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EVALUATION OF LOCOMOTIVE CAB AIR FLOW METERS FOR TRAIN AIR BRAKE LEAKAGE MONITORING

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16. Abstract

Railroad freight train brake systems must be qualified for safe operation by meeting three brake pipe test criteria: (1) a minimum pressure of 60 psig at the rear of the train, (2) a maximum pressure gradient of 15 psi over the length of the train, and (3) a maximum leakage of 5 psi per minute after applying the brakes. With the advent of the pressure maintaining feature on brake control valves (26L equipment or equivalent), the brake pipe leakage limit became a less critical measure of the controllability of the train brake system. By the addition of an air flow meter or indicator to the locomotive control stand instrumentation, an alternative brake system leakage test, the air flow method (AFM), was possible. This method provides advantages in qualifying train brakes for operation in extreme cold weather, as well as a means for over-the-road monitoring of brake system leakage.

This report includes an extensive review of the technical literature and past experience with the AFM. An engineering analysis of air flow meters was conducted in the context of the AFM. This analysis covers the accuracy and reliability of the meters, the required AFM calibration procedures, and the accuracy of the calibration devices themselves.

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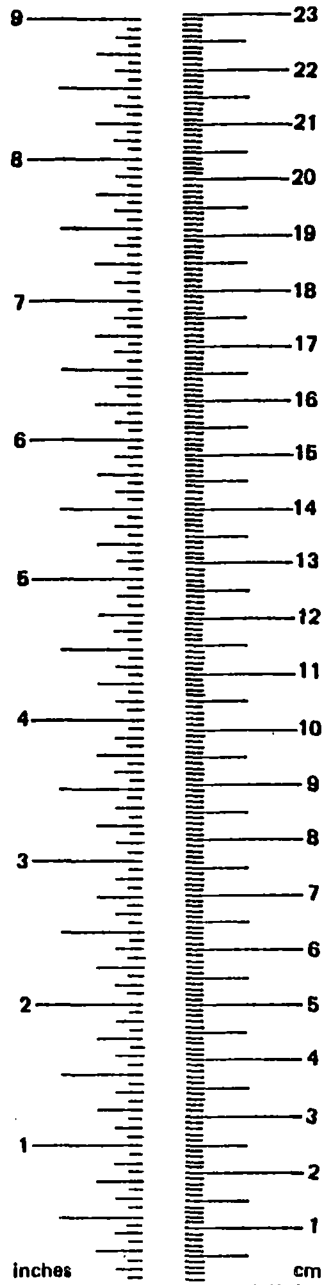
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in. = 2.54 cm (exactly). For other exact conversions and more detail tables see NBS Misc. Publ. 286. Units of Weight and Measures. Price $2.25 SD Catalog No. C13 10 286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	36	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

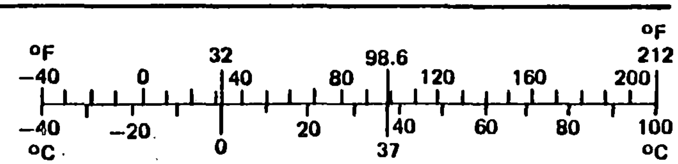


TABLE OF CONTENTS

LIST OF FIGURES

TABLE OF CONTENTS
(Continued)

LIST OF TABLES

EXECUTIVE SUMMARY

Railroad freight train brake systems must be qualified for safe operation by meeting three brake pipe test criteria: (1) a minimum pressure of 60 psig at the rear of the train, (2) a maximum pressure gradient of 15 psi over the length of the train, and (3) a maximum leakage of 5 psi per minute after applying the brakes. With the advent of the pressure maintaining feature on brake control valves (26L equipment or equivalent), the brake pipe leakage limit became a less critical measure of the controllability of the train brake system. By the addition of an air flow meter or indicator to the locomotive control stand instrumentation, an alternate brake system leakage test, the Air Flow Method (AFM), was possible. This method provides advantages in qualifying train brakes for operation in extreme cold weather, as well as a means for over-the-road monitoring of brake system leakage.

Based on the results of laboratory tests of full-scale train brake systems in the early 1970s, the Canadian railways initiated field tests of the AFM in 1974. Since December 1978, the AFM has been used system-wide on the Canadian railways. The method was officially sanctioned by the Canadian Transport Commission on April 30, 1984, as a substitute for the brake pipe leakage rate test when the controlling unit of the locomotive has a pressure-maintaining brake control valve. Over the past several years, certain railroads in the United States have gained experience with the AFM under waiver from the FRA. The extensive experience by both the Canadian and U.S. railroads has uncovered no train safety-related problems with the AFM. The use of the AFM has allowed the operation of longer trains (estimated from 10 to 15 additional cars) in cold weather, and the use of air flow indicators in over-the-road operations has allowed continuous monitoring of train brake system condition. This use has received favorable commentary from the train crews.

This report includes an extensive review of the technical literature and past experience with the AFM. An engineering analysis of

air flow meters was conducted in the context of the AFM. This analysis covers the accuracy and reliability of the meters, the required AFM calibration procedures, and the accuracy of the calibration devices themselves.

The currently-used air flow meters are differential pressure gauges that measure the pressure drop across a 19/64-inch metering orifice. The flow measurement is therefore nonlinear, varying as the square-root of the pressure drop. This results in large changes in air flow per gauge face division at the low end of the scale, and relatively small changes in flow per division at the high end of the scale. The air flow meters are calibrated at 60 standard cubic feet per minute (scfm), which has been established by the industry as a safe leakage flow limit. This calibration point is set mid-range on the meter to minimize the effects of the nonlinear behavior.

With the use of a differential pressure gauge to measure air flow, the air flow indicator reading accuracy is dependent (in addition to the basic gauge accuracy) on three factors: (1) main reservoir air pressure, (2) main reservoir air temperature, and (3) atmospheric (barometric) pressure due to altitude. The compressor is set to cycle main reservoir pressure over a 10-psi range, which produces a 2 cfm change in reading at the nominal 60 scfm calibration air flow. A range of air temperatures causes similar changes in flow reading for an actual flow rate of 60 scfm. Since both the metering orifice and calibration device produce similar changes, however, the calibration reading (or a comparable leakage reading) would remain the same at any temperature, in itself an error. The combination of these errors produces a probable (rms) error range of $\pm$ 2.7 cfm, which exceeds the required accuracy limits of AAR Specification M-980 for air flow indicators.

The AAR Calibration Procedure for AFM Type Air Flow Indicators (RP-402) minimizes the "temperature independence" of the metering devices by requiring that the calibration device provide 60 cfm [0.0764 lb/sec] at a temperature no greater than 20 F. This requirement minimizes the air flow reading error at lower temperatures, where actual leakage is of greater significance.

Currently both the leakage rate test and air flow test methods rely on standard air pressure gauges to qualify the train brake system for service. In the use of differential pressure gauges as air flow indicators, the industry has chosen a rugged and reliable device with a long history in locomotive service. The air flow indicator can be maintained on the same 92-day cycle as the other air pressure gauges in the locomotive cab.

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EVALUATION OF LOCOMOTIVE CAB AIR FLOW METERS FOR TRAIN AIR BRAKE LEAKAGE MONITORING

by

Donald R. Ahlbeck and Steven M. Kiger*

April 28, 1989

1.0 INTRODUCTION

The Federal Railroad Administration (FRA) has been petitioned by several railroads to modify 49 CFR 232 to permit the use of cab air flow meters to conduct initial terminal and road train air brake leakage tests. Current rules require that train brakes meet three criteria at the initial terminal, and at a point other than a terminal where one or more cars are added to the train:

- A minimum brake pipe pressure of 60 psi at the last car of the train,
- A maximum pressure gradient of 15 psi over the length of the train, and,
- A maximum leakage of 5 psi/min measured 30 to 60 seconds after exhaust ceases from a 15-psi service reduction (brake setting), with the brake valve pressure-maintaining function off.

The leakage rate test is a measure of the controllability of the train brake system, assuming a system not equipped with a pressure maintaining valve. Widespread use of pressure maintaining valves on modern locomotive units, plus the addition of air flow meters, may make increased leakage rates practical without adverse effects on operations

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safety. This could increase railroad productivity in colder climates, where leakage rates can be a problem in winter. A flow-related test would evaluate system leakage, not just the brake pipe leakage. In addition, use of the on-board flow meter can provide continuous monitoring of brake system functions during over-the-road operation.

Canadian railroads have conducted tests with brake pipe air flow measurements, establishing a 60 scfm leakage flow rate limit. These railroads have over ten years operational experience using the flow, rather than pressure rate, leakage limit. The use of air flow meters can be particularly beneficial during cold weather when brake pipe leakage is at a maximum. The use of 60 scfm as a criterion for satisfactory brake system leakage permits the railroads to operate longer trains during cold weather. Several U.S. railroads, including the Burlington Northern, have obtained authority to test the use of flow meters.

2.0 TECHNICAL LITERATURE REVIEW

2.1 Federal Regulations

Current Federal Railroad Administration, DOT regulations apropos of train air brake tests are contained in Part 232 - Railroad Power Brakes and Drawbars of 49 CFR Ch. II (10-1-87 Edition)[Ref. 1]. In Section 232.12 Initial terminal road train airbrake tests, the regulation states:

(b) "...inspection will be made to determine that -
(1) Brake pipe pressure leakage does not exceed five pounds [psi] per minute..."

(d)(1) "After the airbrake system on a freight train is charged to within 15 pounds [psi] of the setting of the feed valve on the locomotive, but not less than 60 pounds, as indicated by an accurate gauge at rear end of train,...and upon receiving the signal to apply brakes for test, a 15-pound brake pipe service reduction must be made in automatic brake operations, the brake valve lapped, and the number of pounds of brake pipe leakage per minute noted as indicated by brake pipe gauge,..."

(d)(3) "When the locomotive used to haul the train is provided with means for maintaining brake pipe pressure at constant level during service application of the train brakes, this feature must be cut out during train airbrake tests."

(e) "Brake pipe leakage must not exceed 5 pounds per minute."

In Section 232.13 Road train and intermediate terminal train air brake tests, the leakage test is similarly described:

(d)(1) "At a point other than a terminal where one or more cars are added to a train, after the train brake system is charged to not less than 60 pounds as indicated by a gauge or device at the rear of a freight train..., a brake test must be made to determine that brake pipe leakage does not exceed five (5) pounds per minute as indicated by the brake pipe gauge after a 20-pound brake pipe reduction."

The additional five pound reduction in brake pipe pressure (20, instead of 15) makes the intermediate-point leakage test a little less severe, but allows combining with the leakage test the test that train brakes at the rear will apply.

In a related regulation, Section 232.19 End of train device, the accuracy of the pressure-measuring device is addressed:

(b)(1) "Capable of measuring the rear car brake pipe pressure with an accuracy of ± 3 psig and brake pipe pressure variations of ± 1 psig [resolution]...".

The regulation also defines the operating environment of the rear unit (d) and the front unit (f), in terms of temperature, humidity, altitude, shock and vibration.

