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AN OPTIMIZATION STUDY OF THE UTIAS
IMPESSION-DRIVEN HYPERVELOCITY LAUNCHER MK II

by

Robert F. Flagg

and

Gregory P. Mitchell

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SUMMARY

A detailed study is presented of the optimization of the projectile velocity of the proposed UTIAS MK II Implosion-Driven, Hypervelocity Launcher. The projectile velocity was optimized with respect to four variables, namely explosive weight, initial loading pressure, hemispherical cavity size, and peak projectile acceleration or base pressure. The details of the dynamics of the waves which occur in the chamber and the dynamics of the projectile in the barrel were determined using a finite-difference computer program coded for use with the IBM 1130 computing machine. The code, which uses the von Neumann artificial viscosity technique to solve a set of nonlinear partial differential equations that describe the motion of the gas and projectile, did not contain such effects as radiative or convective heat losses, projectile-barrel friction, or ablation. The calculations therefore represent an ideal performance and set an upper bound on what can be expected in practice.

The results of the study show that there are three operating regimes for this type of device which depend on the ratio of explosive energy to gas energy and explosive thickness to chamber radius. In the first region, where the energy of the gas is comparable to or greater than the explosive energy, the projectile velocity increases markedly with increasing explosive weight. In the second region, where the energy of the explosive is greater than the gas energy, the projectile velocity varies as the square root of the explosive energy. In the third region where the explosive energy is much greater than the gas energy, the thickness of the explosive becomes a significant fraction of the radius of the hemisphere, and the projectile velocity increment decreases to a point where the final muzzle velocity actually decreases with increasing explosive weight. The optimum performance for the present constraints occurs in the third region and exploits a favourable decrease in peak-pressure loading with increased explosive weight to aid in minimizing the projectile integrity problem.

For the optimum case, curves are given of the time history of the pressure on the explosive-metal interface, the pressures produced against the barrel wall, and the total force on the diametral plane for use in mechanical design calculations.
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1. INTRODUCTION

The Institute for Aerospace Studies has been actively engaged in a program of research and development on the UTIAS Implosion-Driven Hypervelocity Launcher. This novel approach to the solution of the current "performance barrier" of hypervelocity launchers was first proposed by Professor I.I. Glass in 1959. The operating cycle, which seeks to exploit the extremely high pressures and temperatures generated in the origin region of a hemispherical implosion, is shown in Figure 1. The launcher consists essentially of a large metal block containing a hemispherical cavity and a launch tube or barrel connected such that the entrance to the barrel and the origin of the hemisphere are coincident. The interior of the hemispherical surface is coated with a thin layer of explosive; a diaphragm and a projectile are placed at the entrance to the barrel; and the remainder of the hemisphere is filled with a detonable gas, typically stoichiometric oxygen and hydrogen. The gaseous mixture is ignited at the origin by an exploding wire with sufficient violence to generate a spherically expanding detonation wave in the gas (Figure la). The detonation wave propagates outward symmetrically and reflects from the surface of the explosive, initiating it uniformly and instantaneously. This in turn generates a strong, explosive-driven, spherical imploding shock wave (Figure lb). This shock wave converges on the origin in a gas already preheated to several thousand degrees Kelvin and monotonically increases in strength as it approaches the origin. On reflection (Figure lc) it leaves a region of very high-pressure, high-temperature gas which acts on the base of the projectile, accelerating it along the barrel.

Sufficient progress in overcoming the many technical problems was made in this program that in 1966 a number of explosive-driven runs were made using a prototype 8-inch-diameter chamber and liners of lead azide and PETN. The latter were the most successful of many explosives that were tried. Velocities as high as 17,600 fps were obtained. A semi-analytical, semi-empirical performance model was constructed by Flagg, which attempted to model the various physical processes that occurred during the launch cycle. While it was moderately successful in that it explained many of the observed effects, it was also clear that a much more sophisticated scheme would be required to precisely determine the performance of the launcher. A numerical code was subsequently obtained from NOL and it was modified and recently used to calculate the anticipated performance of the prototype chamber.

Recently a decision was made to begin the design of a larger, implosion-driven launcher to be called the UTIAS Mark II Implosion-Driven Hypervelocity Launcher, a study model of which is shown in Figure 2. While the level of understanding of this type of launcher has advanced considerably during the past few years, several key problems pertaining to this device still remain to be solved, particularly the solution to the projectile integrity problem and the detailed understanding of the effect of radiative, convective, ablative and frictional losses. It was felt that to wait until the solutions to these problems were in hand would not be reasonable in view of the long lead time required for the design and construction of the Mark II launcher. It was also felt that some reasonable assumptions and forecasts could be made to obtain solutions and consequently a preliminary design was initiated.

The projectile integrity problem, that is, the ability to design a model that will not fail under extreme loading conditions, is one which affects most high-performance launchers and is now under serious study. It essentially places limits on the maximum pressure than can be tolerated by a projectile, and hence limits the ultimate performance. As of this date no specific information

1
useful for assigning realistic limits to projectile strength is available. If
the strengths of materials based on static yield criteria are used, the maxi-
mum velocities that can be produced by the implosion driver are inordinately low.
If strengths based on dynamic yield criteria of presently available materials
are used, then the maximum velocities attainable are improved. However, the
very high ultimate potential of the implosion driver can be obtained only if the
projectile strength limitation will not be a key factor. For the purposes of
the present study, it is assumed that the state of the art of projectile design will
improve in the near future to the point where virtually any acceleration imposed
by the launch cycle can be tolerated. To aid in meeting this ideal goal, the
launcher design is formulated around that case which will give the combina-
tion of the highest projectile velocity with the lowest peak projectile base pressure
consistent with the other design constraints such as chamber size, initial loa-
ding pressure, explosive weight, barrel diameter, and projectile shape, calibre,
and mass.

Radiative, convective, and ablative losses which act to reduce the per-
formance of a launcher over what would be calculated based on ideal, lossless
considerations have not been studied in detail to date. Recent work by Crosby
and Gill, Stanford Research Institute, on an explosive-driven gun indicate
that convective heat transfer is negligible for their gun. However, the calcu-
lated radiative losses were substantial. As their explosive-driven gun is
different in detail from the present device, a direct comparison is not valid.
The general features can, however, be carried over to the implosion-driven
launcher. A qualitative estimate of the overall losses incurred in the launcher
cycle can be made from recent comparisons of measured and predicted velocities
made by Flagg and Sevray for the implosion-driven launcher. Flagg noted that
the velocities predicted using a semi-empirical performance model overestimated
the measured velocities by a factor of about 1.5 for lead azide-driven implo-
sions in an 8-inch-diameter hemisphere, and up to a factor of $\sqrt{3}$ for PETN-driven
runs in the same chamber. The projectiles were 0.22-inch-diameter, 1.0-calibre
polyethylene projectiles in the first case and 0.187 and 0.312-inch-diameter,
1.0-calibre polyethylene, magnesium, and fiberglass projectiles in the second
case. Flagg was not able to prove conclusively that the origins of the discre-
pancy were radiative, convective, or ablative losses, but it is highly probable
that this was the case. Sevray compared the predicted values of projectile velo-
city using the new numerical code (also used in this study), compared them with
measured values of Watson and Flagg, and obtained ratios of $\sqrt{2}$.

It is possible that the losses will decrease as the launcher is scaled
up in size, since the convective losses and blackbody radiative losses are sur-
face effects and the driven gas has a high enough temperature to be considered
black; hence the present calculated velocities may be overestimating the veloc-
ities that can actually be obtained by as much as a factor of 2. However,
proper representations of radiative and convective losses will have to be incor-
porated into the program before any definitive assessment of losses can be made.
It is hoped that these calculations will be done in the near future and made the
subject of a complementary report.
2. PERFORMANCE PROGRAM

The computer program which was used in this study derives from a numeri-
cal code developed by Piacesi, Gates, and Seigel of the Naval Ordnance Labor-
tory. In its original form it was used to predict the performance of conventio-
nal, two-stage, light-gas guns. The original program did not include gas or
projectile friction effects or radiative losses but was able to predict very
accurately the velocities obtained in practice, probably because these effects
are not very significant at the velocities obtained for the types and sizes of
guns that were studied at NOL.

The numerical scheme is quite complicated in its details, but in essence it
integrates numerically a set of finite-difference equations derived from the
nonlinear partial-differential equations of mass, momentum, and energy in
Lagrangian form. These are

\[
\begin{align*}
\text{Mass:} & \quad \frac{1}{p} \frac{\partial V}{\partial m} = v \\
\text{Momentum:} & \quad \frac{\partial u}{\partial t} = -A \frac{\partial}{\partial m} (p + q) \\
\text{Energy:} & \quad \frac{\partial e}{\partial t} = -(p + q) \frac{\partial V}{\partial t}
\end{align*}
\]

Subject to an equation(s) of state of the form

\[ e = e(p,v) \]

An artificial viscosity, after von Neumann and Richtmyer, is assumed in re-
gions containing compression waves to prevent them from steepening and becoming
 discontinuous (shocks). Details of the equations in finite-difference form are
given in References 4 and 8. This numerical method is a very powerful device
for solving time-dependent hydrodynamic problems, some of which would otherwise
be intractable.

