NRL 7354

Metallurgical Considerations in Selection of a Fracture-Safe Explosives Containment Vessel

P.P. Puzak

Strength of Metals Branch
Metallurgy Division

and F.J. Loss

Reactor Materials Branch
Metallurgy Division

January 10, 1972

NAVAL RESEARCH LABORATORY
WASHINGTON D.C.

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Naval Research Laboratory Washington, D.C. 20390	2a. REPORT SECURITY CLASSIFICATION Unclassified—FOUO 2b. GROUP

3. REPORT TITLE

METALLURGICAL AND MECHANICAL CONSIDERATIONS IN SELECTION OF A FRACTURE-SAFE EXPLOSIVES CONTAINMENT VESSEL

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
Final report on the problem.

5. AUTHOR(S) (First name, middle initial, last name)

P.P. Puzak and F.J. Loss

6. REPORT DATE January 10, 1972	7a. TOTAL NO. OF PAGES 26	7b. NO. OF REFS 17
8a. CONTRACT OR GRANT NO. NRL Problems M01-25 and M01-14 b. PROJECT NO. RR 022-01-46-5432 c. RR 022-11-41-5409 d.	9a. ORIGINATOR'S REPORT NUMBER(S) NRL Report 7354 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)	

10. DISTRIBUTION STATEMENT

NONE

11. SUPPLEMENTARY NOTES FOR OFFICIAL USE ONLY	12. SPONSORING MILITARY ACTIVITY Department of the Navy (Office of Naval Research), Arlington, Virginia 22217

13. ABSTRACT

Public safety agencies in many large metropolitan cities need a mobile system which is capable of safely transporting "terrorist-type" bombs from a discovery point to a disposal area. In view of the immediate requirement of such a system by the Government of the District of Columbia, Metropolitan Police Department (DC-MPD), the Naval Research Laboratory has provided an interim solution to this problem by designing and fabricating a prototype explosives containment system. The system capability was successfully demonstrated by proof tests using 14 and 44 sticks of special gelatin, 60-percent-strength dynamite with only minor damage resulting.

The crucial elements of the system which led to the successful demonstration are an ultrahigh-strength, highly fracture resistant steel pressure vessel held in a specially fabricated support base also made of high-strength, fracture tough steel. Materials for the system were selected and evaluated on the basis of the most advanced metals characterization procedures to ensure fracture-safe performance in this unique application. A duplicate system has been donated to the DC-MPD. This system is considered to be the most reliable, highest-strength and lightest-weight mobile explosives containment system available to any metropolitan public safety organization. Recommendations are made to evaluate materials in other similar systems, and concepts for an operational system specifically designed for this function are described.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Bomb transport vehicle Explosives containment vessel Evaluation of bomb container materials Design for safe explosives containment Fracture-safe design Fracture control plan Interpretations of fracture tests Dynamic Tear tests Mechanical tests Metallurgical engineering Ratio Analysis Diagram Structural mechanics						

CONTENTS

ABSTRACT

Public safety agencies in many large metropolitan cities need a mobile system which is capable of safely transporting "terrorist-type" bombs from a discovery point to a disposal area. In view of the immediate requirement of such a system by the Government of the District of Columbia, Metropolitan Police Department (DC-MPD), the Naval Research Laboratory has provided an interim solution to this problem by designing and fabricating a prototype explosives containment system. The system capability was successfully demonstrated by proof tests using 14 and 44 sticks of special gelatin, 60-percent-strength dynamite with only minor damage resulting.

The crucial elements of the system which led to the successful demonstration are an ultrahigh-strength, highly fracture resistant steel pressure vessel held in a specially fabricated support base also made of high-strength, fracture tough steel. Materials for the system were selected and evaluated on the basis of the most advanced metals characterization procedures to ensure fracture-safe performance in this unique application. A duplicate system has been donated to the DC-MPD. This system is considered to be the most reliable, highest-strength and lightest-weight mobile explosives containment system available to any metropolitan public safety organization. Recommendations are made to evaluate materials in other similar systems, and concepts for an operational system specifically designed for this function are described.

PROBLEM STATUS

Work on this problem has been completed. This is a final report summarizing all metallurgical findings related to the materials and criteria for fracture-safe explosives containment vessels.

AUTHORIZATION

This problem was authorized by Director, Naval Research Laboratory, and was done as a public service.

NRL problems M01-25 and M01-14
Projects RR 022-01-46-5432 and RR 022-11-41-5409

Manuscript submitted September 23, 1971.

METALLURGICAL AND MECHANICAL CONSIDERATIONS IN SELECTION OF A FRACTURE-SAFE EXPLOSIVES CONTAINMENT VESSEL

INTRODUCTION

By request channeled through the Department of the Navy, Office of the Assistant Secretary (Research and Development), NRL assisted the Government of the District of Columbia, Metropolitan Police Department (DC-MPD), in designing a mobile system which would safely contain and transport to a disposal area "bombs and other infernal devices" found in the metropolitan area. An important and necessary consideration for this system was the safety of system-operating personnel and innocent bystanders in the event of premature explosion of the devices during transportation.

The challenge posed in this MPD project request was accepted with interest and enthusiasm because of the metallurgical research aspects involved; the definition and interpretation of metal properties required to provide fracture-safe assurance of critical steel structures is and has been a long-term major area of NRL research. The unique expertise of the Metallurgy Division personnel of NRL was therefore engaged to insure that all materials used in the containment system would offer the same high degree of safety against catastrophic fracture as provided by the current mandatory requirements for materials specified for critical Navy structures.

It was required that the basic explosives containment system consist of an open-ended cylindrical pressure vessel mounted vertically on a suitable motor vehicle. In the event of premature explosion of the device, the vessel walls must contain the bomb's blast and resulting fragments at and below the elevation of the vessel. Any uncontained blast and bomb fragments would then be harmlessly directed upward. Cylinder integrity is paramount to the success of the system; this requirement therefore constituted the primary NRL objective. This report describes the metallurgical and material considerations involved in the successful completion of the MPD project. Details concerning pretest calculations, instrumentation, and proof-test findings relating to effects of explosion blasts in the MPD project prototype system are given in NRL Memorandum Report 2392.

CONSIDERATIONS OF STRUCTURAL REQUIREMENTS AND FRACTURE CONTROL PLANS

In many structural applications, the ultimate end use and not the fracture safety often governs how modern steels are specified (e.g., corrosion resistance, formability, and creep behavior). The standard steel specifications provide the designer with a choice of steels having guaranteed minimum properties such as ultimate tensile strength (UTS). Normally designed structures are expected to fail by plastic flow when the metal is overloaded above the UTS. However, real structures can fail in other modes, frequently in a catastrophic manner at elastic stress levels less than the UTS if the fracture toughness of the material is not adequate.

This fact is not always considered by designers of conventional structures, and this oversight has resulted in many unexpected failures.

Unfortunately, very few standard specifications include reliable criteria for fracture toughness even though this property is essential to guarantee the preclusion of catastrophic (brittle) fractures. Fortunately, the mechanical requirements and operational temperatures for many common steel structures (buildings, bridges, and steam generator boilers,) have been such that standard steels with borderline or low fracture toughness properties at ambient temperatures were used with comparatively low rates of service failures. The use of conservative safety factors to preclude plastic deformation, in large measure, contributed to these low rates of service failures. The same low-failure probability could not be postulated for structures, such as the explosives containment vessel, that may be required to undergo plastic deformation. Steels for these applications cannot be purchased on the basis of economy; often the cheaper steel is less fracture resistant.

In the design of high-performance Navy structures, safety considerations override factors of economy where the lives of personnel could be jeopardized as the result of even "low probability" of failures. Many military specifications for steels cover essentially identical requirements for chemical composition and mechanical properties as those contained in the "standard" industrial steel grades used for conventional structural applications. However, supplemental requirements for fracture toughness properties are mandatory in the Navy specifications. These supplementary requirements may vary for different applications because they are aimed at providing different degrees of fracture resistance for different structural applications.

Fracture-safe performance of a structure requires formulation of a fracture control plan (FCP). The principles that define the metal's resistance to fracture extension must first be understood and then used to form the basis for the FCP. Equal consideration must be given to the service requirements that may be unique to a particular application (e.g., a requirement for ship hulls to withstand plastic deformation in the event of an accident). The principles inherent to fracture-safe assurance and proper materials selection have been evolved from long-term (two decades) NRL research; they are now established as Navy requirements and have been widely reported (1-7). From these principles it has been possible to derive practical engineering evaluation procedures, such as the NRL drop-weight nil-ductility transition (NDT) test and the Dynamic Tear (DT) test (8-10). Data from these tests, in combination with appropriate analysis diagrams (1-3), provide the necessary input for optimized FCP for welded structures. Summary reports describing the philosophy, concepts, and engineering significance of the above concepts have been recently published (11,12).

