THE MK II UTIAS IMPLOSION-DRIVEN HYPERVELOCITY LAUNCHER

DESIGN ANALYSIS

by

V. C. D. Dawson, R. A. Waser and D. O. Oakes

March, 1970.

UTIAS Technical Note No. 147
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Manuscript received August, 1969.

March, 1970. UTIAS Technical Note No.147
ACKNOWLEDGEMENT

Considerable effort was devoted to the design of the MK II Launcher by others and the authors of this report, and the help of Dr. R. F. Flagg, who provided the original analysis and design specifications, Dr. I. I. Glass, who provided helpful discussions and guidance during the design, and Mr. W. Czerwinski, who gave positive constructive criticism of the design, are most gratefully acknowledged. This work was financially supported by the Aerospace Research Laboratory of the United States Air Force under Contract No. AF 33(615)-5313 and the National Research Council of Canada.
SUMMARY

Based on initial experiments carried out on the 8 in dia implosion-driven hypervelocity launcher, as well as on a preliminary design study of a larger launcher facility, the design of a 30 in dia hypervelocity launcher was completed, and a set of detailed workshop drawings has been prepared.

This report describes the basic functioning of the implosion-driven hypervelocity launcher, as well as its mechanical design, operation and firing procedures.

A separate section is devoted to the strength requirements and initial stressing. By using a simple analogy with a spherical pressure chamber, the authors, endeavour to estimate the plastic/elastic stress level, from which some prediction of fatigue life for such a launcher was derived.

The last two sections of this report give some recommendations for the proof-testing of the launcher, as well as some basic aspects regarding safety.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>2.</td>
<td>MECHANICAL OPERATION</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(a) Firing Procedure</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>(b) Barrel and Chamber Plate Disassembly</td>
<td>3</td>
</tr>
<tr>
<td>3.</td>
<td>STRENGTH CALCULATIONS</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(a) Design Specifications</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>(b) Bolt Construction</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>(c) Hemispherical Combustion Chamber</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>(1) Static Analysis</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>(2) Dynamic Analysis</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>(d) Bending and Shear of Frosst Chamber Section</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>(e) Fatigue</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>(f) Recoil Forces</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>(g) Hemispherical Aluminum Shell Requirements</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>(h) Blast Tank Requirements</td>
<td>13</td>
</tr>
<tr>
<td>4.</td>
<td>PROOF TEST PROGRAM</td>
<td>15</td>
</tr>
<tr>
<td>5.</td>
<td>SAFETY</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>(a) Experimental Test Chamber</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>(b) Laboratory Building</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>(c) Operational Safety</td>
<td>17</td>
</tr>
<tr>
<td>6.</td>
<td>CONCLUSIONS</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>REFERENCES</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>FIGURES 1-9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Drawings No. SK-10, SK-14, SK-15</td>
<td></td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
<td></td>
</tr>
<tr>
<td>--------</td>
<td>-------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>Area</td>
<td></td>
</tr>
<tr>
<td>a, b, c</td>
<td>radii (p.11)</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>Young's Modulus</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>force</td>
<td></td>
</tr>
<tr>
<td>k</td>
<td>spring constant</td>
<td></td>
</tr>
<tr>
<td>l</td>
<td>length</td>
<td></td>
</tr>
<tr>
<td>m</td>
<td>reciprocal of Poisson's ratio, $v$</td>
<td></td>
</tr>
<tr>
<td>$m_p$</td>
<td>mass of explosive</td>
<td></td>
</tr>
<tr>
<td>$P_b$</td>
<td>burst pressure</td>
<td></td>
</tr>
<tr>
<td>$P_p$</td>
<td>plastic pressure</td>
<td></td>
</tr>
<tr>
<td>$P_y$</td>
<td>elastic breakdown pressure</td>
<td></td>
</tr>
<tr>
<td>r</td>
<td>radius</td>
<td></td>
</tr>
<tr>
<td>S</td>
<td>combined stress</td>
<td></td>
</tr>
<tr>
<td>$T_s$</td>
<td>tensile strength</td>
<td></td>
</tr>
<tr>
<td>t</td>
<td>wall thickness</td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>velocity</td>
<td></td>
</tr>
<tr>
<td>W</td>
<td>loading force</td>
<td></td>
</tr>
<tr>
<td>$Y_s$</td>
<td>yield strength</td>
<td></td>
</tr>
<tr>
<td>$\epsilon$</td>
<td>strain</td>
<td></td>
</tr>
<tr>
<td>$\nu$</td>
<td>Poisson's ratio</td>
<td></td>
</tr>
<tr>
<td>$\rho$</td>
<td>density</td>
<td></td>
</tr>
<tr>
<td>$\sigma$</td>
<td>normal stress</td>
<td></td>
</tr>
<tr>
<td>$\sigma^*$</td>
<td>residual stress</td>
<td></td>
</tr>
<tr>
<td>$\tau$</td>
<td>shear stress</td>
<td></td>
</tr>
<tr>
<td>$\chi$</td>
<td>deflection</td>
<td></td>
</tr>
<tr>
<td>$\omega$</td>
<td>wall ratio</td>
<td></td>
</tr>
</tbody>
</table>
Subscripts

a  axial direction
b  bolt
o  original conditions
r  radial direction
t  tangential
y  conditions at the yield point
1. **INTRODUCTION**

The UTIAS MK II Implosion-Driven Hypervelocity Launcher is a new larger version of the launcher described in Ref. 1. The general assembly is shown in Fig. 9 and on drawing No. SK 10. It consists of a 15 inch inside radius hemispherical chamber having a nominal outside radius of 33 inches. A barrel with a 1 inch inside diameter is connected into the geometric center of the hemispherical chamber.

