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1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE September 1994		3. REPORT TYPE AND DATES COVERED Final, Jan 92-May 92	
4. TITLE AND SUBTITLE Use of Finite-Element Stress Analysis in the Design of a Tank-Cannon-Launched Training Projectile				5. FUNDING NUMBERS PR: 1L162618AH80	
6. AUTHOR(S) Michael S. L. Hollis					
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army Research Laboratory ATTN: AMSRL-WT-WB Aberdeen Proving Ground, MD 21005-5066				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army Research Laboratory ATTN: AMSRL-OP-AP-L Aberdeen Proving Ground, MD 21005-5066				10. SPONSORING/MONITORING AGENCY REPORT NUMBER ARL-MR-149	
11. SUPPLEMENTARY NOTES					
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.				12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) The U.S. Army Armament Research, Development, and Engineering Center (ARDEC) recently expressed a need for a tank-cannon-launched training projectile with reduced penetration capability. The expressed primary design goals for this projectile were to minimize the probability of personnel injury and materiel loss in the event of an accidental impact during a training exercise. In order to meet these design goals, the solid-steel flight body of a current kinetic energy (KE) training projectile, the M865IP, was replaced with a hollow aluminum configuration. Because of the incorporation of aluminum, the structural integrity of the entire projectile during launch was questioned. Thus, a thorough stress analysis of the new design was conducted to alleviate concerns about its structural integrity. Two-dimensional, axisymmetric, quasi-static stress analyses were performed on two new KE training projectile designs. The first analysis indicated that structural failure was possible in the aft portion of the projectile due to compressive loading by the gun gases. Structural failure in this case would be circumferential yielding of the hollow flight body. The aft portion of the round was redesigned, and subsequent stress analysis showed that the possibility of structural failure needed to be resolved. The finite-element modeling approach, the applied boundary conditions, and the results of the stress analyses conducted, based on use of the von Mises failure criterion, will be discussed in detail.					
14. SUBJECT TERMS finite element analysis, computer aided design				15. NUMBER OF PAGES 21	
				16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT UL		

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ACKNOWLEDGMENTS

The author would like to acknowledge the following people who made the design of the Hollow Aluminum Training Round (HATR) possible: Freddie Brandon, Edward Schmidt, Edward Kennedy, and Frederick Robbins, U.S. Army Research Laboratory (ARL); Edward Fennel, U.S. Army Armament Research, Development, and Engineering Center (ARDEC); and my wife, Lori.

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1. INTRODUCTION

ARDEC recently expressed a need for a tank-cannon-launched training projectile with reduced penetration capability. The expressed primary design goal for a KE tank-cannon-launched training projectile was to minimize the probability of personnel injury and materiel loss in the event of an accidental impact during a training exercise. A current state-of-the-art tank-cannon-launched projectile is the M865IP (Figure 1). This is a limited-range training projectile which simulates the launch and flight characteristics of an actual war round. During launch, the M865IP endures a peak base pressure of 288 MPa (42 ksi) and achieves a muzzle velocity of 1,700 m/s. Even though the projectile is only used for target practice, the steel flight body contains 4.6 MJ of KE at a velocity of 1,700 m/s. Thus, accidental impacts result in considerable damage. For example, several years ago in Grafenwoehr, Germany, an M1 tank crew was on the firing range practicing with the thermal sight. The tank gunner accidentally sighted on a group of Bradley Fighting Vehicles in a nearby firing zone and shot at them with a KE training round containing a solid-steel penetrator. One crewman was killed, four others were wounded, and two Bradleys were severely damaged.

The M865IP launch package (Figure 1) consists of three sabot petals (only two shown), a solid-steel flight body, and an aluminum flare. The sabot petals are assembled around the flight body and interface with it by means of threads. A nylon obturator (not shown), which acts as a gas seal, is pressed onto the grooves located on the aft bulkhead of the petals. When assembled, this configuration seals the cannon tube and transfers the energy of the expanding propellant gases to the KE of the projectile. Once the launch package has cleared the cannon tube, aerodynamic forces lift off the sabot petals. The flight body is then stabilized in flight by the high drag aluminum flare at the aft. To meet the primary design goal, the penetration capability of the flight body must be considerably reduced. Four factors—length, diameter, striking velocity, and the ratio of penetrator and target densities—are involved in determining the penetration capability of a KE penetrator. The KE penetrator length, diameter, and striking velocity are fixed by three design criteria which are meant to constrain the design to physically resemble and fly like the M865IP. These three criteria are discussed in more detail later. The penetrator density remains as the only variable to modify. A measure of theoretical hydrodynamic penetration capacity is the density law:

