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BALANCING MACHINES - DESCRIPTION AND EVALUATION VERTICAL, TWO-PLANE, HARD-BEARING TYPE FOR GAS TURBINE ROTORS

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1. SCOPE:

1.1 Characteristics of vertical hard-bearing balancing machines are described which make such machines suitable for gas turbine rotor balancing.

1.2 This document specifies the following:

a. General dimensions and capacities
b. Performance requirements
c. Balancing speed ranges
d. Drive power requirements
e. Balancing machine spindle flange dimensions
f. Test procedures

1.3 Proving rotors and associated test masses required for the performance tests are described in ARP4162.

1.4 Test procedures are described in detail and test log samples along with a polar diagram for evaluating the test results are furnished.

1.5 The predecessor document ARP588, ISO 2953, and the available technology of hard-bearing balancing machines have been considered in the preparation of this document.

1.6 This document was developed for hard-bearing balancing machines but may also be used for existing soft-bearing balancing machines.

1.7 Purpose:

The purpose of this document is to delineate the technical specifications for vertical, rotating type, hard-bearing balancing machines for measuring the amount and angle of unbalance corrections required in one or more transverse planes to balance gas turbine rotors (For Glossary of Terms and Nomenclature, see ISO 1925).

Hard-bearing machines have been used for gas turbine rotor balancing for several years. They have largely replaced soft-bearing machines. Hard-bearing machines provide permanent calibration (see ISO 1925) with first-run readout, simpler operation, easy adaptation to computerization, and eliminate support locking requirements and windage fluctuations.

This document also delineates performance tests to ensure compliance with the document.

This document was prepared to give a general description of balancing equipment capable of balancing gas turbine rotors either now in service or to be put into service in the foreseeable future. Standardization of balancing machine to rotor interfaces is intended to enable a set of tooling for a particular component to be used on a variety of machines in one capacity range.

1.7 (Continued):

This document may also be used as a general specification for purchasers in procuring suitable vertical two-plane balancing machines.

The performance and test requirements may be used for periodic tests and/or after repairs that may have affected the balancing machine's performance. The test procedure shall be the same as described in this document.

The performance and test requirements have been written in terms of "e_{mar}" (minimum achievable residual specific unbalance), and A-units rather than fixed physical values, such as grams, millimeters, ounces, or inches (see ISO 1925).

2. REFERENCES:

The following publications form a part of this specification to the extent specified herein. The latest issue of all SAE Technical Reports shall apply.

The references give some earlier balancing equipment specifications and background information on topics allied to this document.

2.1 SAE Publications:

Available from SAE, 400 Commonwealth Drive, Warrendale, PA 15096-0001.

ARP588	Balancing Machines - Description and Evaluation, Vertical, Single Plane, Soft-Bearing Type for Gas Turbine Rotors
ARP1382	Design Criteria for Balancing Machine Tooling
ARP4048	Balancing Machines - Description and Evaluation, Horizontal, Two-Plane, Hard-Bearing Type for Gas Turbine Rotors
ARP4162	Balancing Machine Proving Rotors

2.2 ANSI Publications:

Available from American National Standards Institute, 11 West 42nd Street, New York, NY 10036.

ISO 1925 - 1990	Balancing Vocabulary
ANSI S2.7 - 1982	Balancing Terminology
ISO 2953 - 1985	Balancing Machines - Description and Evaluation
ISO 7475 - 1984	Balancing Machines - Enclosures and other Safety Measures

2.3 Military Publications:

Available from DODSSP, Subscription Services Desk, Building 4D, 700 Robbins Avenue, Philadelphia, PA 19111-5094.

Report No. 371-V-24; Department of the Navy, Bureau of Ships Code 371
MIL-STD-167; Mechanical Vibrations of Shipboard Equipment, Department of the Navy, Bureau of Ships

3. GENERAL PERFORMANCE REQUIREMENTS:

3.1 Plane Separation:

The balancing machine shall indicate the amount and angle of the unbalance in each of one or more selected planes in the rotor.

3.2 Static and Couple Unbalance Separation:

The balancing machine shall indicate, for the selected planes in the rotor, the amount and angular location of both the static unbalance and couple unbalance.

3.3 Unbalance Indication:

3.3.1 Analog devices indicating amount of unbalance shall have at least 0.125 in (3 mm) pointer movement for measurement of one A-unit over a range of 20 A-units.

