WATERTOWN ARSENAL

PRODUCTION DEPARTMENT

GUN DIVISION

REPORT NO. WGD -11

THE MACRO ETCH TEST AS A MEANS OF JUDGING THE ACCEPTABILITY OF MATERIAL FOR THE MANUFACTURE OF CENTRIFUGALLY CAST "COLD WORKED" GUN TUBES

PROGRESS REPORT #1

THE COLD WORKING OF TEST CYLINDERS OF SELECTED MACRO STRUCTURES

BY

ALFRED J. SMITH
Metallurgist

DATE 31 July 1944

WATERTOWN ARSENAL
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Production Department

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WGD-11

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OBJECT

The object of this U/A report was

To study the behavior of cylinders of specific macro structure when expanded internally by hydrostatic pressure.

SUMMARY

Three cylinders were machined from a casting of large cross-section size and three cylinders were machined from a casting of small cross-section size. Cylinders were from castings of similar macro structure. Two cylinders from each casting were bored off center so as to contain macro structure of both clean and segregated metal. The third cylinder from each casting was bored on center. All cylinders were heat treated, cold worked 6%, boroscoped, replaced in the cold work press and then cold worked to destruction. One off-center bored cylinder from each casting was stress relieved before being cold worked.

Observations made upon the experimental cylinders revealed that three factors were instrumental in influencing the behavior of subject cylinders when expanded by internal hydrostatic pressure. They are as follows:

1. Macro Structure - For any given section size, a correlation exists between macro structure and the ability of specimen to resist checking and tendency to fragment when expanded by internal hydrostatic pressure.

2. Percent Bore Crop - Cylinders machined from small cross-section castings showed less tendency towards bore checking and fragmentation than cylinders machined from large-section castings of similar macro structure. The percent bore crop was greatest on cylinders from the small-section casting.

3. Heat Treatment - A stress relief treatment given to two cylinders prior to cold working reduced the tendency of the bore metal to check, reduced the tendency of the cylinders to fragment and considerably increased the amount of plastic flow before failure.

ALFRED J. SMITH
Metallurgist

INTRODUCTION

The quality of centrifugally cast gun tubes produced at Watertown Arsenal is judged in part by the macro etch test. The Production Department is obliged to produce material which conforms to a standard included in gun tube specifications*.

Some correlation was found in the past between the macro structure and the susceptibility of a gun tube to behave in a ductile or brittle manner when expanded by the cold work process. Since little, if any, service data were available on cast gun tubes made during the early years of the centrifugal casting process, the relationship between macro structure and ability to resist internal pressures was considered valid. It was recognized that cold working provided, in itself, a non-destructive test of considerable value to the manufacturer. It was obvious that material low in ductility would reveal checks or cracks in the bore. Good correlation between ductility and macro structure offered the producer a means of inspecting his product at an early stage of manufacture, thus saving the expense of processing material which would subsequently be rejected.

The rejection of a considerable number of 3" Liner and 76 MM gun tubes within recent months has been based entirely upon the results of the macro etch test. A majority of these tubes had satisfactory physical properties as judged by physical test results and an investigation of their behavior when subjected to expansion by the cold work process was considered worthwhile. All tubes so tested withstood a bore expansion of 6% without the

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* Watertown Arsenal Macro Etch Standard for Centrifugally Cast Gun Tubes - July 1943

occurrence of serious checking. Although the macro structure of many of the tubes was definitely rejectable according to our present tentative standards, no checking whatsoever was found to exist after cold working*.

90 MM M1 castings of undesirable macro quality were found to check much more frequently during the cold work operation than castings of small cast cross-section size. In general, it appeared that tubes of relatively small (76 MM and 3" Liner) cross-section castings having similar macro structure did not behave like the 90 MM castings when subjected to internal pressure. Large section castings (105 MM M2A1 Howitzer) which were cold worked at a larger bore diameter than 90 MM castings were also found to cold work without checking.

The loss to the Production Department represented by macro rejections was sufficient reason to initiate an investigation to determine, if possible, the apparent lack of correlation between macro structure and the behavior of such tubes during the cold work operation.

For the best local means of evaluating performance, it was decided to cut cylinders from gun tubes of similar macro quality but differing in cast section size and to expand them by cold working so that careful observation could be made and presented. Experimental results showing the variations in behavior between castings of different cross-section size with similar macro structure are presented in this report.

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* 1. Memorandum Report - A. J. Smith to Lt. N. A. Birch, 1 May 1944, Subject: - 3" Liner Castings Rejected for Poor Macro Structure

2. Memorandum Report - A. J. Smith to Lt. N. A. Birch, 30 May 1944, Subject: - 76 MM Castings Rejected for Poor Macro Structure

PREPARATION OF TEST METAL

Two centrifugally cast gun tubes were selected for test material. Selection was based upon knowledge of the appearance of the macro structure of these tubes. Both were "larger muzzle hole"* castings with characteristic bore segregation and etch pits. Pertinent data are shown in Tables I and II.

TABLE I

3F-1347	3" Liner M3 casting representing relatively small cross-section castings
3G-2775	90 MM M1 casting representing relatively large-section casting

Heat Treatment**

	3F-1347	3G-2775
Normalize	2200° F 16 hrs.	2200° F 16 hrs.
Harden	1650° F 6 hrs. Water cool	1650° F 6 hrs. Water cool
Draw	1300° F 6.5 hrs. Furnace cool	1335° F 6 hrs. Furnace cool

Stress Relief***

	570° F 12 hrs. Air Cool	570° F 12 hrs. Air Cool Agincourt only

Ladle Analysis

	C	Mn	Si	Cr	Mo	V
3F-1347	.21	.75	.34	1.00	.48	.085
3G-2775	.28	.81	.28	.89	.48	.09

* Smith, A. J. - Macro Uniformity of Centrifugally Cast Gun Tubes, Watertown Arsenal Production Department Report WGD-6, January 1944

** Rough Castings except for the stress relief treatment were heat treated with production gun tubes

*** Smith, A. J. - The Development of a Stress Relief Treatment to Improve the Ductility of Centrifugally Cast Gun Tubes, Watertown Arsenal Production Department Report WGD-3, December 1943

Three cylinders were cut from each casting. The sectioning details are shown in Figure 1 and Figure 2. Details of test cylinder dimensions are shown in Figure 3.

Photographs of "as cast" macro discs cut from the ends of castings after 2.5" discards were cut are shown in Figures 4 and 5.

Table II presents pertinent dimensions for each cylinder.

TABLE II

Gun Type and No.	As Cast Hole Size	Cylinder Number	Bore Diameter	Outside Diameter	Comments	Photo. Ref.
3F-1347 3" Liner M3	B 1 1/16" M 1 1/2	1	2.5"	5.0"	Concentrically Bored	Fig. 7
		2*	2.5	5.0	Bored 1/4" off center	Fig. 8
		3	2.5	5.0	Bored 1/4" off center	Fig. 9
3G-2775 90 MM M1	B 1 1/2 M 2 1/2	1	3.0	6.0	Concentrically Bored	Fig.10
		2*	3.0	6.0	Bored 1/2" off center	Fig.11
		3	3.0	6.0	Bored 1/2" off center	Fig.12

* Stress Relieved

To study the influence of two types of macro structure (light etching and dark etching) in the same test specimen, cylinders #2 and #3 from both the large-section casting and the small-section casting were bored off center. Figure 6 illustrates the off-center machining procedure.

To study the influence of the stress relief treatment upon bore checking, total expansion and fracture characteristics of cylinders of similar macro structure, cylinders #2 from both the large-section casting and the small-section casting were stress relieved while #3 cylinders were not stress relieved.

Physical test specimens were taken tangent to the machined bore on

both ends of each cylinder. Cross-sectional dimensions as machined, macro structure of cylinder end discs, test bar position and physical test results are shown in Figures 6 to 11 inclusive.

All test cylinders had steel collars shrunk on the ends so that the cold work packing could be easily removed after approximately 6% bore expansion.

EXPERIMENTAL TEST PROCEDURE

Using empirically derived values of the strain ratio*, the strains on the outside diameter, and corresponding diametrical expansion of the test cylinders, required to produce a bore expansion of 6% were computed. The cylinders were then cold worked by internal pressure until the outside diameter expansion as measured by special beam expansion gages was equal to this computed value at the two gage points. These expansion gages (shown in Figure 13) consisted of a rigid frame and flexible beam arranged to bend the beam an amount corresponding with the diametrical expansion of the cylinder. Electric resistance-type strain gages were used in conjunction with a wheatstone bridge for reading deflection of the beam as the cylinder expanded. Observed readings of resistance change in the strain gages were calibrated directly in terms of known increments of expansion across the gage. The cylinder was then removed from the cold work press and star-gaged to check the actual bore expansions at increments of 2" throughout the length. After star-gage readings and boroscope examinations were made, the cylinders were returned to the press and cold

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* Newhall, D. H. - Plastic Strains in Thick Hollow Cylinders Overstrained by Internal Pressure, Figure 1, Watertown Arsenal Production Department Report WGD-7, January 1944

worked to destruction. Each cylinder was examined for type of fracture, checks on the outside surface and in the bore, and for macro structure in the area of greatest expansion.

RESULTS AND DISCUSSION

Results of the visual examination of the six experimental cylinders are presented in Tables III and IV. Figures 14 to 19 inclusive are composite photographs of each cylinder showing macro structure, bore condition, fracture and outside surface condition.