$$P/L = (\rho_p/\rho_T) , \quad (1)$$

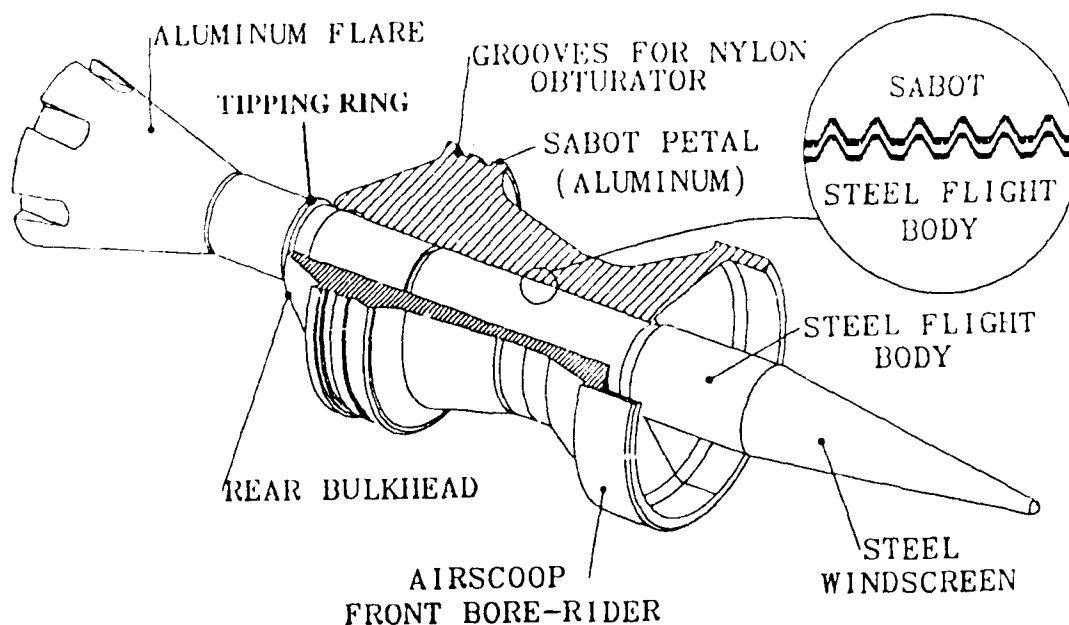


Figure 1. M865IP KE tank-training projectile.

where

P = penetration depth,

L = length of the penetrator,

P_p = density of the penetrator, and

ρ = density of the target.

By decreasing the density of a constant length penetrator, penetration is reduced. Therefore, by replacing the heavy steel core of the M865IP with a lower density material, such as an aluminum alloy, the penetration into a steel target will be reduced by approximately 41%. However, a solid aluminum-alloy flight body was thought to still possess too much penetration capability. To further reduce this, a hollow flight body design was used. The resulting design was thus referred to as the Hollow Aluminum Training Round (HATR). Because of the incorporation of a hollow aluminum flight body, the structural integrity of the entire projectile during cannon launch was questioned, and the new design had to be structurally verified. This verification was done with the use of finite element analysis techniques.

Other design criteria for the HATR were considered as the structural integrity of the launch package was being examined. These criteria fixed the KE penetrator length, diameter, and striking velocity. First: the projectile must resemble the external appearance of a current training projectile so that launching components (i.e., sabot petals and obturator) would not have to be redesigned. The current training projectile design chosen was the M865IP. Secondly, the HATR must be inexpensive to manufacture; hence, maximum use of existing hardware was made. The use of aluminum alloy will also lower the material and machining costs.

Finally, the HATR must be a ballistic match to the M865IP. This ensures that a tank gunner could shoot the HATR without making any changes to the fire control solution of the tank's ballistic computer. The ballistic match requirement is expressed mathematically in equation 2.

$$\frac{W_{M865IP}}{C_{D1}A} = \frac{W_{HATR}}{C_{D2}A}, \quad (2)$$

where:

W_{M865IP} = weight of the M865IP,

W_{HATR} = weight of the HATR,

C_{D1} = coefficient of drag of the M865IP, measured,

C_{D2} = coefficient of drag of the HATR, theoretical, and

A = reference area based on projectile diameter.

The coefficient of drag for the M865IP was the same as that used to generate the M865IP firing table. The coefficient of drag for the HATR is derived from a theoretical aerodynamic computer model (PRODAS 1991). Since the external appearance of the training projectile resembles that of the M865IP, the reference areas are the same. The M865IP has a mass of approximately 3.2 kg (weight = 7.0 lbm) and is stabilized by a high-drag flare. The HATR flight body mass was targeted at 1.0 kg (weight = 2.1 lbm). The coefficient of drag for the HATR must be chosen to balance equation 2. Because the design mass of the HATR is small, compared to the M865IP, C_{D2} must be comparably smaller than C_{D1} , or the velocity of the HATR will retard faster than the M865IP. Therefore, instead of a flare, the HATR has to be stabilized by low-drag fins. The fins for an existing projectile, the M735 KE projectile, were

used (Figure 2). The HATR design depicted in Figure 2 resembles the M865IP. The only differences from the M865IP are the flight body material and the reliance on fins instead of a flare for stabilization.

