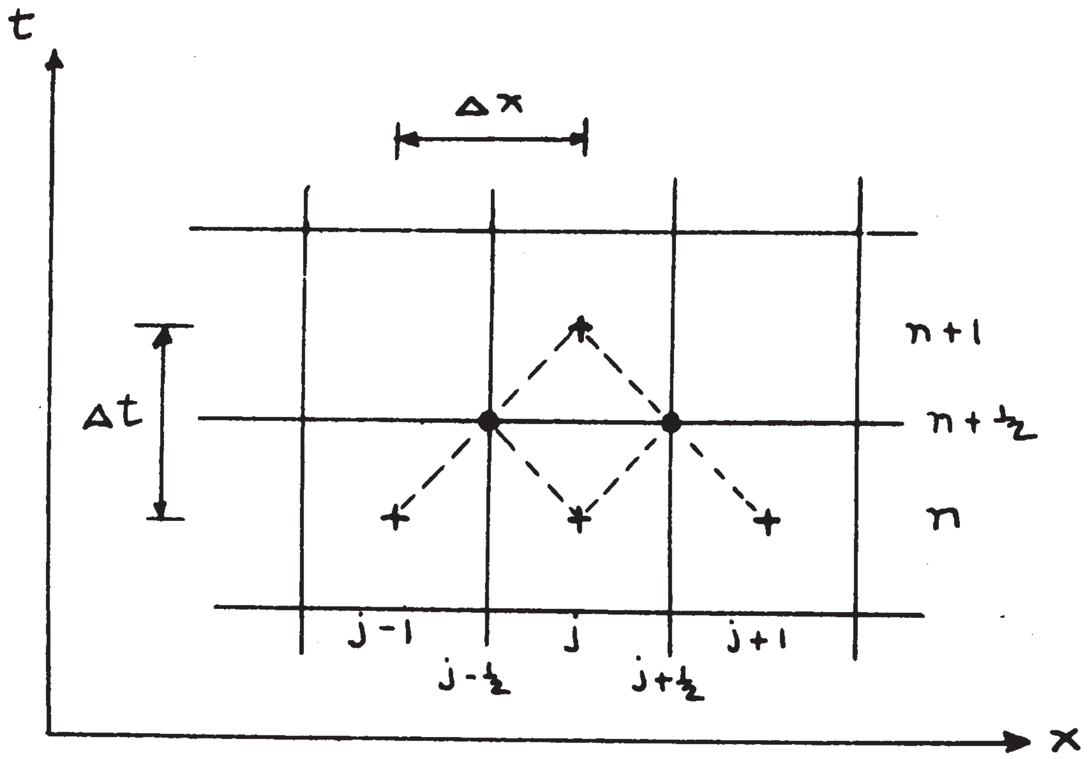
where α and β are experimentally determined coefficients for the propellant being used and C_{er} is the so-called erosive burning rate coefficient. The erosive burning rate term reflects the influence of the gas velocity on the propellant burning rate. More properly, an increase in convective heat and mass transfer at the propellant-gas interface is the phenomenon occurring here.

2.2 Numerical Methods

The system of equations presented in the previous section is applicable to both conventional and recoilless guns and, historically, a variety of techniques have been used to solve this system as applied to conventional guns. Empirical techniques came first and are still used for routine work, e.g., estimating effects due to changing the charge in a well-known gun. Once the basic physical principles had been reasonably well understood, but before the advent of powerful computers, the equations were 'solved' by drastically simplifying them and using nondimensional parameters to derive general solutions. One of the best known of these methods is that described by Corner (Ref. 1) in Chapter 4 of his text on interior ballistics.

As high-speed computers became available it was then practicable to integrate the basic equations, after rewriting them as ordinary differential equations, using numerical techniques. Barriolade followed this approach, using a Runge-Kutta technique to study the interior ballistics of the CARDE 81-mm RCL. A typical solution with a 0.1-ms integration interval required 45 min on an IBM 1620 computer (Ref. 2).

Newer generation computers made integration of the partial-differential equations feasible, a realization which sparked the DREV effort. At first, the Longley Differencing Method was used. This scheme was superseded, however, by the Lax-Wendroff Two-Step Method which was found to be appreciably more accurate than the Longley scheme and four to five times faster while not needing significantly more core storage (Ref. 3).



(+) denotes the initial or final values of the flow variables, (i.e., (n, j).