The operation of this type of launcher is adequately described in Ref. 2. Basically it consists of detonating a stoichiometric mixture of hydrogen and oxygen at an initial pressure of about 250 psi. This detonation is initiated by an exploding wire at the center of the hemispherical chamber, as shown schematically in Fig. 1. The detonation wave propagates spherically and with sufficient energy to detonate an explosive liner on the inside surface of the chamber. A converging shock wave (implosion) is then propagated back through the high-temperature gases to finally focus at the barrel origin. The theoretically-ideal, infinite pressure initially acting on the projectile is utilized to launch a projectile at high velocity for various types of aerodynamic or impact studies.

The MK II Launcher grew out of the experimental studies made with a smaller (4 inch chamber radius) launcher (Ref.2). The analytical and experimental results with the smaller system indicated that a 15 inch chamber radius in conjunction with a 1 inch barrel would provide optimum conditions for high velocity projectile launching for that calibre (Refs.. 3 and 4).

This launcher operates under explosive loading conditions. As a result, the pressures generated are extremely high with fast rise times. In this respect the implosion-driven launcher is subjected to loading conditions that are considerably more severe than the loading conditions in a conventional hypervelocity, light-gas gun. In fact, the containment of the pressure is possible with state of the art techniques only because of the transient nature of the pulse. Even so the MK II Launcher represents a new generation of hypervelocity guns and its design involves an extension of the state of the art.

This report describes the design philosophy including the calculations and the assumptions upon which they are based. It also contains sections on the Mechanical Operations (2), the Proof Test Program (4), and Safety Recommendations (5).

The general arrangement of the Launcher is shown in Fig. 9 and drawing No. SK 10 and the calculations and recommendations in this report are based upon this configuration. No one associated with the operation of the Launcher should be allowed to operate it until the contents of this report have been read and the design limitations of the Launcher completely understood. Particular attention should be given to the sections of this report devoted to the Proof Test Program and Safety.

2. **MECHANICAL OPERATION**

As indicated in Fig. 9 and on drawing No. SK 10 the Launcher consists of two massive steel sections, that contain the hemispherical chamber. Connected to it is the barrel, which is rigidly connected to a
blast tank at the muzzle end. The blast tank is bolted rigidly to the floor. The two chamber sections are connected together by means of thirty-two, 5 inch diameter bolts which are preloaded sufficiently to prevent any separation of the chamber halves during the firing process. Both chamber sections are mounted upon linear bearings that ride on two, 1.5 inch diameter shafts. When unbolted the aft chamber section can be freely moved on the rails and the same condition applies to the front chamber when the barrel is disconnected from the blast tank.

Preload for the bolts is applied by means of two hydraulic tensioning cylinders which are mounted on a carriage that rotates freely and translates on the same rails on which the chamber is mounted. The tensioning carriage is placed on the rails between the front chamber and the blast chamber (see drawing No. SK 33). An overhead 3-ton chain fall hoist is mounted on a monorail above the centerline of the Launcher.

(a) Firing Procedure

Initial Conditions of Launcher:

The front chamber and barrel are connected as indicated in Fig. 9 (see also drawing No. SK 10) the barrel is connected to the blast tank, and the aft chamber is moved rearward to clear bolts and provide working space between chamber sections, approximately 4 feet. Ignition electrodes and instrumentation are installed in the front chamber plate and suitably interlocked and grounded (see Sec. 5 on Safety). A hemispherical aluminum (or other suitable material) liner, previously lined with explosive in a remote explosive loading room and in its own separate container is brought to the Launcher as shown in Fig. 2. This container is placed on a carriage which permits translation to the front chamber section. The fixture rotates so that the liner can be mated to the front chamber section. The projectile is installed in the barrel.

Loading Procedure:

The liner is rotated and translated manually to engage the sealing slot in the front chamber plate, Fig. 2b. While held in this position, a vacuum is drawn on the inner surface of the liner through the gas loading port until sufficient differential pressure exists to hold the hemisphere in place (see Sec. 3g). The loading fixture is then removed and the aft chamber is translated forward manually until the aft and front chambers are engaged. The nuts are now placed on the bolts and tightened and the hydraulic tensioning carriage moved into position. The bolt preload should be applied in at least two incremental steps, i.e., each bolt is loaded to one-half of its final preload before any single bolt reaches the full preload. This will necessitate two complete rotations of the bolt tensioning cylinders. After the first increment of preload has been applied to two bolts the vacuum system may be shut off. The bolt tightening pattern is shown in Fig. 3.

After the required preload has been applied, the tensioner carriage is moved forward toward the blast tank, the specified gas charge of hydrogen and oxygen is remotely loaded into the chamber and the ignition and instrumentation systems connected into the firing circuit. The Launcher is now ready for firing.
After a shot the procedure outlined above is reversed to disassemble the Launcher. Once the chamber sections have been disengaged and the hemispherical liner removed the following items should be investigated for damage or erosion (see drawing No.SK 10)

1. Chamber Seal
2. Electrode Assembly
3. Gas Loading Port
4. Chamber Plate (SK-16)
5. Barrel and Barrel Liner (SK-17)

If any of these have been damaged, they must be replaced before the next shot can be made. In any event it is recommended that the O-ring between the barrel and chamber plate (see drawing No.SK 10) be replaced after any shot that involves heavy loading conditions.

The only replacement operations that require description are those that involve changing to a new chamber plate or a new barrel.

