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EDGEWOOD ARSENAL TECHNICAL REPORT

EP-TR-76007

**THE BOTTLE PUMP-UP TEST METHOD
TESTING THE AN-M4 COMPRESSOR**

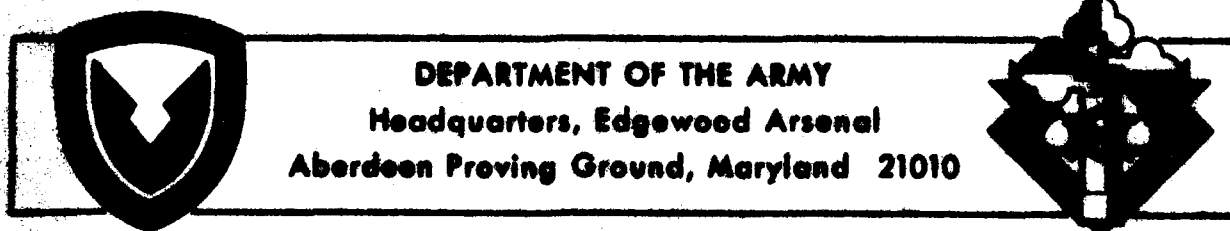
by

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Product Assurance Directorate

October 1976

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The theory of the bottle pump-up test method is developed. The performance requirements, capacity and pump-up time, for the AN-M4 compressor are evaluated. Capacity is a sufficient criterion for evaluating the AN-M4 compressor's air delivery performance.		

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PREFACE

The work described in this report was authorized under PRON No. M145110403F400, M14 Leakage Tester. This work was started in May 1974 and completed in October 1974.

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THE BOTTLE PUMP-UP TEST METHOD TESTING THE AN-M4 COMPRESSOR

1. INTRODUCTION.

A. Purpose.

The purposes of this study are:

1. To develop and present the mathematical and physical theory underlying the bottle pump-up method of determining the delivery performance of air compressors.
2. To develop computational formulas and techniques for calculating air delivery performance factors of the AN-M4 compressor, using data collected from bottle pump-up tests.
3. To investigate the compatibility of current air delivery performance factors, pump-up time and capacity, for the AN-M4 compressor.

B. Scope.

In this report, only capacity and pump-up time will be considered extensively as performance factors for the AN-M4 compressor. By presenting the complete mathematical and physical theory underlying the bottle pump-up method of measuring compressor capacity, this report provides the background necessary for the development of a realistic acceptance test plan for the AN-M4 compressor.

C. The AN-M4 Compressor.

1. Description.

The AN-M4 compressor is a compact, self-contained portable air compressor used to provide high pressure air for the M2A1-7 and M9A1-7 portable flamethrowers and the M3, M5, and M33 irritant dispersers. The compressor is a three-stage reciprocating piston type coupled to a one-cylinder, four-cycle gasoline engine, Military Standard Model 1A08-3. The unit contains an aftercooler and moisture separator assembly, including a pressure relief valve. A complete description of the compressor, including operating instructions and maintenance procedures, is contained in previous publications.¹⁻³ Requirements pertinent to this study are described below.

2. Performance Requirements.

a. Capacity.⁴

When operating at 3600 rpm, the compressor shall deliver standard air at a minimum of 3½ cfm and a minimum pressure of 2000 psig. When operating, as above, the compressor shall not require more than 2.3 brake horsepower The high pressure airflow from the aftercooler to the moisture separator shall be within 15°F of the ambient temperature. The air delivery shall be measured by using the low-pressure discharge nozzle method specified elsewhere⁵ or be the bottle pump-up method The military specification⁴ provides no formulas for actually calculating capacity from the test data collected.

b. Pump-Up Time.⁴

The compressor unit when tested within stated ambient conditions shall deliver the rated capacity in accordance with the requirements specified (see Capacity above) and also perform the following . . . :

Pressurize a 208 ± 3 cubic inch container with air from 0 to 2000 psig in a maximum period of 5.5 minutes under the following atmospheric conditions:

- (1) Temperature, 32° to 95°F.
- (2) Relative humidity, no less than 40%.
- (3) Barometric pressure, 14.7 ± 0.2 psi (29.93 ± 0.41 inches of mercury).

c. Power.