The original NOL program (which was one-dimensional planar) was modified
by Piacesi at the request of UTIAS to include the geometry of the hemispheri-
cal chamber. This modification was also undertaken independently by Sevray,
as the details of the physics required in the modifications were not obvious
and an independent but parallel analysis was felt warranted. Further modifi-
cations have been made to adapt it to the IBM 1130 installation at UTIAS, to
increase its versatility in the present problem and to overcome problems which
are peculiar to the hemispherical driver (for example, zoning and the transi-
tion between the hemispherical geometry of the chamber and the planar geometry
of the barrel which occurs at the origin of the hemisphere).

2.1 Zoning Considerations

The program originally divided the various regions into equal-width
zones. As only constant area regions were considered (except at transitions
between constant area regions, as for example at the chambrage plane), this
resulted in zones of equal mass in each region. This zoning works very well
in practice for planar geometries. However, the direct application to the hemispherical geometry introduced several undesirable side effects. For constant zone size, the mass in the hemispherical cavity varied approximately as the distance from the origin squared, producing zones of very small mass near the origin and very large mass at the outer wall. On implosion, the small origin zones, which experience the highest compression, become inordinately small and slowed the calculations to an unacceptable rate, as very short time steps (related to the zone width) were taken. The variation in mass for constant zone size for a typical case having 20 zones is shown in Figure 3. The mass has been normalized by the total mass divided by the number of zones or, in other words, the mass of an equal mass case. It can be seen that the masses vary by a factor of \(\sqrt[1100]{1100}\) from the origin zone to the outer zone.

The other simple alternative of constant mass in each zone yields zone widths which vary in extremes by only a factor of \(\sqrt{21}\). However, this is also unacceptable for two reasons: (1) The thin layers in the gas nearest the explosive are compressed to very small dimensions when the explosive detonates and again the calculation scheme slows down intolerably; (2) the zones near the origin, which are now very large, do not permit sufficient detail in this important region and when expanded into the barrel they elongate considerably, leaving only one or two zones in the barrel for a typical run. This prevents any detail being seen for the flow in the barrel and probably gives erroneous results.

Previously, to overcome this problem, Sevray chose to divide the gas region into three subregions: (1) an outer region which contained \(\frac{4}{5}\) of the total mass and is divided into 10 zones of equal mass, (2) a mid-region which contained \(\frac{3}{20}\) of the total mass and is divided into 5 zones of equal mass, and (3) an inner region which contained \(\frac{1}{20}\) of the total mass and is divided into 5 equal mass zones. It is known that discontinuities in zone size or mass will produce spurious shocks or expansions which have no physical meaning but occur only in the calculations. Hence, in the present work, a fixed, non-linear (but smooth) variation in zone width was used which varies the zone size in a manner such that those regions likely to experience the largest compressions, as for example the origin zones and the zones nearest the explosive, have the greatest initial thickness, but yet are not large enough that the detail is lost. This variation is given by

\[
\Delta x_j = b_g \sum_{i=1}^{n} \frac{i^{m_z}}{m_z} + \frac{(n-i)^{m_z}}{m_z} - \frac{(n-1)^{m_z}}{m_z}
\]

where \(b_g = \) width of the gas region
\(n = \) number of zones in the region
\(m_z = \) exponent governing the amount of the variation = 3.

In Figure 3 the variation of the zone size and mass for a typical calculation having 20 zones is plotted. It should be noted that the zone size and mass of a zone vary over the region but have significantly less variation than their counterparts in the constant mass or constant zone size calculations. Further, the origin zones have small enough mass to yield adequate detail but are not so small as to slow down the calculations to unacceptably slow values.
It is not claimed that this zoning is the optimum, but rather that it is a workable one for the various conflicting conditions encountered in this problem. Other possible solutions include rezoning during the progress of the calculation to divide up zones which are too large or to recombine those which are too small.

2.2 Transition Between Hemisphere and Barrel

The other major change in the present program is the treatment of the origin region, i.e., the transition between the hemispherical chamber and the planar barrel. It is important to note that in reality the transition between a one-dimensional spherical flow and a one-dimensional planar flow can only be accomplished by a complex two-dimensional flow. As the present program cannot handle two-dimensional, time-dependent flow, the problem is clearly how to represent this complex transition by an approximate one-dimensional relation. Piacesi\textsuperscript{10} chose to consider that the flow is always spherical on the upstream side of the origin and is planar downstream of the origin. A volume which straddles the origin will be comprised of a hemispherical part upstream of the origin and a cylindrical part downstream, as shown schematically in Figure 4.

This approach is open to criticism because the total force on the spherical surface can be less than the total force on the planar surface even if the pressure on the hemispherical surface is the greater of the two because of the possibility that the hemispherical surface (the outer annular surface is not considered) can be much less than the downstream planar surface. In this case the zone propagates upstream in contradiction to physical reality.

Sevray\textsuperscript{11} has made the transition from spherical to planar geometries by permitting the upstream zone surface to take on discrete values of $2\pi r^2$, $1.5\pi r^2$, or $\pi r^2$. This means that the function $A(x)$ is discontinuous in the manner shown in Figure 4b. It was felt that this approach was an improvement over the original transition since upstream-running zones are prevented, but could introduce oscillations and spurious effects due to the discontinuous nature of $A(x)$. In the present work a continuous transition was made by assuming that the upstream surface varies smoothly from $2\pi r_p^2$, the area of the hemispherical cap that has a radius equal to the barrel or projectile radius, to the cross-sectional area of the barrel $\pi r^2$, by using the following relations:

\begin{align*}
A &= 2\pi(R_o - x)^2 \quad 0 \leq x \leq (R_o - r_p) \quad (2.6) \\
A &= \pi[(R_o - x)^2 + r_p^2] \quad (R_o - r_p) < x < R_o \quad (2.7) \\
A &= \pi r_p^2 \quad R_o \leq x \quad (2.8)
\end{align*}

Equation (2.7) gives essentially the area of the curved surface of a spherical segment of height $(R_o - x)$ and of base radius $r_p$.

The volume is calculated based on surfaces defined by these areas, is self consistent with the above, and does not violate conservation-of-mass relations, as suggested by Sevray. The mass in each zone is a constant throughout the calculation and is fixed by the zoning as described in Section 2.1. The specific volume is calculated by dividing the volume of the zone by a quantity which depends on the mass. If the volume is determined properly, or at least in a self-
consistent manner, then the specific volume which follows is also self-consistent, as well as the pressure which follows from the specific volume, and finally the total force which is the product of the pressures and the areas. To calculate pressures based on volumes which are determined in one manner and areas which are determined from another which was apparently done by Sevray, must yield suspect values for force and acceleration.

The above points are inconsequential if the zoning is coarse enough that the surfaces of zones fall in the transition area only infrequently, which would appear to be the case for any practical number of zones. Hence the effect on velocity, an integrated result, would be very small. However, the difference in peak pressures could be significant. A comparison of the results of calculations of identical cases made by Sevray and the present method indicate the gross features of both programs are essentially the same (for example, for \( W = 25 \) kg, \( p_i = 200 \) psia, \( R_0 = 15 \) in., \( V_p = 15.1 \) km/sec at \( x = 318 \) cm, for Sevray, as compared to \( V_p = 15.6 \) km/sec at \( x = 400 \) cm, for the present work). The peak pressures of the first cycle, however, were \( 1.54 \times 10^5 \) bars for the former and \( 1.80 \times 10^5 \) bars for the latter.

Again, while it cannot be stated that the present scheme is the optimum one for the complex phenomena which are occurring in the transition, it should be clear that this representation is to be preferred over the other two because: (a) it avoids discontinuities in \( A(x) \) and (b) it is internally self-consistent.

3. ASSUMPTIONS AND METHOD

3.1 Assumptions

A number of assumptions, explicit and implied, have been made in this study. It is very important in assessing the value of the data and the validity of the results generated by this study that these assumptions and their effects on the results be known and appreciated. Of importance are the assumptions of no losses, the equation of state used for the explosive and driven gas, the initiation of the explosive, and the assumption of rigid walls.

The assumption of no losses, as discussed in Section 1, is particularly important and is probably the major factor in the calculated velocities being high by factors of two or more. The convective heat transfer to the walls of the chamber is probably not a major contributor and its effect is probably limited to a thin thermal layer at the wall. However, since the temperatures are so high (\( 10^4 \) to \( 10^5 \) K) and since radiative losses are such strong functions of temperature (\( T^4 \) for black-body radiators), the losses due to radiation are probably substantial. The expected result will be to limit the peak pressures of an imploding shock to finite values as the rate of increase of pressure due to convergence is balanced by the loss due to radiation and a quasi-steady pressure level is probably reached. (The above remarks are quite aside from the deeper questions of incident and reflected implosion-wave structure based on a viscous or kinetic theory approach). Since the projectile acceleration is impulsive in nature, the the bulk of the velocity increase occurs during the periods of peak pressure, any limit on the peaks will have a considerable bearing on the final velocity.