A detailed summary of observations made upon the experimental cylinders is presented below:

1. Boroscope examination after approximately 6% cold work revealed the following:

   a. Test cylinders bored to give a symmetrical distribution of segregated material around the bore checked uniformly about the circumference of the bore while test cylinders which were bored to give an eccentric distribution of segregated material checked more severely in the location of the maximum segregation.

   b. For similar macro structures, less checking occurred in cylinders which were stress relieved than in cylinders which were not stress relieved.

   c. Cylinders with marked bore segregation were more susceptible to checking than cylinders with scattered etch pits.

   d. For similar macro structures, cylinders from the relatively large-section casting showed more tendency towards bore checking than cylinders from the relatively small-section casting.

   e. At the extremities of the gage length of each cylinder where only 2% cold work was obtained, the checking appeared equally as severe as at the center of the cylinders where 6% cold work was obtained.

OBSERVATIONS ON CYLINDERS MADE FROM 3" LINER CASTING 3F 1347

REPRESENTING

SMALL CROSS SECTION CASTINGS

	Cylinder No. 1 - Bored on Center	Cylinder No. 2* - Bored Off Center	Cylinder No. 3 - Bored Off Center
Bore expanded approximately 6%. Removed from pressure fixture and boroscoped.	Macro Structure - Bore metal considered barely passable.	Macro Structure - (a) Light etched area considered acceptable, (b) dark etched area considered undesirable.	Macro Structure - (a) Light etched area considered acceptable, (b) dark etched area considered undesirable.
	Bore Condition - Very small checks random in location to circumference and gage length.	Bore Condition - Very small checks found in dark etched macro area slightly more severe than in cylinder No. 1. Location of checks random within gauge length. No checks found in area of light etched macro metal.	Bore Condition - Very small checks found in dark etched macro area. Slightly more severe than in cylinders No. 1 and No. 2. Location of checks random within the gauge length. No checks found in area of light etched metal.
Cylinders expanded to destruction	Maximum Bore Expansion - 67.5%	Maximum Bore Expansion - 52.3%	Maximum Bore Expansion - 31.8%
	Bore Condition - (See Fig. 4) Most severe checking occurred in area of greatest expansion and appeared to be confinedfor the most part to the side of the cylinder having the least desirable macro structure.	Bore Condition - (See Fig. 5) Numerous severe checks in area of greatest expansion confined for the most part to area containing poorest macro structure.	Bore Condition - (See Fig. 6) Relatively few checks located somewhat randomly with respect to the circumference, but for the most part confined to the area of greatest expansion. Some of the checks appeared as deep as those found in cylinder No. 2.
	Outside Surface No appreciable checking noted.	Outside Surface - No appreciable checking noted.	Outside Surface - Severe checks noted in vicinity of fracture.
	Fracture - No tendency to fragment. Failure occurred in a ductile manner.**	Fracture - No tendency to fragment. Failure occurred in a ductile manner.**	Fracture - Some tendency for fragmentation to occur. Note crack progression. Failure occurred in a ductile manner.**

* Stress Relieved

** Theoretically a ductile failure is one which occurs in shear

TABLE III

WTN.639-6976

OBSERVATIONS ON CYLINDERS MADE FROM 90 MM CASTING 3G 2775

REPRESENTING

LARGE CROSS SECTION CASTING

	Cylinder No. 1 - Bored on Center	Cylinder No. 2* - Bored Off Center	Cylinder No. 3 - Bored Off Center
Bore expanded approximately 6%. Removed from Pressure fixture and boroscoped.	Macro Structure - Deep pits throughout. By current standards considered undesirable. Bore Condition - Very small checks random in location to circumference and gage length. Checks were comparable to those found in cylinder No. 3 of 3F 1347.	Macro Structure - (a) Light etched area considered acceptable, (b) dark etched area considered undesirable. Bore Condition - Small checks but slightly larger than in cylinder No. 1. Confined to area of undesirable macro structure but uniformly distributed within the gage length of the cylinder.	Macro Structure - (a) Light etched area considered acceptable, (b) dark etched area considered undesirable. Bore Condition - Checks considerably worse than those found in cylinders No. 1 and No. 2 but confined to area of undesirable macro structure. Distribution uniform within gage lengths. Would have caused rejection if found in gun tube.
Cylinders expanded to destruction	Maximum Bore Expansion - 56.0% Bore Condition - (See Fig. 7) Most severe checking occurred in area of greatest expansion and appeared to be uniformly distributed around the bore. Outside Surface - Some slight checking noted in vicinity of the fracture. Fracture - Some tendency for fragmen-** tation to occur. Failure occurred in a ductile manner.	Maximum Bore Expansion - 54.5% Bore Condition - (See Fig. 8) Relatively few checks revealed. Appeared to be for the most part confined to area of poorest macro structure. Outside Surface - Some deep checks noted in clock position opposite the fracture. Fracture - No tendency to fragment.** Failure occurred in a ductile manner.	Maximum Bore Expansion - 34.3% Bore Condition - (See Fig. 9) Revealed very deep checks, most numerous in area of greatest expansion. Checks appeared deeper than on other cylinders tested and were randomly oriented throughout the circumference. Outside Surface - Severe checking noted in vicinity of fracture. Fracture - Some tendency for fragmen-** tation to occur. Note crack progression. Failure occurred in a ductile manner.

* Stress Relieved

** Theoretically a ductile failure is one which occurs in shear

WTN.639-6977

TABLE IV

2. Visual examination after test cylinders had been ruptured by internal pressure revealed the following:

   a. Areas of poorest macro structure revealed most severe checking.

   b. Severe checking was for the most part confined to the zone of greatest expansion.

   c. Bore checking was not prevented in cylinders which were stress relieved. Cylinders containing undesirable macro structure showed a tendency to fragment except when stress relieved while cylinders of acceptable macro structure showed no tendency to fragment even without the stress relief treatment.

   d. Total bore expansion of stress relieved cylinders before failure was more than half again that of non-stress relieved cylinders of similar macro structure.

   e. Cylinders with marked bore segregation and cylinders with scattered etch pits showed equally serious tendency to fragment when not stress relieved.

   f. For all cylinders, failure occurred in the zone of minimum segregation. The lowest yield strength occurred in the zone of minimum segregation.

   g. No correlation was observed between physical test results and tendency to fragment.

It is apparent from the results obtained upon individual off-center bored cylinders that a definite correlation exists between cold work checks and macro structure. The dark etching segregated material at the bore revealed a greater tendency to check than did the light etching non-segregated material.

However, when comparing cylinders which were machined from different cast section sizes but having similar appearing macro structures, it becomes apparent that behavior during the cold work operation depends upon other factors in addition to the macro structure. Cylinders machined from small cross-section castings showed less tendency towards bore checking and fragmentation during cold work than cylinders machined from large-section

castings. A factor such as the relationship between cast section size and cold work bore diameter (% metal cropped from the bore) is obviously worthy of considerable attention in predicting cold work behavior. The experimental evidence checks with those observations made upon production gun tubes. A practical demonstration of this fact can be obtained by comparing the boroscope records* (after cold work) of 90 MM M1 castings with 76 MM M1A2, 3" Liner and 105 MM M2A1 Howitzer castings of similar macro structure.

A third factor influencing the behavior of test cylinders during cold work is the stress relief treatment. In addition to reducing the tendency to bore check, a most striking demonstration of the influence of this treatment upon the plastic flow of metal is obtained by comparing cylinders #2 with cylinders #3. In each of the specimens, there is little choice between macro structures. However, measurements after rupture reveal that the bore expansion of cylinders #2 was approximately an additional 20% greater than cylinders #3.

Cylinder #2 from the small-section casting appears to etch deeper than cylinder #2 from the large-section casting. From Table V, it is evident that segregation is more intense in the large-section casting. Depth of etch, therefore, cannot be considered as reliable means for judging degree of segregation.

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* Report in progress. Records can be obtained at Watertown Arsenal Inspection Department

TABLE V

SEGREGATION ANALYSIS

	C	Mn	Si	Cr	Mo	V
Small-section casting (3F-1347)						
Ladle analysis	.21	.75	.34	1.00	.48	.085
Dark etching area	.28	.72	.28	1.07	.55	.085
Light etching area	.20	.69	.27	.99	.53	.08
Large-section casting (3G-2775)						
Ladle analysis	.28	.81	.28	.89	.48	.090
Dark etching area	.39	.81	.23	.93	.61	.095
Light etching area	.27	.77	.20	.88	.52	.085

Two variables entered into this experiment which were not considered in the original plan. First, the ladle chemistry for the two castings selected for this experiment were not within the same Carbon and Chromium range. At the time of the selection of test specimens, 3" Liner tubes were being cast in the .18 to .22 Carbon range. As this was standard composition for 3" Liner castings, it was considered most logical to investigate material of current analysis. Observations made during the production period on 3" Liner castings of different Carbon content did not reveal any significant differences in cold work behavior. Because of these observations and the fact that all cylinders were heat treated to approximately the same yield strength, such differences in the chemistry of the subject specimens were not believed to be of major importance. The second variable is the difference in machined hole size between the large-section casting and the small-section casting. As it was desired to machine cylinders so that a particular macro condition was present at the bore, the same hole size for both large and small-section castings was

not possible. However, it is believed that if all specimens had been bored to the same diameter, the differences between cylinders from the large and small-section castings would have been greater than those shown for this report.

