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**SAFE MAXIMUM PRESSURE DETERMINATION FOR
THE M829E3/M256 CANNON QUALIFICATION PROGRAM**

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SEPTEMBER 2002



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INTRODUCTION

This report summarizes and records activity related to the Safe Maximum Pressure (SMP) determination, as part of the M829E3/M256 Cannon Qualification Program. The report utilizes input from Mr. Charles Loomis of ARDEC, Picatinny, NJ; Mr. David Moak (refs 1,2); and Mr. Maurice Scavullo of Benét Laboratories, who worked on this program during the period when SMP testing was conducted.

BACKGROUND

The M256 120-mm cannon is the main armament of the M1A1 and M1A2 tanks. The SMP of a cannon, as defined in NATO Standardization Agreement (STANAG) 4110 is, "The value of pressure at each point along the tube which, if exceeded, could result in the occurrence of permanent deformation." As such, SMP is usually determined by analysis and not through firing. Traditionally, the SMP of a cannon is much higher than the pressures usually encountered during firing, even at extreme temperatures; consequently, small errors in the determination of SMP were not important if they made the resulting estimate of SMP conservative (ref 2). The M829E3 cartridge, however, generates extreme pressures, to the point where the current SMP value of the M256 cannon (a minimum of 7263 bars, 105 Ksi, is required) is not sufficient for meeting the performance requirements. A value of approximately 7590 bars (110 Ksi) is needed for the M829E3 program to meet the performance requirements.

DISCUSSION

Based on theoretical calculations of pressure vessel formulas, a yield strength of 168 to 169 Ksi would be required to meet the M829E3 pressure requirements. Since this is above the current maximum observed yield stress of the M256 tube (approximately 160 Ksi, only minimum yield is specified on drawing), this would be impossible. It has been observed (ref 2,3) that the theoretical, calculated, yield point of a pressure vessel is conservative when compared to the actual yield of a cannon subjected to a ballistic firing. We surmised that if the actual yield point of the M256 cannon could be determined empirically via actual tests, this figure could be used as the basis of calculations, rather than the theoretical point. This could result in an acceptable SMP that would allow the M829E3 to be fired.

HYDRAULIC TEST

A hydraulic test to measure tube deformation with increasing pressure pulses was conducted in March 1997. Tests were conducted on 120-mm M256 tubes, serial numbers 1907, 5844, 5356, 4098, 5028, and 7243. Pressure was applied to tubes cyclically, and deformations measured by strain gauges. See Figures 1 and 2 for typical cycles.

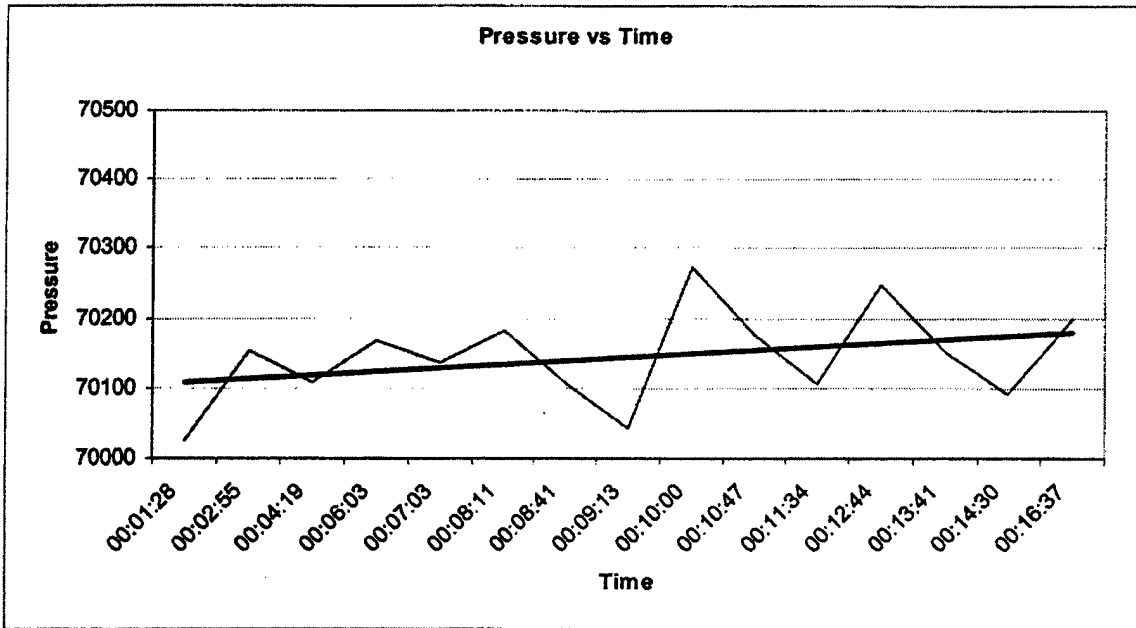


Figure 1. Pressure versus time plot of hydraulic SMP tests for tube number 5028.

