175 MM M113 Cannon: Historical Perspective on the Cannon that changed our Cannon Design Process

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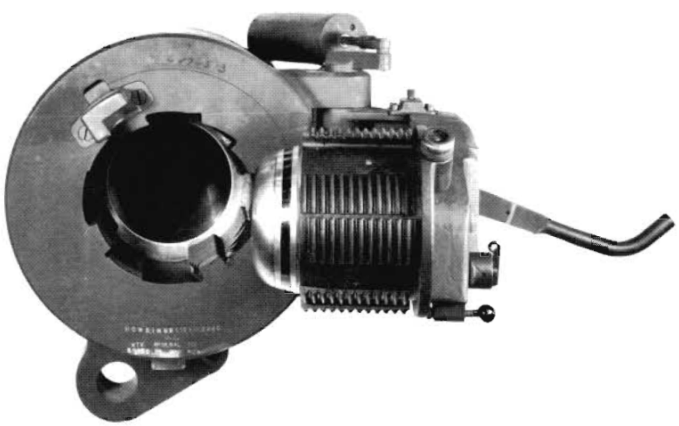
Background – Requirements
Development of 175 MM M107 Howitzer

- Basic Requirements – Increased Mobility & Range in Heavy Artillery
- Development Contract with PACCAR (Pacific Car and Foundry), Renton, WA and a Production Contract with BMY (Bowen & McLaughlin York), York, PA,
- M107 (175 MM Cannon)/M110 (8" Cannon) Self Propelled Howitzer began fielding in 1959
- Long term Plan - convert all 8" cannon-equipped vehicles to 175 MM Cannons and re-designate them M107 Howitzers by the mid-1960s.

- 175 MM Cannon Fielding
  - Roots of the 8”/175 MM Howitzer
    - 8” Artillery System (guns, ammunition) evolved starting in WW1 when US obtained UK 8” howitzers
    - 8” cannons right up to the this timeframe were of the same basic design
    - Well liked by soldiers for accuracy, firepower, simplicity, reliability
    - Enormous supply of 8” ammunition in stockpile
    - ‘New’ design of the 175 MM borrowed heavily from this basic design



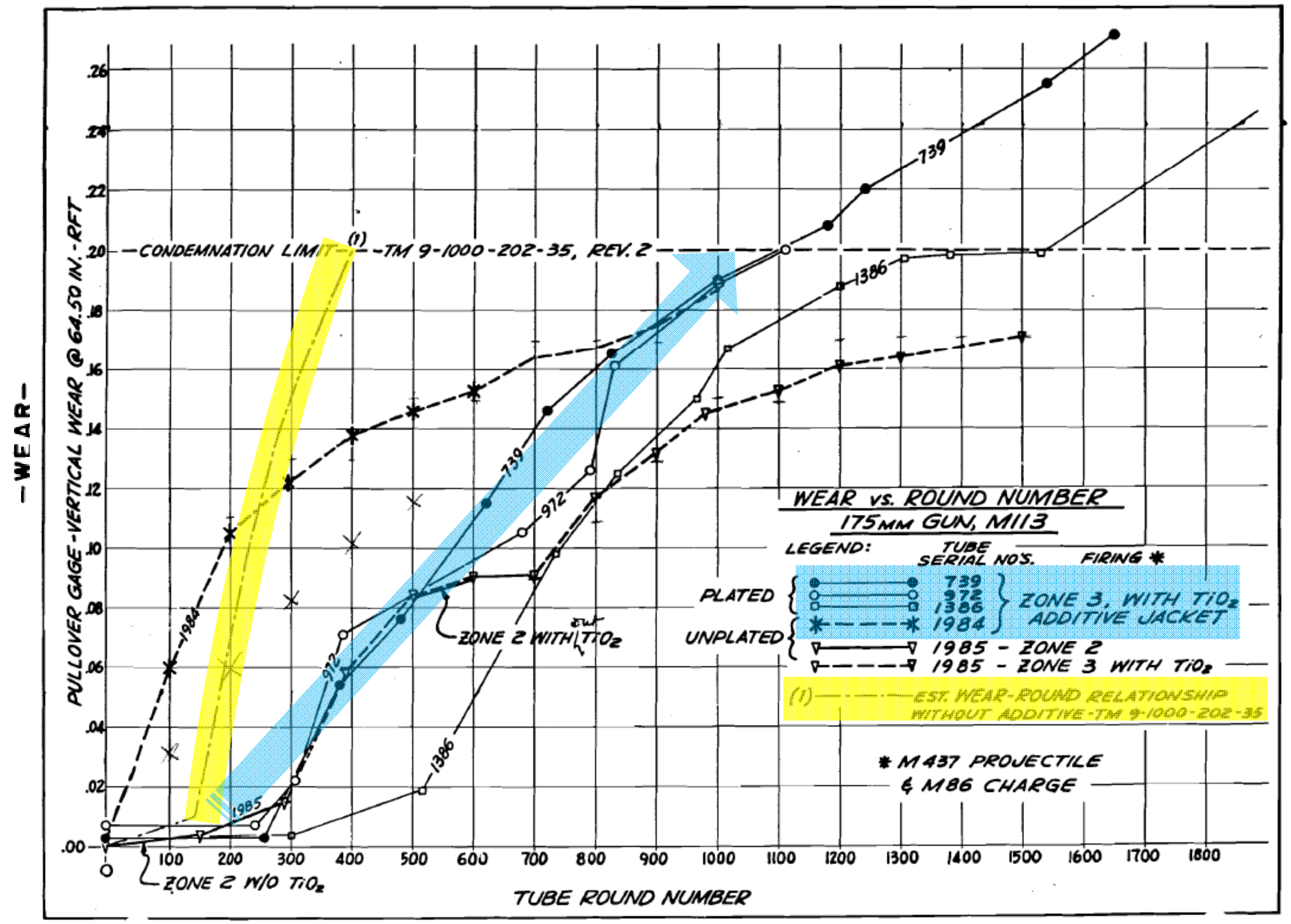
8” M110 Howitzer showing breech and tube (2) circa 1965