In formulating the FCP for the explosives containment vessel, it must be realized that any metal (test specimen or structure) can always be made to fracture when overloaded above its UTS. In the presence of flaws (cracks, notches, or metallurgical defects) the load-carrying capability of a metal can be reduced significantly, and the potential for failure is increased. Thus, the toughness requirements for an explosives containment vessel that must have the capability to withstand plastic deformation are obviously much more severe than those required by conventionally designed structures which see primarily elastic loading.

Stringent safety requirements should be imposed on any explosive containment vessel used within urban areas. Because of the significant degrading effects of "low" temperature on the fracture resistance of the low-strength structural steels, it is imperative to assure the use of materials that exhibit a high resistance to plastic fracture at all probable service temperatures. This requirement means that the properly selected containment vessel material must not develop catastrophic (brittle) fracture at any service temperature. Furthermore, in the event that a very large charge does overload and fail the vessel, this failure must only occur by ductile tearing after the development of significant plastic bulging. This requirement significantly reduces the risk of fragmentation.

EXAMPLES OF CATASTROPHIC PRESSURE VESSEL FAILURES

The use of pressure vessels as explosive containment vessels is not new; some public safety organizations have had operational containment systems for over 30 years (13). Blast chambers are also widely used by the explosives industry. Figure 1 illustrates a conventionally designed pressure vessel before (left) and after (right) its use as an explosion blast chamber. The primary purpose of the vessel was to muffle the sound resulting from the testing of small amounts of experimental explosives being developed by the explosives industry. The materials and fabrication procedures specified for this blast chamber conformed to all requirements for standard materials and regulatory codes for construction of pressure vessels. However, the vessel failed catastrophically when "it wasn't supposed to" because the designer did not consider fracture as a potential failure mode. It is particularly noteworthy to emphasize that the catastrophic failure illustrated in Fig. 1, right, occurred at a temperature of 60° F, that is, well above minimum winter temperatures in the United States.

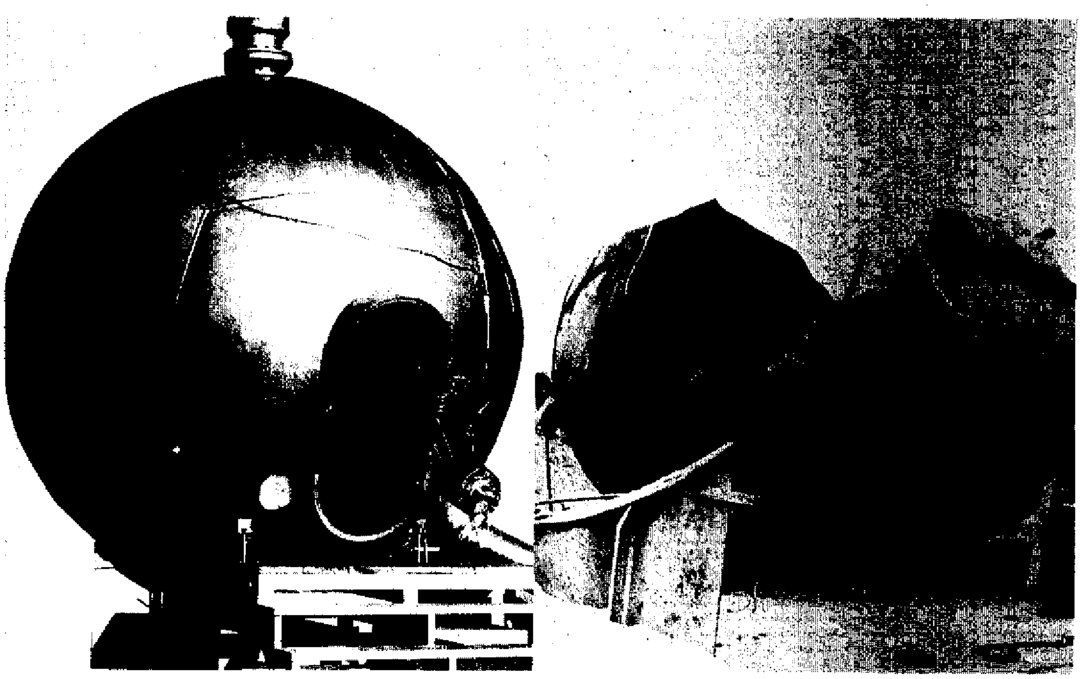

Fig. 1—Explosives blast chamber prior to fracture (left) and after fracture (right). The test took place when the ambient temperature was below the NDT temperature of the steel.

The catastrophic fracture in this blast chamber initiated from a small weld crack located at the intersection of the shell with the door port. This fracture would not have occurred if the vessel temperature had been maintained somewhat above its NDT temperature. Since ambient outdoor temperatures are not controllable, a blast chamber material must be selected to have a sufficiently "low" NDT temperature to preclude catastrophic failure at the service temperatures. Details concerning brittle fractures in relation to the NDT temperature are fully covered in ref. 1.

Figure 2 illustrates the shattering fracture that can be developed in pneumatically loaded pressure vessels at temperatures below or near the NDT temperature of the steel. This failure involved a high-pressure, compressed-air flask of seamless tube construction. The purchased flask had been constructed to conform to standard ASTM A372-IV specifications. Fragmentation of the flask occurred at a nominal shell stress of approximately 1/4 of the UTS during a routine air-leak test conducted at 80° F.

It is obvious from the appearance of the pressure vessel failures shown in Figs. 1 and 2 that high fracture resistance properties should be required for materials contemplated for explosive containment vessels. An improper choice of materials could lead to devastating results if the explosive containment vessel itself performed as a fragmentation bomb in the event of premature detonation during transportation of an explosive device through urban areas. The frightening consequences of possible fragmentation of the containment vessel may be emphasized by pointing out that the failure shown in Fig. 2 not only "destroyed the proof-test-pit facility" but also lost approximately 600 lb of the vessel steel fragments. They were presumed to have been "lost when they fell into the river" located a few hundred feet from the testing-pit facility.

The fracture control plan implemented for the MPD project system was aimed at precluding catastrophic failures within the engineering limits of all materials used irrespective of the size of charge to be contained. The stress to which the containment vessel will be subjected is determined by the size of the bomb, and this cannot be controlled by design restrictions. Therefore, it should be recognized that the capabilities for the explosive containment built into the MPD project system are limited, and the system is not expected to cope with large bombs, such as the truck-load of ammonium nitrate used in early 1970 to destroy one of the buildings on the campus of the University of Wisconsin.

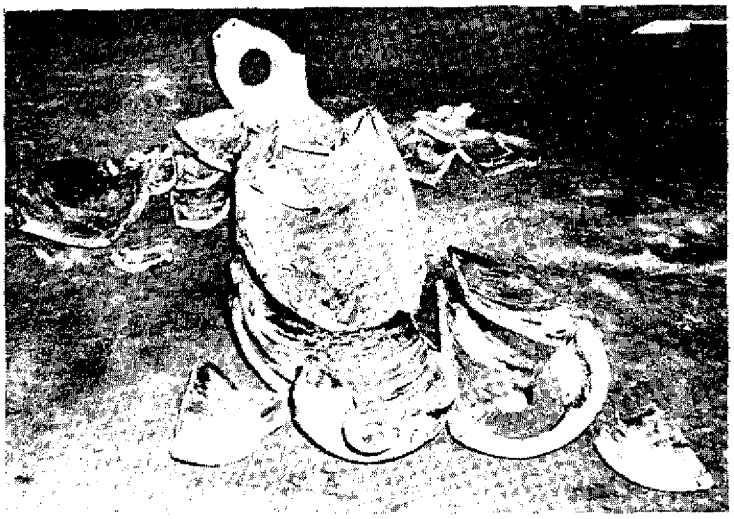

Fig. 2—Catastrophic fragmentation of a seamless, high-pressure, air flask. The failure occurred at a temperature 10°F below the NDT temperature of the steel during a routine air pressure test for leaks.

SELECTION OF THE EXPLOSIVES CONTAINMENT VESSEL FOR THE MPD PROJECT SYSTEM

For use in this program, the Metallurgy Division acquired two steel, 3-ft-diameter, 8-ft-long, cylindrical pressure vessels that were fabricated and tested as part of a research program by Electric Boat Division, General Dynamics Corporation, under National Aeronautics and Space Administration (NASA) Contract NAS 3-11183. The program was aimed at demonstrating the feasibility of using one of the new maraging steel alloys developed during the 1960's for large-diameter, solid-propellant rocket cases. The research program included conventional evaluation of materials, demonstration of industrial fabrication capabilities for section thicknesses (nominally 3/4-in.-thick plate) of interest, extensive nondestructive inspection tests, and final destructive tests by hydrostatic proof tests of the fabricated vessels. A brief summary of the program results is given in Table 1.

The steel involved in the NASA-Electric Boat research program was one of the high-yield-strength maraging steel alloys of a nominal 12% Ni-5% Cr-3% Mo composition. The interactions of metallurgical and mechanical factors in development of optimum strength-toughness relationships for the maraging and other ultrahigh-strength steels have been reported (14). Although studied and used extensively in various research programs, there has been no commercial application of 12% Ni maraging material to date, and consequently, no standard specification has been written for the 12% Ni maraging steels.