This study is not concerned with the power requirements of the AN-M4 compressor. The specifications though stating a power requirement (see Capacity above) make no provision for collecting the data necessary to compute the power required to compress the air delivered.

D. Measuring Compressor Performance.

An extensive literature search indicates that two test methods, the nozzle test method and the bottle pump-up test method, are used to determine the air delivery performance of compressors. Performance is almost universally measured in terms of capacity, the actual amount of air delivered and compressed by the compressor. Other performance factors such as volumetric efficiency are used for specific purposes. Extensive discussions of compressor performance factors may be found in other publications.⁵⁻⁷ Volumetric efficiency is a measure of compressor efficiency. It should not be generally used as a comparative performance factor except for compressors of the same capacity class. In most instances of compressor performance, the primary interest is air delivery and power requirement per unit of air delivered (reference 7, pages 4-8). Volumetric efficiency, if desired, can be computed from the capacity determinations. Pump-up time is used as a comparative performance factor when speed is of essence in pressurizing a container. However, pump-up time for any container may be computed from the capacity rating of the compressor once it has been determined.

1. The American Society of Mechanical Engineers Power Test Code and the Nozzle Test Method.

Standard criteria and procedures adopted by the American Society of Mechanical Engineers for testing compressors are given in a previous publication.⁵ In particular this reference provides extensive procedural details, formulas, and test-condition requirements for testing compressors by the nozzle test method. The performance rating of compressors is based on tests conducted at ambient conditions. Because these conditions vary widely, performance is guaranteed within a given tolerance, usually 3%.⁷

The nozzle test method for measuring compressor capacity is based upon the known discharge rate, size, and measured pressure differential across a standard nozzle. The nozzle selected

for a test depends upon the capacity of the compressor to be tested. This method is extremely accurate and provides not only for the determination of compressor capacity but also for the determination of compressor power requirements. The elaborate test procedures, test conditions, and need for well-trained technical personnel to conduct the test may discourage its use as a routine acceptance test. This method may be used to test displacement compressors such as the AN-M4 compressor, vacuum pumps, and blowers.

2. The Bottle Pump-Up Test Method.

In the bottle pump-up method of determining compressor capacity, the air delivered by the compressor is discharged into a closed tank or bottle of known volume. The time required to achieve a given pressure, the inlet temperature and pressure, and the final tank temperature are measured. From these data, the volume of ambient air delivered by the compressor may be computed and expressed in volume per unit time, such as cubic feet per minute. Because of the difficulty of measuring the true temperature and volume of the tank and piping and the true volume of water vapor condensate, this method yields only approximate results. It should not be used where extreme accuracy is required.

The bottle pump-up test method is ideal for routine acceptance testing if high accuracy is not required. Its advantages are: (1) It is a relatively simple test setup, (2) highly trained personnel are not required to conduct the tests, (3) tests may be conducted under a wide range of test conditions of temperature, pressure, and relative humidity.

The military specification⁴ for the AN-M4 compressor contains detailed test procedures for conducting the bottle pump-up test under a wide range of test conditions. However, it does not provide the necessary formulas for computing the performance factors, capacity and pump-up time, under standard test conditions: i.e., corrected for standard temperature, pressure, relative humidity, and speed. The contractors^{8,9} for the AN-M4 compressor used different formulas to calculate corrected pump-up times. These formulas yield different results for identical test conditions. As stated earlier, one of the purposes of this report is to derive appropriate formulas for the calculation of performance factors from test data collected under ambient test conditions.

II. CONCLUSIONS AND RECOMMENDATIONS.

A. Conclusions.

The joint use of capacity and pump-up time as performance factors for the AN-M4 compressor may lead to inconsistent evaluation of compressor performance when the compressor is tested under a wide range of test conditions.