- 175 MM Cannon Overview and Fielding (cont'd)
  - Performance of the 175 MM
    - Muzzle velocity 3000 fps
    - Range (max) 32,800 meters
    - Allowable recoil (variable)
    - Rate of fire:
      - Normal 1 rd per 2 min
      - Maximum 1 rd per 1 min
      - (widely ignored in the field)
    - Maximum number of rounds fired consecutively at max rate 10
    - Maximum powder pressure permitted - 50,000 psi
    - Average accuracy life - 400 rd ('wear' life term came into use after 1963)

175 MM M113 – 8" Vietnam Experience

- Significant operational readiness problems in early 1965 after 175 MM fielding (9)
  - Inadequately trained maintenance personnel
  - Shortage of manuals
- Logistics Problems
  - rate of fire of these weapons much higher than expected (1 tube per gun every 45 days.)
  - Ammunition Consumption: average 300 rounds/tube/day (8)
- Cannon Failures
  - improper storage of propellant in hot, humid conditions - resulting in 'short rounds'
  - extreme firing rates caused projectiles to become overheated – causing in-bore malfunctions

175 MM M113 – 175 MM Cannon Fielding



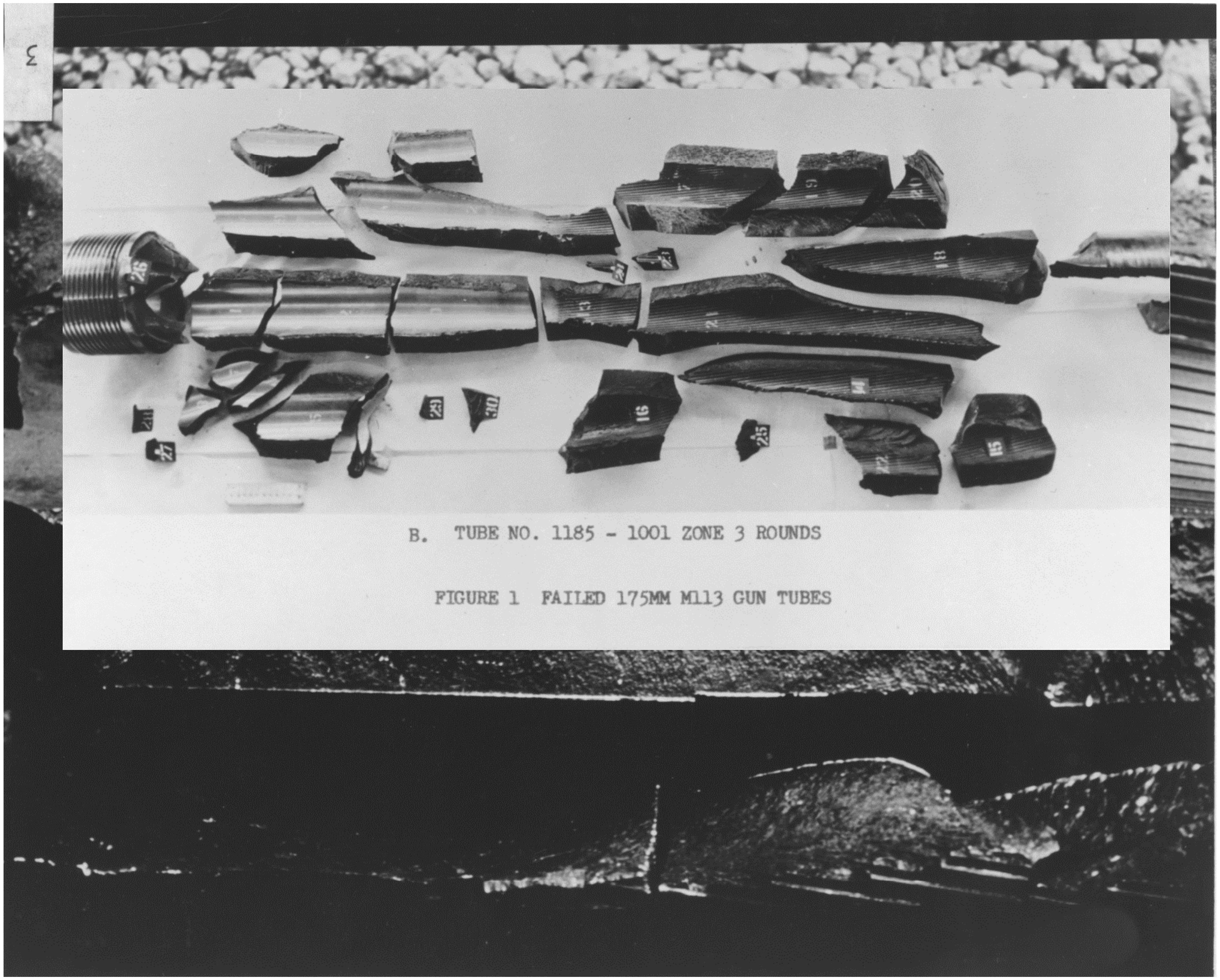
Testing of M1 Wear Additive showing drastic improvement in wear life (6)