(b) Barrel and Chamber Plate Disassembly

Initial Condition of Launcher:

As outlined in a.l. above, i.e., the chamber sections are separated sufficiently to provide bolt clearance and working space between the two chambers. This means that the aft chamber section will be as far rearward as the rail system permits.

Procedure: (see SK 10)

a.) Remove the electrode and gas loading assemblies from the forward chamber.
b.) Remove the vacuum seal ring from inside the blast tank.
c.) Remove the bolts fastening the recoil collar to the blast tank, translate the forward chamber section and barrel rearward, and remove the recoil collar from the barrel.
d.) Loosen the nuts on the chamber side of the barrel lock ring. Tighten the nuts on the forward side of the barrel lock ring until the chamber plate and segmented cone loosen. Remove all the nuts and bolts from the barrel lock ring and remove the barrel lock ring from the barrel.
e.) Move the barrel and chamber plate rearward until an eyebolt can be screwed into the tapped hole in the chamber plate. Translate the forward chamber section and barrel as far forward as possible.
f.) Support the chamber plate with the overhead crane using the eyebolt and move the plate and barrel rearward until the assembly is clear of the forward chamber section. Lifting up on the chamber plate will separate the segmented cone and permit the insertion of shims between the cone segments to keep them clear of the barrel.
A new barrel and/or chamber plate are put into the Launcher by reversing the procedure outlined above. For firing, the nuts on both sides of the barrel lock ring must be tight.

As indicated on SK-17, the barrel consists of an outer jacket and a liner. For general use it is expected that only the liner will have to be replaced. It is recommended that at least two barrel assemblies with additional liners be available. In this way one barrel assembly can be used in a test while the other one is being relined.

3. STRENGTH CALCULATIONS

(a) Design Specifications

Based upon the stated operating conditions given in Ref's. 3 and 4, the total force acting on the Launcher front plate and hemispherical chamber is $50 \times 10^6$ lbs. For design purposes it has been assumed that the internal pressure could act out to the vent grooves on the front plate(1) on drawing No. SK-10) so that a total force of

$$F = \left( \frac{33.0}{30.0} \right)^2 \times 50 \times 10^6 = 61 \times 10^6 \text{lbs}.$$ 

has been used in the design calculations.

(b) Bolt Construction

With a design of $61.0 \times 10^6$ lbs and 32 bolts the force due to pretensioning in each bolt is

$$F_b = \frac{61.0 \times 10^6}{32} = 1.90 \times 10^6 \text{lbs}.$$ 

This is a sizeable bolt force and the final bolt size and configuration are shown on drawing No. SK-14. The bolt has been hollow bored as shown, to provide better mechanical properties by means of a reduced wall thickness for heat treatment and to provide higher impact fatigue strength than a conventional bolt. As indicated in Fig.4, it should easily be possible to obtain yield strengths of 150,000 psi and tensile strengths of 175,000 during heat treatment.

The servicibility of the Launcher was an additional constraint and several methods of pretensioning the bolts were considered. These included the following:

1. Heating the bolts to achieve the necessary strain.

2. Using a hydraulic torque wrench and torquing the bolts in a conventional manner.

3. Using a commercial stud pretensioner.

ITEM 1) was discarded because of the high temperatures required (something greater than $500^\circ F$) and because an explosive charge resides in the chamber.
ITEM 2) was discarded because it was felt that a severe galling condition would occur and because the combined stress due to the longitudinal load and the tightening torque becomes excessive. It was decided that the only practical solution for bolts of this size with such a large pretensioning load was to use a commercial stud tensioner.

With such a device the bolt is hydraulically strained the required amount and the nut tightened. The stud tensioner is then released and removed. The only stress acting is the axial stress ((2 on drawing No. SK-10)

\[ \sigma = \frac{1.905 \times 10^6}{(5^2 - 2.5^2)} = 130,000 \text{ psi} \]

\[ \varepsilon = \frac{\sigma}{E} = \frac{130,000}{30 \times 10^6} = 4.33 \times 10^{-3} \text{ in/in} \]

Bolt stretch required = \( \ell \varepsilon = 52 \times (4.33 \times 10^{-3}) = 0.225 \text{ in.} \)

Compressive bearing stress at bolt head ((3) on drawing No. SK-10):

\[ A_{\text{head}} = 0.785 (7.876^2 - 5.5^2) = 25 \text{ in}^2 \]

\[ \sigma_{\text{bearing}} = \frac{1.905 \times 10^6}{25} = 76,200 \text{ psi} \]

Shear stress in bolt head ((4) on drawing No. SK-19):

\[ A_{\text{shear}} = \pi(5) 4 = 62.8 \text{ in}^2 \]

\[ \tau = \frac{1.905 \times 10^6}{62.8} = 30,400 \text{ psi} \]

Maximum combined stress in vicinity of head

\[ S = \frac{\sigma}{2} + \sqrt{\left( \frac{\sigma}{2} \right)^2 + \tau^2} \]

\[ = 65,000 + \sqrt{(65,000)^2 + (30,400)^2} \]

\[ = 136,800 \text{ psi} \]

The nut associated with each bolt is shown on drawing No. SK-15. Head bearing stress ((5) on drawing No. SK-10):

\[ A_{\text{bearing}} = 0.785 (6.876^2 - 5.02^2) = 17.35 \text{ in}^2 \]
\[ \sigma_{\text{bearing}} = \frac{1.905 \times 10^6}{17.35} = 95,400 \text{ psi} \]

Shearing of threads ((6) on drawing No. SK-10):

\[ A_{\text{threads}} = \frac{\pi(5.02)(5.5)}{2} = 43.4 \text{ in}^2 \]

\[ \tau = \frac{1.905 \times 10^6}{43.4} = 44,000 \text{ psi} \]

The yield strength of the nut was intentionally made less than that of the bolt to provide a slight mismatch of hardness and to insure yielding of the nut prior to yielding of the bolt.