The capacity and pump-up time specifications for the AN-M4 compressor are compatible in the sense that, if the compressor performs at its rated capacity under standard test conditions, it will also meet its pump-up time requirements within the specified range of operating conditions. However, "within-tolerance" pump-up times obtained under a wide range of test conditions cannot be used to imply that the compressor will perform at its rated capacity.

Correcting pump-up time and capacity for relative humidity rather than the amount of condensate collected provides a better estimate of these performance factors.

The bottle pump-up test method yields only approximate values for capacity and pump-up time. However, the values are adequate for evaluating the performance of the AN-M4 compressor.

B. Recommendations.

If a more definitive measure of the AN-M4 compressor air delivery performance is desired, the following recommendations are suggested:

1. Air delivery performance should be measured by capacity, corrected to standard or specified conditions.
2. Capacity should be computed using the relative humidity method developed in this report.
3. If pump-up time is desired, it should be computed using the relative humidity method.

III. DEFINITIONS AND NOTATION.

A. Definitions.

Actual capacity -- quantity of air actually delivered and compressed per unit time by the compressor.

Adiabatic compression -- compression with no heat transferred to or from the air being compressed.

Clearance -- clearance volume divided by the displacement of the cylinder.

Clearance volume -- volume remaining in the cylinder at the extreme position of the piston at the end of the compression stroke.

Compression ratio -- ratio of absolute discharge pressure to absolute inlet pressure.

Displacement -- volume displaced by the piston including clearance volume. For multistage compressors, displacement refers to the first stage cylinder only.

Free air -- air at ambient conditions.

Isothermal compression -- compression at constant temperature; discharge temperature = intake temperature.

Standard air -- air at 68°F, 36% relative humidity, and 14.7 psia.

Standard conditions -- atmospheric conditions of 68°F, 14.7 psia barometric pressure, and 36% relative humidity.

Volumetric efficiency -- ratio of actual capacity to displacement.

B. Notation.

1. Symbols.

- A -- actual capacity
- B -- barometric pressure
- C -- volume of condensate
- c -- conversion factor, cc/hr or ml/hr to cu ft/sec
- D -- compressor displacement
- d -- average density of water for temperature range of 32° to 131°F,
d = 62.1145 lb/cu ft
- E -- volumetric efficiency
- F -- volume of free air delivered
- G -- universal gas constant. $G = 1545.324458 \text{ ft-lb (lb-moles)}^{-1}(\text{deg R})^{-1}$
- H -- relative humidity
- M -- molecular weight
- n -- number of moles
- P -- absolute pressure
- P' -- vapor pressure
- P'' -- partial pressure
- R -- characteristic gas constant. $R = G/M$
- R' -- characteristic gas constant, air. $R' = 53.353117 \text{ ft/deg R}$
- R'' -- characteristic gas constant, water. $R'' = 85.778257 \text{ ft/deg R}$
- r -- moisture condensation rate
- S -- compressor speed
- T -- absolute temperature
- t -- pump-up time
- V -- volume
- v -- volume of measuring tank or bottle. $v = 0.12037 \text{ cu ft}$
- W -- weight

2. Subscripts.

- 0 -- standard conditions
- 1 -- ambient or initial conditions
- 2 -- discharge, bottle or final conditions

3. Abbreviations.

cc	cubic centimeters
cf	cubic feet
cfm	cubic feet per minute
ml	milliliter
psia	pounds per square inch absolute
psig	pounds per square inch gage
rpm	revolutions per minute

IV. THE THEORETICAL BASIS OF THE BOTTLE PUMP-UP TEST METHOD.

Capacity.

All computations of compressor capacity, regardless of the method used to measure it, are based upon some form of the equation of state for an ideal gas. Air in particular may be considered an ideal gas for most practical applications and the equations may be used without modifications.

Various forms of the equation of state for an ideal gas are:

$$PV = nGT \quad (1)$$

$$PV = WRT \quad (2)$$

$$R = \frac{G}{M}$$

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2} \quad (3)$$

For an ideal gas undergoing adiabatic change, the law becomes

$$P_1 V_1^k = P_2 V_2^k \quad (4)$$

where k is a constant characteristic of the gas undergoing change.