175 MM M113 – 175 MM Cannon Fielding Tube Failure and Immediate Impact

- April 1965, a 175 mm M113 gun tube failed during firing in Vietnam at a total of 428 Equivalent Full Charge (EFC) rounds and the failure was attributed to fatigue
- Almost immediately -
  - fatigue limit was reset to 400 EFC (300 maximum Zone 3 rounds) fatigue life on the tube
  - major investigation and analysis was launched
  - gun tubes with same properties (whole production run) were removed from service
- Now - cannons that could fire effectively (based on the new wear additive) past 1,000 rounds were now being taken out of service at 400 rounds or less.
- Given the amount of firing on-going, this was a potential crisis for field units, and the impact was heard at the Secretary of Defense level.

175 MM M113
Tube Serial Number 733

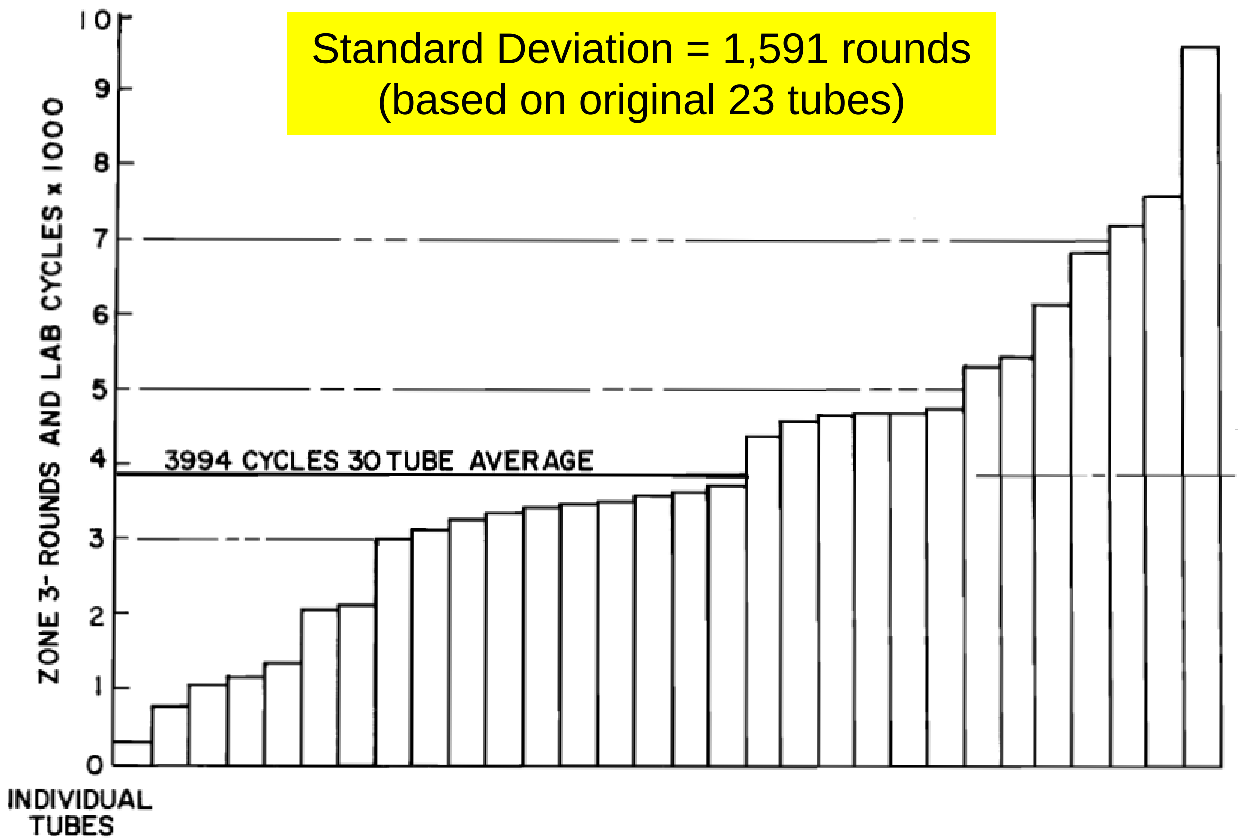
Soon after this, the fatigue failure was duplicated during a test. Tube (S/N 1185 failed with 1001 Zone 3 rounds.