As noted in Table 1, the particular heat (L-50897) of 12% Ni maraging steel (from which one large plate was rolled to provide material for the research pressure vessels) was processed from double-vacuum-melted material; i.e., an electric furnace heat of steel was vacuum-induction melted (VIM) and subsequently vacuum-arc remelted (VAR). NRL studies have shown that such advanced VIM + VAR metal processing techniques are required to develop optimum strength-toughness relationships in all ultrahigh-strength steel alloys (14). It is also noted in Table 1 that the pressure vessels were fabricated exclusively with the gas-tungsten arc (GTA) welding process using similarly high-purity, premium-quality filler metal. Because of the optimum strength-toughness relationship and excellent fabrication procedures (14,15), two of these unique 12% Ni maraging steel pressure vessels were acquired by NRL for use in the MPD Project.

These vessels each contained a through-thickness fatigue crack in the cylindrical shell near one of the longitudinal weld regions. These flaws resulted from a pressurization fatigue test in the NASA-Electric Boat program. The cracks were weld-repaired by Electric Boat using the same filler metal and GTA welding procedures employed for the original circumferential head-to-shell and longitudinal shell welds in these pressure vessels. In addition, it was necessary to remove one hemispherical end closure from each vessel because of the MPD requirement for an open-ended containment vessel. A 1-ft segment of the cylindrical section was removed from each vessel to provide roadway clearance for the explosive containment system vehicle.

EVALUATION OF CONTAINMENT SYSTEM MATERIALS

Even before the vessels were obtained for the MPD project, the adequacy of the 12% Ni maraging steel for use in an explosives containment system was predetermined by DT test methods and associated Ratio Analysis Diagram (RAD) interpretive procedures developed by NRL (3). The DT test provides a unique method for characterizing fracture resistance over the full range of fractures potentially possible in structural steels. These fractures can range

Table 1
Summary of Program Results for 12% Ni Maraging Steel Pressure Vessels, NASA Contract 3-11183

(a) Nominal Composition and Processing

Materials	Heat No.	Melt Process		%NI	%CR	%Mo	%Al		%Ti
Shell and Heads Weld Metal Weld Metal	L-50897 G-04836 G-1686A	VIM+VAR VIM VIM		12.22 11.69 11.91	5.10 5.04 5.01	2.95 3.16 3.15	0.31 0.29 0.26		0.32 0.32 0.27
Materials	Heat No.	%C	%S	%P	%Mn	%Si	0*	N*	H*
Shell and Heads Weld Metal Weld Metal	L-50897 G-04836 G-1686A	0.001 0.006 0.020	0.004 0.005 0.005	0.002 0.010 0.004	0.13 0.03 0.01	0.07 0.13 0.08	2 10 13	40 52 46	1 1 1

*Parts per million

Note: Heat treatment and welding process: Shell plate and head materials were furnished in the mill-annealed (1575°F/1 hr) and water-quenched conditions. Pressure vessels were welded with gas-tungsten-arc (GTA) process using 100% argon-shield gas. Pressure vessels aged after fabrication (900°F/8 hr) followed by air cooling.

(b) Average Mechanical Properties

Materials	YS (ksi)	UTS (ksi)	El (%)	RA (%)	Charpy V at 75°F (ft-lb)
Shell Weld	190 180	197 187	15 14	68 55	52(WR); 110(RW) 53(all weld)

(c) Pressure Vessel Tests

No.	Flaw Condition	Test	Result
1	None	Hydrostatic proof	Burst at 10,600 psig (Nominal hoop stress, σ_H = 228 ksi).
2	None	Hydrostatic proof	Burst at 9850 psig (Nominal hoop stress, σ_H = 212 ksi).
3	1/4-in. radial mismatch	Hydrostatic proof	Burst at 10,200 psig (Nominal hoop stress, σ_H = 220 ksi).
4	2-1/2-by-5/8-in. EDM† notch	Fatigue cycled	Pressurized 509 cycles 0 to 3400 psig + one cycle to 5600 psig when leak-without-fracture occurred from 3-in.-long crack.
5	2-1/2-by-5/8-in. EDM† notch	Fatigue cycled	Pressurized 401 cycles 0 to 3400 psig + one cycle 0 to 7210 psig + five cycles 500 to 6550 psig + one cycle 500 to 7150 psig when leak-without-fracture occurred from 3-in. long crack.

†EDM = Electrical Discharge Machine.

from the low stress-brittle type to the highly ductile-plastic type. The RAD provides a simple graphical means for translating fracture toughness criteria into structural performance parameters.

Figure 3 presents the results of DT tests conducted with full-thickness (0.8-in.) plate specimens in the final heat-treated condition that is equivalent to that of the pressure vessel material. The DT energy values are not degraded by test temperatures ranging from −20° to 70°F. Thus, for the span of ambient service temperatures expected in the metropolitan District of Columbia area, the fracture resistance of the 12% Ni maraging steel pressure vessels

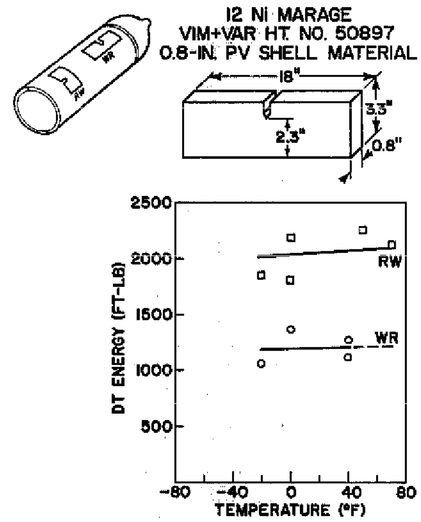

Fig. 3—DT test results from the shell material of the 12% Ni maraging steel comprising the MPD vessel. The difference in the RW (strong) and WR (weak) orientation data reflect the anisotropy expected from plate material that is not uniformly cross rolled. Note that the toughness is essentially constant over a wide temperature range.

remains essentially constant. The significant difference in DT energy obtained for different orientations of specimens results from directionality characteristics normally developed in large plates that are not uniformly cross rolled. This directionality is used to good advantage in vessel fabrication, however. The plates which form the cylindrical section are oriented such that the maximum toughness is encountered by a flaw which tends to develop longitudinal splits in the vessel. A longitudinal split is most likely to occur because it is the result of the maximum or hoop stress in a cylinder.

To determine the significance of DT energy values with respect to expected structural performance, the data must be indexed to the RAD developed for standard 1-in.-thick DT specimens of high-strength steels. The average DT energy values shown in Fig. 3 for the 12% Ni maraging steel pressure vessel shell material are plotted on the RAD shown in Fig. 4*. Engineering representations of fracture toughness are given on the RAD in terms of either DT energy or plane strain fracture toughness K_{Ic} values. Neither of these values by itself provides a measure of absolute fracture toughness in terms of a stress level-flaw size tolerance. Instead it is better to think in terms of the ratio of K_{Ic}/σ_{ys}. This ratio is a measure of the amount of local plasticity that must develop in the vicinity of a flaw for fracture to occur. Hence, it is an absolute measure of fracture toughness.

The system of K_{Ic}/σ_{ys} ratio lines on the RAD are related to expected flaw sizes for fracture of brittle alloys stressed to $(1/2)\sigma_{ys}$ or σ_{ys} as noted on the RAD. The slope of the K_{Ic}/σ_{ys} lines on the RAD illustrates the general requirement for an increase in fracture resistance as yield strength is increased to maintain a fixed level of structural performance.

*All fracture toughness scales on the RAD are referenced to standard 1-in.-thick DT specimens (9). DT energy values measured with other size specimens are normalized for RAD plots using the relationship developed by NRL investigators (16):

$$DTE = P_r(d)^2(B)^{1/2},$$

where DTE is the dynamic tear energy, P_r is the plastic instability resistance factor (a material constant), d is the distance the fracture propagates (the net width), and B is the section thickness.

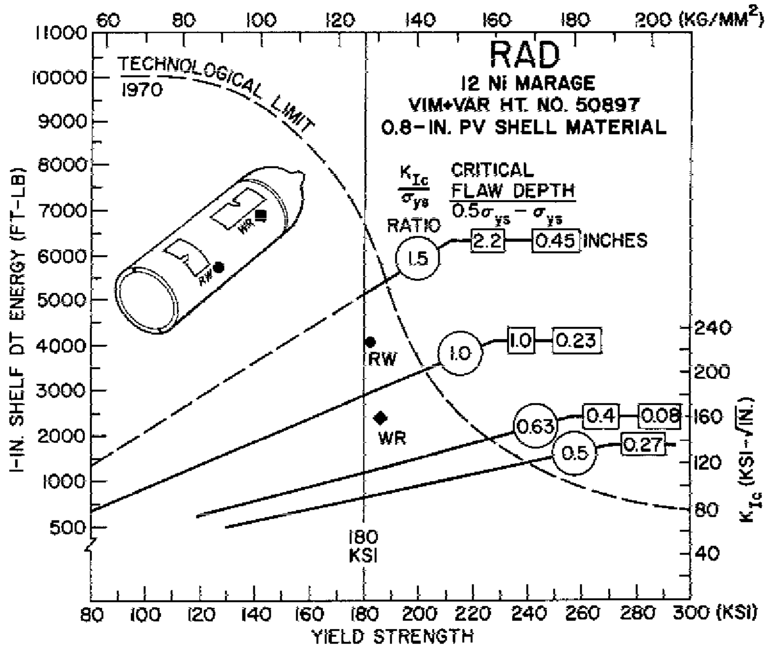

Fig. 4—RAD used to assess the practical significance of fracture toughness determined by means of DT or fracture mechanics K_{Ic} tests. The RAD position of the MPD vessel material from both RW and WR orientations indicates that brittle fracture, at stresses below the yield stress, is not possible.