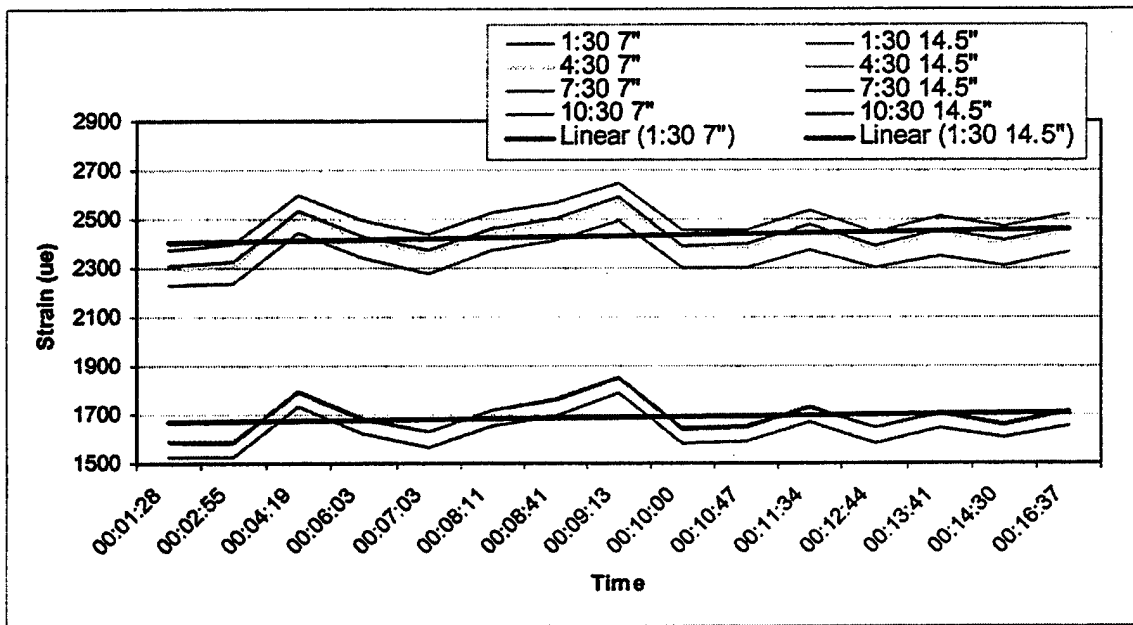


Figure 2. Strain versus time plot of hydraulic SMP tests for tube number 5028.

Unfortunately, some of the data and test plan for this activity have been lost. Appendix A contains charts showing some of the data. As can be observed on these charts, yielding was observed at pressures as low as 94 Ksi. Pressures above this value have been achieved in firing without yield. Moreover, the M256 tube has been hydraulically fatigue tested at 97 Ksi, again with no indication of yielding. The basic conclusion was that hydraulic testing could not duplicate yield, as it would occur during firing of high-pressure rounds. It has been surmised that this is due to strain-rate effects (rate and duration of loading). The rate of loading and time that the peak pressure was held was much slower than that of firing and as a result, yielding occurred at a much lower pressure than what would be expected from firing. Consequently, a firing test was conducted to establish the yield point.

FIRING TEST

The SMP testing involved shooting rounds at increasing pressures until the gun tube was permanently yielded. Extreme difficulty in measuring the tubes to determine the actual point of yield was encountered. Currently the stargage equipment used to measure the inner diameters of gun tubes has an accuracy of ± 0.001 -inch (0.0254-mm) under laboratory conditions. In order to test at a reasonable pace, measurements of the tubes had to be performed in the firing fixture, further hampering efforts to obtain precise measurements. Based on this, we set a criterion that the yielding would be indicated by a diameter measurement of 0.002-inch (0.050-mm) greater than the pretest (baseline) measurement.

Other difficulties were encountered during the test, especially in measuring the actual pressure. The pressures required—110 to 120 Ksi—would be pushing the limit of electronic pressure gauges. Due to this, copper crusher gauges were also used to provide additional pressure data. It should be remembered that these gauges, electronic or otherwise, have an accuracy of $\pm 2\%$, which means the reading in this range could be off by 2 Ksi (138 bars).

Based on the initial data, it was projected that the measured yield (actual yield will be lower) would occur in the 8000 to 8140 bar (116 to 118 Ksi) range. A sample of six gun tubes would be needed to provide a statistically sufficient basis for the analysis. The current minimum tube yield strength is 149.4 Ksi, and it was projected that this value will need to be increased to 155 Ksi to meet the 110 Ksi M829E3 performance requirement. The SMP test was conducted with tubes having yield strengths of 155 Ksi or less.