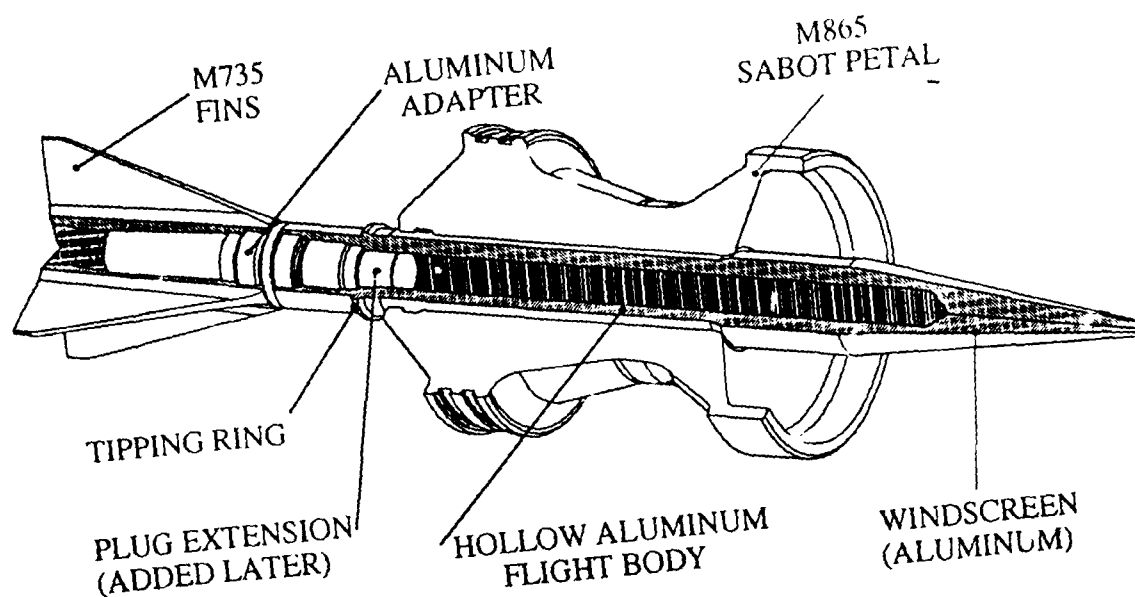


Figure 2. HATR

2. MODELING

2.1 Assumptions. A two-dimensional, axisymmetric, quasi-static stress analysis was performed on the HATR design shown in Figure 2. This method of analysis has been performed on KE projectiles in the past (Drysdale 1981). A number of simplifications to the HATR were effected to facilitate axisymmetric analysis. Although the HATR has fins, the mass of the fin blades was incorporated into the mass of the fin hub to form a composite axisymmetric body with the same total mass. The interface threads between the sabot and the flight body were also approximated by axisymmetric grooves.

The quasi-static assumption was made to further simplify the analysis. Even though the launch package is subjected to a range of pressures over a very short period of time, dynamic analyses have shown that the effects of wave propagation are not significant. Therefore, the maximum dynamic loads can be replaced by quasi-static loads (Sorenson 1992). To further simplify the model, it is also assumed that the gun tube is perfectly straight and balloting of the launch package is nonexistent.

2.2 Model. With all of the previous assumptions, the HATR configuration in Figure 2 is approximated with a two-dimensional, axisymmetric geometry which was discretized using a free meshing technique. The resulting mesh (Figure 3) consists of linear triangles. Triangular elements were used because of the accuracy and ease these elements afford in modeling complicated geometries. Further, linear elements were chosen for ease of calculation. In regions of predicted high stress, a finer mesh was used than in other areas of the model. This was done to improve the accuracy of the model and the speed of the solution's convergence. The following nominal material properties for aluminum alloy were used in the model:

Density (kg/m ³ [lbm/in ³])	Young's Modulus (MPa [psi × 10 ⁶])	Poisson's Ratio
2,710 [0.101]	6,890 [10]	0.33

The composite fin hub model was assigned a slightly higher density to account for the mass of the fin blades.

To eliminate rigid body motion between all parts of the model and ensure proper force transmission, node-to-node gap elements were used along the threaded interfaces. The gap elements also prevent interpenetration of elements along the threaded interface.

2.3 Loads and Boundary Conditions. The HATR is to be launched from an M256 120-mm smoothbore tank cannon. The launching environment is very harsh, with hydrostatic pressure on the base of the launch package reaching a peak magnitude of 207 MPa (30 ksi). This pressure corresponds to an acceleration of the 3.7-kg (weight = 8.1 lbm) launch package of 66,000 g's. Since the tank cannon has a smooth bore (i.e., has no rifling), torque loading on the projectile is negligible.