A given K_{Ic}/σ_{ys} ratio line also defines the frangibility (easily broken or glasslike) limit that can be measured with a given section thickness specimen. The frangibility limits are indicated by $K_{Ic}/\sigma_{ys} = 0.5$ for 5/8-in.-thick plate, 0.63 for 1.0-in.-thick plate, and 1.0 for 2-1/2-in.-thick plate. The significance of DT energy values, which lie above the frangibility ratio line for the section thickness being evaluated, is that the higher RAD positions represent increasing resistance to plastic (ductile) fracture. Conversely, the DT values that lie below the frangibility ratio line signify that the metal can fracture in a brittle fashion at stress levels below yield.

The RAD locations of the 12% Ni maraging steel pressure vessel shell material (normalized to a 1-in. thickness) are shown in Fig. 4 to be significantly above the frangibility limit ratio line for 1-in. plate ($K_{Ic}/\sigma_{ys} = 0.63$) for both orientations of specimens evaluated. Prediction of structural performance, therefore, is that catastrophic *brittle* fractures (involving fragments) cannot be developed, and only failure by plastic ductile tearing preceded by bulging of the vessel material can be expected for both orientations of the 0.8-in.-thick pressure vessel shell material. This type of failure would be caused by a bomb larger than the rating of the vessel. In other words, this explosive containment vessel cannot fail unless bulging develops causing the shell stresses to rise above the UTS.

The material used in the hemispherical head is similar to that of the shell in terms of toughness and yield strength. Since the thickness of the head is 1-1/8 in., as compared to 0.8 in. for the shell, and the stresses are no greater than those of the shell (even for the same thickness), the cylindrical shell is considered to be the critical area for fracture initiation.

FABRICATION AND MATERIALS EVALUATION OF A PROTOTYPE MPD PROJECT SYSTEM

Fabrication and assembly of a prototype MPD system was started after establishing from the RAD that the 0.8-in.-thick maraging steel pressure vessels would not fail at elastic stress levels. The metallurgical characteristics of fully annealed and aged (hardened) maraging steels are unique; the heat-affected zone (HAZ) produced by welding on hardened maraging steels becomes soft and the UTS is decreased significantly. Prolonged-aging heat treatments also can result in overaging with a reduction in both strength and fracture resistance. These facts dictated that the weld repair of the fatigue-cracked region in each vessel could not proceed in an arbitrary fashion. Restoration of the strength and fracture resistance properties of the weld-repaired regions required local postweld-aging heat treatments at 900°F for 3 hrs, obtained with electrical resistance strip heaters on the area monitored with thermocouples. To preclude the necessity for additional aging heat treatments and to maintain strength and fracture resistance in the vessels, it is considered essential to stipulate that no further welding be permitted on the vessel material.

A special base was designed by the authors and fabricated by the Engineering Services Division, NRL, to hold the vessels in an upright position. Mounting of the base and pressure vessel on a truck provided a mobile explosive containment system. The base and pressure vessel mounted on a surplus (nonoperable) dump truck are shown in Fig. 5. The four restraining hooks connected to 1/2-in. steel cables with turnbuckles shown in Fig. 5 were

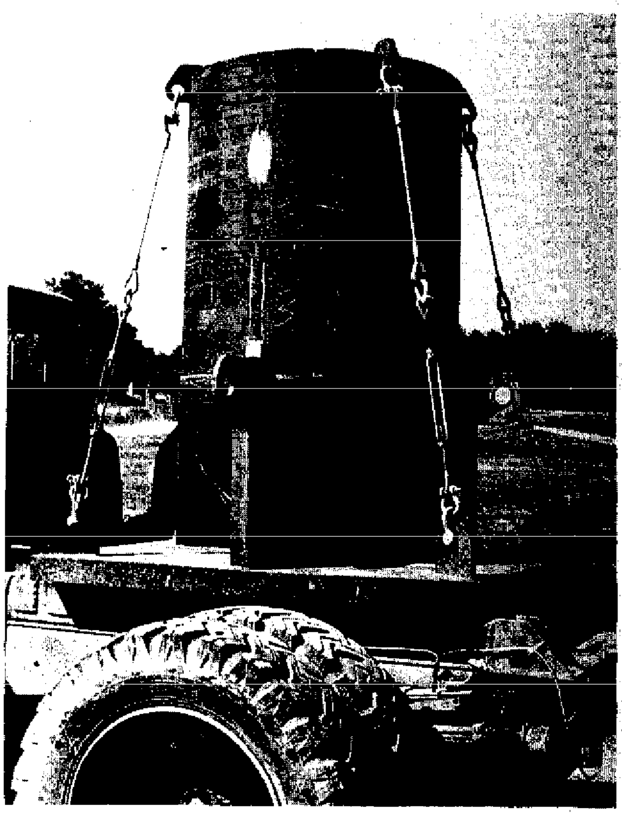

Fig. 5—MPD explosives containment vessel mounted to truck body just before the initial proof test.

added to the system to comply with the Department of Transportation requirements to hold the vessel securely while it was towed on interstate highways from NRL to the site for proof tests.

A schematic drawing of the support base used for the MPD project prototype system is shown in Fig. 6. The support consists of a 3-by-42-by-56-in. base plate to which a pair of vertical saddles (designated P-L cross) of 2.2-by-24-by-41-in. steel plates were welded. The base was fabricated from HY-80 steel plate available at NRL and welded with MIL-S-11018 shielded-metal arc (SMA) electrodes. Each section was prepared for welding (including the interior radii of the P-L cross members) with oxyacetylene torch burning equipment to minimize normally expensive machining operations. A 1/2-in.-thick brass shim was placed between the bottom of the hemispherical vessel head and interior radii of the vertical P-L cross members to preclude steel-to-steel indentation contact between the pressure vessel and support base members during an explosion test.

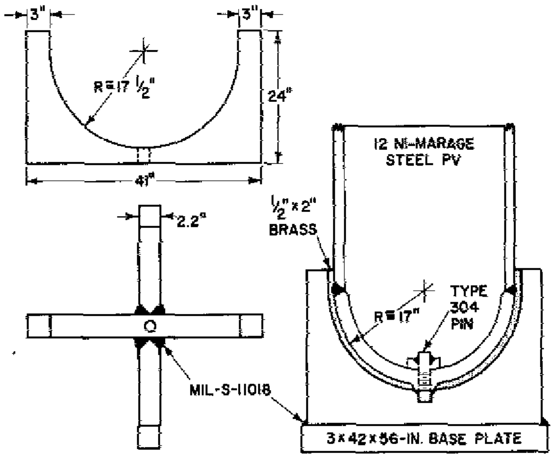

Fig. 6—Schematic illustration of the P-L cross that supports the explosives containment vessel. This support system, pictured in Fig. 5, was used for the two proof tests.

The specification and use of HY-80 steel and MIL-S-11018 SMA welding electrodes for the support base precluded the necessity of evaluating fracture resistance of these materials. These materials had been procured to military specifications (MIL-S-16216G and MIL-E-22200/1 which assured sufficiently high fracture toughness to prevent the possibility of brittle fracture even at temperatures below 0°F. Structural performance expected of HY-80 steels is shown in Fig. 7 by typical results obtained in explosion bulge tests of an HY-80 weldment conducted at 0°F. The material exhibits a capacity to sustain large plastic deformations before final separation is caused by overload of the explosive charge.

PROOF TESTS OF THE PROTOTYPE MPD PROJECT SYSTEM

Using one of the modified pressure vessels, the MPD project prototype system, as shown in Fig. 5, was proof-tested by the Naval Weapons Laboratory, Dahlgren, Virginia. Two proof tests using different size charges were considered essential to (a) demonstrate the integrity and safety of the system, (b) develop parameters reported in Ref. 17 relating to effects of different intensity explosions detonated within the system, (c) establish data required for refinements of the original system design, and (d) determine the capability of the spring-suspension system of a heavy-duty 4-by-2 dump truck being considered to provide mobility for the system.