3.3.2 Digital devices indicating amount of unbalance shall have a resolution of at least 10% of one A-unit.

3.3.3 The angle resolution shall be at least 1°.

3.3.4 The amount and angle indication shall be simultaneous in two planes.

3.3.5 The amount and angle readout shall be provided on the first spin up of the rotor.

3.3.6 The radius setting shall be selectable, with a minimum of 1 in or, alternatively, of 10 mm.

3.3.7 Amount indication shall be available in metric and/or English units (grams, ounces and fractions thereof).

3.3.8 Unbalance indication shall be available for clockwise and counterclockwise direction of rotation.

3.4 Balancing Machine Construction:

3.4.1 The machine must be constructed for floor mounting.

3.4.2 An appropriate size of shroud must be interlocked for operator safety.

3.4.3 The machine must be equipped with the appropriate spindle mounting flange as specified in Appendix A.

3.5 Drive For Workpiece:

3.5.1 The drive system shall include all components necessary to drive the proving rotor.

3.5.2 The drive system shall be functional in both directions of rotation.

3.6 Speed of Rotation During Balancing:

The machine shall be capable of operating at variable speeds within the range shown in Table 1, paragraph 4.5.2.

3.7 Drive Motor and Controls:

The machine shall be capable, within the agreed upon time period, of making six consecutive starts and stops to the balancing speed of the rotor requiring the most drive power.

4. DIMENSIONS AND CAPACITIES:

Table 1 lists the required dimensions and capacities for each machine size and associated proving rotor.

5. VERIFICATION TESTS:

5.1 Requirements for Tests:

To verify the claimed performance of a balancing machine, separate tests are required. The first test is for minimum achievable residual specific unbalance (e_{mar} test), and the second is the test for unbalance reduction ratio (URR test). These tests represent a minimum test procedure designed to establish essential compliance with the requirements for minimum achievable residual unbalance and for combined accuracy of amount of unbalance indication, angle indication, and plane separation. The test procedure will not prove compliance with all requirements over the full range of variables nor will it define the exact reason in case the machine fails to comply.

If the machine is equipped with a compensator, its performance shall be tested.

Equipment parameters, including physical inspection of various dimensions, features, instrumentation, tooling and accessories, shall be verified.

TABLE 1

Characteristic	Dimensions and Capacities					
4.1 Machine Class	25	50	100	250	500	1000
4.2 Load Capacity (lb)						
4.2.1 Maximum 1)	25	50	100	250	500	1000
4.2.2 Minimum 2)	1	2	4	10	20	50
4.2.3 Maximum $W \cdot h^2 \cdot n^2$ 3) (lb-ft^2 x rpm^2 x 10^6)	20	32	45	140	325	400
(kgm^2 x rpm^2 x 10^6)	0.8	1.4	2.0	6.0	14	17
4.3 Rotor Dimensions (in)						
4.3.1 Maximum diameter	16	24	39	57	70	82
4.3.2 Maximum height at maximum diameter	10	10	10	20	20	24
4.3.3 Rotor envelope	see Appendix A	see Appendix A	see Appendix A	see Appendix A	see Appendix A	see Appendix A
4.3.4 Spindle flange (Figure)	A2	A3	A3	A3	A3	A4
4.4 Unbalance Measurement (Microinch)						
4.4.1 Required e_{per} (equal to 1 A-unit)	30	30	30	50	50	50
4.4.2 Required URR	95%	95%	95%	95%	95%	95%
4.5 Drive and Balancing Speeds						
4.5.1 Drive power (hp) 4)	1	2	5.0	7.5	10	15
4.5.2 Balancing speed range (rpm)	900 2,000	750 1,500	600 1,200	600 1,100	600 1,100	400 900
4.5.3 Test speed range (rpm)	1,200 1,900	900 1,300	800 1,100	800 1,000	800 1,000	600 900
4.6 Proving rotors (see ARP4162 for details)						
4.6.1 Mass (lb)	8	25	25	80	250	250
4.6.2 Interface dia.(in)	2.0	4.5	4.5	4.5	4.5	4.5

TABLE 1 (Continued)

1) Total mass (rotor and tooling), mounted to machine spindle.

2) Approximate guideline. Minimum rotor limits are generally governed by the spindle flange dimensions and the required e_{mar}.

3) The maximum Wh^2n^2 value, specified by the machine manufacturer, should have the stated capacity as a minimum requirement.

W = Rotor + tooling mass, expressed in pounds (kilograms).
h = $h_1 + h_2$, where h_1 is the height from the spindle flange to the rotor + tooling mass center, expressed in feet (meters) and h_2 is an assumed machine constant of 0.33 ft (0.1 m).
n = Balancing speed (test speed) in rpm.

If the balancing speed is given in units of 1/min, the units of the equation are $lb\text{-}ft^2/min^2$ (kgm^2/min^2).

4) Approximate guideline. The user should specify to the supplier the horsepower requirements at specific balancing speeds.

5.2 Duties of Supplier and User[1]:

5.2.1 For these tests, the user shall provide an examiner trained in the use of balancing machines. The supplier shall instruct the examiner in the use of the machine. The examiner may either operate the machine or satisfy himself/herself that he/she could obtain the same results as the operator. The supplier shall ensure that his/her written instructions are followed by the examiner.