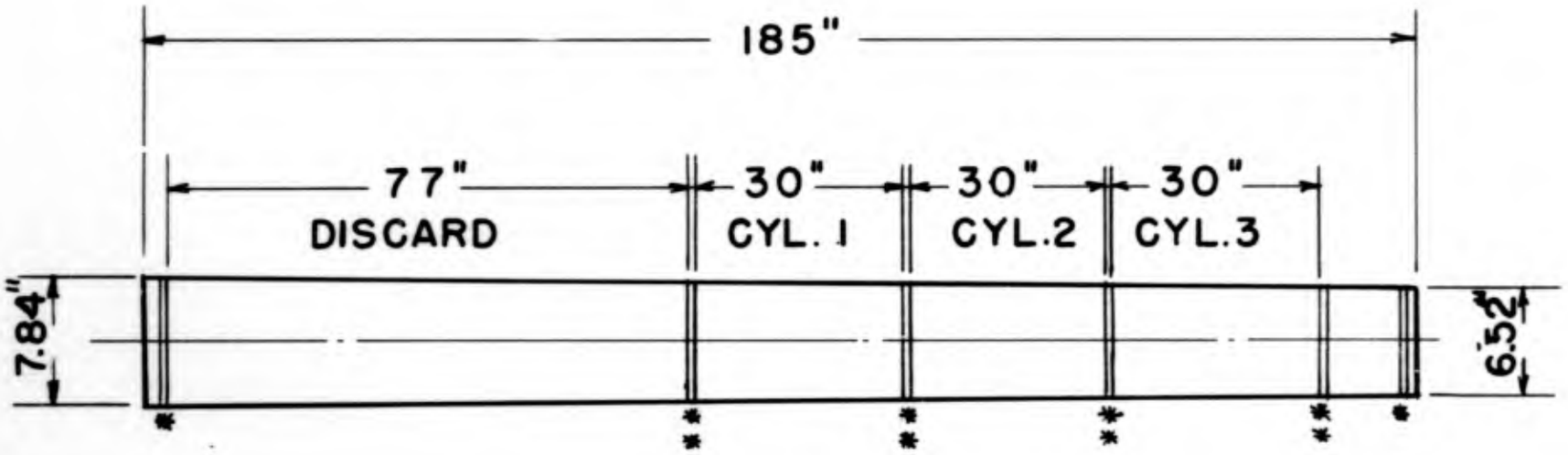
The fracture characteristics of the cylinders depends upon individual interpretation. If strict interpretation is desired, all cylinders must be considered as exhibiting ductile properties because all failures occurred in shear. Three of the cylinders (See Figures 16, 17 and 19) have serious crack progressions which could conceivably lead to fragmentation under high strain rates. Therefore, for purposes of evaluating quality differences, the performance of such cylinders is considered unsatisfactory.

FUTURE WORK

Additional experimental work is now in progress upon cylinders of selected macro structures. It is intended to evaluate variables such as chemistry, heat treatment and cast section size of various size centrifugally cast gun tubes.

3" LINER 3F-1347

CASTING DIMENSIONS AND TEST CYLINDER POSITIONS



* — AS CAST MACRO DISCS $(\frac{3"}{4})$

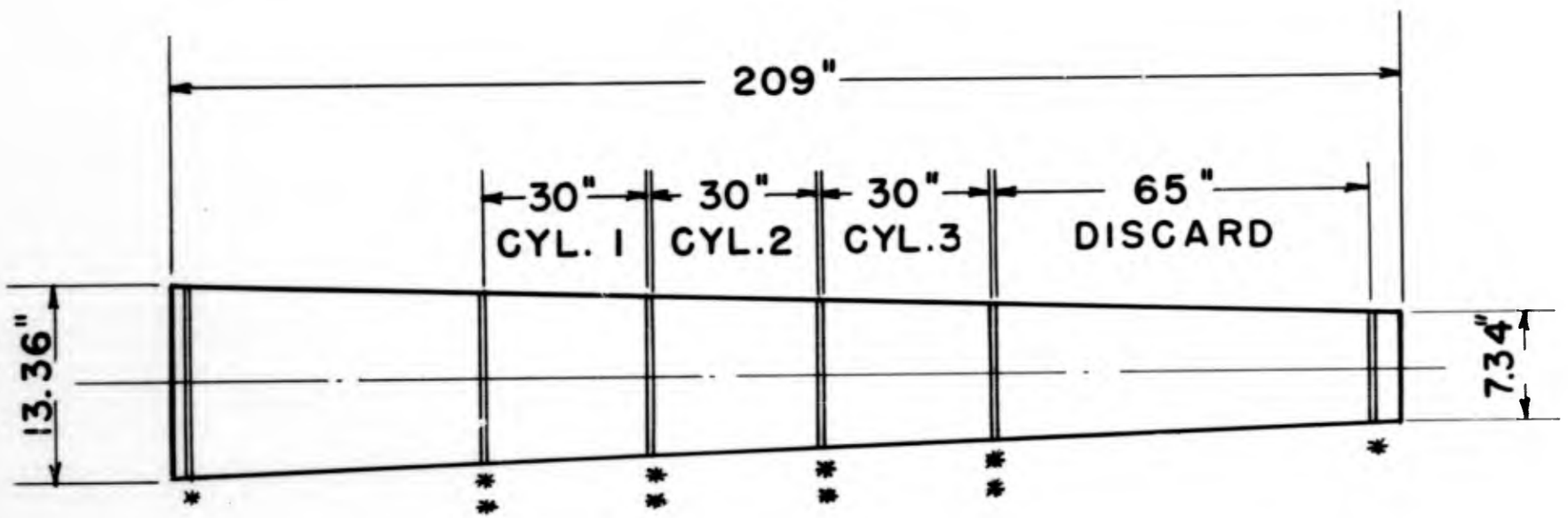
*
* — HEAT TREATED MACRO DISCS $(\frac{3"}{4})$

WTN.639-6979

FIG. 1

—90 M/M MI-3G-2775—

CASTING DIMENSIONS AND TEST CYLINDER POSITIONS



*-AS CAST MACRO DISC ($\frac{3}{4}$")

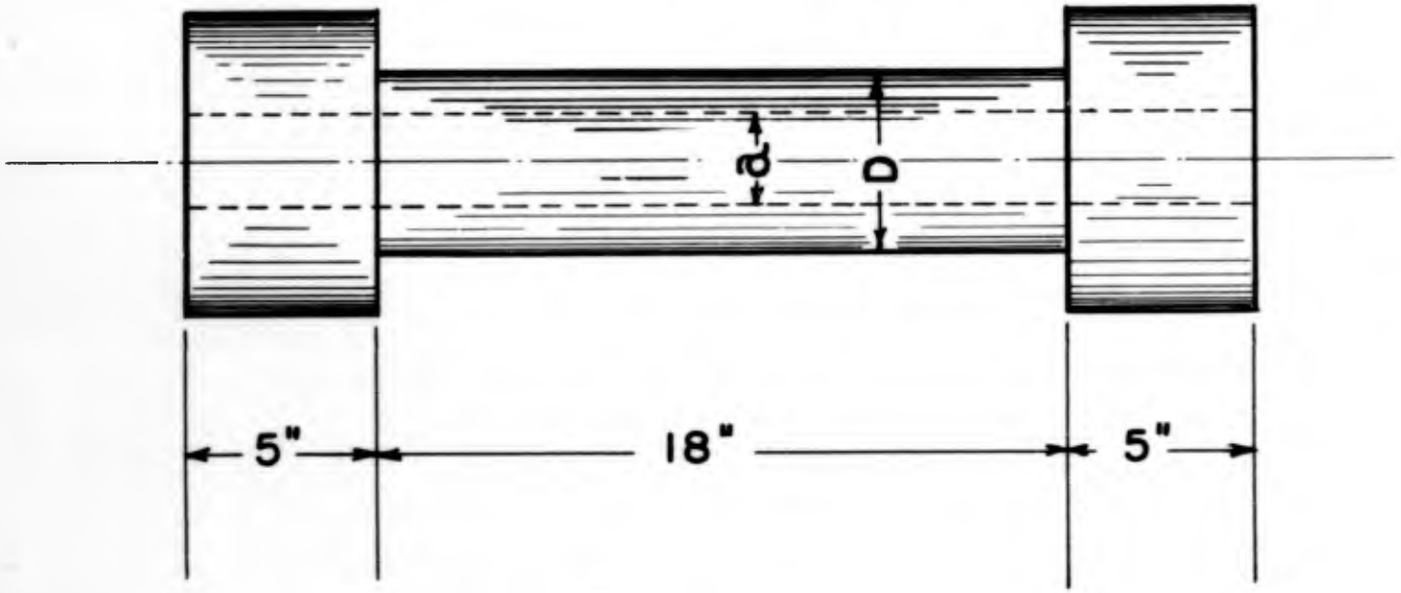
**-HEAT TREATED MACRO DISC ($\frac{3}{4}$")