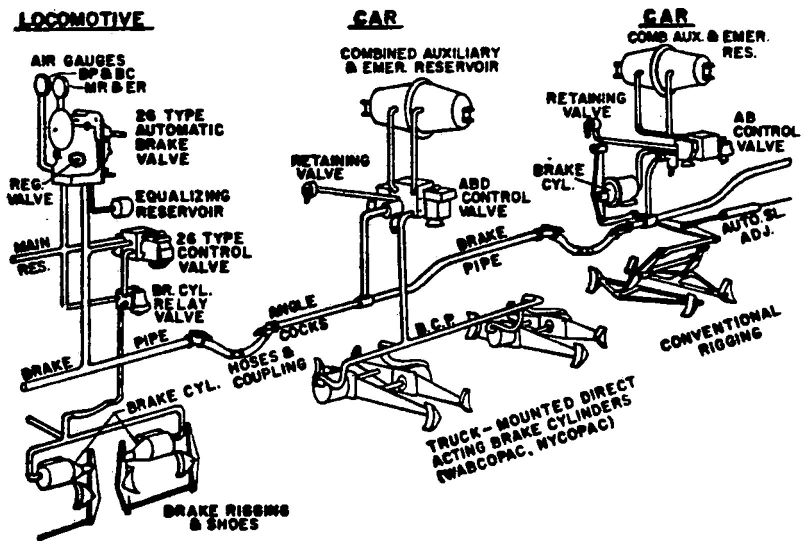
2.2 Train Air Brake System Operation

Train air brake system operations and testing procedures are described in a definitive 1971 technical paper by Blaine and Hengel [Ref. 2]. This paper describes the basic elements of the air brake system, as well as the effects of brake operations and test procedures on train performance.

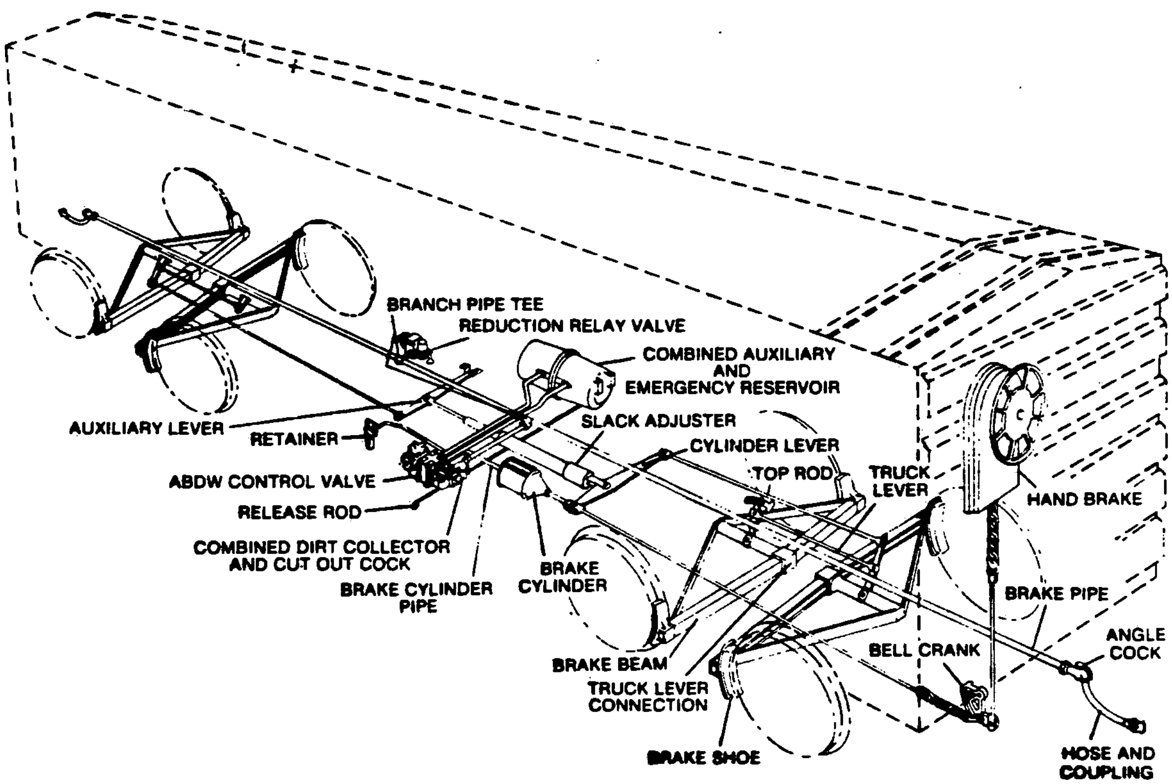
The basic car-mounted unit of the air brake system consists of the brake pipe, a control valve, auxiliary and emergency air reservoirs, the brake cylinder, and mechanical linkages to the brake shoes. These elements are shown in Figure 2-1. The brake pipe forms the train-common air pressure source and pressure communications line. The train brake system is charged by locomotive-mounted air compressors to the nominal brake pipe pressure setting, usually 75 to 90 psig at the locomotive control valve, depending on local operating procedures. This brake pipe pressure will droop with distance toward the rear of the train (the "gradient") due to flow-induced pressure losses, depending on localized leakage in hose couplings, fittings, etc.

Operation of the train brakes is initiated by reducing the brake pipe pressure by blowing off air through the automatic brake valve in the locomotive. A "service reduction" consists of a brake pipe pressure reduction of 5 to 25 psig. A "full service reduction" is one sufficient to cause pressure equalization between the brake cylinder and the auxiliary reservoir. Individual car control valves will sequentially sense the pressure drop and divert air from the auxiliary reservoir to the brake cylinder, building up cylinder pressure and braking force on the wheels. These valves are sensitive to the rate of brake pipe pressure drop: a 20-psi drop in more than about 1.4 seconds constitutes a normal service application of brakes, while a drop of 20 psi in less than about 1.2 seconds will induce an emergency brake application. Normal quick-service brake action (type ABD or ABDW valves) propagates toward the rear at 400 to 600 feet per second, while an emergency application will propagate at 900 to 950 ft/second.

Typical brake action times are cited in the paper. For a single car, a full-service reduction in brake pipe (BP) pressure from 80 to 55 psig will bring the brake cylinder (BC) pressure from 0 to 50 psig in about 10 seconds, and to 57 psig in 15 to 16 seconds. For a 150-car train with minimum leakage, BP pressure at the first car drops to 60 psig and the BC pressure rises to about 48 psig at roughly 55 seconds. At the 150th car, the BP pressure drops to 60 and the BC pressure rises to about 46 psig in roughly 125 seconds. Since slack action propagates at 200 to 400 ft/second, the reason for generation of slack run-in during braking of long trains becomes apparent.



Source: R. L. Wilson [Ref. 4]



Source: Simmons-Boardman, The Car and Locomotive Cyclopedia, 1984

FIGURE 2-1. MAJOR ELEMENTS OF A FREIGHT TRAIN AIR BRAKE SYSTEM

2.3 Air Brake System Flow and Leakage Relationships

Air flow and leakage in the train brake system have several important effects on brake testing, operation and response. The paper by Blaine and Hengel [2] makes several salient points with regard to brake system leakage:

- Train air leakage is checked after making a 15 [or 20] psig BP reduction, setting the brakes, and timing the BP gauge drop over one minute. However, this measures only brake pipe leakage. With the brakes released, air leakage of control valves and reservoirs are added to give total "system" leakage.

- Brake pipe leakage over 5 psi/min or gradients over 15 psi can cause erratic brake response (undesired applications or releases, or brakes may not respond).

- Leakage in the rear of the train has the more significant effect on train brake operations, therefore there is more benefit if corrected.

- Train length affects BP reduction time and train average BC pressure. Leakage tends to speed up BP reduction. Therefore, leakage-induced gradient reduces available pressure, but leakage speeds up application time. The effect increases notably with train length. Leakage up to about 5 psi/min produces shorter stops. At 8 to 10 psi/min of BP leakage, stopping distance is adversely affected.

- The practical limit for satisfactory brake control is a leakage and gradient situation where flow demand in a full-charge condition is less than 60 cubic feet per minute (cfm).

In an undated paper by R. L. Wilson entitled "Factors Affecting Air Brake Operation" [Ref. 3], the effects of leakage, pressure level and train length are explored in terms of train charge time, brake application time, and pressure gradient. A later (1976) paper by the same author, "Leakage and Gradient Considerations in Train Braking" [Ref. 4] presents results from the Westinghouse Air Brake Division (WABCO) 150-car test racks under laboratory conditions. In these tests, an 80 psig BP pressure at the source (brake valve) was used, with 50 feet of brake pipe per "car" and evenly-distributed leakage. Results of these tests were used to determine (1) train gradient and resulting air flow, (2) brake cylinder application time, (3) brake cylinder pressure buildup time, (4) average train brake cylinder pressure, (5) simulated train stopping distance, and (6) release and recharge times. Results were plotted for various brake pipe lengths (number of "cars") up to 7500 ft (150 cars).

A correspondence between brake valve air flow and evenly-distributed brake pipe leakage is shown in Figure 2-2, based on Figure 2 of Wilson's paper. In this "carpet plot", both train length (solid lines) and pressure gradient (dashed lines) are shown. For a given flow and leakage, leakage concentrated toward the front of the train would produce less pressure gradient, while leakage concentrated toward the rear would create a higher gradient. Although not specifically stated, leakage is assumed to be measured by the AAR method, after a 15-psi service reduction in BP pressure and a 30 to 60-second time delay. It was noted that higher leakage values for given flow rates were implied in the pressure gradient values cited by Blaine and Hengel [2]. However, the laboratory rack test data reported by Wilson [4] were confirmed by tests conducted during January 1978 by CN Rail Operations at Transcona, Manitoba, cited in J. G. Smith's paper of October 1978 [Ref. 5].

Wilson's paper [4] explores brake cylinder pressure build-up time at the last car as a function of brake pipe leakage and train length. The tests showed distinct time minima, particularly with longer train lengths, as shown in Table 2-1:

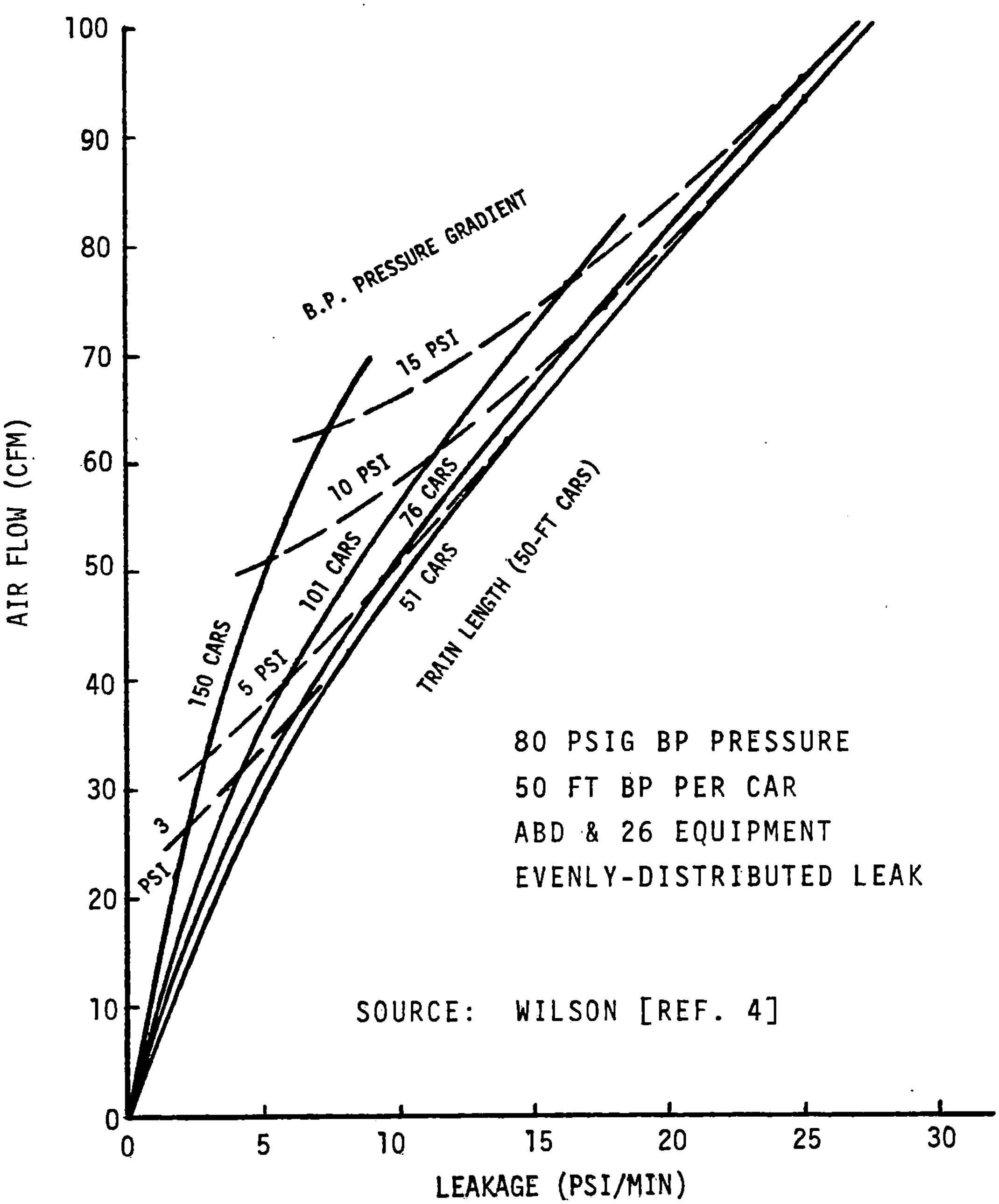


FIGURE 2-2. CORRESPONDENCE OF AIR FLOW TO BRAKE PIPE LEAKAGE RATE BY TRAIN LENGTH AND PRESSURE GRADIENT

TABLE 2-1. BRAKE CYLINDER PRESSURE BUILD-UP TIME VERSUS VERSUS TRAIN LENGTH AND BRAKE PIPE LEAKAGE [4]