B. TUBE NO. 1185 - 1001 ZONE 3 ROUNDS

FIGURE 1 FAILED 175MM M113 GUN TUBES

- Gun tubes with fracture related mechanical properties, . . in the same range as those of the failed tube were removed from service (7)
- Immediate additional testing was started – From May 1965 - September 1965 - 23 tubes were tested. Additional tubes were added over the next few months.



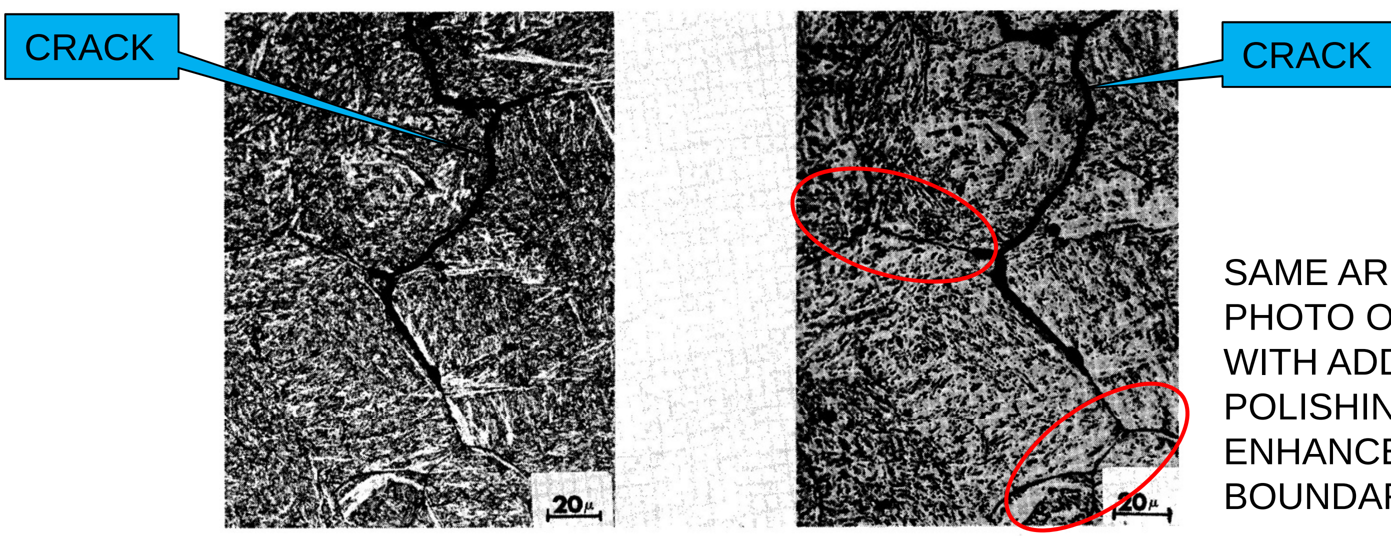
- In parallel, an intense Metallurgical Analysis was started and a review of design and testing processes used.
- First step here was to review the recorded characteristics of the tubes under test
  - 'Gun Card' data from tubes in the field – noted as unreliable for detailed review
  - Fracture toughness – at this point, understood as a general indicator of fatigue characteristics did not always correlate with the fatigue data observed.
  - Also – the brittle failure mode noted in some tubes was not consistent across the population.

Tube No.	Firing Cycles	Total Cycles to Failure	Yield Stress ksi	Charpy Energy ft-lb	Fracture Toughness ksi√in.	Critical a in.	Crack Size a/2c -
733	373	373	171	6	80	0.37	0.33
863	1005	1011	184	9	$\boxed{94}$	1.7	0.41
1131	330	9322	182	14	129	1.7	0.10
1382	1005	1411	185	11	98	1.5	0.36
1386	1705	4697	181	14	$\boxed{106}$	1.8	0.30
typical values from 35 tubes		4000	180	12	110	1.5	0.35

Investigations – Findings

- Next Step – detailed metallurgical examinations:
  - grain size was examined and no unique characteristics were found
  - near bore microstructures examined - ranged from bainite to martensite to a mixture - no correlation to fatigue life, crack size or growth
  - inclusions in the microstructure were noted and there was some correlation with number and fatigue life, however, cracks did not seem to originate or favor the inclusions, so this link was dismissed as a primary source.
  - Hydrogen embrittlement - understood to contribute to lower life was examined and dismissed as a potential cause
- After some examination it was determined that the lower life tubes exhibited inter-granular cracking vs the longer lived tubes that primarily exhibited trans-granular cracking
- It was further noted that the lower life tubes were linked to longer timed - lower temperature tempering processes.
- Temper embrittlement was specifically noted as a concern.