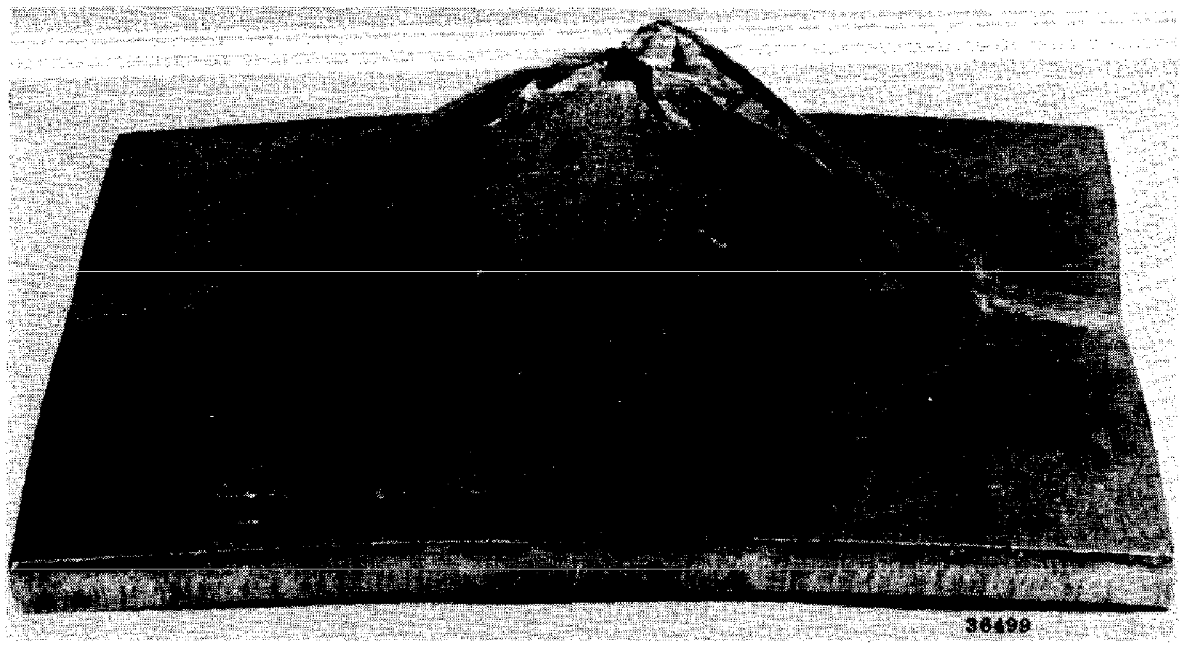

Fig. 7—Typical explosion bulge tests results at 0°F illustrating the high fracture toughness characteristics of welded HY-80 steel plate. Note that this material exhibits extensively high plastic deformation before the metal finally separates because of overload by the explosive charge.

The first test was conducted with a bundle of 14 sticks of special gelatin 60-percent-strength dynamite. The relative intensity of this charge is considered to be approximately equal to that exploded in the U.S. Capitol on March 1, 1971. This explosion was sustained by the prototype MPD project system without damage to the pressure vessel, base, or truck. A stainless-steel plug which had been welded to close the small tapped end penetration in the hemispherical head was found loose inside the pressure vessel, and this end penetration was left open for the next test. The four transportation tie-down steel cables were loosened by the blast and were retightened before proceeding with the next test.

A second proof test was designed to simulate the largest "terrorist type" bomb that could be inconspicuously carried by hand. This bomb consisted of a hard-sided, metal-hinged briefcase (5-by-9-by-17-in.) filled to capacity with 44 sticks of special gelatin 60-percent-strength dynamite. To simulate a detonator mechanism, the contents of the briefcase included a 9-volt dry cell, a standard D-cell battery, and 10 ft of insulated wire.

The larger charge used in this test bulged and cracked the prototype vessel and popped-out the windshield from the truck, but there was no catastrophic failure in the system. Figure 8 illustrates the position of the vessel at the conclusion of the test. Only one of the four transportation tie-down cables and hooks remained engaged with the pressure vessel, but the turnbuckle threads on this cable were severely damaged. Three of the cable hooks were not engaged with the pressure vessel and one of these cables was broken at the lower threaded portion of the turnbuckle. Except for the popped-out windshield, there was no other apparent damage to the dump truck, the base, or the MIL-S-11018 fillet welds holding the P-L cross base to the frame of the truck.

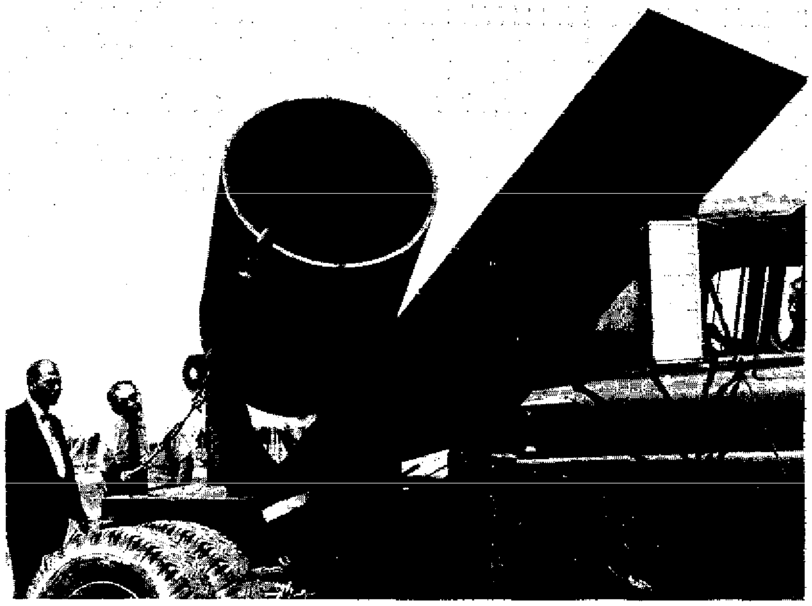

Fig. 8—MPD explosives containment vessel after the second proof test involving 44 sticks of 60% gelatin dynamite. The vessel sustained some local bulging and tearing, but no fragmentation resulted that would have injured bystanders or the driver of the vehicle.

METALLURGICAL AND MECHANICAL ANALYSIS OF PRESSURE VESSEL DAMAGE CAUSED BY SECOND PROOF TEST

As expected, the charge used in the second proof test was large enough to develop stresses that locally exceeded the UTS of the vessel material. The development of bulging and subsequent ductile tearing was in accord with prior predictions. This damage was localized to the cylindrical portion of the vessel at the shell-to-head weld and consisted of a 38-in. circumferential crack, a 1-in. longitudinal shell-plate crack, and localized bulging that caused a 1% increase in the vessel circumference near the head-to-shell weld (local bulging exceeded the tensile ductility).

Figure 9 presents a general view of the 38-in.-long circumferential crack developed in the pressure vessel at the shell-to-head juncture. The area of greatest bulging and widest crack opening is generally located in the center of the photograph within the outlined rectangle 1. At this location, the inside wall of the shell and hemispherical head contained several small craters (approximately 1/4-in. diameter by 1/4-in. deep for the largest) which appeared to have resulted from high-velocity impact of metallic debris. The vertical white arrow marked B⟷B on the vessel indicates the location midway between the two longitudinal shell-to-shell welds. The region of greatest bulging was developed slightly to one side of this location. The two black arrows near the upper right corner of rectangle 1 mark the terminal ends of a 1-in.-long, through-thickness, plate metal crack (white line in photograph) which could be seen from both inside and outside the pressure vessel.

One end of the 38-in. crack terminated in the circumferential weld metal approximately 4 in. to the left of the longitudinal shell weld which is visible in Fig. 9. An enlarged view of

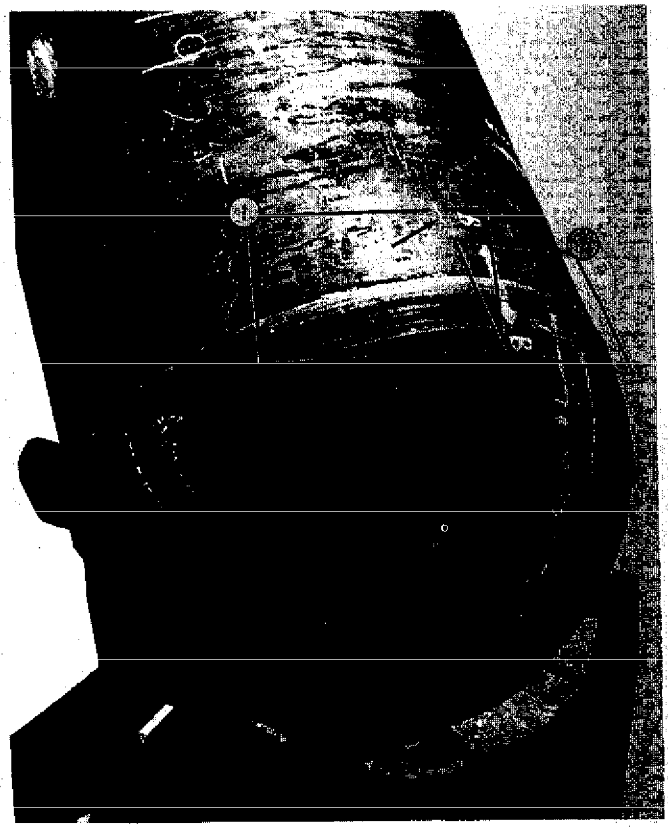

Fig. 9—Region of the MPD explosives containment vessel which sustained the greatest damage as a result of the second proof test. The black arrows indicate a short longitudinal tear sustained by the shell material. Details in the two boxed zones are given in Figs. 10 and 11.

the outlined area in rectangle 1 is shown in Fig. 10. The other end of this crack terminated in plate metal near the right side of the vessel as shown in Fig. 9. An enlarged view of the outlined area contained in rectangle 2 of this illustration is shown in Fig. 11. The relative amount of bulging in the pressure vessel can also be seen in Fig. 11. Except for the terminal ends, visual examination inside and outside of the vessel indicated that all of the 38-in. circumferential crack was in the heat-affected-zone (HAZ) of the cylindrical shell material.

