SSC-32

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FINAL REPORT

ON

HIGH SPEED ROTATING DISK PROJECT

BY

C. W. MacGREGOR, W. D. TIERNEY AND
H. MAJORS, JR.

Massachusetts Institute of Technology
Under Bureau of Ships Contract NObs-46302

COMMITTEE ON SHIP CONSTRUCTION

DIVISION OF ENGINEERING AND INDUSTRIAL RESEARCH

NATIONAL RESEARCH COUNCIL

ADVISORY TO

SHIP STRUCTURE COMMITTEE

UNDER

Bureau of Ships, Navy Department
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August 29, 1949

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Dear Sir:

Attached is Report Serial No. SSC-32 entitled "High Speed Rotating Disk Project." This report has been submitted by the contractor as the final report of the work done on Research Project SR-102 under Contract Nobs-46302 between the Bureau of Ships, Navy Department and the Massachusetts Institute of Technology.

The report has been reviewed and acceptance recommended by representatives of the Committee on Ship Construction, Division of Engineering and Industrial Research, NRC, in accordance with the terms of the contract between the Bureau of Ships, Navy Department and the National Academy of Sciences.

Very truly yours,

C. Richard Soderberg

C. Richard Soderberg, Chairman
Division of Engineering and
Industrial Research

CRS:mh
Enclosure

PREFACE

The Navy Department through the Bureau of Ships is distributing this report to those agencies and individuals who were actively associated with the research work. This report represents a part of the research work contracted for under the section of the Navy's directive "to investigate the design and construction of welded steel merchant vessels."

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FINAL REPORT ON HIGH SPEED ROTATING DISK PROJECT AT M. I. T.

by

C. W. MacGregor, W. D. Tierney, H. Majors, Jr.

Contract NObs-46302

Research Laboratory for

Mechanics of Materials

Massachusetts Institute of Technology

Cambridge, Massachusetts

TABLE OF CONTENTS

ABSTRACT

The general objectives of this experimental program were (1) to develop a suitably supported solid disk type specimen, having no disturbing central nib, which would permit unrestrained plastic expansion under high rotation at speeds up to bursting, (2) to measure the strain patterns at several stages of flow up to bursting on specimens of this type to disclose the basic mechanism of flow and provide a means of calculating bursting stresses and (3) to make low-temperature tests on full-size disks of this type to determine the transition temperature from ductile to brittle fracture. Since parts (2) and (3) depend directly on part (1), this was first attacked. Various designs were tried in order to perfect such a specimen. Several attempts were successful in carrying a special flange-supported type specimen containing no central nib well up into the plastic range; up to the present, it has not been possible to develop one which could be carried successfully to bursting. Since most of the time was thus utilized for part (1) of the program, only a limited amount of data was accumulated for part (2). Some of the necessary equipment for part (3) was either designed or acquired but no tests were conducted for the reasons explained above.

PREVIOUS WORK

The Welding Research Council, through its Weld Stress Committee, financed the construction of the early Whirl Pit. When the project was initiated, its object was to construct the apparatus for, and to conduct tests on welded ship plates. Emphasis was on the effect of residual stresses, resulting from welding, on cleavage failure in welded ships. The method employed was to weld a four inch core in a twenty-six inch outside diameter by four inch inside diameter by one inch thick plate. Unless precautions were taken to avoid them, large residual stresses would result from such a "circumferential butt" weld. X-ray techniques for measuring the magnitude of residual principal stresses were available in the Metallurgy Department of M.I.T. At the end of the war, when construction of the pit began, the Weld Stress Committee's interest in residual stresses was waning. The committee felt that the disk method would provide information redundant to the recent results of other investigations into the problem. In spite of the consequent financial limitations, some apparatus was assembled, and successful tests on both welded and un-welded disks were conducted. However, due to the shift of interest from residual stresses to brittle-ductile transition phenomena, a decision was made to employ the Whirl Pit as a means of determining the plastic flow characteristics of mild steel, subjected to bi-axial tension, up to fracture strains, and further, to determine the brittle-ductile transition behavior of this steel under bi-axial tension.

Because of this change of interest, it was not possible for the Welding Research Council to continue its support of the project beyond December 1947. In January 1948 the Ship Structure Committee assumed responsibility for the investigation and the work has been continued under Bureau of Ships Contract

NObs-46302. The present termination date of the contract is June 30, 1949.

As part of the Ship Structure Committee's support of this work, arrangements have been made through the transfer of funds by the Transportation Corps of the U. S. Army (one of the agencies constituting the Ship Structure Committee) to Watertown Arsenal for the machine work, etc. necessary in the development of the test equipment and for the production of test specimens.

Before undertaking the brittle transition tests, it was necessary to improve the Whirl Pit apparatus. The five pieces of armor plate of which the protective pit housing is constructed were shipped to the Watertown Arsenal for extensive welding and machining. This work was necessary in order to permit maintenance of a high vacuum in the pit for brittle tests. Without a very high vacuum, the windage heating of the disk would prohibit brittle bursts.

Advantage was taken of the down-time required for machining the pit to develop numerous auxiliary pieces of equipment and to have the cathetometer repaired. The cathetometer is a 20 power microscope mounted on a lead screw such that it may be used to take readings to one ten-thousandths of an inch (.0001) of the spacing of a "strain grid" scribed upon the specimen surface by a special scribing diamond. Among the pieces of auxiliary equipment constructed were a measuring stand for traversing the specimen under the cathetometer; a special deep throated micrometer for measuring thickness changes in the disk, a lead smelting apparatus to recast the ton of lead pigs used to absorb the disk fragments; a special pot chuck (made at the Watertown Arsenal) for turning the disks and flanges; numerous improvements in the high pressure steam line; and construction of a new remote control panel for added safety to the personnel.

ADVANTAGES OF THIS TYPE OF TEST

In a rotating disk of uniform thickness, two of the principal stresses are equal tensions at the disk center - the third principal stress is essentially zero. Moreover, these values of the principal stresses are a maximum and remain very nearly equal for an appreciable distance from the center. By reasons of the symmetry necessary to maintain rotational balance of a spinning disk, the equality of these center principal stresses is maintained throughout plastic yielding to fracture. Thus the rotating disk provides a means of studying large plastic deformations in materials subjected to pure biaxial tension.

Research has demonstrated that tri-axial and bi-axial stress conditions modify considerably the behavior that steel shows under simple stress. Since present test methods do not present a convenient way of predicting tri-axial stress values (for example, the stresses at the root of notches) and since structures fabricated from thin plates are subjected chiefly to bi-axial stress patterns, a test method which produces a well defined purely bi-axial stress pattern is very useful. In particular, equal tension is the most severe condition of bi-axial stress. The rotating disks appear to be the only type of specimen available which will provide a region of equal bi-axial tensile stress throughout the entire plate thickness while maintaining the ratio of the principal stresses throughout large plastic deformations and up to rupture.

To reiterate, the desirable features of the Rotating Disk Method as compared to other available procedures are:

(a) The rotating disk maintains equal bi-axial stresses all the way to fracture at the center, which is where fracture begins. These are uniformly distributed across the entire thickness of the disk and there is a considerable area, near the axis of the disk, over which they vary little.

(b) A wide range of plate thicknesses may be tested by the rotating disk method at minimum cost. Full size weldments may thus be tested. The M.I.T. Whirl Pit has a capacity for disks of any thickness up to about 8" and any diameter up to 30". For bursting tests, however, the minimum specimen diameter (for ship plate) is 12" O.D.

(c) Tests can be conducted on disks which are unwelded and investigations thus carried out on the base material. This is not possible for internal pressure tube tests of plate material.

(d) It should be possible to obtain brittle failures at low temperatures in rotating disks made of normally ductile ferritic steels by using a simple expendable refrigeration system as now considered. The strain velocity and temperature of the test can be varied quite widely. This is difficult and extremely costly to accomplish on large scale tests of tubes under internal pressure (and in such case it can only be carried out on welded tubes, not on the base metal only) and the lowest temperature is limited by viscosity problems. It is thus anticipated that the brittle transition temperature can be obtained on full size assemblies by this method. Comparisons of the brittle transition temperatures of notched bars and of rotating disks can thus be made.

(e) It is simple to test the rotating disks at elevated temperatures also.

THE WHIRL PIT EQUIPMENT

The M.I.T. Whirl Pit is composed essentially of three heavy pieces of Class B armor plate. The center armor plate, 17" thick, containing the cavity in which the disks are rotated, is bolted around the edges to 4" thick bottom and top cover plates. The latter have 4" thick bosses attached to them which project into the cavity for greater protection. The available chamber is thus 40" in diameter and 9" deep. The armor walls surrounding the cavity are 10" thick and additional protection is achieved by lining the pit with lead or steel plates. See Fig. 1 and 2.

Specimens are suspended in the pit on a 5/8" diameter flexible steel drive shaft as shown in Fig. 2. An 8", 30,000 R.P.M. G.E. horizontal steam turbine is coupled directly to this shaft. To prevent excessive windage, the pit is evacuated by a special vacuum pump. The steam pressure is 200 p.s.i. and although the turbine has considerable reserve power, it is limited to a top speed of 35,000 R.P.M. The remote control panel located behind a concrete protective wall is shown in Fig. 3. The vacuum system is shown in Fig. 4. A schematic diagram outlining the entire Whirl Pit System is given in Fig. 5.

Fig. 5B is a schematic arrangement of the oil-air system. An electric driven pump fprces oil at about 16 lbs. per sq. in. pressure from an oil tank reservoir thru a strainer thence to the upper thrust bearing through 3/8 in. diameter copper tubing at four horizontal inlets spaced 90 degrees apart. Part of the oil is bled to a hydraulic damping system which controls the spindle vibration.

Air is throttled from a main air supply at about 12 lbs. per sq. in. pressure and supplied to the thrust balancing piston, an area of about 10 sq. in. on the bottom face of the turbine wheel, to limit the load on the thrust bearing. Also, part of the air is bled from the thrust balancing piston chamber in order to return the lubricating oil to the supply tank.

PROGRAM

As originally conceived, the experimental program consisted of three parts. The first involved the development of a suitable means for supporting a solid rotating disk which has no discontinuity (i.e., hole or change in thickness) near the center of the disk and at the same time allowing the disk to expand plastically under the action of high rotational speeds. The purpose of this was to provide a means of studying the flow and fracture characteristics in the presence of a uniform and undisturbed completely definable set of equal bi-axial tensions. The nib-type of specimen used successfully heretofore had the disadvantage of a local disturbance of the stress and strain patterns near the center of the disk.

The second part of the program entailed the measurement of the principal strains in the disk with this new type of specimen to provide basic data on large plastic deformations in a field of bi-axial tensions, to check the performance of the specimen.

The third portion of the program was to probe for the brittle-ductile transition temperature of a rotating disk. It was planned to cool the disks with liquid nitrogen and to measure both temperature and maximum center stress by means of SR-4 gages and a slip ring system.

PILOT TESTS FOR DEVELOPMENT OF FLANGE-SUPPORT TYPE SPECIMEN

After several preliminary conferences with representatives of the Ship Structure Committee, it was decided to concentrate first upon part one of the program and attempt to develop a suitable supported specimen, since the value of the second and third parts would be directly dependent upon its successful development.

Table I includes a list of the various disks tested using different support methods. The different types of supports are shown in Figs. 6 to 9 inclusive. The speeds attained and the method of failure at each speed are also listed in Table I. Views of the armor driving flange are included in Figs. 10 and 11. Typical plan views of bursts for the center-nib type disks are illustrated in

Figs. 12 to 15 inclusive. Some side views of the fractured surfaces are seen in Figs. 16 and 19.

While time did not permit the successful development of a flange support method for room temperature tests to bursting speeds, it was possible to completely plastically deform such specimens to within 88 per cent of such speeds. Figs. 20 and 21 show views of typical flange-supported disks which have been deformed plastically throughout.

FLOW PATTERNS FOR DISKS TESTED

Strain data was taken on a number of the disks tested and Figs. 22 to 29 inclusive show the flow patterns received for these cases. Of interest is the fact that the strain patterns for disks W-29 and W-27 are practically the same to within 2 inches of the center for the speed 11,000 R.P.M. At the center, the nib alters the strain distributions as shown.

NEW FLANGE SUPPORT METHOD PROPOSED FOR FUTURE TESTS

The object of the attempts to develop a flange method of driving specimens was to make possible a spin to destruction of a disk which would have no change in section (i.e., center nib or hole) in the central area. The principal stresses are a maximum at the center and fall to small values at the periphery. By bolting a specimen disk to a slotted flange (the flange of very high strength material) it was hoped to permit radial expansion to occur without restraint; to maintain the very delicate balance necessary at the high rotational speeds; and to bolt the disk in such a manner that the resulting stress concentration be less than that of the center stress. In all the tests to date it has been impossible to maintain balance all the way to bursting speeds. Although spins for which the disk is completely plastic are possible, the bolt hole in the disk has always expanded to such an extent that the disk could slip on the flange bolts, move off center, and fatigue the drive shaft. Consideration of the values of the principal stress at each point in a rotating thin disk shows that the axial stress is zero; the radial stress is nearly zero; and the tangential stress is 40% of center stress near the periphery. This means that a bolt hole in this region is practically in simple tension. By using pairs of bolt holes (1/4" diameter; 5/8" apart) it was found that the hole spacing would not change as the disk yielded. This meant that no unbalance would develop due to the expansion of the bolt holes. There developed however, one other means of losing the disk balance, this due to the thinning of the disk at the bolt holes. This thinning permits precession. To counteract this difficulty, wedges (as shown in Fig. 30) which are driven by the centrifugal force appear to be a solution. Unfortunately, however, the high centrifugal forces 50,000 to 80,000 g's and the inclined plane mechanical advantage of the wedges failed the bolts on the first design attempt. By utilizing the best available magnesium alloys in combination with high alloy steels and very light wooden wedges, a flange bolt support has been designed which all concerned feel certain will accomplish this difficult task.

SUMMARY

The present state of development of the Whirl Pit is discussed, showing that this valuable piece of equipment is now completely and satisfactorily operable.

Tests are described which were made in an attempt to develop a suitable flange-supported disk containing no change in section at the center. It has been possible to bring these disks to within only 88 per cent of bursting speeds, however, allowing the disks to be plastically deformed throughout. Strain patterns were determined for several of these disks. Sufficient tests have

been made, however, to indicate promise of this new flange support method.