- Electron microscopic examination (a very recent tool for the period) revealed that the impurities in the lower life tubes were most prevalent in the grain boundaries, where in the longer life tubes, they appeared well distributed.
- Findings:
  - longer tempering times allowed impurities to migrate to grain boundaries
  - Weakened grain boundary zones allowed localized (fatigue) crack growth to progress quicker in an ***intergranular*** cracking failure mode
  - Inclusions tended to contribute to the faster crack growth - and brittle failure mode
  - Temper embrittlement also contributed to brittle failure mode



SAME AREA AS PHOTO ON LEFT WITH ADDITIONAL POLISHING TO ENHANCE GRAIN BOUNDARIES.

Investigations – Findings

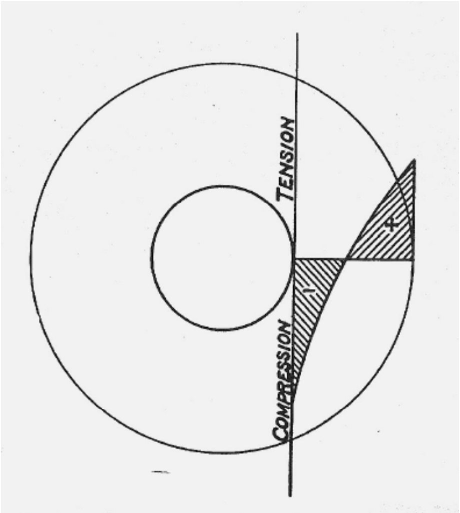
- Mean fatigue life was 3994 Zone 3 rounds or cycles,
  - data exhibited an unusually large spread from 373 rounds to 9652 rounds plus laboratory cycles. * (3)
- Wide spread in data, (which resulted in retention of the 400 EFC fatigue life) , was attributed to:
  - intergranular cracking caused by the low tempering temperatures and/or long tempering times necessary to achieve a high yield strength level.
  - Inclusions were noted as a strong contributing factor
- Additionally:
  - Considerable variation was observed in mechanical properties along the length of some tubes. (4)
  - Environmental factors were strongly suspected, but could not be proven
- At this point, the materials community had postulated that fracture toughness was directly linked to fatigue.
  - Investigation, revealed it was only partially true,
  - Less so for low cycle fatigue environments (like cannon fire).

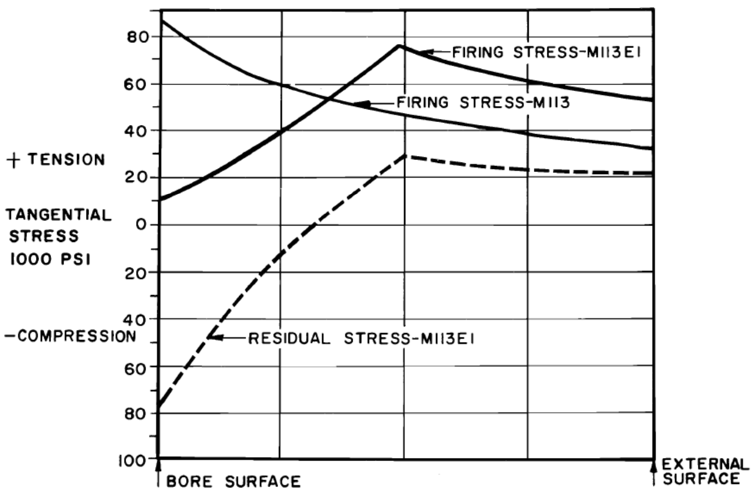
•It should be noted that the laboratory cycling had not been confirmed as equivalent to firing. It was not until 1971, as a result of this program, this finding was eventually confirmed.

	OCT 63	APR 66	MAR 67	OCT 67	NOV 68
TUBE DESIGN	MONOBLOC →				AUTOFRETTAGED
MIN YIELD STRENGTH (1000 PSI)	170	170	160	160	140
MINIMUM TESTS EACH END (TENSILE & CHARPY)	2	2	4	4	4
MINIMUM CHARPY IMPACT STRENGTH (FT-LBS @ -40°)	6	10	12	15	25
MINIMUM REDUCTION IN AREA (%)	9	13	20	25	30