(.) denotes the midway mark values, i.e., (n + 1/2, j± 1/2)

FIGURE 2 - Illustration of Lax-Wendroff finite-difference method

The essence of the Lax-Wendroff Method is that a partial-differential equation of the form:

$$\frac{\partial f}{\partial t} = \frac{\partial g}{\partial x} \qquad [15]$$

can be integrated using the pair of difference equations:

$$f^{n+\frac{1}{2}}_{j\pm\frac{1}{2}} = \tfrac{1}{2}(f^{n} + f^{n}_{j+1}) \pm \tfrac{1}{2}\,\frac{\Delta t}{\Delta}\,(g^{n}_{j\pm 1} - g^{n}) \qquad [16]$$

and

$$f^{n+1}_{j} = f^{n}_{j} + \frac{\Delta t}{\Delta x}\,(g^{n+\frac{1}{2}}_{j+\frac{1}{2}} - g^{n+\frac{1}{2}}_{j-\frac{1}{2}}) \qquad [17]$$

where the subscripts j and n refer to space and time, respectively. Figure 2 illustrates the scheme. The error term is of the order of Δt^3, Δx^3 and the set of difference equations is stable for:

$$(|u| + c)\,\frac{\Delta t}{\Delta x} < \sqrt{\frac{1}{2}} \qquad [18]$$

where u is the local gas velocity and c is the local speed of sound. This condition can be met if the time step, Δt, is adjusted after each iteration so that:

$$\Delta t < \sqrt{\frac{1}{2}}\;\frac{\Delta x}{(|u| + C} \qquad [19]$$

In order to cut down somewhat on computer time requirements 0.85 is used in place of $\sqrt{(1/2)}$ with no appreciable effect on the accuracy of the solution.

Applying eqs. 16 and 17 to the fluid dynamic relations (eqs. 9 to 11), we obtain the finite-difference equations given below.

Conservation of Mass

Step 1:

$$\rho_{j+\frac{1}{2}}^{n+\frac{1}{2}} = \left(\rho_j^n \Delta x_{j+1} + \rho_{j+1}^n \Delta x_j\right) / \left(\Delta x_{j+1} + \Delta x_j\right)$$

$$+ \frac{\Delta t}{\Delta x_j + \Delta x_{j+1}} \left(\rho_j^n u_j^n - \rho_{j+1}^n u_{j+1}^n\right)$$

$$- \frac{\Delta t}{(\Delta x_j + \Delta x_{j+1}} \left(\rho_j^n u_j^n \Delta x_{j+1} + \rho_{j+1}^n u_{j+1}^n \Delta x_j\right)$$

$$\left(\ln A_{j+1}^n - \ln A_j^n\right)$$

Step 2:

$$\rho_j^{n+1} = \rho_j^n + \frac{\Delta t}{\Delta x_j} \left(\rho_{j-\frac{1}{2}}^{n+\frac{1}{2}} u_{j-\frac{1}{2}}^{n+\frac{1}{2}} - \rho_{j+\frac{1}{2}}^{n+\frac{1}{2}} u_{j+\frac{1}{2}}^{n+\frac{1}{2}}\right)$$

$$- \frac{\Delta t}{2\Delta x_j} \rho_j^n u_j^n \left(\ln A_{j+\frac{1}{2}}^n - \ln A_{j-\frac{1}{2}}^n\right)$$

Conservation of Momentum

Step 1:

$$\rho_{j+\frac{1}{2}}^{n+\frac{1}{2}} u_{j+\frac{1}{2}}^{n+\frac{1}{2}} = \left(\rho_j^n u_j^n \Delta x_{j+1} + \rho_{j+1}^n u_{j+1}^n \Delta x_j\right) / \left(\Delta x_{j+1} + \Delta x_j\right)$$

$$+ \frac{\Delta t}{\Delta x_j + \Delta x_{j+1}} \left[\left(\rho_j^n (u_j^n)^2 + p_j^n\right) - \left(\rho_{j+1}^n (u_{j+1}^n)^2\right.\right.$$

$$\left.\left. + p_{j+1}^n\right)\right]$$

$$-\frac{\Delta t}{(\Delta x_j + \Delta x_{j+1})}\, 2 \left(\rho_j^n (u_j^n)^2 \Delta x_{j+1} + \rho_{j+1}^n (u_{j+1}^n)^2 \Delta x_j\right)\left(\ln A_{j+1}^n - \ln A_j^n\right)$$

Step 2:

$$\rho_j^{n+1} u_j^{nX1} = \rho_j^n u_j^n + \frac{\Delta t}{\Delta x_j}\left[\left(\rho_{j-\frac{1}{2}}^{n+\frac{1}{2}} (u_{j-\frac{1}{2}}^{n+\frac{1}{2}})^2 + P_{j-\frac{1}{2}}^{n+\frac{1}{2}}\right) - \left(\rho_{j+\frac{1}{2}}^{n+\frac{1}{2}} (u_{j+\frac{1}{2}}^{n+\frac{1}{2}})^2 + P_{j+\frac{1}{2}}^{n+\frac{1}{2}}\right)\right]$$

$$- \frac{\Delta t}{2\Delta x_j} (u_j^n)^2 \rho_j^n \left(\ln A_{j+\frac{1}{2}}^n - \ln A_{j-\frac{1}{2}}^n\right)$$

Conservation of Energy

Step 1:

$$\rho_{j+\frac{1}{2}}^{n+\frac{1}{2}} E_{j+\frac{1}{2}}^{n+\frac{1}{2}} = \left(\rho_j^n E_j^n \Delta x_{j+1} + \rho_j^n \bar{E}_j^n \Delta x_j\right) / \left(\Delta x_{j+1} + \Delta x_j\right)$$

