AFRL-ML-TY-TP-2007-4511

PREPRINT

EXHAUST RECIRCULATION – A TECHNOLOGY TO MINIMIZE ENERGY USE IN AIRCRAFT PAINTING OPERATIONS

Joe Wander
Air Force Research Laboratory
139 Barnes Drive, Suite 2
Tyndall Air Force Base Florida 32403

Gerald Doddington
HQ Air Force Civil Engineering Support Agency
139 Barnes Drive, Suite 1
Tyndall Air Force Base, Florida 32403

Steve Frere
3 Civil Engineering Squadron
6326 Arctic Warrior Drive
Elmendorf Air Force Base, Alaska 99506

Final Paper, June 2007

Submitted for publication in the conference proceedings for the 100th Air & Waste Management Association Meeting, Session EE-1c, 26-29 Jun 2007 in Pittsburgh PA.

Air Force Research Laboratory
Materials and Manufacturing Directorate
Airbase Technologies Division
139 Barnes Drive, Suite 2
Tyndall AFB, FL 32403-5323

NOTICE AND SIGNATURE PAGE

REPORT NUMBER AFRL-ML-TY-TP-2007-4511 HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION IN ACCORDANCE WITH THE ASSIGNED DISTRIBUTION STATEMENT.

This document will be included on the CD containing the conference proceedings for the 100th Annual Meeting of the Air & Waste Management Association (http://www.awma.org).

//signature//
JOSEPH D. WANDER
Work Unit Manager

//signature//
DANIEL M. SAUCER, Major, USAF
Acting Chief, Airbase Sciences Branch

//signature//
WENDELL D. BANKS
Chief, Airbase Technologies Division

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
01-APR-2007	Technical Paper (PREPRINT)	01-MAR-2005 - 31-AUG-2006

4. TITLE AND SUBTITLE

Exhaust Recirculation—A Technology to Minimize Energy Use in Aircraft Painting Operations

5a. CONTRACT NUMBER F08637-98-C-6002

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER 63723F

6. AUTHOR(S)

Wander, Joe; Doddington, Gerald; Frere, Steve

5d. PROJECT NUMBER 2103

5e. TASK NUMBER 70

5f. WORK UNIT NUMBER 21037097

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory
Materials and Manufacturing Directorate
139 Barnes Drive, Suite 2
Tyndall AFB, FL 32403-5323

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory
Materials and Manufacturing Directorate
139 Barnes Drive, Suite 2
Tyndall AFB, FL 32403-5323

10. SPONSOR/MONITOR'S ACRONYM(S) AFRL/MLQL

11. SPONSOR/MONITOR'S REPORT NUMBER(S) AFRL-ML-TY-TP-2007-4511

12. DISTRIBUTION/AVAILABILITY STATEMENT

Distribution Statement A: Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

Submitted for publication in conference proceedings for the 100th Air & Waste Management Association Meeting, Session EE-1c, 26-29 June 2007, Pittsburgh PA. Document contains color images.

14. ABSTRACT

The mandate in DoDD 5000.1 to manage risk as an element of acquisition cost control enabled Robins AFB's justification for incorporation of 80% exhaust recirculation into the design for construction of a corrosion control facility (CCF) for C-5 aircraft that will enter service in 2007. A key tool in developing their justification was the LaPuma model, a process model into which a user inputs facility and process parameters to calculate the steady-state background air concentration of process-derived contaminants as a function of percent exhaust recirculated. The assumption that isocyanates-the exposure risk driver in topcoats-are an inert, ideal gas rather than a reactive, sticky vapor causes their concentration to be overestimated, and exposure data from the C-5 CCF are expected to clarify the extent and moment of this overestimation.
In 2005 Elmendorf AFB followed Robins' lead and precedents in designing a C-17 CCF at 80% recirculation to save several $M in construction costs and $0.5M annually in fuel costs to operate. (continued on p. ii)

15. SUBJECT TERMS

aircraft, chromate, coating, isocyanate, maintenance, recirculation, spray painting

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
U	U	U	UU	13	Joe Wander/DR-III
					19b. TELEPHONE NUMBER *(Include area code)*

Reset

14. Abstract (Concluded):

Predicted isocyanate concentrations for a (smaller) F-22 component repair facility (CRF) required interpretation and Elmendorf specified a conventional design in their bid request. That the only proposal whose cost was within the project budget included 80% recirculation created a situation that was ultimately resolved by a meeting of the design team, users, bioenvironmental engineering and the successful bidder that ended in consensus that the proposed design as modified in the meeting constituted an acceptable risk–benefit trade. However, that the situation arose demonstrates the need for explicit guidance to ensure that future decisions about recirculating hangar designs be made early on as a consensus among key offices at base level.