TABLE I

PILOT TESTS USED IN DEVELOPING FLANGE SUPPORT

Disk No.	Type	Speed of Test	
W-28	W-17 See Fig. 6	8,750 R.P.M.	Strain Data Taken
W-28	W-17 " " "	9,600	" " "
W-28	W-17 " " "	11,000	" " "
W-28	W-17 " " "	12,700	" " "
W-28	W-17 " " "	13,100 BURST	" " "
W-27	W-17 " " "	11,000	" " "
W-27	W-17 " " "	12,500	" " "
W-27	"-17 " " "	13,000 BURST	" " "
W-20	W-12 See Fig. 7	8,500	Center Nib Fatigued
W-21	W-12 " " "	9,625	Strain Data Taken
W-21	W-12 " " "	11,500	" " "
W-21	W-12 " " "	12,500	Shaft Failed
W-29	W-18 See Fig. 8	8.700	Strains too small to measure
W-29	W-18 " " "	11,000	Strain Data Taken
W-29	W-18 " " "	11,400	Shaft Failed
W-30	W-18 " " "	11,400	" "
W-30	W-18 " " "	10,900	" "
W-23	X-28 See Fig. 9	8,800	" "
W-23	X-28 " " "	8,500	" "
W-19	X-28 " " "	10,500	" "