No. Cars	Time (sec)	BP Leakage (psi/min)
51	38	12.3
76	53	11.2
101	85	7.3
150	111	4.5

The minimum brake cylinder pressure build-up time occurred at about the same BP pressure gradient, 5 to 7 psi. Similar effects were found for brake application time. These data were used to determine average train brake cylinder pressures and to calculate train stopping distances for a full service brake application. Calculated stopping distances are plotted in Figure 2-3 versus initial gradient, flow and leakage for different train lengths of loaded 100-ton cars from an initial speed of 50 mph. From a train safety viewpoint, it is noted that the curves are relatively "flat", and some variation in BP pressure gradient and leakage can be tolerated.

Other aspects of brake pipe leakage and pressure gradient are brake release time and reservoir recharge time, both of which increase sharply with increased gradient and train length. A longer recharge time increases the time during which a "false gradient" exists within the train, which can cause undesired brake release during repeated brake applications. Recharge time to within two psi of brake pipe pressure can take typically 15 to 30 minutes at the last car, following a full service reduction.

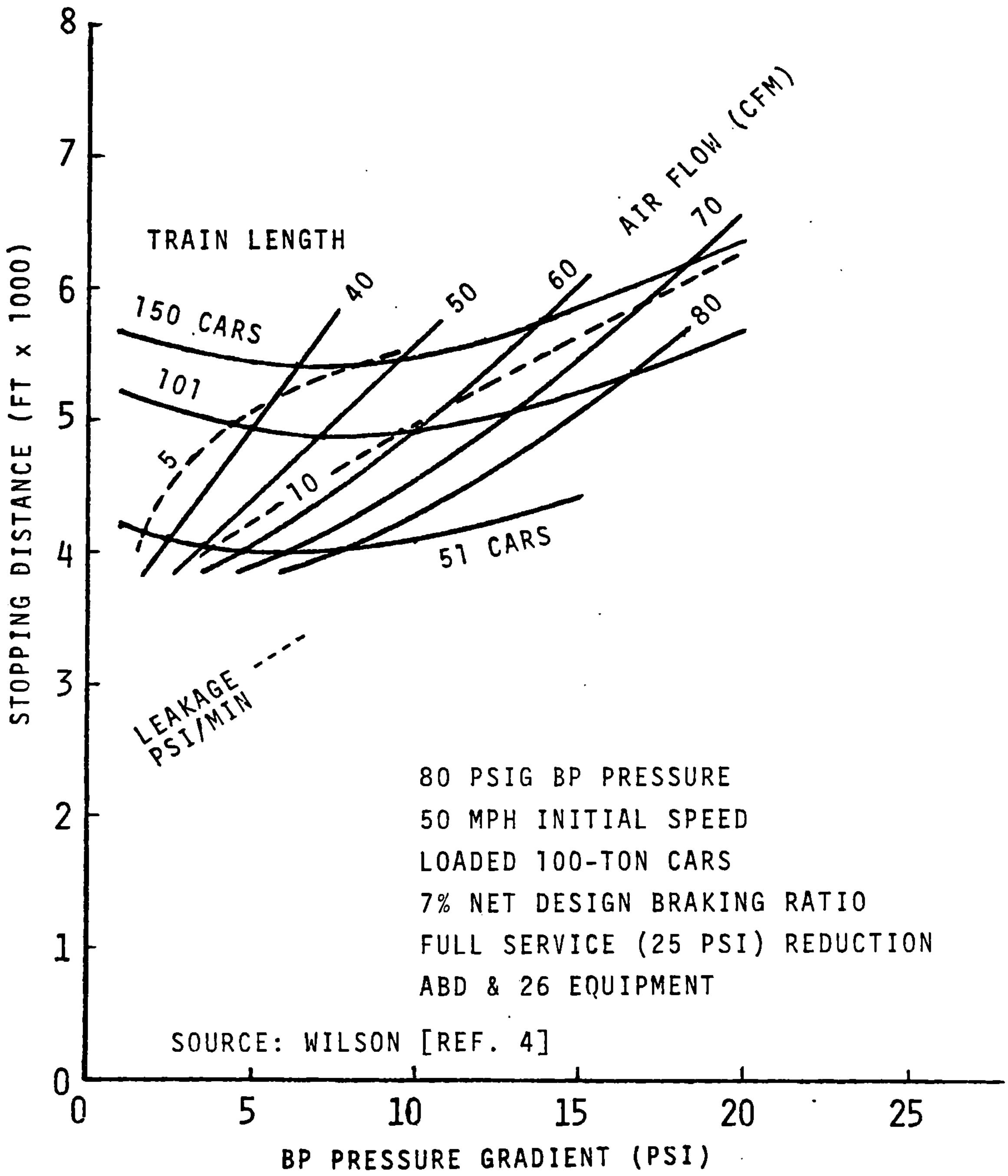


FIGURE 2-3. CALCULATED TRAIN STOPPING DISTANCE VERSUS BRAKE PIPE PRESSURE GRADIENT AND TRAIN LENGTH

2.4 Air Flow Test Method

The 1978 papers by Smith [Ref. 5] and Wickham [Ref. 6] address the air flow alternative to the pressure-drop leakage test. Several pertinent observations are made in these papers:

- Pressure maintaining valves [the 26-L locomotive brake equipment or equivalent] appear to be the key development, where BP pressure will stay where the locomotive engineer sets it, thus avoiding increasing brake cylinder pressures and braking forces as BP pressure falls due to leakage, and consequently the periodic release and reapplication of train brakes.

- BP leakage allowance cannot simply be raised to, say, 8 psi/min to take advantage of the pressure maintaining feature. Continuous quick-service valves have a stability level a little over 5 psi/min, and accelerated application valves about 7 psi/min. During a leakage test, a true leakage of 8 psi/min would cause some valves to operate, giving a false leakage of perhaps 11 psi/min.

- BP pressure drop tests only BP leakage after a 15 psi reduction, whereas air flow tests total system leakage at the full BP pressure.

- Trains with non-maintaining valves have to meet the 5 psi/min leakage controllability limit, while trains with maintaining brake valves can utilize the 60 cfm flow controllability limit.

- For most trains, the Air Flow Method (AFM) would normally take longer than the BP leakage method, since the 15 psi gradient is usually not the final stabilized value. For longer trains, where the 15 psi gradient is the deciding factor, the AFM would save time. The "break-even" point is about 147 50-ft cars.

- The AFM can "allow trains to be put into service which otherwise might be rejected for no good reason".

Computer predictions of the effects of leakage distributions are given in a 1979 paper by Schute [Ref. 7]. Results showed that...

- Brake pipe pressure gradient is sensitive to location of leakage in a train, increasing as leakage moves rearward.

- For leakage less than about 10 psi/min, brake pipe flow is not sensitive to the distribution of leakage.

Both References 6 and 7 cite air flow levels less than Reference 4 (or the corroborating field tests of Reference 5) for the given leakage rate of pressure gradient.

The extensive 1981 report on the Air Flow Method by CN Rail Operations to the Canadian Transport Commission [Ref. 8] covers the background of the AFM, tests, railway experience, training, operations, and economic factors. One section (2.17) provides a direct comparison of the Leakage and Air Flow Methods of testing train air brakes. This comparison is given in Figure 2-4 and contains basically the same important points cited in the above references. Economic benefits identified by CN Rail in the three years following implementation of the AFM included a 15.4 percent increase in the winter train load, resulting in crew wage savings, diesel unit and caboose mile savings. Identified annual operating savings exceeded $6M Canadian. Additional savings were projected (but not quantified) for motive power and caboose acquisitions, revenue freight car requirements, and plant capacity.

The Air Flow Method is also cited in a 1981 paper by Blaine, Hengel and Peterson [Ref. 9] in the section titled "determination of a

Brake Pipe Leakage Test	Air Flow Method Test
a) Test is made in an unrealistic manner unrelated to operating procedures, i.e. pressure maintaining feature is "cut out".	a) Test is made with the brake system in the same condition and with the same operations as normally used when braking a train enroute.
b) Test is made at 15 psi less than the standard working brake pipe pressure for the train	b) Test for flow made at the full working brake pipe pressure for the train.
c) Only brake pipe and branch pipes are tested for AB equipment. Auxiliary and Emergency reservoirs and control valve are not tested for leakage.	c) Brake pipe, brake branch pipe, emergency and auxiliary reservoirs and control valve are tested for leakage.
d) Test only determines the rate of brake pipe pressure drop as indicated by the locomotive gauge, with no indication given of the capacity of the locomotive to supply air.	d) Test indicates the flow of air to the entire train brake system measured at its origin, the locomotive regulating valve, and relates to the capacity to supply air.
e) Test is awkward and difficult because it requires reading a moving gauge needle and co-ordinating with a watch after establishing the correct moment or "wait period" to commence the readings after cutting out pressure maintaining.	e) Test is simple and clear.
f) Test is clearly not meaningful. It is possible to have a 100 car train with a leakage rate which fails the test but if a block of cars is removed, the shorter remaining train may easily have a higher leakage rate. This effect is due to the variables in concentration of leaks and volume of train brake pipe from which air is escaping. The reverse situation can also occur where leakage rate can be decreased by adding blocks of cars.	f) The 60 CFM limit is used as an indication of the ability of the automatic brake valve to charge the brake system of the train. Train size is regulated by flow and gradient.
g) Test of leakage rate cannot be made while the train is moving and there is no reference mark to relate changes in conditions.	g) Permits constant enroute monitoring of CFM, with a meaningful reference mark to relate changes in conditions.
h) Test originated in the days of the steam locomotive, without Pressure Maintaining or Brake Pipe Flow Indicators and with older designs of car brake systems. Test inhibits improvements in equipment designs. For today this antiquated method results in decreased transportation efficiency and increased train delays and attendant fuel consumption. Plant capacity is severely restricted.	h) Tests take advantage of availablity of modern technological advances in air brake equipment. Use of this equipment and test method will permit increased transportation efficiency and reduced fuel consumption. This has a major economic effect and also increases plant capacity to permit the railways to handle increased traffic.