Exhaust Recirculation—A Technology to Minimize Energy Use in Aircraft Painting Operations

Extended Abstract # 369

Joe Wander
AFRL/MLQL, 139 Barnes Drive, Suite 2, Tyndall AFB, FL 32403-5323

Gerald Doddington
HQ AFCESA/CESM, 139 Barnes Drive, Suite 1, Tyndall AFB FL 32403-5323

Steve Frere, Shawn Moser
3 CES/CECCM, 6326 Arctic Warrior Drive, Elmendorf AFB, AK 99506

INTRODUCTION

For aircraft to which low-observable coatings are applied and for painting operations at bases in the Northern and Southern tiers, limitations of the coating materials require adjusting temperature and humidity. This causes ventilation of the painting workspace to be a very expensive, energy-intensive process during spray painting and curing. A number of factors have historically contributed to the magnitude of this cost item:

- Coating manufacturers specify temperature (*T*) and relative humidity (*RH*) windows for application and for curing of the coatings;
- Aircraft coatings contain air toxic constituents, exposure to which is a work-related health risk, and the risk-aversive path is to comply with all standards as literally as possible, *e.g.*,
- 29 CFR 1910.94(c)(6)(i) specifies a linear ventilation rate no less than 100 ft/min for many aircraft, and design values of 120 ft/min with clean filters are typical to allow for head loss as filters load;
- Aircraft do not bend, fold or otherwise compress and they must be completely contained in the painting facility with 10-foot clearance, so the cross section for airflow is comparatively enormous, *e.g.*, for a C-5 (75 ft high, 250 ft wide), 75 x 250 = 18,750 sq.ft; at 120 ft/min, air movement would be 2.3 million cfm.

During early design stages of a new military construction (MILCON) project for a corrosion control facility (CCF) to service C-5 aircraft at Robins AFB, an engineer in the environmental management office followed a 2001 description[1] of a CCF located at Mountain Home AFB, which had incorporated partial exhaust recirculation as an energy conservation measure, to the base bioenvironmental engineer, who referred her to the Air Force Research Laboratory (MLQL). MLQL responded with a detailed electronic message that included copies of several documents[2–5] containing relevant precedents and directed her to consult with the bioenvironmental engineering office (78 AMDS/SGPB [the base industrial hygiene team]) as the next step.

After a month digesting the information package, plus additional research and discussions, she and engineers in the base construction engineering group (778 CES/CECCM) approached an industrial hygienist in SGPB, who in turn invested several months investigating the practicality and safety of a recirculating paint hangar design and concluded that the potential cost avoidances and energy savings justified the slight increase in workspace air toxic concentrations predicted to occur during spray painting operations. The pivotal argument came from an air toxic concentration model[6,7] that was developed by Major Peter LaPuma as an Air Force Institute of Technology PhD project, which calculates the average background concentration of individual coating constituents from inputs describing the facility and application, ventilation and recirculation rates. The users expressed concerns about their personal safety in a recirculated work environment, and L-3 Communications Integrated Systems generously hosted a site visit to their recirculating large-aircraft painting hangar at Greenville, Texas, which allayed the painters' concerns within a few minutes after they stepped inside the immaculate facility.

The driving financial considerations for using recirculation were substantial—roughly estimated at $5 million cost avoidance for the initial construction and $1.5 million savings annually in energy to operate the process air conditioning equipment during coating and curing of approximately 25 C-5s. After almost a year of arguments and negotiations on numerous fronts, the team of CECCM and BEE shop engineers secured a full set of approvals from all cognizant command organizations to contract for an 80% recirculating design for the C-5 CCF. The final exam came in the form of a challenge from the architectural & engineering (A&E) contractor citing the prohibition in 29 CFR 1910.107(d)(9). Copies of Robins' response to the A&E's objections—a *précis* of their case—and several documents they cited in making their case to the Air Force are included as appendices to the long abstract[8] for a progress report of their campaign presented to the 2004 A&WMA conference. This document was assembled as a one-stop resource to guide subsequent hangar design teams in decisions to include or not to include recirculation in their plans. The LaPuma model emerged in this process as the *de facto* standard for such decisions.

ACQUISITIONS INFLUENCED BY THE ROBINS PRECEDENTS

C-17 Corrosion Control Facility at Elmendorf AFB

At Elmendorf the construction engineering shop (3 CES/CECCM) made the first recommendation to consider recirculation as part of a FY05 MILCON project to build a new C-17 CCF. A short notice about the new C-5 hangar design and its progressive approach to energy management appeared in *Robins Rev Up* (an electronic newsletter) and CECCM followed that lead to their counterparts at 778 CES/CECM, who were eager to share what they had done and learned. AFRL was invited in as a consult and then to an informational meeting that provided assurance to the stakeholders—including a representative from PACAF/CEC, Elmendorf's command organization—that what Robins had put in place could also be accomplished in their C-17 CCF design without an equally elaborate approval process.