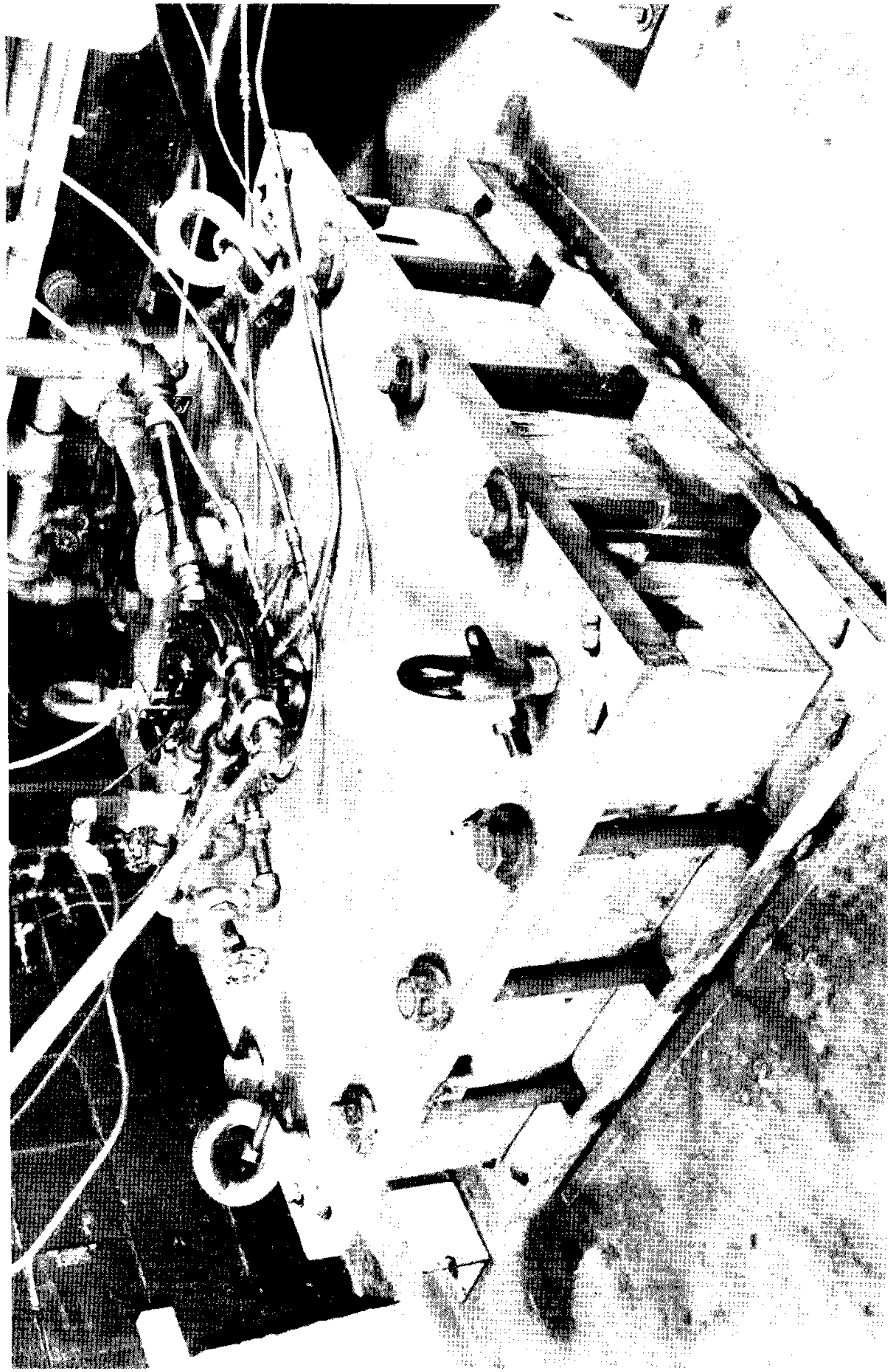


Figure 1. General View of Whirl Pit

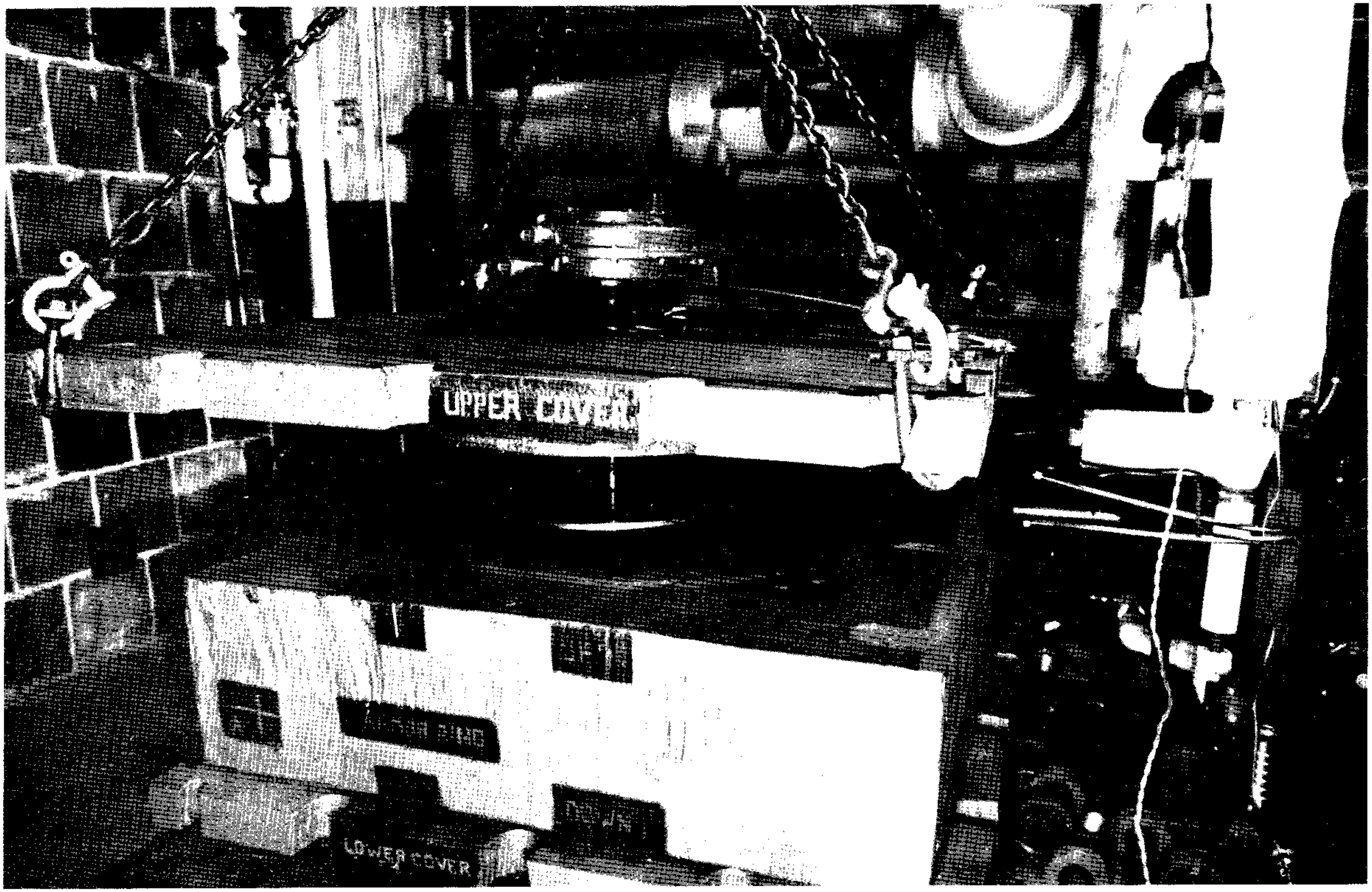


Figure 2. View of Whirl Pit with Cover Removed Showing Disc Specimen

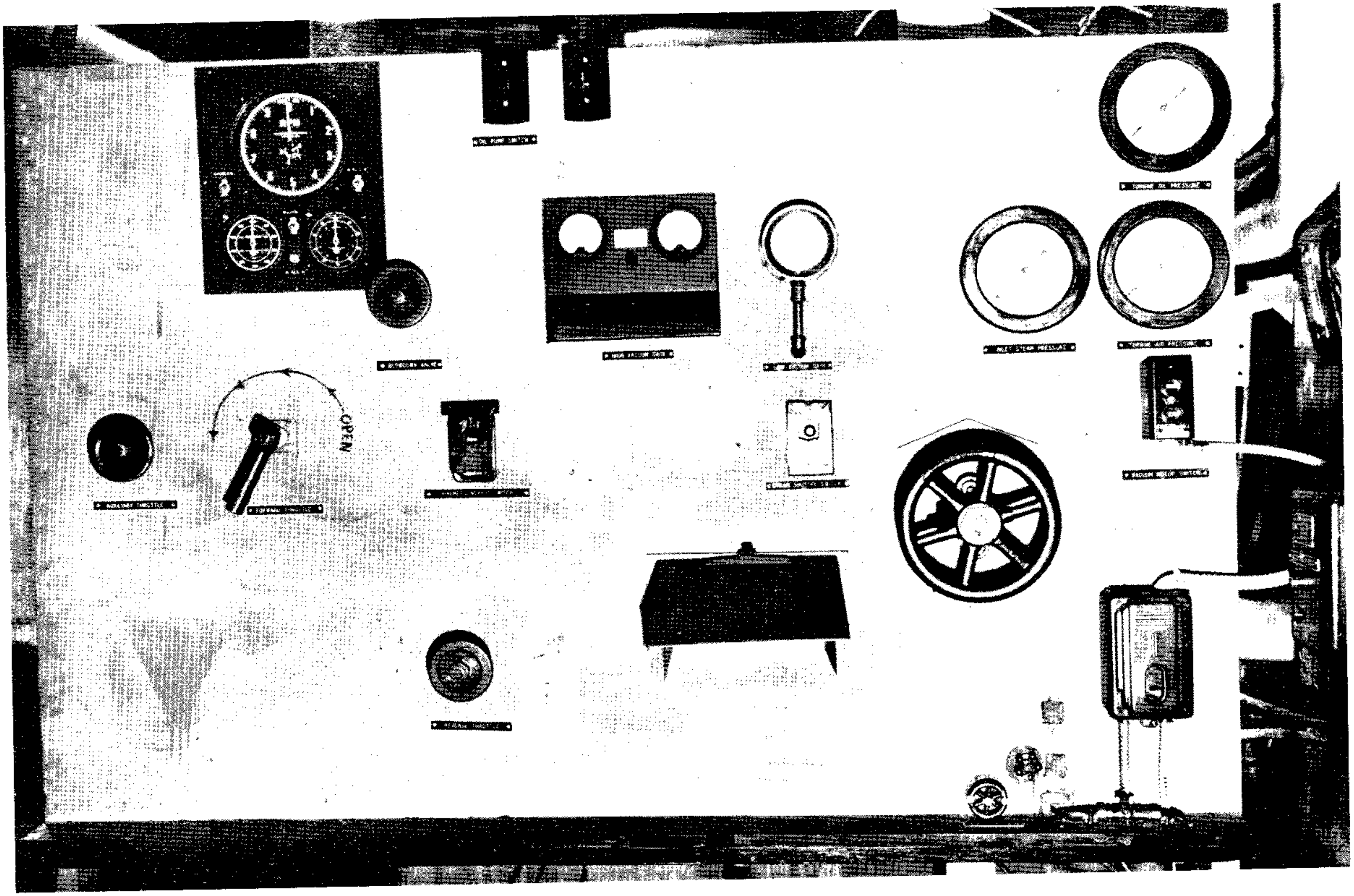


Figure 3. Remote Control Panel

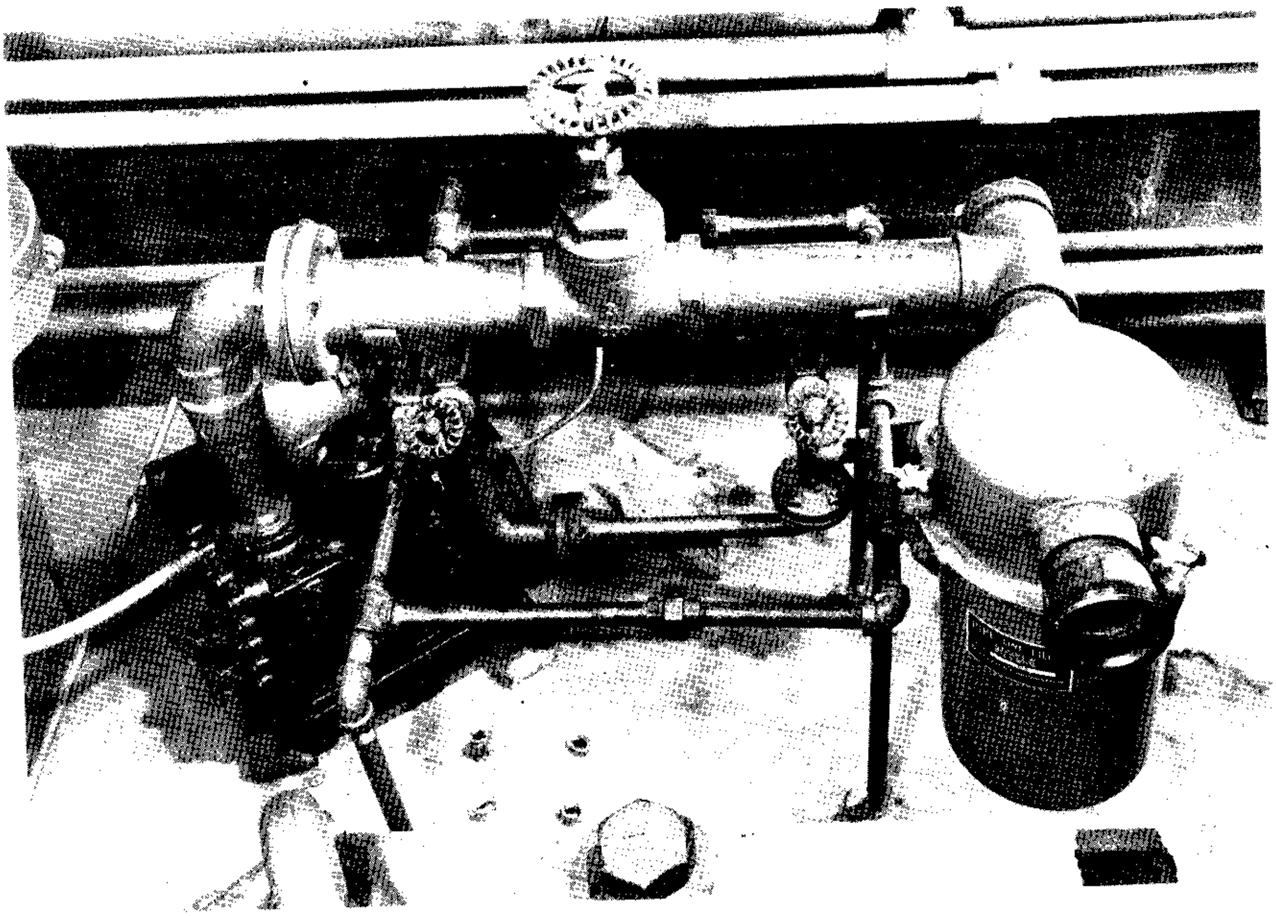


Fig. 4. Vacuum System for Whirl Pit

WHIRL PIT STEAM SYSTEM

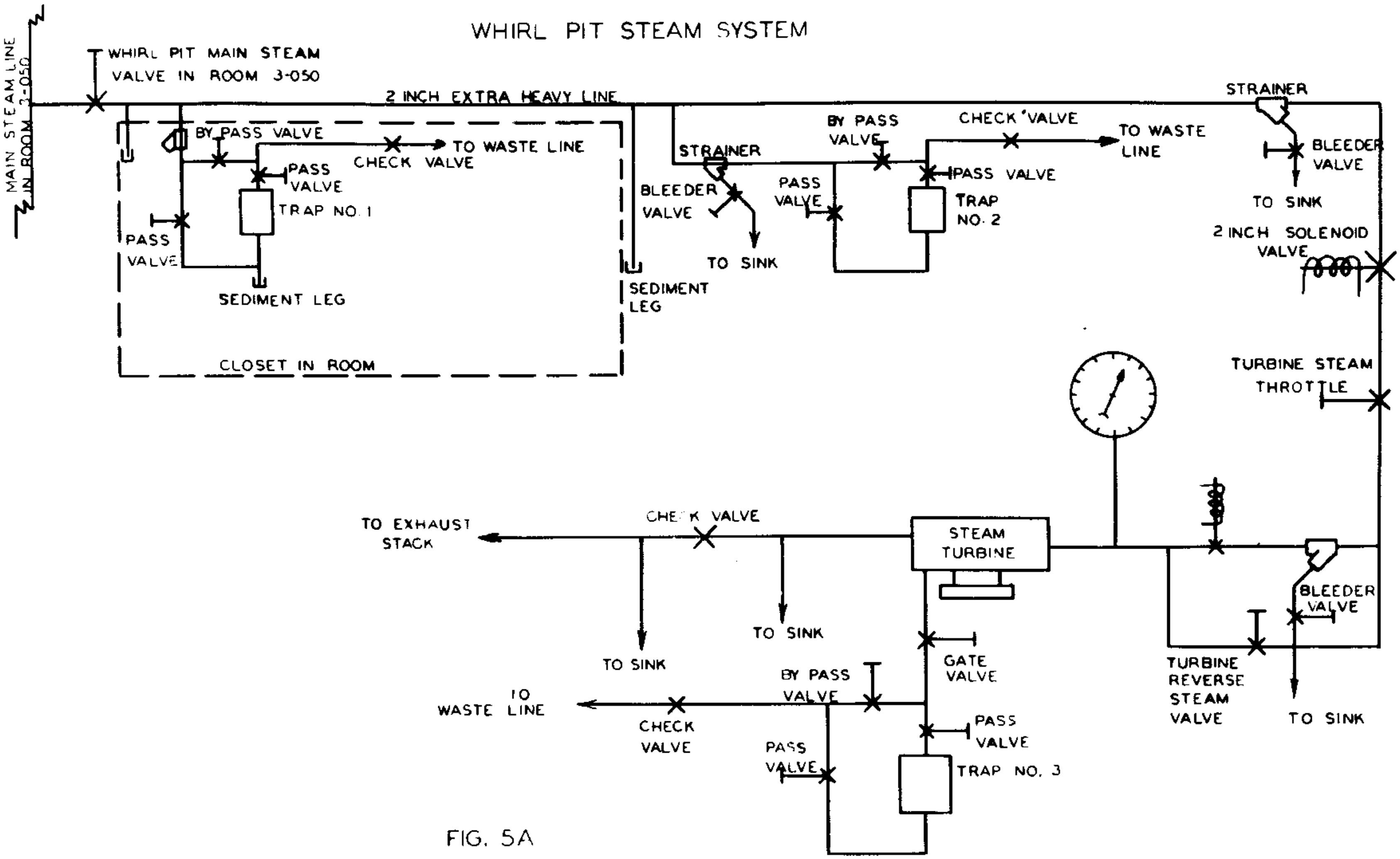


FIG. 5A

WHIRL PIT OIL - AIR SYSTEM

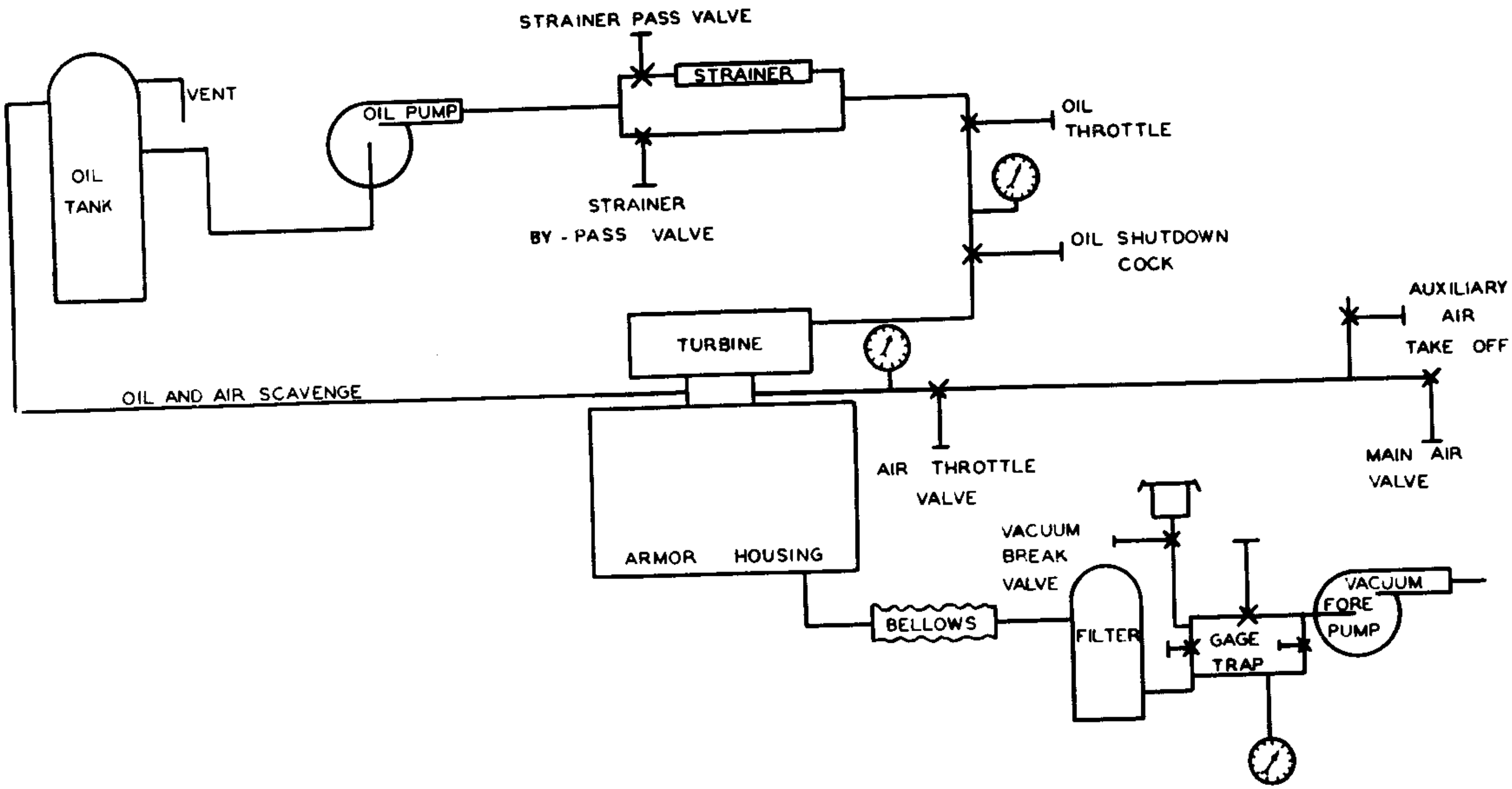


FIG. 5B

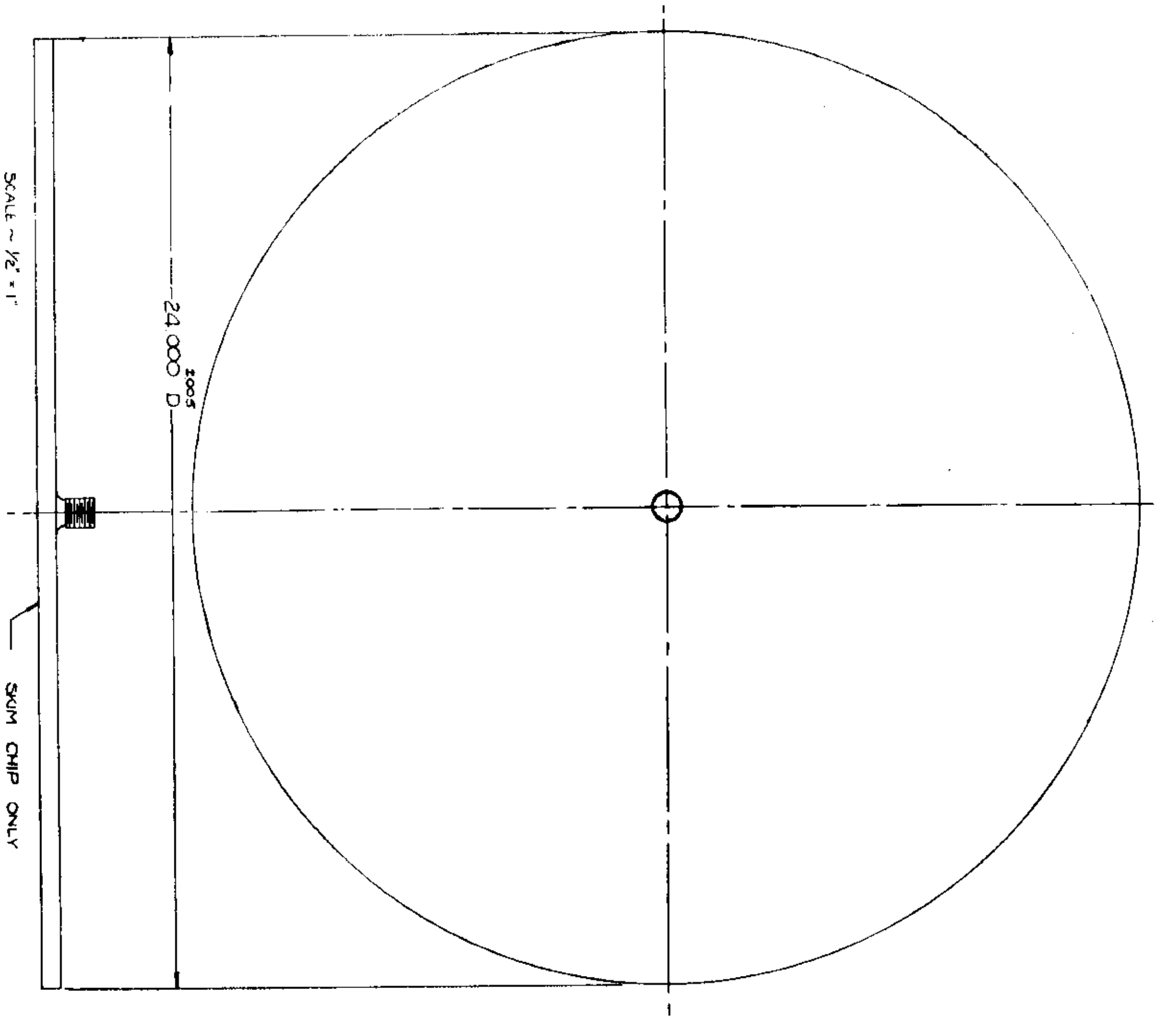
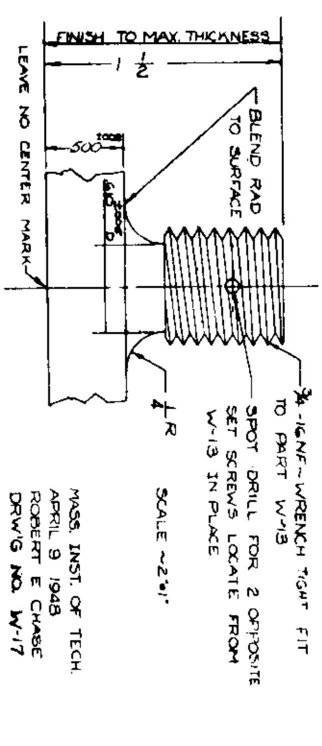


Fig. 6



MACHINING SEQUENCE

1. MATERIAL - 1 1/2" HOT ROLLED, LOW CARBON, SEMI-KILLED STEEL.
2. MOUNT 25" D X 1 1/2 THICK FLAME CUT BLANK IN FOUR JAW CHUCK.
3. LINE UP THE BLANK SO THAT A MINIMUM OF STOCK WILL BE FACED OFF, AND APPROXIMATELY CENTER THE BLANK.
4. FACE ONE SIDE, REMOVING A MINIMUM OF STOCK. LEAVE NO CENTER MARK.
5. TURN TO 24.000 .005 AT LEAST 5/8" BACK FROM FINISHED FACE.
6. REVERSE THE BLANK IN THE CHUCK AND LINE IT UP WITH A DIAL INDICATOR TO A MAXIMUM ECCENTRICITY READING OF .0005", AND A MAXIMUM RUNOUT OF .0005" AT 23" D.
7. FACE DISK TO FINISH THICKNESS, AND THREAD CENTER NIB.
8. SCREW HUB (DRAWING W-13) ON CENTER NIB AND SPOT DRILL FOR HUB SET SCREWS.
9. TIGHTEN HUB SET SCREWS AND BORE HUB IN PLACE. TAKE LIGHT FACING AND TURNING CHIPS ON HUB FOR CONCENTRICITY.