FIG. 2

WTN.639-6980

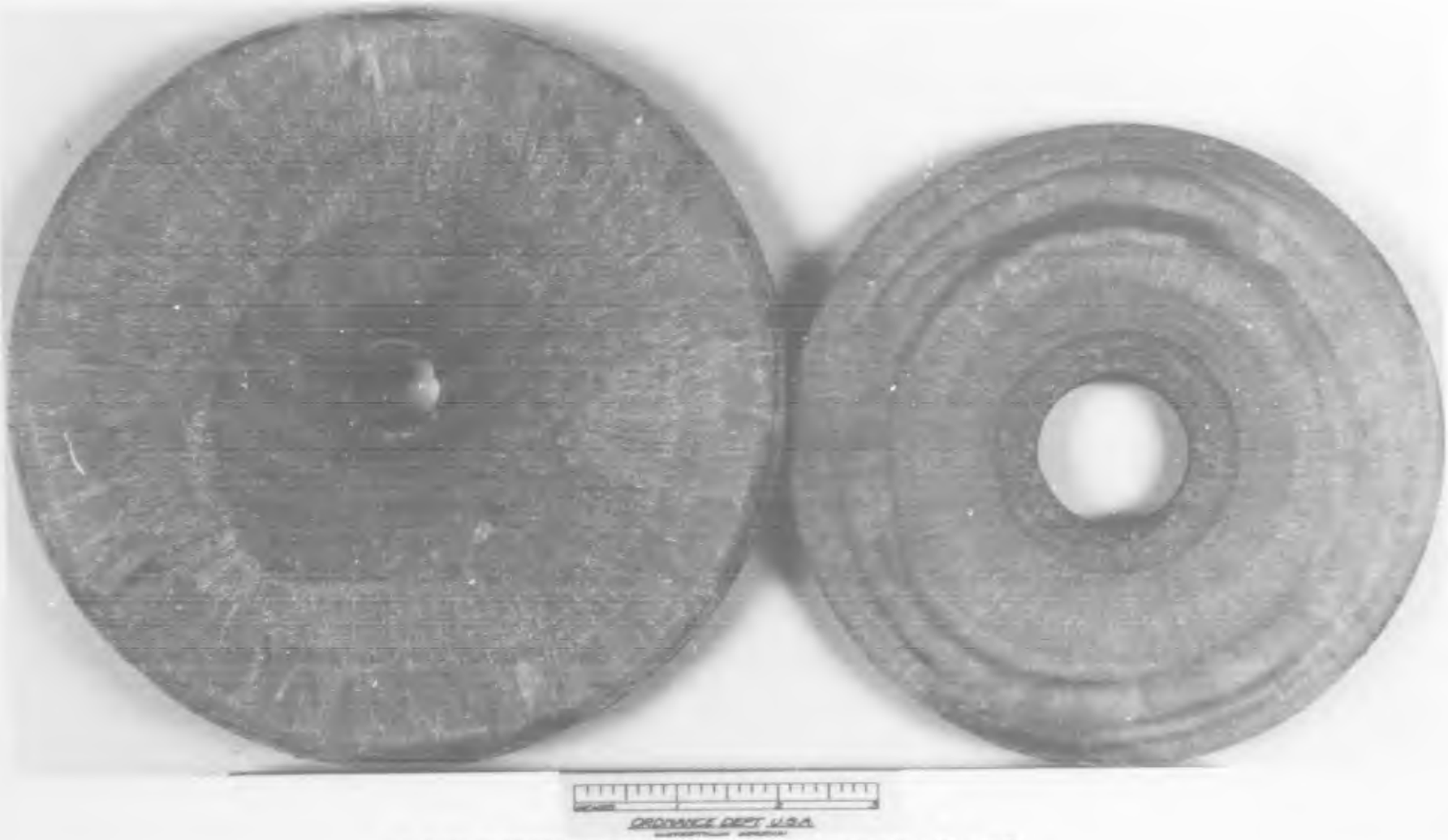
STANDARD TEST CYLINDER DIMENSIONS

WALL RATIO $\frac{D}{d} = 2$



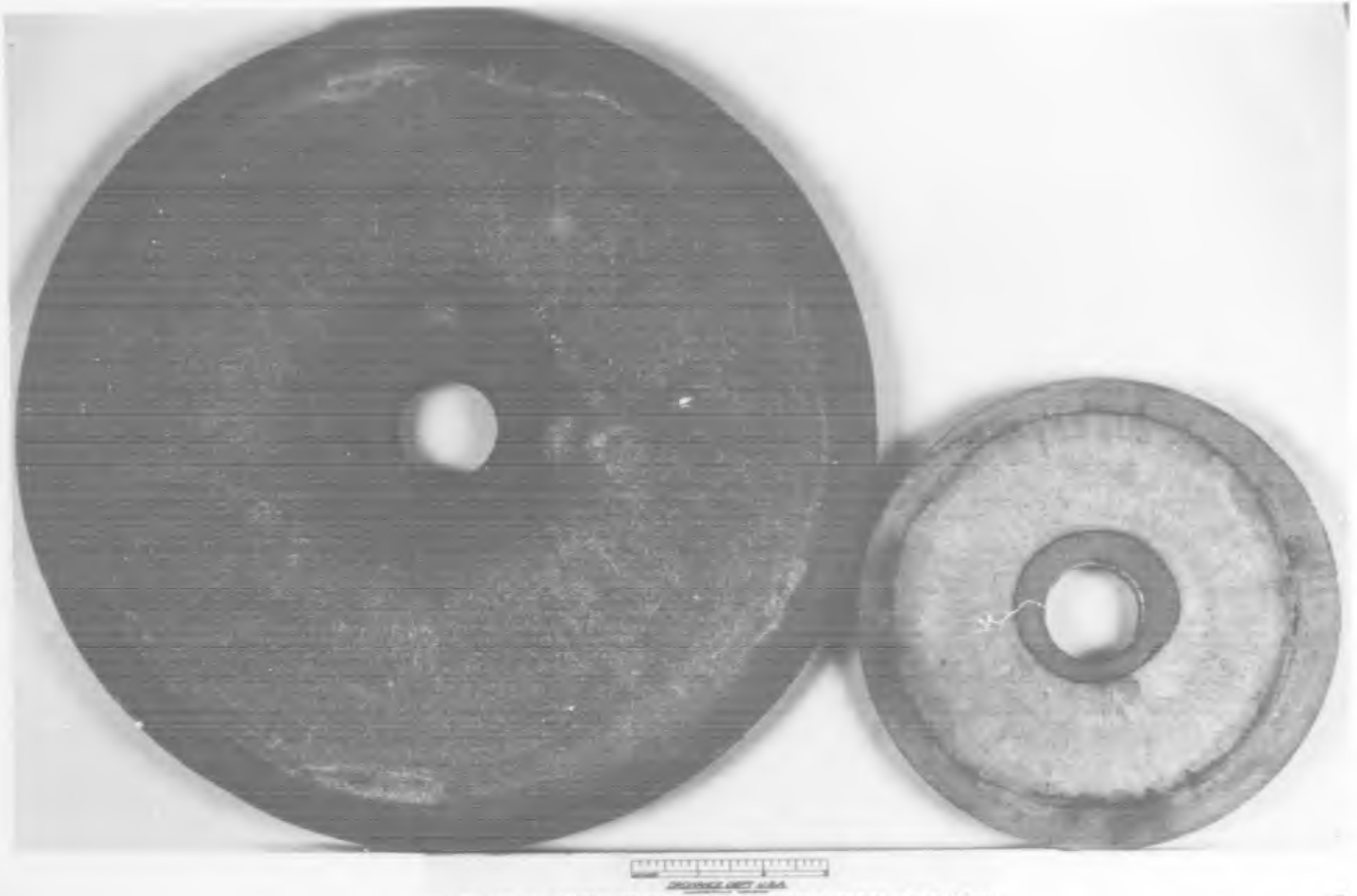
WTN.639-6981

FIG. 3



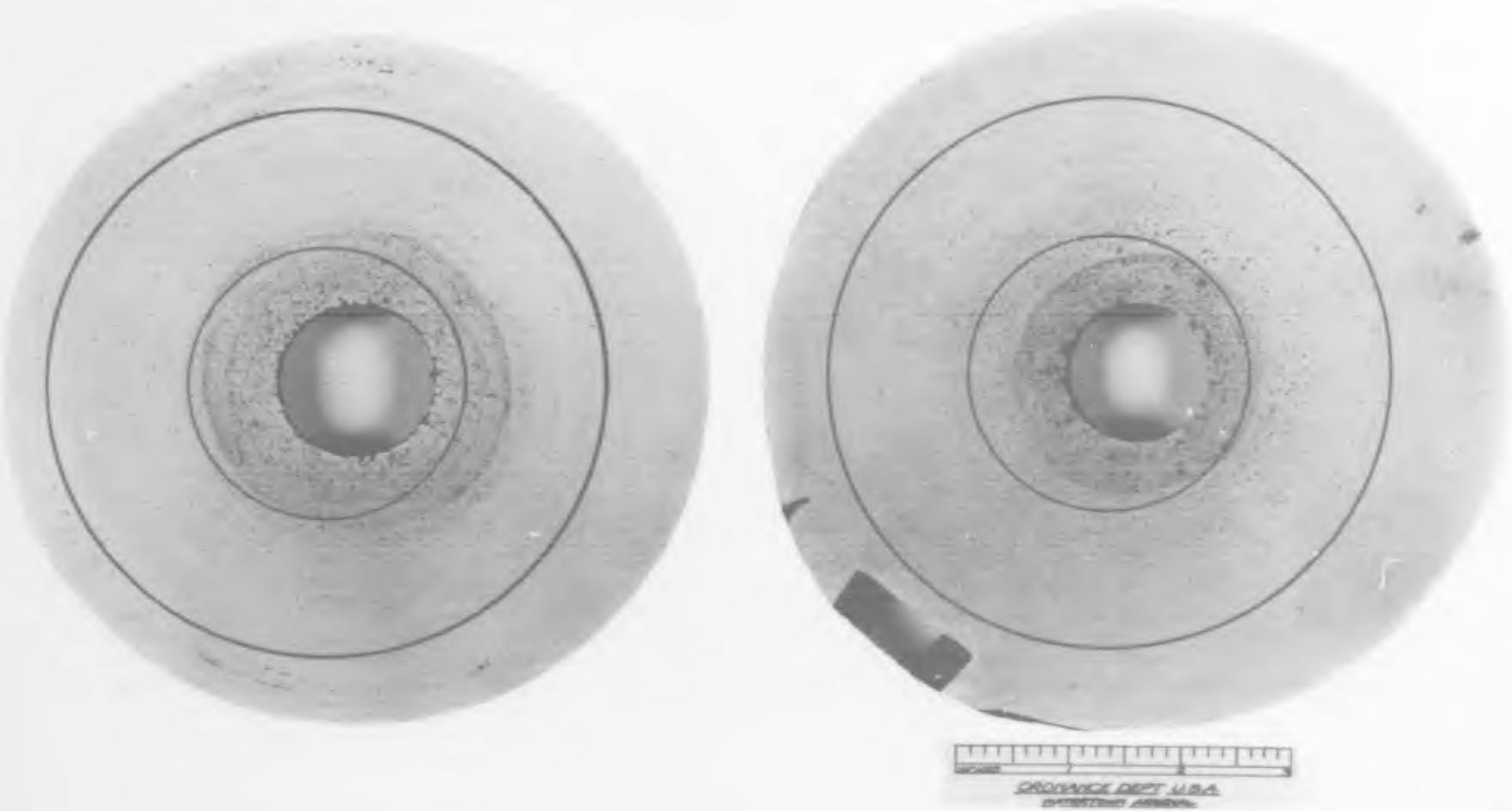
AS CAST MACROETCHED BREECH AND MUZZLE DISCS FROM 3" LINER
CASTING 3F1347. 27 NOVEMBER 1943 WTN.223-4043