FIGURE 2-4. COMPARISON OF LEAKAGE AND AIR FLOW METHODS OF TESTING (QUALIFYING) TRAIN AIR BRAKES

satisfactory train [brake system] condition". Two figures in this paper show the relationships of brake pipe pressure gradient, air flow and leakage to train (brake pipe) length for both the leakage and AFM tests. These are repeated in Figure 2-5. Here, the flow versus leakage values are in close correspondence with those cited by Wilson [4] and shown in Figure 2-2. The authors state: "The validity of the 60 cfm limit has been the subject of extensive service trials and the AFM has been used over a three-year period for over 1,000,000 initial and intermediate terminal train tests on Canadian railways."

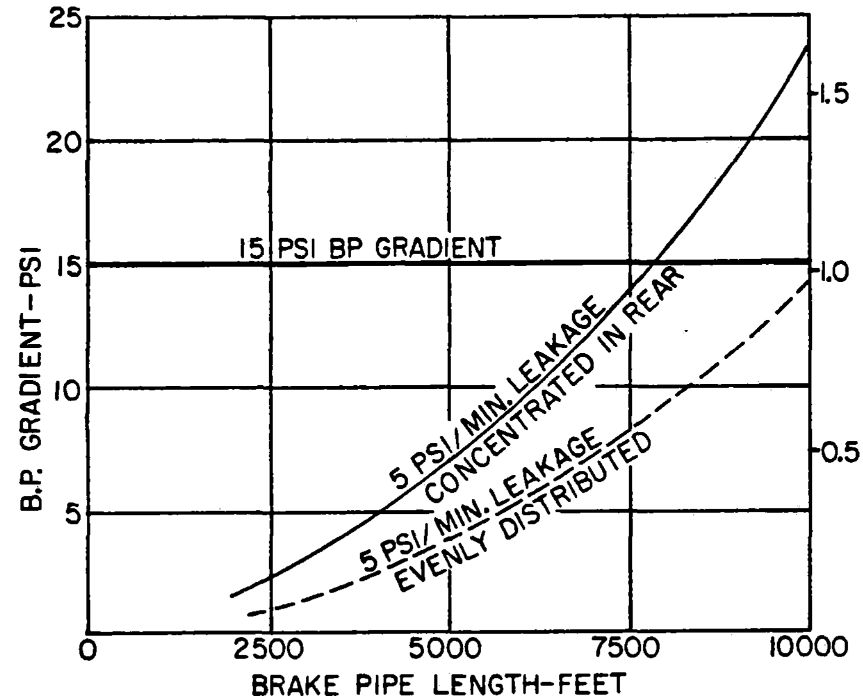
Several presentations on operating experience with the AFM have been made in recent years to The Railway Fuel and Operating Officers Association [Refs. 5,10,11,12]. In addition to CN Rail [5,10] and CP Rail [11], experience gained by the Burlington Northern and Soo Line Railroads were also presented in these papers. Operating experience included reports by locomotive engineers and a sampling of train brake tests by both methods for direct comparison. No problems in train handling or train safety were found attributable to the AFM.

2.5 Recent Brake System Studies

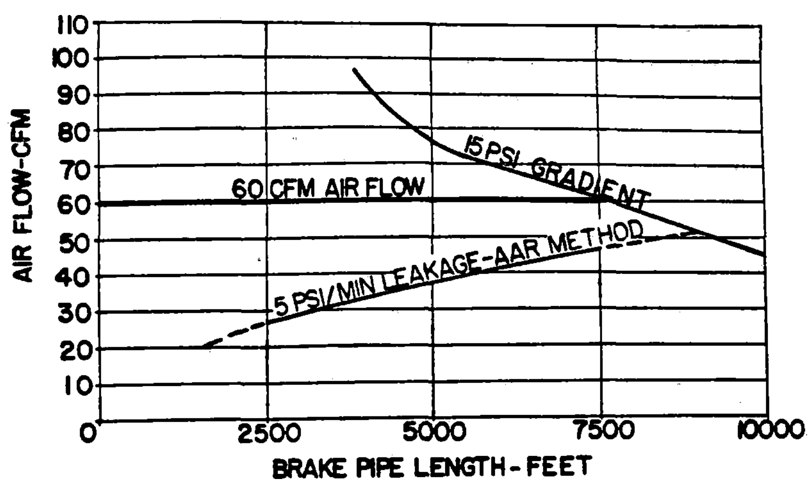
The Federal Railroad Administration has sponsored several recent freight train brake system safety studies aimed at a better understanding of brake system operations and train dynamic response. One of these studies [Ref. 13] addressed two items (among several others) under brake system dynamic performance that touch on the Air Flow Method:

a. "Study the feasibility of requiring locomotives to be equipped with brake pipe flow indicators to enable engineers to measure trainline air flow." [NTSB Safety Recommendation R-79-85, January 10, 1980.]

b. "Can train leakage be increased at the initial terminal brake test over the present 5 psi per minute safely?"



a. Leakage, Gradient versus Train Length (B.P. Leakage Test)



b. Air Flow, Gradient, Leakage Limits versus Train Length
Source: Blaine, Hengel, Peterson [Ref. 9]

FIGURE 2-5. COMPARISON OF LEAKAGE AND AIR FLOW LIMIT CRITERIA

In this study, pressure gradient, leakage and train stopping distance models were developed. Conclusions reached were essentially the same as the previous references cited:

- Increased leakage rates are possible only because of the widespread adoption of pressure maintaining valves and flow meters on locomotives.

- The leakage rate test is a measure of controllability of a brake system, assuming the system is <u>not</u> equipped with pressure maintaining equipment.

- A relaxed leakage rate test (7 psi/min) would not compromise controllability with pressure maintaining equipment, but some valves would operate, increasing the leakage and nullifying the test.

- Air flow would test for <u>system</u> leakage, whereas the current method tests only for brake pipe leakage [typically 70 percent of total system leakage].

- A flow rate meter allows continuous monitoring of the brake system.

- The air flow rate method is more straight-forward, with less room for error.

A simple formula was developed for pressure drop (in the leakage test) versus time, as an exponential decay in pressure. The <u>time constant</u> in this formula varies as the inverse square-root of absolute temperature, so that for a fixed leakage area the warmer the brake pipe air, the faster the pressure drop. This time constant may vary by 15 to 20 percent over typical winter-to-summer temperatures. However, leakage area generally increases at colder temperatures, tending to offset this change in time constant.

Other efforts toward the mathematical modeling of train air brake systems have been reported [Refs. 14-18]. The most recent (1988) publication by Abdol-Hamid, Limbert and Chapman [Ref. 18] entitled "The Effect of Leakage on Railroad Brake Pipe Steady State Behavior" discusses a mathematical model for pneumatic transmission lines (the brake pipe) with leakage. This model utilizes one-dimensional continuity and momentum equations, using finite-difference techniques for solution. The conclusions of this study include the following:

- Pressure gradient is larger as the leakage moves toward the rear.

- For small leakage (< 2 percent), leakage location has little effect on flow rate ; for larger leakage (> 8 percent), there is increased flow as leakage moves forward.

- Leakage size has great effect on the pressure distribution.

- Larger leakage size (> 8 percent) does not have a great effect on inlet flow, since pipe friction tends to control flow.

- Fitness of the brake pipe cannot be determined based on pressure gradient or on flow alone: both must be used.

A recent study, "The AAR Undesired Emergency Study" [Ref. 19] was reviewed in the context of the Air Flow Method of train brake qualification. None of the conclusions in this study of undesired emergency applications of train brakes indicated that the AFM would in any way jeopardize brake system integrity or train safety.

3.0 EVALUATION OF AIR FLOW METHOD

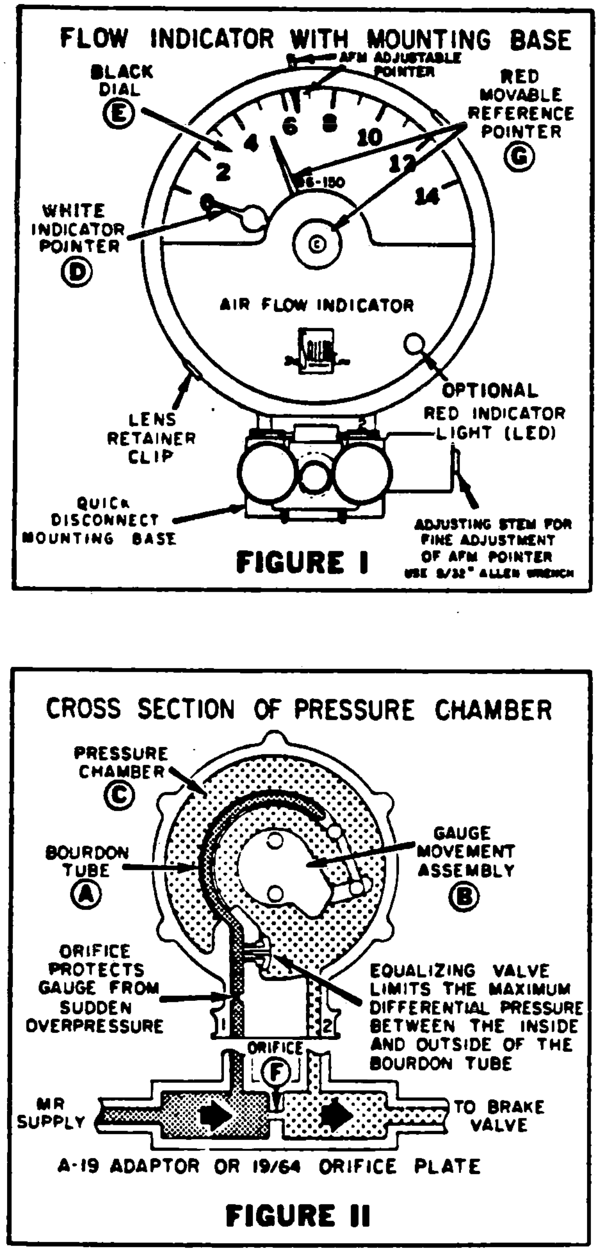
3.1 Air Flow Measurement

Air flow measurements in locomotive air brake systems are made currently by measuring the pressure differential across an orifice in the main reservoir supply pipe to the brake valve. The air flow indicator is, therefore, an air pressure gauge, usually of the bourdon tube type. The gauge is connected across an A-19 Flow Indicator Adapter, which is a drilled orifice in a spring-seated check valve (to allow unrestricted air flow during brake system charging), or across a 19/64-inch diameter orifice plate. A typical air flow indicator is shown in the sketches of Figure 3-1.

The air flow through an orifice varies by the square-root of the pressure differential across the orifice. Therefore the linear scale on the indicator face (numbers 2 through 14) relate to flow in a highly nonlinear way. For example, tests have shown a change in flow of 18 cubic feet per minute (cfm) between marks 2 and 3, and only 4 cfm between marks 7 and 8. Fortunately, the device becomes more sensitive to change in flow in the range near the AFM test limit of 60 cfm, which falls near mark 8. The device will generally run off-scale during brake system charging, but is protected internally and by the A-19 adapter from damage during this part of normal operation.

Air flow through an orifice is also dependent on the source (main reservoir) pressure and temperature, varying as a "constant" times the square-root of pressure divided by the square-root of absolute temperature. (The "constant", which consists of the orifice discharge and expansion coefficients, may also vary, depending on air velocity.) These factors can affect the readings of the device.

The air flow indicator (pressure gauge) is generally maintained by the railroads with the same frequency and standards established for other air pressure gauges in the locomotive cab.



Source: Salem 796 Series, Bulletin 95 (Graham-White Sales Corp.)