The authors specified that the proof-test charges be centrally located at the apex of the hemispherical end closure head. A schematic illustration of the position of the charges for both proof tests is shown at the top of Fig. 12. It is probable that the placement of the detonators in the charges, as shown at the top of Fig. 12 imparted directional characteristics to the blast which resulted in bulging that was not uniform around the vessel circumference.

The reasons for the resulting 38-in. circumferential crack and the 1-in. longitudinal crack are explained as follows. During the initial instant of the explosion the open-ended containment vessel is expected to behave as if it were a closed vessel. For this case there are three major categories of vessel stresses: (a) the hoop stress σ_H that acts in a direction to

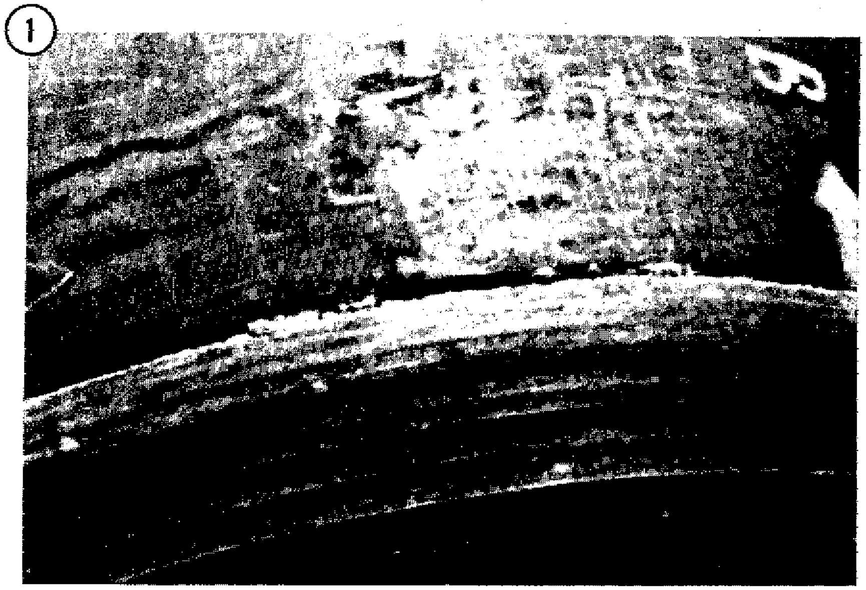

Fig. 10—Close-up to region 1, as illustrated in Fig. 9, showing a portion of the 38-in.-long circumferential tear at the head-to-shell junction weld as a result of the second proof test.

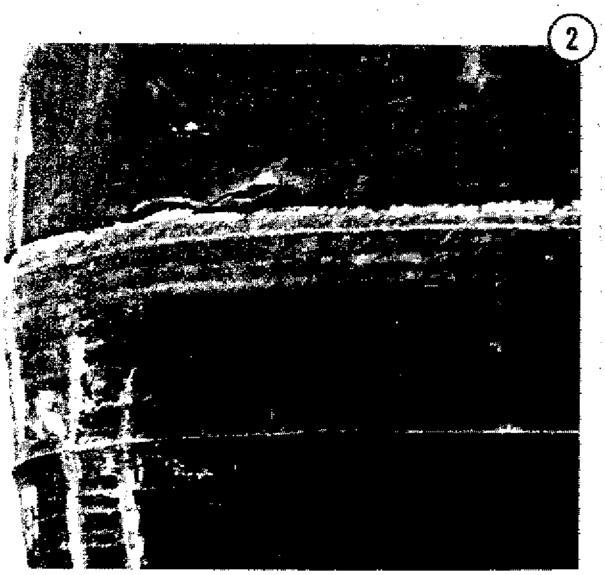

Fig. 11—Close-up of region 2 as illustrated in Fig. 9 showing one end of 38-in. circumferential tear in shell (center) and profile of area of greatest damage in the containment vessel after the second proof test. Localized bulging in the cylindrical shell resulted in a 1/4-in. shift outward (left) from original position in the circumferential shell-to-head weld.

longitudinally split the vessel, (b) the longitudinal stress σ_L that acts to blow the head off the vessel, and (c) a stress in the hemispherical head that is the same in both orientations. The hoop stress is always twice the longitudinal stress ($\sigma_H = 2\sigma_L$); if the head thickness is equal to the cylindrical shell thickness, the stresses in the head are equal to the lower stress value σ_L in the shell.

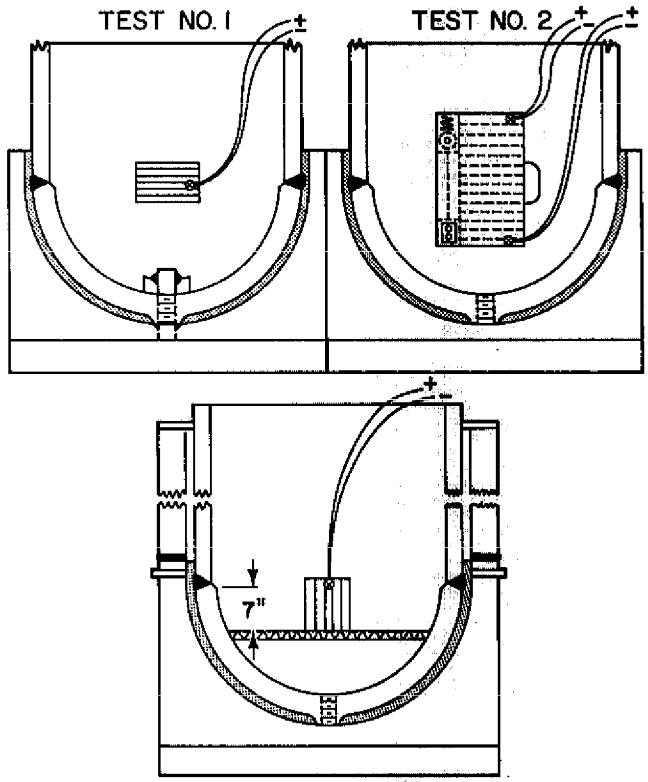

Fig. 12—Schematic illustration of placement of proof-test charges (top) and recommended locations for future tests (bottom). The placement of the detonators in the proof-test charges is believed to have resulted in a directional blast that caused nonuniform bulging of the vessel shell.

An apparent paradox exists in that the 38-in. circumferential tear was many times larger than the 1-in. longitudinal split; yet the relative magnitude of the stresses acting to develop these tears would suggest the opposite occurrence. This result can be accounted for by the anisotropy of the toughness of the vessel material as seen from the DT results in Figs. 3 and 4. Since the vessel is fabricated to take advantage of this anisotropy, the metal's resistance to a longitudinal split is significantly greater than its resistance to a circumferential tear, Fig. 4.

Note that the circumferential crack resided mainly in weld HAZ as opposed to plate material. Toughness data for the HAZ material are not available. However, it is known from the earlier NASA-Electric Boat tests on these vessels that the toughness of this region was only slightly below that of the plate. As proof of this, the longitudinal shell welds exhibited no tearing (in weld or HAZ) during the proof tests while the shell material did develop a small tear at the region of greatest bulging.

The stress pattern in the circumferential weld was also aggravated by two additional mechanical considerations. First, this region was GTA welded from the outside using a consumable weld insert to provide a sound weld. The use of a consumable insert is standard practice in providing high-quality pipe joint welds. Nevertheless, the inside portion of the weld was not ground smooth and therefore provided a stress concentration. The stress concentration results in a higher local stress than the expected σ_L value. The longitudinal shell welds, on the other hand, were ground smooth to eliminate this stress concentration. Second, the hemispherical head thickness was 40% greater than that of the shell (1-1/8 in. vs 0.8 in.). The joining of the "thin" shell to the "thick" head resulted in a second stress concentration. The fact that the head material was so much thicker than that of the shell resulted in even lower than expected σ_L stresses in the head region. This explains why the circumferential tear resided in the HAZ on the thinner "shell side" of the weld as opposed to the thicker "head side."

Consideration of all the above factors suggests that the optimum location for future charges in the MPD vessel should be within the hemispherical head, below the circumferential head-to-shell weld, as shown at the bottom of Fig. 12.