FIG. 4



AS CAST MACROETCHED BREECH AND MUZZLE DISCS FROM 90MM
GUN CASTING 3G2775. 27 NOVEMBER 1943 WTN. 223-4042

FIG. 5

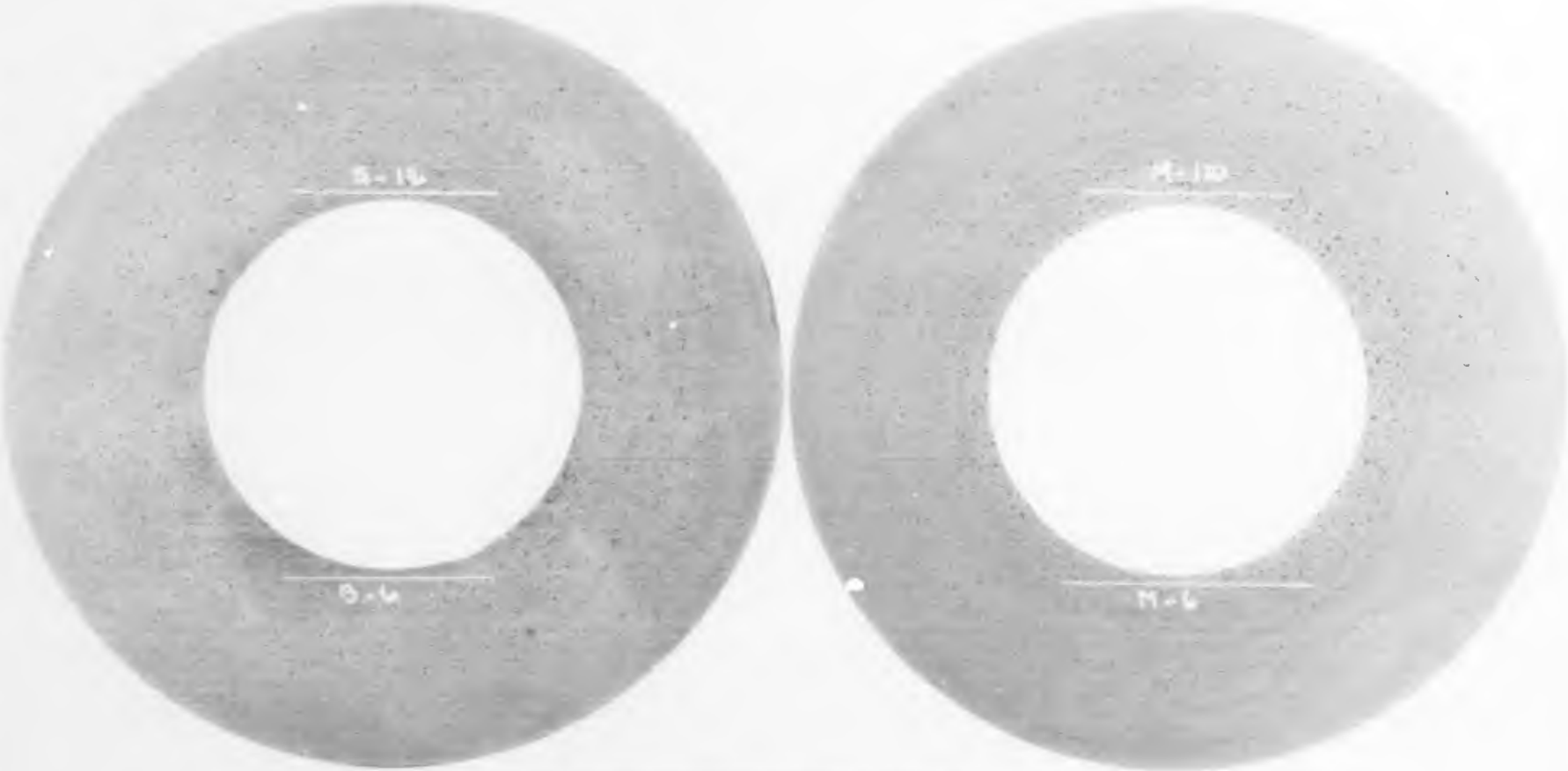


BREECH AND MUZZLE DISCS FROM CYLINDER #2 OF 3" LINER CASTING 3F 1347. BLACK CIRCLES INDICATE FINISHED MACHINED DIMENSIONS OF CYLINDER. THIS PICTURE SHOWS HOW OFF-CENTER BORING PRESENTS TWO MACRO CONDITIONS IN THE BORE OF THE TEST CYLINDER.

20 APRIL 1944

WTN.639-631

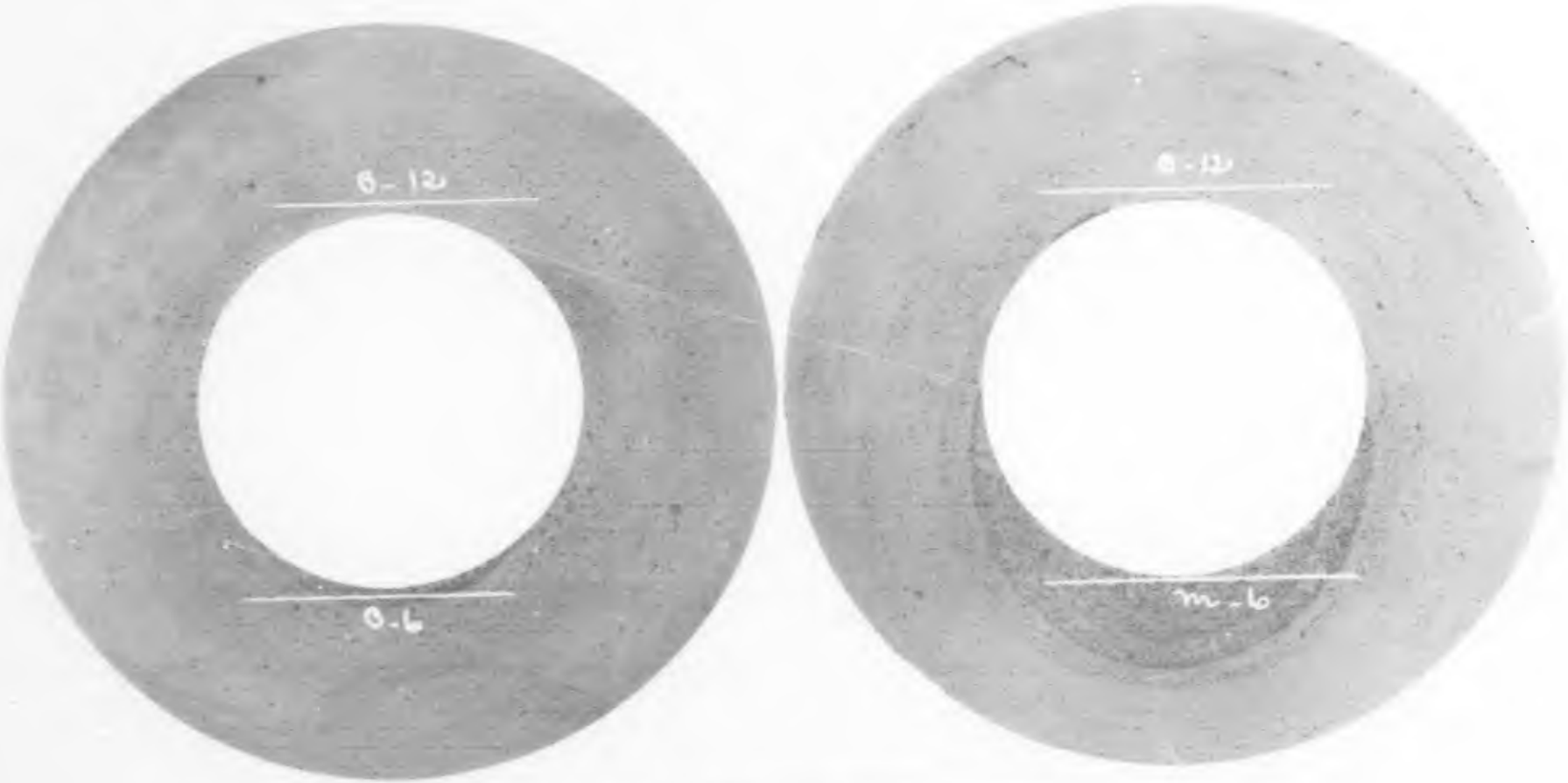
FIG. 6



B – 12	B – 6		M – 12	M – 6
74,000	75,000	Y. S.	75,000	77,000
93,200	93,500	T. S.	97,000	97,300
65.4	57.8	% R.A.	57.4	62.6
C-LC	I-LC	FRACT.	C-LC	C-GLC

MACROETCHED BREECH AND MUZZLE DISCS AND PHYSICAL PROPERTIES FROM CYLINDER #1 OF 3" LINER CASTING 3F1347 BORED ON CENTER.
3 JAN 1944
WTN.223-4134

FIG. 7

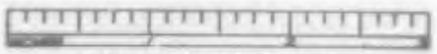


ORDNANCE DEPT U.S.A.