σ

$$+ \frac{\Delta t}{\Delta x_j + \Delta x_{j+1}}\left[\left(\rho_j^n u_j^n E_j^n + P_j^n u_j^n\right) - \left(\rho_{j+1}^n u_{j+1}^n E_{j+1}^n + P_{j+1}^n u_{j+1}^n\right)\right]$$

$$- \frac{\Delta t}{(\Delta x_j^n + \Delta x_{j+1})^2}\left[\left(\rho_j^n u_j^n E_j^n + P_j^n u_j^n\right) \Delta x_{j+1}\right.$$

$$+ \left(\rho_{j+1}^{n} \; u_{j+1}^{n} \; E_{j+1}^{n} \; + \; P_{j+1}^{n} \; u_{j+1}^{n}\right) \Delta x_{j} \Big] \left(\ln A_{j+1}^{n} \; - \; \ln A_{j}^{n}\right)$$

Step 2:

$$\rho_{j}^{n+1} \; E_{j}^{n+1} = \rho_{j}^{n} \; E_{j}^{n} + \frac{\Delta t}{\Delta x_{j}} \; \Big[\left(\rho_{j-\frac{1}{2}}^{n+\frac{1}{2}} \; u_{j-\frac{1}{2}}^{n+\frac{1}{2}} \; E_{j-\frac{1}{2}}^{n+\frac{1}{2}} + P_{j-\frac{1}{2}}^{n+\frac{1}{2}} \; u_{j-\frac{1}{2}}^{n+\frac{1}{2}}\right)$$

$$- \left(\rho_{j+\frac{1}{2}}^{n+\frac{1}{2}} \; u_{j+\frac{1}{2}}^{n+\frac{1}{2}} \; E_{j+\frac{1}{2}}^{n+\frac{1}{2}} + P_{j+\frac{1}{2}}^{n+\frac{1}{2}} \; u_{j+\frac{1}{2}}^{n+\frac{1}{2}}\right)\Big]$$

$$- \frac{\Delta \; t}{2 \; \Delta x_{j}} \left(\rho_{j}^{n} \; u_{j}^{n} \; E_{j}^{n} + P_{j}^{n} \; u_{j}^{n}\right) \left(\ln A_{j+\frac{1}{2}}^{n} \; - \; \ln A_{j-\frac{1}{2}}^{n}\right)$$

At the end of the first time step (i.e. $n + \frac{1}{2}$), the propellant burning rate is computed using $p_{j}^{n+\frac{1}{2}}$ and $u_{j}^{n+\frac{1}{2}}$ substituted into eq. 14. The revised web thickness, f_{j}^{n}, is then:

$$f_{j}^{n} = \frac{\beta}{D} \, P_{j}^{n+\frac{1}{2}\;2} \quad \left(1 + C_{e} \left| u_{j}^{n+\frac{1}{2}} \right| \right) \Delta \, t \qquad [23]$$

At the end of the second step, the flow variables are corrected for the added mass and energy, by taking the average of the variables at the cell boundaries. Flow variables are also computed for a dummy cell added to the end of the nozzle to allow the averaging procedure to be applied to the last real cell in the nozzle.

The increments in projectile velocity and travel as well as nozzle thrust are also computed at this point and added to their current values. Bore friction is taken into account by multiplying the velocity increment by the friction coefficient specified by the user in the input data file. In equation form:

$$U^{n+1}_{proj} = U^{n}_{proj} + K_{frict}\ P^{n+1}_{base}\ A\ \Delta\ t/M_{proj} \qquad [24]$$

The new projectile travel is, simply:

$$X^{n+1}_{proj} = X^{n}_{proj} + U^{n+1}_{proj}\ \Delta\ t \qquad [25]$$

A special Lagrangian cell is used to contain the projectile, its left boundary moving with the projectile base. The location of this cell in the fixed system is evaluated during each cycle based on the current projectile travel. The location of the projectile cell is important because the finite-difference calculations described above must be carried out through the barrel up to the projectile base. Also, the end of a run is signified by the projectile cell reaching the muzzle.

The increment of nozzle thrust, i.e., the momentum impulse imparted to the weapon by propellant gases escaping through the nozzle, is computed using the equation:

$$I_{nozzle} = m_{nozzle}\ u_{throat}\ \Delta\ t + (P_{exit} - P_{amb})\ A\ \Delta\ t \qquad [26]$$

At the end of a run the net recoil is computed by subtracting the momentum of the projectile from the summation of the nozzle thrust increments. The momentum of the gases remaining within the weapon at the time of shot ejection, while quite small, is also taken into account in the final calculation.

The last quantity whose incremental increase is computed at each time step is the heat lost to the barrel, calculated using eqs. 4 and 5. The total computed heat transfer is printed at the end of each run.

