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DEPARTMENT OF DEFENCE

DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION

MATERIALS RESEARCH LABORATORIES

MELBOURNE, VICTORIA

REPORT

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MECHANICAL PROPERTIES AND FRACTURE TOUGHNESS ASSESSMENT OF M795 AND M549 155 MM ARTILLERY PROJECTILE BODIES MANUFACTURED FROM HF-1 STEEL

D.S. Saunders

Approved for Public Release

JULY, 1986

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Arc-tension, A(T), tests established that the fracture toughness (K_{IC}) of the M549 projectile body was significantly greater than that of the M795 body. It was found that the M549 projectile body had been correctly heat-treated to produce a fully martensitic microstructure, while the M795 projectile body was incorrectly heat-treated resulting in a large volume fraction of non-martensitic transformation products.

For the M549 body, fracture toughness values determined using A(T) specimens agreed well with values reported elsewhere determined using Charpy-sized three point bend (3PB) specimens. For the M795 body, however, good agreement was obtained for fracture toughness values determined at -40°C using both A(T) and 3PB specimens while room temperature fracture toughness values determined using A(T) and 3PB specimens vary significantly because the dimensions of the 3PB specimens were inadequate to obtain valid K_{IC} values.

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CONTENTS

MECHANICAL PROPERTIES AND FRACTURE TOUGHNESS ASSESSMENT OF M795 AND M549 155 MM ARTILLERY PROJECTILE BODIES MANUFACTURED FROM HF-1 STEEL

1. INTRODUCTION

Extending the range of high-explosive (HE) projectiles has been achieved by employing higher muzzle velocities and projectiles with longer, thinner-walled and more ballistically efficient shapes. These changes have resulted in significant increases in the launch stresses experienced by the projectile body, and have required the use of shell steels with higher yield stress values.

When the projectile functions at the target, the steel body is often required to produce a high density of relatively fine fragments. For steels, relatively fine fragmentation behavior is almost invariably associated with relatively low levels of fracture toughness [1-3], i.e. less than 50 MN $m^{-3/2}$. Thus, the combination of high launch stresses and relatively low toughness levels leads to small critical defect sizes, and the possibility of break-up of the projectile during launch, [4].

Steel conforming to MIL-S-50783 (HF-1) is used in the manufacture of bodies for a number of current HE projectiles of US origin which require improved fragmentation characteristics. The 155 mm HE M795 and M549 projectiles are of particular importance to Australia because they can be fired from M198 howitzers which have recently entered service with the Australian Army.

Assessment of the fracture toughness of bodies from the above projectiles can provide a guide to the overall launch safety of the projectiles. In particular, if the stresses within the bodies during rough-handling and launch are known, calculations of critical defect sizes can be made which will provide a basis for acceptance of projectiles into service.

It is essential that basic material data for projectile forgings be compiled in order to assess the quality of production projectile body forgings of low toughness steels. Considerable fracture toughness data for HF-1 steel barstock already exists [5]; however, these values are not necessarily representative of those which will be achieved in production forgings.

The measurement of fracture toughness of thin-walled projectile bodies presents difficulties because only small sections are available for test. This means that not all specimens will meet the size requirements for valid fracture toughness measurements and fracture toughness may have to be inferred from 'invalid' tests using non-standard size specimens.

2. AIM

The aim of this work was to characterize the mechanical properties and fracture toughness of two HF-1 steel bodies from the US M795 and M549 HE projectiles which are shown (un-fuzed) in Fig. 1.

The fracture toughness was to be measured using small-sized specimens; and in the case of the M795 projectile, in two orientations in the projectile wall, viz. the transverse and the longitudinal directions. Arc-tension, A(T), and pre-cracked Charpy three point bend, 3PB, specimens were used in the work described here. Both conform to the dimensional proportions recommended in ASTM standard E399 [6] and represent the largest specimens which can be taken from the walls of the projectiles. The overall sizes of the specimens are tested against the recommendations of the standard, based on the yield strength and toughness of the material.

3. MATERIAL

The two projectile bodies characterized in this work were forged from HF-1 steel (see specification in Table 1). It should be noted, however, that the metal parts specification for the M795 projectile allows the use of AISI 9260 steel as an alternative to HF-1 [7].

The M795 projectile characterized in this work was supplied to MRL under an international defence agreement by the US Army Materials Technology Laboratory (formerly US Army Materials and Mechanics Research Center). A number of M549 projectiles was furnished by the US Government for the trials of the M198 Howitzer held at Pt Wakefield, SA in 1977. One of these projectiles was retained for this metallurgical examination and mechanical property evaluation.

The chemical analyses of the projectile bodies assessed in this work are given in Table 1.

TABLE 1

Chemical Analyses of the M795 and M549 Projectile Bodies
wt %

	C	Mn	P	S	Si	Ni	Cr	Cu	Al	Mo
M795	1.14	1.91	0.023	0.016	0.75	0.09	0.14	0.07	<0.003	<0.01
M549	1.09	1.84	0.010	0.021	0.88	0.09	0.13	0.23	<0.003	<0.01
SPECIFICATION MIL-S-50783										
max.	1.15	1.9	0.035	0.040	1.00	0.25	0.20	0.35	0.02	0.06
min.	1.0	1.6	–	–	0.70	–	–	–	–	–

4. EXPERIMENTAL PROCEDURE

The tensile properties of both projectile bodies were measured using specimens machined in both the longitudinal and the transverse orientations.

An extensive survey of the fracture toughness of the M795 projectile body was undertaken. However, limited availability of material from the M549 projectile after the removal of tensile specimens permitted only a very small number of fracture toughness tests to be undertaken. The orientations of the fracture toughness specimens and tensile specimens taken from the projectile bodies are shown schematically in Figures 2 (a,b) and 3 (a,b).

The fracture toughness of the M795 projectile body was measured using both Arc-tension, (A(T) also known as C-shaped specimens) and 'Charpy' sized three point bend (3PB), specimens conforming to the respective geometries specified in ASTM standard E 399 [6]. The A(T) specimen was cut from annular sections of the projectile and only the inner wall surface was machined to bring the annular section to the required dimensions. The final width (W), of the specimen was 12.9 mm; the outer radius, R_2, was 77.35 mm; the pin-hole displacement to width ratio, (X/W), was 0.5 and the specimen thickness was 6.5 mm. A drawing of the A(T) specimen from the M795 projectile is shown in Figure 4. The A(T) specimens were designated as the C-R orientation, consistent with ASTM E399, and this is the transverse orientation of the forging.

The 3PB specimens, (Figure 5), were taken from both the C-R (T-S) and the L-S orientations. Some 70 3PB specimens were taken from the M795 projectile body with the expectation that the scatter in fracture toughness results [8] could be assessed on a limited statistical basis. The problems encountered with this assessment are discussed in Section 6(c).

The fracture toughness of the M549 projectile body was measured using only a small number of A(T) specimens of geometry similar to those taken from the M795 projectile (Figure 4).

