CTX1931-3 Compressed Air Systems (CAS) Memo

Summary of Literature Review and Recommendations

Memo To: CT Energy Efficiency Board (EEB)

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OVERVIEW

The objective of this study is to create entries for industrial Compressed Air Systems (CAS) measures to be incorporated into the 2022 CT PSD. The new measures were developed through secondary literature review and through discussions with program administrators (PA) and program implementers. The primary source of information for the development of the new measures was the literature review. The team reviewed over 15 sources published between 2000 – 2021, including the following TRMs: IL, MA, Mid-Atlantic, MN, NH, NY, VT, WI.

The following measures were developed as part of this study:

1. Variable Speed Drive-Controlled Air Compressors
2. High Efficiency Refrigerated Air Dryers.
3. Efficient Compressed Air Nozzles
4. Compressed Air Leak Detection.

The 2021 CT PSD did not include any compressed air systems measures. The team developed the electric energy and demand savings methodologies and inputs for each measure based on secondary research which included the evaluation and assessment of several TRMs' methodologies. The team selected and developed the most appropriate savings calculation methodology for each measure by critically examining and evaluating the referenced sources, target system and baseline descriptions, and applicability of the measure in the reviewed TRMs.

The sections below describe the savings calculation methodology for each measure. See Appendix A for complete write-up of each measure for entry into the PSD.

1. VARIABLE FREQUENCY DRIVE-CONTROLLED AIR COMPRESSORS

This measure covers the installation of oil flooded, rotary screw compressors with Variable Frequency Drives (VFD) instead of one load/unload control. This measure applies only to air compressors that are ≥ 15 HP and ≤ 75 HP.

The savings calculations and factors were estimated based on a study of prescriptive compressed air systems[1], which used actual compressed air systems loading measurements and metered operation hours to estimate a savings factor.

The energy and demand savings methodology formulas below are included in the measure write-ups:

$$Energy\ Savings = CAS\ Nominal\ Rated\ Horsepower \times Operating\ hours \times Savings\ Factor$$

$$Summer\ Peak\ Demand\ Savings = CAS\ Nominal\ Rated\ Horsepower \times Savings\ Factor \times Summer\ Coincidence\ Factor$$

$$Winter\ Peak\ Demand\ Savings = CAS\ Nominal\ Rated\ Horsepower \times Savings\ Factor \times Winter\ Coincidence\ Factor$$

[1] DNV KEMA (2015), *Impact Evaluation of Prescriptive Chiller and Compressed Air Installations*, pp. 8-11

Table 1 highlights the main inputs required to calculate the measure savings and their corresponding sources.

Table 1. Main inputs for the VFD-controlled air compressors measure

Parameter	Value	Source
Savings Factor	0.189 kW/HP	DNV GL, 2015
Summer Coincidence Factor	94.7%	Coincidence Factor & Load shape Study for 2022 CT PSD
Winter Coincidence Factor	74.3%	Coincidence Factor & Load shape Study for 2022 CT PSD

2. HIGH EFFICIENCY AIR DRYERS

This measure covers the installation of cycling or Variable Frequency Drives (VFDs)-controlled refrigerated air dryers instead of non-cycling refrigerated dryers. This measure is applicable to single compressor systems and to systems with one main compressor and other backup compressors. This measure is not applicable to sequentially staged multiple compressors systems.

The savings calculations and factors were estimated based on a study of prescriptive compressed air systems[2], which used actual compressed air systems loading measurements and metered operation hours to estimate a savings factor.

The energy and demand savings methodology formulas below are included in the measure write-ups:

$$Energy\ Savings = Air\ Dryer\ Full\ Flow\ Rated\ Capacity \times Operating\ hours \times Savings\ Factor$$

$$Summer\ Peak\ Demand\ Savings = Air\ Dryer\ Full\ Flow\ Rated\ Capacity \times Savings\ Factor \times Summer\ Coincidence\ Factor$$

$$Winter\ Peak\ Demand\ Savings = Air\ Dryer\ Full\ Flow\ Rated\ Capacity \times Savings\ Factor \times Winter\ Coincidence\ Factor$$

Table 2 presents the main inputs required to calculate the measure savings and their corresponding sources.