2.3 Initial Conditions

One of the most significant simplifying feature of REGUN is its treatment of the initial phase of pressure buildup to the shot-start pressure. Quantitative calculation of this phase is difficult because of uncertainties in propellant burning rates at low pressures and the performance of igniters. In order to sidestep this problem and provide a coherent set of initial conditions for our numerical calculations, computation is only started for the combustion chamber at the shot-start pressure, it being assumed that the diaphragm has burst. Also assumed is a linear gas Mach number profile through the combustion chamber from zero at the projectile base to one at the nozzle throat. The usual gas dynamic relations are then used to compute the initial velocities, densities, pressures and energies for cells in the combustion chamber and nozzle.

The computation of the initial conditions begins with a calculation of the amount of propellant burnt in compressing the combustion chamber gases to the shot-start pressure. The contribution of the igniter is taken into account by a small increase in the propellant charge. The relation used is

$$Z_o \, WF = P_o \left(V_{ch} - \frac{W}{\rho_p} \right) - WZ_o \, B + \frac{WZ_o}{\rho_p} \qquad [27]$$

where

P_o = shot-start pressure

Z_o = fraction of propellant burnt

W = original propellant charge

F = propellant force constant

V_{ch} = combustion chamber volume

ρ_p = propellant density

B = co-volume of propellant gases

Note that the right-hand side of eq. 7 is simply the work done in compressing the propellant gases with the term in square brackets being the volume occupied by the propellant gases within the combustion chamber. The left-hand side is the chemical energy released by the burning of the propellant. Solving for Z_o, we obtain:

$$Z_o = (P_o/W) \times (V_{ch} - W/_{\rho_p}) \; / \; (F + P_o \times B\text{-}1/_{\rho_p}) \qquad [28]$$

Given Z_o, the two other gas parameters of interest may be computed.

$$\rho_{gas_o} = Z_o \; W/V_{gas} \qquad [29]$$

and

$$T_{gas_o} = P_o/R\rho_{gas_o} \qquad [30]$$

Note that up to this point the gas velocity and the resulting compressibility effects have been neglected. The shot-start pressure and the values computed for ρ_{gas} and T_{gas} are, therefore, stagnation values.

The next step, as was indicated above, is to assume a linear increase of gas Mach number from zero at the projectile to one at the nozzle throat. The Mach number is computed from the area ratio, A/A*, using an exponential curve fit to the isentropic compressible flow table's entries in the region of interest ($1.0 < A/A^* < 2.5$), the resulting relation being:

$$M = e^{0.1747} (A/A^* - 1)^{0.4982} + 1.0 \qquad [31]$$

Equation 31, when compared with the isentropic flow table, has an accuracy of better than 1.5%.

The initial pressure, density, energy and velocity distributions in the combustion chamber and nozzle are then determined using the appropriate gas dynamic relations:

$$P = (1 + \frac{\gamma-1}{\gamma} M^2) \frac{\gamma-1}{2} \times P_0 \qquad [32]$$

$$\rho = (1 + \frac{\gamma-1}{\gamma} M^2)^{\gamma-1} \times \rho_0 \qquad [33]$$

$$e = C_V T_0 / (1 + \frac{\gamma-1}{\gamma} M^2)$$

$$= (\gamma-1) R T_0 / (1 + \frac{\gamma-1}{\gamma} M^2) \qquad [34]$$

and

$$u = M \times C$$

$$= M (\gamma P_0 / \rho_0 (1-\rho_0 B))^{\frac{1}{2}} \qquad [35]$$

3.0 THE ROLE OF REGUN IN SOLVING INTERIOR BALLISTIC PROBLEMS

As with conventional gun interior ballistic codes, REGUN's predictions must first be 'fitted' to experimental data by modifying several arbitrary input parameters before the code may be used in extending the experimental data and in performing parametric studies. Factors which are difficult to quantify a priori and which are varied in order to 'fit' the code output to experimental data include bore friction, propellant losses through the nozzle, blockage of the nozzle by solid debris and boundary layer effects, and the erosive burning rate. In certain cases, the shot-start pressure may not be known exactly and the burning rate coefficient, β, may require 'adjusting' as in studies of conventional gun interior ballistic.

For a single type of cartridge and round the experimental data should provide measurements of the muzzle velocity, the recoil impulse, and a pressure vs time curve. Four values provided by REGUN have been used in trial-and-error 'fitting' investigations: the peak pressure, the muzzle velocity, the net recoil and the time between shot-start and peak pressures in the combustion chamber.

Of the unknown input parameters, the erosive burning rate and bore friction factors have been described previously. The approach taken to propellant losses and to blockage of the nozzle will be described here.

As mentioned in Recoilless Rifle Weapon Systems (Ref. 4) all recoilless rifles eject a significant portion of their propellant charge through the nozzle, the percentage varying from 10 to 30% depending on the interior ballistic configuration. In REGUN, the approach taken is to assume that the ejection of unburnt propellant is equivalent to a reduction in the force constant. The value for the force constant given in the input data is assumed to be an effective value with the percentage difference between this and the true value being due to propellant losses.