Figure 4 displays the loads and constraints on the model. Roller restraints are placed on the sabot to simulate the presence of the tube wall. To assure that axial motion is eliminated, a node near the center-of-gravity of the model is axially constrained. The axial stresses at this node will be negligible once the axial loads are properly balanced. This usually requires some iterative fine-tuning of the applied pressure and acceleration loads. The inertial acceleration necessary to maintain the axial static state is derived from Newton's Second Law:

$$F = ma_z = P_{\text{BASE}} * A_{\text{BORE}} \quad (3)$$

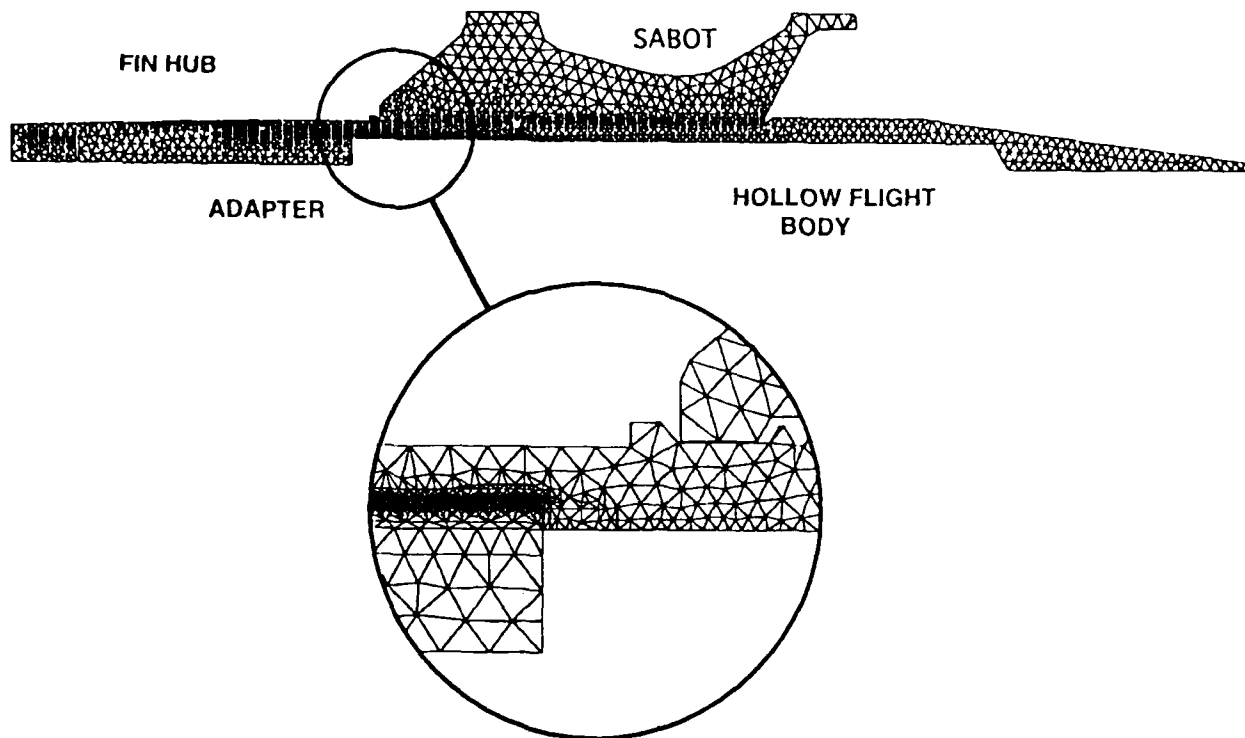


Figure 3. Element plot of the HATR model.

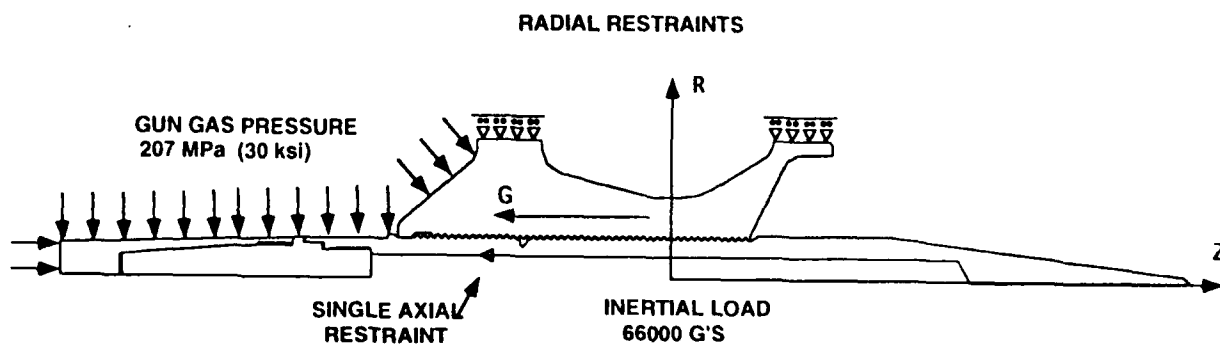


Figure 4. HATR boundary conditions and cylindrical coordinate system.

where:

- F = total axial force,
- m = total launch mass, 3.7 kg (weight = 8.1 lbm),
- a_z = peak axial acceleration of the launch mass,
- P_{BASE} = peak base pressure on the projectile, 206.8 MPa (30.0 ksi), and
- A_{BORE} = bore area of the gun tube, 113.1 cm² (17.5 in²).