Based on the discussions above, a test was constructed and conducted at the U.S. Army Aberdeen Test Center in January 2000 and the U.S. Army Yuma Proving Ground in November 2000 (refs 1,4). In all, eight cannon tubes, see Table 1, were fired during the test, including serial numbers 2514, 1266, 1707, 1129, 1686, 1164, 1116, and 5184. Data from 1686 and 2514 were discarded. Tube 2514 was deformed on the first round because the pressure reached 118 Ksi. Tube 1686 was suspected of having deformation before the test began. To be on the safe side, this tube was not used.

Table 1. Tube Serial Numbers and Yield Limits

Tube Serial Number	Breech-End Yield Strength		Chamber Pressure Deformation Limit (0.002-Inch)	
	(MPa)	(Ksi)	(MPa)	(Ksi)
1266	1062	154	785	114
1707	1062	154	785	114
1129	1055	153	799	116
1164	1069	155	785	114
1116	1062	154	779-792	113-115
5185	1069	155	792-834	115-121

Along with the measurement difficulties discussed earlier, it also proved difficult to provide charges and projectiles that would generate exactly the right pressure required. In fact, the first tube fired, serial number 2514, was yielded immediately on the first round with a pressure of 118 Ksi. Subsequently, the test procedure was altered to maintain charge temperatures and propellant weights and to vary the projectile weight to change the pressure. Figure 3 shows a typical resultant plot of the data.

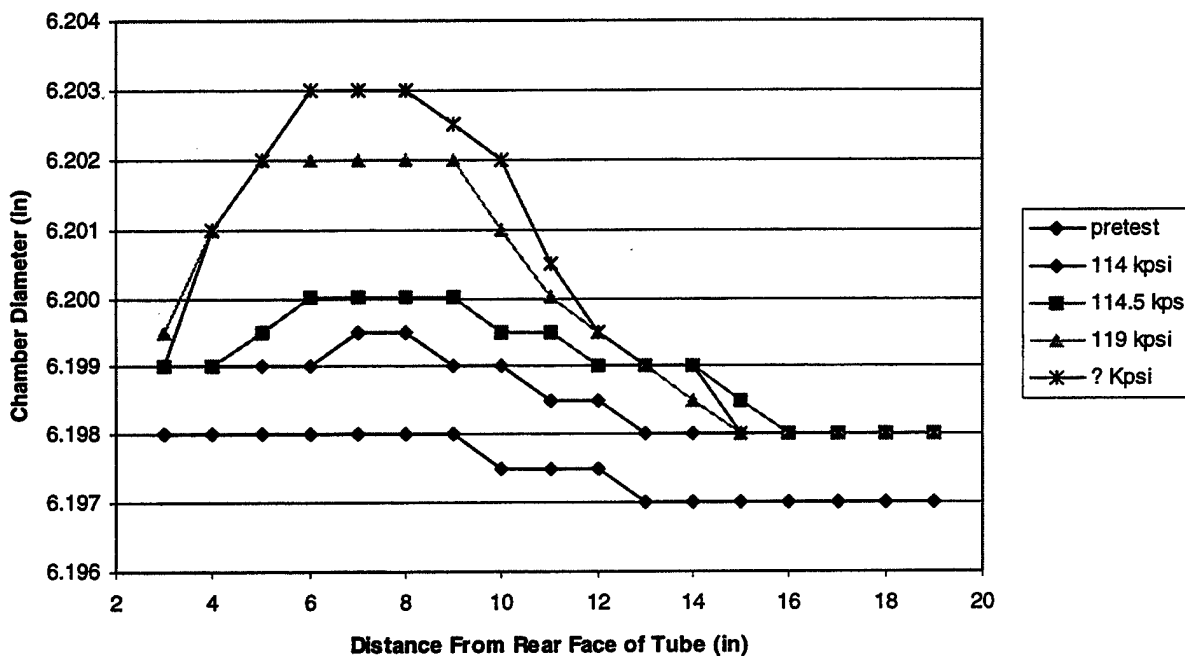


Figure 3. Bore enlargement for tube 1707 firing test.

The data for tubes 1116 and 5185 are somewhat inconsistent, due to the difficulties mentioned above in measuring chamber pressure and yield. For this reason, the yield points for these tubes are listed as a range. We are reasonably certain, for example, that tube 1116 had not yet reached the 0.002-inch yield limit at 113 Ksi, but had passed it by 115 Ksi. This uncertainty has been taken into account in the analysis of the data.

Figure 4 shows the actual test data points that resulted from this test. Firing data from tubes are attached as Appendix B. The theoretical yield points are also shown so the reader can gauge the impact of the strain-rate increase on the actual yield point.