5.2.2 The examiner shall print or read the unbalance indication off the machine's instrumentation, log the values, and subsequently plot them. The supplier shall be entitled to check the accuracy of the examiner's work.

5.2.3 The supplier as well as the examiner shall be allowed to verify the condition of the proving rotor, the correctness of the test masses, and the location of the test masses.

5.3 Requirement for Machine Spindle Mounting Flange:

The female location pilot of the drive spindle flange shall have a radial runout not to exceed 0.0005 in F.I.R. The axial runout of the locating surface shall not exceed 0.0005 in F.I.R. (0.001 in for class 1000 flange). Each reading should be taken using five complete revolutions of the spindle and be taken with a low friction dial indicator with a resolution of 0.0001 in/division.

[1] The supplier is understood to be the balancing machine manufacturer and/or supplier, the user is understood to be the prospective or actual user of the machine.

5.4 Requirement for Proving Rotor:

The machine shall undergo the following tests with the appropriate proving rotor described in ARP4162. The correction planes on the rotor are designated:

a. Plane 1: Lower Plane
b. Plane 2: Upper Plane
c. Plane 3: Center Plane

5.5 Requirement for Weighing Scale:

A weighing scale shall be available having sufficient accuracy to verify the correctness of the test masses.

5.6 Test and Rechecks:

When a machine fails either the e_{mar} or the URR test, the manufacturer shall be permitted to adjust the machine, after which a complete retest shall be made and the machine shall then pass. If it does not, it is considered not acceptable.

5.7 Balancing Speed for Test:

The balancing speed for tests must fall within the range specified in 4.5.3.

5.8 Test for Minimum Achievable Residual Specific Unbalance (e_{mar} Test):

5.8.1 Perform the mechanical adjustment, calibration, and/or setting of the machine for planes 1 and 2 of the proving rotor, ensuring that the unbalance in the proving rotor is smaller than five A-units per plane.

NOTE: Figure D1 gives examples to convert A-units to units of unbalance.

5.8.2 Readings: Unbalance readings for successive runs are recorded on the test sheet copies, i.e., logged and subsequently plotted.

5.8.3 Add two unbalance masses (such as balancing clay) to the rotor. They shall be equivalent to 10 to 20 A-units. The unbalance masses shall not be:

a. In the same transverse plane
b. In plane 1 and/or 2
c. At the same angle
d. Displaced by 180°

Log the unbalance readings in test sheet Figure D3 under "Initial Unbalance".

5.8.4 Balance the rotor as well as possible (following the standard procedure for the machine) using four runs. Apply correction masses in planes 1 and 2. Log the readings of all four runs on test sheet Figure D3.

NOTE: If residual unbalance after four runs is more than 0.5 A-units in each plane, the machine will not pass the following tests.

5.8.5 Attach the test mass of 10 A-units sequentially to each of the positions in plane 3, using a sequence that is arbitrary. Record in Figure D4 of the e_{mar} test sheet (see Appendix D) the amount-of-unbalance readings in each plane for each position of the mass.

5.8.6 Calculate the arithmetic mean value per plane by adding the values of each reading per plane and dividing the result by 12. Log arithmetic mean value into Figure D4: "Mean Value".

Divide each reading by the "mean value" of the respective plane and log the results into Figure D4 under:"Multiples of Mean Value".

5.8.7 Plot the logged readings into Figure D5, "Residual Specific Unbalance Diagram" of the e_{mar} test sheet (see Appendix D).

5.8.8 The horizontal line (mean value) represents the arithmetic mean of the readings in each plane. Two dotted lines represent ±12% of the arithmetic mean for each plane, which account for 1 A-unit + 20% for the effects of variation in the position of the masses and scatter of the test data.

5.8.9 The machine is deemed to have passed the e_{mar} test, i.e., the claimed minimum achievable residual unbalance has been reached, if the following condition is met:

a. All but one plotted point is within the range given by the two lines representing ±12% of the arithmetic mean line.

5.9 Test for Unbalance Reduction Ratio (URR Test):

5.9.1 This test is intended to check the combined accuracy of amount-of-unbalance indication, angle indication, and plane separation.

The test consists of a set of 11 runs. The test is run with a stationary 25 A-unit test mass ($U_{stationary}$) and a travelling 125 A-unit test mass in each plane. The instrument is set to read planes 1 and 2 of the proving rotor (see ARP4162).

5.9.2 Readings: Unbalance readings for successive runs are recorded on the test sheet copies, i.e., logged and subsequently plotted.

5.9.3 Preparation of Test Sheets (Appendix E): Prepare the test logs on the test sheet prior to making the actual runs so that test data are entered in proper order.