The magnitude of the pressure loading was determined with the ARL interior ballistic computer code IBHVG 2. IBHVG 2 is a lumped parameter interior ballistic model. The code is used for calibration of interior ballistic data, including gas pressure, projectile displacement, and projectile velocity as a function of time (Anderson and Fickie 1987).

3. STRESS ANALYSIS

The von Mises stress criterion is a theory that specifies that plastic yielding will occur when the combined stresses of a body equal or exceed the tensile yield stress of a metal. The von Mises stress failure criterion has been validated by previous empirical studies (Sorenson 1992). Von Mises, σ' , can be represented by the following equation:

$$\sigma' = \{[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2]/2\}^{1/2} \quad (4)$$

$\sigma_1 > \sigma_2 > \sigma_3,$

where σ_1 , σ_2 , and σ_3 are the principal stresses.

Plastic yielding is predicted to occur when the von Mises stress is equal to or greater than the yield stress, σ_{yield} , of the material. If the design has extensive areas of plastic yielding, then it is likely to suffer unacceptable deformations, and possibly even fracture in service. However, if only small localized regions of yielding are predicted, then it is presumed that some redistribution of material through plastic flow will alleviate these high stress areas. The HATR analysis showed some localized areas of high stress on some of the teeth in the threaded interface of the sabot/flight body region. Plastic flow of these teeth was assumed so that the loads would be distributed to other teeth and the high stresses would be alleviated.

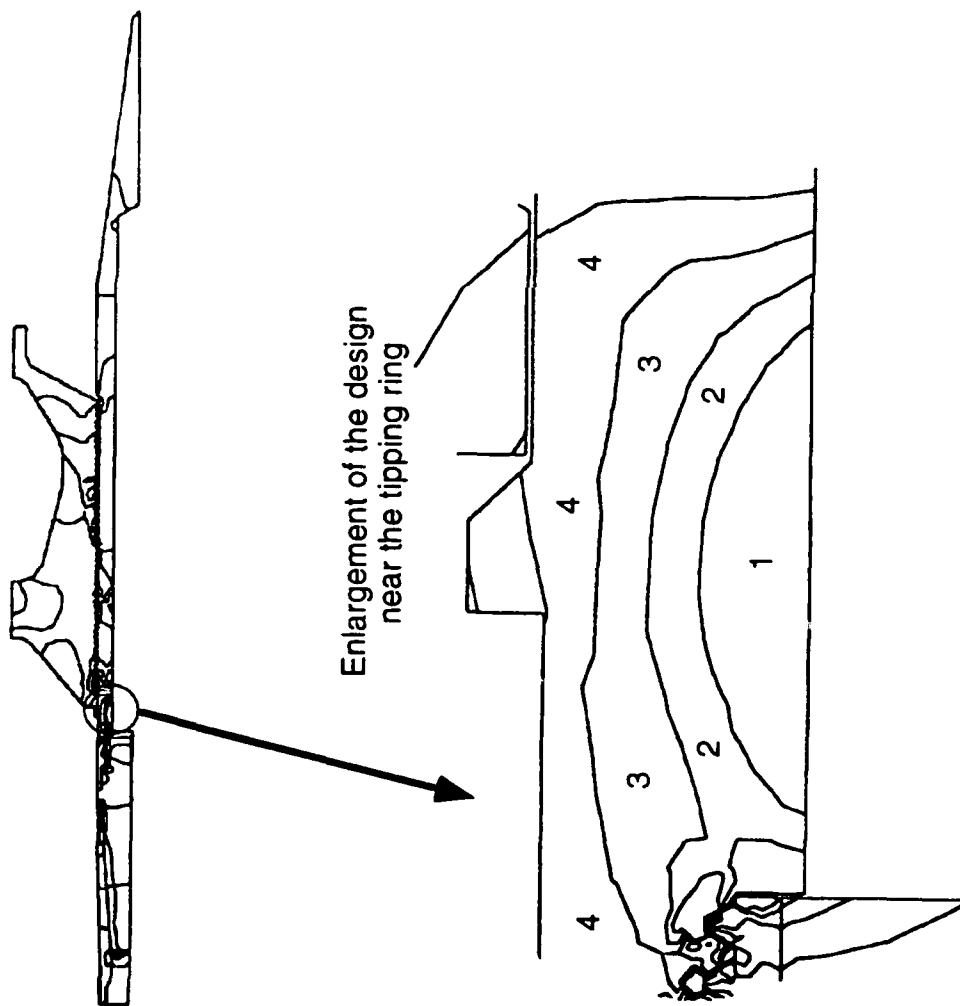
Although the predicted von Mises stress is well below yield over most of the structure, a region near the tipping ring exceeded the yield stress of aluminum (Figure 5). The yield strength of aluminum 7075-T6 is reported as 503 MPa (73 ksi). Notice that in stress region 1, the stresses range from 495 MPa (72 ksi) to 558 MPa (81 ksi). Since the stresses exceed the yield stress of aluminum, it is assumed that undesirable plastic yielding will occur.