* See Appendix B
The calculations are also only as accurate as the equations of state which are used to represent the interior driven gas and the gaseous products of detonation of the explosive. The equation of state assumed for the combustion products of stoichiometric oxygen-hydrogen is a numerical fit by BrodelI to thermodynamic data calculated by Moffatt12 and is of the form \( e(p,v) \).

\[
e = 6.57 \, pv + \frac{974.0 \, (pv)^2}{1140.0 + (pv)^4} + \alpha \left[ 0.101 \times 10^{-3} \ln \frac{p}{1.013 \times 10^{-3}} - 0.2325 \times 10^{-3} \right]
\]

where

\[
\begin{align*}
\alpha &= 0 \\
&= 8600 \, pv - 9000 \\
&= 21.0 \times 10^3
\end{align*}
\]

Unfortunately, the data are valid only for the region defined by

\[
\begin{align*}
0.01 \leq p \times 10^5 \text{ atm} \\
1600 \leq T \leq 6000^\circ \text{C}
\end{align*}
\]

and extrapolation well beyond the original region of interest has been necessary. It will be seen that temperatures in the range 10^5 \(^\circ\) C and pressures of \( \approx 10^7 \) psi have been calculated. The effects of assuming this extrapolation are not known. It has been shown from other work3 that this equation of state at high pressures corresponds very closely to a 'gamma-law' gas where \( \gamma \approx 1.14 \). As peak gas densities are \( 0.1 \leq p \leq 10 \, \text{gm/cc} \), it is expected that van der Waals' forces are probably significant and should be included. Seigel13 has shown that rather large changes (generally favorable) occur for hydrogen when conditions are reached such that these forces are significant. Unfortunately, calculations are not available in this range for stoichiometric oxygen-hydrogen. Hence, the present calculations, which are the best available using existing knowledge, suffer from these shortcomings.

The equation of state assumed for the PETN is a numerical fit to experimental data for Pentolite (50% PETN, 50% TNT)10, in the form \( p(e,v) \).

\[
p(e,v) = A(p) + B(p)e
\]

where

\[
\begin{align*}
A(p) &= 0.002164 \, p^4 + 2.0755 \, e^{-6.0/p} \\
B(p) &= 0.35 \, p
\end{align*}
\]

Implied in writing an equation of state of the above form is the assumption of thermodynamic equilibrium. For the pressures and temperature considered, this is probably valid. The density of the PETN liner was taken to be 0.588 gm/cc with the exception of a single computer run (HL-12), where 1.5 gm/cc was assumed. The energy densities at these packing densities were assumed to be 1.255 kcal/gm and 1.415 kcal/gm, respectively, after the work of Cook14.

The assumption as to the manner in which the explosive initiates is very important. In this study, as in Reference 4, it is assumed that the explosive initiates at the explosive-gas interface. This is true provided the initial gas pressures are well above an initiation threshold of the explosive, which for PETN at a packing density of 0.588 gm/cc is between 25 and 50 psia3. The pattern of the shock and detonation waves that result is a direct consequence of this assumption. If the explosive liner is thin, then there will probably be little discernible difference between the two resulting wave systems. However, if the explo-
sive is thick, then radically different wave systems will result and care must be used in the interpretation of the results. This will be discussed further in Section 4.

It is also assumed that the chamber and barrel walls are rigid. It is unlikely that the motion of the rear and side walls of the hemisphere have any significant effect on the motion of the projectile. However, in the regions of the hemisphere near the origin, and in the barrel near the entrance, it will be shown that the pressures are extremely high ($\sim 10^5$ to $10^6$ bar). Since the volumes are relatively small, motion induced by the high pressure could be significant. For example, in iron which is compressed by the shock to $5 \times 10^5$ bar, the particle velocity is $\sim 1.0$ mm/µsec. Assuming an initial barrel radius of 1.0 cm, means that the radius could double in $\sim 10^4$ µsec, a time which is comparable with the time this pressure is applied. For conditions where peaks of lower pressure are produced wall motion around the origin may not be important, but for cases where a single high-pressure peak is produced, significant wall motion is possible, resulting in a loss in pressure on the projectile and a reduction in the final muzzle velocity. It has been observed that copper elements near the origin have experienced significant deformation during runs using only modest amounts of explosive (100 to 200 grams).

A projectile, 1.0 in dia x 1.0 calibre long, having a density of 1.0 gm/cc, and weighing 12.65 gm was assumed for all the calculations. Presently there is no known material of this density that has fracture properties that will permit transient loadings to $\sim 10^5$ bars. However, some progress is being made in this direction. For example, magnesium-lithium projectiles ($\rho = 1.43$) have been successfully launched in explosive-driven guns after experiencing peak pressures in excess of $4 \times 10^4$ bars. However, much more is required in the development of new materials if the potential of this type of launcher is to be realized.

3.2 Method of Analysis

The problem is essentially to find that condition which yields the highest projectile velocity subject to limits placed on the possible ranges of four parameters: (1) initial loading pressure of stoichiometric hydrogen-oxygen, (2) hemispherical cavity size, (3) explosive weight, and (4) peak projectile base pressure.

As mentioned in Section 2.1 the initial pressure must be high enough to insure detonation of the explosive, i.e., $\geq 50$ psia. However, to insure that the explosive detonates at the front surface as is assumed, requires higher pressures, of the order of 200 psia. Hence the constraint taken on pressure is $p_i \geq 200$ psia. Preliminary structural feasibility studies have revealed that limitations on the maximum weight that can be handled by any known forge places an upper limit on chamber inside diameter at $\sim 30$ inches. Hence, it would be helpful to keep the chamber diameter, i.e., $D_o \leq 30$ inches.

No constraint is placed on the amount of explosive other than it must be limited to less than the chamber volume for the given density; i.e., $W \leq \rho_{exp} V_{chamb}$. However, it is clear that the minimum possible amount of explosive is to be sought. Furthermore, it is also desirable to have a driver gas mass that is several fold that of the projectile. As mentioned in Section 1, no realistic limits can be set on the maximum base pressure that can be tolerated without restricting performance to an
uninterestingly low level. Hence, the criteria used was to obtain as high as performance as practical with as low a peak base pressure as possible. It will be seen that an unexpected, nonlinear behaviour of peak base pressure versus explosive weight allows a minimum in peak base pressure to be exploited to considerable advantage.

The parameter sweeps were carried out in the following general manner. The chamber was fixed at 30 in. dia., the initial pressure was set at 200 psia, and cases corresponding to a range of explosive weights from 0 to 50,000 gm were run. Fifty thousand grams represents a practical limit for this chamber size since the chamber is nearly filled with PETN at this density (ρ = 0.588 gm/cc). To completely fill the 30-inch-diameter cavity requires ~68,000 grams. The initial pressure was then increased to 1000 psia and a similar sweep performed. Then another sweep was made for 100 psia.

The chamber size was subsequently reduced to 20 in. dia. (25.4 cm rad) and similar sweeps made. Not nearly as extensive a study was made with the 20-in. dia. chamber as the results indicated clearly the superiority of the previous size. Then a few additional runs were made to provide better definition and to verify the trends that were indicated from the previous runs. In all, 25 computer runs were made, which (as each run represented approximately 4 hours of computing time on the IBM 1130, about 3 hours minimum to 6 hours maximum) resulted in ~100 computer hours. The IBM 7094 takes about six minutes to run each case. However, as better control over the output, in terms of being able to change printing cycles, the availability of punch card output for automatic plotting of the data, the changing of convergence criteria during the run, as well as immediate access to the computer (the IBM 7094 is located 15 miles away), the IBM 1130 was used exclusively for this study.*

4. RESULTS AND DISCUSSION

The results of the computer study and the important values and parameters are tabulated for convenience in Table 1 and plotted in Figs. 5 through 25. First, the projectile base pressures and velocities will be discussed in detail to demonstrate the physically observable results. Then, non-dimensionalized and cross-plotted values will be discussed to point out the various regimes and controlling parameters and to demonstrate the origins of these effects.

4.1 Specific Results

Plotted in Figs. 5 and 6 are the results obtained from the 200 psia stoichiometric oxygen-hydrogen, 38.1 cm.-radius (30 in. dia.), chamber series of runs covering a range of explosive weights from 1,000 g to 50,000 g of PETN. Only a limited number of cases, sufficient to indicate the trends are included in these two figures. Comprehensive results can be found in Appendix A and the complete detailed numerical printouts have been filed at UTIAS and are available for further analysis if required. Plotted in Fig. 5 are the projectile base pressures in bars, (1 bar = 14.504 psi ~ 1 atm), versus time from initiation of the gaseous detonation wave at the origin in microseconds and in Fig. 6 are plotted the corresponding projectile velocities in km/sec versus projectile position in centimeters. A projectile position of 38.1 cm. corresponds to the chamber origin, i.e., the entrance to the barrel, for these cases. Position 0.0 cm. corresponds to the explosive/metal interface, i.e., the hemispherical wall. This notation is for con-

* See Appendix B
Consider first the results of case HL-2 which used an explosive loading of 1000 grams of PETN. This case is an example of a low ratio of explosive energy to gas energy situation, \((E_{\text{exp}}/E_{\text{gas}} \approx 0.51)\). The explosive liner is only 0.187 cm. thick and represents a small fraction, 0.005, of the chamber radius. The thickness of the explosive liner at a density of 0.588 g/cc for chambers of 38.1 and 25.4 cm. radius is given for convenience in Fig. 7. It is seen that the projectile experiences a single pressure pulse which reaches a maximum of \(6.33 \times 10^4\) bars and which falls smoothly in time as the projectile moves along the barrel. It may be confirmed from Fig. A-1 that the origin pressure follows the projectile base pressure very closely, i.e., for all practical purposes the pressure at the projectile and at the origin are identical at any given instant of time. This condition which was assumed in the performance model of Ref. 3 occurs primarily because the projectile velocity is low compared to the sound speed of the gas between it and the origin and the pressure variations can be transmitted rapidly between origin and the projectile. From the plot of projectile velocity versus position, it can be seen that the final projectile velocity of 2.5 km/sec is reached in essentially one step. Eighty percent of the final velocity or 2.0 km/sec is reached in \(\sim 7\) cm.