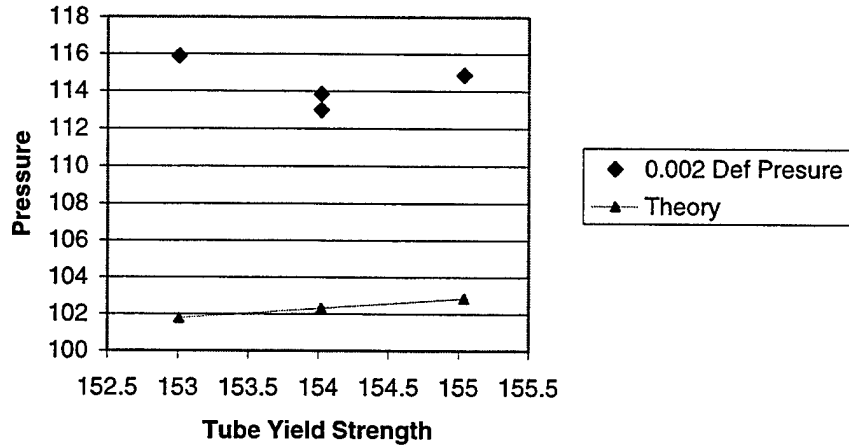


Figure 4. Tube bore enlargement points showing exceeded yield strength.

The data were analyzed statistically using a three-parameter Weibull model. This model includes a "threshold" parameter, which is taken to the SMP. Based on this model, we can say with 90% confidence that SMP is at least 110 Ksi.

CONCLUSIONS

Based on the findings above, the Extreme Service Condition Pressure of the M829E3 cartridge of 110 Ksi will generate a stress in the tube of 155 Ksi. Based on this, the new minimum yield strength requirement in the tube will have to be set at 155 Ksi. Note that this is well within the manufacturing capability of Watervliet Arsenal, and most of the tubes made within the last several years are above this limit. It should be noted that unlike fatigue testing and other cannon design practices, this is the first time that the SMP has been determined in this manner. Caution is urged in ensuring that the resultant final pressures generated by the M829E3 cartridge do not exceed the figures used in the testing.

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1. "Test Program Request - M256 120-mm Cannon Safe Maximum Pressure Test, #191," 24 November 1999.
2. Loomis, Richard, and Moak, David, "M829E3 M256 Gun Tube Program Safe Maximum Pressure and Fatigue Design Pressure Testing," Picatinny Arsenal, Dover, NJ, undated.
3. Kendall, D.P., and Davidson, T.E., "The Effect of Strain Rate on Yielding in High Strength Steels," *Journal of Basic Engineering*, Vol. 88, Series D, No. 1, 1966, pp. 37-44.
4. Dowling, N.E., *Mechanical Behavior of Materials*, Prentice Hall, 1999, pp. 123-5.
5. "Firing Report No. 00-TF-0044-L5," TECOM Project 1-MU-001-829-073, U.S. Army Yuma Proving Ground, 24 April 2000.

**APPENDIX A
HYDRAULIC SMP TEST DATA**

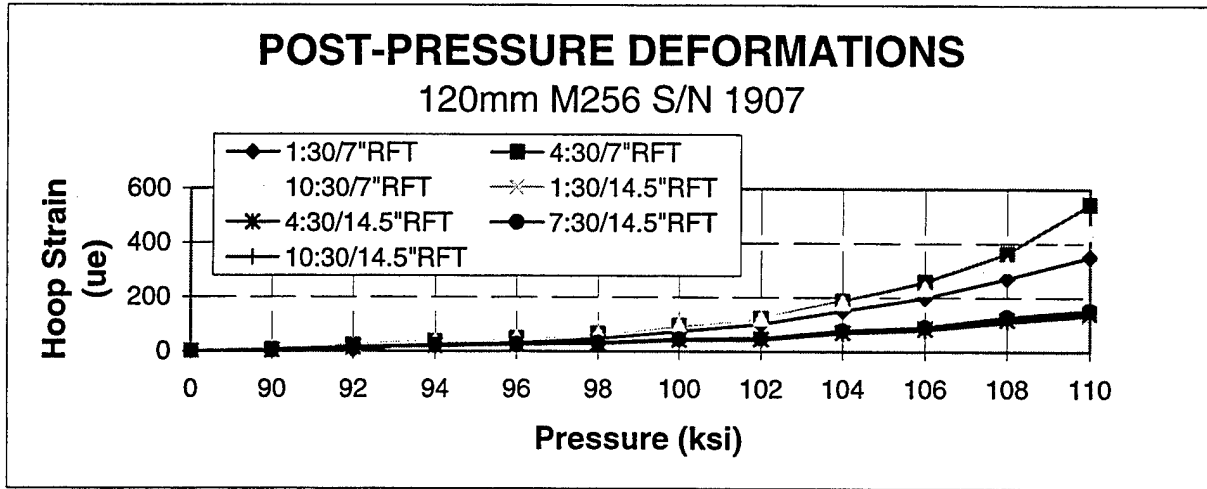


Figure A-1.