B – 12	B – 6		M – 12	M – 6
76,000	77,500	Y. S.	76,000	83,000
93,600	98,000	T. S.	95,000	106,200
65.7	58.5	R.A.	60.6	43.2
C-SLC	C-LC	FRACT.	C-SLC	I-LC

MACROETCHED BREECH AND MUZZLE DISCS AND PHYSICAL PROPERTIES FROM CYLINDER #2 OF 3" LINER CASTING 3F1347 BORED 1/4" OFF CENTER. 3 JAN 1944 WTN.223-4135

FIG. 8



B – 12	B – 6		M – 12	M – 6
69,000	71,500	Y. S.	71,500	69,500
90,000	90,700	T. S.	90,800	90,400
49.8	58.9	R.A.	61.3	57.8
I-LLC-F	I-LC-F	FRACT.	C-LC-F	C-LC-F

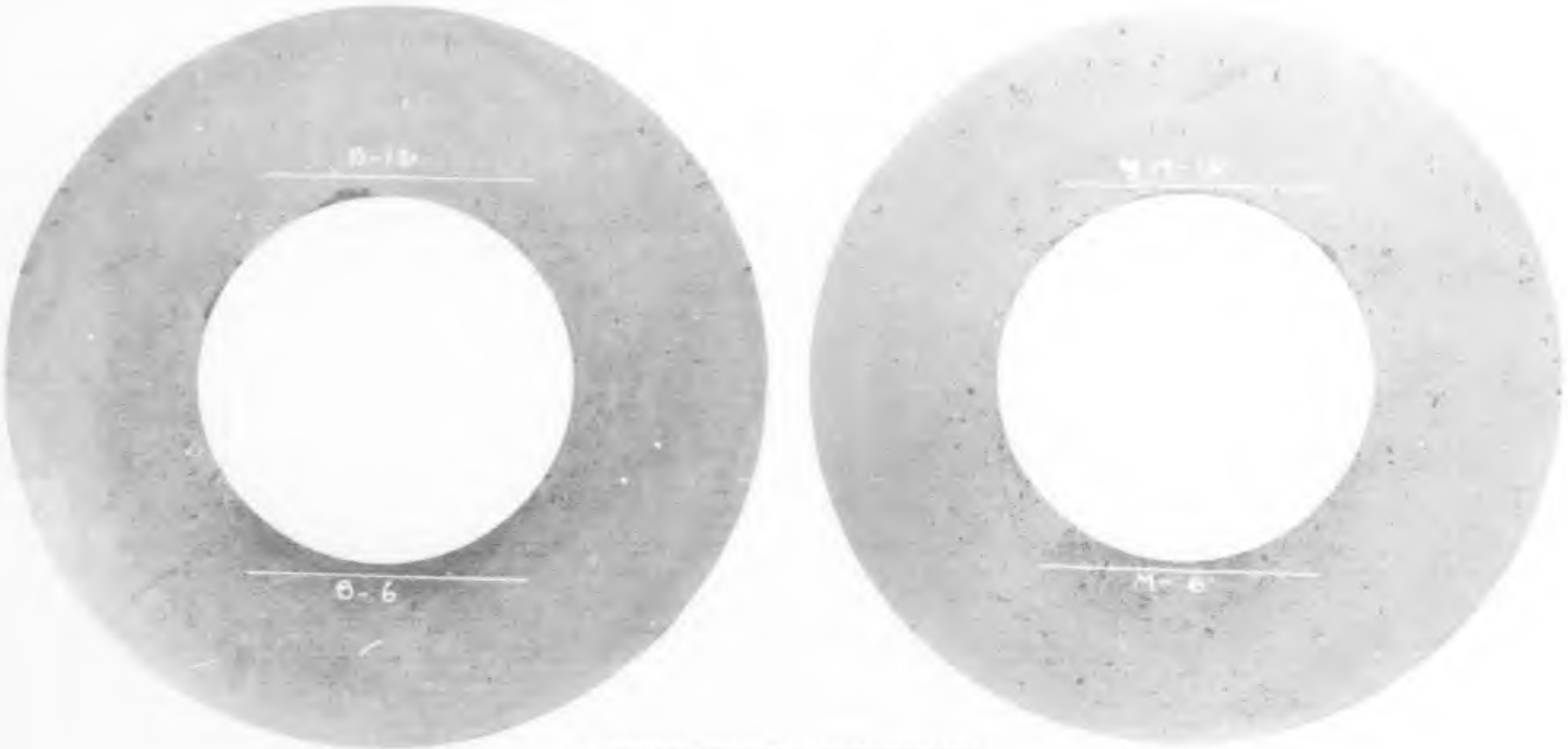
MACROETCHED BREECH AND MUZZLE DISCS AND PHYSICAL PROPERTIES OF CYLINDER #1 FROM 90MM CASTING 392775 BORED ON CENTER. 3 JAN 1944 WTN.223–4137

FIG. 10

B – 12	B – 6		M – 12	M – 6
73,500	72,500	Y. S.	73,500	71,500
94,500	99,800	T. S.	93,600	94,400
63.4	45.7	%R.A.	63.0	30.8
C	I-LC	FRACT.	C	I-LC

MACROETCHED BREECH AND MUZZLE DISCS AND PHYSICAL PROPERTIES OF CYLINDER #2 FROM 90MM CASTING 382775 BORED 1/2" OFF CENTER. 3 JAN 1944 WTN. 223–4138

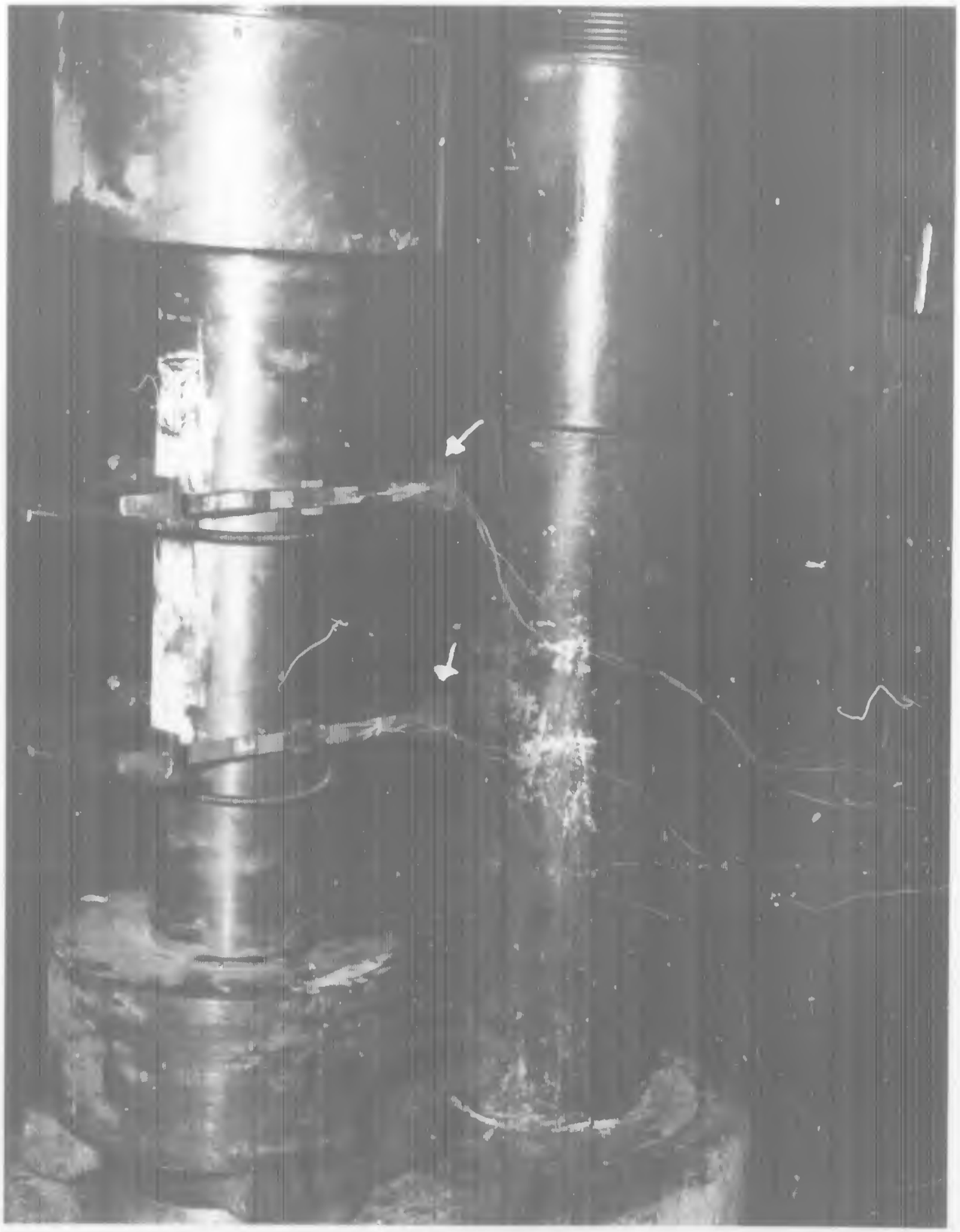
FIG. 11



B – 12	B – 6		M – 12	M – 6
73,500	77,000	Y. S.	73,000	75,500
94,800	103,300	T. S.	94,300	98,400
58.1	39.4	%R.A.	63.4	56.7
C-LC	I-LC	FRACT.	C-LC	C

MACROETCHED BREECH AND MUZZLE DISCS AND PHYSICAL PROPERTIES FROM CYLINDER #3 OF 90MM CASTING 3G2775 BORED 1/2" OFF CENTER. 3 JAN 1944 WTN.223-4139