### FACTORS OF SAFETY*

<table>
<thead>
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<th></th>
<th>BOLT</th>
<th>Nut</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>(Y_s = 145,000)</td>
<td>(T_s = 168,000)</td>
</tr>
<tr>
<td>(2)</td>
<td>1.12</td>
<td>1.29</td>
</tr>
<tr>
<td>(3)</td>
<td>1.90</td>
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<td>(4)</td>
<td>2.31</td>
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</tbody>
</table>

* Shear strengths are assumed to be one-half of the associated tensile strengths.

NOTE: The pretensioning of the bolt will require a force greater than \(1.905 \times 10^6\) lbs. for each bolt because of subsequent relaxation of the bolt and bolted pieces. The manufacturer estimates a 12% overload during pretensioning. Therefore during this phase of the operation the bolt stress will be \(1.12 \times 130,000 = 145,000\) psi but it will relax to 130,000 psi.

(c) Hemispherical Combustion Chamber

1. Static Analysis (Ref.5)

The tremendous pressures generated in the implosion Launcher cause the hemispherical chamber to become plastic during firing. The plastic zone may progressively advance with continued firing. Ultimately the chamber could have a residual stress distribution similar to a chamber of similar size that has been autofrettaged in a conventional manner, i.e., by statically pressurizing the chamber at a pressure level sufficient to cause plastic yielding throughout the entire thickness.

While the implosion launcher chamber does not have complete spherical symmetry it has been analyzed statically using the equations applicable to a sphere in order to gain some insight into the residual stress pattern that might be expected to occur.
Based upon the Distortion Energy theory of failure, the elastic breakdown pressure is

\[ P_y = \frac{2Y_o}{3} \left( \frac{\omega^3 - 1}{\omega^3} \right) = \frac{2(125,000)}{3} \left( \frac{9.64}{10.64} \right) \]

\[ = 75,400 \text{ psi} \]

This represents the pressure at which the inner surface of the chamber may be expected to begin yielding.

The pressure required to cause full over-strain, i.e., for the wall to be fully plastic

\[ P_P = 2Y_o \ln \omega = 2(125,000) \ln 2.2 \]

\[ = 197,000 \text{ psi for a perfectly elastic-plastic material.} \]

Burst pressure

\[ P_b = 2Y_o \ln \left[ \omega \left(2 - \frac{Y_o}{T.S.} \right) \right] \]

\[ = 2(125,000) \ln \left[ 2.2 \left(2 - \frac{125,000}{150,000} \right) \right] \]

\[ = 236,000 \text{ psi} \]

The burst pressure is the maximum pressure which the chamber may be expected to take under static conditions without rupturing.

As a result of plastic flow in the wall, residual stresses will be established upon pressure release. For the case where the entire wall goes plastic, these residual stresses will be

\[ \sigma^*/Y_o = 1 + 2 \ln \frac{r/a}{\omega} - \frac{2 \ln \omega}{\frac{3}{3-1} + \frac{\omega^3 \ln \omega}{(\omega^3 - 1)(r/a)^3}} \]

\[ \sigma^*/Y_o = 2 \ln \frac{r/a}{\omega} + \frac{2 \ln \omega}{\frac{3}{3-1} + \frac{\omega^3 \ln \omega}{(\omega^3 - 1)(r/a)^3}} \]

If the chamber did not have a limiting compressive yield strength
the residual stress distribution, as given by the equations above, would look like the curves shown on Fig.5. However, the yield condition for the sphere is $\sigma^* / \sigma_0 = (\sigma^* - \sigma_0^*) / \sigma_0$ and the value of $\sigma^*$ at the inside radius is zero. Thus when $\sigma^*/\sigma_0$ becomes greater absolutely than 1, the inside surface will begin to yield in compression. The limiting wall ratio for a sphere that has gone fully plastic during initial pressurization and has residual stresses which combine to put the inside surface just at the yield point in compression is given by the equation

$$\ln \omega = \frac{2(\omega^3 - 1)}{3 \omega^3}$$

which, when solved, gives $\omega = 1.7$ (compared to 2.22 for a cylinder). Thus it is possible that the implosion launcher chamber will eventually have a residual stress distribution as shown on Fig.6 and that there will be a small re-yielded zone which is plastic.

2. Dynamic Analysis

References (7) and (8) are concerned with the propagation of stress waves into an infinite medium under the action of a short duration high pressure pulse. Reference (7) employs a one-dimensional approach and investigates the propagation of a plastic front when the pressure pulse propagates through a 10 cm liner of either lead or copper and then into the iron medium. Reference (8) considers the propagation of a stress wave into an infinite medium with a short duration pressure pulse applied to a spherical cavity within the medium. In both cases the calculations indicate that the zone of plasticity will extend from 8 to 11 inches into the wall of the chamber for a pressure pulse similar to that expected in the Implosion Launcher.

During the design phase of the Implosion Launcher a simplified analysis of this problem was made by the designers. This analysis was based on the following assumptions:

1. Uniaxial yield strength of chamber - 125,000 psi
2. Plane strain conditions
3. Hugoniot properties similar to those given for Armco iron in reference (7)
4. Stress waves decay inversely proportional to penetration distance squared
5. Pressure pulse as given in reference (4)
6. No liner was considered

Based upon these assumptions it was calculated that the plastic zone would extend into the chamber material approximately 9 inches, i.e., to a radius of 24 inches or a wall ratio of 1.6. If a static pressure of 169,000 psi were applied to a spherical chamber constructed of a material with a yield strength of 125,000 psi the plastic zone would extend to a wall ratio of
1.6. The residual stress distribution would be as shown in Fig.7.