In the bottle pump-up method, a tank of known volume v is pressurized to a pressure P_2 and the pump-up time t is used to compute the capacity of the compressor. The volume V_1 of air required to pressurize the tank to a given pressure P_2 may be calculated using equation 3.

$$V_1 = \frac{T_1 P_2 V_2}{P_1 T_2}$$

The tank contains a volume v of ambient air, hence the volume F'' of air delivered to the tank by the compressor is

$$F'' = V_1 - v = \frac{T_1 P_2 V_2}{P_1 T_2} - v$$

$$F'' = \frac{v(P_2 T_1 - P_1 T_2)}{P_1 T_2} \quad (5)$$

since $V_2 = v$.

1. Correction for Moisture Content.

The volume of air F_1'' actually delivered to the tank is dry air. Because of the high pressure (2000 psig) and relatively small temperature change during compression, all vapor is condensed from the air delivered by the compressor. The moisture content of the original air in the tank at the start of pump-up is negligible due to the small volume of the tank, 0.1204 cu ft. A typical volume of the condensate in the tank due to the original vapor is approximately 0.00037 cu ft. The total volume F_1 of free air handled by the compressor is F'' plus the equivalent volume C of the condensate. The correction for moisture content, C , may be calculated by either the condensate method or the relative humidity method (below). However, in sample calculations, the relative humidity method yields corrections nearly twice as large as those calculated using the condensate method. This is possibly due to the loss of condensate during compression due to leakage, condensation in piping, evaporation, etc.

a. Condensate Method.

This method is the simplest to use and does not require the availability of a table of vapor pressures for water vapor. The correction for condensation is:

$$C = \frac{drtR''T_1}{P_1} \quad (6)$$

and the volume F_1 of free air handled by the compressor under ambient conditions is

$$F_1 = F_1'' + C_1$$

$$F_1 = \frac{v(P_2 T_1 - P_1 T_2)}{P_1 T_2} + \frac{drtR''T_1}{P_1} \quad (7)$$

where

- d = average density of water
- r = rate of condensation

By definition, the compressor capacity A is the total volume delivered per unit time. The capacity A_1 under ambient condition corrected for vapor condensation is

$$A_1 = \frac{v(P_2 T_1 - P_1 T_2)}{t P_1 T_2} + \frac{dr R'' T_1}{P_1} \quad (8)$$

b. Relative Humidity Method.

The theory of this method is given in appendix B. The total volume F_1 of free air handled by the compressor corrected for relative humidity H_1 is

$$F_1 = \frac{P_2 V_2 T_1}{T_2 (B_1 - H_1 P_1')} \quad (9)$$

Note that equation 9 requires the use of a table of vapor pressures, P_1' , for water vapor. However, this method provides a more realistic correction than the condensate method because, at high relative humidities, 80% and above, the capacity loss is significant. A compressor tested at high relative humidity may have a computed capacity significantly different from its true capacity if correction is made using the condensate method.

2. Conversion to Standard Conditions.

In general, compressors will be tested under conditions varying from those for which performance standards have been set. Equations are needed for calculating performances at standard or specified conditions using data accumulated from tests conducted at ambient conditions.

Standard or specified test conditions refer to conditions of pressure, temperature, relative humidity, and compressor speed. For the AN-M4 compressor, the specified conditions are⁴

- a. Intake pressure 14.7 ± 0.2 psia (29.93 ± 0.41 inches of mercury).
- b. Intake temperature 32° to 95° F.
- c. Relative humidity not less than 40%.
- d. Compressor speed 3600 rpm.

Under these conditions, the compressor must pressurize a 208 ± 3 cu in. tank to a pressure of 2000 psig within 330 seconds, pump-up time t . At the same time, the compressor must deliver standard air at the rate of 3.25 cfm. It is shown in section V. A, that the requirement for both a pump-up time specification and a capacity specification are confusing and redundant. It is possible to meet the pump-up time specification without meeting the capacity specification. However, if the compressor meets the capacity specification it also meets the pump-up time specification. The pump-up time t_0 corrected for standard conditions of temperature, pressure, relative humidity, and speed may be found by using the equation

$$t_0 = \frac{0.01006(B_1 - H_1 P_1') S_1 t_1}{T_1} \quad (10)$$

B_1 and P_1' are in psia

If the condensate method is used to correct for vapor loss, we use

$$t_0 = \frac{0.00998 B_1 S_1 t_1}{T_1} \quad (11)$$

B_1 is in psia.