Preparation of the test log requires the following steps:

a. Enter the requested data in log Figure E1, so that the test conditions are permanently recorded.

b. Arbitrarily choose one of the 12 mass positions in plane 1 for the stationary mass and enter the degree value in the "Plane 1 Stationary" column on the "Run No. 1" line of the log (Figure E2). Next, choose a position for the stationary mass in plane 2. This should neither be the same nor opposite the stationary test mass position in plane 1. Enter the degree value in the "Plane 2 Stationary" column on the "Run No. 1" line of the log.

c. Arbitrarily choose one of the remaining 11 positions as the starting position for the travelling test mass in plane 1 and enter the degree value in the log (Figure E2). Arbitrarily chose a starting position for the travelling test mass in plane 2. This should neither be the same nor opposite the travelling test mass in plane 1. Enter the degree value in the log.

d. Enter successive positions for successive runs in the log for both travelling masses, letting the one in plane 1 travel in ascending 30° intervals, the one in plane 2 in descending 30° intervals. Skip each stationary mass position, since both masses cannot occupy the same position.

5.9.4 Unbalance Reduction Ratio Test Runs:

a. Perform steps described in 5.8.1 through 5.8.4 unless an e_{mar} test has immediately preceded this one.

b. Add the stationary and travelling test masses in starting position (Run No. 1 line) to both test planes of the proving rotor as shown in the respective log (Figure E2).

c. Make 11 successive runs. After each run record the readings for both planes in the log, and advance the travelling test masses to the next position as shown in the log.

NOTE: Record amount and angle readings in test sheet, Figure E2.

d. Divide amount readings by the value of the stationary mass to obtain values in multiples of the stationary mass.

Enter these in the columns "Multiples of $U_{stationary}$" of the log (Reference E1).

5.9.5 Plotting the Test Data:

a. The test sheet (Figure E3) contains a diagram with 11 sets of concentric URR limit circles. From the inside outwards, the concentric circles designate the limits for URR values of 95, 90, 85, and 80%. If a test point falls within the innermost circle (or on the line), the reading qualifies for a 95% URR. If a test point falls between the 95% and the 90% circle, the reading qualifies for a 90% URR.

b. Enter the angular position of the stationary test mass in plane 1 on the short line above the arrow in the URR limit diagram. Mark radial lines in 20° intervals by entering degree markings in 20° increments (rising clockwise) on all short lines around the periphery of the diagram.

c. Since the Stationary test mass in plane 2 has a different angular position, a second angular reference system shall be entered into the diagram for plane 2. To avoid interference with the degree markings for plane 1, enter the degree markings for plane 2 in the ovals provided halfway between the degree markings for plane 1.

d. Using the amount and angle values from the log, plot the results of plane 1 (multiples of $U_{stationary}$, Figure E2), and then the results of plane 2 in the form of test points (dots) on the URR diagram, using the amount scale as shown next to the vertical arrow. In order to avoid confusing plane 1 test points with plane 2 test points, mark plane 1 points with "x", plane 2 test points with dots and circles.

5.9.6 Evaluation of Plotted Test Points: The test points on the test sheet shall lie within the URR limit circles that correspond to the value stated in 4.4.2. However, one per plane is allowed to lie outside. If these requirements are not met, the machine fails the test, in which case the rules given in 5.6 apply.

5.10 Compensator Test:

5.10.1 Specific Performance Requirements: The compensation shall provide a consistent readout of 0.5 A-units or less, per plane, at the end of the compensation procedure.

NOTE: This test checks the compensator by simulating the indexing of a rotor by only moving test masses.

5.10.2 Test Procedure:

a. Use the balanced proving rotor (after 5.8.1), or ensure that the unbalance is smaller than five A-units per plane.

Log the unbalance readings in test sheet Figure F1 under "Initial Unbalance".

5.10.2 (Continued):

b. Add a 25 A-unit test mass at 30° and a 125 A-unit test mass at 150°, both in plane 1.

c. Add a 125 A-unit test mass at 30° and a 25 A-unit test mass at 150°, both in plane 2.

d. Run the balancing machine and set the compensator for the first step, according to the manufacturer's manual.

e. Move the 125 A-unit test mass in plane 1 from the 150° position to 330°, (180° shift), move the 125 A-unit test mass in plane 2 from the 30° position to 210°, (180° shift), to simulate the indexing procedure.

f. Run the balancing machine and set the compensator for the second step according to the manufacturer's manual.

g. Remove the 125 A-unit test mass in plane 1 located at 330° and the 125 A-unit test mass in plane 2 located at 210°.

h. Run the balancing machine and set the compensator to read rotor unbalance.