(d) **Bending and Shear of Front Chamber Section**

The thickness of the outer diameter of the plate is 24 inches - that of the inner section is 24.5 inches. Hence, the plate is essentially uniform in thickness with the centre simply displaced forward. We shall therefore treat it as a flat plate 24 inches thick, simply supported at a diameter midway between the bolt circle diameters, and line loaded on a diameter at the midpoint of the bearing area of the conical segments. The whole diameter will be taken at the point of maximum stress, i.e., the front surface where D = 8 inches.

\[ a = \frac{3}{4}" \]
\[ b = \frac{1}{4}" \]
\[ c = 25.5" \]
\[ d = 12" \]
\[ t = 24" \]
\[ W = 61 \times 10^6 \text{ lbs} \]

From Roark (Ref.10), case 16

\[
S_{\text{max}} = - \frac{3W}{2\pi t^2} \left[ \frac{2a^2(m+1)}{a^2 - b^2} \ln \frac{c}{d} + (m-1) \frac{c^2 - d^2}{a^2 - b^2} \right]
\]

\[
S_{\text{max}} = \frac{3W}{2\pi(3.3)(24)^2} \left[ \frac{(2)(34)(4.3)}{(34)^2 - (4)^2} \ln \frac{25.5}{12} + (2.3) \frac{(25.5)^2 - (12)^2}{(34)^2 - (4)^2} \right]
\]

\[
S_{\text{max}} = \frac{3W}{11,970} \left[ \frac{9940}{1140} (.754) + (2.3) \frac{506}{1140} \right]
\]

\[
S_{\text{max}} = \frac{3W}{11,970} \left[ 6.56 + 1.02 \right] = \frac{22.74 W}{11,970}
\]

\[
S_{\text{max}} = 1.9 \times 10^{-3} W = (1.9 \times 10^{-3})(61 \times 10^6) = 116,000 \text{ psi}
\]

Shear at inner bolt circle diameter

\[
\text{Area} = (\pi D - 16 \times \text{bolt dia}) t
\]
\[
= (44\pi - 16 \times 5) 24
\]
\[
\text{Area} = (138 - 80) 24 = 1390 \text{ in}^2
\]

\[
\sigma = \frac{61 \times 10^6}{1390} = 44,000 \text{ psi}
\]

This shear calculation is extremely conservative since the bearing surface of the nuts gives additional support.
(e) **Fatigue**

Calculation of the fatigue life of the chamber is complicated by the following facts:

1) There are little data available on the very low cycle fatigue life of cylindrical chambers and none, to the designers' knowledge, on spherical chambers.

2) Any fatigue analysis under conditions of combined stresses, with large residual stresses present, is necessarily complicated and highly empirical.

3) The dynamic loading conditions that ensue during the detonation process.

In spite of these problems, however, an estimate of the fatigue life has been made and is believed to be conservative.

The S-N curve (stress-number of cycles) for the particular alloy steel used to construct the chamber is estimated to be as shown on Fig.8. This curve was constructed by assuming the endurance limit to be 40% of the ultimate tensile strength and to occur at $6 \times 10^6$ cycles. The chamber was assumed to have a residual tangential stress at the inner radius of $-125000$ psi and to be pressurized to a combined stress equal to the yield point. Thus the combined stress before detonation is

$$S_i = -125,000$$

and after implosion

$$S_f = 125,000$$

Thus the mean combined stress is zero and the alternating stress is 125,000 psi. Entering Fig.8 with a stress of 125,000 psi yields 75 as the estimated number of cycles of operation. This result obviously depends upon the S-N curve which is probably over-conservative. If, for example, it is assumed that the endurance limit is 50% of the ultimate tensile strength and that this is reached at $6 \times 10^6$ cycles, then repeating the above procedure yields 200 cycles.

There is evidence, that cylinders that are loaded statically to just below the burst pressure have a fatigue life of approximately 800 to 1,000 cycles, reference (9). Whether this same behaviour would apply to a spherical chamber, of the type considered here, under dynamic loading conditions is unknown. If it does apply then both of the estimates of fatigue life given above are conservative. In the absence of further test results it is the judgement of the designers that the chamber will operate at the design load for at least 75 shots and perhaps as many as 200.

(f) **Recoil Forces**

The launcher will experience a thrust due to the ejection of the projectile and the explosive gases. For all practical purposes the thrust forces created by the change in momentum of the projectile can be neglected in comparison to the force exerted by the motion of the explosive gases.
An estimate of this force was made, based upon the following assumptions:

Density of explosive gases = \( \frac{\text{mass of explosive}}{\text{volume of chamber}} \)

\[ = \frac{55 \times 1728}{7050} = 13.5 \text{ lb/ft}^3 \]

Molecular weight of gases = 29 lb/lb mol.

Temperature of gases = 40,000°K.

Specific heat ratio = 1.25

Sound speed of gases = 11800 fps.

The gases are assumed to issue from the \( \frac{1}{\text{inch}} \) barrel at the sound speed and density calculated above. Hence

\[
\text{Thrust} = \text{density} \times (\text{velocity})^2 \times \text{area}
\]

\[
= 13.5 (11800)^2 (0.785) (1)^2
\]

\[
= 318,000 \text{ lbs.}
\]

This thrust force acts for a limited time interval which is given by

\[
\frac{m_p}{\rho_p V A} = \frac{55 (144)}{13.5 (11800)(0.785)(1)^2}
\]

\[
= 63.5 \times 10^{-3} = 63.5 \text{ msec.}
\]

Several methods of handling the recoil forces were considered in the design phase and included the following:

1) Recoil cylinders similar to those used on large artillery pieces.