FIGURE 3-1. SKETCH OF TYPICAL AIR FLOW INDICATOR DEVICE

3.2 Operations and Experience with the AFM

Railways in Canada are currently authorized to use the AFM under Order No. R-36502, dated 30 April 1984, of the Railway Transport Committee, Canadian Transport Commission. The Order established the following standards for the AFM:

1. "The train and engine crew must have been instructed as to how to conduct the Air Flow Method brake test."

2. "The controlling motive power unit of the train to be tested must be equipped with schedule 26-L brake equipment or the equivalent and must have a pressure maintaining feature in operating condition."

3. "The controlling motive power unit of the train to be tested must have a Brake Pipe Flow Indicator which is calibrated to indicate a flow of 60 cubic feet per minute."

In addition to instructions for AFM tests at initial and intermediate terminals, and road tests, Schedule "B" of the Order states:

> "When a train operating under AFM Rules experiences an increase in brake pipe air flow and/or brake pipe gradient above the permissible limits (other than normal brake application and release) the employee in charge shall take appropriate action to repair leaks, if possible, set off cars, if necessary, or operate with due caution to the next point where inspection and corrective action can be taken, having full regard for safety and train brake handling."

Several U.S. railroads have received authorization from the FRA to conduct the Air Flow Method of testing and qualifying freight train brakes. Experiences of two of these railroads were given in the 1983 presentation by Fiedler and Fry [12] to The Railway Fuel and Operating Officers Association. In this presentation, comments are given on the AFM in the context of brake tests, air flow meter calibration, and operating experiences on both the Burlington Northern and Soo Line Railroads. Some conclusions are: "Over 6000 AFM tests [1983] have been performed on BN trains...To date, there has [sic] not been any difficulties reported associated with AFM testing" (BN), and "...the Air Flow Method has been accepted readily by our on-train employees. The engineers are extremely pleased with their capability of now being able to monitor their train line while enroute" (Soo).

As part of this study, several railroads were contacted to determine their current experience with, and/or opinions on the AFM. The following comments were noted:

<u>**Burlington Northern.**</u> BN engineers routinely use the flow meters to monitor the train brake system over-the-road. Apparently the flow meters were introduced on the BN predecessor Great Northern Railway by Mr. Jim Herrin, who later went to the Penn Central (Conrail predecessor) and introduced it there before retiring. Operations personnel on BN have not reported any problems with either the AFM or the flow meters. BN has established operating, calibration and maintenance procedures, which are given in the BN "Air Brake, Mechanical and Train Handling Rules", Form 15338 - Revised 2/1/87.

BN has not tried to quantify the cost benefits: the AFM does not really save time in the yards, and it costs money to apply, calibrate and maintain the flow meters. However, it is a proven tool in operations, and it can allow short, leaky trains to be run in cold weather.

<u>**Conrail.**</u> Conrail has equipped 100 percent of their locomotives having the 26L brake valves with air flow meters (about 75 percent of the total fleet). Conrail has conducted AFM tests for the last two winters, and no problems have been experienced [these have, however, been relatively mild

winters]. Both AFM and pressure drop (leakage) air brake tests were run during this period on about 30,000 trains. Not one instance was reported of train handling problems enroute after an AFM test qualification. From the data, less than 1/2 percent of the trains indicated greater than a 10 psi pressure gradient.

Conrail has established operating, calibration and maintenance procedures. They have achieved high consistency and repeatability in the calibrations. The key, they feel, is a complete understanding by shop forces of the procedure: for example, that setting the calibration marker must be done with rising main reservoir pressure (see Section 3.3). Both WABCO and Graham-White (Salem) air flow meters are currently used. Maintenance problems with air flow meters have been virtually non-existent. Calibration is done with purchased orifices certified for 60 scfm calibration at a 90 psig brake pipe and 125 psig (rising) main reservoir pressure.

Cost benefits have not been quantified, but it is felt that costs can be reduced, since longer trains can be run in the winter (perhaps 10-15 additional cars). There are generally no time-savings, since the train gradient must still be met before AFM tests, and the train line (gaskets, etc.) must be "worked over". The AFM is viewed as oriented more toward train handling safety than just a leakage test.

Union Pacific. UP experience is similar to the BN. Between 30 to 40 percent of locomotive units are equipped with Salem air flow meters. For now, the UP has put on hold any effort to get a waver from the FRA. The respondent was not sure that UP has yet developed procedures for operations, calibration and maintenance. The engineers like the air flow meters (which, however, are not calibrated), and no problems have been reported.

Denver & Rio Grande Western. Air flow meters are not in use, and there are no plans to use them. D&RGW feels that the end-of-train devices (rear-end brake pipe pressure) are a better way to determine train brake system condition.

Southern Pacific. SP uses air flow meters, but not on all units.

Atchison, Topeka and Santa Fe. ATSF does not currently use air flow meters, and has not for a number of years. Cost control was cited as the probable reason.

CSX Transportation. CSX does not buy air flow meters for their locomotives, and has adopted a "wait and see" position with respect to testing and use of the AFM.

3.3 Air Flow Meter Calibration

3.3.1 Canadian National

Procedures for calibration of air flow meters are given by CN Maintenance Regulations No. 3420 (August 1977, revised August 1980) for locomotives with 26L, 26LU or 26LUM brake systems. The locomotive is first "prepared" by assuring the accuracy and currency of maintenance of the gauges, and securing the locomotive in an area where third-notch engine speed can be used. The calibrating hose and choke assembly sketched in Figure 3-2 are attached to the front of the engine unit. With the brake pipe pressure set at 75 psig, and the main reservoir pressure set at 130 psig, the calibration procedure is as follows:

1. Increase engine speed.
2. Slowly open brake pipe angle cock to a fully open position.
3. Observe black pointer on brake pipe flow indicator and, when main reservoir pressure is at 130 psig, move the red pointer to coincide with the black pointer.
4. Reduce throttle. Close angle cock.
5. Note the precise red pointer indication on the dial face.

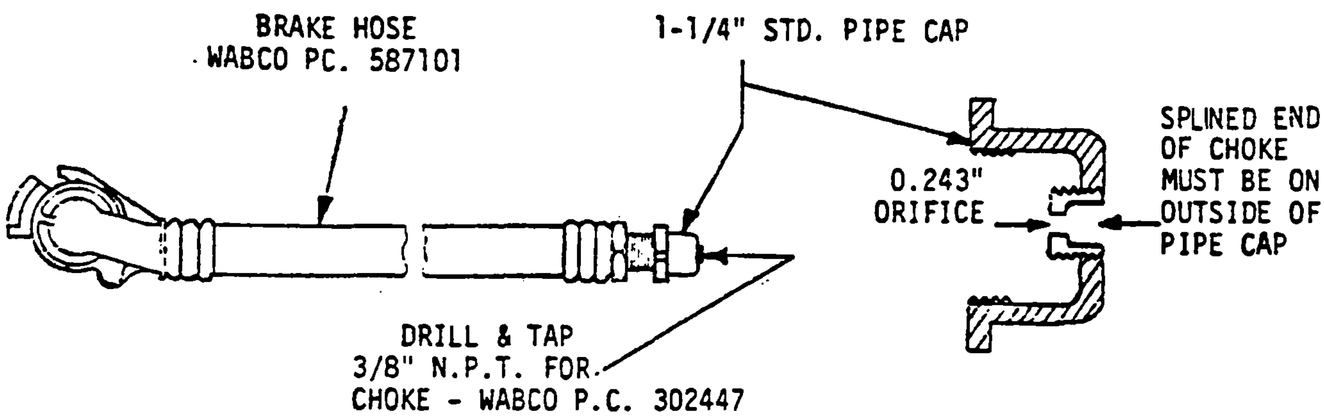


FIG. 1
CALIBRATING HOSE & CHOKE ASSEMBLY

FIG. 2
CHOKE ORIENTATION

Source: CN Maintenance Regulations No. 3420

FIGURE 3-2. SKETCH OF CALIBRATING HOSE AND CHOKE ASSEMBLY USED BY CN RAIL

6. [Remove the face plate of the WABCO air flow meter]...and position the moveable plastic calibration marker (orange tip) to coincide with the noted reading previously taken by means of the red pointer...
7. Repeat steps 1, 2 to ensure that the black hand corresponds with the plastic marker to indicate precise marking for re-calibration.
8. Note that the calibration must be done and rechecked with the main reservoir pressure at 130 psig, and with the brake pipe pressure set at 75 psig prior to opening the angle cock.
9. Reduce engine speed to normal. Close angle cock. Remove test assembly. Secure brake pipe hose.

3.3.2 Burlington Northern

A more detailed procedure for air flow meter calibration has been developed by Burlington Northern, as shown in Figure 3-3. This procedure is a modification of that given in the 1987 BN Air Brake, Mechanical and Train Handling Rules (Section 522 C, pp. 565-566). In contrast to CN Rail, BN sets the main reservoir pressure on freight and switch locomotives to cycle between 115 and 125 psig, and uses a brake pipe pressure of 80 psig (90 psig in mountain territory). These changes made necessary some considerable experimentation to determine the proper calibration device. According to Mr. Carl Stendahl (and to Ref. 12), a large calibrated gas flow meter was rented from Northern States Power in Minneapolis, and a number of tests were conducted using an SD40-2 locomotive unit. A sharp-edged (ASME) orifice diameter of 0.235 inch [now given as 0.234 in the procedures] was determined. In the first attempts to fabricate the orifice, everything seemed to change the results: edge sharpness, paint, etc. Fabrication of the orifices was finally contracted out, and machining was held to tolerances of three ten-thousandths of an inch.

****

MMC630 01 FEB 89 08:03 DISPLAY OF DETAIL INSTRUCTIONS

DETAIL INSTRUCTIONS FOR: MNT-044

CALIBRATE AFM FOR 60 CU. FT. A MIN.

1. SET HAND BRAKE TO PREVENT MOVEMENT.

2. FULLY APPLY INDEPENDENT BRAKE VALVE ENSURING LOCOMOTIVE BRAKE CYLINDER PRESSURE HAS DEVELOPED TO MAXIMUM.

3. MAIN RESERVOIR ON CAB GAUGE MUST READ 115-125 PSI.

4. CLOSE ALL MU CUT OUT COCKS AND ANGLE COCKS AT BOTH ENDS OF LOCOMOTIVE.

5. CONNECT TEST DEVICE (DUMMY COUPLING WITH .234 ORIFICE, PRIME PART NO P-32522) TO BRAKE PIPE HOSE AT FRONT (SHORT HOOD) OF LOCO.

6. SLOWLY OPEN FRONT ANGLE COCK TO FULL OPEN POSITION SO BRAKE PIPE AIR BLOWS THROUGH TEST DEVICE ORIFICE.

7. PLACE REVERSER IN CENTER POSITION AND GENERATOR FIELD SWITCH OFF.

8. AUTOMATIC BRAKE VALVE MUST BE IN RELEASE POSITION AND CUT OUT VALVE MOVED TO FRT OR IN POSITION AS APPLICABLE.

9. ADJUST REGULATING VALVE, IF NECESSARY, SO BRAKE PIPE READS EXACTLY 80 PSI.

10. ALLOW MAIN RESERVOIR PRESSURE ON CAB GAUGE TO DROP TO APPROXIMATELY 105 PSI. PLACE THROTTLE IN RUN 3 POSITION. THE FACE OF THE AIR FLOW GAUGE SHOULD BE TAPPED LIGHTLY AND WHEN MAIN RESER-PRESSURE REACHES 115 PSI. THE LOCATION OF THE WHITE AIR FLOW INDICATOR POINTER SHOULD BE NOTED. IT IS DESIRED TO HAVE THE WHITE INDICATOR POINTER AT "8" OR AS CLOSE TO "8" AS POSSIBLE. IF IT IS NOT AT "8", ADJUST THE 1/4 INCH BY-PASS NEEDLE VALVE LOCATED IN THE AIR BRAKE EQUIPMENT COMPARTMENT, OR THE 5/32 INCH ALLEN ADJUSTMENT LOCATED ON AIR FLOW GAUGE BASE. OPENING BY-PASS NEEDLE VALVE WILL CAUSE POINTER TO DROP, CLOSING IT WILL CAUSE POINTER TO RISE. HAVE THE WHITE AIR FLOW INDICATOR POINTER AT "8" OR AS CLOSE TO "8" AS POSSIBLE WITH MAIN RESRVOIR PRESSURE AT 115 PSI.