In an effort to determine the mechanism that generated the high von Mises stress, the axial (σ_z), circumferential ($\sigma_{\theta\theta}$), and radial (σ_{rr}) stress components of the tipping ring region were reviewed. Figures 6–8 contain the contour plots of the σ_z , $\sigma_{\theta\theta}$, and σ_{rr} , respectively. Notice that in Figure 7, the compressive $\sigma_{\theta\theta}$ stresses range from 386 MPa (56 ksi) to 473 MPa (69 ksi). Though these stresses do not exceed σ_{yield} of aluminum, they are much greater in magnitude than the other components. It was assumed that if the circumferential stresses could be reduced, the von Mises stresses would also be decreased.

To improve the design, the adapter (Figure 2) was extended further into the hollow flight body to add support to the tipping ring region. This would allow loads near the tipping ring region to be distributed throughout the hollow flight body wall and the plug extension, thus alleviating the high stresses. With this modification, the projectile was reanalyzed, and the stresses in the vicinity of the tipping ring were found to be reduced below yield stress. Figure 9 contains a von Mises stress contour plot of the redesigned region. This figure shows that the stresses are significantly reduced as compared to the old design.

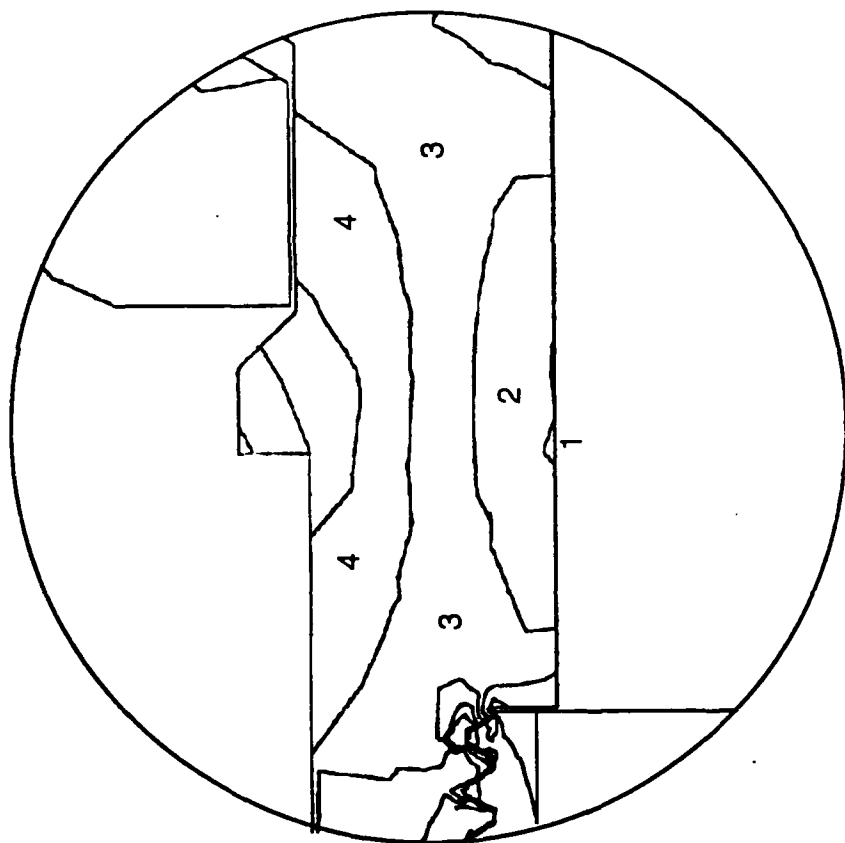
4. CONCLUSION

After the final stress analysis predicted that the HATR would survive gun launch, 15 of the projectiles were fabricated and test fired. All 15 were successfully launched. Figure 10 shows a high-speed photograph of the newly designed projectile in flight. Aeroballistic experiments were performed on six of these projectiles. It was demonstrated that the fin-stabilized HATR exhibits similar flight characteristics to the flare-stabilized M865IP in terms of trajectory. The other nine projectiles were shot into various armors to determine penetration capacity. The HATR demonstrated a substantial reduction in penetration into armor steel, on the order of one magnitude less than that for the M865IP steel training projectile. A cost analysis, performed by ARDEC, found a substantial cost savings with the HATR design. In conclusion, analysis of the HATR concept is appealing for two reasons: (1) reduced potential for inflicting damage in the event of a training accident and (2) lower production costs compared to the M865IP.