Nozzle blockage results in lower mass flow rates through the nozzle than would otherwise be expected, i.e., an effect equivalent to a reduction in the effective area of the nozzle throat. A line in the input data file allows the user to specify any desired diameter for the nozzle throat with, then:

$$\text{nozzle efficiency} = 1 - (d_{eff}/d_{actual})^2 \qquad [36]$$

The trial-and-error procedure is made somewhat easier by the fact that not all input factors affect each output parameter to the same extent. For example, the erosive burning rate coefficient only affects the peak pressure while changes in the effective force constant have a negligible effect on the net recoil.

4.0 INPUT REQUIREMENTS AND OUTPUT OPTIONS

4.1 Input Requirements

The format of the file of propellant, geometric, and housekeeping variables required by REGUN is given in Table I. A copy of a typical file is given in a following section as part of the solution of a sample problem.

Regarding Table I, it should be noted that the line numbering starts at 525 for historical reasons (the file used to be attached to REGUN). Also worth noting is that the number of cell radii must be equal to or greater than the value given for the number of cells in the combustion chamber nozzle plus one (for the cell containing the projectile whose radius is the first value in the list). Finally, since the web length is assumed by REGUN to be equal to the length of the combustion chamber, the actual web width must generally be modified slightly to keep the propellant charge in the computer model equal to that of the weapon being simulated. The interior ballistic effects of such a change are minimal, the important quantities being the propellant charge and the web thickness.

TABLE I

FORMAT OF INPUT DATA FILE

LINE	PARAMETERS	FORMAT
525	barrel radius (in); shot-start pressure (psi); cell width (in); projectile weight (lb_f).	4F10.0
526	number of cells in barrel; number of cell in combustion chamber; number of cell in combustion chamber of nozzle; cell in which projectile base is located.	4I10
527-531	radii of cells from projectile base through combustion chamber of end of nozzle (in).	8F10.0 (per line)
532	number of iterations between printing ballistic variables.	
533	propellant force constant ($ft\text{-}lb_f/lb_m$); γ; α (eq. 14); propellant density (lb_m/in^3); co-volume (in^3/lb_m); web thickness (in); effective web width (in).	7F10.0
534	erosive burning rate coefficient (s/in); no. of propellant strips.	F10.0, I10
535	barrel friction factor; β(eq. 14).	2F10.0
536	effective throat radius (in); throat cell number.	F10.0, I10
537	input table parameter; output table parameter (see following section).	2L1

4.2 Output Options

Some flexibility exists within REGUN, as currently configured, for obtaining results only to the desired detail. In its full output mode, REGUN prints a table of input data, including parameters such as propellant charge and combustion chamber volume, which are calculated from the values read from the input data file. As output, tables of pressure (psi), velocity (ft/s), sonic velocity (ft/s), density (slugs/ft^3) and total energy (ft-lb_f) are printed for each cell behind the projectile at several times during the interior ballistic cycle. Also printed are the projectile travel (ft), projectile velocity (ft/s), and the fraction of propellant which has been burnt.

The use of two logical variables allows for printing of either or both of the input and output tables to be skipped. Setting the first parameter in the last line of the input data file to T will eliminate the printing of the input data, while setting the second parameter to T will give an abbreviated output of the three quantities listed above, for each time, as well as an 'End of Run' summary. Either, or both, parameters may, of course, be set to F.

A table of maximum pressure values for each cell is written into file 106 (i.e., using a WRITE (106, ...) ... statement) and a SET command may be used to save this file in any desired manner.

4.3 Running REGUN

Standard on line terminal time sharing commands are used in running REGUN. The desired input data file is chosen by entering:

```
! SET  F:5  DC/file name; IN
```

Entering

```
! SET  F:106/file name; SAVE; OUT
```

will save the table of cells and pressures mentioned in Section 5.2 in the file chosen. This procedure is, however, optional.

REGUN is then run by entering

```
! FLAG  REGUN  ON  XGUN
```

The computer responds

```
WITH >
```

to which the user need only enter ZM (for Zero Memory) and a carriage return.

A typical run on the DREV Sigma 7 computer uses about 2 minutes of CPU time.

```
 525.000 00001.6500001500.0000000.5000000003.9700
 526.000 000000005000000000140000000039000000050
 527.000 00001.650000001.650000001.650000001.650000001.650000001.650000001.650000001.6500
 528.000 00001.650000001.650000001.650000001.650000001.650000001.650000001.650000001.6500
 528.500 00001.650000001.650000001.5549
 529.000 00001.437000001.437000001.437000001.492000001.545000001.599000001.652000001.7050
 530.000 00001.758000001.812000001.865000001.918000001.971000002.024000002.078000002.1310
 531.000 00002.184000002.237000002.290000002.344000002.3970002.4500
 532.000 0000000100
 533.000 0290000.00001.2383000000.78800000.05665000028.7700000.0157000000.55100
 534.000 0.00006400000000231
 535.000 0000.81000000.002500
 536.000 001.170000000000021
 537.000 F,1
*END
```