5.10.3 Conformance Requirements: The compensator conforms if readings are 0.5 A-units or less per plane with the remaining test masses of:

a. 25 A-units at 30° in plane 1
b. 25 A-units at 150° in plane 2

Log the unbalance readings in test sheet under Figure F1 under "Unbalance with Compensation".

NOTE: Appendix D, Figure D1 gives examples to convert A-units to units of unbalance.

PREPARED BY SAE SUBCOMMITTEE EG-1A, BALANCING OF
COMMITTEE EG-1, AEROSPACE PROPULSION SYSTEMS SUPPORT EQUIPMENT

APPENDIX A
ROTOR ENVELOPE ABOVE SPINDLE FLANGE IN ENCLOSURE/SPINDLE FLANGE DIMENSIONS

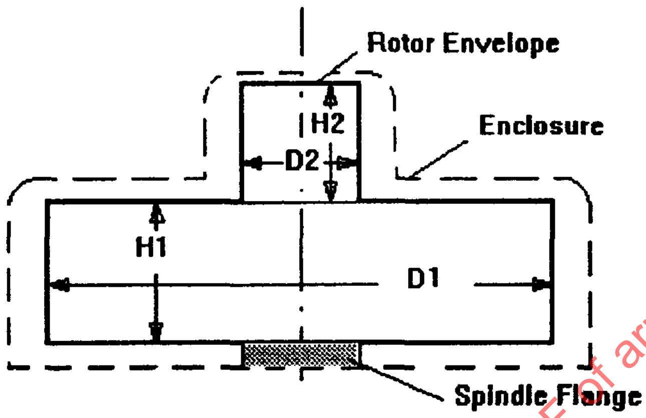


FIGURE A1 - Rotor Envelope

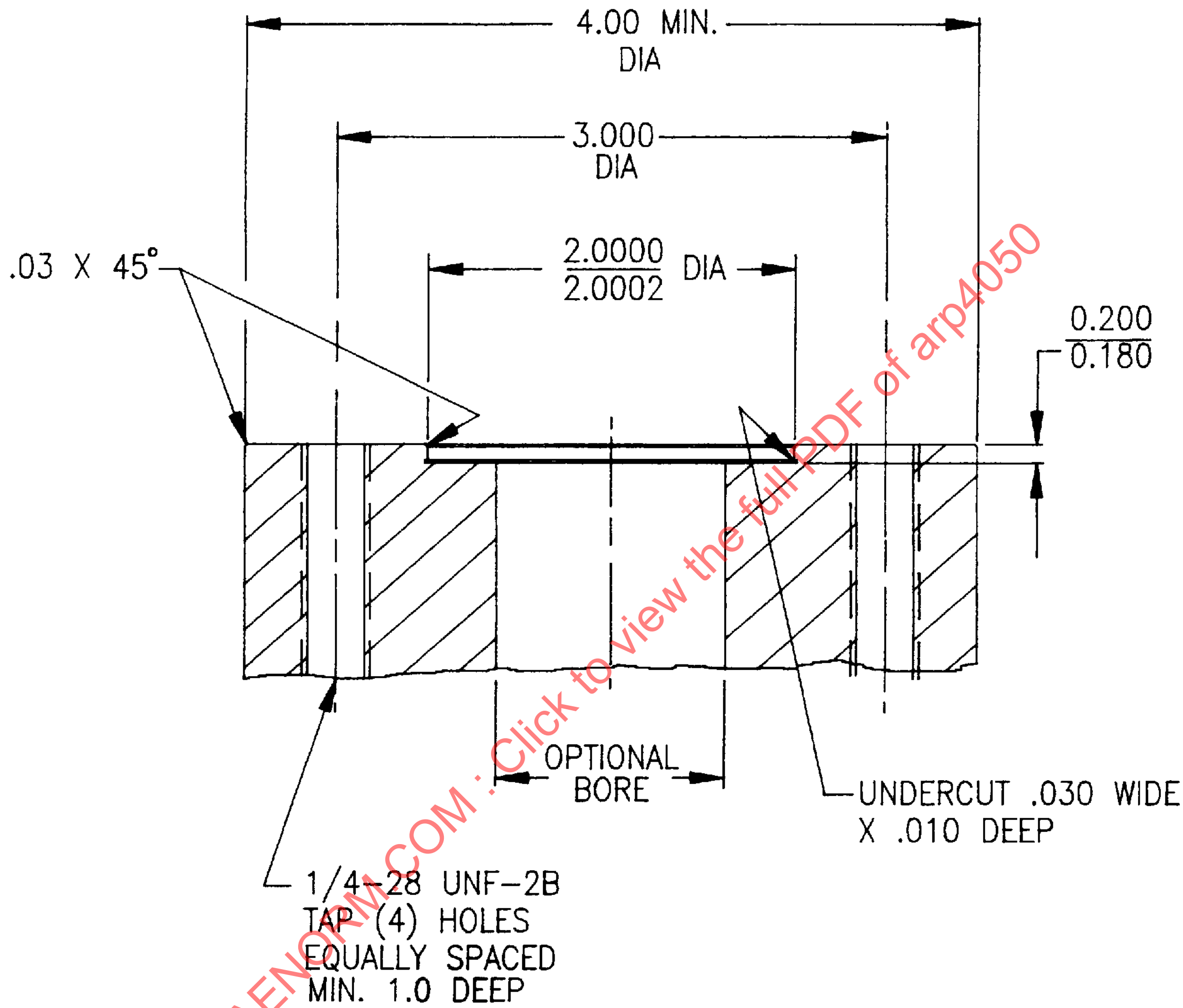
TABLE A1 - Maximum Rotor Envelope Dimensions in Enclosure