To compute the capacity under standard conditions, use

$$A_0 = \frac{(2000 + B_1) 26006.4 T_1}{(B_1 - H_1 P_1') T_2 S_1 t_1} \text{ cfm} \quad (12)$$

t_1 is in seconds

B_1 is in psia

P_1' is in psia

S_1 is in rpm

If the condensate method is used to correct for vapor loss, then

$$A = \frac{v T_1 S_0 (P_2 T_0 - B_0 T_2)}{T_0 T_2 B_1 S_1 t_1} + \frac{dr R'' T_0}{B_0} \quad (13)$$

Substituting the known values for the initial conditions, we obtain

$$A = \frac{26006.4T_1(2000 + B_1 - 0.02784T_2)}{T_2B_1S_1t_1} + 7.8222 \times 10^{-4}R \quad (14)$$

where

B_1 is in psia

S_1 is in rpm

t_1 is in seconds

A is in cfm

R is in ml/hr or cc/hr

V. APPLICATION TO THE AN-M4 COMPRESSOR.

Capacity and Pump-Up Time as Specifications of Performance.

The specified or rated capacity A'_0 of the AN-M4 compressor is 3.25 cfm of standard air delivered at 2000 psig. The specified pump-up time t'_0 is 330 seconds under the conditions:

1. Temperature range -- 32° to 95°F.
2. Relative humidity -- not less than 40%.
3. Barometric pressure -- 14.7 ± 0.2 psia (29.93 ± 0.41 inches of mercury).

We wish to determine the compatibility of these specifications with respect to each other.

By definition

$$t'_0 = \frac{F_0}{A'_0} = \frac{P_2V_2T_0}{T_2B_0A'_0}$$

$$t'_0 = \frac{990.0811T_0}{A'_0T_2} \quad \text{sec} \quad (15)$$

A'_0 is in cfm.

If $A'_0 = 3.25$ cfm, t'_0 assumes its maximum value when $T_0 = T_2$, that is if compression is isothermal. For this case, $t'_0 = 305$ seconds; thus, a pump-up time specification of 330 seconds for practical situations is consistent with the capacity and temperature specifications.

Equation 15 illustrates the fact that if the compressor meets or exceeds its capacity specification then it meets or exceeds its pump-up time specification. If it does not meet its capacity specification, however, it may still meet its pump-up time specification if T_2 is large enough. Although the specification (reference 4, para. 3.7.2) states that both pump-up time and capacity requirements must be met by the compressor unit, test reports of acceptance tests by the manufacturers^{8,9} do not compute capacity for the units. Apparently it is assumed that if pump-up time is within tolerance then capacity is also. Table A-1, appendix A, presents actual test data⁸ illustrating the pump-up time-capacity relationships.

Computation of capacity sufficiently describes the air delivery performance of the compressor since if the capacity specification is met the pump-up time must be less than the desired 330 seconds. It is not necessary to calculate the corrected pump-up time: Equation B6 in appendix B yields the capacity corrected for pump-up time and specified test conditions of pressure, temperature, relative humidity, and compressor speed.

VI. DERIVATIONS OF EQUATIONS.

A. Moisture Correction.

During the compression cycle of the AN-M4 compressor, condensed water vapor is removed from the compressed air prior to discharge into the receiving tank and collected in the water separator of the compressor. The amount of water removed is periodically recorded during testing. Due to the high compression ratio and cooling of the air before discharge, all moisture is removed and the compressed air discharged into the tank is dry air.

At high relative humidities, the volume loss due to moisture condensation may significantly reduce the computed capacity of the compressor if no correction is made for this loss. This is due to the fact that, in the bottle pump-up method, capacity calculations are based upon the volume and pressure of air in the tank after compression. Without correction for vapor loss, this volume does not represent the total volume of free air handled by the compressor.