FIGURE 3 - Typical input data file for REGUN

```
INPUT DATA: GUN
                                                                  CALIBRE =      3.300  IN.
                                                            BARREL LENGTH =     25.000  IN.
                             CHAMBER VOL. AVAILABLE FOR GAS EXPANSION =     59.871  CU. IN.
                                                           CHAMBER LENGTH =      7.000  IN.
                                                       TOTAL LENGTH OF GUN =     44.500  IN.
                                                    NOZZLE THROAT DIAMETER =      2.340  IN.

                                   NUMBER OF                  CELLS IN :     BARREL =         50
                                                               CHAMBER =          14
                                                             TOTAL GUN =          89

                                 CELL BOUNDARY RADII (IN) THROUGH CHAMBER AND NOZZLE:
                              RB( 1) =          1.65000    RB( 2) =          1.65000    RB( 3) =          1.65000
   RB( 4) =         1.65000   RB( 5) =          1.65000    RB( 6) =          1.65000
   RB( 7) =         1.65000   RB( 8) =          1.65000    RB( 9) =          1.65000
   RB(10) =         1.65000   RB(11) =          1.65000    RB(12) =          1.65000
   RB(13) =         1.65000   RB(14) =          1.65000    RB(15) =          1.65000
   RB(16) =         1.65000   RB(17) =          1.65000    RB(18) =          1.55490
   RB(19) =         1.43700   RB(20) =          1.43700    RB(21) =          1.17000
   RB(22) =         1.49200   RB(23) =          1.54500    RB(24) =          1.59900
   RB(25) =         1.65200   RB(26) =          1.70500    RB(27) =          1.75800
   RB(28) =         1.81200   RB(29) =          1.86500    RB(30) =          1.91800
   RB(31) =         1.97100   RB(32) =          2.02400    RB(33) =          2.07800
   RB(34) =         2.13100   RB(35) =          2.18400    RB(36) =          2.23700
   RB(37) =         2.29000   RB(38) =          2.34400    RB(39) =          2.39700
   RB(40) =         2.45000   RB(

         PROPELLANT                                      FORCE CONSTANT =290000.000 FT-LBFLB
                                                                   GAMA =    1.23830
                                                                   BETA =     .00250   (IN/SEC)/( LB/SQ.IN)**ALPHA
                                                                  ALPHA =     .7880
                                                                DENSITY =    .056650   LB./CU.IN.
                                                              CO-VOLUME =    28.7700   CU.IN/LB.
                                                 EROSIVE BURNING FACTOR =   .0000640
                                                          WEB THICKNESS =      .0157   IN.
                                                         WIDTH OF STRIP =       .551   IN.
                                                       NUMBER OF STRIPS = 231
                                                          CHARGE WEIGHT =     .79243   LB.

         COMPUTATIONAL VARIABLES                             CELL WIDTH =       .500   IN
                                                     STABILITY CONSTANT =      .8500
                                                   SHOT START PRESSURE =   1500.000   PSI.

                                                   TIME CYCLE NO.= 100
                                                 TIME=     .3651 MILLISEC
                              CELL NO.          PRESSURE        VELOCITY      SONIC VEL.        DENSITY         TOT.ENERGY

                                           PROJECTILE TRAVEL =      .007FT.
                                         PROJECTILE VELOCITY =    -44.1705 FT./SEC.
                                FRACTION OF PROPELLANT BURNT =        .09
      VPROJ=   -44.170

                                                   TIME CYCLE NO.= 200
                                                 TIME=     .7420 MILLISEC
                              CELL NO.          PRESSURE        VELOCITY      SONIC VEL.        DENSITY         TOT.ENERGY

                                           PROJECTILE TRAVEL =      .039FT.
                                         PROJECTILE VELOCITY =  -131.5425 FT./SEC.
                                FRACTION OF PROPELLANT BURNT =        .21
      VPROJ= -131.543
```