Consider next the data from run HL-3, which corresponds to a 10,000 g PETN case. This represents a one order of magnitude increase in explosive weight over the previous one. However, the results are generally similar. The projectile experiences a single pressure pulse. The velocity rises rapidly in a single step and reaches 80 percent of the final muzzle velocity of 11.9 km/sec in about 30 cm. It can be verified from Fig. A-2 that the projectile pressure follows the origin pressure for most of the time, being slightly lower due to the decrease in pressure of the rapidly expanding gas. However, after the projectile has traversed approximately 20 cm. of the barrel, the pressure at the origin beings to increase. The projectile does not feel this increase because the higher projectile velocity in this case has allowed the projectile to move far enough down the barrel and fast enough that the pressure at the origin cannot be transmitted rapidly enough to the projectile to be effective in time. The peak pressure in this case is \(5.83 \times 10^5\) bars, about an order of magnitude greater than the previous case. The peak also occurs earlier in time as the imploding shock, having a much greater pressure ratio, hence shock velocity, travels the radius from the explosive surface to the origin in a much shorter time.

Shown also in Fig. 5 are the results of run HL-10, which has a 25,000 g PETN case. This case has 2.5 times the amount of explosive of the previous case. The explosive liner is now 5.4 cm. thick and represents a non-negligible fraction, 0.14, of the chamber radius. Now the projectile experiences two pressure pulses. The initial pulse, which is weaker than the previous case even though more explosive is used, while the projectile is near the origin and a second pulse of nearly equal magnitude when the projectile is approximately 18 cm. from the origin. The first pressure pulse is the result of the arrival of the shock which is generated by the detonating explosive acting on the driver gas. The second pulse is the result of the detonation wave in the explosive reflecting from the explosive/metal interface, i.e., the hemispherical wall. In the low explosive weight cases these two shocks had coalesced before arriving at the origin. In this case the larger thickness of the explosive layer separated the two shocks to the extent that they could not coalesce in the available time and distance (see Ref. 4 for detailed \((x,t)\)-plane diagrams of these cases). The final muzzle velocity for this last case was 15.1 km/sec. As can be seen from Fig. 6, the velocity increment due to the first pulse is much smaller than that obtained previously and it is the second pulse which is responsible for the bulk of the total muzzle velocity. It will be
shown later that the optimum performance lies in this nonlinear region.

Also shown in Fig. 5 are the results of run HL-4, which corresponds to an explosive loading of 50,000 g of PETN. As the maximum amount of explosive that can be contained in this chamber at this packing density is 68,000 g, this liner, which is 13.6 cm. thick, takes up 0.36 of the chamber radius and can be expected to introduce significant effects. Both peaks are higher than the previous case and occur earlier in time due both to their increased strength and the fact that the first shock at least originates closer to the origin. The final velocity is 18.4 km/sec. While this is higher than the previous case it is less than what would be expected from an extrapolation of previous results. Additional runs which are not plotted here for reasons of graphical clarity, but which will be discussed later, indicate a minimum in peak base pressure as well as a local maximum in projectile velocity in this nonlinear region that can be exploited to advantage.

Shown in Figs. 8 and 9 are the projectile base pressure and velocity histories for the 100 psia stoichiometric oxygen-hydrogen series in a 38.1 cm. radius chamber. The range of explosive weights covered is from 5000 g to 50,000 g of PETN. The essential difference between this series and the previous one is a reduction in initial pressure by a factor of 2. However, the same general character of the results is evident. For example, the case HL-16, using the smallest amount of explosive, 5000 g, produced nearly a single pulse situation, i.e., a pressure profile which has a high initial pressure peak of 3.8 x 10^5 bars and a second almost negligible peak of only 8.2 x 10^3 bars. Most of the final velocity of 10.7 km/sec is produced by the first pulse. This is a typical low explosive energy to gas energy, E_{exp}/E_{gas} = 5.1, and thin explosive layer, d/R_0 0.0251, case.

Increasing the amount of explosive by a factor of 2, to 1,000 g, case HL-13, produces a two pulse base pressure with the second peak still less than the initial one, 2.0 x 10^5 bars as compared to 1.3 x 10^5; however, both peaks are substantially lower than that of the single peak of the previous case. The final velocity, however, has now increased to 15.1 km/sec and is obtained after two steps, the first step increasing the velocity to approximately 8.2 km/sec.

Increasing the explosive weight further, by a factor of 2.5, to 25,000 g gives the results shown for case HL-14. Again a two pulse pressure profile is produced except that now the first peak is much less than the second, 1.2 x 10^5 bars as compared to 3.6 x 10^5 bars. The velocity after the first pulse is now only 5.5 km/sec. However, the final velocity, 16.7 km/sec, is greater than the previous case.

The last case studied in this series, case HL-15, is for 50,000 g. Again, a two pulse projectile base pressure history results with the first peak diminishing from that obtained in the previous case and being almost an order of magnitude less than the second pulse, 9.1 x 10^4 bars compared to 6.6 x 10^5 bars. The velocity after the first pulse is only 3.8 km/sec but the final muzzle velocity has increased to 17.8 km/sec. On the basis of these results alone it would be expected that more explosive might yield even higher velocities. As the chamber is very near its limit of 68,000 g it is unlikely that any significant gain could be made by further increases in explosive weight. In fact, whether the wave diagram calculated for this case could be obtained in practice is questionable owing to the low initial pressure and the initiation limit. This point is discussed further in Section 4.2.

Shown in Figs. 10 and 11 are the results of the 1000 psia stoichiometric
oxygen-hydrogen, 38.1-cm. radius chamber series which cover a range of explosive weights from 10,000 g to 50,000 g. The essential difference between this series and the previous one is an increase in initial pressure by a factor of 10. In Fig. 10 is given the projectile base pressure as a function of time and Fig. 11 gives the corresponding velocity-position histories. The trends are essentially the same as the two previous series. However as the initial pressure is high, the amount of explosive can be increased proportionately before a different regime is encountered. For example, 10,000 g at 1000 psia behaves roughly similar to 1000 g at 100 psia, i.e., they are both essentially single pulse situations. The small peak which occurs prior to the arrival of the main explosive-driven wave is incidental. It is the result of allowing the diaphragm to open too early, i.e., too low a burst pressure. In all the previous calculations the pressure generated at the origin by the detonated gas was not sufficient to open the diaphragm and it remained closed until after the arrival of the main implosion wave. The 1000 psia initial pressure is sufficient, on detonation, to cause the diaphragm to open. In terms of contributions to the projectile velocity this early opening is negligible. The bulk of the velocity for case HL-7 comes from the single high peak of 2.0 x 10^5 bars. Increasing the explosive weight to 25,000 g brings the character of the resulting wave system into the two pulse regime and a velocity of 11.8 km/sec. Finally, increasing the explosive weight to 50,000 g results in a decrease in projectile velocity to 9.8 km/sec as nonlinear effects due to the very thick explosive layer and high initial pressures predominate.

In Figs. 12 through 17 are given the individual results of cases using 25.4 cm. radius chamber. They include series at 100 psia, Figs. 12 and 13, 200 psia, Figs. 14 and 15, and 1000 psia, Figs. 16 and 17. The results of these cases are basically the same in character as the previous larger chamber, the essential difference being the magnitude of the pressures and velocities produced. Exit velocities for the smaller chamber were generally lower than those of the larger chamber for a given initial pressure and energy per unit volume ratio, hence the larger chamber is clearly to be preferred from a velocity performance point of view. From this it is expected that a larger chamber would give still higher velocities. This has been shown to be true in recent work by Sevray. However, a larger chamber, 40 in. in diameter for example, is probably beyond the manufacturing capability of existing forges.

For the 100 psia small chamber series, two cases at 5,000 g and 10,000 g of explosive gave essentially the same velocity indicating a maximum in that range. The 200 psia series shows clearly the results of increasing the explosive weight beyond an optimum amount, and the same is true with the 1000 psia series. Not nearly as extensive a study was made with this chamber size as was done with the previous one as the maximum velocities that were obtained were generally lower indicating the superiority of the previous larger chamber.