The A(T) specimens were fatigue pre-cracked and tested in a servo-hydraulic test machine. The 3PB specimens were pre-cracked in a modified National Physical Laboratory fatigue testing machine [9]. The stress intensity factor, K, applied to these 3PB specimens was estimated using the analysis of Tada [10] for the cyclic load applied by the NPL machine. In all cases the final 1 mm of crack growth occurred under a maximum, alternating value of K of $\pm 10\ \mathrm{MNm}^{-3/2}$. The 3PB specimens were tested in a bend rig which incorporated roller bearings. This rig, shown in Figure 6, had been developed earlier for the measurement of fracture toughness using the J integral method [11] and hence in this experimental work plane strain fracture toughness was estimated from back-face-displacement records rather than from conventional crack mouth opening displacement with a clip gauge as required by ASTM E399.

Fracture toughness values, K_Q, using the A(T) specimens were determined using the Kapp et al. calibration [12], thus:

$$K = (P/BW^{1/2})[3(X/W) + 1.9 + 1.1\,(a/W)][1 + 0.25(1 - a/W)^2(1 - R_1/R_2)]F(a/W) \tag{1a}$$

where P_Q = load, kN
B = specimen thickness, m
X = offset of the loading pin holes, m
W = specimen width, m
a = crack length, m
R_1 = inner radius, m
R_2 = outer radius, m

and

$$F(a/W) = [(a/W)^{1/2}/(1 - a/W)^{3/2}][3.74 - 6.30(a/W) + 6.32(a/W)^2 - 2.43(a/W)^3] \tag{1b}$$

for $0.3 \leq (\frac{a}{w}) \leq 0.7$; $0 \leq (x/w) \leq 0.7$; $0 \leq R_1/R_2 \leq 1.0$

Fracture toughness values from the 3PB specimens were determined using the following equation, [7].

$$K_Q = (P_Q S)/BW^{3/2}) \times f(\frac{a}{w}) \qquad (2a)$$

where P_Q, B and W are defined above

S = loading span, m

and

$$f(\frac{a}{w}) = 3(a/w)^{1/2} \left[\frac{1.99 - (a/w)(1 - a/w)_{x}(2.15 - 3.93(a/w) + 2.7(\frac{a}{w})^2)}{2(1 + 2(a/w))\ (1 - a/w)^{3/2}} \right] \qquad (2b)$$

5. RESULTS

Summaries of the tensile data for each of the projectile bodies are given in Tables 2 and 3. (Details of individual tests are provided in Tables A1 and A2 of the Appendix).

TABLE 2

Tensile Data for the M795 Projectile Body at 21°C

Orientation	Proof Stress 0.1% MPa	Proof Stress 0.2% MPa	Tensile Strength MPa	Reduction of Area %	Elongation on $4\sqrt{So}$ %
Longitudinal[1]	771 ± 23	782 ± 20	1195 ± 18	19.0 ± 3.0	13.5 ± 1.2
Transverse[2]	766 ± 17	779 ± 16	1194 ± 19	16.5 ± 1.7	11.5 ± 0.7

Notes: 1. 11 tests
2. 8 tests

TABLE 3

Tensile Data for the M549 Projectile Body at 21°C

Orientation	Proof Stress 0.1% MPa	Proof Stress 0.2% MPa	Tensile Strength MPa	Reduction of Area %	Elongation on $4\sqrt{So}$ %
Longitudinal[1]	975 ± 12	978 ± 11	1272 ± 4	19.0 ± 2.7	11.2 ± 1.2
Transverse[2]	976 ± 9	982 ± 5	1279 ± 4	15.8 ± 1.6	9.5 ± 1.1

Notes: 1. 11 tests
2. 8 tests

Summaries of the fracture toughness data for the M795 projectile body are given in Tables 4 and 5 below. (Details are provided in Tables A3 (A(T) specimens), and A4 and A5 (3PB specimen) of the Appendix).

TABLE 4

Fracture Toughness Data for the M795 Projectile Body Measured Using Arc Tension Specimens

Orientation	Fracture Toughness $MNm^{-3/2}$	$2.5\,(K_{Ic}/\sigma_{0.2})^2$ mm	Test Temp. °C
C-R	37.7 ± 2.9	5.9 ± 0.9	21
C-R	31.3 ± 3.0	4.1 ± 0.7	-40

Value of $\sigma_{0.2}$ is taken from Table 2; room temperature value.

TABLE 5

Fracture Toughness Data for the M795 Projectile Body Measured Using Charpy-sized Three Point Bend Specimens

Orientation	Fracture Toughness $MNm^{-3/2}$	$2.5\,(K_{Ic}/\sigma_{0.2})^2$ mm	Test Temp. ^{o}C
C-R(T-S)	47.4 ± 1.4	9.3 ± 0.6	21
C-R(T-S)	32.3 ± 2.0	4.3 ± 0.5	-40
L-S	45.0 ± 3.7	8.3 ± 1.4	21
L-S	35.7 ± 2.2	5.2 ± 0.7	-40

Values of $\sigma_{0.2}$ are taken from Table 2; room temperature values.

The fracture toughness data for the M549 projectile body are summarized in Table 6 below. (Details are provided in Table A6 (A(T) specimens) in the Appendix).

TABLE 6

Fracture Toughness Data for the M549 Projectile Body Measured Using Arc Tension Specimens

Orientation	Fracture Toughness $MNm^{-3/2}$	$2.5\,(K_{Ic}/\sigma_{0.2})^2$ mm	Test Temp. ^{o}C
C-R	47.5 ± 3.4 (1)	5.8 ± 0.8	21

(1) Three A(T) specimens tested

Value of $\sigma_{0.2}$ is taken from Table 3; room temperature value.

6. DISCUSSION

(a) Metallographic Examination

Metallographic examination of specimens taken from the side walls of both projectiles showed significant differences, although both were manufactured from steels conforming in chemical composition to the specification for HF-1 [6].

The M549 RAP projectile body was fully tempered martensite with uniform platelet size through the wall of the projectile; a typical micrograph is shown in Figure 7. The microstructure of the M795 projectile, however, was a mixture of fine pearlite, bainite and approximately 15% tempered martensite; a representative micrograph is shown in Figure 8. It is believed that the desirable microstructure for these 155 mm projectiles manufactured from HF-1 is tempered martensite, and it has been shown that other microstructures tend to reduce the fracture toughness of the steel [13]. On this basis it is considered that the M795 projectile characterized in this work has been heat-treated incorrectly. This mixed microstructure may have been formed by not allowing the projectile to quench to room temperature prior to tempering, since the Ms temperature is approximately $150^{\circ}C$ and the Mf temperature is approximately $0^{\circ}C$ [5].

Both microstructures exhibited appreciable volume fractions of undissolved carbides which is not unexpected for a hyper-eutectoid steel of this composition. These undissolved carbides and the sulphides tended to be present in bands along the forging directions of the projectiles. This was more easily observed in the fully martensitic microstructure of the M549 projectile body, as shown in Figure 9.

The overload fracture mechanisms were studied by scanning electron microscopy. Typical room temperature fracture surfaces are shown in Figures 10 and 11 for the M549 and M795 artillery projectiles respectively. The overload fracture surfaces of both projectile bodies at room temperature were predominantly quasi-cleavage with traces of micro-void coalescence initiated at carbides and inclusions. The quasi-cleavage in the case of the fracture surface from the M549 projectile, Figure 10, appeared to be more fragmented than in the case of the M795 projectile suggesting that the microstructure of the M549 (fully tempered martensite) was tougher than than that of the M795. The fracture surface from the M549 projectile also exhibited fracture along prior austenite grain boundaries due to the presence of thin carbide films on these surfaces. The fracture surface from the M795, Figure 11, showed more classical quasi-cleavage fans due to the largely continuous paths through the ferrite in the non-martensitic transformation products formed because of the incorrect heat-treatment of the projectile.