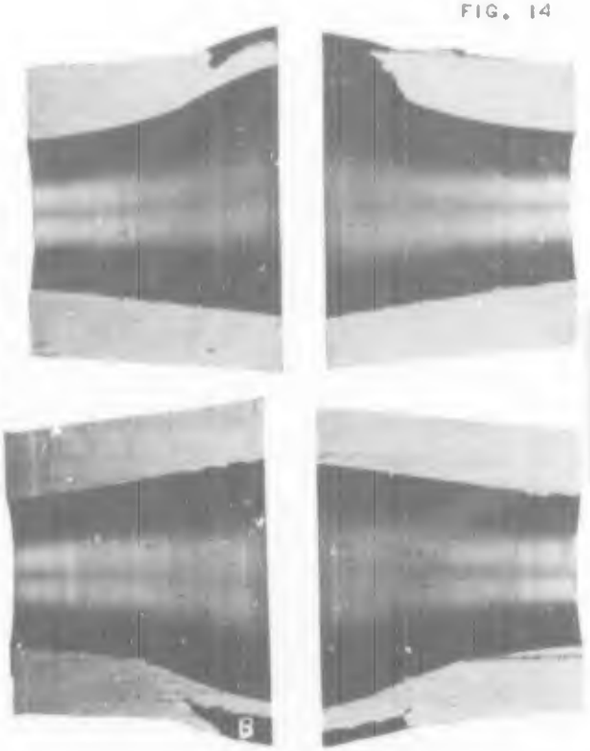
FIG. 12

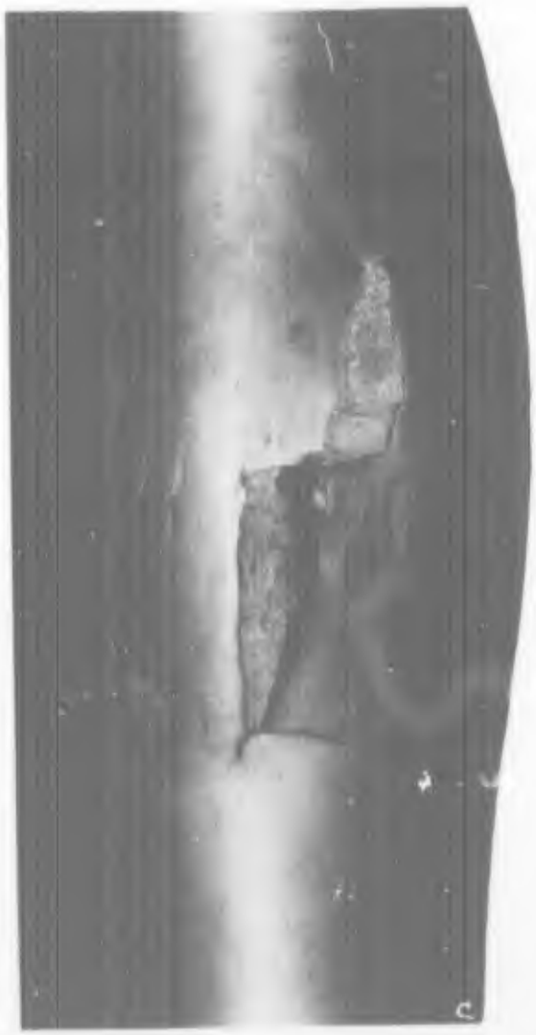


WATERTOWN ARSENAL

EXPERIMENTAL SET-UP FOR THE COLD WORKING OF SHORT TEST CYLINDERS
4 FEB 1944
WTN.660-145

FIG. 14





(A) ETCHED DISC FROM ZONE OF GREATEST EXPANSION OF CYLINDER #1 SHOWING MACRO STRUCTURE.

(B) LONGITUDINAL CROSS SECTION SHOWING CHECKS IN BORE.

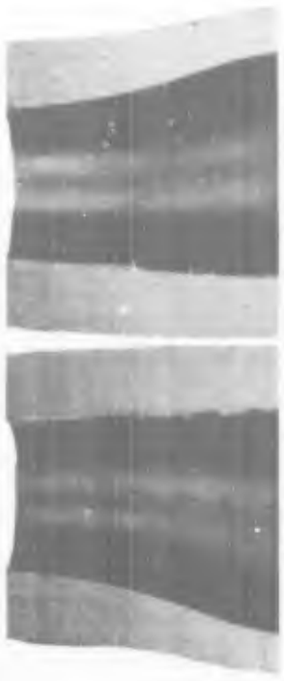
(C) FAILURE NEAR CENTER OF CYLINDER SHOWING TYPE OF FRACTURE.

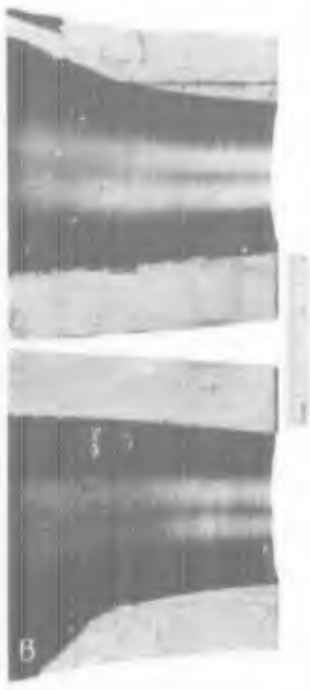
WATERTOWN ARSENAL

CYLINDER #1 FROM SMALL CROSS SECTION CASTING COLD WORKED TO DESTRUCTION.
CYLINDER BORED ON CENTER.

WTN.639-6153

FIG. 15





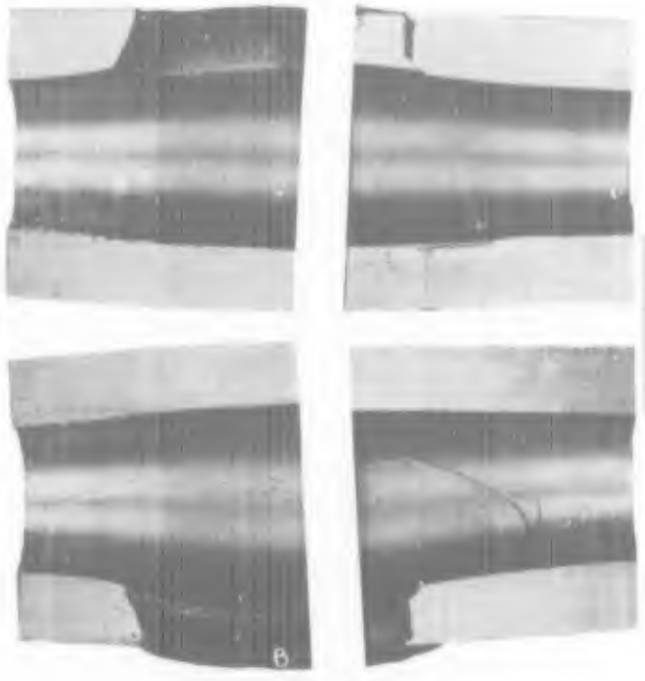
(A) ETCHED DISC FROM ZONE OF GREATEST EXPANSION OF CYLINDER SHOWING ECCENTRIC MACRO STRUCTURE OBTAINED BY BORING OFF CENTER. FAILURE OCCURED OPPOSITE UNDESIRABLE MACRO AREA.

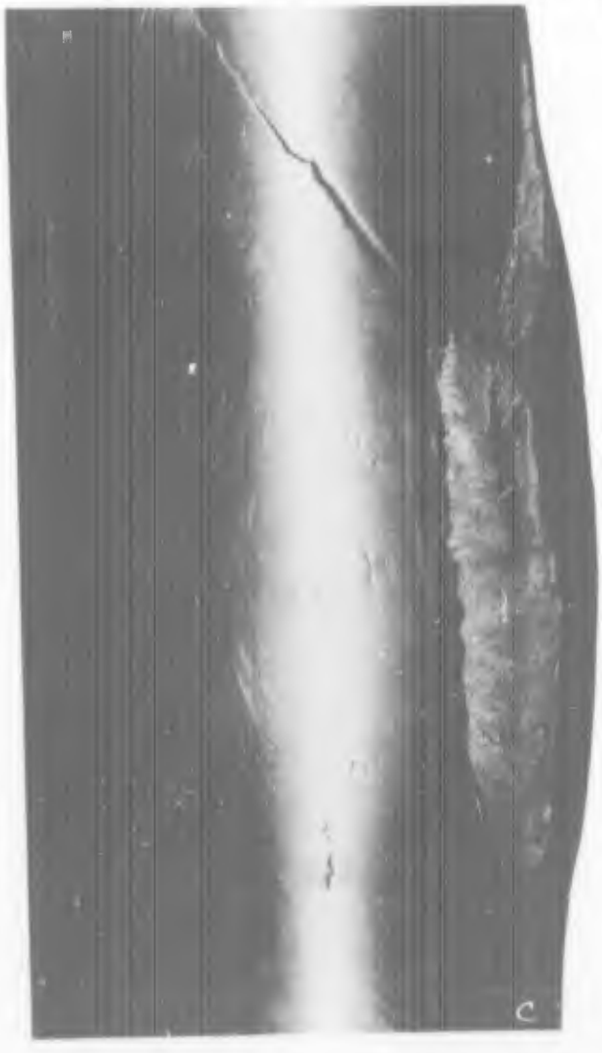
(B) LONGITUDINAL CROSS SECTION SHOWING CHECKS IN BORE.

(C) FAILURE NEAR CENTER OF CYLINDER SHOWING TYPE OF FRACTURE.