4.2 Generalized Results

From a comparison of runs in a given series and between series the general trends and behaviour of this type of launcher cycle can be seen. Recall that for small amounts of explosive that the projectile base pressure history consists of a single pressure pulse. It can be seen from Figs. 18 through 20, which are plots of the peak projectile base pressure for the 100, 200 and 1000 psia series in the 38.1 cm radius hemisphere cases, that as the amount of explosive is increased, the peak pressure increases linearly with explosive weight. The peak is also nearly independent of initial pressure. The pulses
also occur earlier in time because the increased strength of the imploding wave makes the transit time for the inbound imploding shock shorter.

It should be noted that as the printouts occur at finite increments in the computing cycle, it is possible that the absolute peak pressures could be missed by an unknown amount. The outputs were monitored visually during the computing cycle and if it appeared that a peak or local maximum would be occurring, the time between printouts was reduced in an attempt to accurately define the peak pressure. In this regard later runs, i.e., higher run numbers, tend to be more accurate as experience was gained in anticipating the cycles and peaks.

From Figs. 18 through 20 it can be seen that, as the amount of explosive is increased further, a maximum is reached, which is also approximately independent of initial pressure, after which the first peak begins to decrease in magnitude and a second pulse and corresponding peak appears. This signals entry into the nonlinear region. The thickness of the explosive is beginning to represent a significant fraction of the chamber radius and the reflected detonation wave will generally not have time to overtake the incident imploding wave; hence the two pulse system\(^4\). Further, the front edge of the explosive/gas interface lies closer to the origin and the distance over which the first implosion can strengthen by convergence is reduced. The second pulse originates in the reflection of the detonation wave at the explosive/metal interface. The regimes are shown schematically in Fig. 21 and will be discussed further below. As will be seen subsequently, the rate of increase in projectile velocity with explosive weight also begins to decrease as does the overall efficiency, i.e., the ratio of projectile kinetic energy to total chemical energy (gas and explosive, see Table 1).

For further increases in explosive weight, the first peak continues to decrease while the second peak increases. At one point corresponding to 12,500 g of PETN for the 100 psia series and approximately 25,000 g for the 200 psia series both peaks are equal and are much less than for an equivalent single peak of equal velocity. This effect is of considerable significance since it provides for a means of getting the highest projectile velocity for the least peak base pressure. By splitting the pressure history into two smaller peaks rather than a single large peak, the chances of projectile survival are enhanced. Increasing the explosive weight further generally results in an increase in the second peak and a further decrease in the first peak as well as a decrease in projectile velocity. The 200 psia series has one exception to this general trend at 50,000 g, which is as yet unexplained. The projectile velocity, which is the prime parameter of interest, follows the same general character in that a step type velocity history is obtained since it is essentially the integral of the "pulse-like" pressure-time history experienced by the projectile.

The projectile velocity is given in terms of the amount of explosive and total energy in the chamber in Figs. 22 and 23 for the 38.1 cm. radius hemisphere and Figs. 24 and 25 for the 25.4 cm. radius hemisphere. It can be seen that a family of performance curves appears in this type of representation. As the amount of explosive is increased in Fig. 22 the projectile velocity increases as the square root of the explosive weight. In other terms, the projectile kinetic energy remains a fixed percentage of the explosive energy (i.e., all efficiency lines have a slope tan\(^{-1}\) 62.5°). This variation of projectile velocity was predicted by the physical model proposed originally by Flagg\(^3\), which assumed that the energy release occurred over a vanishingly thin layer over the
hemispherical surface. Reducing the initial pressure, results in a shift of the curve to higher velocities (a higher efficiency of conversion of chemical energy into directed energy), presumably due to the higher sound speeds generated in the lower pressure gas.

Up to a certain weight, approximately 10,000 g for this case, the projectile velocity varies in the predicted fashion. Beyond this limit, the projectile velocity increases but at a decreasing rate and eventually decreases with explosive weight. This is the nonlinear, two pulse, region which is the result of the finite thickness of the explosive liner. This conclusion is demonstrated very clearly by the solid data point at a velocity of 108,000 fps, which is the result of using 50,000 g of PETN at a density of 1.5 g/cc instead of the 0.588 g/cc that was used for the rest of the runs. For this case, roughly the same amount of energy is involved except that condensing the explosive results in a thinner liner (by a factor of 2.6) and the effects due to liner thickness are essentially suppressed. It is important to note that this point lies on a curve defined by extrapolating to the other points that were not affected by liner thickness, i.e., the velocity vs explosive-weight curve would remain a straight line indefinitely if the liner thickness effects were absent.

Also plotted in Fig. 22 is an overlay of efficiency, where efficiency is defined as the ratio of projectile kinetic energy to the explosive energy in the chamber. (A scale of overall efficiency defined above as the ratio of the projectile directed energy to the total chemical energy cannot be put on this plot as it requires a different curve for each initial pressure to account for the energy contribution of the gas). A scale for the projectile kinetic energy is also included for convenience. It can be seen that the explosive efficiencies are small varying from ~2 percent for the 1000 psia cases to ~6 percent for the 100 psia cases. It is expected that in practice, where radiative and convective losses are present, the actual values will be reduced even further from the calculated ideal values. It is also clear that if initial pressures could be reduced further without other effects emerging that projectile velocities could never exceed the 100 percent efficiency line. It should also be noted that the explosive will not initiate if the initial pressure is reduced below 25 to 50 psia for this density PETN and that it is probably being initiated at the explosive/metal interface for pressures immediately above this limit. Therefore, the wave diagram obtained for the 100 psia case will probably not be obtained in practice unless the initiation characteristics of PETN are improved. For the 200 and 1000 psia cases it is expected that the explosive does initiate at the explosive/gas interface hence the results given here are ideally applicable.

A similar plot is given in Fig. 23 except that the projectile velocity is now plotted versus total, (gas plus explosive), energy in the chamber. A list of gas energies for chambers of several diameters and initial pressures is given in Table 2 for convenience. It can be seen from this figure that for small amounts of explosive or equivalently where the explosive energy to gas energy is low, generally 5 or less that the projectile velocity increases rapidly with increases in explosive weight. In effect, the addition of the explosive improves the efficiency of the implosion process. It was shown in Ref. 3 that the shock pressure on implosion varied as $r^{-0.64}$ for $\gamma = 1.2$ for cases using gas only, but as $r^{-1.21}$ for explosive driven cases. This first region is in effect a transition region where the implosion process is changing from a "gas-detonation like" process to a truly explosive-driven implosion. It is characterized by a marked improvement in projectile velocity and overall efficiency with explosive weight and thin liners.
For moderate amounts of explosive, but for liners that can still be considered thin, the projectile velocity varies as the square root of the total energy (or explosive energy since generally the contribution of the gas energy is now small), as predicted by Ref. 3. From another point of view, the projectile kinetic energy becomes a fixed percentage of the total energy in the chamber and increasing the energy results in a corresponding increase in projectile velocity (Fig. 22). It is seen that for the 1000 psia cases that this region becomes compressed between the first and third regions. As the initial pressure is reduced this linear region emerges from between the other two as is evident from the 100 and 200 psia data.

Increasing the explosive weight further results in liners which have a significant fraction of the chamber radius and the pressure profiles gain an additional peak. On first entering this regime the peak pressures begin to decrease while the projectile velocity continues to increase. However, as one gets well into this regime the velocity actually decreases. It will be shown below that this early nonlinear region can be exploited to advantage.

A scale of overall efficiency (Fig. 23) defined as the ratio of the kinetic energy of the projectile to the total energy in the chamber is included for reference. It can be seen from this overlay that the overall efficiency improves initially as the explosive weight is increased and reaches a maximum depending on initial pressure. Further increases in explosive weight are nearly at constant efficiency after which efficiency beings to fall as the explosive liner beings to get "thick".

For completeness, the predicted performance of this size of chamber, as calculated using the semi-analytical model developed in Ref. 3, is also included. It is clear that this simple model, while not adequate for predicting precise values of projectile velocity (the predicted values are generally high by 20 percent) does indicate the trends of the first two regimes rather faithfully. At higher explosive loadings, the simple model does not predict the drop in velocity with increased explosive weight. As this model assumed a thin explosive liner, the failure to predict this third region can be understood in retrospect.

Plotted in Figs. 24 and 25 are the data for the 25.4-cm. radius cases. The same general features are observed for this size as were seen in the previous larger chamber. From Figs. 22 and 24 it can be seen that the maximum in explosive efficiency occurs at a lower explosive weight than the peak in velocity.

5. OPTIMUM CASE

5.1 Design Condition

The optimum condition can be obtained using the data given in Section 4 by straightforward inspection of the various figures. For example, a comparison of the projectile-velocity maxima (Figs. 22 and 24) versus explosive weight for the two chamber sizes indicates the 38.1-cm. radius chamber is better. A larger chamber is expected to be even more favorable. However, as noted previously the 38.1-cm. radius (30-in. diameter) chamber will result in about the largest forging that can be handled by presently available equipment, hence the design radius was fixed at 38.1 cm.