2) A semi-rigid support (i.e., rigid except for the elasticity of the support and launcher) in back of the explosive chamber.

3) Recoil absorption by using the barrel itself as the recoil spring. From the viewpoint of economy and ease of operation it was decided to use method 3. This involves connecting the barrel to the blast tank which is rigidly connected to the floor of the facility. Under these conditions the chamber and barrel become a spring mass system with a thrust pulse as shown.
For this system with a pulse as shown the maximum deflection is

\[ \chi = \frac{F_0}{k} \left( 1 - \cos \frac{2\pi t}{T} \right) \]

where

\[ k = \frac{E A_o}{L_o} = \text{spring constant of the barrel} \]

\[ T = 2\pi \sqrt{\frac{m}{k}} = \text{natural period of the spring-mass system} \]

\[ m = \text{mass of the chamber} \]

\[ A_o = \text{metal cross section of the barrel} \]

\[ L_o = \text{length of the barrel} \]

\[ E = \text{Young's modulus of steel} \]

Since the strain in the barrel is \( \chi / L_o \) the stress is

\[ \sigma = \frac{E \chi}{L_o} = \frac{E}{L_o} \frac{F_0 L_o}{E A_o} \left( 1 - \cos \frac{2\pi t}{T} \right) \]

\[ = \frac{F_0}{A_o} \left( 1 - \cos \frac{2\pi t}{T} \right) \]

\[ k = \frac{E A_o}{L_o} = \frac{30(10^6)}{12} \left( \frac{0.785 (4^2 - 1.75^2)}{12} \right) = 2.12 \times 10^6 \text{ lb/in.} \]

\[ T = 2\pi \sqrt{\frac{50000}{2.12(10^6)(386)}} = 48.7 \times 10^{-3} = 48.7 \text{ msec.} \]
Since the length of the pulse is greater than one-half the natural period the maximum stress is

\[ \sigma_{\text{max}} = \frac{2F_0}{A_0} = \frac{2(318000)}{0.785 \left(4^2 - 1.75^2\right)} = 62,500 \text{ psi.} \]

This stress is well within the strength limits of the barrel.*

(g) **Hemispherical Aluminum Shell Requirements**

The hemispherical shell, to which the explosive is joined adhesively, is 3/8 inches thick and 30 inches in diameter. The operational procedure calls for it to be supported by a vacuum during the initial joining of the two chamber sections. The vacuum requirements are as follows:

![Hemispherical Shell Diagram]

Projected area = 706 in\(^2\)

Weight (shell + explosive) = 160 lb.

\[ \Delta P \left(706\right) 15 = 160 \left(7.4\right) \]

\[ \Delta P = 0.112 \text{ psi} \]

Thus only a very small pressure differential is required to hold the shell in place.

The maximum pressure differential that the shell can withstand without buckling is (in case of aluminum)

\[ \Delta P_{\text{cr}} = \frac{2Et^2}{r^2 \sqrt{3(1-v^2)}} \]

\[ = \frac{2 \left(10^7\right) \left(0.375\right)^2}{\left(15\right)^2 \sqrt{2.73}} = 5,550 \text{ psi.} \]

The shell is therefore capable of withstanding a complete vacuum without buckling.

(h) **Blast Tank Requirements**

The requirements for the blast tank were based upon the following

* A more exact analysis by UTIAS has indicated a maximum barrel stress of 70,000 psi under maximum loading conditions.
considerations:

a) In ballistic range studies it is desirable to have sufficient room for mounting instrumentation, such as x-ray heads, in the vicinity of the launcher muzzle. This dictates a useful diameter of 8 feet.

b) Inasmuch as instrumentation will probably be inside the tank, it is desirable to maintain the average pressure in the tank at about 30 to 45 psi. However, localized stagnation pressures up to about 165 psi should be expected.

The volume of the tank was obtained by assuming the average pressure in the launcher chamber equals the design load divided by the projected area of the chamber, i.e.,

$$\text{Volume of tank} = V_{\text{chamber}} \left( \frac{P_{\text{chamber}}}{P_{\text{tank}}} \right)^{1/8}$$

$$= 4.1 \left( \frac{86,500}{45} \right)^{0.8} = 1,730 \text{ ft}^3$$

Length of tank = 34.4 ft ≈ 35 ft.

The wall thickness is established by assuming that a localized internal stagnation pressure of 165 psi is possible and that the weld strength is 16,000 psi. Hence,

$$t = \frac{P r}{\sigma_t} = \frac{165 (8) (12)}{16,000} \approx 1''$$

The vacuum capability, i.e., differential external pressure, is

$$P_{\text{critical}} = \frac{E t^3}{4(1-v^2)r^3}$$

$$= \frac{30 (10^6) 1}{4(0.91)(48)^3} = 74.5 \text{ psi}$$

Since the barrel is rigidly connected to the tank, the latter must withstand the recoil forces. If the domed end of the tank is 3'' thick, then with a recoil force of 636,000 lbs the stresses in the head are 81,000 psi. This result is obtained by considering the end heads as a hemispherical unstiffened plates with an unfixed edge support and with a concentrated load of 636,000 lbs at the centre Ref (10). The design incorporates the use of a single domed head that is reinforced with gussets and calls for construction
with HY-80 steel which is weldable and has a yield of 80,000 psi or greater. Thus, the stress levels in the end closures should be very well below the strength capabilities of the design. The gussets are primarily used to transfer the loads on the ends to the main tank wall. The thickness of 3" on the domed ends is necessary to prevent the welding neck from shearing out.