FIGURE 4 - Typical condensed output from REGUN

```
                                          TIME CYCLE NO.= 300
                                        TIME=  1.1287 MILLISEC
                        CELL NO.          PRESSURE          VELOCITY      SONIC VEL.       DENSITY        TOT.ENERGY

                                       PROJECTILE TRAVEL =    .115FT.
                                     PROJECTILE VELOCITY = -269.7068 FT./SEC.
                          FRACTION OF PROPELLANT BURNT =       .36
VPROJ= -269.707

                                          TIME CYCLE NO.= 400
                                        TIME=  1.5248 MILLISEC
                        CELL NO.          PRESSURE          VELOCITY      SONIC VEL.       DENSITY        TOT.ENERGY

                                       PROJECTILE TRAVEL =    .256FT.
                                     PROJECTILE VELOCITY = -439.4082 FT./SEC.
                          FRACTION OF PROPELLANT BURNT =       .55
VPROJ= -439.408

                                          TIME CYCLE NO.= 500
                                        TIME=  1.9304 MILLISEC
                        CELL NO.          PRESSURE          VELOCITY      SONIC VEL.       DENSITY        TOT.ENERGY

                                       PROJECTILE TRAVEL =    .470FT.
                                     PROJECTILE VELOCITY = -613.0500 FT./SEC.
                          FRACTION OF PROPELLANT BURNT =       .75
VPROJ= -613.050

                                          TIME CYCLE NO.= 600
                                        TIME=  2.3352 MILLISEC
                        CELL NO.          PRESSURE          VELOCITY      SONIC VEL.       DENSITY        TOT.ENERGY

                                       PROJECTILE TRAVEL =    .750FT.
                                     PROJECTILE VELOCITY = -767.1287 FT./SEC.
                          FRACTION OF PROPELLANT BURNT =       .91
VPROJ= -767.129

                                          TIME CYCLE NO.= 700
                                        TIME=  2.7064 MILLISEC
                        CELL NO.          PRESSURE          VELOCITY      SONIC VEL.       DENSITY        TOT.ENERGY

                                       PROJECTILE TRAVEL =  1.057FT.
                                     PROJECTILE VELOCITY = -875.9551 FT./SEC.
                          FRACTION OF PROPELLANT BURNT =       .98
VPROJ= -875.955

                                          TIME CYCLE NO.= 800
                                        TIME=  3.0838 MILLISEC
                        CELL NO.          PRESSURE          VELOCITY      SONIC VEL.       DENSITY        TOT.ENERGY

                                       PROJECTILE TRAVEL =  1.402FT.
                                     PROJECTILE VELOCITY = -948.9436 FT./SEC.
                          FRACTION OF PROPELLANT BURNT =     1.00
VPROJ= -948.944

                                          TIME CYCLE NO.= 900
                                        TIME=  3.4219 MILLISEC
                        CELL NO.          PRESSURE          VELOCITY      SONIC VEL.       DENSITY        TOT.ENERGY

                                       PROJECTILE TRAVEL =  1.731FT.
                                     PROJECTILE VELOCITY = -990.4695 FT./SEC.
                          FRACTION OF PROPELLANT BURNT =     1.00
VPROJ= -990.469
                                              END OF RUN
                 HEAT TO GUN =   25660.31FT.LB.

                 MAX. PRESSURE = 8822.1250  PSI           IN CELL     70     AT TIME =     1.6904

                                     TOTAL IMPULSE =          .60   POUND-SECONDS

                          MUZZLE VELOCITY =-1017.3999
*STOP*
```

FIGURE 4 (contd)

```
                              TIME CYCLE NO.= 200
                            TIME=   .7419 MILLISEC
                  CELL NO.          PRESSURE        VELOCITY      SONIC VEL.        DENSITY        TOT.ENERGY


                         PROJECTILE TRAVEL =    .039FT.
                       PROJECTILE VELOCITY = -131.5439 FT./SEC.
                    FRACTION OF PROPELLANT BURNT =      .21
VPROJ= -131.544
                    50           .52280E+04     -.18987E+03     .35211E+04     .78866E-01     .38383E+08
                    51           .55852E+04     -.27843E+03     .32550E+04     .99944E-01     .32000E+08
                    52           .53627E+04     -.86214E+02     .34012E+04     .86929E-01     .35546E+08
                    53           .55137E+04     -.81636E+02     .33809E+04     .90627E-01     .34982E+08
                    54           .54550E+04      .14964E+02     .33750E+04     .89766E-01     .34955E+08
                    55           .54724E+04      .61457E+02     .33741E+04     .90249E-01     .34872E+08
                    56           .54233E+04      .14135E+03     .33651E+04     .90077E-01     .34636E+08
                    57           .53943E+04      .21750E+03     .33617E+04     .89911E-01     .34532E+08
                    58           .53476E+04      .31626E+03     .33499E+04     .89931E-01     .34251E+08
                    59           .52966E+04      .42485E+03     .33499E+04     .89212E-01     .34252E+08
                    60           .52433E+04      .55583E+03     .33319E+04     .89474E-01     .33868E+08
                    61           .51512E+04      .69309E+03     .33386E+04     .87660E-01     .34082E+08
                    62           .50622E+04      .86318E+03     .33115E+04     .87787E-01     .33579E+08
                    63           .48452E+04      .10183E+04     .33214E+04     .83540E-01     .33997E+08
                    64           .47085E+04      .12798E+04     .32797E+04     .83558E-01     .33346E+08
                    65           .42946E+04      .14409E+04     .32942E+04     .75206E-01     .34155E+08
                    66           .45788E+04      .12653E+04     .32788E+04     .80984E-01     .33484E+08
                    67           .43889E+04      .12585E+04     .33537E+04     .73957E-01     .35232E+08
                    68           .45369E+04      .15982E+04     .32808E+04     .80606E-01     .33820E+08
                    69           .36186E+04      .14155E+04     .33503E+04     .61112E-01     .35611E+08
                    70           .52428E+04      .19421E+04     .33348E+04     .91326E-01     .34879E+08
                    71           .62622E+03      .57358E+04     .26572E+04     .17980E-01     .37294E+08
                    72           .50487E+03      .60129E+04     .25617E+04     .15122E-01     .38089E+08
                    73           .44650E+03      .61182E+04     .25326E+04     .13642E-01     .38350E+08
                    74           .39852E+03      .62106E+04     .25061E+04     .12398E-01     .38582E+08
                    75           .35757E+03      .62962E+04     .24812E+04     .11316E-01     .38799E+08
                    76           .32274E+03      .63738E+04     .24578E+04     .10381E-01     .38995E+08



                    77           .29170E+03      .64487E+04     .24348E+04     .95353E-02     .39184E+08
                    78           .26522E+03      .65165E+04     .24132E+04     .88023E-02     .39353E+08
                    79           .24217E+03      .65786E+04     .23927E+04     .81557E-02     .39503E+08
                    80           .22186E+03      .66363E+04     .23729E+04     .75786E-02     .39638E+08
                    81           .20410E+03      .66884E+04     .23540E+04     .70680E-02     .39751E+08
                    82           .18782E+03      .67393E+04     .23351E+04     .65945E-02     .39859E+08
                    83           .17348E+03      .67862E+04     .23171E+04     .61722E-02     .39954E+08
                    84           .16055E+03      .68310E+04     .22996E+04     .57875E-02     .40043E+08
                    85           .14878E+03      .68747E+04     .22825E+04     .54329E-02     .40131E+08
                    86           .13816E+03      .69163E+04     .22659E+04     .51091E-02     .40214E+08
                    87           .12823E+03      .69583E+04     .22494E+04     .48026E-02     .40302E+08
                    88           .11930E+03      .69987E+04     .22337E+04     .45228E-02     .40391E+08
                    89           .11131E+03      .70361E+04     .22187E+04     .42697E-02     .40471E+08
```