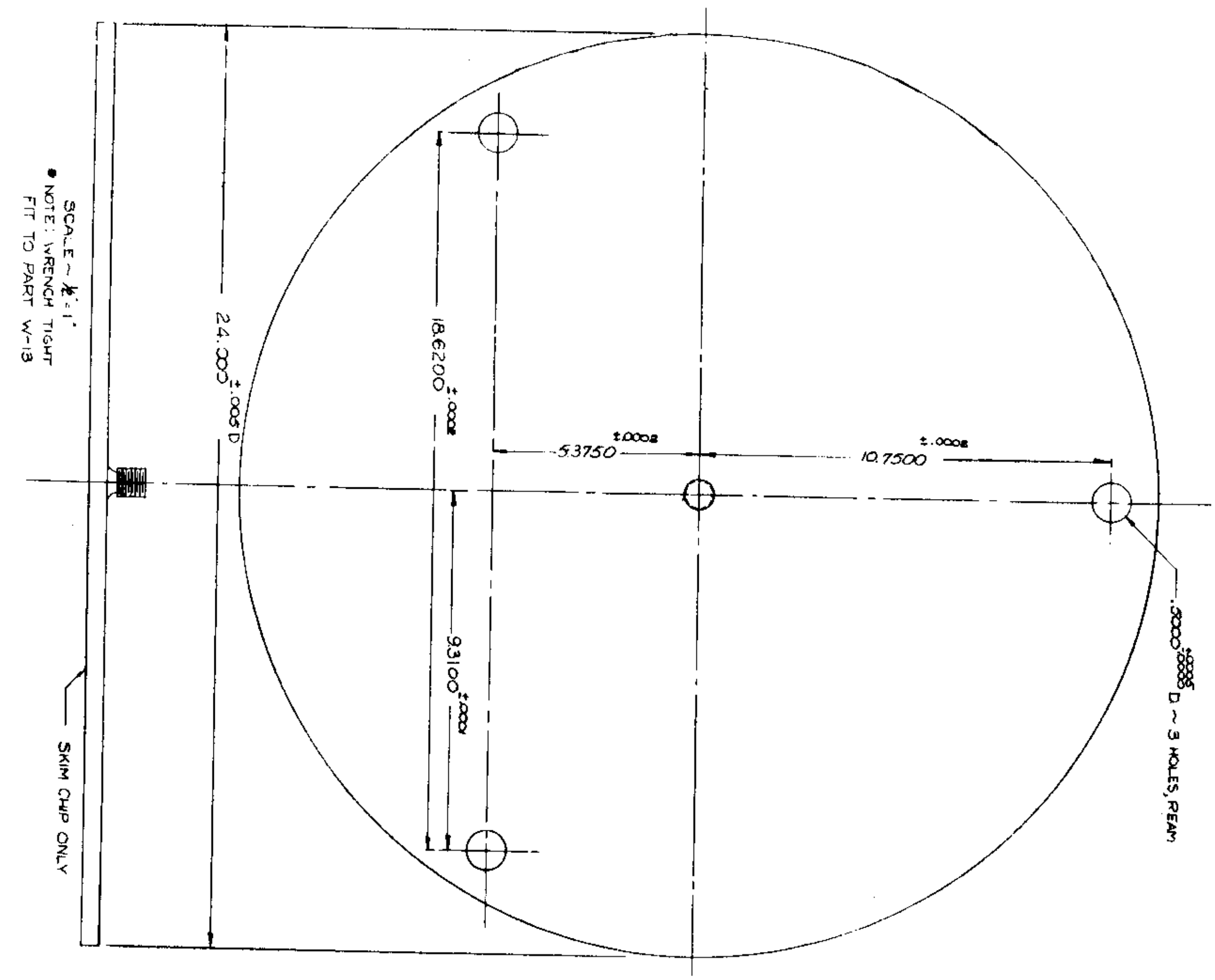
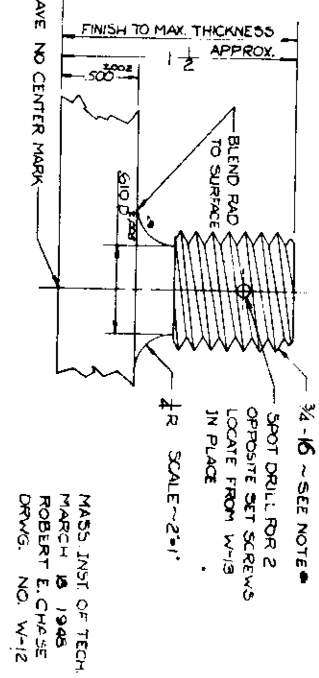


Fig. 7



MACHINING SEQUENCE

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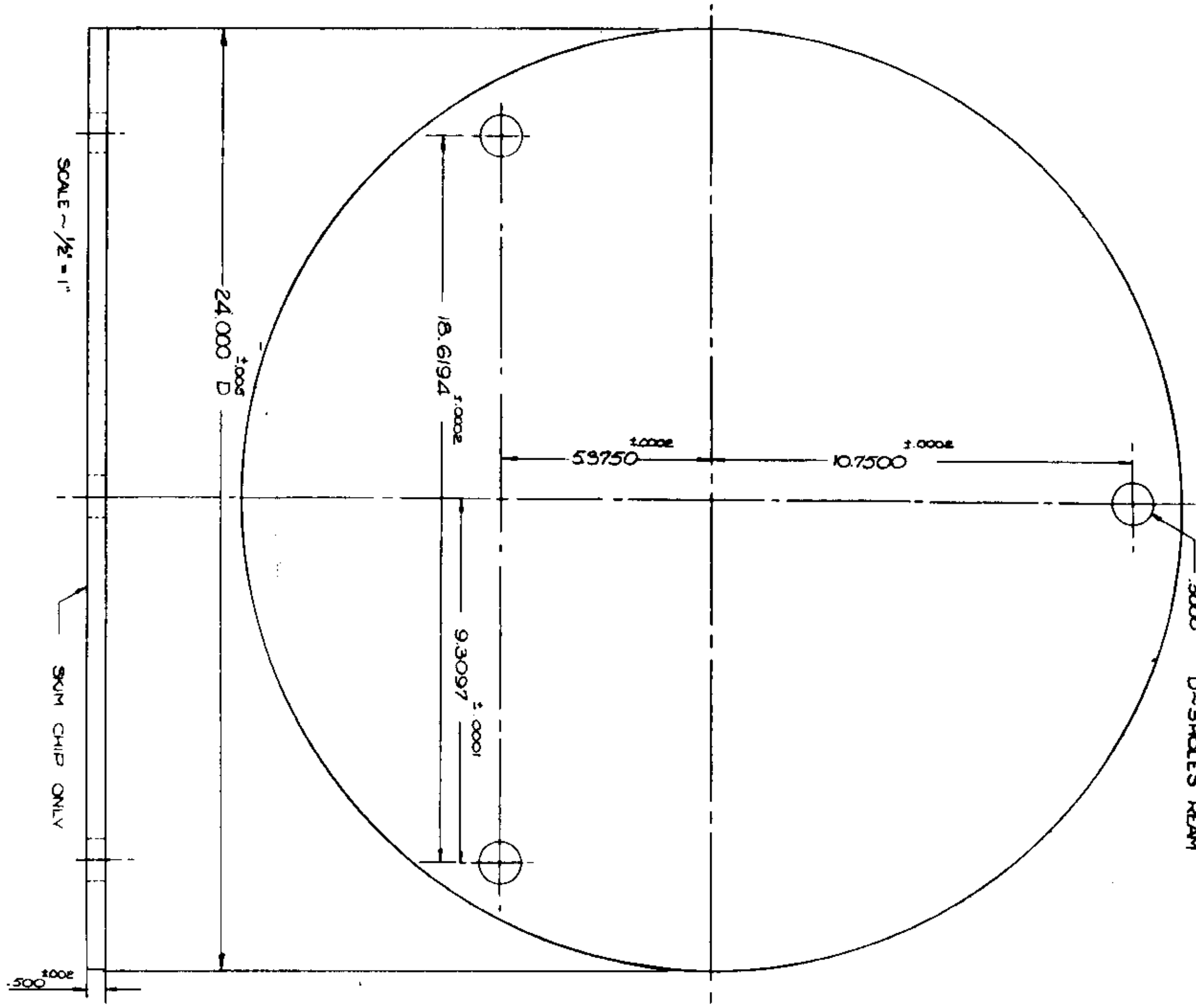
9. TIGHTEN HUB SET SCREWS AND BORE HUB IN PLACE. TAKE LIGHT FACING AND TURNING CHIPS ON HUB FOR CONCENTRICITY.
10. LOCATE 3 .5000" D HOLES BY JIG BORER.



MACHINING SEQUENCE

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2. MOUNT 25" D X 1 1/2 THICK FLAME CUT BLANK IN FOUR JAW CHUCK.
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6. REVERSE THE BLANK IN THE CHUCK AND LINE IT UP WITH A DIAL INDICATOR TO A MAXIMUM ECCENTRICITY READING OF .0005", AND A MAXIMUM RUNOUT OF .0005" AT 23" D.
7. FACE DISK TO FINISH THICKNESS.
8. LOCATE 3 .5000" D HOLES BY JIG BORER.

Fig. 8

MASS INST. OF TECH.
APRIL 9 1948
ROBERT E CHASE
DRW'G NO. W-18

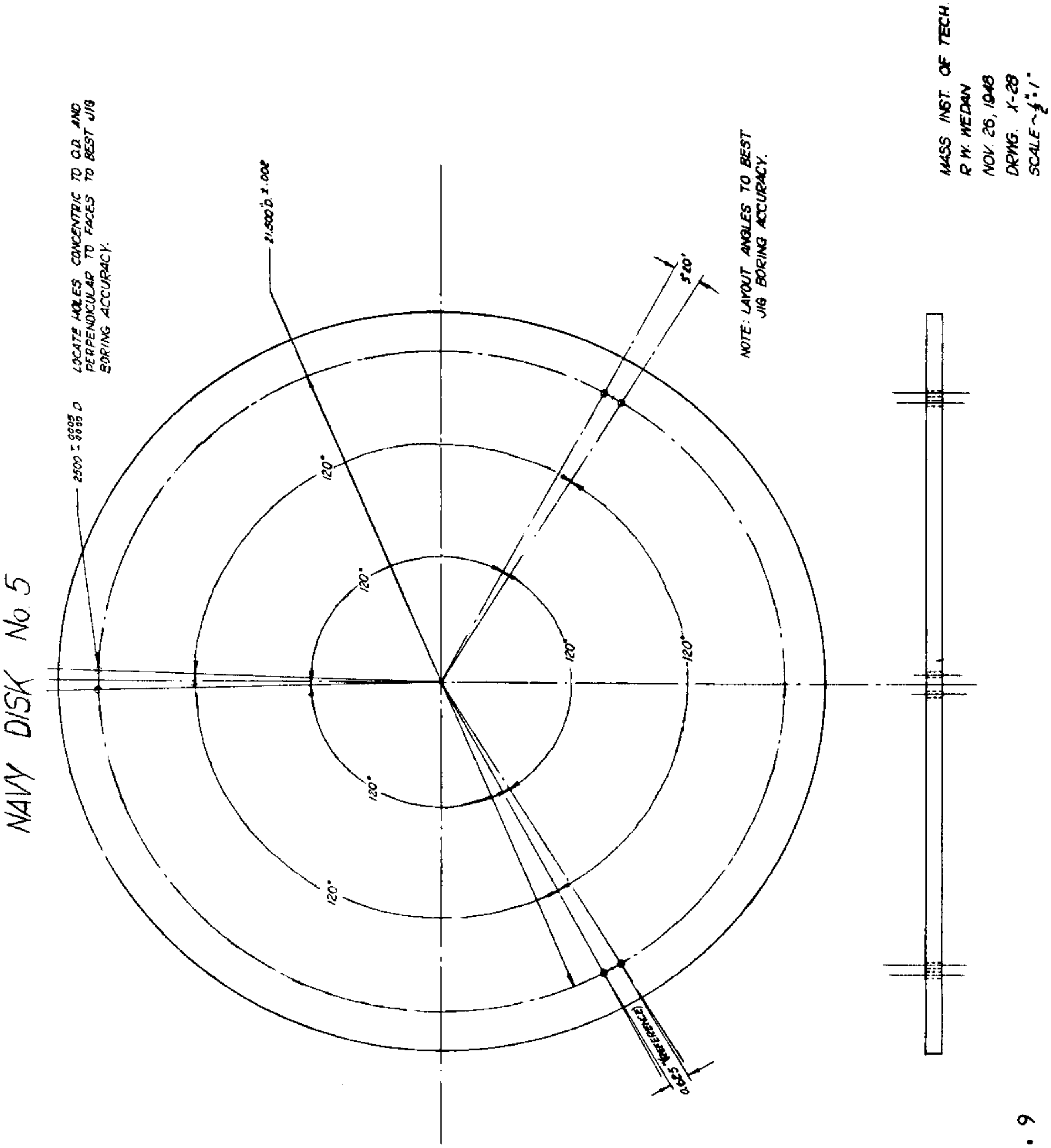

NAVY DISK No. 5
LOCATE HOLES CONCENTRIC TO O.D. AND PERPENDICULAR TO FACES TO BEST JIG BORING ACCURACY.
21.500 D ± .002
NOTE: LAYOUT ANGLES TO BEST JIG BORING ACCURACY.
5°20'
120°
120°
120°
120°
120°
120°
.0625 (REFERENCE)
MASS. INST. OF TECH.
R.W. WEDAN
NOV 26, 1948
DRWG. X-28