FINAL FABRICATION OF THE MPD PROJECT SYSTEM

The primary NRL objective of providing the DC-MPD with a fracture-safe explosives containment vessel was achieved; convincing evidence was provided by the successful proof tests of the prototype MPD system. Observations of the proof-test results (which were documented on high-speed movie film), however, suggested that some modification be made to the support base to provide improved performance for the final MPD project system.

Figure 13 presents a view of the modifications made to the original support base developed in this study. These modifications consisted of (a) welding a 1/2-by-42-by-42-in. HY-80 plate section to add rigidity to the top of the original P-L cross and serve at that level as a stepping platform for systems operating personnel, (b) welding 2-by-3-by-33-in. steel sections to extend the vertical members of the P-L cross, and (c) welding a 1/2-by-3-by-42-in.-O.D. ring of HY-80 steel plate at the top of the vertical members of the P-L cross.

To eliminate the "rocket-jet" effect noticed in the second proof test, the tapped end penetration in the hemispherical head was closed by inserting a threaded bolt from outside the vessel. The presence of the P-L cross precludes any hazardous ejection of the bolt during an explosion in the containment vessel. The 1/2-in.-thick brass shim was "glued" between the bottom of the hemispherical vessel head and interior radii of the vertical P-L cross members using silicone rubber instead of epoxy cement which had been used and separated easily in the first proof test of the prototype MPD system.

After final assembly of the modified base and duplicate pressure vessel (nominally identical in all respects to the one proof tested), the MPD project system was mounted and welded to the chassis of a new truck procured by the DC-MPD. Figure 14 illustrates the completed MPD project system.

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

The concept of using pressure vessels for explosives containment is not new; approximately one dozen bomb container transport systems constructed within the past 30 years for other metropolitan jurisdictions have been reported by Stevenson (13). These explosives containment systems vary in size and design. For example, some systems feature single- or double-walled pressure vessels open at one or both ends; other systems feature rectangular box configurations or loosely woven, steel-cable cylinders to contain, disperse, and/or direct blast pressures and fragments. All of the systems are constructed with steel and although none reported have yet been required to withstand the detonation of an actual terrorist bomb, several are reported to have withstood one or more test detonations conducted with charges comprised of 40% dynamite.

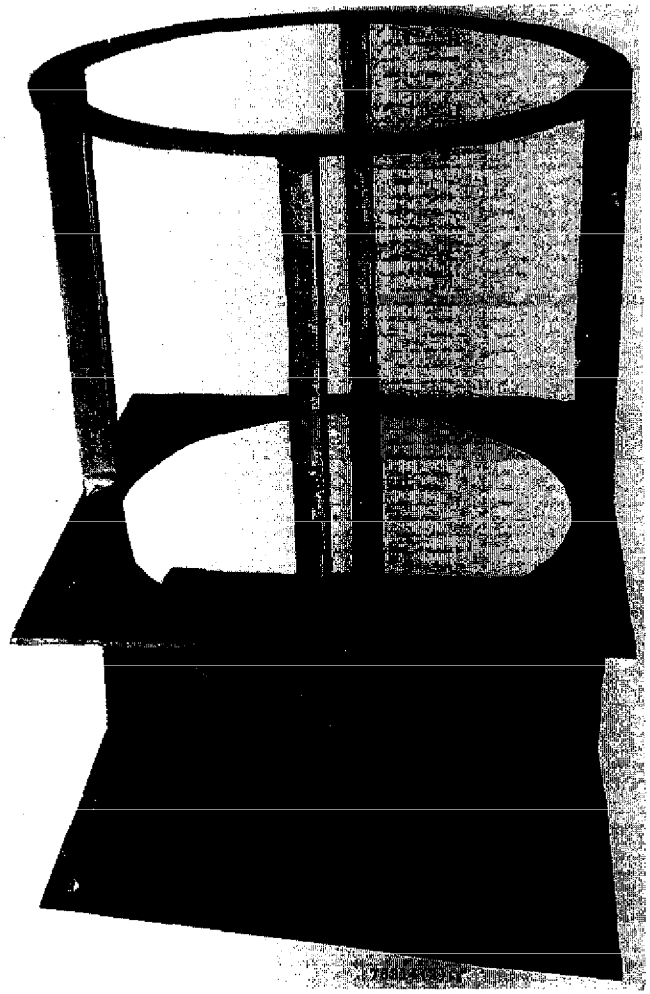

Fig. 13—Final construction of P-L cross support base as modified by extensions of vertical members and 1/2-in.-thick rectangular and circular plates to hold the containment vessel upright.

The steels involved in construction of these bomb container transport systems are described as "1-in.-thick armor plate steel," "3/4-in.-thick cold-rolled steels," "1/2-in.- and 1-in.-thick mild steel," "1/4-in.-thick steel plate" and "5/8-in. heat-treated 125-ksi UTS steel." Such nondefinitive identification of the steels suggests that these systems are of conventional design made with standard steels without specification or knowledge of fracture resistance properties. In the absence of this information, the adequacy of any test to insure fracture-safe performance at all ambient temperatures can be questioned. In fact, a warm summer-day proof test could give highly misleading confidence in the expected performance of one of the above steels on a cold winter day. The same vessel might be fragmented or shattered catastrophically on a cold day by the detonation of a terrorist bomb or even by another test charge of one-half the size used in the summer-day proof test.

Something new has been presented in completion of the MPD project described herein. For the first time in any explosives containment system, all materials used in the system were selected and evaluated on the basis of meaningful fracture control plan (FCP) criteria. The FCP was aimed at assuring the absence of catastrophic (brittle) fractures within the

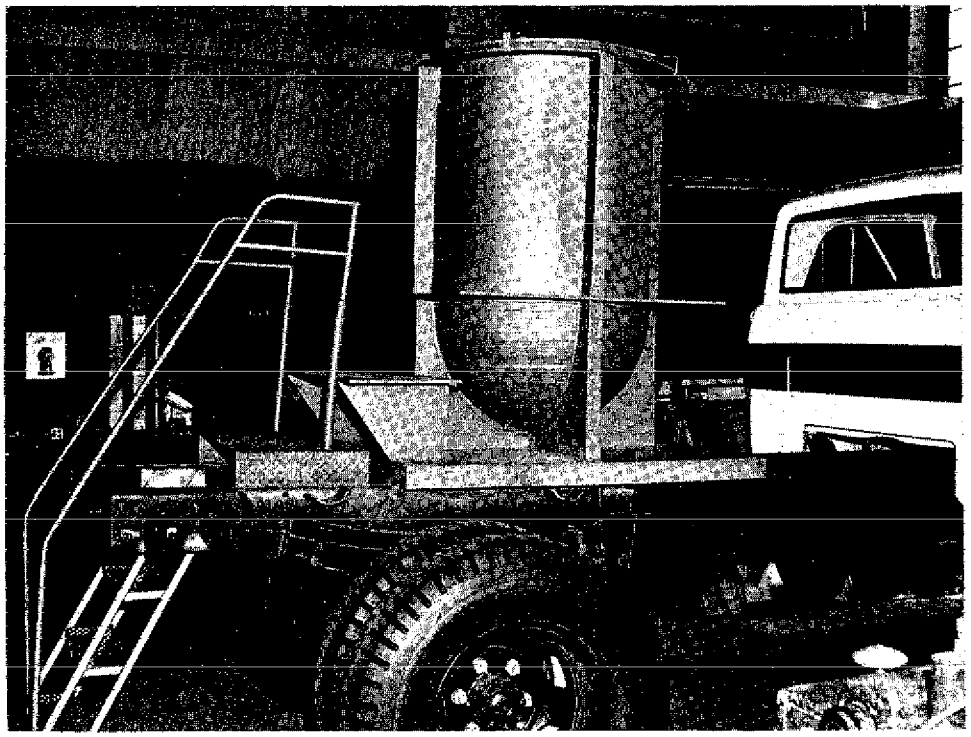

Fig. 14—Completed MPD project explosives containment system assembled and mounted on new DC-MPD truck.

engineering limits of all materials used in the explosives containment system irrespective of the size of charge detonated within the system. Fracture toughness criteria determined with the most advanced metal characterization procedures were used in combination with NRL-developed principles for fracture-safe design. It was concluded that even large detonations that exceed the UTS of the containment vessel could do so without fragmentation of system materials. Proof tests of a prototype system were conducted with charges larger than conceivable terrorist bombs that could be inconspicuously carried by hand. The results obtained in these tests demonstrated conclusively that the structural performance of all MPD project system materials conformed to predictions established by the FCP criteria.

The following conclusions and recommendations are warranted:

1. The DC-MPD has been provided with an explosives containment system that is considered to be fracture-safe within the limits established by proof tests of the prototype system described above.

2. The DC-MPD project system should be proof-tested using a charge equivalent in intensity to that developed by 14 sticks of 60-percent-strength special gelatin dynamite to demonstrate the adequacy and capability of the new truck to provide required mobility for the system. To obtain the worst conditions for this purpose, the location of detonators in all test charges should be aimed (as shown at the bottom of Fig. 12) to direct the blast toward the bottom of the hemispherical head rather than toward the circumferential shell-to-head weld.