(b) Tensile Properties

The tensile yield strength properties of the M795 projectile body were lower than those of the M549, although these data exhibited more scatter than for the M549. The tensile properties of the M549 were consistent with production specifications for the forgings, but those of the M795 were below specification because the projectile body was not a fully martensitic microstructure. The mechanical properties of the projectile forgings are summarized in the table below.

TABLE 7

Tensile Strength Levels for 155 mm High Fragmentation Artillery Projectiles Manufactured from HF-1

		Minimum Yield Strength Spec [14] MPa	Minimum Elongation Spec [14] %	Yield Strength This Work MPa	Elongation This Work %
M549 (RAP)	Side Wall	965 (Long)	5	967 (Long)	11.3
	Base	930	4	-	-
M795	Side Wall	825 (Long)	8	782 (Long)	13.5
	Base	550	4	-	-

The directionality of tensile properties was not particularly marked for either projectile body in the side wall and only a small reduction in elongation in the transverse direction was evident, see Tables 2 and 3; and A1 and A2.

(c) Fracture Toughness

The Charpy-sized specimen 3PB rig used in this work did not readily allow the measurement of crack mouth opening displacement which is used in a conventional K_{IC} test [7]. The rig was designed for the measurement of back-face-displacement of the specimen (or load-point-displacement) used in the J_{IC} test method [11]. The K_Q measurements reported in this work were calculated on the maximum load values where the force/back-face-displacement records exhibited Type III behaviours and at "pop-ins" where these crossed a 5% secant line for Type II behaviours.

The greatest problem with the 3PB specimens used was in meeting the minimum specimen size requirements for a valid K_{IC} test as specified in ASTM E399. For this reason many of the results reported in Tables A4 and A5 must be treated as K_Q values only. The tests for validity on each specimen are summarized in these tables.

The 3PB fracture toughness test data from specimens machined from the M795 projectile body exhibited about 10% scatter for all tests at 21°C and about ± 7% for all tests at -40°C in both the C-R and the L-S orientations. This relatively small degree of scatter in the toughness data for the M795 appears to be inconsistent with the mixed microstructure of the steel. Furthermore, the spread to the high values may be enhanced because of the sub-sized specimens used in this work, since at 21°C all data are invalid.

In the present work on the M795 projectile all room temperature fracture toughness data and some of the low temperature data measured using 3PB specimens are invalid, see Tables A4 and A5. In most cases this is because the geometric requirement that B and/or a $\geq 2.5\ (K_Q/\sigma_{0.2})^2$ is violated. This means that at room temperature all fracture toughness tests will over-estimate K_{IC} and hence the K_Q values presented here cannot be compared reliably with other toughness test data. In the present work the estimation of toughness, K_Q, for the Charpy-sized 3PB specimens admits only the data which satisfy $a \geq 1.25\ (K_Q/\sigma_{0.2})^2$ and $B \geq 2.5\ (K_Q/\sigma_{0.2})^2$. This is quite arbitrary and cannot produce a lower-bound K_Q value, (viz K_{IC}). Comparison with other data is thus strictly not possible.

The room temperature fracture toughness results from the A(T) specimens taken from the M795 projectile body did not agree well with the 3PB specimens of the same orientation. Generally, these tests met the desired specimen geometry requirements for a valid test and it is considered that a lower bound K_Q value was measured. The reason for the discrepancy between the A(T) and 3PB fracture toughness results at room temperature is that the over-all specimen geometry is too small in the case of the 3PB specimens, in particular the crack length. The 3PB and A(T) specimens of the C-R orientation were taken from adjacent regions in the projectile wall, see Figure 2b, and so metallurgical and heat-treatment differences should be minimal.

Agreement between the fracture toughness data from the 3PB and the A(T) specimens tested at -40°C was particularly good. The A(T) specimens gave a mean value of 31.3 $\mathrm{MNm^{-3/2}}$ and the 3PB specimens gave a mean value of 33.7 $\mathrm{MNm^{-3/2}}$. Only toughness data from tests which conformed to the specimen size requirements of ASTM E399 were considered and hence the results for the M795 projectile at -40°C give a lower bound value of K_Q.

In the case of the M549 projectile agreement between fracture toughness values measured using A(T) specimens in this work and Charpy-sized 3PB specimens in Ref. 3 is good. There is some evidence of orientation differences between the two specimens.

From [3] it appears that there is also appreciable round-to-round variation in fracture toughness, K_Q, for the M549 projectile bodies, (and for M795 projectile bodies [8]). The value obtained in the present work is on the high side of the wide scatter for M549 projectiles reported in [3]. For both examples this scatter in toughness could be accounted for in terms of the relative cleanliness of the steel (a result of steel-making process), the presence of non-martensitic transformation products and the level of uniformity of martensite platelet size through the walls of the projectile body (a consequence of heat-treatment). Thus the M549 projectile body studied in the present work had a particularly uniform martensite platelet size, with no evidence of other transformation products and so the fairly high toughness value of 47.5 $MNm^{-3/2}$ is not unexpected. Generally, however, HF-1 heat-treated to within the yield strength range specified for the M549 projectile would have a fracture toughness below this value [15]. The steel from the particular projectile studied in the present work was at the minimum specified yield strength level, Table 7, and this gave rise to the higher level of fracture toughness measured in this work.

The value of a mechanical test to measure the round-to-round variations in forging lots is readily apparent, however some care must be used when comparing invalid K_Q data. Provided these limitations are recognised then the pre-cracked Charpy specimen can provide, at the very least, a qualitative assessment of the defect tolerance of a projectile body. Valid K_{IC} data is also desirable and in many instances the arc-tension specimen ($W = 12.9$ mm) taken from the walls of the projectile may provide this information. An empirical correlation between K_{IC} (A(T)) and K_Q (3PB) may have to be used if large numbers of specimens have to be tested where clearly the 3PB specimen is much less expensive to manufacture and test.

7. CONCLUSIONS

This work has characterized the mechanical properties and fracture toughness of one M795 and one M549 155 mm projectile body and has shown that:

(i) The M795 projectile body was not fully martensitic in microstructure whereas the M549 was fully martensitic. The mixed microstructure of the M795 projectile body was probably the result of poor heat-treatment. This microstructure can be formed if the projectile is not cooled down to room temperature after quenching prior to tempering.

(ii) The presence of non-martensitic transformation products in the microstructure of the M795 projectile body appeared to reduce the room temperature plane strain fracture toughness, K_{IC}, of the body, below that of a fully-martensitic structure (the M549) as expected from previous work; but this effect may have been partly compensated for by the lower yield strength of the M795 projectile body. These conclusions are based on the fracture toughness results produced by the arc-tension specimens. The three point bend specimens produced invalid data at 21°C.

(iii) The Charpy-sized 3PB specimen may be unsuitable for use as a plane strain fracture toughness test specimen for the testing of some thin-walled projectile bodies at room temperature. This appears to be the case with the M795 projectile body. A lower bound K_Q is not measured if the minimum size requirements as specified in ASTM E 399 are not met. Under circumstances where the specimens are subsize the K_Q value has limited use, and alternative test procedures such as the J-integral [16], or fracture stress [17], should be used.