11. IF THE ORANGE CALIBRATION MARK DOES NOT COINCIDE EXACTLY WITH THE WHITE POINTER WITH MAIN RESERVOIR PRESSURE AT 115 PSI, THE THREE-HOLE GAUGE FACE PLATE MUST BE REMOVED. WHEN WHITE POINTER IS AT "8" OR AS CLOSE TO "8" AS POSSIBLE, MOVE SMALL ORANGE ADJUSTABLE POINTER ON AIR FLOW GAUGE TO COINCIDE EXACTLY WITH THE WHITE POINTER.

12. THROTTLE CAN BE RETURNED TO IDLE, THREE-HOLE GAUGE FACE PLATE RE-INSTALLED IF REMOVED, FRONT ANGLE COCK CLOSED AND TEST DEVICE RE-MOVED FROM BRAKE PIPE HOSE.

13. AIR FLOW INDICATOR IS NOW CALIBRATED TO INDICATE 60 CFM WHEN WHITE POINTER IS AT CALIBRATION MARK.

PART LIST:

FLOW METER GAUGE SALEM 796-150 23-047-05404

FIGURE 3-3. CURRENT PROCEDURE FOR CALIBRATING AIR FLOW METERS -- BURLINGTON NORTHERN RAILROAD

The calibration procedure was observed at BN's Northtown Diesel Shop in Minneapolis, Minnesota, in a demonstration by Mr. Ron Huroff, using an EMD GP50 locomotive. In this demonstration, the calibration device (dummy coupling with the 0.234-inch diameter orifice) was attached, angle cock opened, and locomotive throttle set in notch 3 position. The brake pipe pressure was maintained at 80 psig by the pressure maintaining feature of the 26L brake control valve equipment. The main reservoir pressure (in this demonstration) would rise to 122 psig with the compressor running, then droop slowly to about 112 psig before the compressor would again cut in. Pressure fluctuations would occur with moisture trap blowdown. Before adjustment, the air flow meter (white needle) varied from about 7.2 on the dial at 122 psig to about 7.8 at 114 psig. It was noted by Mr. Huroff that the main reservoir pressure gauge may read about 2 psi low with flows of 60 cfm due to the length of the gauge line [and the adjusting needle valve bypass flow].

To calibrate the air flow meter, the white needle would be adjusted to the "8" mark on the dial by an Allen wrench adjustment in back of the gauge . A few older units have a needle valve adjustment down on the main reservoir piping. This provides a bypass flow between the main reservoir supply and the Number 30 port on the automatic brake valve [12], so that the air flow meter does not go off scale with 60 cfm flow at 115 psig main reservoir pressure, 80 psig brake pipe pressure. This requires two men for calibration, one in the cab, one down below on a ladder. The white needle would be set at "8" as the main reservoir pressure hit 115 psig <u>on the rise</u> (and while tapping the gauge face with a finger) with the nominal 60 scfm through the brake pipe orifice. The small orange calibration marker would then be moved (if not already in correspondence) to coincide with the white needle at 115 psig main reservoir pressure.

Mr. Huroff noted that BN uses a 90-psig brake pipe pressure in mountain territory. The air flow meter would move from "8" to about "10" under these conditions with the calibration (0.234 orifice) device.

BN's air flow meters are maintained the same as other pressure gauges in engine service, with a 92-day maintenance cycle. Gauges are tested to within ± 1 psi of a calibrated test gauge, which is matched to a master gauge or dead weight tester every 30 days. In Section 116, General Rules - Locomotives, of the BN Air Brake, Mechanical and Train Handling Rules, it is stated "An air gauge may not be more than one pound per square inch in error when being tested. It must not be more than three pounds per square inch in error during train or locomotive operation."

3.3.3 Association of American Railroads

The Association of American Railroads (AAR) has established an abbreviated calibration procedure in its Recommended Practice RP-402 (adopted 1988), which is shown in Figure 3-4. The procedure does not (nor can it) contain the detail of either the Canadian National or BN procedures. However, two important points are noted:

2.1 A flow control calibration device that provides exactly 60 cfm at the desired brake pipe pressure **at not more than 20 degrees F** must be used to calibrate air flow indicators.

4.2 Adjust the air flow indicator point to coincide with the 60 cfm marking on the indicator **with the main reservoir at the lowest pressure (compressor cut-in pressure).**

Since weight-rate of flow of air varies by the inverse square root of absolute source temperature, the flow control calibration device will pass 4.1 percent more air (by weight) at 20 F than at 60 F (the "standard" temperature), and 11.3 percent more air at -20 F than at 60 F. A given train leak area will, similarly, pass a greater mass flow of air

CALIBRATION PROCEDURE FOR AFM TYPE AIR FLOW INDICATORS

Recommended Practice RP-402

Adopted 1988

1.0 SCOPE

The following procedures must be used for calibrating AFM type air flow indicators installed on locomotives that are to be used in the air flow method of qualifying trains.

2.0 CALIBRATION DEVICE

2.1

A flow control calibration device that provides exactly 60 cfm at the desired brake pipe pressure at not more than 20 degrees F must be used to calibrate air flow indicators.

2.2

Each calibration device must be clearly marked with operating brake pipe pressure at which 60 cfm is obtained. In addition, each calibration device must be identified by manufacturer with a unique serial number and registered by the owner with the AAR Mechanical Division.

3.0 LOCOMOTIVE PREPARATION

On a single locomotive unit to be calibrated, the regulating valve must be adjusted to the standard brake pipe pressure set by railroad and the main reservoir gauge at control stand must show that the air compressor is operating within prescribed limits set forth by the railroad. Multiple unit cutout cocks and angle cocks must be closed on both ends. The automatic valve must be in RELEASE position, with the independent brake applied. The automatic brake valve cutoff valve must be in the FRT or IN position. The calibration device must be attached to the brake pipe hose at the front of the locomotive. The reverser handle must be in neutral or center position (or removed) and the generator field switch in the off (open) position.

4.0 CALIBRATION PROCEDURE

4.1

The front angle cock must be SLOWLY opened to the full open position noting that brake pipe air is being discharged through the test device.

4.2

Adjust the air flow indicator pointer to coincide with the 60 cfm marking on the indicator with main reservoir at the lowest pressure (compressor cut-in pressure).

5.0 COMPLETION OF CALIBRATION

Close front angle cock and remove calibration device.

FIGURE 3-4. RECOMMENDED PROCEDURE FOR CALIBRATING AIR FLOW INDICATORS -- ASSOCIATION OF AMERICAN RAILROADS at lower temperatures (disregarding, for the moment, the usual increase in leakage area due to colder temperatures). For an air flow indicator of the pressure-differential type (a pressure gauge), the reading would be the same for all three example temperatures; and for a given train leak area, the reading would be the same. In other words, currently-used air flow indicators are temperature-independent. With an air flow indicator of a mass-flow type, a given train leak area will produce a lower (true) reading on the indicator at summertime temperatures, and a higher (true) reading on the indicator during severe winter temperatures. Therefore, the AAR calibration specification intends that the "60 cfm" mark be established at a lower temperature, so that cold-temperature errors in readings (when leakage is most important) are smaller. The calibration orifice size must therefore be adjusted and certified at a temperature of 20 F or lower.

The second noted paragraph from RP-402, above, emphasizes the fact that the pressure-differential measurement of air flow (the currently-used method) varies as the inverse of the main reservoir (source) pressure. Therefore the "air flow" reading will drop as main reservoir pressure rises, even though the actual air flow through the calibration device is constant from the maintained brake pipe pressure.

4.0 ENGINEERING EVALUATION OF THE AIR FLOW METHOD

An engineering evaluation of the Air Flow Method (AFM) was conducted to investigate the safety aspects of flow measurements of brake pipe (BP) leakage. This investigation addressed potential problems associated with the calibration and accuracy of air flow meters, and the possibilities of an air flow meter failing to indicate excessive leakage. An error analysis was conducted to compare leakage measurements by air flow meters with the current pressure-drop leakage measurement technique. These errors, along with the relative reliability, advantages and disadvantages of the two methods, are discussed in the following sections.

4.1 Air Flow Relationships

In order to appreciate an engineering analysis of the Air Flow Method, one must first address the basic relationships of compressible fluid flow in the context of metering orifices and nozzles. These are found in Marks' Handbook [20] and in representative references [21, 22, 23]. In the Air Flow Method, reference is made to volumetric flow, with standard cubic feet per minute (scfm, at a pressure of 14.7 psi, and a temperature of 60 F) either stated or implied. Since air pressures (and therefore air densities) change at different points in the brake system, it is simpler to deal with weight-rate (or mass-rate) of air flow. The primary relationship in compressible flow is:

$$\dot{W} = C\,Y\,A_o\,g\sqrt{2\,\rho_1\,\Delta p} \qquad (4\text{-}1)$$

where $\dot{W}$ = weight-rate of flow, lb/sec,

C = flow coefficient [Ref. 22, p. A-20], which is a function of the Reynolds Number (air density times velocity times pipe diameter divided by air viscosity),

Y = net expansion factor [Ref. 22, p. A-21], which is a function of the pressure ratio, $\Delta p/p_1$, or p_2/p_1.

A_o = orifice area, in^2,

g = gravity constant, 386 in/sec^2,

ρ_1 = density of upstream air, lb-sec^2/in^4,

Δp = pressure drop across the orifice or nozzle,

= $p_1 - p_2$.

Using the standard density for air, Equation 4-1 may be stated in terms of the upstream (source) pressure and temperature:

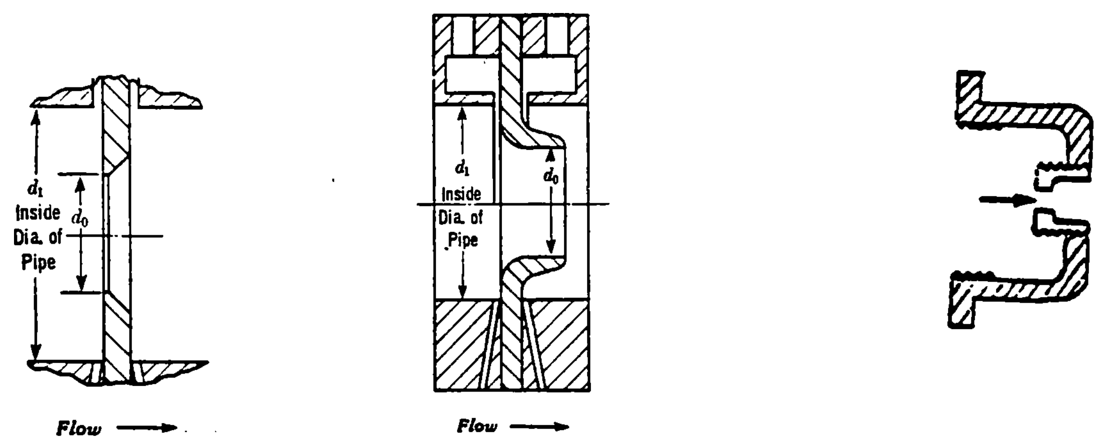
$$\dot{W} = 0.863\ C\ Y\ d_o^2 \sqrt{p_1\ \Delta p\ /\ T_1} \qquad (4\text{-}1a)$$

where d_o = orifice diameter, in.,

p_1 = upstream (source) pressure, psi,

T_1 = upstream gas temperature, deg R (459.7 + deg F).