3. Insofar as is practicable, the proof test of the DC-MPD project system should be monitored with quantitative-type blast gages around the test area to establish effects of blast wave and determine the degree of danger to system operating personnel, innocent bystanders, and structural damage (e.g., window breakage). This information should prove useful in the event of unplanned explosions during transit with a suspected bomb.

4. The use of a bed of solid material (e.g., sand or fiberglass) in the bottom of the pressure vessel is considered objectionable because it adds considerably to the amount of solid-debris that can be ejected from the top of the pressure vessel. It is suggested that a flat-bottomed nylon net be suspended horizontally to position bombs or test charges at a location approximately 7 in. below the circumferential head-to-shell weld.

5. The use of a bomb-blanket thrown or held loosely over the open end of the pressure vessel to reduce blast velocity and trap fragments directed upward is NOT recommended until a suitable "hold-down" system is devised and proved safe by adequate tests. The violent release of compressed air in deliberate burst tests of air flasks conducted by the Navy following the flask failure shown in Fig. 2 was found to be sufficient to lift and move a 20-ton mass (comprised of 4-by-4-in. timbers supporting a steel frame secured by a torpedo net) some 10 feet above and 10 feet to one side of its original position over the 10-by-15-by-20-ft test-pit enclosure.

In final summary, it is sad to realize that bomb container transports are needed or even desired by some public safety agencies. However, it is even more tragic to recognize that some existing or proposed explosives containment systems are constructed with "standard" steels which may possibly behave as lethal fragmentation bombs because of the effects of cold temperature and/or the failure of designers to specify adequate fracture toughness requirements. (These containers must be proof-tested at low temperatures.) What is needed is a safe and functional bomb container and an efficient transport system at a reasonable cost. The MPD project system is safe and functional, but the cost of procurring an equivalent 12% Ni maraging steel pressure vessel, which was salvaged for this application, is conservatively estimated at approximately $35,000.00 to $50,000.00. However, other materials of lesser cost are available and should perform in an acceptable manner. Nevertheless, the authors recommend that safety and protection in this application should not be compromised in the interests of budget limitations. It is also emphasized that there need be no compromise if the explosives container system is designed and constructed using standard steels with added supplementary requirements for fracture toughness as is the practice for critical Navy structures.

The design of new and improved systems should consider double-walled pressure vessel construction. The space between the walls should be filled with compressible, energy absorbing materials rather than incompressible solids, such as dry sand. The latter would tend to promote destruction of the system by detonation of any charge large enough to produce plastic deformation of the inner vessel wall. The resultant forces would be transmitted by the incompressible solid to the outer vessel wall. The concept of a double-walled pressure vessel specifically designed for explosives containment purposes is shown in Fig. 15. Welding of the inner vessel wall to the hemispherical head is not required, and the inner wall and material placed between the walls should be considered expendable. A research program is recommended to optimize a design and construct and evaluate (at the lowest expected service temperature) a prototype system which would combine features of safety, economy, and efficiency in a bomb transport system that could be locally manufactured using properly specified "standard" steels and weld metals.

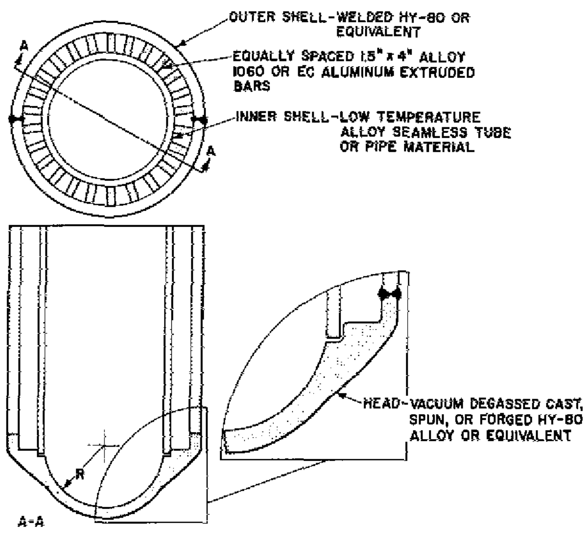

Fig. 15—Concept of double-walled pressure vessel construction recommended for design studies to develop a safe, economical, and efficient bomb transport system.

ACKNOWLEDGMENTS

The two pressure vessels used as primary explosives containment vessels in the prototype and final MPD project system were donated by the National Aeronautics and Space Administration (NASA). Other materials used in the system were donated by NRL. Proof tests of the MPD project system were conducted by the Naval Weapons Laboratory (NWL), Dahlgren, Virginia. All materials and work authorized or conducted by NRL, NASA, and NWL under the MPD project were donated as a public service.

Significant contributions received from other NRL personnel during various stages of the MPD project are acknowledged as follows: B. F. Brown and D. A. Halcombe for technical coordination in starting the project; J. P. Manning, L. H. Mowbray, and W. R. Payne for fabrication of the prototype and final project system; J. Davenport, C. Forsht, and M. Martin for conduct of experimental studies; G. J. O'Hara for discussions concerning effects of explosions in artillery weapons and development of improved explosives containment systems; and E. A. Lange for the concept of using light-weight aluminum extruded bars instead of heavy lead balls as an energy absorbing medium in the double-walled pressure vessel presented by the authors in Fig. 15 of this report.

REFERENCES

1. W.S. Pellini and P.P. Puzak, "Fracture Analysis Diagram Procedures for the Fracture-Safe Engineering Design of Steel Structures," NRL Report 5920, Mar. 1963; Weld. Res. Council Bull. 88, 1963.

2. W.S. Pellini and P.P. Puzak, "Practical Considerations in Applying Laboratory Fracture Test Criteria to the Fracture-Safe Design of Pressure Vessels," NRL Report 6030, Nov. 1963; Trans. ASME (Series A): J. Eng. Power 86, 429-443 (1964).

3. W.S. Pellini, "Advances in Fracture Toughness Characterization Procedures and in Quantitative Interpretations to Fracture-Safe Design for Structural Steels," NRL Report 6713, Apr. 1968; Weld. Res. Council Bull. 130, 1968.

4. R.J. Goode, R.W. Judy, Jr., and R.W. Huber, "Procedures for Fracture Toughness Characterization and Interpretations to Failure-Safe Design for Structural Titanium Alloys," NRL Report 6779, Dec. 1968; Weld. Res. Council Bull. 134, 1968.

5. R.W. Judy, Jr., R.J. Goode, and C.N. Freed, "Fracture Toughness Characterization Procedures and Interpretations to Fracture-Safe Design for Structural Aluminum Alloys," NRL Report 6871, Mar. 1969; Weld. Res. Council Bull. 140, 1969.

6. W.S. Pellini and F.J. Loss, "Integration of Metallurgical and Fracture Mechanics Concepts of Transition Temperature Factors Relating to Fracture-Safe Design for Structural Steels," NRL Report 6900, Apr. 1969; Weld. Res. Council Bull. 141, 1969.

7. W.S. Pellini, "Evolution of Engineering Principles for Fracture-Safe Design of Steel Structures," NRL Report 6957, Sept. 1969.

8. "Method for Conducting Drop-Weight Test to Determine Nil-Ductility Transition Temperature of Ferritic Steels," ASTM Designation E208-69.

9. P.P. Puzak and E.A. Lange, "Standard Method for 1-Inch Dynamic Tear (DT) Test," NRL Report 6851, Feb. 1969.

10. E.A. Lange, P.P. Puzak, and L.A. Cooley, "Standard Method for the 5/8-Inch Dynamic Tear Test," NRL Report 7159, Aug. 1970.

11. W.S. Pellini, "Principles of Fracture-Safe Design," Adams Lecture 1971, Part I, Welding J. 50, No. 3, 91-s-109-s (Mar. 1971); Part II, Welding J. 50, No. 4, 147-s-162-s (1971).

12. W.S. Pellini, "Integration of Analytical Procedures for Fracture-Safe Design of Metal Structures," NRL Report 7251, Mar. 1971.

13. C.S. Stevenson, "Bomb Transport Vehicles," Police Weapons Center Report Series 6-70.

14. P.P. Puzak and E.A. Lange, "Fracture Toughness Characteristics of the New Weldable Steels of 180- to 210-ksi Yield Strengths," NRL Report 6951, Sept. 1969; Metals Engineering Quarterly, No. 1, 6-16 (1970).

15. P.P. Puzak and E.A. Lange, "Effects of Metallurgical Variables on the Fracture Resistance of 180 ksi (126.5 kgf/mm^2) Yield Strength Steel Weld Metals," NRL Memorandum Report 2234, Apr. 1971.

16. W.S. Pellini and R.W. Judy, Jr., "Significance of Fracture Extension Resistance (R-curve) Factors in Fracture-Safe Design for Nonfrangible Metals," NRL Report 7187, Oct. 1970.

17. R.L. Bort, "The MPD Project: Proof Tests of a Truck-Mounted Container for Explosives," NRL Memorandum Report 2392, to be published.