Figure 22 also demonstrates the superiority of low initial pressures. As noted in Section 3, initiation at the front surface, which was assumed
throughout this study, is not possible unless the initial pressure is of the order of 200 psia, hence the initial pressure is presently arbitrarily fixed at the "initiation limit" of 200 psia. As noted, improvements in performance are predicted if the explosive can be made to initiate at the explosive/gas interface at lower pressures.

The remaining two design criteria, peak projectile base pressures and explosive weights must be considered together. If any base pressure could be tolerated, then as can be seen from Fig. 19, 50,000 g of PETN at a density of 0.588 g/cc would yield ~60,000 fps. Or the same amount of explosive at a density of 1.5 g/cc would yield 108,000 fps. However this is not possible with present day materials. A much more realistic optimum, having a local maximum of 49,500 fps occurs at 25,000 g. The corresponding two base pressure peaks are almost equal, (160 and 180 kbars) and are nearly a minimum for this explosive range. Increasing the explosive weight above 25,000 g decreases the peak pressures slightly but also decreases the projectile velocity. Decreasing the explosive weight increases the peak pressures but also decreases the projectile velocity. It might be argued that explosive weights in the range 15,000 to 30,000 g are equally attractive as the velocity curve is relatively flat. According to the data, going to 35,000 g decreases the peak base pressures even further. However, the velocity is beginning to fall off rapidly.

In practice, which weight is chosen as a design condition will depend heavily on reaching a compromise between the difficulty of trying to insure an intact projectile and that of designing a chamber to contain the explosive. The projectile integrity is the more serious problem of the two. Therefore, the 25,000 g case is desirable. The design parameters for this case are summarized in Table 3.

5.2 Detailed Calculations

Various pressure-time histories necessary for the detailed design of the chamber and barrel can now be presented based on the previously determined optimum. Shown in Fig. 26, for example, is the pressure history at the explosive/metal interface. It can be seen that the detonation wave in the explosive arrives at the explosive/metal interface at ~ 100 microseconds after initiation of the cycle. A sharp front pulse is experienced that has a maximum pressure of 5.8 x 10^4 bars. Subsequently, the pressure decays in a logarithmic manner to 1.1 x 10^3 bars at 300 microseconds. The reflected shock arrives at the wall at this time and the pressure increases to 1.35 x 10^4 bars. This pulse in turn also decays and a pattern of peaks and valleys is produced with the peaks decreasing, the cycle increasing in period, and the pressure profile generally "smoothing out" with time. This decaying cyclic pattern should be kept in mind in the design of the chamber block to prevent destructive fracture.

Shown in Fig. 27 is the pressure experienced by the explosive/metal interface versus time from reflection of the detonation wave in the explosive plotted in logarithmic coordinates. From ideal explosion theory, i.e., the explosive liner is thin and planar considerations hold, the pressure should decay as \( t^{-2/3} \). After an initial transient region, which occurs due to the finite pressure that can be generated by a real explosive, the data follows this relation. For an ideal explosive the pressures increase without bound as time approaches zero. As the packing density of the explosive increases, say from 0.588 g/cc to 1.5 g/cc the pressures tend to follow the ideal slope to shorter and shorter times indicating that much higher pressures will be felt by the
wall for the higher density explosive. For long times, the two data curves approach one another since they have essentially the same total energy. From this example one of the possible performance compromises can be seen. For example, the projectile velocity can be increased, virtually without limit by increasing the density of the explosive. However, the peak pressures experienced by the projectile and the containing vessel also increase. For this particular case, 108,000 fps can be obtained by using the higher density explosive but at an increase of projectile base pressure and wall pressure by about one order of magnitude. This point should be kept in mind as a possible means of increasing launcher performance if projectile strengths and chamber limits can be improved. For the present the low density PETN is to be preferred since it minimizes the peak projectile base pressure and chamber pressure while maintaining an acceptably high muzzle velocity.

In Fig. 28 is shown the total force on the breech block as a function of time for the 38.1 cm. radius chamber. In the computer code the initial pressure ahead of the gaseous detonation wave is set equal to zero, hence the calculation shows zero pressure at zero time. The minimum load on the block is actually 1.42 x 10^5 pounds and occurs when the chamber is loaded with the 200 psia initial charge of stoichiometric oxygen-hydrogen. From the figure it is seen that the load increases to 5.0 x 10^5 pounds as the gaseous detonation wave propagates outward and loads the block with the pressure behind the detonation wave. The area of contact is described by a circle with a radius that increases at constant velocity. The explosive liner is reached and begins to detonate at t ~ 80 microseconds. The total load increased rapidly and reaches a local maximum of 35 x 10^6 pounds as the explosive is completely consumed at t ~ 100 microseconds. The total load remains approximately constant, decreasing slowly and then recovering during the implosion phase of the cycle. After the implosion wave reflects from the origin the load increases further as the high pressures behind the reflected implosion act over an increasing area as the reflected shock moves outward from the origin. When the shock reaches the hemispherical wall the load reaches an absolute maximum of 1.51 x 10^8 pounds. Subsequently the load decays slowly showing evidence of relatively weak waves that continually reflect in the chamber. The projectile exits the barrel at t ~ 472 microseconds. The details of the load are shown only through 750 microseconds. The calculations were carried through 4600 microseconds and show loads no higher than 60 x 10^6 pounds nor lower than 35 x 10^6 pounds. For design purposes it might be sufficient to represent the total load by a constant load of 50 x 10^6 pounds on which is superimposed a triangular pulse of half width of 35 microseconds and a peak of 150 x 10^6 pounds.

Shown in Fig. 29 are the pressure-distance profiles experienced by the barrel at various instants of time for the design case. It can be seen that for the first few centimeters of barrel the pressure is subject to rapid fluctuations. As the projectile is accelerated down the barrel, the pressure profiles tend to become more uniform and approach a "limiting" profile. At later times, 1942 microseconds for example, the pressure profile is essentially that given by the profile at 366 microseconds. It can be appreciated from the figure that the pressure in the first few tens of centimeters are generally in excess of the elastic yield strengths of most materials and barrel design must be based accordingly.

6. CONCLUSIONS AND RECOMMENDATIONS

A number of important results and conclusions can be drawn from this study. The optimum implosion-driven system for launching a 1.0-in. dia., one-calibre projectile has been determined and analysed. It has been shown that limitations
on the maximum size of forgings that can presently be manufactured limits the hemispherical chamber diameter to 76.2 cm., (30 in.), although larger sizes may be more desirable. Explosive initiation characteristics also require a minimum initial loading pressure of 200 psia, although lower pressures would be advantageous. The optimum explosive weight has been determined to be 25,000 g of PETN at a density of 0.588 g/cc. This weight exploits a favorable decrease in peak projectile base pressure while maintaining an acceptable projectile velocity to minimize the projectile integrity problem.

There are several other important results. The ideal operating characteristics of this type of launcher and the physical basis for some effects have been demonstrated. The study shows that there are three operating regimes for this type of launcher: a region where the ratio of the explosive energy to gas energy is small, i.e., \( \leq 5 \). In this region the projectile velocity and the overall efficiency increase markedly with increasing explosive weight. In a second region, the ratio of explosive energy to gas energy is large, i.e., \( \leq 15 \), but the explosive layer is thin by comparison to the chamber radius. In this region the projectile velocity varies as the square root of the energy in the chamber, i.e., the projectile kinetic energy becomes a fixed fraction of the total energy in the chamber, and the overall efficiency has a maximum. A third nonlinear region occurs when the explosive liner thickness becomes a significant fraction of the chamber radius (0.1 \( \leq t/R_o \leq 0.35 \), see Ref. 4). In this region the projectile velocity reaches a maximum and then decreases with increasing explosive weight. The "optimum" performance for the present constraints occurs in this region (\( t/R_o = 0.14 \); explosive-to-gas energy ratio = 20.0; see Table 1).

It is very important to note that the details of the wave diagrams determined by this study are a direct consequence of the assumption that the explosive initiates at the explosive/gas interface. If the explosive were to initiate at the explosive/metal interface or uniformly everywhere in a manner approximating constant volume combustion then very different wave systems would be produced with entirely different results. For thin explosive layers there is probably very little difference between the two modes of initiation. For thick layers the difference will become increasingly important. It is recommended that explosive/metal interface and constant volume combustion initiation modes by investigated using the present numerical code, as it is possible that these modes of initiation might be encountered in practice either intentionally or accidentally.

It is strongly recommended that efforts be made to incorporate loss mechanisms, particularly radiative and ablative losses into this program as they will probably have a substantial effect on the performance and on the determination of an optimum configuration.

Further it appears that efforts to reduce the initial pressure at which explosives will initiate would be profitable, as increased performance is predicted for lower initial pressures.

Finally, it must be kept in mind in using the data obtained in this study, that as no losses were included the velocities predicted represent those obtainable in an ideal situation and as such represent an upper bound on velocities that can be obtained in practice.
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Driven Shock Tube. UTIAS Technical Note (to be 
published).
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$E_0 = 1.255 \text{ kcal/g } @ \rho = 0.588 \text{ g/cc}$

$E_0 = 1.415 \text{ kcal/g } @ \rho = 1.5 \text{ g/cc}$
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Energy given in Kcal

*based on a 10.0 cm hemisphere at 100 psia equalling 22.4 Kcal (Ref. 3)
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APPENDIX A

Complementary Data

The results for the individual runs discussed in the body of this report are collected herein. In addition, pressures at the origin are plotted versus projectile positions. They represent the origin pressure at the instant of time that the projectile appears at a given position. These results are included for completeness and to allow for further analysis if desired. Complete numerical printouts have been filed at UTIAS and are available for further work.