Three possible metering configurations are sketched below in Figure 4-1, along with representative values of C and Y for the flow calibration device in this particular application to the Air Flow Method:



a. Sharp-Edged Orifice	b. Nozzle (Rounded Entry)	c. Elongated Hole
C = 0.60	C = 0.99	C = 0.8-0.9
Y = 0.74	Y = 0.71	Y = 0.8-1.0

FIGURE 4-1. THREE TYPES OF METERING DEVICE

At high flow rates, where the pressure ratio across the metering device, p_2/p_1, is less than about 0.53, sonic ("choke") flow can exist. For nozzles and rounded-entrance holes, this becomes the limiting flow rate, independent of downstream pressure. However, this phenomenon has not been observed in tests of sharp-edged orifices [20, 23].

These flow relationships appropos of metering are important at three points in the Air Flow Method: first, at the metering orifice or A-19 adapter across which "flow" is measured; second, at the calibration device; and finally, at the various brake pipe leaks. The measurement and calibration system is sketched below in Figure 4-2:

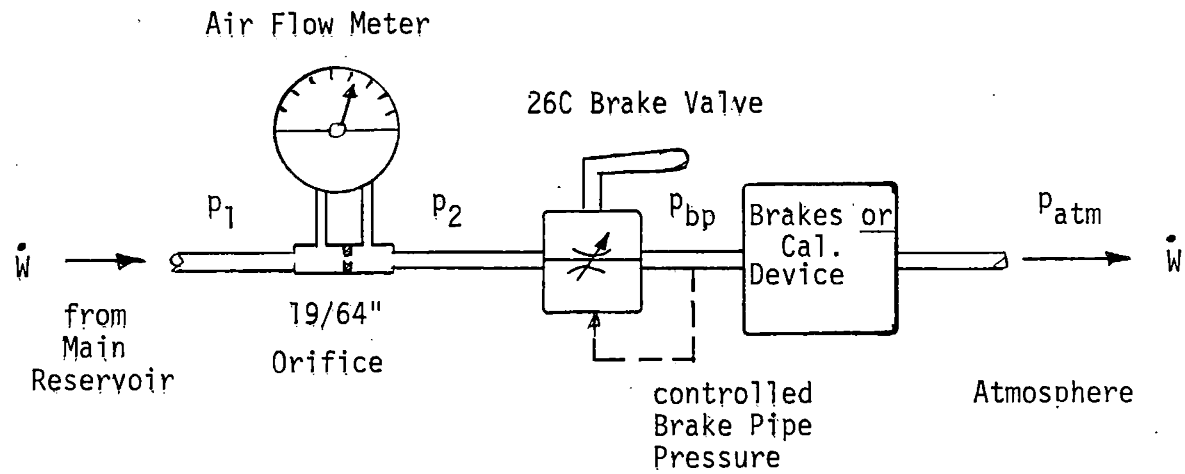


FIGURE 4-2. SKETCH OF AFM MEASUREMENT AND CALIBRATION

Across the air flow meter (pressure gauge) orifice, pressure drops of roughly 10 psi are typical at a 60 scfm (0.0764 lb/sec) flow rate. With a pressure ratio of p_2/p_1 = 0.92 to 0.93, well above the critical ratio, the expansion factor Y = 0.97 to 0.98 [22]. Across the calibration device, however, the critical ratio is far exceeded; and the geometry, condition and tolerances of the metering device become of great importance. Any deviations from the sharp-edged orifice geometry can result in "choke" flow or can affect the repeatability of calibrations.

At high flow rates, where the pressure ratio across the metering device, p_{bp}/p_{atm}, is less than about 0.53, sonic ("choke") flow can exist. For nozzles and rounded-entrance holes, this becomes the limiting flow rate, independent of downstream pressure. However, this phenomenon has not been observed in tests of sharp-edged orifices [20, 23].

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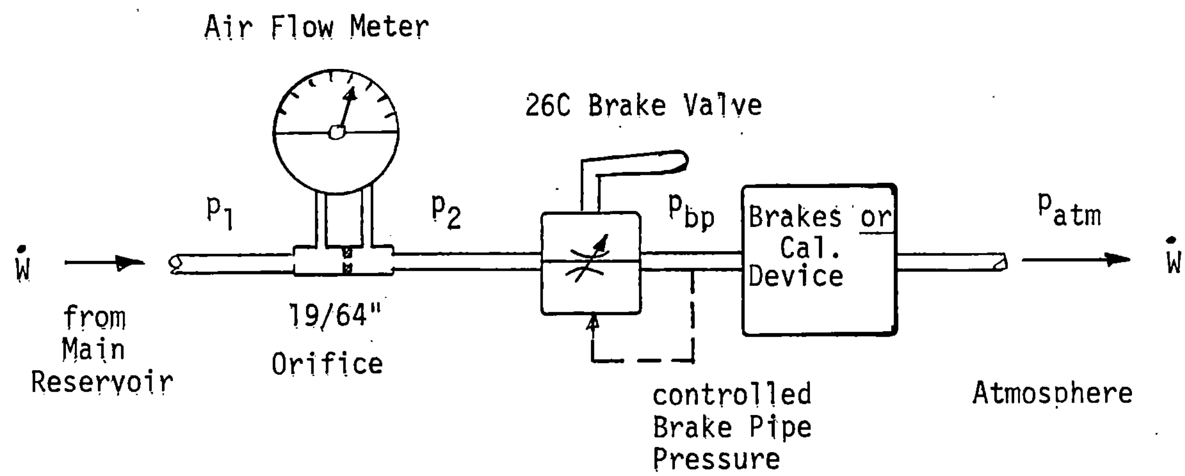

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4.2 Error Analyses

4.2.1 Leakage Rate Test Method

In the currently-used pressure-drop test for brake pipe leakage, loss in BP pressure is measured over a one-minute time period. Once the minimum rear-end pressure (60 psig) and the maximum pressure gradient (15 psig) criteria are met, a 15-psi service reduction in BP pressure is made and the brake valve lapped (or pressure-maintaining function turned off). The drop in BP pressure is timed over a 60-second period following a 30- to 60-second delay after brake application exhaust ceases.

A simplified formula was developed by Bender, et al [13] for pressure drop (in the leakage test) versus time, as an exponential decay in pressure. This formula can provide some insights into the various error factors inherent the test:

$$\Delta p_{bp} = p' e^{\alpha t'} [e^{-\alpha t} - e^{-\alpha (t+60)}] \qquad (4\text{-}2)$$

where... $\alpha = 0.532 C_D A R \sqrt{T} / V$

Δp_{bp} = change in BP pressure over a 60-second period, psi,

p' = absolute value of equalized BP pressure (after service reduction), psia, [assumed 66.4],

α = inverse of BP system leakage time constant, 1/sec,

t' = time to equalized BP pressure, sec [assume 12],

t = delay time after brake application, sec [assume 30],

C_D = leakage hole(s) discharge coefficient [assume 0.9],

A = leakage area per car, in^2 [assume 0.00015],

R = gas constant, in-lb/lb-^oR [640],

T = BP air temperature, deg R (deg F + 460) [assume 530],

V = BP air volume per car, in^3 [assume 706].

Using these representative values, a train leakage rate, Δp, of 5.6 psi/min is calculated. Increasing the delay time from 30 to 60 seconds after brake application to start timing the pressure drop will decrease the rate to 5.3 psi/min, about a five percent error. Errors in reading the watch during timing will introduce errors of roughly 1-1/2 percent per second. The exponential factor, a, in this formula is shown to vary as the square-root of absolute temperature, so that for a fixed leakage area the warmer the brake pipe air, the faster the pressure drop. In the above example, a range of ambient temperature from -30 F to +110 F would increase the leakage from 5.0 to 5.8 psi/min. However, leakage (Equation 4-1a) varies as the inverse square root of temperature, so that this result from Equation 4-3 is questionable.

Pressure gauge errors can consist of absolute (range) errors, linearity, backlash, friction and hysteresis, and resolution errors. Gauges are typically from 0-160 to 0-200 psig full scale in 10-psi major increments (markings), and 2-psi minor increments. Gauges are tested on BN to 1 psi accuracy, and held to ±3 psi (all errors) in operation. The full-scale accuracy has little effect on the measurement of change in pressure during a leakage test. Resolution (interpolation) errors are more important, and may be typically ±1 psi. Errors may also be induced by gauge movement "stiction" and hysteresis, so that tapping the gauge face with a finger may be necessary to assure proper measurement. Engine vibrations while pulling a train will normally provide sufficient "dither" to the gauges, but these vibrations are at lower levels during a terminal brake test.

From the above, we can assume 0.5 psi errors at both the start and 60-second gauge readings, and 0.4 psi errors due to delay time and pressure-drop timing. These can be combined to cause total errors in BP leakage measurement (for a 5 psi/min BP leakage) of ±0.9 psi (rms) to ±1.8 psi (worst-case), an 18 to 36 percent error.

More importantly, however, the timed pressure drop will be directly proportional to the equalized BP pressure, which is lower than the normal BP pressure with brakes released. This measurement therefore predicts a leakage rate at least 19 percent lower than that with the BP pressure at its normal level.

4.2.2 Air Flow Method

The AFM to date utilizes a pressure gauge to measure pressure differential across an orifice, generated by brake pipe air flow at the locomotive control valve into the train line (Figure 4-2). The gauges may typically range from 0-15 to 0-20 psi full scale with 1-psi markings, with an accuracy well within ±1/2 psi, and resolution to about 1/4 psi. At flows near 60 scfm, these gauge tolerances translate into flow accuracies of ± 1.5 scfm. With the 19/64-inch diameter orifice, 60 scfm air flow will develop pressure differentials of 10 to 12 psi. Therefore with a 0-15 psi range, some bypass (parallel) flow is needed to set the gauge at "8" (or at mid-range) during calibration.

To explore the effects of several error sources on this method for measuring air flow, we will assume an example case of exactly 60 scfm air flow (0.0764 lb/sec) into the brake pipe from the main reservoir supply. For the moment, we will ignore any bypass flow, which will reduce the sensitivity of the air flow meter to change. Using the proper values for the flow and expansion coefficients for a 19/64-inch diameter sharp-edged orifice [22], Equation 4-1a may be stated as:

$$\Delta p = 3.01\ T_1 / p_1 \qquad (4\text{-}3)$$

Assuming a main reservoir pressure of 115 psig and temperature of 60 F, a pressure drop of 12.1 psi will occur across the gauge at 60 scfm.

4.2.2.1 Effects of Main Reservoir Pressure. Air compressors on freight locomotives typically cycle over a 10-psi range, cutting in when the main reservoir pressure drops to its minimum setting. This minimum is 115 psig on the Burlington Northern, 130 psig on Canadian National.

Variations in air flow meter readings as the main reservoir pressure cycles are given below in Table 4-1.

TABLE 4-1. EFFECTS OF MAIN RESERVOIR PRESSURE VARIATIONS ON AIR FLOW METER (PRESSURE GAUGE) READINGS

p_1 (psig)	Δp (psi)	ΔQ (cfm)	Error (%)
115	12.1	0*	0
125	11.2	-2.2	-3.6
130	10.8	0*	0
140	10.1	-2.0	-3.3

* Assumed calibrated at minimum pressure; 60 scfm, T_1 = 60 F.

These apparent changes in flow will occur as the locomotive air compressors cycle on and off, even though the 60 scfm flow remains constant.

4.2.2.2 Effects of Main Reservoir Temperature. The locomotive main reservoir air temperature may range from ambient to somewhat warmer than ambient, depending on how hard the compressor has been working. The reservoirs are located beneath the locomotive frame, directly exposed to outside air, so that the source air temperature can easily range from below -30 F to above +100 F.