The recoil forces are finally transferred from the tank to the floor by means of forty 1" diameter studs which rigidly connect the tank to the floor.

4. Proof Test Program

The proof test program is designed to provide operational experience to personnel and to determine any limitations that may exist in the Launcher due to design, manufacturing, or material deficiencies. With this goal in mind, it is expected that the operators will have performed the following functions prior to firing any test shot.

1) Replaced any seals that appear damaged.

2) Insured that the prescribed preload exists in the bolt-nut system that joins the chamber sections.

3) Carefully monitored the gas loading pressures and explosive charge.

4) Strain gaged the chamber in several locations and in particular, the front chamber in the region of the gas vent holes and the rear chamber in the spherical part. Also strain gauges should be applied to several of the bolts to monitor the preload as well as the stress variation during firing. See drawing SK-10 for recommended location of strain gauges.

5) Insured that the recoil collar bolts and the nuts on the barrel lock ring are tight.

6) Monitored the system carefully for leaks prior to firing.

TEST 1: Stoichiometric load of hydrogen and oxygen at a total pressure of 250 psi. No explosive.

TEST 2: Same gas load as 1 with 15 lb explosive.

TEST 3: Same gas load as 1 with 25 lb explosive.

TEST 4: Same gas load as 1 with 35 lb explosive.

TEST 5: Same gas load as 1 with 40 lb explosive.

TEST 6: Same gas load as 1 with 45 lb explosive.

TEST 7: Same gas load as 1 with 50 lb explosive.

TEST 8: Same gas load as 1 with 55 lb explosive.
Thestrainreadingsobtainedduring each test should be carefully 
analyzed to see that excessive stresses are not occurring at any positions 
on the launcher. After each test the chamber should be opened and carefully 
inspected for damage or leakage. The most serious complication that can 
occur in this program, other than a catastrophic rupture of one of the com-
ponents, is to have a high pressure leak. Such a leak with gas at high 
pressure and temperature will cause excessive erosion and damage to the 
steel parts in the vicinity, which could necessitate re-machining or even 
replacement. Thus it is imperative that careful inspection of the chamber 
and seals be made after each test. Any shot that is suspect in any way, 
either as to the exact conditions of loading or the visual inspection and 
strain gauge analysis, should be repeated before proceeding to the next test. 
If the strain gauge readings begin to show excessive stresses at any test, the 
proof program should be changed at that stage to 1/2 to 1 lb additional ex-
plosive increments.

The successful operation of this launcher depends critically upon 
cleanliness. All components must be carefully cleaned before assembly; this 
is particularly true for the bolt and nut threads, the barrel and flange 
threads, and the hydraulic tensioner threads. The threads, as manufactured, 
are permanently lubricated and do not require further lubrication. Failure 
to observe cleanliness will result in galling of the assembled pieces which 
will make normal dis-assembly impossible.

5. Safety

Few people are more cognizant of the hazards that can be encountered 
in the use of hypervelocity guns and high pressure equipment than the designers 
who, among them, have some 40 years experience in the design, testing, and 
operation of such equipment. This section is intended to spell out, un-
equivocally, the safety precautions that should be followed with respect to 
the MK II Implosion Driven Launcher. The safety philosophy should be that a 
catastrophic failure is possible and therefore measures must be taken to 
sure the safety of personnel in such an event.

The design of this launcher was dictated by considerations not only 
of the performance specification but also of economy. The designers feel that 
the final design represents a compromise between these two extremes but 
readily admit that, even without the economical restriction, the design would 
be essentially as shown. The design is based upon providing sufficient pre-
load to contain the explosive forces generated in the chamber and within the 
limitations of the chamber itself, it should provide this function.

The MK II Launcher uses stoichiometric mixtures of hydrogen and 
oxxygen in conjunction with explosives. The pressures generated are orders 
of magnitude higher than the pressures normally encountered, in two stage 
light gas guns. It is apparent that this device represents a new generation 
of launchers and requires extension of the state of the art and design philo-
sophy that is normally followed in the containment of high pressures. This 
is particularly true in the area of fatigue analysis which, unfortunately, 
is not well understood even at considerably lower pressures. The safety 
recommendations that follow are based upon these facts, namely, the high 
dynamic pressures involved, the advanced state of the art of the launcher, 
and the lack of experimental data for the conditions under which it operates.
(a) **Experimental Test Chamber**

The equations governing the stresses in a chamber subjected to high internal pressures indicate that these stresses will be of the same value in a small chamber provided it is geometrically similar to the larger chamber. Thus, considerable information could be obtained by building a small launcher which is scaled by the same factor in all dimensions. Such a launcher would also provide data on the performance from a gas dynamic viewpoint. Obviously such a device would be safer to operate, because the amounts of explosive involved would be considerably less; could be operated faster, and would provide data on the load limitations and fatigue within the limitations of only one test specimen.

The first recommendation therefore, regarding safety, is that a geometrically similar launcher be constructed (1/4 to 5" radius of chamber) and tested before or concurrently with the large one. Attempts should be made to obtain geometric similarity of all components with regard to size and exact similarity with respect to material and physical properties. This small scale chamber should be subjected to the same proof test program, appropriately scaled, as outlined in Section 4. Subsequent test firings should be made in the small launcher prior to being made in the large one.

(b) **Laboratory Building**

The MK II Launcher should be housed in a remote, separate building that is designed to stop flying pieces of metal but which will exhaust high gas pressures. Two types of building construction are possible.