The figures in this appendix are arranged according to run number, i.e., HL-3, HL-4, etc. The case corresponding to each run number can be determined from Table 1. Run numbers HL-1, HL-5, HL-6, HL-8 are nonexistant. They were dropped from the original program as being redundant.
The Influence of the Number of Zones on the Numerical Results

Owing to the limited storage capability of the IBM 1130 computer at UTIAS, the maximum number of zones permitted in the calculations of this report was 10 in the explosive and 20 in the gas. Calculations made by Sevray using 65 zones did not compare favourably with results obtained in this report, indicating that the smaller number of mass points was inadequate. To investigate this discrepancy in results, the run HL-10 was duplicated on the IBM 7094 machine using 65 zones. The results of this calculation are compared with the corresponding data from the IBM 1130 in Figures B-1 and B-2.

The major difference in the two runs is a higher shock velocity obtained with the smaller number of zones, causing the implosion to occur earlier (~160 µsec compared with 208 µsec). Furthermore, it may be seen from Figure B-1 that while the pressures of the first pulse on the projectile are comparable, the second pulse is considerably weaker when more zones are used.

An unexpected result of the run with an increased number of zones was the appearance of marked instabilities in the projectile base pressure profile when the gas is expanding. Although there is some indication of these pressure fluctuations in the earlier runs, the problem appears to be aggravated by the reduction in zone size. These instabilities occur because of the small mass of the last gas zone relative to the adjacent gas zone (a mass ratio of 6 approx.). Thus the smaller gas zone is "sandwiched" between two heavy zones (one of which is the projectile) which react slowly to changes in pressure in the small zone. Consequently, fluctuations in pressure about a mean value are created in the gas zone next to the projectile.

The solution to such a problem is to eliminate or at least reduce, the disparity in mass between two adjacent gas zones, either by having equal mass zones around the origin, or by increasing the mass of successive zones by a small percent (10% or less) as one moves away from the origin towards the periphery.

Figure B-2 gives projectile velocity versus position for the two runs. With the larger number of zones the final projectile velocity is smaller because of the weakened second pulse ($v_f = 12.1$ km/sec for 65 zones, compared with 13.4 km/sec for 30 zones). Figure B-2 also indicates that the total impulse supplied by the first implosion is evidently higher when more zones are used.

From this comparison run, one may conclude that the results presented in the body of the report must be taken as reasonable values of pressures and velocities, rather than accurate predictions of these parameters. This is true, of course, even if more zones are used, since the computations do not include any loss mechanisms, such as radiative or ablative losses.

A critical discussion can be found in Ref. 17. The entire numerical computational procedures are presently being reevaluated.

J.C. Poinssot
1A IGNITION PHASE
A GASEOUS DETONATION WAVE PROPAGATES OUTWARD FROM THE ORIGIN IN A $2H_2 + O_2$ MIXTURE

1B IMPLOSION PHASE
THE DETONATION WAVE IGNITES THE EXPLOSIVE LINER WHICH IN TURN GENERATES A STRONG IMPLODING WAVE

1C REFLECTION PHASE
THE IMPLOSION WAVE REFLECTS FROM THE ORIGIN LEAVING A REGION OF HIGH PRESSURE - HIGH TEMPERATURE GAS WHICH BURSTS THE DIAPHRAGM AND ACCELERATES THE PROJECTILE

FIGURE 1 SCHEMATIC OF THE PRINCIPLE OF OPERATION OF THE IMPLOSION DRIVEN HYPERVELOCITY LAUNCHER
FIGURE 2

STUDY MODEL OF THE 30 INCH INSIDE DIAMETER MK II IMPLOSION DRIVEN HYPERSONIC VELOCITY LAUNCHER
FIGURE 3
ZONE WIDTH AND MASS FOR VARIOUS ZONING SCHEMES
n=20
4a) PIACESI'S METHOD

only 3 discrete values

4b) SEVRAY'S METHOD

infinite no. of possible values

4c) PRESENT METHOD

FIGURE 4 SCHEMATIC OF METHODS OF APPROXIMATING THE SPHERICAL-PLANER TRANSITION
FIGURE 5
PROJECTILE BASE PRESSURE VERSUS TIME FROM INITIATION FOR A 38.1 CM RADIUS HEMISPHERE-INITIAL PRESSURE = 200PSIA
2H₂ + O₂

TIME FROM INITIATION (microsec)

PROJECTILE BASE PRESSURE (bars)

10⁶
10⁵
10⁴
10³
10²
0

HL-10
W = 25.000GM

HL-4
W = 50.000GM

HL-3
W = 10.000GM

HL-2
W = 1.000GM
FIGURE 6
PROJECTILE VELOCITY VERSUS PROJECTILE POSITION FOR A 38.1 CM RADIUS HEMISPHERE
INITIAL PRESSURE = 200 psia 2H₂ + O₂
FIGURE 7
EXPLOSIVE LINER THICKNESS
VERSUS EXPLOSIVE WEIGHT
FOR 25.4 CM AND 38.1 CM
RADIUS HEMISPHERES

\[ d = 1.86 \times 10^{-4} \text{ W} \]
\[ R = 25.4 \text{ cm (10.0")} \]

\[ d = 4.20 \times 10^{-4} \text{ W} \]
\[ R = 38.1 \text{ cm (15.0")} \]

\[ \rho_{\text{exp}} = 0.588 \text{ g/cc} \]
FIGURE 8
PROJECTILE BASE PRESSURE VERSUS TIME FROM INITIATION FOR A 38.1CM. RADIUS CHAMBER - INITIAL PRESSURE = 100PSIA
2H₂+O₂

PROJE E TLS E PRE S S URE VER SUS TIME FROM INITIATION FOR A 38.1CM. RADIUS CHAMBER - INITIAL PRESSURE = 100PSIA
2H₂+O₂
FIGURE 11
PROJECTILE VELOCITY VERSUS PROJECTILE POSITION FOR A 38.1 CM RADIUS HEMISPHERE
INITIAL PRESSURE 1000 PSIA \(2H_2 + O_2\)

- HL-9: \(W = 25,000 \text{ GM}\)
- HL-7: \(W = 10,000 \text{ GM}\)
- HL-11: \(W = 50,000 \text{ GM}\)
FIGURE 12
PROJECTILE BASE PRESSURE VERSUS TIME FROM INITIATION FOR A 25.4 CM RADIUS HEMISPHERE - INITIAL PRESSURE = 100 PSI
$2H_2 + O_2$
FIGURE 13
PROJECTILE VELOCITY VERSUS PROJECTILE POSITION FOR A 25.4 CM RADIUS HEMISPHERE INITIAL PRESSURE 100 psia 2H₂ + O₂
FIGURE 14
PROJECTILE BASE PRESSURE VERSUS TIME FROM INITIATION FOR A 25.4 CM RADIUS HEMISPHERE - INITIAL PRESSURE=200 PSIA

- HL-17
  W=10,000 GM

- HL-18
  W=5,000 GM

- HL-19
  W=1,000 GM

TIME FROM INITIATION (microsec)
FIGURE 15
PROJECTILE VELOCITY VERSUS PROJECTILE POSITION FOR A 25.4 CM RADIUS HEMISPHERE
INITIAL PRESSURE 200psia 2H₂ + O₂

- HL-18
  W=5,000 GM
- HL-17
  W=10,000 GM
- HL-19
  W=1,000 GM
FIGURE 16
PROJECTILE BASE PRESSURE VERSUS TIME FROM INITIATION FOR A 25.4 CM RADIUS HEMISPHERE - INITIAL PRESSURE 1000 PSIA

TIME FROM INITIATION (microsec)

PROJECTILE BASE PRESSURE (bars)

10^3
10^2
10
1
10^{-1}

HL-21
W=10,000 GM

HL-20
W=5,000 GM
FIGURE 17
PROJECTILE VELOCITY VERSUS PROJECTILE POSITION FOR A 25.4 CM RADIUS HEMISPHERE INITIAL PRESSURE 1000 PSIA $2H_2 + O_2$
FIGURE 18
PEAK PROJECTILE BASE PRESSURE VERSUS EXPLOSIVE WEIGHT, INITIAL PRESSURE = 100 PSIA
Figure 19
Peak Projectile Base Pressure versus Explosive Weight, Initial Pressure = 200 psia
FIGURE 20
PEAK PROJECTILE BASE PRESSURE VERSUS
EXPLOSIVE WEIGHT, INITIAL PRESSURE = 1000 PSIA
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<th>PROJECTILE BASE PRESSURE HISTORY</th>
<th>WAVE DIAGRAM</th>
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| Transition (gas driven to explosive driven) | Improving efficiency  
Thin explosive liner  
Low velocity  
Single pressure pulse | ![Pressure vs Time](chart1) | ![Wave Diagram](chart2) |
| Linear (true explosive driven) | Peak efficiency  
Thin explosive liner  
Moderate to high velocities  
Single pressure pulse | ![Pressure vs Time](chart3) | ![Wave Diagram](chart4) |
| Non Linear               | Decreasing efficiency  
Thick explosive liner  
Peak velocities  
Double pressure pulse | ![Pressure vs Time](chart5) | ![Wave Diagram](chart6) |