Machine Class	D1	H1	D2	H2
25	16	10	-	-
50	24	10	-	-
100	39	10	-	-
250	57	20	10	16
500	70	20	10	16
1000	82	24	10	16

NOTE 1 - Dimensions given in inches. For specific applications dimensions of the enclosure should be agreed upon between user and supplier.

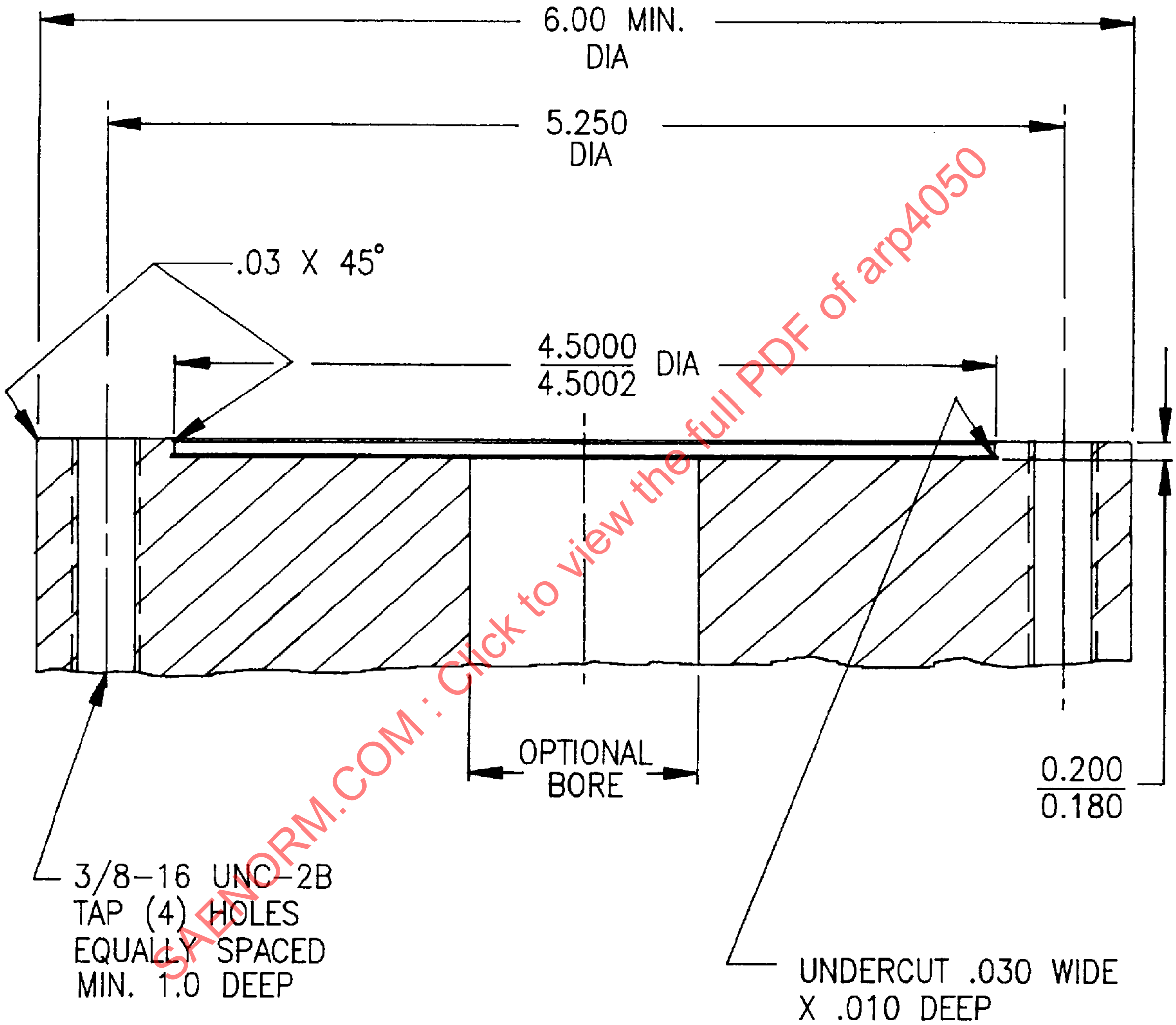
NOTE 2 - For safe operation with bladed rotors the enclosure should be interlocked with the drive and have a zero speed interlock to prevent the enclosure from being opened when the rotor is turning.