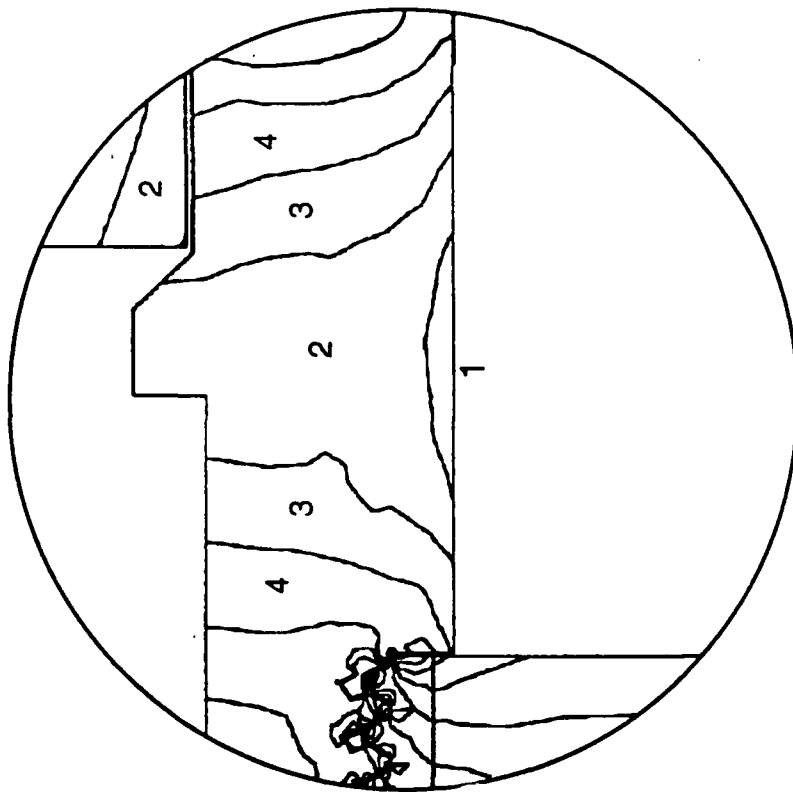
Stress Region	From	To
1	495 MPa 72 ksi	558 MPa 81 ksi
2	434 MPa 63 ksi	495 MPa 72 ksi
3	372 MPa 54 ksi	434 MPa 63 ksi
4	309 MPa 45 ksi	372 MPa 54 ksi

Figure 5. The von Mises contour stress plot of the region near the tipping ring.



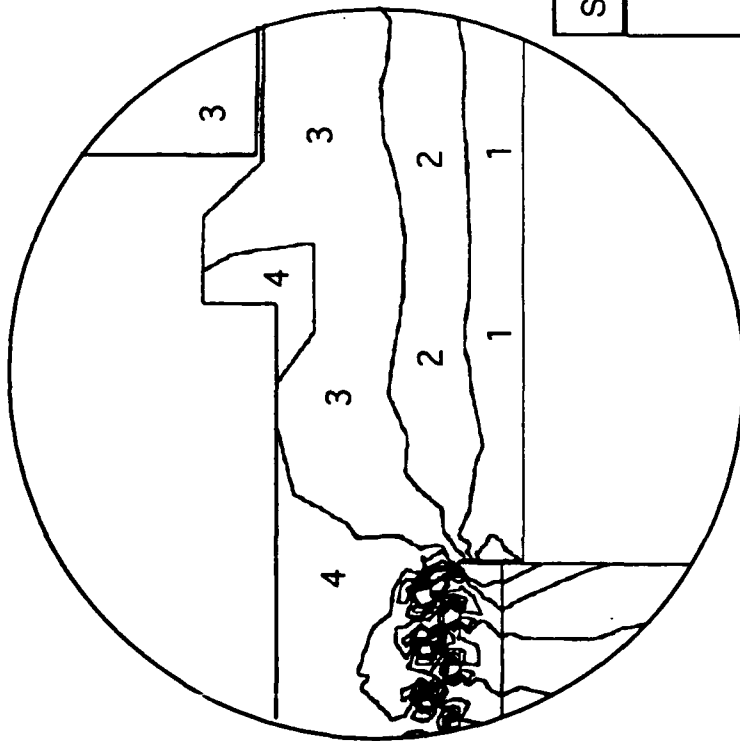
Stress Region	From	To
1	284 MPa 41ksi	372 MPa 54 ksi
2	195 MPa 28 ksi	284 MPa 41 ksi
3	106 MPa 15 ksi	195 MPa 28 ksi
4	18 MPa 3 ksi	106 MPa 15 ksi

Figure 6. The axial stress contour plot of the region near the tipping ring.