WATERTOWN ARSENAL

CYLINDER #2 FROM SMALL CROSS SECTION CASTING COLD-WORKED TO DESTRUCTION. THIS SECTION WAS STRESS RELIEVED AT 570°F FOR 12 HOURS PRIOR TO THE COLD WORK OPERATION—CYLINDER BORED OFF CENTER WTN.639-6155





(A) ETCHED DISC FROM ZONE OF GREATEST EXPANSION SHOWING ECCENTRIC MACRO STRUCTURE OBTAINED BY BORING OFF CENTER. FAILURE OCCURED AWAY FROM AREA OF MOST UNDESIRABLE MACRO STRUCTURE.

(B) LONGITUDINAL CROSS SECTION SHOWING CHECKS IN BORE AND NATURE OF FAILURE.

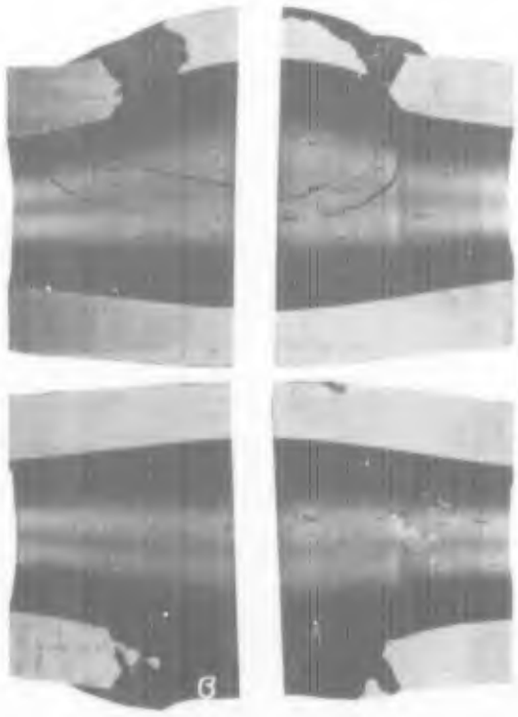
(C) FAILURE NEAR CENTER OF CYLINDER SHOWING TYPE OF FRACTURE. NOTE CHECKS ON OUTSIDE SURFACE.

WATERTOWN ARSENAL

CYLINDER #3 FROM SMALL CROSS SECTION CASTING—COLD WORKED TO DESTRUCTION. CYLINDER WAS BORED OFF CENTER.

WTN.639-6152

FIG. 17



(A) ETCHED DISC FROM ZONE OF GREATEST EXPANSION OF CYLINDER SHOWING PITTED MACRO STRUCTURE.

(B) LONGITUDINAL CROSS SECTION SHOWING DETAILS OF FAILURE AND CHECKS IN BORE.

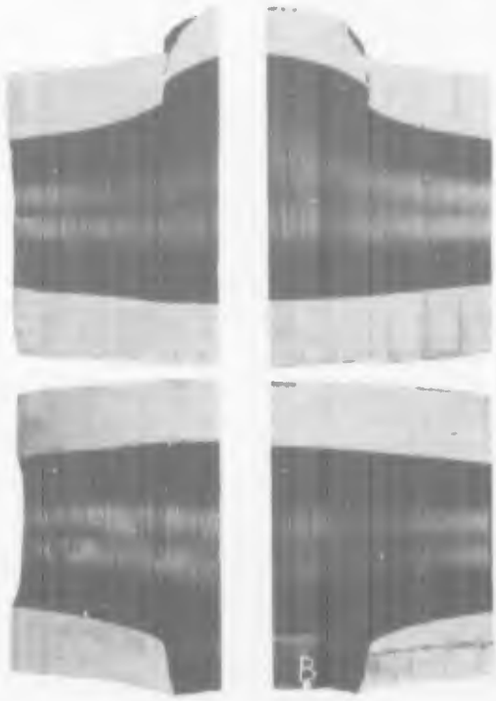
(C) FAILURE NEAR CENTER OF CYLINDER SHOWING TYPE OF FRACTURE.

WATERTOWN ARSENAL

CYLINDER #1 FROM LARGE CROSS SECTION CASTING. COLD WORKED TO DESTRUCTION. CYLINDER BORED ON CENTER.

WTN.639-6151

FIG. 16



(A) ETCHED DISC FROM ZONE OF GREATEST EXPANSION OF CYLINDER SHOWING ECCENTRIC MACROSTRUCTURE OBTAINED BY BORING OFF CENTER. FAILURE OCCURED OPPOSITE UNDESIRABLE MACRO AREA.

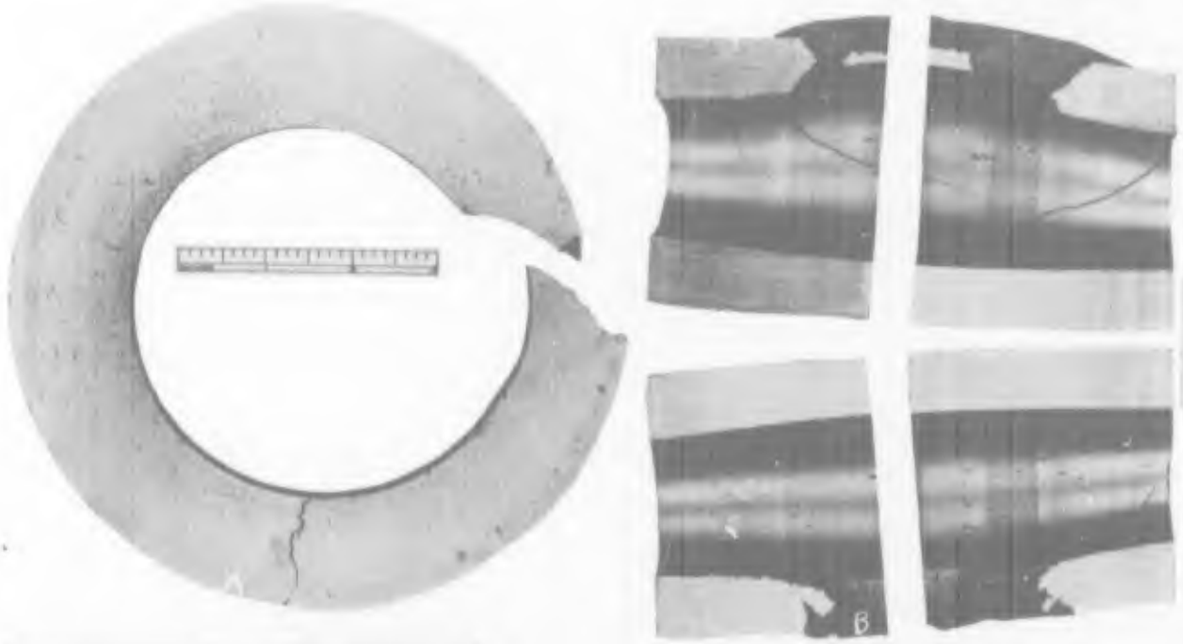
(B) LONGITUDINAL CROSS SECTION SHOWING DETAILS OF FAILURE AND CHECKS IN BORE.

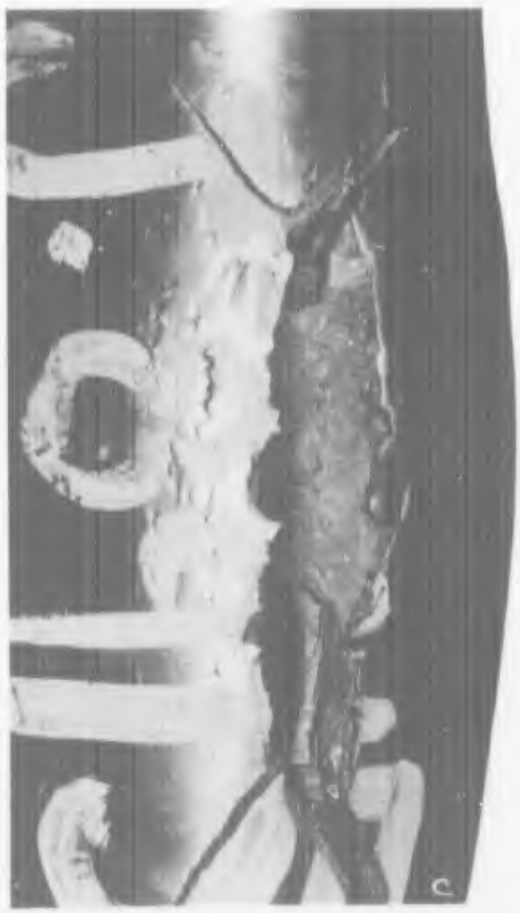
(C) FAILURE NEAR CENTER OF CYLINDER SHOWING TYPE OF FRACTURE. NOTE SLIGHT CHECKS ON OUTSIDE SURFACE.

WATERTOWN ARSENAL

CYLINDER #2 FROM LARGE CROSS SECTIONED CASTING COLD WORKED TO DESTRUCTION. THIS SECTION WAS STRESS RELEIVED FOR 12 HOURS PRIOR TO THE COLD WORK OPERATION. CYLINDER WAS BORED OFF CENTER. WTN.639-6150

FIG. 19





(A) ETCHED DISC FROM ZONE OF GREATEST EXPANSION OF CYLINDER SHOWING ECCENTRIC MACRO STRUCTURE OBTAINED BY OFF CENTER BORING. FAILURE OCCURED OPPOSITE UNDESIRABLE MACRO AREA.

(B) LONGITUDINAL CROSS-SECTION SHOWING DETAILS OF FAILURE AND CHECKS IN BORE.

(C) FAILURE NEAR CENTER OF CYLINDER SHOWING TYPE OF FRACTURE. NOTE BAD CHECKS ON OUTSIDE SURFACE.

WATERTOWN ARSENAL

CYLINDER #3 FROM LARGE CROSS SECTIONED CASTING. COLD WORKED TO DESTRUCTION. CYLINDER BORED OFF CENTER. WTN.639-6154