**Figure 21** Schematic diagram of the operating regimes of an implosion driven hypervelocity launcher (see also Ref. 4)
**Figure 22**

**Projectile Velocity and Energy versus Explosive Weight or Energy for the 38.1 cm Radius Hemisphere Cases**

- Explosive Energy: $10^3$ to $10^5$ kcal
- Explosive Weight: $10^3$ gm to $10^5$ gm

- Projectile Velocity: $10^3$ ft/sec to $10^6$ ft/sec

- Explosive Efficiency:
  - 0.1%
  - 1%
  - 10%
  - 100%

- Notes:
  - $v \propto V^{1/2}$
  - $6.83 \times 10^4$ g (Maximum weight for $\rho = 0.588$ g/cc)
  - $p = 0.588$ g/cc
  - $p = 1.5$ g/cc
  - REF. 4

- Symbols:
  - △ 100 PSI
  - ○ 200 PSI
  - □ 1000 PSI
  - • 200 PSI $\rho = 1.5$ g/cc
  - ◊ REF. 4
FIGURE 23
PROJECTILE VELOCITY AND ENERGY VERSUS TOTAL ENERGY FOR THE 38.1 CM RADIUS HEMISPHERE CASES

EXPLOSIVE WEIGHT = 50 KG

SEMI-ANALYTICAL PERFORMANCE MODEL; 200 psia REF. 3

OVERALL EFFICIENCY

PROJECTILE VELOCITY (ft/sec)

PROJECTILE ENERGY (kcal)
FIGURE 24
PROJECTILE VELOCITY AND ENERGY VERSUS EXPLOSIVE WEIGHT OR ENERGY FOR THE 25.4 CM RADIUS HEMISPHERE CASES
FIGURE 25
PROJECTILE VELOCITY AND ENERGY VERSUS TOTAL ENERGY FOR THE 25.4 CM RADIUS HEMISPHERE CASES

OVERALL EFFICIENCY

EXPLOSIVE WEIGHT

TOTAL ENERGY (kcal)

VELOCITY (ft/sec)

PROJECTILE ENERGY (kcal)
Figure 27
Pressure at the Explosive-Metal Interface as a Function of Time for the Design Case

\[ P \propto t^{-2/3} \]
Figure 28
Total force on the breech block vs time from initiation.

EXPLOSIVE INITIATES

MINIMUM LOAD AT 200 PSIA

INSTANT OF IMPLOSION

EXPLOSIVE COMPLETELY DETONATED

REFLECTION FROM CONTACT SURFACE

REFLECTION FROM OUTER WALL

PROJECTILE EXITS BARREL

30" DIA CHAMBER
200 PSIA 2H₂ + O₂
25 KGS PETN @ 0.588 G/CC

MIN & MAX TO t = 4600 μsec
FIGURE 29
PRESSURE-DISTANCE PROFILES OF THE GAS IN THE BARREL AT SEVERAL INSTANTS OF TIME

ENTRANCE TO BARREL OCCURS AT 38.1 CM

DESIGN CASE

\[ R_0 = 38.1 \text{ cm} \]
\[ W = 25,000 \text{ g} \]
\[ P_1 = 200 \text{ psia} \]
FIGURE A-1
RUN NO. HL-2
$R_0 = 38.1$ cm.
$P_x = 200$ psia $\text{H}_2 + \text{O}_2$
$W = 1000$ g. PETN
FIGURE A-2
RUN NO. HL-3
$R_0 = 38.1 \text{ cm.}$
$p_x = 200 \text{ psia } 2H_2 + O_2$
$W = 10,000 \text{ g. PETN}$
FIGURE A-3
RUN NO. HL-4
$R_o = 38.1\, cm.$
$p_x = 200\, \text{psia} \ 2H_2+O_2$
$W = 50,000\, g. \ \text{PETN}$
FIGURE A-4
RUN NO. HL-7
\( R_o = 38.1 \text{ cm} \)
\( p_x = 1000 \text{ psia} \)
\( W = 10,000 \text{ g PETN} \)
FIGURE A-5

RUN NO. HL-9

$R_o = 38.1 \text{ cm}$

$p_x = 1000 \text{ psia}$

$2H_2 + O_2$

$W = 25,000 \text{ g PETN}$
FIGURE A-6
RUN NO. HL-10
$R_o = 38.1\text{ cm.}$
$p_x = 200\text{ psia } 2H_2 + O_2$
$W = 25,000\text{ g. PETN}$
FIGURE A-7
RUN NO. HL-11
$R_o = 38.1$ cm.
$p_o = 1000$ psia
$2H_2 + O_2$
$W = 50,000$ g. PETN

PROJECTILE VELOCITY
PROJECTILE BASE PRESSURE
ORIGIN PRESSURE

PRESSURE (bars)

PROJECTILE POSITION (cm)
FIGURE A-8
RUN NO. HL-12
$R_o = 38.1\, \text{cm.}$
$p_x = 200\, \text{psia} \quad \text{2H}_2 + \text{O}_2$
$W = 50,000\, \text{g. PETN}$
$\rho = 1.5\, \text{gm./cc}$
FIGURE A-9
RUN NO. HL-13
$R_0 = 38.1 \text{ cm.}$
$p_x = 100 \text{ psia } 2\text{H}_2 + \text{O}_2$
$W = 10000 \text{ g. PETN}$
FIGURE A-10
RUN NO. HL-14
$R_0 = 38.1$ cm.
$p_f = 100$ psia $2H_2 + O_2$
$W = 25,000$ g. PETN

ORIGIN PRESSURE

PROJECTILE VELOCITY

PROJECTILE BASE PRESSURE

PRESSURE (bars)

PROJECTILE VELOCITY (km/sec)

PROJECTILE POSITION (cm)
FIGURE A-11
RUN NO. HL-15
$R_0 = 38.1 \text{ cm.}$
$p_i = 100 \text{ psia}$
$2\text{H}_2 + \text{O}_2$
$W = 50,000 \text{ g. PETN}$
FIGURE A-12
RUN NO. HL-16
$R_o = 38.1$ cm.
$p_i = 100$ psia $2H_2 + O_2$
$W = 5,000$ g. PETN

PROJECTILE POSITION (cm)
PRESSURE (bars)
PROJECTILE VELOCITY (km/sec)
ORIGIN PRESSURE
PROJECTILE BASE PRESSURE
FIGURE A-13
RUN NO. HL-17

$R_s = 25.4$ cm.

$p_i = 200$ psia $2H_2 + O_2$

$W = 10,000$
FIGURE A-14
RUN NO. HL-18
$R_0 = 25.4$ cm.
$p_1 = 200$ psia $2H_2+O_2$
$W = 5,000$ g. PETN
FIGURE A-15
RUN NO. HL-19
$R_o = 25.4$ cm.
$p_i = 100$ psia $2H_2 + O_2$
$W = 5,000$ g. PETN

PROJECTILE POSITION (cm)

PRESSURE (bars)

PROJECTILE VELOCITY

PROJECTILE BASE PRESSURE

ORIGIN PRESSURE

PROJECTILE VELOCITY (km/sec)
FIGURE A-16

RUN NO. HL-20

$R_0 = 25.4 \text{ cm.}$

$p_i = 1,000 \text{ psia}$ $2H_2 + O_2$

$W = 5,000 \text{ g. PETN}$
FIGURE A-17
RUN NO. HL-21
$R_o = 25.4 \text{ cm.}$
$p_i = 1000 \text{ psia}$
$W = 10,000 \text{ g. PETN}$
FIGURE A-18
RUN NO. HL-22
R_0 = 25.4 cm.
p_0 = 100 psia 2H_2 + O_2
W = 5,000 g. PETN
FIGURE A-19
RUN NO. HL-23
$R_0 = 25.4$ cm.
$p_i = 1,000$ psio $2H_2 + O_2$
$W = 10,000$ g. PETN
FIG. B-1 PROJECTILE BASE PRESSURE VERSUS TIME
25 KG. PETN/ 200 PSI $2\text{H}_2+\text{O}_2$

- 30 (10 IN PETN; 20 IN GAS) ZONES, $V_{proj} = 13.4$ KM/SEC AT 200 CM.
- 65 (25 IN PETN; 40 IN GAS) ZONES, $V_{proj} = 12.1$ KM/SEC AT 200 CM.
- SEVRAY, 65 (25 IN PETN; 40 IN GAS) ZONES (REF 4)
FIG. B-2  PROJECTILE VELOCITY VERSUS PROJECTILE POSITION
25 KG. PETN / 200 PSI 2H₂ + O₂

- 30 ZONES
- 65 ZONES
- SEVRAY (REF 4)