Fig. 9

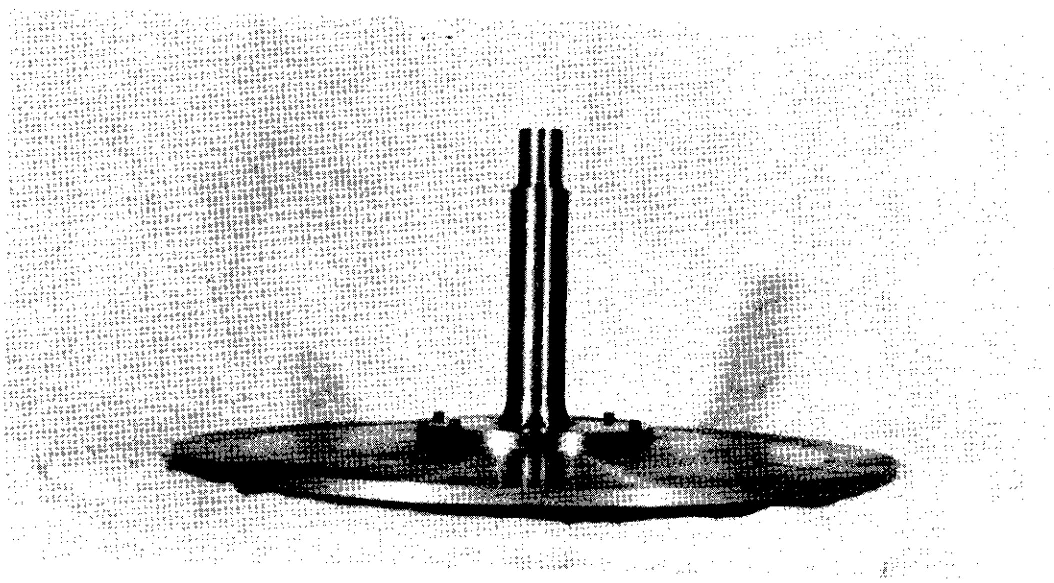


Fig. 10. Armor Driving Flange

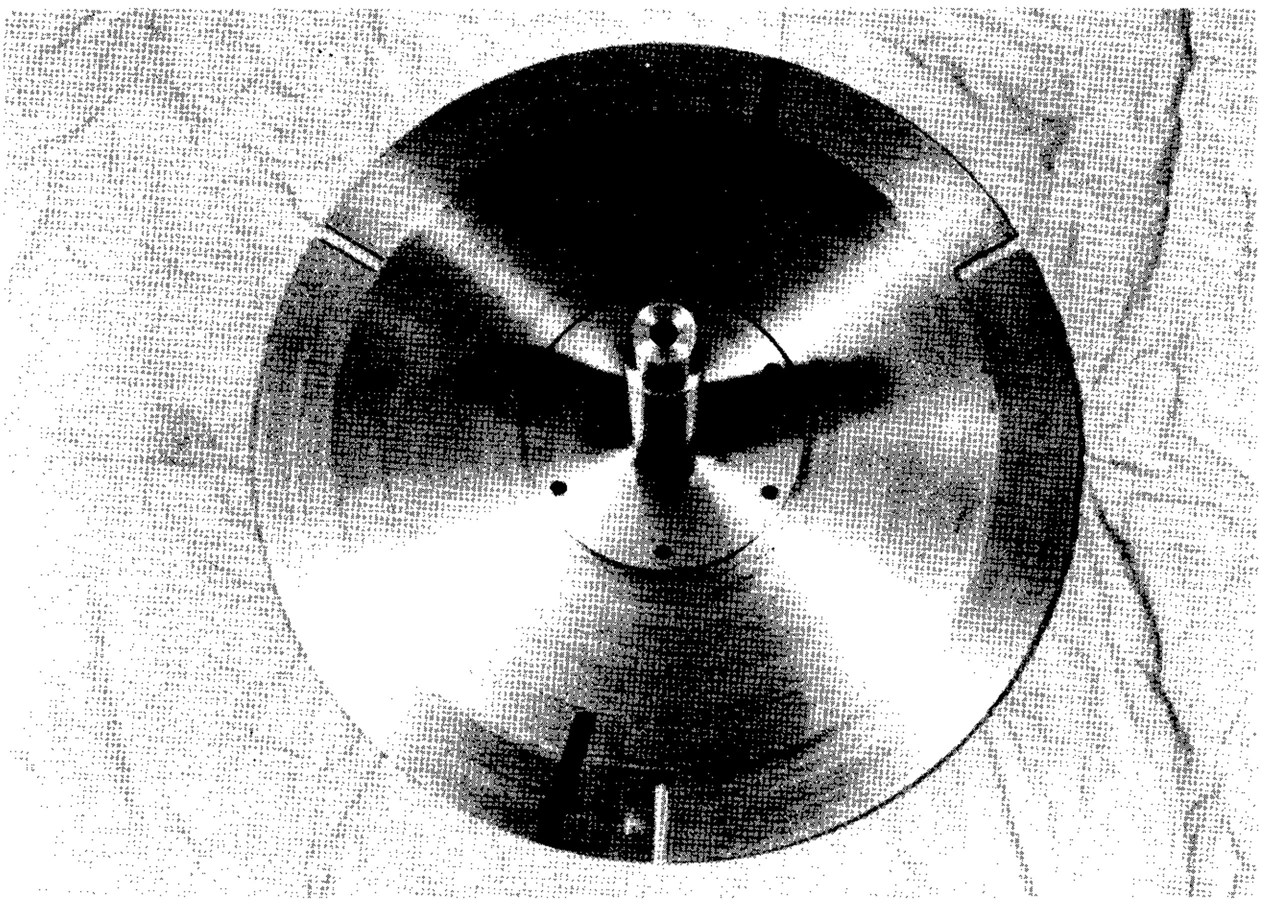


Fig. 11. Armor Driving Flange

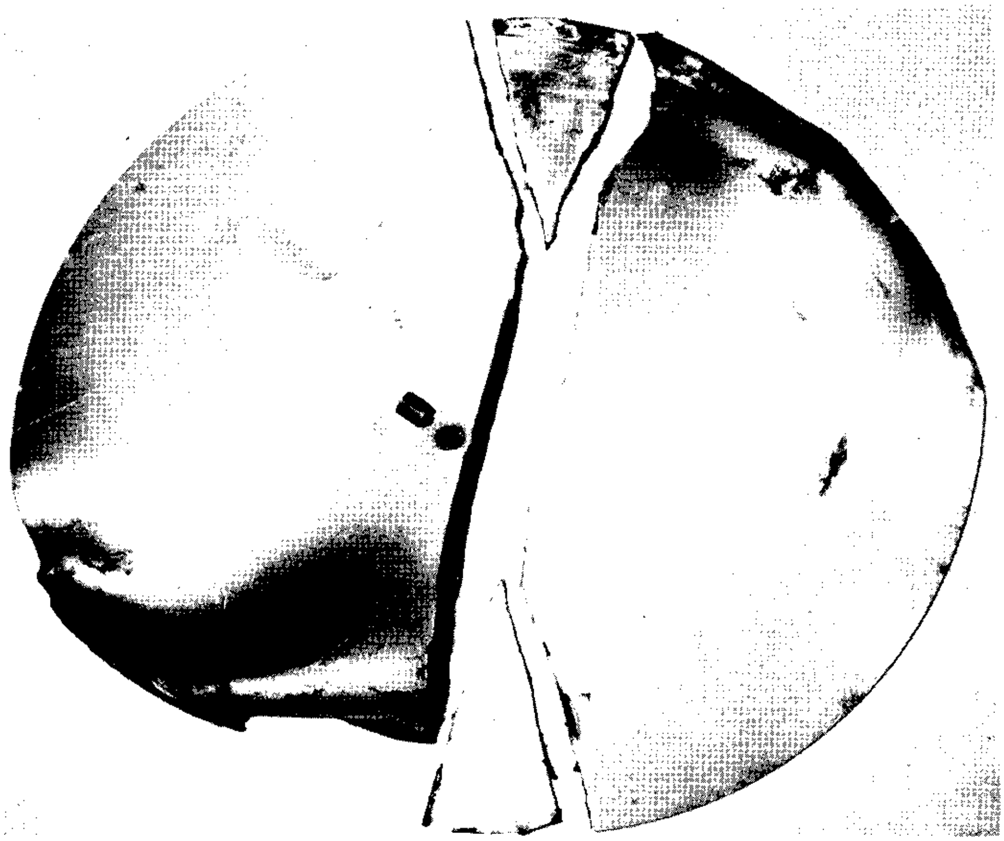


Fig. 12. Plan View of Fractured Disk #W-28 with Center Nib

Fig. 13. Plan View of Fractured Disk #W-28 with Center Nib

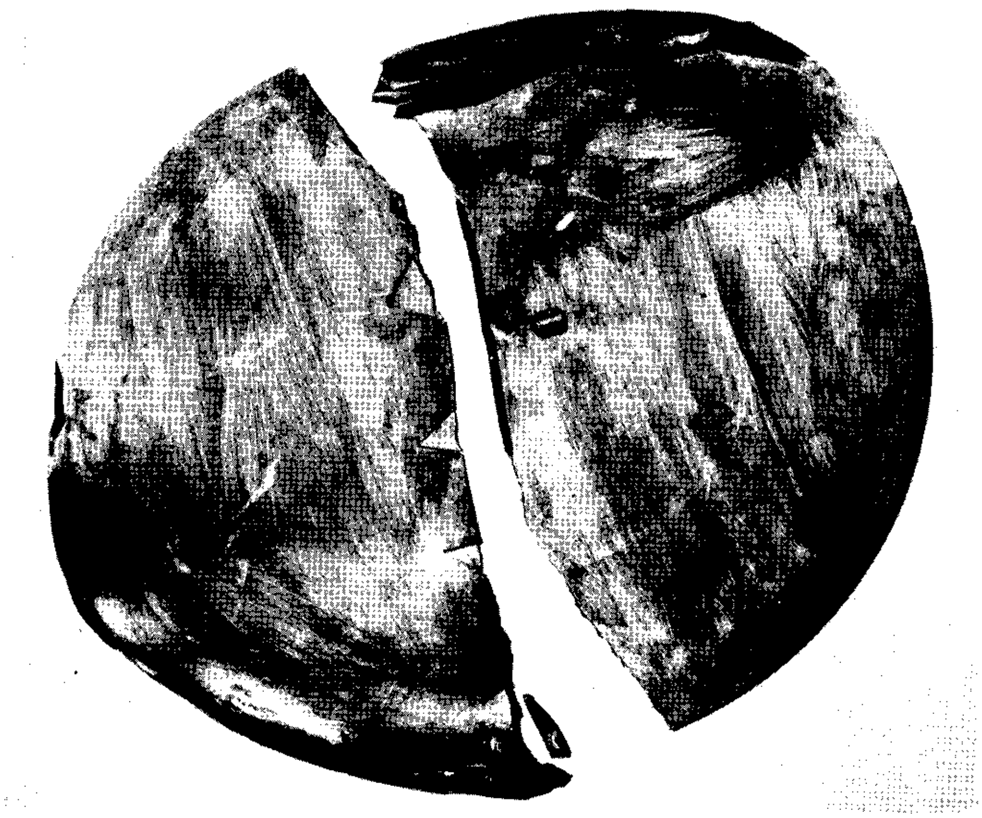


Fig. 14. Plan View of Fractured Disk #W-27 with Center Nib

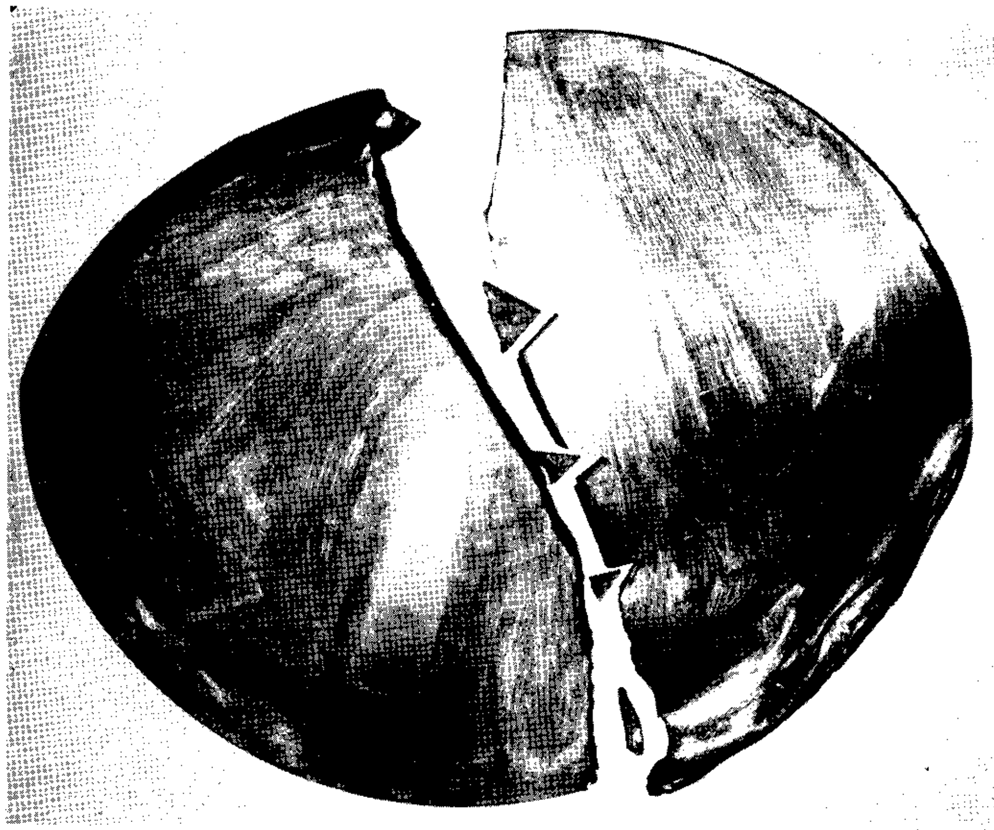


Fig. 15. Plan View of Disk #W-27 with Center Nib

Fig. 16. Side View of Fractured Disk #W-28

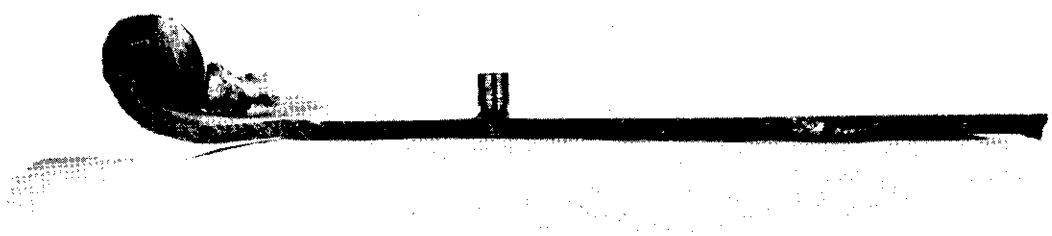


Fig. 17. Side View of Fractured Disk #W-27 with Center Nib