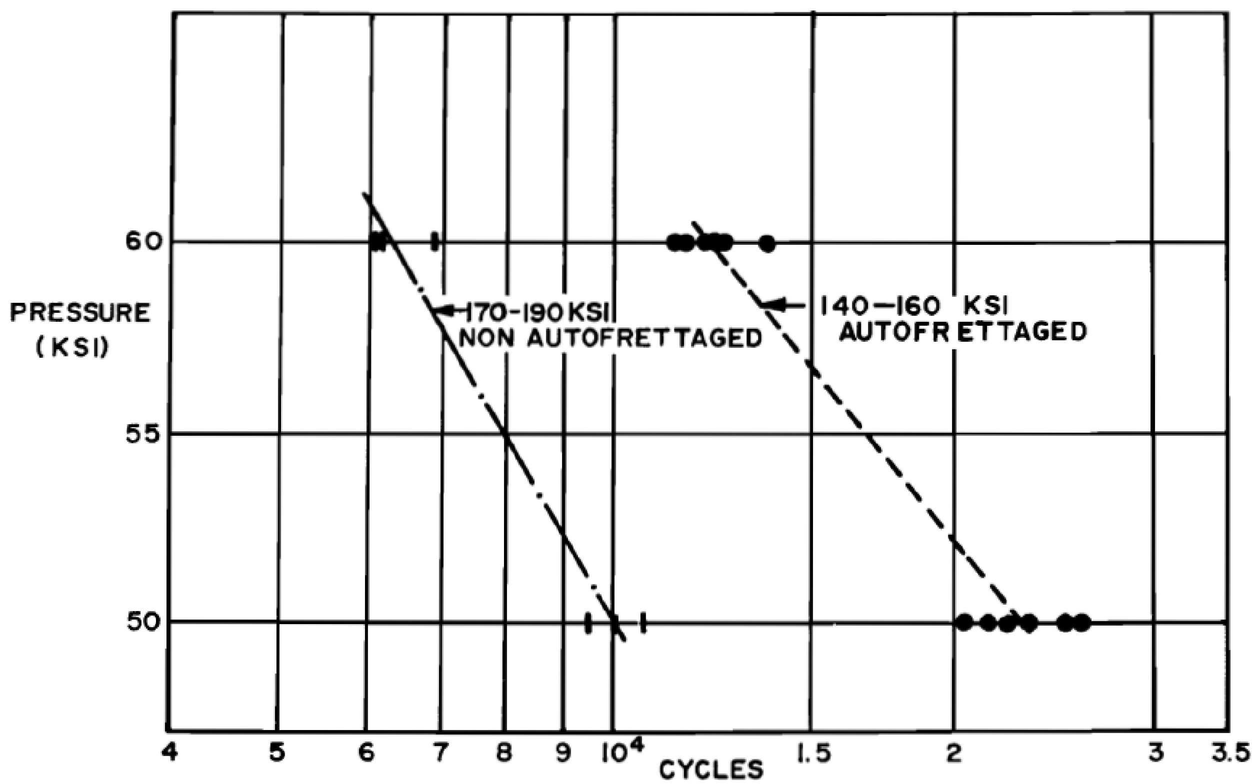
Changes in Design - Autofrettage

- Prior designs and analysis had applied autofrettage with considerable improvement in fatigue life on 105 mm and smaller systems.
- Previous small caliber design used 100% overstrain at max pressure location – using a complete containment vessel
- Initial calculations showed that 40% overstrain should yield sufficient residual stresses (80 ksi) in the origin of rifling and (49 ksi) in the chamber to withstand expected pressures.
  - provide enough elastic strength in the chamber
  - result in a substantial improvement in fatigue life
  - extensively employed on smaller caliber tubes,