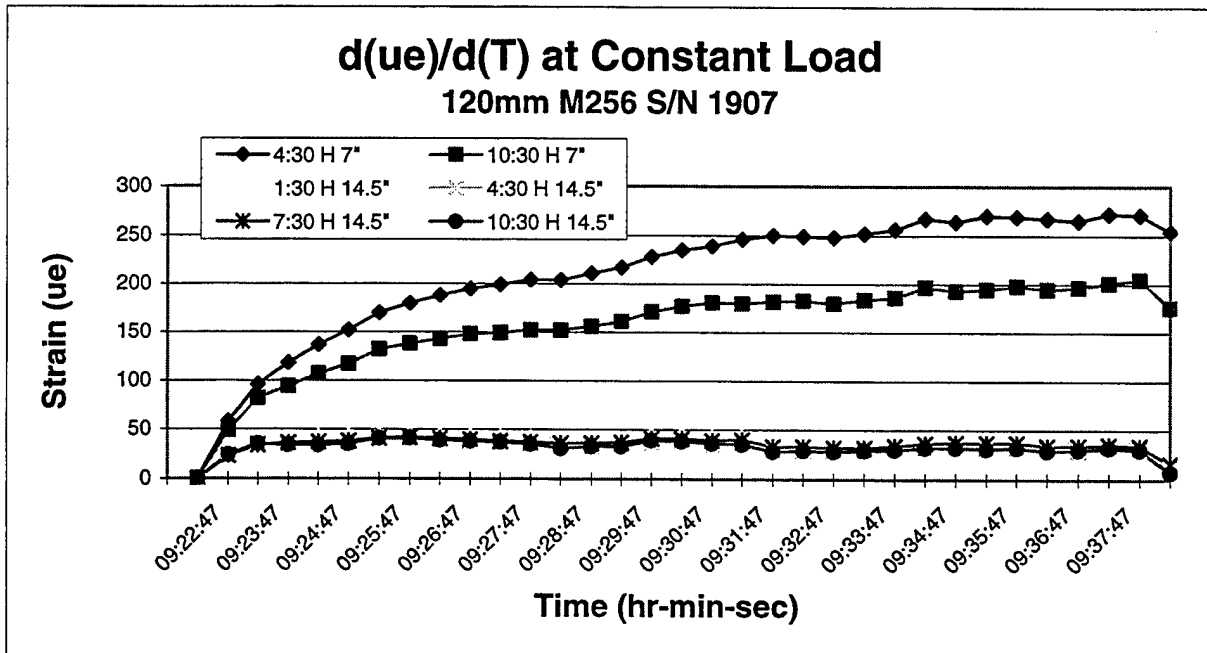


Figure A-2.

Note: ue = microstrain (microinches/inch)