Fig. 18. View of Shear Surface in Disk #W-28

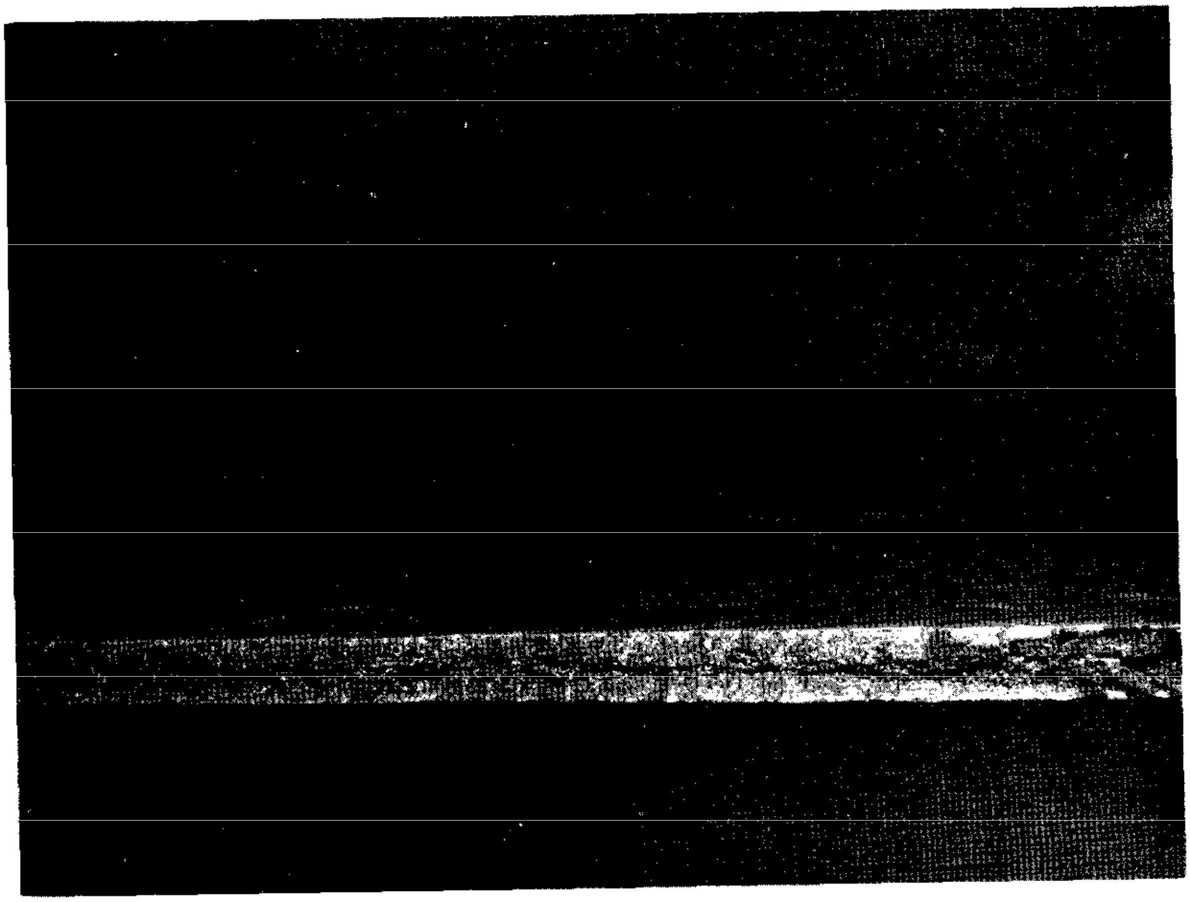


Fig. 19. View of Cleavage Surface in Disk #W-28

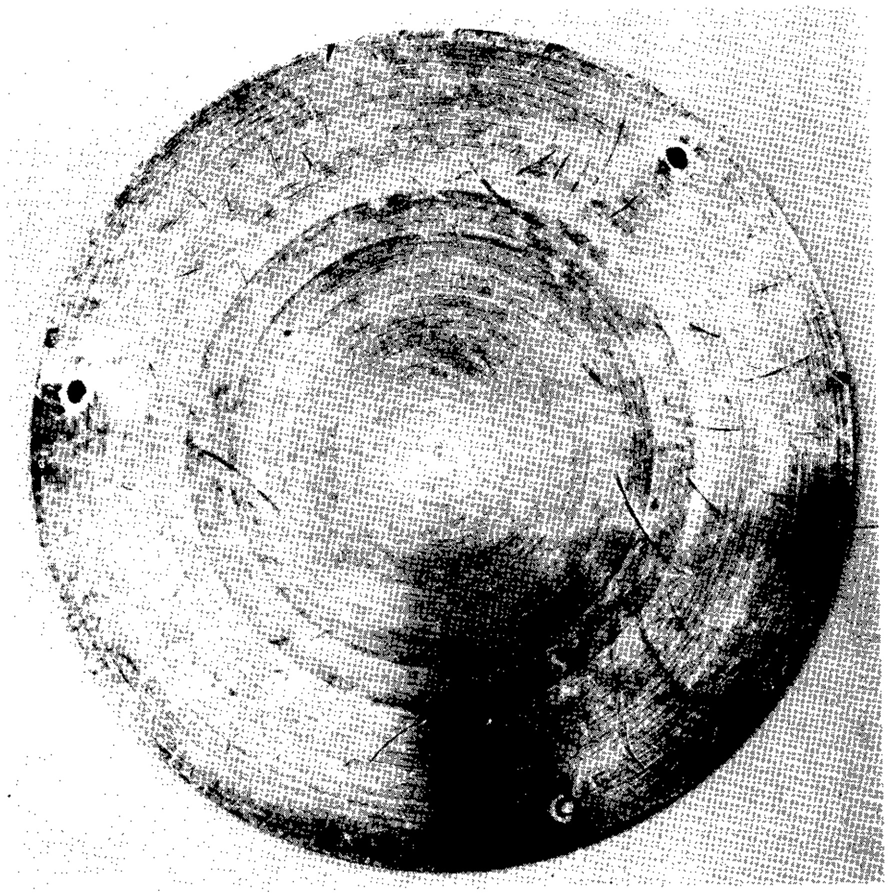


Fig. 20. Plan View of Flange Type Disk #W-29 Plastically Deformed

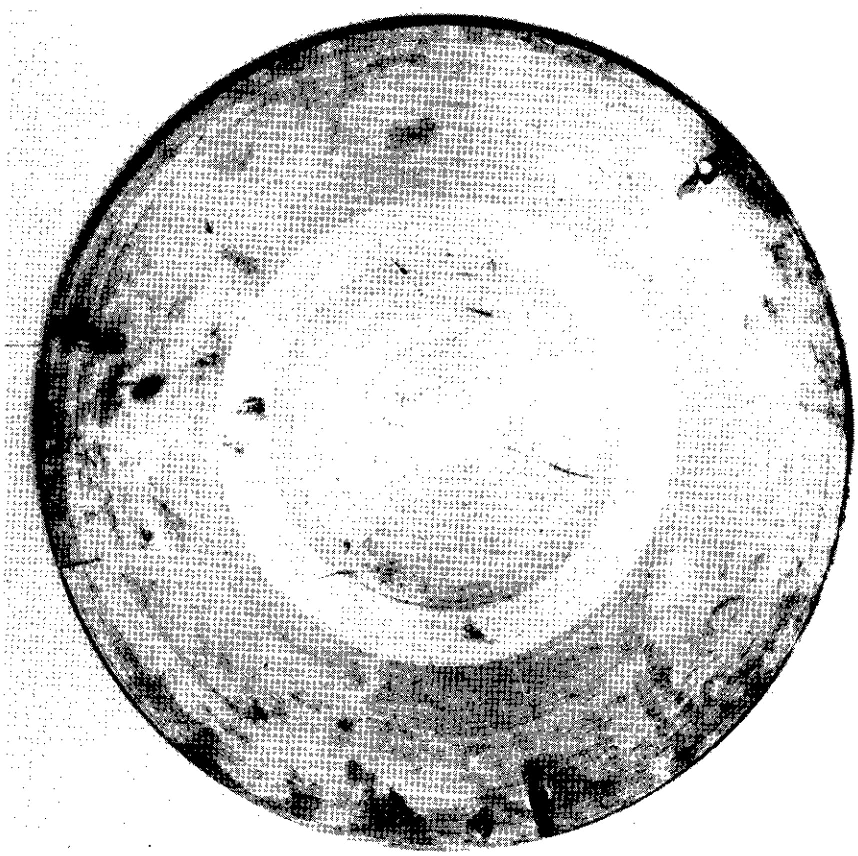
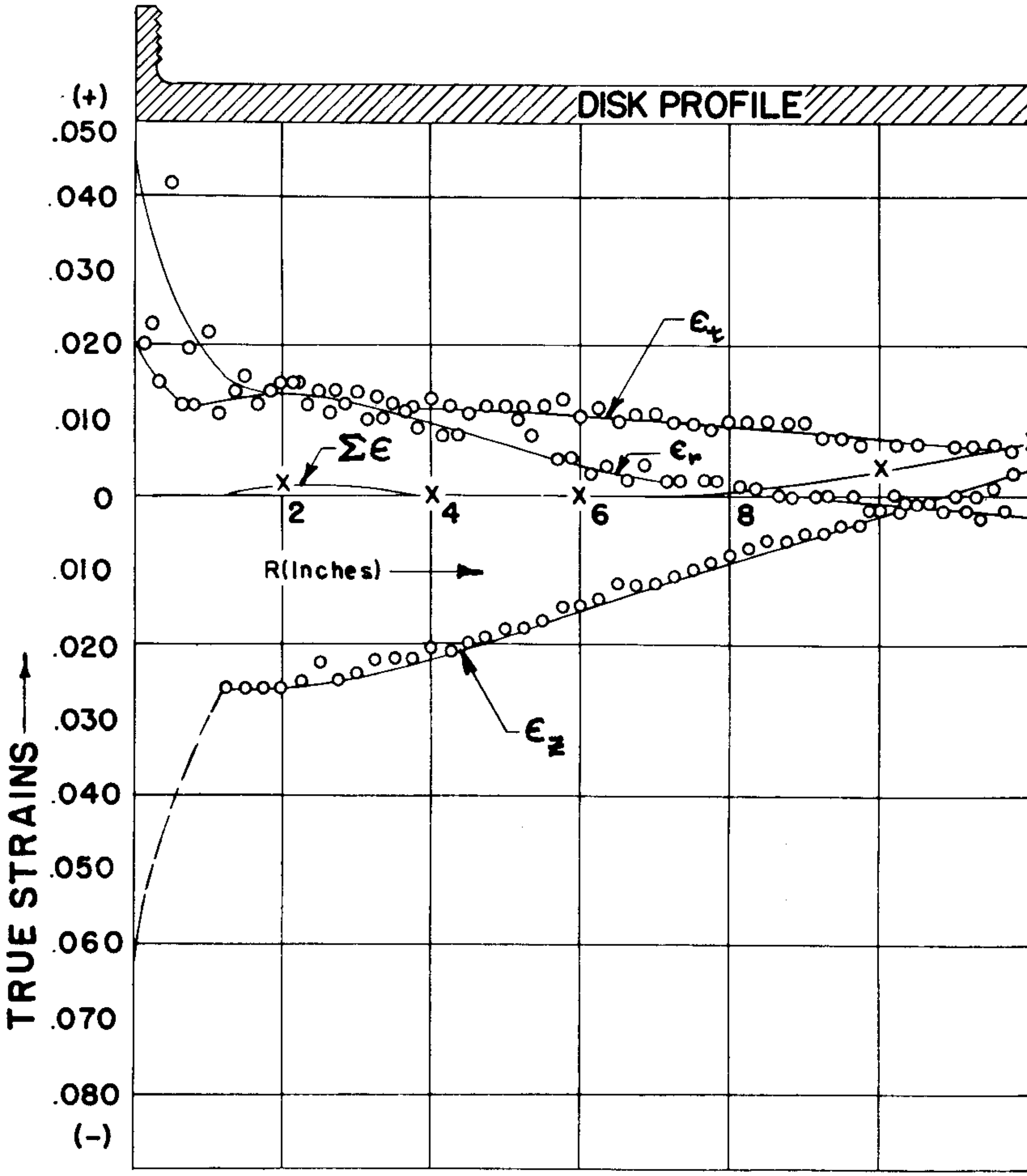


Fig. 21. Plan View of Flange Type Disk #W-30 Plastically Deformed



TRUE STRAIN DISTRIBUTIONS
IN DISK NO. W-28 AFTER
SPINNING TO 9,600 R.P.M.
FIG. 22

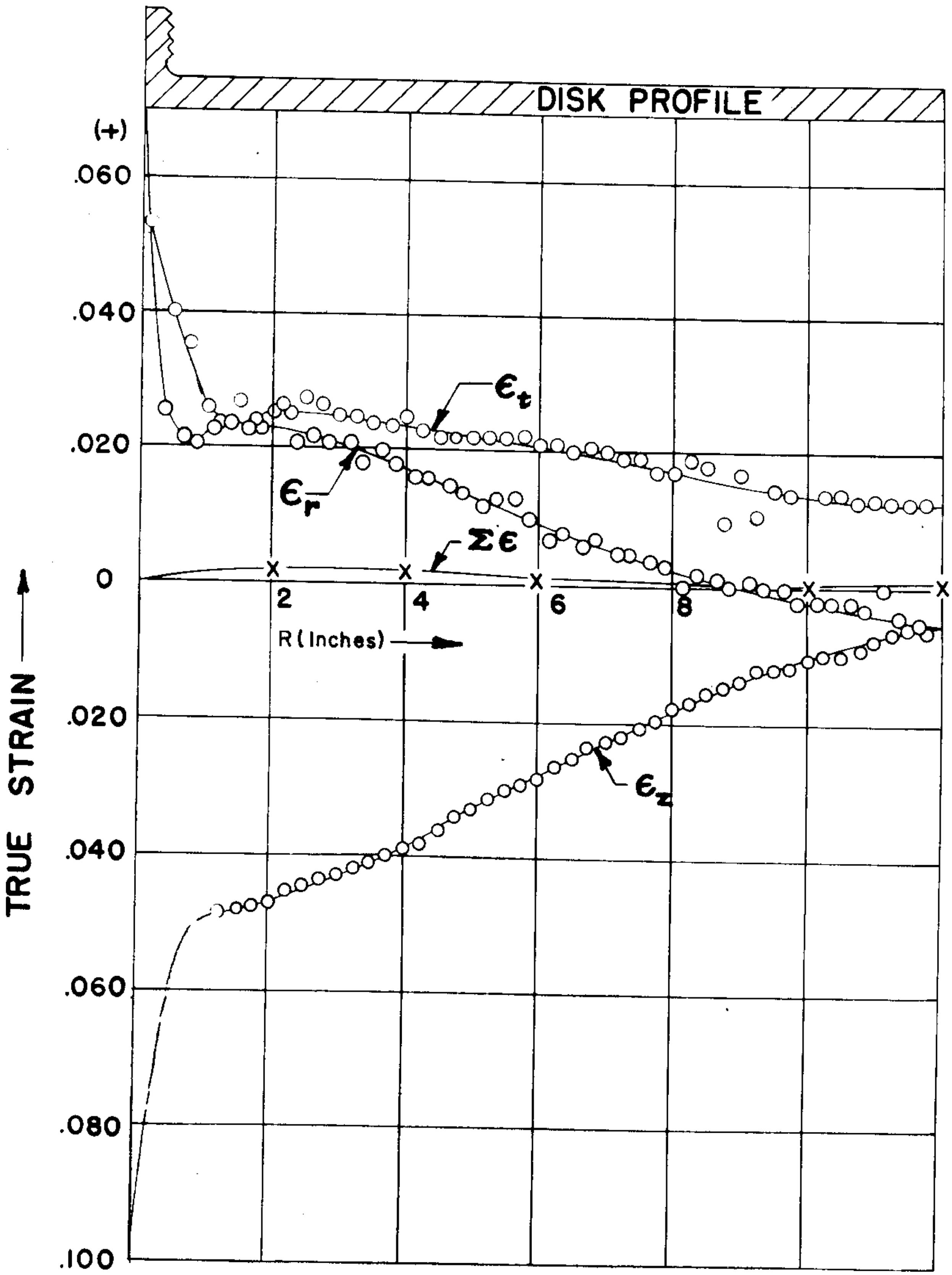


FIG. 23 TRUE STRAIN DISTRIBUTIONS IN DISK NO. W-28 AFTER SPINNING TO 11,000 R.P.M.