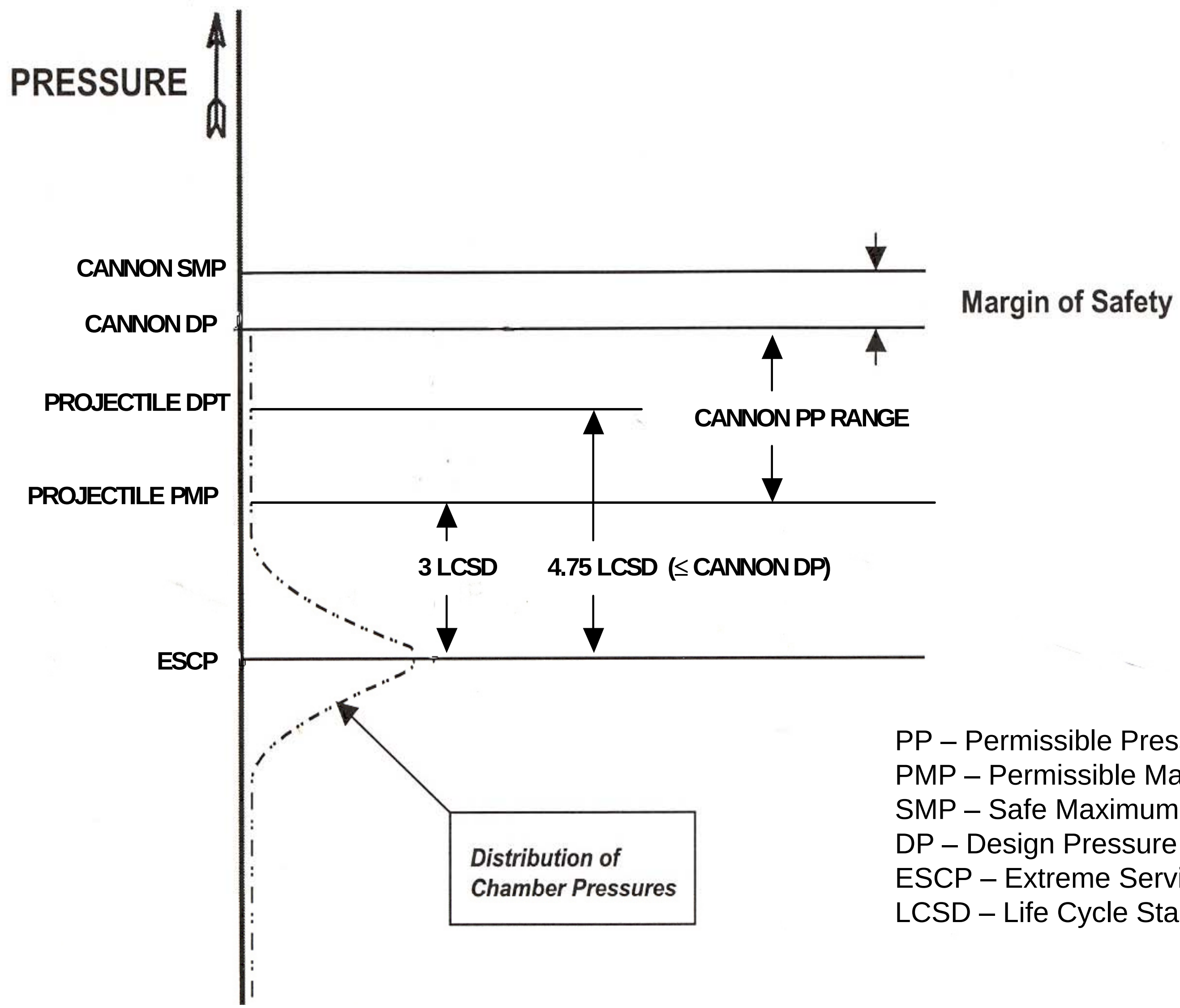


- Validation Testing of the M113A1 in 1969 revealed that the autofrettage process did improve the fatigue life.



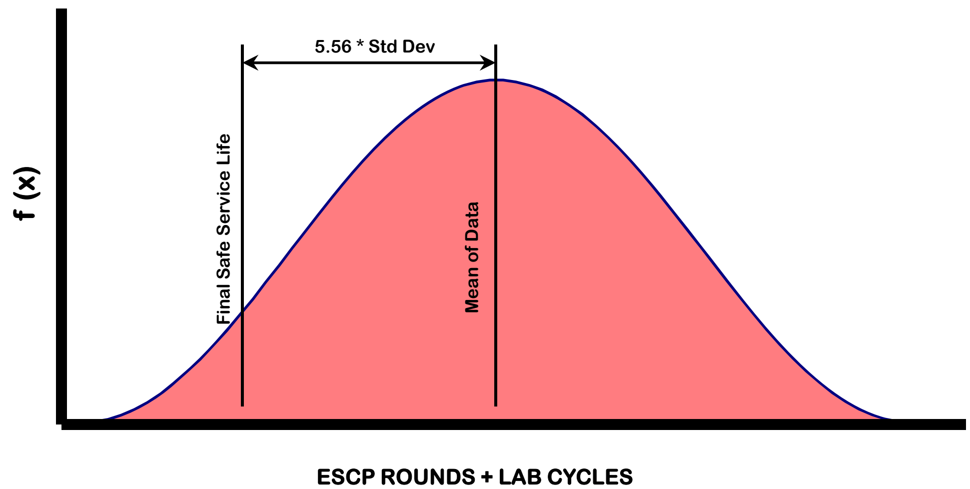
Changes in Design Process

- Key tools/understanding
  - Probabilistic limits of data became an inherent design tool guideline
  - Weibull distribution of data was historically used as a model in life estimation.
  - Currently, log normal distributions are being used (due to difficulty in predicting Weibull data with limited data in early design phases)
  - Firing pressure variations addressed by use of a ***Life Cycle Standard Deviation (LCSD).*** LCSD is by combining the standard deviations of:
    - Cannon to Cannon (data from multiple tubes firing)
    - Lot-to-Lot (propellant from multiple different production runs)
    - Occasion-to-Occasion (data on different days, different locations)
    - Round-to-Round (data from the different firings
- Design techniques and tools were matured
  - Standard calculations emerged for use – and continuous improvements made.
  - All large cannons are now autofrettaged
  - Finite Element Analysis has been integrated into the design process
  - New engineers receive specialized courses developed in house on gun design



PP – Permissible Pressure
PMP – Permissible Max Pressure
SMP – Safe Maximum Pressure
DP – Design Pressure
ESCP – Extreme Service Conditions Pressure
LCSD – Life Cycle Standard Deviation