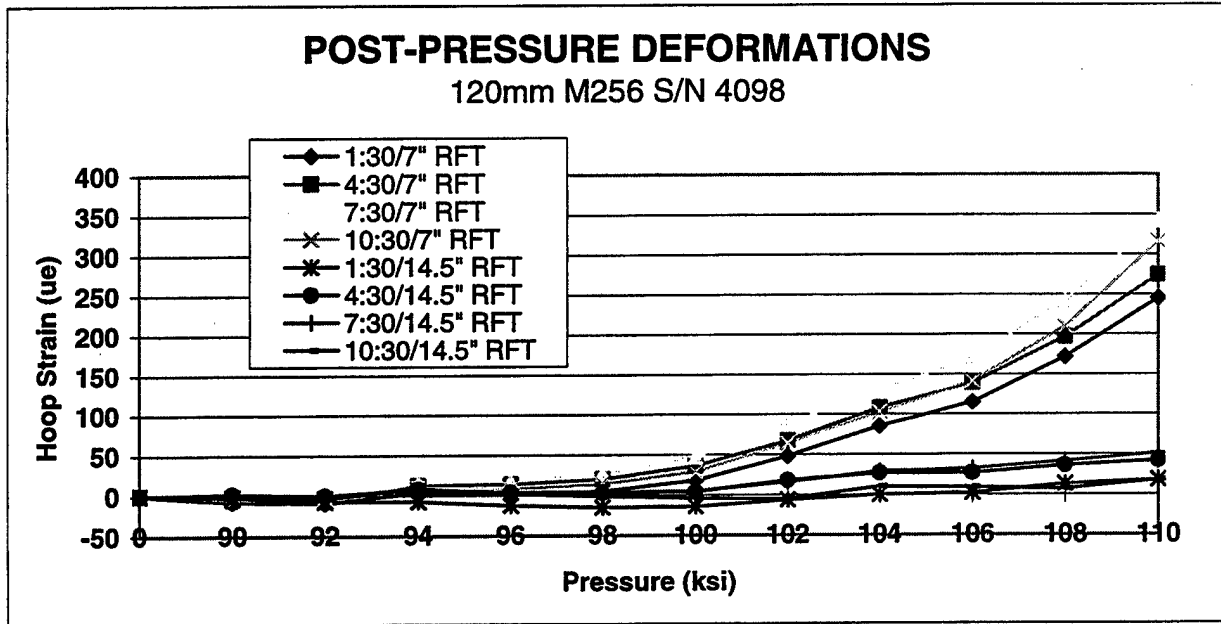


Figure A-3.

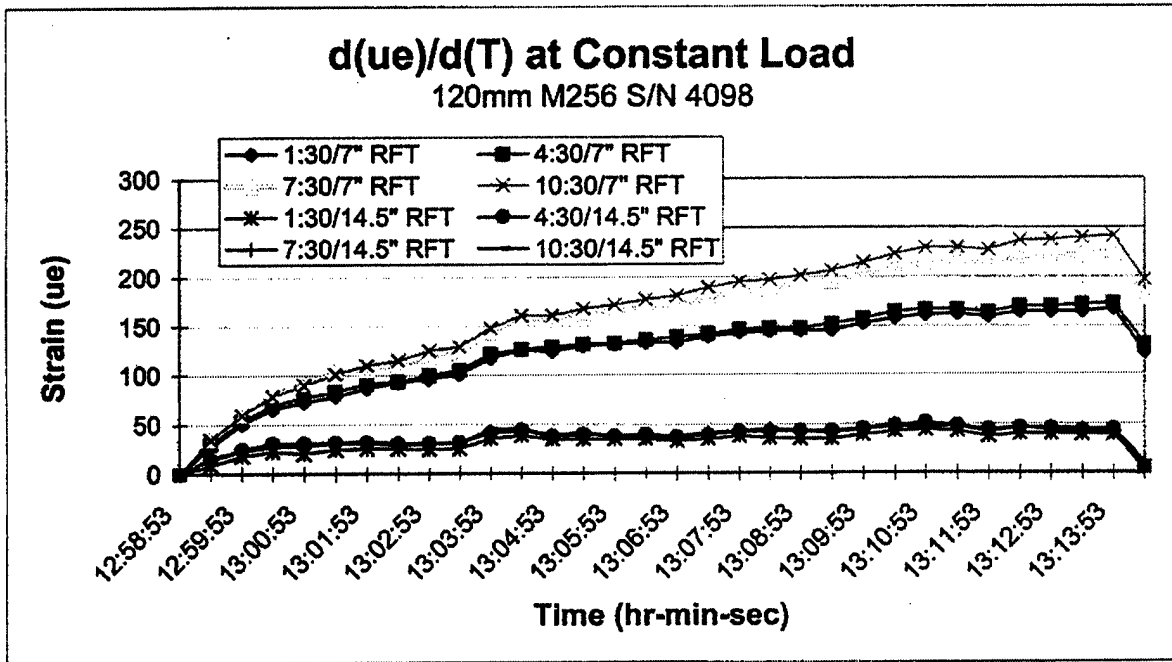


Figure A-4.