Nevertheless, the Charpy sized 3PB specimen is considered to be a useful means of testing batches or 'lots' of projectiles for fracture toughness, once the relationships between toughness measured using these sub-sized specimens and valid K_{Ic} data are known.

8. ACKNOWLEDGEMENTS

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9. REFERENCES

1. Riffin, P.W. (September 1972), "High Fragmentation Steels for Artillery and Tank Munitions". AMMRC SP72-17.

2. Mulherin, J.H. et al (February 1976), "Fracture Mechanics Study of 155 mm 107 El Projectile made from Isothermally Transformed HF-1 Steel". Frankford Arsenal TR-76015.

3. Bruggeman, G.A. and Smith, J.M. (1978), Private communication.

4. Saunders, D.S. (January 1979), "Fracture Mechanics Approach to High Fragmentation Shell Steel Acceptance - A Review". MRL-R-733, Limited Release.

5. Saunders, D.S. (May 1981), "Fracture Mechanics Approach to High Fragmentating Shell Steel Acceptance - A Compilation of Fracture Toughness Data and Mechanical Properties of Candidate Steels". MRL-R-816, Limited Release.

6. American Society for Testing and Materials Book of Standards 03.01 (1983), "Standard Method of Test for Plane-Strain Fracture Toughness of Metallic Materials". E 399 83.

7. Military Specification DOD-P-63245(AR) (January 1979), "Projectile, HE, 155 mm, XM795, Metal Parts Assembly".

8. Mulherin, J.H. (1983), private communication.

9. Baldwin, N.J., Saunders, D.S. and Burman N.M. (December 1980), "Instrumentation of National Physical Laboratory Fatigue Testing Machine", MRL-TN-448.

10. Tada, H. et al. (1973), "The Stress Analysis of Cracks Handbook". Del Research Corp., Hellertown, PA.

11. Saunders, D.S. and Burch, I.A. "Measurement of the Toughness of STA64 Using 3 Point Bend, Compact Tension and Arc-Shaped Specimen Configurations". MRL Report in preparation.

12. Kapp, J.A., Newman, J.C. and Underwood, J.H. (1980). "A Wide Range Stress Intensity Factor Expression for the C-Shaped Specimen", Journal of Testing and Evaluation, 8, pp 314-317.

13. Weimer, R.T., Phillips, W.L. and Kim, C. (1979), "Loss of Fracture Resistance in High Carbon Steel due to Non-Martensitic Phases". Naval Research Lab. Report, NRL Mem. Rep. 4031.

14. Bruggeman, G.A. (1979), private communication.

15. Saunders, D.S. (1981). Unpublished data.

16. American Society for Testing and Materials Book of Standards 03.01 (1983). "J_{Ic} a Measure of Fracture Toughness", E 813-81.

17. ibid. "Crack Strength of Slow-Bend Pre-Cracked Charpy Specimens of High Strength Metallic Materials", E 812-81.

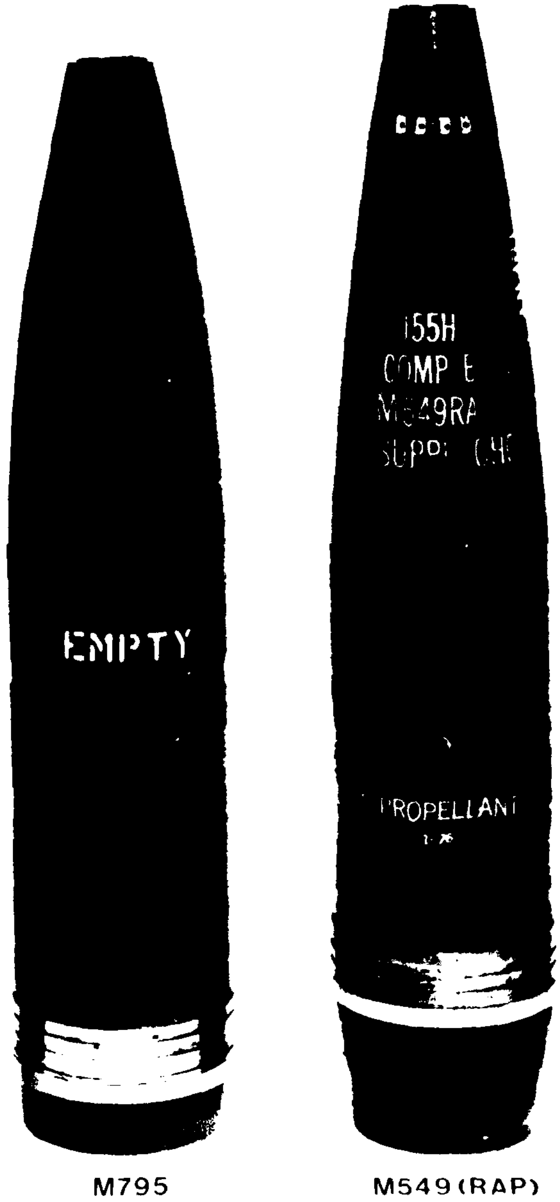
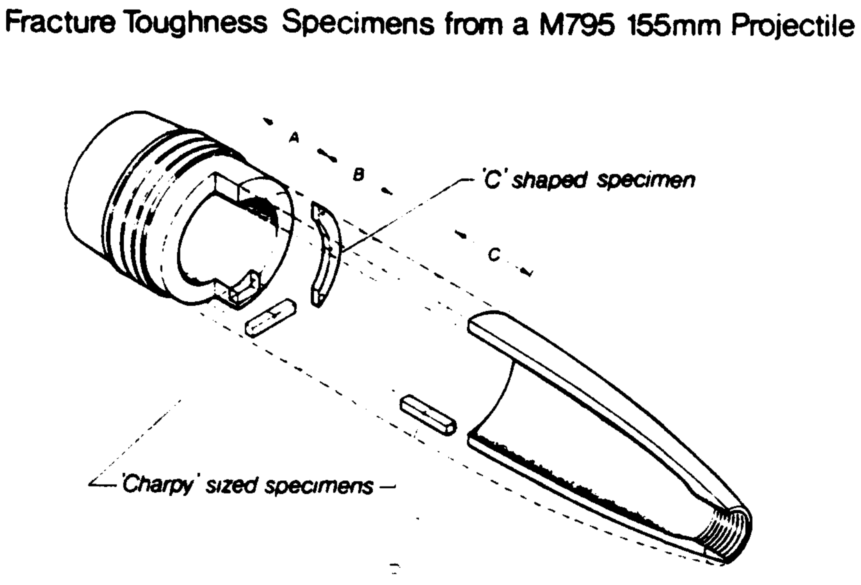
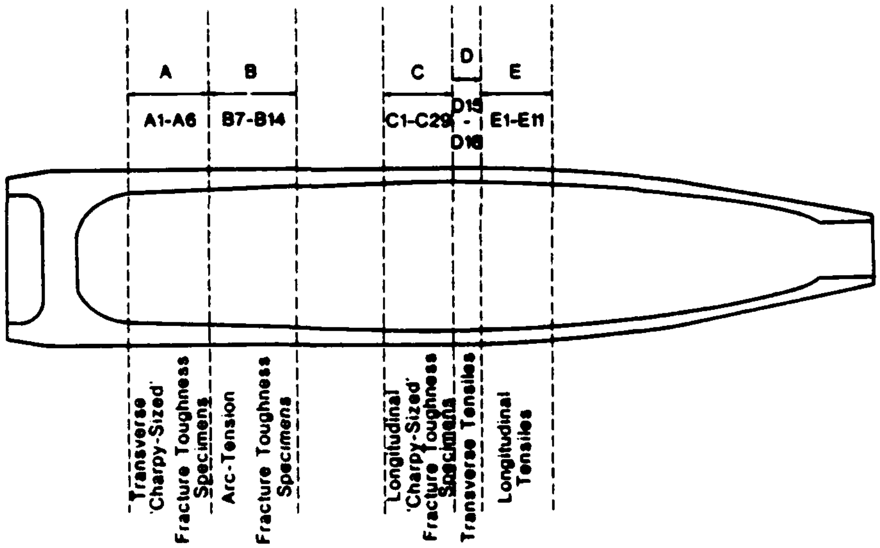


FIGURE 1 The two 155 mm projectiles; M795 and M549 (RAP).