The effects of main reservoir air temperature are shown in Table 4-2. Again, for this example, we are assuming a fixed (actual) flow rate of 60 scfm. In the table, there is an apparent change in flow rate with change in temperature, even though we have assumed a constant 60 scfm flow rate. Note, however, that a given leak (such as the calibration device itself) will show no change in reading, but will change in actual flow rate. Therefore, the "calibration" should read the same, no matter what the temperature at which it is done. (This assumes no changes in air temperature through the brake control valve into the brake pipe.) Note that a true mass flow indicator would show this actual change in flow with temperature.

TABLE 4-2. EFFECTS OF MAIN RESERVOIR TEMPERATURE VARIATIONS ON AIR FLOW METER (PRESSURE GAUGE) READINGS

T_1 (deg F)	Δp (psi)	Apparent Q (cfm)	Apparent ΔQ (cfm)	Apparent Error (%)
-30	10.0	54.6	-5.4	-9.1
0	10.7	56.4	-3.6	-5.9
20	11.1	57.6	-2.4	-3.9
60	12.1	60.0	0	0
100	13.0	62.3	+2.3	+3.8

Note: for an actual flow of 60 scfm (0.0764 lb/sec)

4.2.2.3 Effects of Barometric Pressure. Normal variations in the barometric pressure due to weather conditions range roughly ± 1 percent at sea level. The effects of these changes on absolute main reservoir or brake pipe pressures can be ignored. Changes with altitude, however, can be substantial. At 10,000 ft altitude, a pressure ratio of 0.6877 of standard atmosphere exists. The effects on air flow measurements with a pressure gauge are given in Table 4-3.

Leakage, however, is also affected by the lower atmospheric pressure. If we assume the same total leakage area at choke flow, and the same brake pipe temperature and pressure (80 psig, for this example), a 60 scfm leak (0.0764 lb/sec) at sea level would decrease to 57.1 scfm (0.0727 lb/sec) at a 10,000-ft elevation.

TABLE 4-3. EFFECTS OF BAROMETRIC PRESSURE VARIATIONS ON AIR FLOW METER (PRESSURE GAUGE) READINGS

Patm (psia)	P1 (psig)	Δp (psi)	ΔQ (cfm)	Error (%)
14.7	115	12.1	0*	0
10.1	115	12.5	+1.1	+1.8
14.7	130	10.8	0*	0
10.1	130	11.2	+1.0	+1.6

* Assumed calibrated at minimum p_1 pressure; 60 scfm, T_1 = 60 F.

4.2.2.4 Effects of Humidity. Moisture in air has a minor effect on the density of the air and will therefore have little influence on the thermodynamics of the AFM. [Note that "standard" air, 14.7 psia and 60 F, ignores humidity; while "normal" air is defined at 14.7 psia, 68 F and 36 percent relative humidity.] Some moisture is removed from the source air by the compressor interstage cooler trap. Enough moisture remains in the air, however, to cause problems in train brake systems at extreme cold temperatures. None of these problems have been associated with the AFM or the air flow meters.

4.2.3 Air Flow Meter Calibration

Air flow meter calibration procedures have been discussed previously in Section 3.3. The need to catch the calibration mark at the lowest main reservoir pressure, with the pressure rising, has been emphasized. The effects of varying main reservoir pressure on air flow measurements are shown in Table 4-1, where errors of 3 to 4 percent can be introduced in the calibration.

Brake pipe air temperature has a strong effect on the actual flow rate through the calibration device. If we assume the published values of C and Y for an ASME sharp-edged orifice [20, 21, 22], and the nominal procedural conditions for calibration on BN and CN, the flow variations can be calculated. These are given in Table 4-4.

TABLE 4-4. EFFECTS OF BRAKE PIPE AIR TEMPERATURE VARIATIONS ON CALIBRATION DEVICE AIR FLOW RATE

Burlington Northern: d_o = 0.234 in., BP @ 80 psig

T_{bp} (deg F)	W (lb/sec)	Q (scfm)	Error (%)
-30	.0874	68.6	+9.9
0	.0845	66.3	+6.3
20	.0827	64.9	+4.0
60	.0794	62.4	0
100	.0766	60.1	-3.7

Canadian National*: d_o = 0.243 in., BP @ 75 psig

T_{bp} (deg F)	W (lb/sec)	Q (scfm)	Error (%)
-30	.0888	69.7	+9.9
0	.0858	67.4	+6.3
20	.0840	66.0	+4.1
60	.0807	63.4	0
100	.0778	61.1	-3.6

* Assuming the Canadian National device is a sharp-edged orifice.

From tests reported by BN, it appears that actual C and Y values are slightly lower than the published values. These air flow calculations are predicated on the 26C control valve maintaining the brake pipe pressure at the desired value: 80 or 75 psig, respectively. As noted in previous sections, the air flow meter would indicate the same flow, independent of temperature, because of the compensating effect of the orifice and pressure differential gauge. The "calibration", however,would be in error, with actual flow rates proportional to those of Table 4-4. For this reason, the calibration device must be certified (calibrated itself) at a lower temperature, to minimize this reading error in cold weather, when leakage problems can be accentuated. And for this reason, the AAR Calibration Procedure RP-402 (Figure 3-4) requires the device to pass 60 scfm flow at some temperature not exceeding 20 F.

The calibration device must be treated with care, because any dirt or damage (nicks on the orifice edge, etc.) can cause significant changes to the flow or expansion coefficients and consequent changes in the calibration air flow.

4.3 Air Flow Meter Accuracy Requirements

The AAR Mechanical Division has issued specifications for air flow meterrs in the Manual of Standards and Recommended Practices, "Air Flow Indicators, Specification M-980, effective January 1, 1989". Specification M-980 is included as Appendix A of this report. In these specifications, the device must be accurate within ± 2 cfm at a flow rate of of 60 cfm (M-980, Section 3.3).

In Section 4.2.2 of this report, flow accuracies of ± 1.5 scfm were calculated, based on typical pressure gauge errors and a flow rate of 60 scfm. However, flow measurement by pressure differential across an orifice was found dependent on three important factors:

- Main reservoir air pressure, both the minimum setting and the cycle range: 0 to -2 cfm over compressor cycle.
- Main reservoir air temperature: ± 2 cfm over a "reasonable" temperature range (30 to 90 F).
- Altitude: + 1 cfm at 10,000 ft elevation.

These errors can combine to give total errors ranging from + 4.5 cfm to - 5.5 cfm at a nominal 60 scfm, with an rms (more probable) error of ± 2.7 cfm. Therefore the currently-used devices cannot in the strictest sense meet the AAR requirement.

Orifice flow and expansion coefficients, C and Y, tend to increase at lower flow velocities (Reynolds Number) and lower pressure drops, which adds to the basic nonlinearity of the current air flow meters. These errors, however, are dominant only at flows less than about 5 scfm.

4.4 Air Flow Meter Reliability

Currently both the leakage rate test and air flow test methods rely on standard pressure gauges to qualify the train brake system for service. From long service experience, pressure gauges are known for high reliability and endurance. Gauges used in the AFM require the same 92-day inspection cycle as other air pressure gauges in the locomotive cab. The metering orifice at the air flow indicator is a passive device, except for the pressure relief function at high (charging) flow rates. There is no evidence from past experience with the AFM of any problems with air flow indicators. Therefore, in terms of equipment reliability, both methods are comparable.

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APPENDIX A

AAR SPECIFICATION M-980

AIR FLOW INDICATORS

SPECIFICATION M-980

Effective January 1, 1989

1.0 PURPOSE

The purpose of this specification is to define minimum functional, mechanical, test and approval requirements for Air Flow Method (AFM) type flow indicators. This indicator is for use on a locomotive equipped with a 19/64" orifice per RP-505, Section F, Manual of Standards and Recommended Practices.

2.0 SCOPE

All AFM type flow indicators used on locomotives must meet the requirements of these specifications and shall be subject to approval by the Mechanical Division, Association of American Railroads, for design, method of application, operation, testing and approval.

2.1

The manufacturer will apply in writing to the Director Technical Committees: Quality Assurance, Mechanical Division, Association of American Railroads, Washington, D.C., to initiate the approval process.

2.2

The request for approval must include fifteen (15) sets of drawings showing the assembled flow indicator device, sectional views with component parts numbered and a parts list showing the piece number, reference and description of the component parts. In addition, fifteen (15) copies of manufacturer's recommended test code and shop maintenance instructions for the flow indicator device on which approval is desired are to be submitted.

2.3

A representative of the AAR will select six (6) flow indicator devices for test purposes from a production lot of not less than fifty (50) devices of the design being submitted for approval. Two (2) devices will be tested in accordance with Sections 3.0 and 4.0. Two (2) devices will be tested in accordance with Section 5.0. Two (2) devices will be tested in accordance with Section 6.0.

2.4

The manufacturer must submit in writing a request to change or modify the design, material, manufacture of parts, location of manufacture or assembly of conditional or approved flow indicator device or related equipment. Changes cannot under any circumstances be introduced into production before the AAR Brake Equipment Committee has approved the change and the manufacturer advised of approval by the AAR.

2.5

All replacement parts used in flow indicator device maintenance must be equal to or better than original equipment material and, where possible, include the manufacturer's identification.

2.6

Following AAR Brake Equipment Committee conditional approval, the manufacturer is required to furnish semi-annually a report of distribution and service performance, which is due within thirty (30) days of the January 1 and July 1 reporting dates. The distribution portion must include the total distribution at the end of the reporting period. The service performance portion must include all known malfunctions or difficulties experienced. This report must be submitted until unconditional approval is granted.

2.7

In the event the foregoing is not complied with, the AAR Brake Equipment Committee will consider withdrawal of approval.

3.0 REQUIREMENTS

3.1

The device must be clearly identified as an air flow indicator or AFM indicator. The manufacturer's name and a unique serial number must be clearly marked on each device so it can be read when indicator is installed.

3.2

The device must be capable of in-place adjustment for calibration purposes but so designed to discourage tampering.

3.3

The device must be accurate within ±2 cfm at a flow rate of 60 cfm.

3.4

The device must be capable of withstanding 300 psig proof pressure and differential pressure rating up to 40 psig.

3.5

The device sensitivity must be capable of indicating a ±2 cfm change in flow at the 60 cfm level. The device must respond to 1/2 psi changes in differential pressure.

3.6

The device may be of the pneumatic or electronic type. It must be easily readable day or night, illuminated as required, producing minimum glare.

3.7

The device may be equipped with indicator lights or warning buzzer, with reset feature, for special functions.

3.8

The device must indicate flow in units of cfm, and be designed and calibrated so that the pointer or reading indicating a flow of 60 cfm be located near the center of the scale. Gauge face must display markings from 10 cfm to 80 cfm, in 10 cfm or less increments, with numerals indicating 20, 40, 60 and 80 cfm markings for continuous monitoring of flow. The gauge scale, from bottom marking to top marking, must cover a linear length of at least 3 inches. (Digital air flow indicator must display flow continuously from 10 cfm to 80 cfm in 1 cfm increments.)

6.0 VIBRATION AND SHOCK TESTS

6.1

Subject device to a sinusoidal vibration input of 2G. The frequency is to be varied at a rate of one octave per minute from 10 Hz to 200 Hz and then back from 200 Hz to 10 Hz. The device shall be vibrated in each of the three major axes. An accelerometer will be mounted on the device to detect natural frequencies. The device shall be vibrated continuously at the frequency with the highest feedback for a period of one hour with a 2G input load. Subject device to vertical and lateral shock of 2G peak for 0.01 second and longitudinal shock of 5G peak for 0.01 second.

6.2

At completion of vibration and shock tests, the device shall be recalibrated and tested per paragraphs 3.3 through 3.5 to ensure that the device is operational.