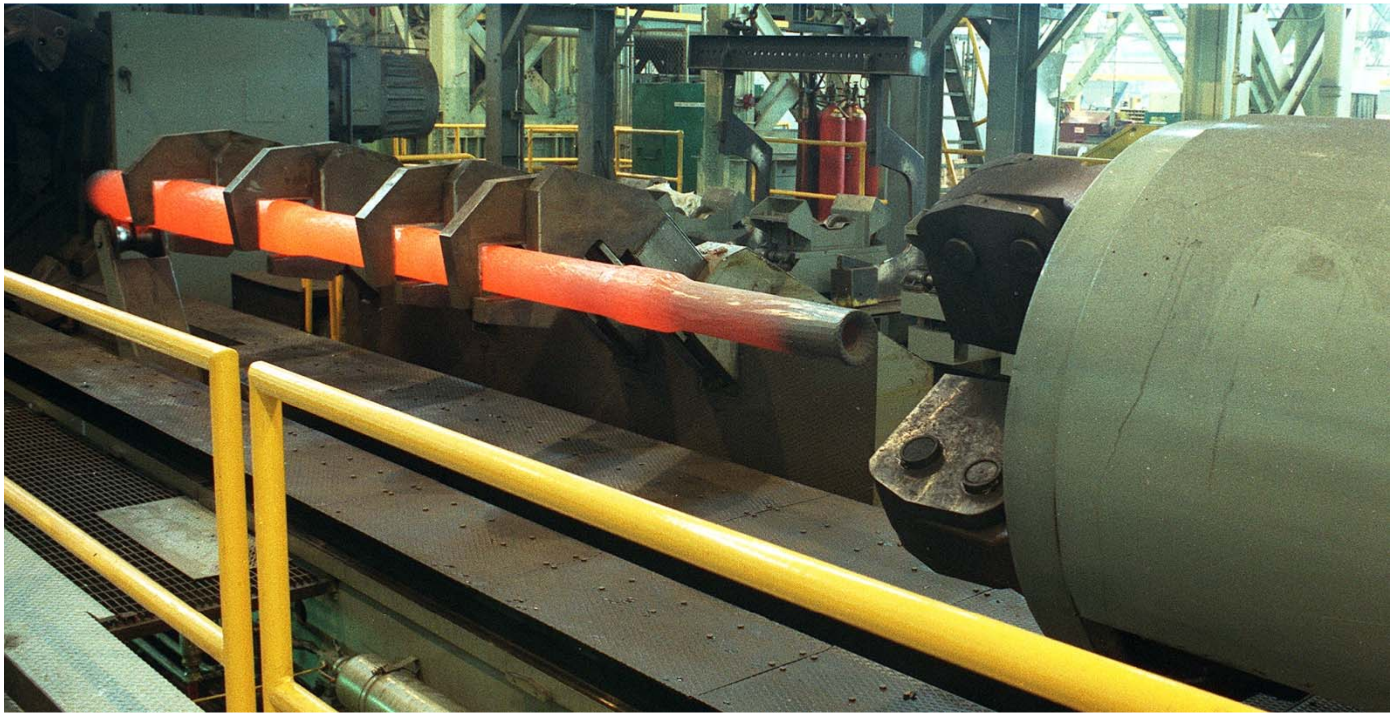
- Testing:
  - Generally, all new cannon designs now are subject to a full suite of firing tests in the field, ranging from climatic extremes to overpressure rounds
  - Six (6) cannons are tested right to failure (separately cycling the tubes and breeches) in an advanced hydraulic lab set up at Benet
  - The failed cannons are checked to ensure a slow, ductile failure occurs and that the failure mode is consistent. Probabilistic analysis of the test results gives us our life ratings



- Changes in the Design Process
  - Extensive research related to metallurgy, processing and mechanics of cannon tubes continued well past this incident.
  - Findings spurred an industry wide increase in the understanding of pressure vessels and design

Changes to Production Processing

- In 1982, the Watervliet Arsenal embarked on the 'REARM' program - as part of this program,
  - Tube autofrettage techniques and design were significantly refined
  - a rotary forge was developed and installed at Watervliet to ensure tighter quality control . Included was extensive equipment to take samples from each tube produced for examination.



Epitaph
What happened to the 175 MM?

- In the mid-1970s, immediately following the Vietnam War, the US developed a requirement for an improved 8" cannon that would incorporate the lesson's learned from the 175 MM cannon to create a longer range, more accurate, heavy artillery system.
  - This system upgrade resulted in the M201A1 Cannon (M110A2 Howitzer)
    - an upgraded steel formulation and processing in the cannon
    - a higher impulse longer range charge and projectile system
    - a muzzle brake to maintain the impulse level delivered to the carriage
- In the 1980s, this system became the core of the cannon launched nuclear projectile program.
- This system was in use by the US Army until 1994.
- It is still in use with 5 other armies

Back Up Design Standards & Criteria

- Design standards evolved and the lessons learned spawned the development of
  - MIL-C-13931: A military specification developed by Benet Labs that addresses the overarching general metullurgical standards, quality assurance factors, and related documentation that a cannon system must meet.
  - NATO Standardization Agreement 4110 - that governs the design, rating, and standardizes limits and practices in cannon design. It includes specific language governing the use of samples and probabilistic criteria in cannon design.
  - International Test Operational Procedure 3-2-829 that spells out how a cannon shall be test fired, governs the use of laboratory cycling processes, and addresses how data will be interpreted and used on assessing the design.
- The US Army also adopted guidelines that establishes distinct areas of responsibility:
  - Training & Doctrine Command (TRADOC): Develops requirements for systems
  - Army Material Command (AMC): Develops material to meet these requirements (Benet is an agency of AMC)
  - Test Centers (Several agencies): Tests the material (including cannon) to assess performance against requirements
  - Army Test Evaluation Command (ATEC): Assesses the test results, design data, and establishes an independent Safety Certification for all material (each cannon system)

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