(a)

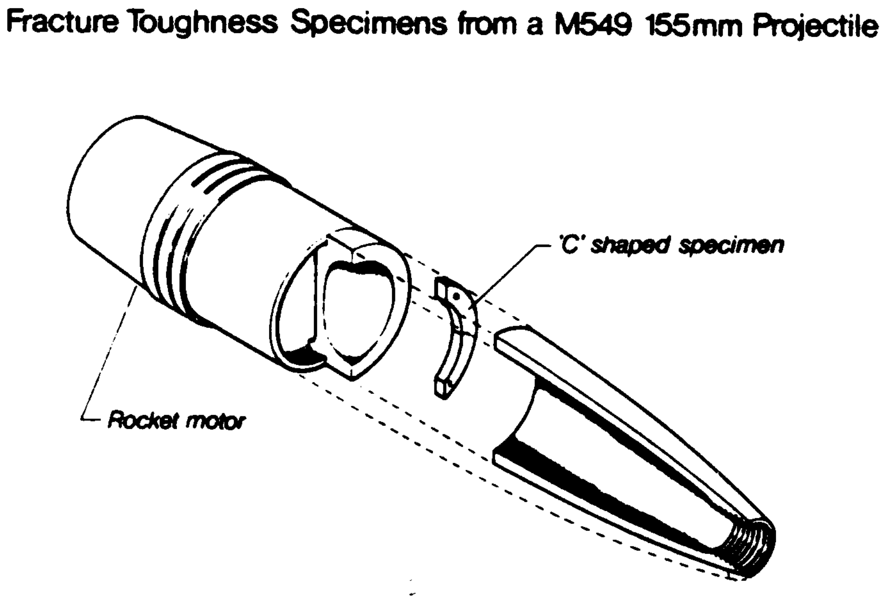
Schematic diagram showing the orientations of the fracture toughness specimens



(b)

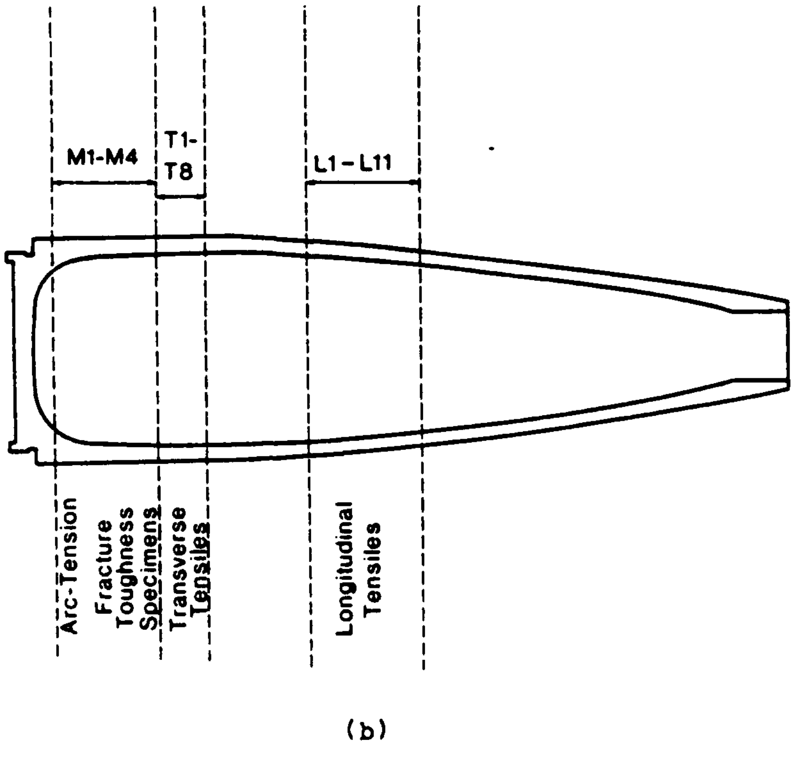
Diagram showing the locations of the tensile and fracture toughness specimens

FIGURE 2 The locations and orientations of specimens taken from the wall of the M795 155 mm artillery projectile body.



(a)

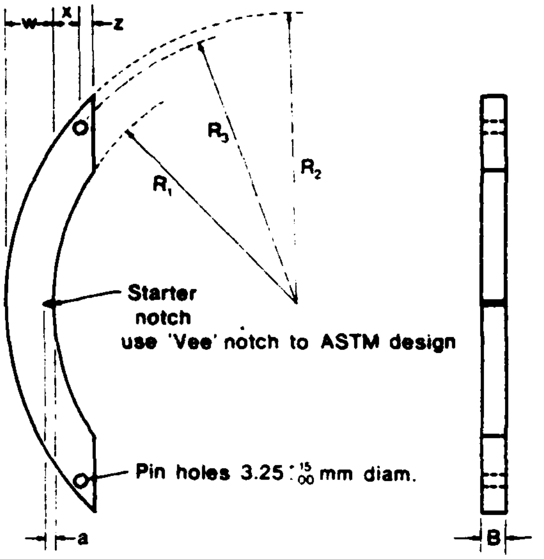
Schematic diagram showing the orientations of the fracture toughness specimens



(b)

Diagram showing the locations of the tensile and fracture toughness specimens

FIGURE 3 The locations and orientations of specimens taken from the wall of the M549 155 mm artillery projectile body.



$w = 12.9^{+05}_{-05}$ mm

$x = 6.45^{+05}_{-05}$ mm

$z = 3.2^{+5}_{-5}$ mm

$B = 6.5^{+05}_{-05}$ mm = specimen thickness

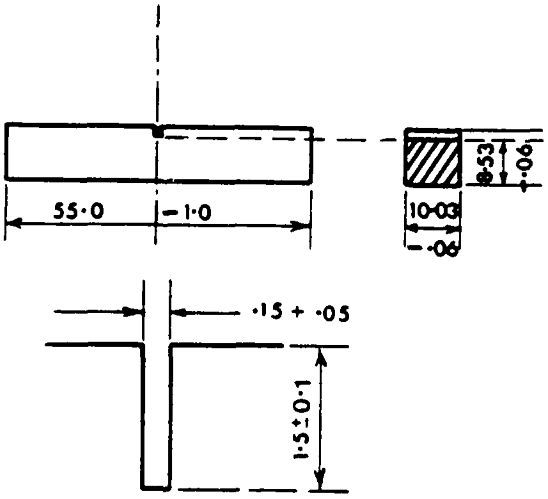
a = 4.0 mm starter crack depth

$R_1 = 64.45^{+05}_{-05}$ mm

$R_2 = 77.35$ mm

$R_3 = 74.0^{+20}_{-00}$ mm

FIGURE 4 Dimensions of the arc-tension specimen.



notch detail

all dimensions in mm.