1. Condensate Method.

The volume C of vapor handled by the compressor is

$$C = \frac{WR''T}{B} \quad (16)$$

where W is the weight of the condensate. The water vapor condensation rate is measured in cubic centimeters per hour or milliliters per hour, hence

$$W = dcr t$$

and it follows that

$$C_1 = \frac{dcr t_1 R'' T_1}{B_1} \quad (17)$$

The volume V_1 of dry air required to pressurize the tank is

$$V_1 = \frac{P_2 V_2 T_1}{B_1 T_2}$$

Hence the total volume F_1 of free air handled by the compressor during pump-up time t_1 is

$$F_1 = \frac{P_2 V_2 T_1}{B_1 T_2} + \frac{dcr t_1 R'' T_1}{B_1}$$

$$F_1 = \frac{T_1}{B_1 T_2} (P_2 V_2 + dcr t_1 R'' T_2) \quad (18)$$

$$F_1 = \frac{T_1}{B_1 T_2} (240.8 + 0.1204 B_1 + 3.6296 \times 10^{-7} r t_1 T_2) \quad (19)$$

B_1 is in psia

r is in cc/hr

t_1 is in seconds

or

$$F_1 = \frac{T_1}{B_1 T_2} (240.8 + 0.1204 B_1 + 3.6297 \times 10^{-7} r t_1 T_2) \quad (20)$$

B_1 is in psia

r is in ml/hr

t_1 is in seconds

Example.

$$T_1 = 97^\circ\text{F} = 557^\circ\text{R}$$

$$B_1 = 29.4 \text{ in. of Hg}$$

$$H_g = \text{Mercury}$$

$$T_2 = 100^\circ\text{F} = 560^\circ\text{R}$$

$$r = 56 \text{ cc/hr}$$

$$t_1 = 329 \text{ seconds}$$

$$P_1' = 0.8689 \text{ psia}$$

$$S_1 = 3477.5 \text{ rpm}$$

using equation 18

$$F_1 = \frac{557}{29.4 \times 0.4912 \times 560} \left(240.8 + 0.1204 \times 29.4 \times 0.4912 + 3.6296 \times 10^{-7} \times 329 \times 560 \right)$$

$$F_1 = 16.96 \text{ cf}$$

If no correction is made,

$$F_1 = \frac{(2000 + 29.4 \times 0.4912) 0.1204 \times 557}{560 \times 29.4 \times 0.4912}$$

$$F_1 = 16.70 \text{ cf}$$

a difference of 0.26 cf.

2. Relative Humidity Method.

The volume V_1 of dry air required to pressurize the tank is

$$V_1 = \frac{P_2 V_2 T_1}{T_2 B_1}$$

Let F_1 be the total volume of free air required to pressurize the tank. The partial pressure of the water vapor in the free air is

$$H_1 P_1' = P_1''$$

$$P_1'' F_1 = B_1 V_1'$$

$$V_1' = \frac{P_1'' F_1}{B_1}$$

V_1' is the volume occupied by the vapor at barometric pressure B_1 . The volume of free air required to pressurize the tank is

$$F_1 = V_1 + V_1'$$

$$= \frac{P_2 V_2 T_1}{B_1 T_2} + \frac{P_1' F_1}{B_1}$$

$$F_1 = \frac{P_2 V_2 T_1}{T_2 (B_1 - H_1 P_1')} \quad (21)$$

and since $P_2 = 2000 + B_1$, $V_2 = 0.1204$ cf

$$F_1 = \frac{(2000 + B_1) 0.1204 T_1}{T_2 (B_1 - H_1 P_1')} \quad (22)$$

B_1 , P_1' are in psia.