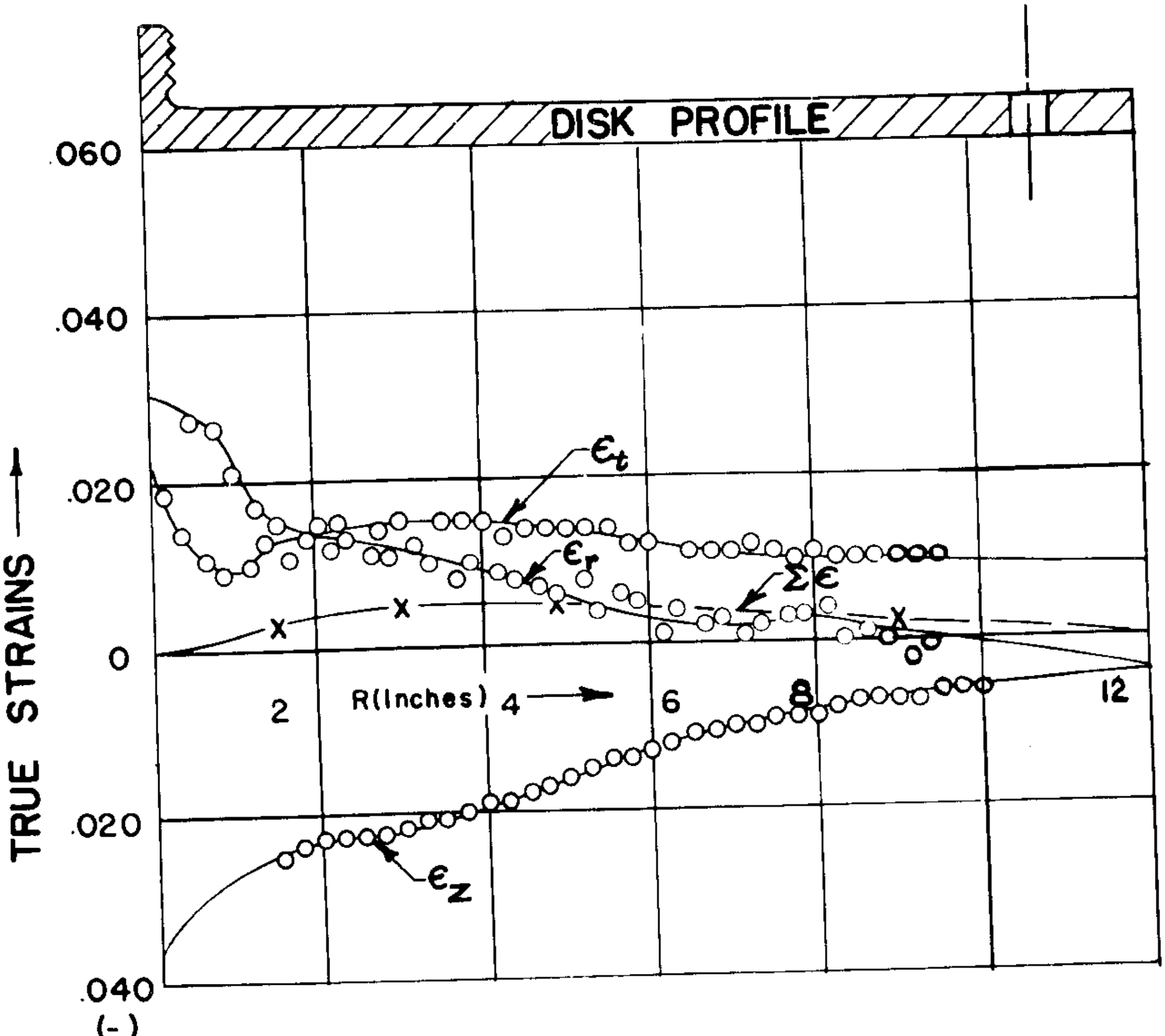


FIG. 24 TRUE STRAIN DISTRIBUTIONS IN DISK NO. W-21 AFTER SPINNING TO 9,600 R.P.M.

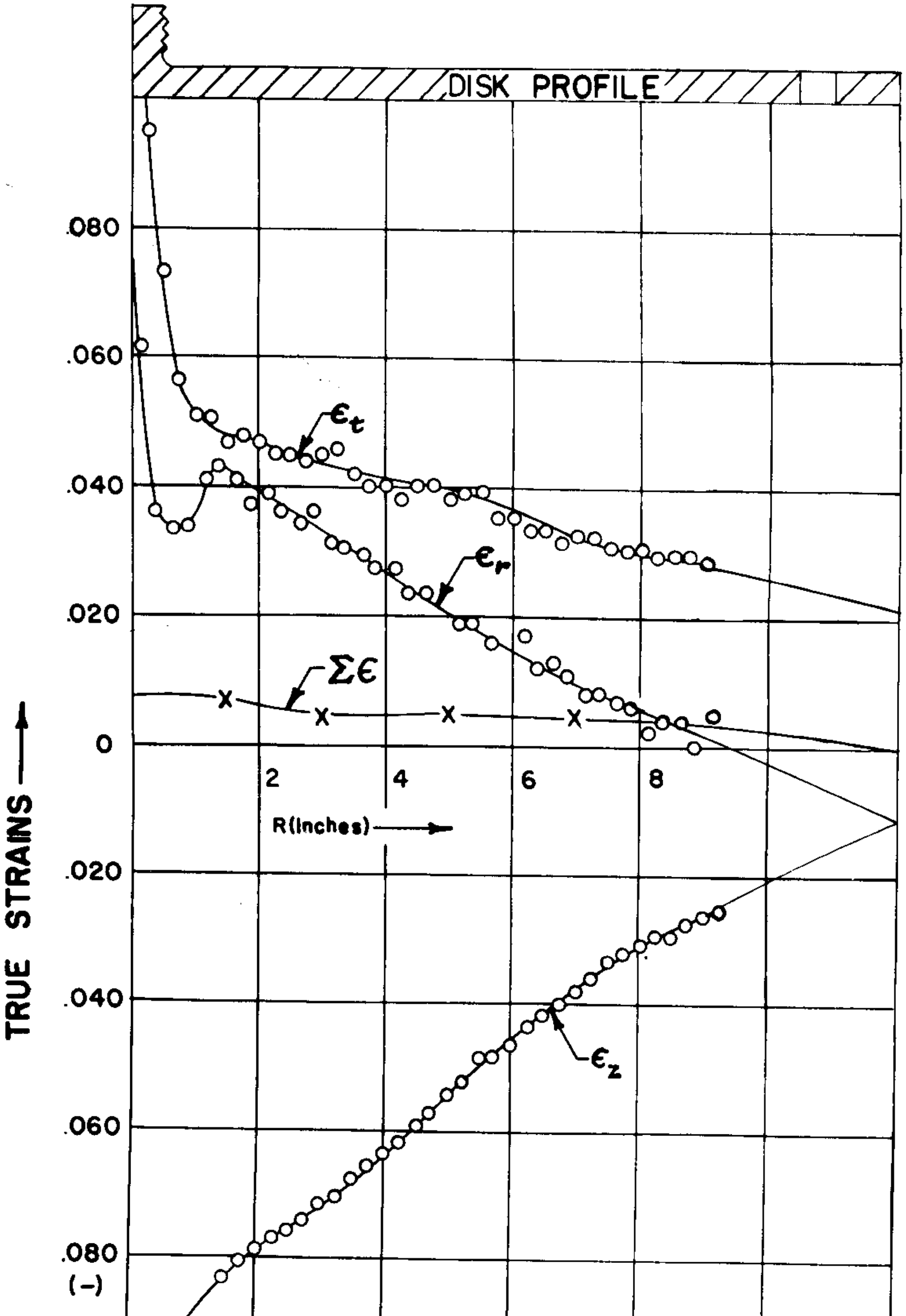
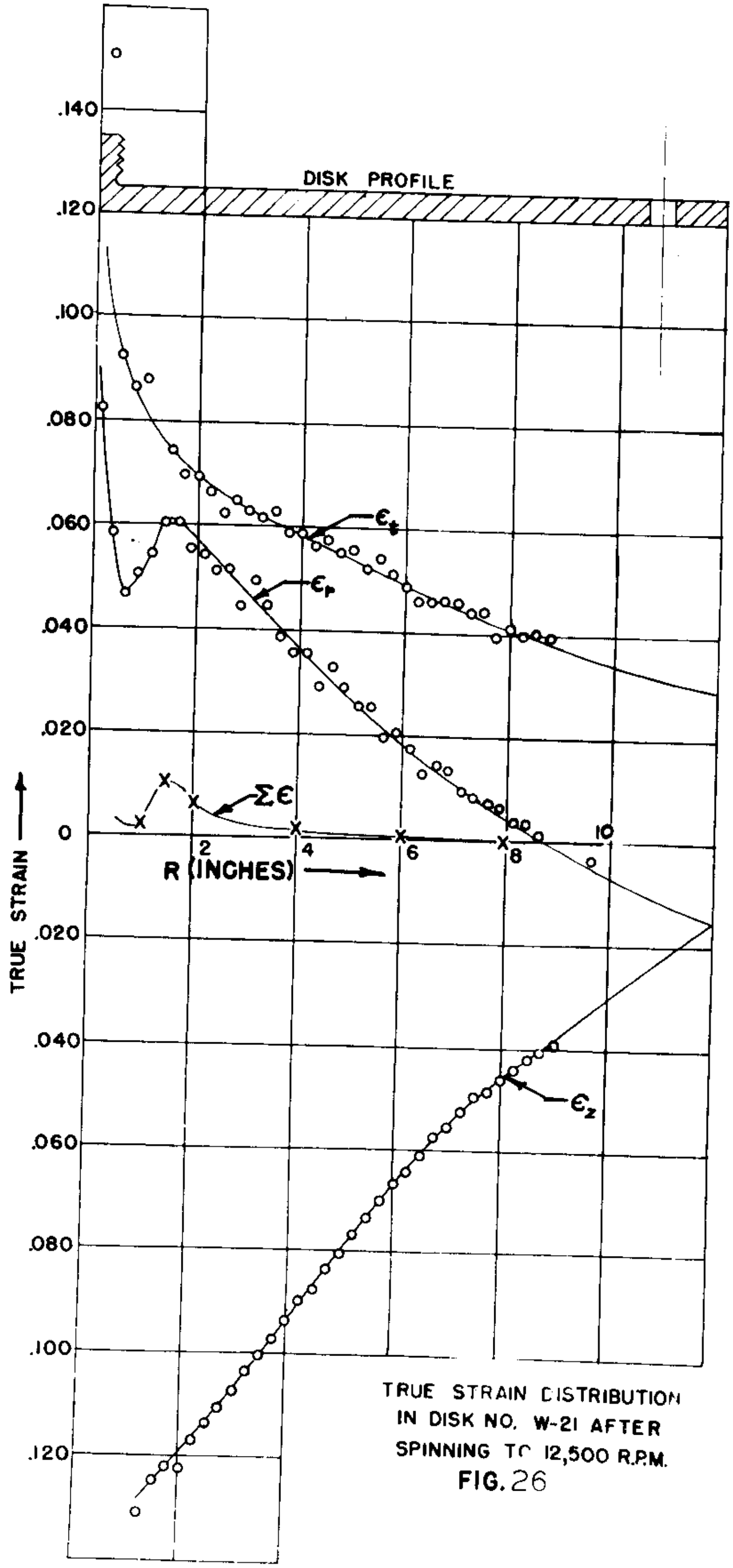
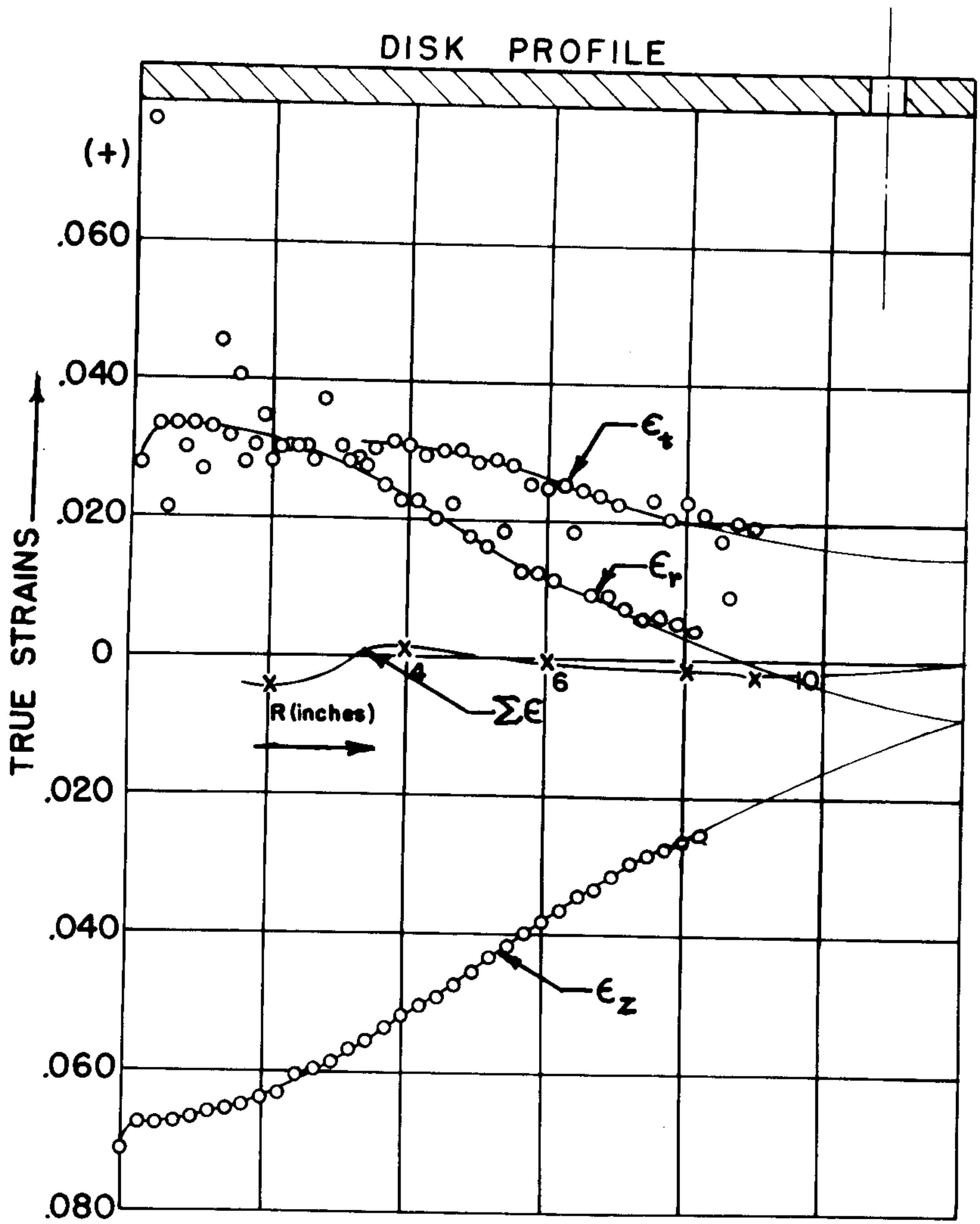


FIG. 25 TRUE STRAIN DISTRIBUTIONS IN DISK W-21 AFTER SPINNING TO 11,500 R.P.M.