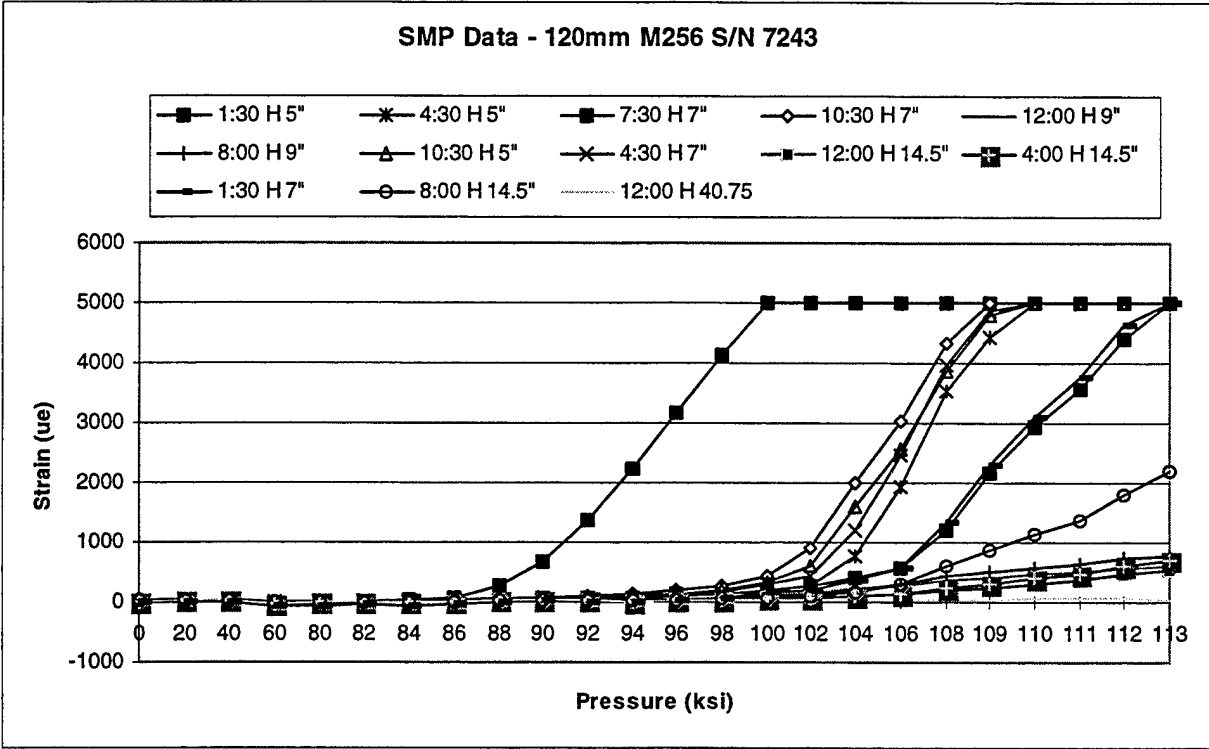


Figure A-5.

**APPENDIX B
SMP FIRING TEST DATA**

Pressure Data:

P1L = Piezoelectric Gauge at Left Breech End of Chamber
 P1R = Piezoelectric Gauge at Right Breech End of Chamber
 P3L = Piezoelectric Gauge at Left Muzzle End of Chamber
 P3R = Piezoelectric Gauge at Right Muzzle End of Chamber
 Cu = Average of Two Copper Crusher Gauges

Table B-1. Tube Serial Number 2514 (154 Ksi Yield Strength)

Round Number	Slug Weight (lbs)	Charge Weight (lbs)	Muzzle Velocity (ft/sec)	Pressure (Ksi)				Maximum Yield (in.)
				P1L	P1R	P3L	P3R	
1	21.5	18.20	5423	119	118	114	112	0.002
2	21.5	17.54	5204	101	101	97	96	
3	21.5	17.70	5233	107	107	102	101	
4	22.0	17.70	5233	108	108	104	102	
5	23.0	17.70	5200	111	111	107	106	
6	24.0	17.70	5098	115	118	110	111	

Table B-2. Tube Serial Number 1266 (154 Ksi Yield Strength)

Round Number	Slug Weight (lbs)	Charge Weight (lbs)	Muzzle Velocity (ft/sec)	Pressure (Ksi)				Maximum Yield (in.)
				P1L	P1R	P3L	P3R	
1	21.50	17.70	5250	102	102	100	98	
2	22.00	17.70	-	107	107	104	103	
3	22.50	17.70	-	108	108	105	105	
4	23.00	17.70	5158	109	109	106	105	0.0005
5	23.50	17.70	5138	113	114	109	109	0.002
6	23.75	17.70	5118	110	110	106	106	
7	24.00	17.70	5125	115	115	109	-	
8	24.25	17.70	5088	112	114	109	110	
9	24.50	17.70	5088	116	117	111	109	0.0025
10	24.75	17.70	5095	115	118	106	101	0.003
11	24.75	17.70	5056	119	-	115	115	0.004
12	24.75	17.70	5082	121	121	-	-	

Table B-3. Tube Serial Number 1707 (154 Ksi Yield Strength)

Round Number	Slug Weight (lbs)	Charge Weight (lbs)	Muzzle Velocity (ft/sec)	Pressure (Ksi)				Maximum Yield (in.)
				P1L	P1R	P3L	P3R	
1	21.50	17.70	4948	99	106		91	
3	21.50	17.70	4934	98	104		99	
5	21.50	17.70	5289	108	107		99	
6	22.00	17.70	5246	109	110		104	
7	22.25	17.70	5249	114	111		101	0.002
8	22.50	17.70	5217	113	113		105	
9	22.75	17.70	5200	115	109		105	
11	23.00	17.70	5181	113	111		106	
12	23.25	17.70	-	107	114		103	
13	23.50	17.70	5161	108	108		107	
14	23.75	17.70	5164	117	118		114	
15	24.00	17.70	5138	119	118		115	0.004
16	24.25	17.70	5082	117	115		101	0.005

Table B-4. Tube Serial Number 1129 (153 Ksi Yield Strength)