NOTE 3 - Design of enclosure is to conform to the requirements of ISO 7475 - 1984 (Balancing Machines - Enclosures and Other Safety Measures).



DIMENSIONS IN INCHES. TOLERANCE ± .005 UNLESS OTHERWISE NOTED.

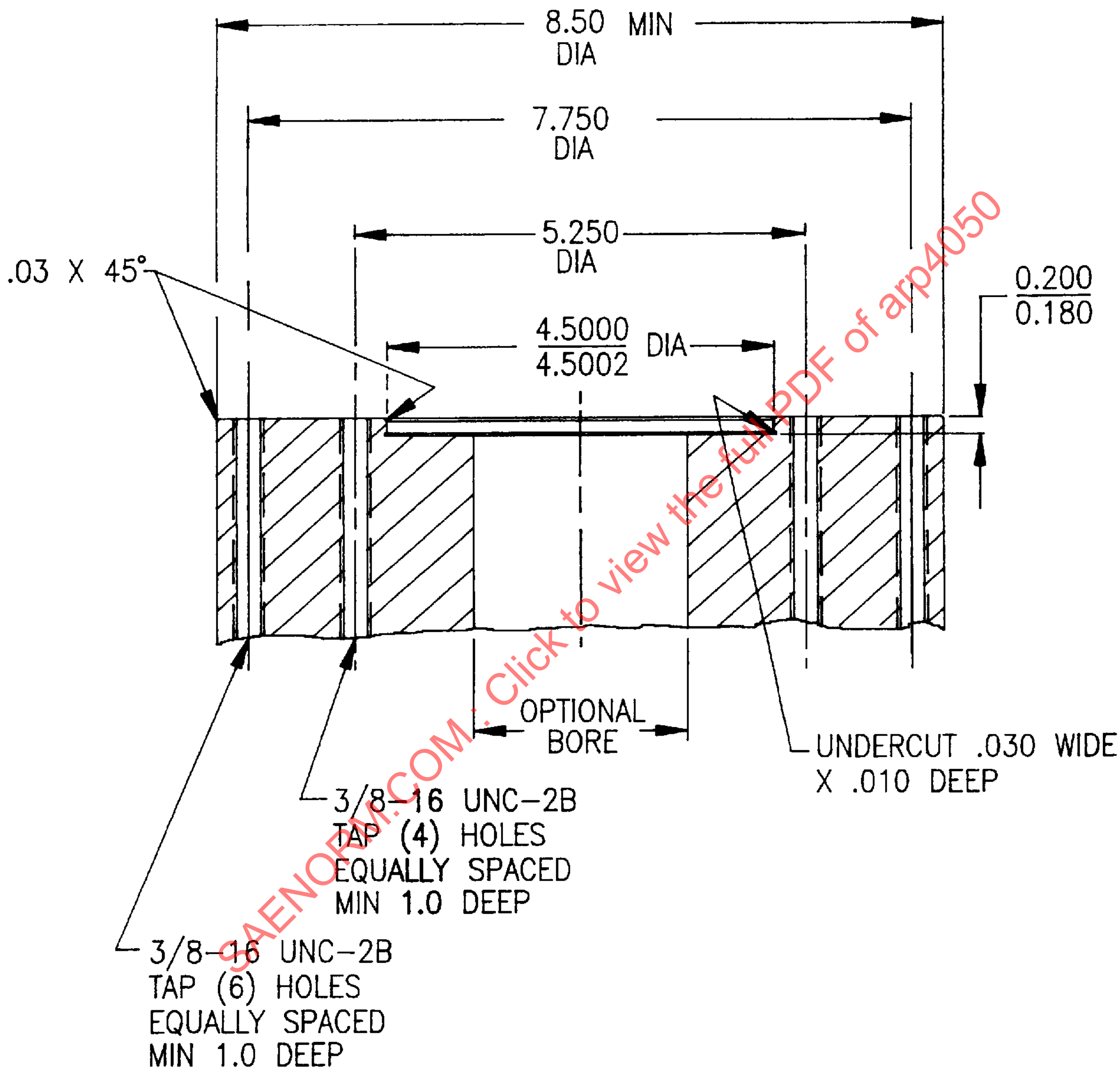
FIGURE A2 - Spindle Flange, Machine Class 25



DIMENSIONS IN INCHES.