1) A building below ground level with a heavy wood, concrete roof construction that is not integrally connected to the ground. In the event of catastrophic failure, metal pieces would embed in the wall or wood of the roof and the roof would lift sufficiently to vent explosive gases. The building should be remote enough from adjacent occupied areas that shock waves generated by the venting process cannot cause personal or material damage. A separate underground control bunker should be provided for operating personnel.

2) A remote, separate building of reinforced concrete having sufficient strength and volume to withstand the maximum pressure generated during a catastrophic failure of the launcher. Escape of the high pressure gases within the facility should be provided by open vent areas. A separate control bunker should be provided for operating personnel.

(c) **Operational Safety**

The mechanical operation of this launcher was described in Section 2. The handling of the explosive liner should be done within the accepted safety precautions prescribed for explosive handling and loading should be done in a separate explosion proof room by experienced personnel who are properly instructed in the handling of explosives and wear clothing that meets the safety requirements. Hydrogen and oxygen should be loaded remotely.
The ignition system of the launcher and all instrumentation should be electrically deactivated and grounded while the chamber is being locked. All personnel, other than those actively engaged in the loading and locking procedure, should be prohibited from the area. A positive, fail-safe, inter-lock system on all electrical connections should be made. A senior engineer responsible for overall operation and safety should be available and should have established an operational procedure, which must be followed by all personnel.

6. Conclusions

The MK II Launcher is considered to be an advancement in the state of the art of hypervelocity launchers. It provides an extremely useful tool for the study of gasdynamics, high-velocity launching techniques, hypervelocity impact, shock interaction effects, dissociation and ionization of gases, and the study of plastic flow effects in materials. The design that has been described in this report, meets the specifications, at least theoretically, that were required. While the designers had hoped to provide a system that could be cycled faster than the present design, it is felt that the MK II Launcher represents as sound a solution to the specifications as could be accomplished.
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STOICHIOMETRIC $\text{H}_2$,$\text{O}_2$

EXPLODING WIRE

IMPLOSION PROJECTILE

EXPLOSIVE

FIGURE 1
Figure 2: Loading Apparatus

- Overhead Crane
- Centroid below this
- Vacuum fitting
- Vertical adjustment
- Liner and container lift free of carriage
- Right, left adjustment
- Frame inserted in bolt holes
- Front chamber section
- View from behind gun (a)
- Side view (b)

FIG. 2 LOADING APPARATUS
FIG. 3 BOLT TIGHTENING PATTERN NUMBER ON BOLT INDICATES ORDER IN WHICH EACH ONE IS PRELOADED. TOTAL PRELOAD IS APPLIED IN AT LEAST TWO STEPS.
AISI-SAE 4340
NORMALIZED 1600 F
OIL QUENCHED FROM 1550 F
TEMPERED AT 1000 F

TENSILE STRENGTH

YIELD STRENGTH

STRENGTH (10^3 psi)

BAR SIZE (INCHES)

FIG. 4
FIG. 5

RESIDUAL STRESS DISTRIBUTION IN CHAMBER
UNLIMITED YIELD STRENGTH IN COMPRESSION

RADIUS (INCHES)

RESIDUAL STRESS / YIELD STRENGTH

\[ \frac{\sigma_r^*}{Y_o} \]

\[ \frac{\sigma_t^*}{Y_o} \]
FIG. 6

ESTIMATED RESIDUAL STRESS DISTRIBUTION IN CHAMBER IF CHAMBER IS COMPLETELY PLASTIC ASSUMED COMPRESSIVE YIELD STRENGTH = -125,000 p.s.i.
FIG. 7

RESIDUAL STRESS DISTRIBUTION IN CHAMBER
FIG. 9
IMMOLSION-DRIVEN HYPERVELOCITY LAUNCHER ASSEMBLY
Based on initial experiments carried out on the 8 inch diameter Hypervelocity Launcher, as well as preliminary design study for a larger launcher unit, the design of a 30 inch diameter Hypervelocity Launcher was completed, and a set of detailed workshop drawings was prepared. This report describes the basic functioning of the Implosion Driven Hypervelocity Launcher, as well as the mechanical design, operation and firing procedures. A separate chapter is devoted to the strength requirements and initial stressing. By using a simple analogy with a spherical pressure chamber, the authors endeavor to estimate the plastic/elastic stress level, from which, some prediction of fatigue life for such a launcher could be derived. The last two chapters of this report give some recommendations for proof testing of the launcher, as well as some basic aspects of safety of operation.

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The MK II UTIAS Implosion-Driven Hypervelocity Launcher Design Analysis

V. C. D. Dawson, R. A. Waser and D. O. Oakes
19 pages 9 figures

1. Implosion-Driven Hypervelocity Launcher 2. Launcher Design and Operation

I. V. C. D. Dawson, R. A. Waser, D. O. Oakes
UTIAS Technical Note No. 147

Based on initial experiments carried out on the 8 inch diameter Hypervelocity Launcher, as well as preliminary design study for a larger launcher unit, the design of a 30 inch diameter Hypervelocity Launcher was completed, and a set of detailed workshop drawings was prepared. This report describes the basic functioning of the Implosion Driven Hypervelocity Launcher, as well as the mechanical design, operation and firing procedures. A separate chapter is devoted to the strength requirements and initial stressing. By using a simple analogy with a spherical pressure chamber, the authors, endeavour to estimate the plastic/elastic stress level, from which, some prediction of fatigue life for such a launcher could be derived. The last two chapters of this report give some recommendations for proof testing of the launcher, as well as some basic aspects of safety of operation.

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