Round Number	Slug Weight (lbs)	Charge Weight (lbs)	Muzzle Velocity (ft/sec)	Pressure (Ksi)				Maximum Yield (in.)
				P1L	P1R	P3L	P3R	
1	865	865	-	68	67		66	
2	21.50	17.70	5266	106	106		102	
3	22.00	17.70	5263	108	109		105	
4	22.25	17.70	5253	109	110		106	0.001
5	22.50	17.70	5230	111	110		105	
6	22.75	17.70	5187	112	112		107	
7	23.00	17.70	5187	113	114		109	
8	865	865	-	67	67		64	
9	23.25	17.70	5154	111	110		106	
10	23.50	17.70	-	111	112		107	
11	23.75	17.70	5115	113	113		109	
12	24.00	17.70	5109	114	114		110	
13	24.25	17.70	5056	111	110		107	
14	24.25	17.70	5112	116	116		112	0.002
15	24.50	17.70	5112	118	118		113	0.003
16	24.75	17.70	5059	115	115		112	

Table B-5. Tube Serial Number 1686 (154 Ksi Yield Strength)

Round Number	Slug Weight (lbs)	Charge Weight (lbs)	Muzzle Velocity (ft/sec)	Pressure (Ksi)				Maximum Yield (in.)
				P1L	P1R	P3L	P3R	
2	21.50	17.7	5217	105	104		104	
3	22.00	17.7	5194	105	105		105	0.001
4	22.50	17.7	5161	108	107		108	
5	22.75	17.7	5148	115	109		110	
6	23.00	17.7	5121	110	110		110	
7	23.25	17.7	5118	110	109		110	
8	23.50	17.7	5082	111	111		112	
9	23.75	17.7		115	113		114	0.0025
10	24.00	17.7		115	114		115	
11	24.25	17.7		116	116		116	0.0035
12	24.50	17.7		116	116		116	
13	24.75	17.7		114	114		114	

Table B-6. Tube Serial Number 1164 (153 Ksi Yield Strength)

Round Number	Slug Weight (lbs)	Charge Weight (lbs)	Muzzle Velocity (ft/sec)	Pressure (Ksi)					Maximum Yield (in.)
				P1L	P1R	P3L	P3R	Cu	
1	21.50	17.5	5144	98	96	90	90		
2	22.00	17.7	5125	100	105	97	101		0.001
3	22.50	17.7	5174	102	106	98	98		
4	23.00	17.7	5148	108	110	100	101		0.0015
5	23.25	17.7	5141	108	109	100	102		
6	23.75	17.7	5095	109	111	100	103		
7	24.00	17.7	5069	107	114	101	103		
8	24.25	17.7	5075	112	118	101	106		0.002
9	24.50	17.7	5049	110	107	105	106		
10	24.75	17.7	-	-	-	-	-		
11	M865	-	5774	81	79	73	74		
12	M865	-	5801	80	81	77	77		
13	M865	-	5768	80	80	75	76		
14	21.50	18	5305	106	103	100	101	110	0.001
15	22.00	18	5249	106	108	106	101	113	
16	22.50	18	5220	108	111	106	103	114	0.002
17	23.00	18	5167	111	114	111	105	114	0.0025
18	23.25	18	5226	110	111	111	107	114	
19	23.50	18	5184	113	118	110	110	116	0.003
20	23.75	18	5157	111	118	109	108	120	0.0035

Table B-7. Tube Serial Number 1116 (154 Ksi Yield Strength)

Round Number	Slug Weight (lbs)	Charge Weight (lbs)	Muzzle Velocity (ft/sec)	Pressure (Ksi)					Maximum Yield (in.)
				P1L	P1R	P3L	P3R	Cu	
1	21.50	18	5285	1026	103	106	103	112	
2	21.75	18	5262	103	104	97	96	111	0.001
3	22.00	18	5213	103	97	97	96	112	
4	22.25	18	5246	102	104	102	104	113	0.002
5	22.50	18	5259	110	109	110	110	115	0.0035
6	22.75	18	5217	109	109	109	109	115	0.004
7	23.00	18	5230	111	111	114	113	116	

Table B-8. Tube Serial Number 5185 (155 Ksi Yield Strength)

Round Number	Slug Weight (lbs)	Charge Weight (lbs)	Muzzle Velocity (ft/sec)	Pressure (Ksi)					Maximum Yield (in.)
				P1L	P1R	P3L	P3R	Cu	
1	21.40	18	5289	106	109	-	105	110	0.0005
2	21.50	18	5318	-	-	-	-	110	
3	21.75	18	5233	106	110	98	106	113	
4	22.00	18	5226	106	112	105	107	112	
5	22.25	18	5233	109	111	108	109	115	0.0015
6	22.50	18	5230	108	115	107	110	115	
7	22.75	18	5194	119	122	111	115	121	0.004

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