Example. Using the data given in the example above,

$$F_1 = \frac{(2000 + 29.4 \times 0.4912) 0.1204 \times 557}{560(29.4 \times 0.4912 - 0.51 \times 0.8689)}$$

$$F_1 = 17.23 \text{ cf}$$

B. Pump-Up Time.

Pump-up time t is directly proportional to the volume F of air compressed and the speed S of the compressor.

$$t = \frac{kF}{S}$$

Pump-up times are measured under ambient conditions. A formula is needed for conversion to standard or specified conditions. Set

$$t_0 = \frac{kF_0}{S_0}$$

$$t_1 = \frac{kF_1}{S_1}$$

Then

$$\begin{aligned}
 t_0 &= \frac{F_0 S_1 T_1}{F_1 S_0} \\
 &= \frac{P_2 V_2 T_0}{T_2 B_0} \times \frac{T_2 B_1}{P_2 V_2 T_1} \times \frac{S_1}{S_0} t_1 \\
 t_0 &= \frac{T_0 B_1 S_1}{T_1 B_0 S_0} t_1
 \end{aligned} \tag{23}$$

If the corrections for relative humidity are applied to equation 23,

$$t_0 = \frac{T_0 (B_1 - H_1 P'_1) S_1 t_1}{T_1 (B_0 - H_0 P'_0) S_0} \tag{24}$$

Since $T_0 = 528$, $B_0 = 14.7$, $H_0 = 0.36$, $P'_0 = 0.3394$, and $S_0 = 3600$ rpm,

$$t_0 = \frac{0.01006 (B_1 - H_1 P'_1) S_1 t_1}{T_1} \tag{25}$$

B_1 is in psia

P'_1 is in psia

S_1 is in rpm

Example. Using the data given in the first example

$$t_0 = \frac{0.01006 (29.4 \times 0.4912 - 0.51 \times 0.8689) 3477.5 \times 329}{557}$$

$$t_0 = 298.3 \text{ seconds}$$

If t is calculated using equation 23, e. g., no correction made for relative humidity:

$$t_0 = \frac{528 \times 29.4 \times 0.4912 \times 3477.5 \times 329}{577 \times 14.7 \times 3600}$$

$$t_0 = 296 \text{ seconds}$$

a difference of 2.3 seconds.

C. Capacity Under Standard Conditions Corrected for Speed

By definition, capacity A_0 under standard conditions is

$$A_0 = \frac{F_0}{t_0}$$
$$A_0 = \frac{P_2 V_2 T_1 S_0}{T_2 (B_1 - H_1 P_1') S_1 t_1} \quad (26)$$

and since $P_2 = 2000$ psig, $V_2 = 0.1204$ cf, $S_0 = 3600$ rpm

$$A_0 = \frac{(2000 + B_1) 26006.4 T_1}{T_2 (B_1 - H_1 P_1') S_1 t_1} \text{ cfm} \quad (27)$$

t_1 is in seconds

B_1 is in psia

P_1' is in psia

Example. Using data in the first example:

$$A_0 = \frac{(2000 + 29.4 \times 0.4912) 26006.4 \times 557}{560(29.4 \times 0.4912 - 0.51 \times 0.8689) 3477.5 \times 329}$$

$$A_0 = 3.25 \text{ cfm}$$

If no correction is made for relative humidity, we use B_1 in equation 27 rather than $B_1 - H_1 P_1'$. Then

$$A_0 = 3.15 \text{ cfm}$$

Here the correction for relative humidity is significant; without the correction, the compressor does not meet its rated capacity specification of 3.25 cfm.

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APPENDIX A

TABLE

Table A-1 Pump-Up Time and Capacity for ANM4 Compressor
Under Various Test Conditions*