Table 2. Main inputs for the high efficiency air dryers measure

Parameter	Value	Source
Savings Factor	0.00554 kW/CFM	DNV GL, 2015
Summer Coincidence Factor	83.8%	Coincidence Factor & Load shape Study for 2022 CT PSD
Winter Coincidence Factor	77.7%	Coincidence Factor & Load shape Study for 2022 CT PSD

3. EFFICIENT COMPRESSED AIR NOZZLES

This measure covers the replacement of standard air nozzle with high-efficiency nozzle in compressed air system. The engineered air nozzles entrain compressed air with surrounding air as it leaves the nozzle. This increases air flow volume with less compressed air use. The engineered air nozzles reduce the velocity of the resulting airflow but increase the mass flow of the air which improve the cooling and drying effects. Efficient nozzles typically have the added benefits of noise reduction and improved safety in systems with line pressure greater than 30 psig.

The energy and demand savings methodology formulas below are included in the measure write-ups:

[2] DNV KEMA (2015), *Impact Evaluation of Prescriptive Chiller and Compressed Air Installations*, pp. 8-11

$$Energy\ Savings = Specific\ Air\ Flow\ Rate \times Specific\ Air\ Flow\ Reduction\ Percentage\ \times Efficiency\ of\ Air\ Compressor \times Marginal\ Efficiency\ Factor \times Nozzle\ Usage\ Percentage\ of\ Total\ System\ Operation \times Operating\ hours$$

$$Peak\ Demand\ Savings = Energy\ Savgins\ /\ (Operating\ Hours \times Coincidence\ Factor)$$

The high-efficiency air nozzle must meet must exceed certain SCFM ratings which are listed in the measure writeup. Table 3 presents the main inputs required to calculate the measure savings and their corresponding sources.

Table 3. Main inputs for the efficient air nozzles measure

Parameter	Value	Source
Specific Air Flow Reduction Percentage	50%	Based on review of several manufacturers' technical specification sheets
Nozzle Usage Percentage of Total System Operation	0.03	Site specific. If unknown use 0.03, based on 15 mins per 8 hours shift

* The values of the marginal efficiency factor, efficiency of air compressor, and standard specific flow rates for various orifice diameter are to be determined from separate tables that are included in the measure write-ups.

EFFECTIVE USEFUL LIFE

The effective useful life (EUL) is an estimate of the median number of years that a measure installed through a program is still in place and operable. For efficient compressed air nozzles, the recommended EUL of 15 years.[3]

4. COMPRESSED AIR LEAK DETECTION

This measure covers the detection of compressed air losses through ultrasonic leak detection, and the repair of compressed air leaks.

Air leaks are common in compressed air systems, often wasting 20%-30% of the compressor's output. Air leak loss rate depend on the supply pressure in an uncontrolled system, as well as leak size quantity and time. This measure is applicable for general plant compressed air systems in manufacturing environments (70 to 125 psig).

The energy and demand savings methodology formulas below are included in the measure write-ups:

$$Energy\ Savings = Number\ of\ Leaks \times Flow\ rate\ loss\ per\ leak\ \times Efficiency\ of\ Air\ Compressor \times Marginal\ Efficiency\ Factor \times Nozzle\ Usage\ Percentage\ of\ Total\ System\ Operation \times Operating\ hours$$

$$Peak\ Demand\ Savings = Energy\ Savgins\ /\ (Operating\ Hours \times Coincidence\ Factor)$$

Table 4 presents the main inputs required to calculate the measure savings and their corresponding sources.

Table 4. Main inputs for the compressed air leak detection measure

Parameter	Value	Source
Summer Coincidence Factor	94.7%	Coincidence Factor & Load shape Study for 2022 CT PSD
Winter Coincidence Factor	74.3%	Coincidence Factor & Load shape Study for 2022 CT PSD

* The values of the marginal efficiency factor, efficiency of air compressor, and standard specific flow rates for various orifice diameter are to be determined from separate tables that are included in the measure write-ups.

[3] PA Consulting Group (2009), Business Programs: Measure Life Study. Prepared for State of Wisconsin Public Service Commission.

Appendix A

COMPRESSED AIR SYSTEMS

VARIABLE FREQUENCY DRIVE-CONTROLLED AIR COMPRESSORS

Description of Measure

Installation of oil flooded, rotary screw compressors with Variable Frequency Drives (“VFDs”) instead of one with load-unload control. This measure applies only to air compressors that are ≥ 15 HP and ≤ 75 HP.