FIGURE 5 Dimensions of the Charpy-sized three point bend specimen.

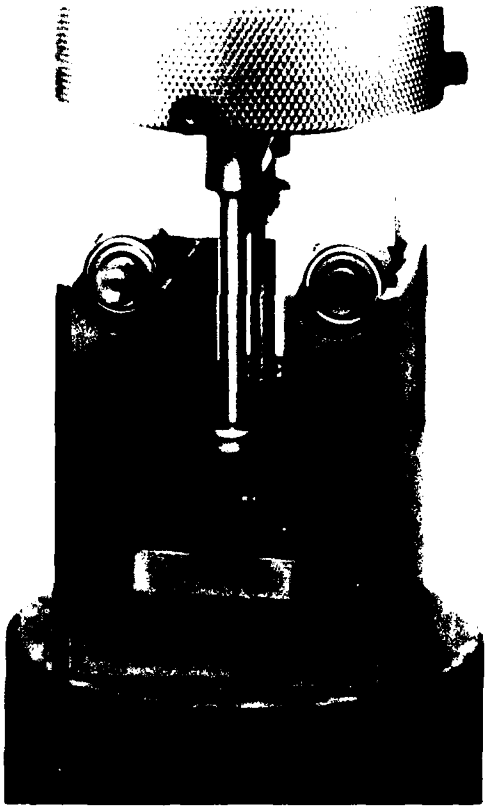


FIGURE 6 The three point bend rig [11] incorporating needle roller bearings and displacement measurement using LVDTs.

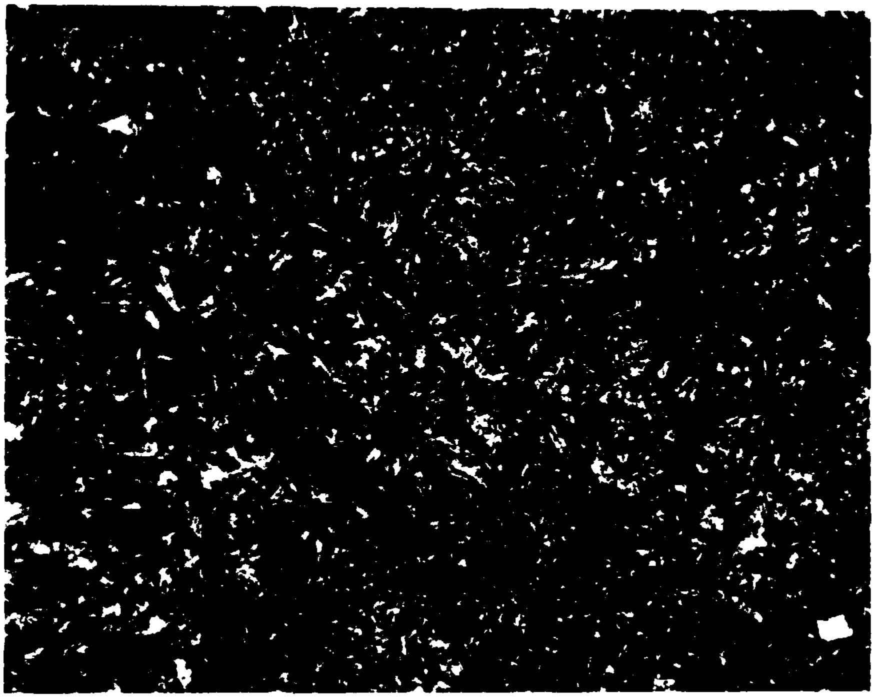


FIGURE 7 Microstructure of M549 projectile body
2% Nital 500 X

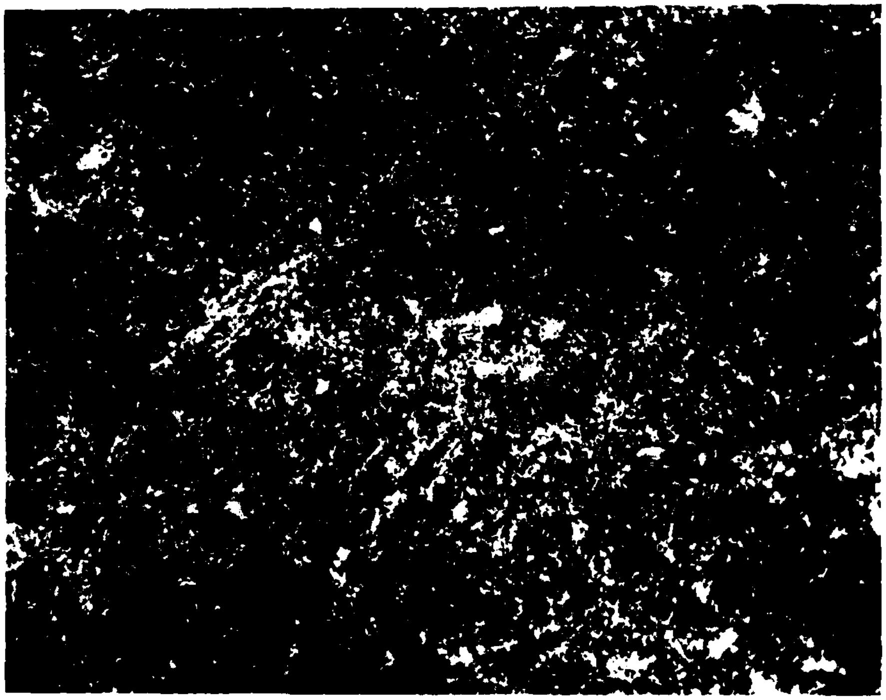


FIGURE 8 Microstructure of M795 projectile body
Picral 500 X

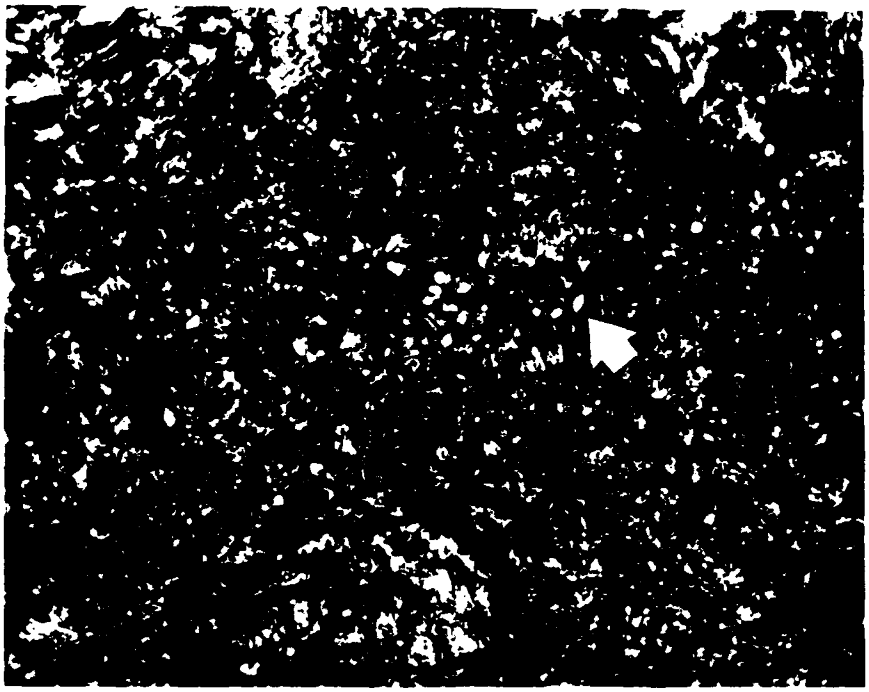


FIGURE 9 Undissolved carbides (shown arrowed) in the microstructure of the M549 projectile body. 2% Nital 1000 X