Intake temperature	Bottle temperature	Intake pressure	Relative humidity	Vapor pressure	Compressor speed	Condensation rate	Pump up time**		Capacity corrected	
							Observed	Corrected	Relative humidity method	Condensation method
°F	°F	in. of Hg		psia	rpm	ml/hr	sec		cfm	
75	102	30.17	0.90	0.4298	3300	41.8	296	265	3.54	3.42
75	100	30.18	0.82	0.4298	3400	53.1	272	253	3.74	3.66
84	95	30.05	0.65	0.5781	3400	39.24	304	273	3.43	3.37
75	90	29.99	0.85	0.4298	3500	52.6	331	313	3.06	3.00
70	79	30.03	0.66	0.3631	3575	25.9	318	313	3.17	3.07
70	79	30.03	0.66	0.3631	3575	38.9	324	319	3.07	3.02
81	95	29.90	0.49	0.5247	3575	29.5	318	305	3.11	3.06
81	96	29.90	0.49	0.5247	3575	36.9	330	317	2.99	2.95
83	105	30.06	0.52	0.5603	3575	28.1	324	311	3.00	2.94
83	99	30.06	0.52	0.5603	3575	35.0	324	311	3.04	2.98
79	94	30.07	0.54	0.4915	3500	32.4	337	319	2.98	2.93
79	94	30.07	0.54	0.4915	3450	40.5	335	313	2.94	3.00
85	107	29.93	0.73	0.5959	3575	56.3	396	373	2.49	2.44
85	104	29.93	0.73	0.5959	3575	42.4	324	305	3.06	2.98
84	98	29.71	0.73	0.5781	3575	41.8	330	309	3.06	2.98
84	102	29.69	0.73	0.5781	3575	53.7	315	295	3.18	3.11
89	114	30.01	0.56	0.6777	3500	49.0	330	304	3.02	2.96
78	100	30.02	0.77	0.4761	3500	53.5	324	305	3.09	3.03
77	95	30.01	0.77	0.4606	3500	53.5	318	300	3.17	3.11
76	100	30.02	0.79	0.4452	3500	53.5	320	303	3.11	3.05
76	95	30.03	0.82	0.4452	3500	53.5	318	301	3.16	3.10
83	101	29.91	0.76	0.5603	3575	42.4	392	323	2.91	2.83
80	95	29.91	0.79	0.5069	3575	42.4	326	310	3.06	2.99
80	94	29.89	0.80	0.5069	3575	42.4	325	309	3.08	3.00
79	93	29.89	0.82	0.4915	3575	42.4	321	306	3.12	3.04
78	91	29.90	0.84	0.4761	3575	42.1	324	309	3.09	3.02

* These data were taken from reference 8.

** Pump-up time is corrected by the relative humidity method.

APPENDIX B

BASIC EQUATIONS FOR THE BOTTLE PUMP-UP TEST METHOD

The equations below use the relative humidity method to correct for moisture content. B and P are in psia, T is in degrees R, and t is in seconds.

1. Volume of Free Air Delivered.

$$F = \frac{P_2 V_2 T_1}{T_2 (B_1 - H_1 P'_1)} \quad (B1)$$

To obtain the volume of standard air delivered replace the subscript 1 by 0.

Applied to AN-M4 compressor

Volume of free air delivered:

$$T_1 = \frac{(2000 + B_1) 0.1204 T_1}{T_2 (B_1 - H_1 P'_1)} \text{ ft}^3 \quad (B2)$$

Volume of standard air delivered:

$$F_0 = \frac{(2000 + B_1) 4.3608}{T_2} \text{ ft}^3 \quad (B3)$$

2. Capacity.

$$A_0 = \frac{P_2 V_2 T_1}{T_2 (B_1 - H_1 P'_1) t_1} \quad (B4)$$

$$A_0 = \frac{P_2 V_2 T_1 S_0}{T_2 (B_1 - H_1 P'_1) S_1 t_1} \quad (B5)$$

Applied to AN-M4 compressor

$$A_0 = \frac{(2000 + B_1) 26006.4 T_1}{T_2 (B_1 - H_1 P'_1) S_1 t_1} \text{ cfm} \quad (B6)$$

3. Pump-Up Time.

$$t_1 = \frac{P_2 V_2 T_1}{A_1 (B_1 - H_1 P_1') T_2} = \frac{F_1}{A_1} \quad (\text{B7})$$

$$t_0 = \frac{T_0 (B_1 - H_1 P_1') S_1 t_1}{T_1 (B_0 - H_0 P_0') S_0} \quad (\text{B8})$$

Applied to AN-M4 compressor

$$t_0 = \frac{0.01006 (B_1 - H_1 P_1') S_1 t_1}{T_1} \text{ sec} \quad (\text{B9})$$

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