Savings Methodology

Load-unload controlled compressors have significant cycling losses. They work as follows: The compressor runs loaded, producing compressed air. Once the system reaches the maximum pressure setpoint, they unload or “cut-out.” The system must release the compressed air from the oil separator and surrounding air lines just downstream of the compressor. The compressor then idles until system pressure drops to the minimum pressure setpoint, at which point it “cuts in” and reloads for the next cycle. Variable speed drive-controlled compressors avoid these cycling and idling losses.

The baseline is a typical load/unload compressor. The high efficiency replacement is an oil flooded, rotary screw compressor with VFD part load control.

The savings calculations are estimated based on a study of prescriptive compressed air **Ref [1],** which used actual compressed air systems loading measurements and metered operation hours to estimate a savings factor.

Inputs

Table 1-A: Inputs

Symbol	Description
HP	Air compressor nominal rated horsepower
H	Annual hours the compressed air system is pressurized

Nomenclature

Table 1-B: Nomenclature

Symbol	Description	Units	Values	Comments
AKWH	Annual electric energy savings	kWh/yr		
SkW	Summer demand savings	kW		
WkW	Winter demand savings	kW		
HP	Air compressor nominal rated horsepower	HP		
SF	Savings factor	kW/HP	0.189	**Ref [1]**
CF_S	Summer coincidence factor			*Appendix One*
CF_W	Winter coincidence factor			*Appendix One*
H	Annual hours the compressed air system is pressurized			Site specific (must be provided on application form) or default, use table 1-C

Table 1-C: Default Operation Hours of Compressed Air Systems

Shift	Hours	Notes
Single shift (8/5)	1,976	7 AM – 3 PM, weekdays, minus some holidays and scheduled down time
2-shift (16/5)	3,952	7AM – 11 PM, weekdays, minus some holidays and scheduled down time
3-shift (24/5)	5,928	24 hours per day, weekdays, minus some holidays and scheduled down time
4-shift (24/7)	8,320	24 hours per day, 7 days a week minus some holidays and scheduled down time

Lost Opportunity Gross Energy Savings, Electric, see Note [1]

$$AKWH = HP \times H \times SF$$

Lost Opportunity Gross Seasonal Peak Demand Savings, Electric (winter and summer)

$$SkW = HP \times SF \times CF_S$$

$$WkW = HP \times SF \times CF_W$$

References

[1] DNV KEMA (2015), *Impact Evaluation of Prescriptive Chiller and Compressed Air Installations*, pp. 8-11.

Notes

[1] In case sufficient site-specific information or/and metered data are available, custom savings calculation should be used to calculate more accurate savings.

HIGH EFFICIENCY REFRIGERATED AIR DRYERS

Description of Measure

Installation of cycling or Variable Frequency Drives ("VFDs")-controlled refrigerated air dryers instead of non-cycling refrigerated dryers. This measure is applicable to single compressor systems only[4].

Savings Methodology

Refrigerated compressed air dryers use a refrigeration system to reduce the compressed air temperature below its dewpoint (about 35°F) to condense and remove moisture from a compressed air stream. The baseline condition is a compressed air system equipped with a non-cycling air dryer that uses hot gas bypass controls to modulate refrigeration capacity. Hot gas bypass requires constant refrigeration system operation at near-full input power. In contrast, a high efficiency air dryer cycles on and off or uses a variable frequency drive (VFD) to modulate refrigeration capacity instead, which allows load reduction.

The savings calculation is based on a study of prescriptive compressed air **Ref [1]**, which used the actual compressed air systems loading measurements and metered operation hours to estimate a savings factor.

This measure is not applicable for conversion from another type of dryer such as desiccant dryer to a refrigerated dryer.

Inputs

Table 1-D: Inputs

Symbol	Description
CFM_{Dryer}	Full flow rated capacity of the refrigerated air dryer in cubic feet per minute (CFM)
H	Annual hours the compressed air system is pressurized

[4] This measure is also applicable to systems with one main compressor and other backup compressors, but not applicable to sequentially staged multiple compressors systems.