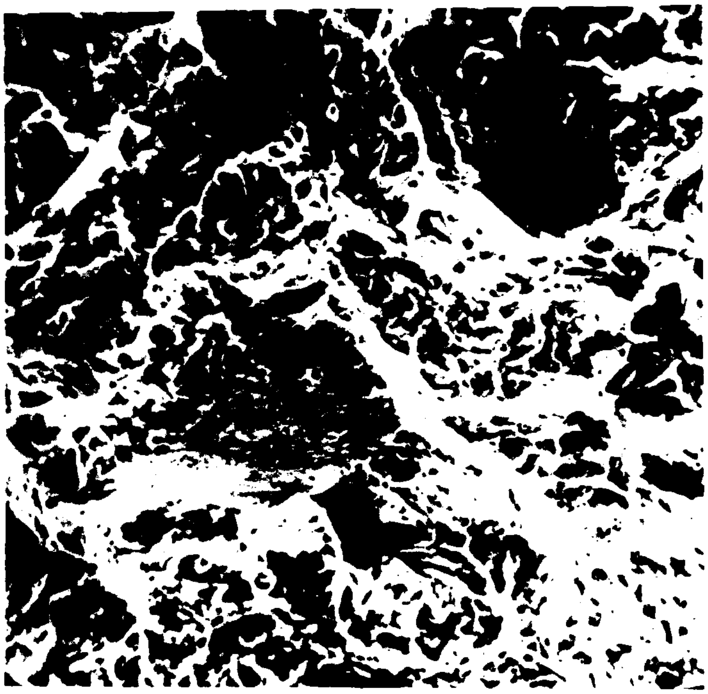


FIGURE 10 Room temperature fracture surface from the M549 projectile body. Specimen M-2 1100X

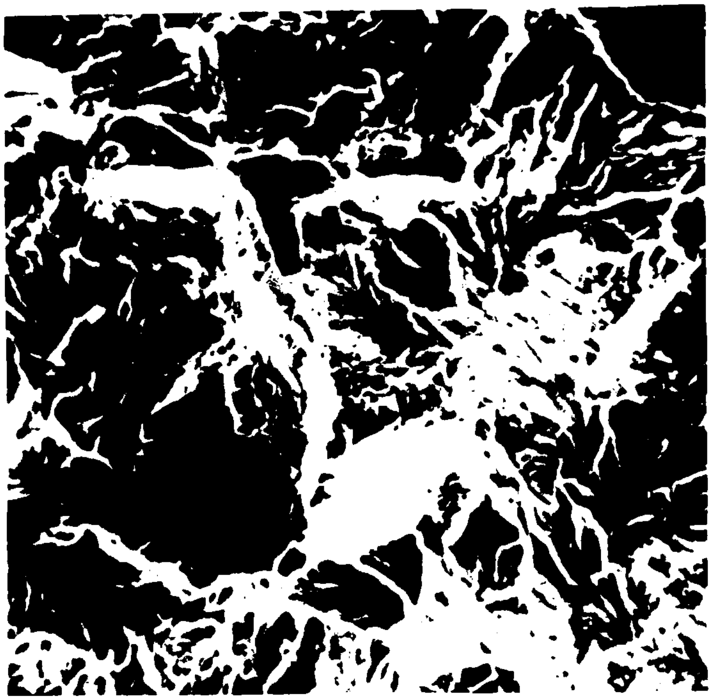


FIGURE 11 Room temperature fracture surface from the M795 projectile body. Specimen B7-1 1100X

APPENDIX 1

A COMPILATION OF TEST DATA FOR THE M795 AND THE M549 (RAP) 155 MM ARTILLERY PROJECTILES

TABLE A1

Tensile Data for the M795 Projectile Body, at 21°C

TEST PIECE	PROOF STRESS 0.1% MPa	PROOF STRESS 0.2% MPa	TENSILE STRENGTH MPa	REDUCTION IN AREA %	ELONGATION ON $4\sqrt{So}$ %
E1	810	815	1220	18	13
E2	750	765	1180	15	12
E3	770	785	1190	23	15
E4	770	780	1189	15	12
E5	790	795	1220	23	15
E6	805	810	1210	20	14
E7	750	765	1180	17	12
E8	745	760	1190	18	14
E9	755	765	1180	20	14
E10	780	795	1210	17	13
E11	756	765	1170	23	15
Mean Values	771 ± 23	782 ± 20	1195 ± 18	19.0 ± 3.0	13.5 ± 1.2
D15-1	755	765	1180	17	12
D15-2	790	800	1220	15	11
D15-3	775	790	1200	16	12
D15-4	755	765	1170	19	12
D16-1	750	760	1180	17	12
D16-2	745	765	1180	15	11
D16-3	775	790	1200	14	11
D16-4	785	795	1220	18	10
Mean Values	766 ± 17	779 ± 16	1194 ± 19	165 ± 1.7	11.5 ± 0.7

TABLE A2

Tensile Data for the M549 Projectile Body, at 21°C

TEST PIECE	PROOF STRESS		TENSILE STRENGTH MPa	REDUCTION IN AREA %	ELONGATION ON $4\sqrt{So}$ %
	0.1% MPa	0.2% MPa			
L1	995	995	1270	24	9
L2	995	1000	1280	15	10
L3	985	985	1270	22	12
L4	975	975	1270	16	10
L5	965	970	1270	17	11
L6	975	975	1270	17	13
L7	965	975	1270	20	11
L8	970	970	1270	19	12
L9	965	975	1270	21	12
L10	965	970	1280	18	12
L11	965	970	1270	20	12
Mean Values	975 ± 12	978 ± 11	1272 ± 4	19.0 ± 2.7	11.2 ± 1.2
T1	965	975	1280	14	8
T2	975	980	1280	16	10
T3	990	990	1270	16	9
T4	980	985	1280	16	11
T5	975	985	1280	15	9
T6	975	980	1280	14	9
T7	985	985	1270	17	9
T8	965	975	1280	19	11
Mean Values	976 ± 9	982 ± 5	1278 ± 5	15.8 ± 1.6	9.5 ± 1.1

TABLE A3

Fracture Toughness Data for the M795 Projectile Body using 'C'-shaped (A(T)) Specimens.