Stress Region	From	To
1	-473 MPa -69 ksi	-427 MPa -62 ksi
2	-427 MPa -62 ksi	-386 MPa -56 ksi
3	-386 MPa -56 ksi	-338 MPa -49 ksi
4	-338 MPa -49 ksi	-296 MPa -43 ksi

Figure 7. The circumferential contour stress plot of the region near the tipping ring.



Stress Region		From	To
1		-59 MPa -9ksi	0 MPa 0 ksi
2		-118 MPa -17 ksi	-59 MPa -9 ksi
3		-177 MPa -26 ksi	-118 MPa -17 ksi
4		-236 MPa -34 ksi	-177 MPa -26 ksi

Figure 8. The axial contour stress plot of the region near the tipping ring.

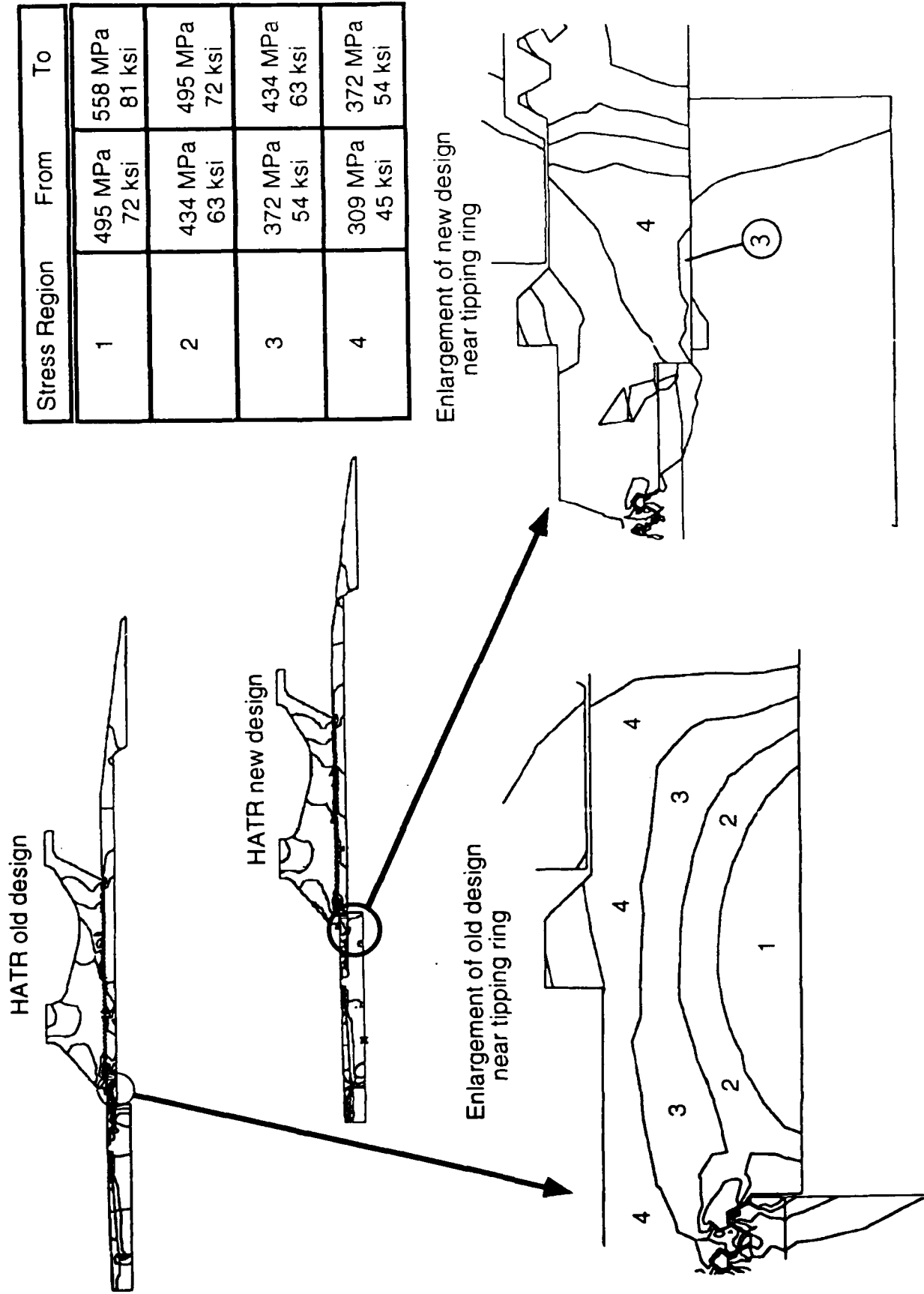


Figure 9. A comparison of von Mises contour stress plots of regions near the tipping ring for both the old and new design.



Figure 10. A successful launch of the HATR.

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