Nomenclature

Table 1-E: Nomenclature

Symbol	Description	Units	Values	Comments
AKWH	Annual electric energy savings	kWh/yr		
SkW	Summer demand savings	kW		
WkW	Winter demand savings	kW		
CFM_{Dryer}	Full flow rated capacity of the refrigerated air dryer in cubic feet per minute (CFM)	CFM		Obtain from equipment's Compressed Air Gas Institute Datasheet
SF	Savings factor	kW/CFM	0.00554	**Ref [1]**
CF_S	Summer coincidence factor			*Appendix One*
CF_W	Winter coincidence factor			*Appendix One*
H	Annual hours the compressed air system is pressurized	Hrs/yr		**Site Specific** or default, use table 1-F

Table 1-F: Default Operation Hours of Compressed Air Systems

Shift	Hours	Notes
Single shift (8/5)	1,976	7 AM – 3 PM, weekdays, minus some holidays and scheduled down time
2-shift (16/5)	3,952	7AM – 11 PM, weekdays, minus some holidays and scheduled down time
3-shift (24/5)	5,928	24 hours per day, weekdays, minus some holidays and scheduled down time
4-shift (24/7)	8,320	24 hours per day, 7 days a week minus some holidays and scheduled down time

Lost Opportunity Gross Energy Savings, Electric, see Note [1]

$$AKWH = CFM_{Dryer} \times H \times SF$$

Lost Opportunity Gross Seasonal Peak Demand Savings, Electric (winter and summer)

$$SKW = CFM_{Dryer} \times SF \times CF_S$$

$$WKW = CFM_{Dryer} \times SF \times CF_W$$

References

[1] DNV KEMA (2015), *Impact Evaluation of Prescriptive Chiller and Compressed Air Installations*, pp. 8-11.

<u>Notes</u>

[1] In case sufficient site-specific information or/and metered data are available, custom savings calculation should be used to calculate more accurate savings.

EFFICIENCT COMPRESSED AIR NOZZLES

Description of Measure

Replacement of standard air nozzle with high-efficiency nozzle in compressed air systems.

Savings Methodology

Engineered air nozzles entrain compressed air with surrounding air as it leaves the nozzle. This increases air flow volume with less compressed air use. The engineered air nozzles reduce the velocity of the resulting airflow but increase the mass flow of the air which improve the cooling and drying effect. The energy savings associated with the engineered air nozzles are due to the reduced compressor work. Efficient nozzles typically have the added benefits of noise reduction and improved safety in systems with greater than 30 psig line pressure.

The baseline condition is standard air nozzle. The high-efficiency air nozzle must meet the following specifications:

1. High-efficiency air nozzle must replace standard air nozzle.
2. High-efficiency air nozzle must meet SCFM rating at 80psig less than or equal to: 1/8” 11 SCFM, 1/4" 29 SCFM, 5/16” 56 SCFM, 1/2" 140 SCFM.
3. Manufacturer’s specification sheet of the high-efficiency air nozzle must be provided along with the make and model.

Inputs

Table 1-G: Inputs

Symbol	Description
SCFM	Air flow through standard air nozzle
H	Annual hours the compressed air system is pressurized

Nomenclature

Table 1-H: Nomenclature

Symbol	Description	Units	Values	Comments
AKWH	Annual electric energy savings	kWh/yr		

kW	Electric peak demand savings	kW		
SCFM	Air flow through standard nozzle	CFM		Use actual rated flow at 80 psi. If unknown use table 1-G.
SCFM%Reduced	Percent in reduction of air loss per nozzle	%	0.5	**Note [1]**
EFF_{Comp}	Efficiency of air compressor	kW/CFM		Use table 1-H. If unknown, use 0.19 kW/CFM
MEF	Marginal efficiency factor per control type for air compressor	kW/Percent Load		Use table 1-I. If unknown, use 0.3%kW/%load
%USE	Percent of the system total annual pressurized hours during which the nozzle is in use	%	0.03	Site specific. If unknown, use 0.03
CF_S	Summer coincidence factor			*Appendix One*
CF_W	Winter coincidence factor			*Appendix One*
H	Annual hours the compressed air system is pressurized	Hrs/yr		Site specific or default, use table 1-I