SPECIMEN NO.	ORIENTATION	FRACTURE TOUGHNESS $MNm^{-3/2}$	$2.5\left(\frac{K_{IC}}{\sigma_{0.2}}\right)^2$ mm	TEST TEMP °C
B7-1	C-R	40.0[(a)]	6.6 NA[(b)]	21
B9-1	C-R	37.2	5.7	21
B10-1	C-R	33.0	4.5	21
B11-1	C-R	39.1	6.3	21
B12-1	C-R	40.1	6.6	21
B13-1	C-R	42.2[(a)]	7.3 NA[(b)]	21
B14-1	C-R	39.3	6.4	21
Mean Value		37.7 ± 2.86	5.9 ± 0.9	21
B7-2	C-R	29.0	3.5	-40
B8-2	C-R	28.6	3.4	-40
B9-2	C-R	28.7	3.4	-40
B10-2	C-R	29.0	3.5	-40
B11-2	C-R	35.1	5.1	-40
B12-2	C-R	32.2	4.3	-40
B13-2	C-R	32.6	4.4	-40
B14-2	C-R	35.0	5.0	-40
Mean Value		31.3 ± 2.8	4.1 ± 0.7	-40

(a) K_Q test result is invalid for at least one of the following:

(1) B or a (or both) $< 2.5\left(\frac{K_Q}{\sigma_{0.2}}\right)^2$

(2) $a_{surface} < .90\,\bar{a}$

(b) data not admitted in the calculation of a mean toughness value.

$\sigma_{0.2}$ from Table A1, room temperature value.

TABLE A4

Fracture Toughness Data for the M795 Projectile Body using Charpy-sized Three Point Bend, 3PB, Specimens

SPECIMEN NO.	ORIENTATION	FRACTURE TOUGHNESS MNm$^{-3/2}$	$2.5\left(\frac{K_{IC}}{\sigma_{0.2}}\right)^2$ mm	TEST TEMP ^{o}C
A1-1	C-R	46.7(a)	9.0	20
2	C-R	47.7(a)	9.4	20
3	C-R	51.4(a)	10.9 NA(b)	20
4	C-R	30.1	3.7	-40
5	C-R	–	–	–
6	C-R	35.3	5.1	-40
A2-1	C-R	45.5(a)	8.5	20
2	C-R	53.2(a)	11.7 NA(b)	20
3	C-R	45.6(a)	8.6	20
4	C-R	48.6(a)	9.7	20
5	C-R	33.0	4.5	-40
6	C-R	34.0	4.8	-40
A3-1	C-R	47.3(a)	9.2	20
2	C-R	45.6(a)	8.6	20
3	C-R	48.4(a)	9.7	20
4	C-R	29.8	3.7	-40
5	C-R	32.3	4.0	-40
6	C-R	37.8(a)	5.9 NA(b)	-40
A4-1	C-R	61.8(a)	15.7 NA(b)	20
2	C-R	49.3(a)	10.0	20
3	C-R	31.5	4.1	-40
4	C-R	34.8	5.0	-40
5	C-R	31.0	4.0	-40
6	C-R	31.7	4.1	-40

TABLE A4 (Continued)

SPECIMEN NO.	ORIENTATION	FRACTURE TOUGHNESS $MNm^{-3/2}$	$2.5\left(\frac{K_{IC}}{\sigma_{0.2}}\right)^2$ mm	TEST TEMP °C
A5-1	C-R	47.3(a)	9.2	20
2	C-R	51.2(a)	10.8 NA(b)	20
3	C-R	57.9(a)	13.8 NA(b)	20
4	C-R	28.7	3.4	-40
5	C-R	37.8(a)	5.9 NA(b)	-40
6	C-R	34.8	5.0	-40
A6-1	C-R	49.2	10.0	20
2	C-R	52.0	11.1 NA(b)	20
3	C-R	50.3	10.4 NA(b)	20
4	C-R	32.3	4.3	-40
5	C-R	30.8	3.9	-40
6	C-R	33.8	4.7	-40
Mean Value		47.4 ± 1.4	9.3 ± 0.6	20
Mean Value		32.3 ± 2.0	4.3 ± 0.5	-40

(a) K_Q test result is invalid for at least one of the following

(1) B or a (or both) $< 2.5 \left(\frac{K_Q}{\sigma_{0.2}}\right)^2$

(2) $a_{surface} < .90\ \bar{a}$

(b) data not admitted in the calculation of a mean toughness value.

$\sigma_{0.2}$ from Table A1, room temperature value.

TABLE A5

Fracture Toughness Data from the M795 Body using Charpy-sized Three Point Bend, 3PB , Specimens.

SPECIMEN NO.	ORIENTATION	FRACTURE TOUGHNESS $MNm^{-3/2}$	$2.5(\frac{K_{IC}}{\sigma_{0.2}})^2$ mm	TEST TEMP ^oC
C-1	L-S	61.4(a)	15.4 NA(b)	20
C-2	L-S	48.8	9.7	20
C-3	L-S	41.4	6.9	20
C-4	L-S	45.0	8.2	20
C-5	L-S	39.4	6.3	20
C-6	L-S	42.2	7.3	20
C-7	L-S	44.5	8.1	20
C-8	L-S	45.1	8.3	20
C-9	L-S	46.5	8.8	20
C-10	L-S	51.0	10.6	20
C-11	L-S	52.7	11.3 NA(b)	20
C-12	L-S	51.5	10.8	20
C-13	L-S	41.1	6.9	20
C-14	L-S	45.7	8.5	20
C-15	L-S	43.5	7.7	20
Mean Value		45.0 ± 3.7	8.3 ± 1.4	20
C-16	L-S	34.4	4.8	-40
C-17	L-S	35.5	5.2	-40
C-18	L-S	35.7	5.2	-40
C-19	L-S	35.7	5.2	-40
C-20	L-S	34.9	5.0	-40
C-21	L-S	35.6	5.2	-40

TABLE A5
(Continued)

SPECIMEN NO.	ORIENTATION	FRACTURE TOUGHNESS $MNm^{-3/2}$	$2.5\left(\frac{K_{IC}}{\sigma_{0.2}}\right)^2$ mm	TEST TEMP °C
C-22	L-S	33.3	4.5	-40
C-23	L-S	38.7	6.1	-40
C-24	L-S	34.4	4.8	-40
C-25	L-S	40.2	6.6	-40
C-26	L-S	32.1	4.2	-40
C-27	L-S	-	-	-
C-28	L-S	38.2	6.0	-40
C-29	L-S	35.3	5.1	-40
Mean Value		35.7 ± 2.2	5.2 ± 0.7	-40

(a) K_Q test result is invalid for at least one of the following:

(1) B or a (or both) $< 2.5 \left(\frac{K_Q}{\sigma_{0.2}}\right)^2$

(2) $a_{surface} < .90\,\bar{a}$

(b) data not admitted in the calculation of a mean toughness value.

$\sigma_{0.2}$ from Table A1, room temperature value.

TABLE A6

Fracture Toughness Data for the M549 Projectile Body Using Arc-Tension Specimens

SPECIMEN NO.	ORIENTATION	FRACTURE TOUGHNESS $MNm^{-3/2}$	$2.5(\frac{K_{IC}}{\sigma_{0.2}})^2$ mm	TEST TEMP ^oC
M-2	C-R	50.2	6.5	21
M-3	C-R	48.6	6.1	21
M-4	C-R	43.6	4.9	21
Mean Value		47.5 ± 3.4	5.8 ± 0.8	21

* K_Q test result is invalid for at least one of the following:

(1) B or a (or both) $< 2.5 (\frac{K_Q}{\sigma_{0.2}})^2$

(2) $a_{surface} < .90 \bar{a}$

$\sigma_{0.2}$ from Table A2, room temperature value.