TOLERANCE ± .005 UNLESS OTHERWISE NOTED.

FIGURE A3 - Spindle Flange, Machine Class 50, 100, 250, 500



DIMENSIONS IN INCHES.

TOLERANCE ±.005 UNLESS OTHERWISE NOTED.

FIGURE A4 - Spindle Flange, Machine Class 1000

APPENDIX B
DETAILS FOR CONTRACTURAL NEGOTIATIONS

B.1 The following paragraphs should help the buyer and the seller of balancing machines during contractual negotiations. The xx-values may be adjusted for any particular requirement. Test procedures to ensure compliance with these requirements are beyond the scope of this document.

B.1.1 The balancing machine should operate in a satisfactory manner over an ambient temperature range of xx - xxx °F, and at xx% relative humidity.

B.1.2 The machine should comply with all applicable local, state, and federal electrical, mechanical, and safety codes and standards.

B.1.3 The electrical system should operate satisfactorily with line voltage variations up to +/-xx%, line frequency variations up to +/-xx% and waveform harmonic distortion of up to xx%.

B.1.4 All electrical systems should be arranged for operation from a supply of xxx Volts +/- xx Volts, x-phase, xx cycles per second.

B.1.5 Any need for radio interference suppression should be specified.

B.1.6 Balancing machine performance is sensitive to environmental vibrations. No general requirement can be specified due to the wide range of environmental frequencies and amplitudes, and due to the varied response of different balancing systems to these excitations.

B.1.7 The prospective balancing machine user should specify the rotor envelope, if deviating from Table A1.

B.1.8 The prospective balancing machine user should specify the required horsepower at specific balancing speeds. See 4.5.1.

B.1.9 By mutual agreement, all tests should be run either at the supplier's plant before shipment and/or at the user's plant after installation. Proving rotors, test masses etc. for all tests are to be provided by the supplier or the user. See ARP4162.

B.1.10 Installation and service.

B.1.11 Operating and maintenance personnel training.

B.1.12 Operating manual, maintenance manual, circuit diagrams, spare parts ordering information.

B.1.13 Balancing machines are sensitive to foundation conditions. For optimum performance, manufacturer's instructions for foundation requirements are to be followed.

APPENDIX C
PROVING ROTORS

C.1 A full description of proving rotors and test masses to perform the described tests can be found in ARP4162.

Masses and interface diameters of related proving rotors for balancing machine classes 25 to 1000 can be found in 4.6

APPENDIX D
TEST SHEETS FOR e_{mar} TEST

D.1 For explanation of the test, i.e., logging and plotting of readout and evaluation of the results, see 5.8.

1 A - Unit	Mass of Proving Rotor	Units of Unbalance	Amount of Unbalance
(a) micro-inches	(b) lbs	ounce-inch (oz-in)	$(a) \times (b) \times 16 \times 10^{-6}$
		gram-inch (g-in)	$(a) \times (b) \times 454 \times 10^{-6}$
		gram-millimeter (g-mm)	$(a) \times (b) \times 11.5 \times 10^{-3}$

Example 1:

1 A - Unit = 30 micro-inches
Mass of Proving Rotor: W = 25 lbs
Units of Unbalance: gram-inch (g-in)

$$U = (a) \times (b) \times 454 \times 10^{-6}$$

$$U = 30 \times 25 \times 454 \times 10^{-6}$$

$$U = 0.3405 \text{ g-in}$$

Example 2:

1 A - Unit = 50 micro-inches
Mass of Proving Rotor: W = 250 lbs
Units of Unbalance: gram-millimeter (g-mm)

$$U = (a) \times (b) \times 11.5 \times 10^{-3}$$

$$U = 50 \times 250 \times 11.5 \times 10^{-3}$$

$$U = 143.75 \text{ g-mm}$$

FIGURE D1 - Conversion from A-Units to Units of Unbalance

Date of test:..Location of test:....................................

Machine operated by:...

Readings taken and logged by:...

Machine tested, make:.............................. Model:..

Proving rotor, type:....................................Nr.:............................ Mass:............lbs

..............kg

1 A Unit = ...micro-inch Test speed:...................................rpm

10 A Unit test mass...................oz Effective radius...............................in

.....................g ....mm

Effective unbalance...[1]

[1] Units of effective unbalance in oz-in, g-in, or g-mm

FIGURE D2 - Log for e_{mar} TEST

	Plane 1		Plane 2	
	Amount	Angle	Amount	Angle
Initial Unbalance				
Run 1				
Run 2				
Run 3				
Run 4				

FIGURE D3 - Balancing of Proving Rotor - Log