Table 1-I: Default Operation Hours of Compressed Air Systems

Shift	Hours	Notes
Single shift (8/5)	1,976	7 AM – 3 PM, weekdays, minus some holidays and scheduled down time
2-shift (16/5)	3,952	7AM – 11 PM, weekdays, minus some holidays and scheduled down time
3-shift (24/5)	5,928	24 hours per day, weekdays, minus some holidays and scheduled down time
4-shift (24/7)	8,320	24 hours per day, 7 days a week minus some holidays and scheduled down time

Table 1-J: Specific Flow Rates for Various Orifice Diameters, see Ref [1]

Pressure (psig)	Orifice Diameter (inches)					
	1/64	1/32	1/16	1/8	1/4	3/8
70	0.29	1.16	4.66	18.62	74.4	167.8
80	0.32	1.26	5.24	20.76	83.1	187.2
90	0.36	1.46	5.72	23.1	92	206.6
100	0.40	1.55	6.31	25.22	100.9	227
125	0.48	1.94	7.66	30.65	122.2	275.5

* Assuming 100% orifice flow for the standard nozzle in the baseline condition. If the orifice flow is <100%, the savings equation must be multiplied by the partial flow percentage.

Table 1-K: kW/CFM Efficiencies for Several Air Compressor Types (EFF_{Comp}), see Ref [2]

Air Compressor Type	SAVE (kW/CFM)
Single-acting Reciprocating Air Compressor	0.230
Double-acting Reciprocating Air Compressor	0.155
Lubricant-injected Rotary Screw Compressor	0.185
Lubricant-free Rotary Screw Compressor	0.200
Centrifugal Compressor	0.180
Average	**0.190**

Table 1-L: Marginal Efficiency Factors per Control Type for Air Compressor Types (MEF), see Ref [3]

Control Type	Percent kW/Percent Load
Inlet Valve Modulated	0.31
Variable Displacement	0.69
Variable Speed Drive	0.85

Retrofit Gross Energy Savings, Electric [Note 2]

$$SKW = AKWH / H \times CF_S$$

$$WKW = AKWH / \mathrm{H} \times CF_W$$

Retrofit Gross Peak Demand Savings, Electric

$$AKWH = (SCFM \times \ SCFM\%Reduced) \times EFF_{Comp} \times MEF \times \%USE \times H$$

Effective Useful Life (EUL)

The measure EUL is 15 years, see Ref **[4].**

References

[1] U.S. Department of Energy. Energy Tips – Compressed Air. August 2004. Available online: https://www.energy.gov/sites/prod/files/2014/05/f16/compressed_air3.pdf. Originally from Fundamentals of Compressed Air Systems Training offered by the Compressed Air Challenge®.

[2] Compressed Air Challenge "Fundamentals of Compressed Air Systems" Pgs. 28-32.

[3] Compressed Air Challenge "Fundamentals of Compressed Air Systems" Pgs. 90-91.

[4] PA Consulting Group (2009), Business Programs: Measure Life Study. Prepared for State of Wisconsin Public Service Commission.

Notes

[1] Conservative estimate based on the technical specification sheets for several manufacturers as shown in the table below. In addition, the Illinois Statewide Technical Reference Manual for Energy Efficiency (Version 6.0) uses a similar calculation methodology and assumes an average of 50% in reduction of air loss per nozzle savings.

Table 1-M: Reported Savings Percentages for Engineered Air Nozzles from Several Manufacturers

Manufacturer	Savings Percentage	Comments	Links
Exair 2" Flat Super Air Nozzle	0.60	The manufacturer's website reports that savings range between 50% and 70%	https://www.exair.com/2inhpflat-ssh.html#:~:text=On%20a%2024%20hour%20production,use%20by%2050%2D70%25!
IKEUCHI	0.45		https://www.ikeuchi.us/eng/download/catalog/pdf/700c.pdf
Meech	0.70		https://meech.com/application/product-blowing-using-air-nozzles/
Silvent Air Nozzle 700m	0.47		https://www.silvent.com/products/air-nozzles/700-m/

[2] In case sufficient site-specific information or/and metered data are available, custom savings calculation should be used to calculate more accurate savings.

COMPRESSED AIR LEAK DETECTION

Description of Measure

This measure covers the detection of compressed air losses through ultrasonic leak detection, and the repair of compressed air leaks.

Savings Methodology

Air leaks are common in compressed air systems, often wasting 20%-30% of the compressor's output. Air leak loss rate depend on the supply pressure in an uncontrolled system, as well as leak size quantity and time. This measure is applicable for general plant compressed air systems in manufacturing environments (70 to 125 psig).