FIGURE 5 - Typical full output for one time-step

5.0 SAMPLE PROBLEM SOLUTION

Presented in Figs. 3-5 are listings of a typical input data file, a listing of a typical run with abbreviated output, and the full output obtained for a time step.

6.0 CONCLUSION

The basis for - and implementation of - a computer code for the analysis of the interior ballistics of recoilless rifles has been presented. Further reports will deal with the application of REGUN to various problems and a comparison of certain of the results obtained with experimental data.

7.0 ACKNOWLEDGEMENTS

Credit is due to my predecessor Dr. Leigh Moyls for his work on the REGUN code and to Mr. W.J. Robertson for his constant encouragement in improving and applying REGUN.

8.0 REFERENCES

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3. Dumouchel, P., and Alexander, R., "A Review of Internal Ballistics and a Description of Comdev Computer Programs", Computing Devices of Canada R690/102/R1 (Final Report to DREV), March 1974. UNCLASSIFIED

4. U.S. Army Materiel Command, "Recoilless Rifle Weapon Systems", AMCP 706-238, Jan.1976, (available from NTIS as AD-A 023 513).

(See also reference citations following Appendix A)

APPENDIX A

USEFUL REFERENCES

A good introduction to the interior ballistics of recoilless guns is provided by A.K. Celmins in a chapter of Ref. A1, Interior Ballistics of Guns. In his article, Celmins reviews recoilless gun literature, develops the relevant basic equations, and surveys numerical methods for their solution. Other chapters of Ref. A1 are also useful for their treatment of more general gun interior ballistics problems, gun propellants, thermochemistry, experimental methods, etc.

The only good general reference on recoilless guns is the U.S. Army Engineering Design Handbook entitled Recoilless Rifle Weapon Systems (Ref. A2). This handbook is a comprehensive and authoritative source of relevant aspects of external and terminal ballistics and on various mechanical aspects (e.g. trigger mechanisms). Most useful for our purposes is the detailed treatment (although the mathematics is kept simple) of the interior ballistics. Many useful design charts are presented along with information on the key interior ballistic parameters of weapons which were designed, i.e. optimum solutions for various weapon calibers. Also useful are sections describing the types of cartridge cases, propellants, and igniters used in U.S. recoilless guns.

A report of considerable interest, especially to Canadians, is Briercliffe's "Some Comments on the Internal Ballistics of Recoilless Weapons" (Ref. A3) which, quoting Celmins, "gives an excellent and short description of important practical and theoretical aspects of recoilless rifle design". Briercliffe discusses the various design trade-offs and compares the advantages and disadvantages of recoilless rifles and in-tube burning rockets.

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A1. Krier, J., and Summerfield, M., ed., "Interior Ballistics of Guns", Progress in Astronautics and Aeronautics, AIAA, New York, 1979.

A2. Recoilless Rifle Weapon Systems, AMCP 706-238, U.S. Army Materiel Command, Jan 1976.

A3. Briercliffe, C., "Some Comments on the Internal Ballistics of Recoilless Weapons", DREV TN-1890/70, October 1970, UNCLASSIFIED

DREV R-4223/82 (UNCLASSIFIED)

Research and Development Branch, DND, Canada.
DREV, P.O. Box 8800, Courcelette, Que. GOA IRO

"A computer code for analysing the interior ballistics of recoilless rifles" by D. Gladstone

A computer code, called REGUN, for analysing the interior ballistics of recoilless rifles is described and its capabilities are presented. This code uses a finite-difference numerical technique to integrate the full partial-differential equations. The practical aspects of using REGUN are fully described and an Appendix provides general references in this area. (U)

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