TRUE STRAIN DISTRIBUTION IN DISK NO. W-21 AFTER SPINNING TO 12,500 R.P.M.

FIG. 26



(–) FIG. 27 TRUE STRAIN DISTRIBUTIONS IN DISK NO. W-29 AFTER SPINNING TO 11,000 R.P.M.

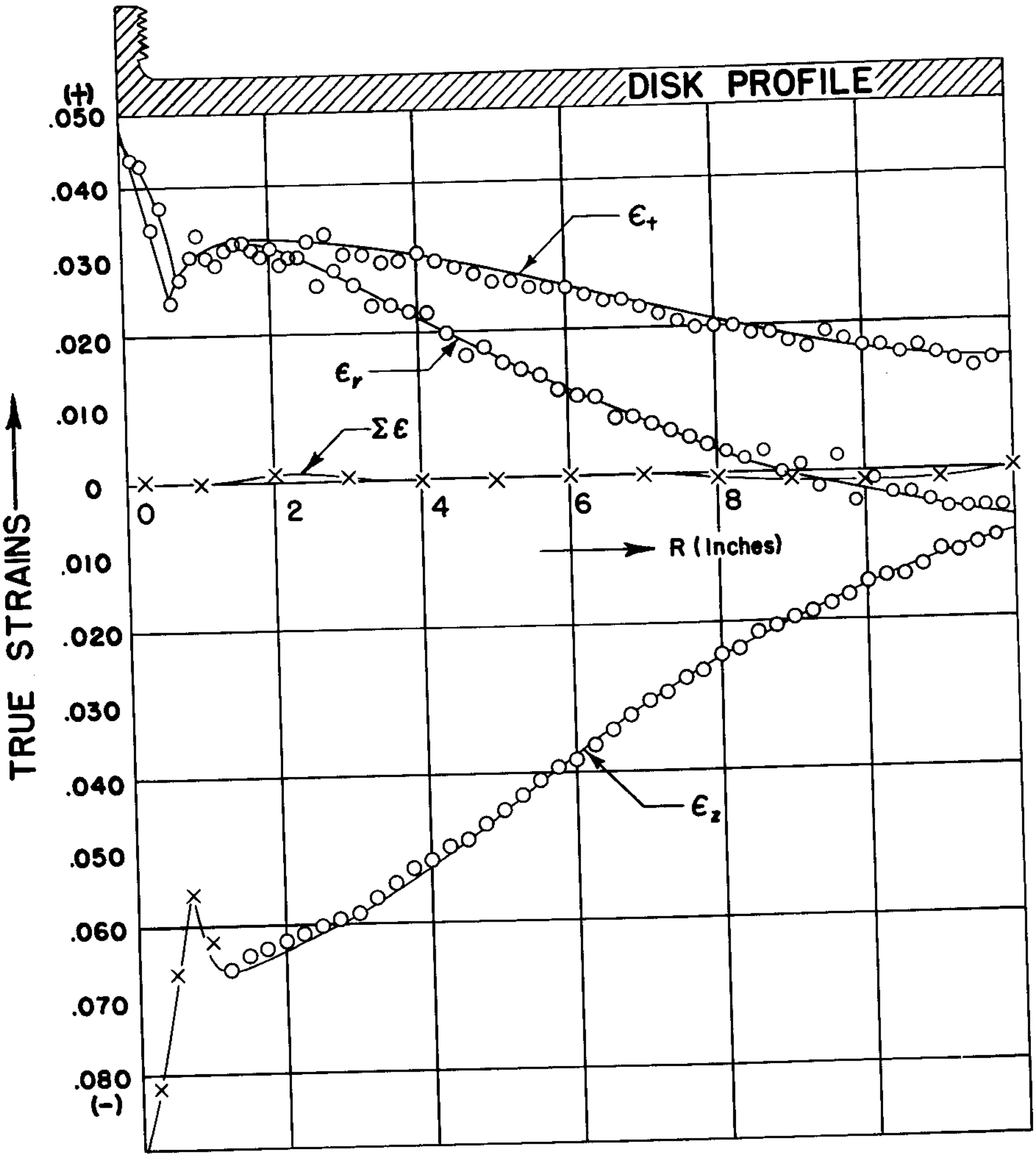


FIG. 28 TRUE STRAIN DISTRIBUTIONS IN DISK NO. W-27 AFTER SPINNING TO 11,000 R.P.M.

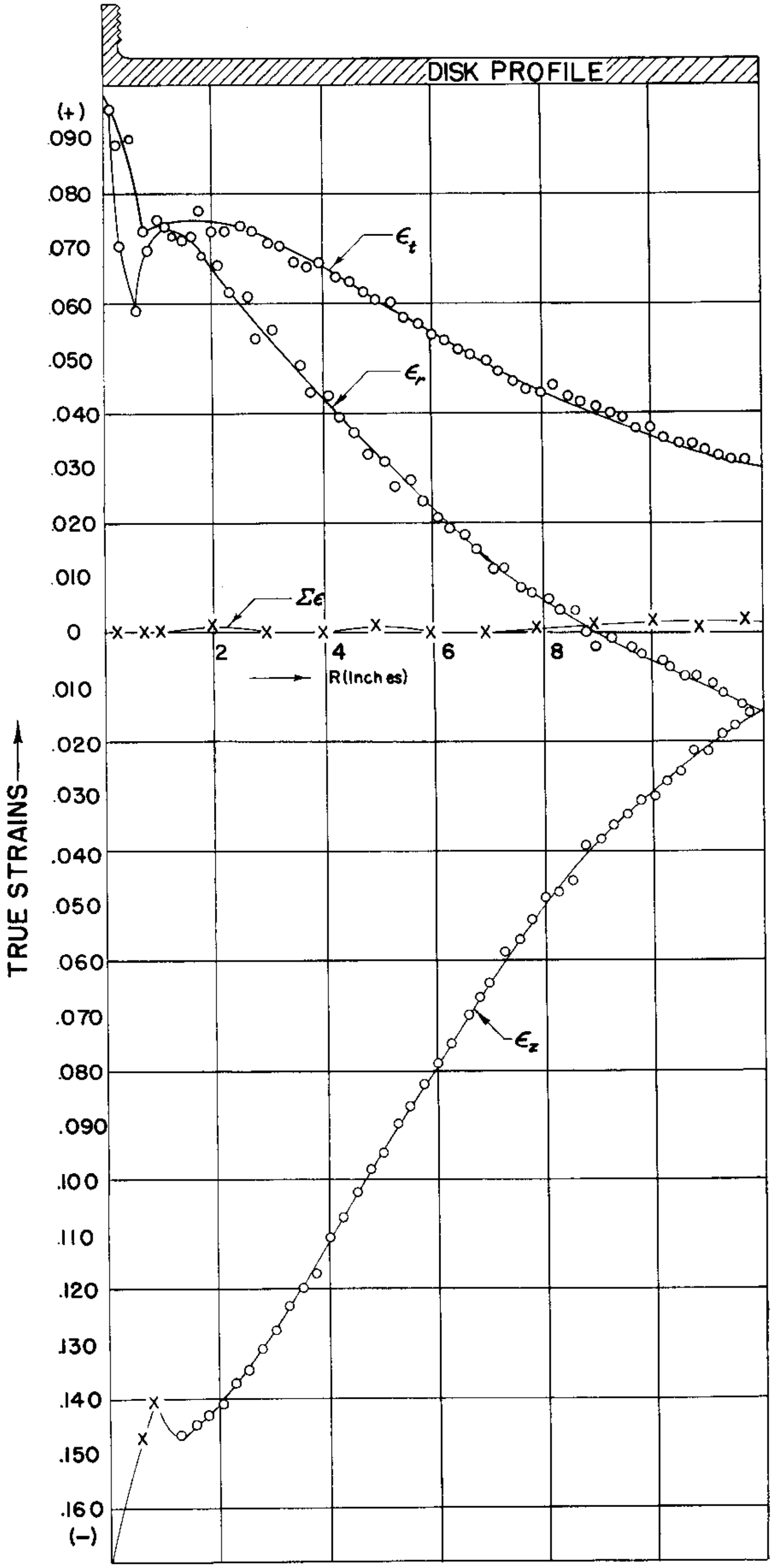


FIG. 29 TRUE STRAIN DISTRIBUTIONS IN DISK NO. W-27 AFTER SPINNING TO 12,500 R.P.M.

FLANGE · BOLT ASSEMBLY

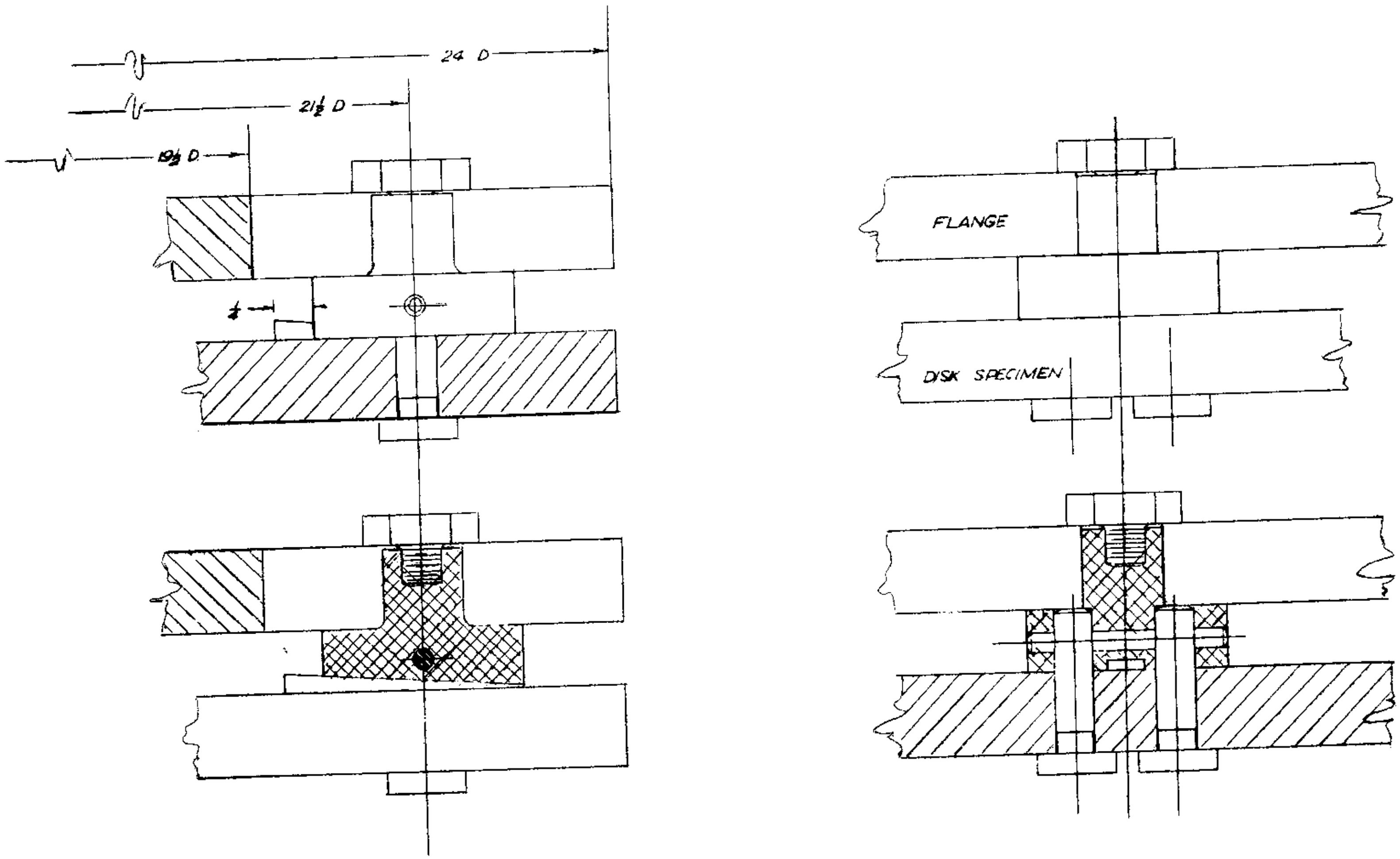


Fig. 30

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13. ABSTRACT

The general objectives of this experimental program were (1) to develop a suitably supported solid disk type specimen, having no disturbing central nib, which would permit unrestrained plastic expansion under high rotation at speeds up to bursting, (2) to measure the strain patterns at several stages of flow up to bursting on specimens of this type to disclose the basic mechanism of flow and provide a means of calculating bursting stresses and (3) to make low-temperature tests on full-size disks of this type to determine the transition temperature from ductile to brittle fracture. Since parts (2) and (3) depend directly on part (1), this was first attacked. Various designs were tried in order to perfect such a specimen. Several attempets were successful in carrying a special flange-supported type specimen containing no central nib well up into the plastic range; up to the present, it has not been possible to develop one which could be carried successfuly to bursting. Since most of the time was thus utilized for part (1) of the program, only a limited amount of data was accumulated for part (2). Some of the necessary equipment for part (3) was either designed or acquired but no tests were conducted for the reasons explained above.

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