Inputs

Table 1-N: Inputs

Symbol	Description
H	Annual hours the compressed air system is pressurized

Nomenclature

Table 1-O: Nomenclature

Symbol	Description	Units	Values	Comments
AKWH	Annual electric energy savings	kWh/yr		
kW	demand savings	kW		
NL	Number of detected leaks			
CFM_{Leak}	Flow rate loss per leak in cubic feet per minute (CFM)	CFM		Use table 1-Q
EFF_{Comp}	Efficiency of air compressor	kW/CFM		Use table 1-R. If unknown, use 0.19 kW/CFM
MEF	Marginal efficiency factor per control type for air compressor	kW/Percent Load		Use table 1-S. If unknown, use 0.3%kW/%load
CF_S	Summer coincidence factor			*Appendix One*
CF_W	Winter coincidence factor			*Appendix One*
H	Annual hours the compressed air system is pressurized	Hrs/yr		Site specific or default, see table 1-O

Table 1-P: Default Operation Hours of Compressed Air Systems

Shift	Hours	Notes
Single shift (8/5)	1,976	7 AM – 3 PM, weekdays, minus some holidays and scheduled down time
2-shift (16/5)	3,952	7AM – 11 PM, weekdays, minus some holidays and scheduled down time
3-shift (24/5)	5,928	24 hours per day, weekdays, minus some holidays and scheduled down time
4-shift (24/7)	8,320	24 hours per day, 7 days a week minus some holidays and scheduled down time

Table 1-Q: CFM per Leak Size for Compressed Air Leaks, see Ref [2]

Table 1-P shows leakage rates for ideal orifices. Most gaps are irregular and sometimes ragged, which decreases the flow rate relative to the equivalent area.

Pressure (psig)	Orifice Diameter (inches)					
	1/64	1/32	1/16	1/8	1/4	3/8
70	0.29	1.16	4.66	18.62	74.4	167.8
80	0.32	1.26	5.24	20.76	83.1	187.2
90	0.36	1.46	5.72	23.1	92	206.6
100	0.40	1.55	6.31	25.22	100.9	227
125	0.48	1.94	7.66	30.65	122.2	275.5

* For well-rounded orifices, values should be multiplied by 0.97 and by 0.61 for sharp ones.

Table 1-R: kW/CFM Efficiencies for Several Air Compressor Types (EFF_{Comp}), see Ref [3]

Air Compressor Type	SAVE (kW/CFM)
Single-acting Reciprocating Air Compressor	0.230
Double-acting Reciprocating Air Compressor	0.155
Lubricant-injected Rotary Screw Compressor	0.185
Lubricant-free Rotary Screw Compressor	0.200
Centrifugal Compressor	0.180
Average	**0.190**

Table 1-S: Marginal Efficiency Factors per Control Type for Air Compressor Types (MEF), see Ref [4]

Control Type	Percent kW/Percent Load
Inlet Valve Modulated	0.31
Variable Displacement	0.69
Variable Speed Drive	0.85

Retrofit Gross Energy Savings, Electric

$$AKWH = NL \times CFM_{Leak} \times EFF_{Comp} \times MEF \times H$$

Retrofit Gross Peak Demand Savings, Electric

$$SKW = AKWH / H \times CF_S$$

$$WKW = AKWH / \mathrm{H} \times CF_W$$

References

[1] An average value derived from two coincidence factors that were developed through two separate studies. The 1st study is Aspen Systems Corporation, Prescriptive Variable Speed Drive Incentive Development Support for Industrial Air Compressors Executive Summary, June 20, 2005. The 2nd study is KEMA, New Jersey's Clean Energy Program Energy Impact Evaluation and Protocol Review, July 10, 2009.

[2] U.S. Department of Energy. Energy Tips – Compressed Air. August 2004. Available online: https://www.energy.gov/sites/prod/files/2014/05/f16/compressed_air3.pdf. Originally from Fundamentals of Compressed Air Systems Training offered by the Compressed Air Challenge®.

[3] Compressed Air Challenge "Fundamentals of Compressed Air Systems" Pgs. 28-32.

[4] Compressed Air Challenge "Fundamentals of Compressed Air Systems" Pgs. 90-91.