The environmental circumstances at Elmendorf are polar opposites of those at Robins: Most of the year air used in painting aircraft has to be both heated and humidified to bring the temperature and water content of the air up to meet the coatings' requirements. CECCM followed Robins' lead on criteria for background concentrations of the personnel exposure drivers—again chromate in primers and isocyanates in the topcoats—and determined from inputting the facility dimensions and process parameters into the LaPuma model that 80% recirculation would produce maximum average concentrations within the upper limits defined in Robins' request for proposals (RFP). A conservative calculation estimated that 80% recirculation would produce energy cost avoidances of $0.3 million annually, and 3 AMDS/SGPB (the base BEE) concurred with the proposed design concept. The request for proposals (RFP) was crafted to include the process information and specified that a recirculating design was desired. Contractor bids in response to the RFP revealed that the decrease in equipment size and heating capacity lowered the initial construction cost by several million dollars—which proved to be just enough to bring the total cost down to the amount programmed for the project. The path forward through design completion and into construction has so far been routine, with the usual wrangles about details but no significant impediments, presumably due in part to the similarity of applications and dimensions in the two CCFs.

The temptation was strong to conclude both that the groundwork is now in place for recirculation to be implemented as a routine engineering technology and that design teams will follow the same three-step sequence: analyze the application, justify the use of recirculation, build it into the design. Fortunately a second example surfaced at once to highlight the single directive stated in the first Air Force tech report[2] on recirculation: *the base BEE must concur with the cost–benefit justification* before the design can be undertaken.

F-22 Component Repair Facility (CRF)

Recirculation was proposed by MLQL in June 2001 at the 10% design charrette (the meeting at which the concepts that will go into the eventual facility are selected and sketched into an initial, conceptual design) for the MILCON project to build the CRF that supports the initial fielding of the F-22 at Tyndall AFB. The A&E embraced the idea immediately and convinced the rest of the room to include it in the design. He was later overruled because the F-22 System Program Office (SPO) was on the usual tight schedule to deliver initial capability to Tyndall and was understandably unwilling to imperil that delivery schedule to incorporate an energy-saving option that might cause approval delays. However, the configuration of the painting bays appears to allow for a reasonably simple later conversion to install a recirculating duct, and a retrofit to recirculation is being considered to realize the energy savings that are still available.

Four years later, during the design charrette for the MILCON project to build an F-22 CRF at Elmendorf, Tyndall's CRF environmental manager introduced a member of the F-22 SPO to MLQL in an effort to open the SPO's minds to the idea of recirculating the new CRF's painting bays. The differences at issue from the previous two painting operations were the presence in the coatings of nanoparticulate components and of heavy metals—both toxic and both without measured precedents in painting operations to guide a model calculation. However, both would be expected to be bound into paint droplets and the heavy metal is less toxic than hexavalent chromium, which is a ubiquitous component of aircraft prime coatings. After a day of intensive exchanges of e-mail messages, a majority of the SPO team was willing to consider a recirculated facility.

At Elmendorf the base BEE who had evaluated and concurred with the C-17 design and with considering a recirculating design for the F-22 CRF had retired. Having access to only minimal process information, CECCM (who led the campaign for recirculating in the C-17 CCF) made a number of engineering estimates in applying the LaPuma model to the much smaller F-22 facility. Their results suggested that circulating concentrations of the isocyanate component of the topcoat would exceed the LEL at about 50% recirculation. The local user was concerned that a recirculated facility would create additional maintenance requirements and might also impair his productivity. The consensus of the design team was that the RFP would specify single-pass ventilation.

When the earlier RFP for the C-17 facility was edited to specify the direct-fired, single-pass ventilation design for the F-22 CRF some extraneous material about the C-17 CCF procurement and recirculation was inadvertently left in. One of the responders' bid packages included an option for an 80% recirculated design priced $2.4 million less than their single-pass design. CECCM criticized the deviation from the single-pass specification in the RFP on two grounds: 1). the bidder had based it on information specific to the C-17 and 2). the bidder included no modeling support or other information to alter the conclusions from CECCM's earlier calculations or to predict that the design would operate in compliance with 29 CFR 1910.1000(e) and, by extension, 1910.107(d)(9). The user's opposition was unchanged. However, overseers in the command organization pointed out that the project budget fit the recirculating design but was nearly $2 million less than the price for the single-pass bid, and that Elmendorf had already contracted for a CCF operating at 80% recirculation.

CECCM and the user were joined by MLQL in opposing arbitrarily overriding the earlier risk-based decision to forgo recirculation, although MLQL also encouraged reconsideration of the earlier decision. In the assumptions intrinsic to the LaPuma model the risk driver, diisocyanates—which are both sticky and reactive as a vapor—are treated as an inert, ideal gas. In consequence, the airborne concentration is predicted to be several times higher than will be realized. A second exaggerating factor is that this model calculates the maximum concentration at steady state, which is approached only after all of the guns have been operating constantly for a number of minutes. An empirical estimate of the extent of the model's overestimation of isocyanate concentration will become available after Robins' new CCF is accepted this summer. This value will place such model calculations on much firmer footing, and we expect the overestimation factor to be 5~10, which is more than the discrepancy in the initial calculations.

In an effort to negotiate a unanimous decision following several weeks of exchanges of electronic messages, the design team member from PACAF/CECC convened a meeting of the stakeholders—including the incumbentbase BEE and several members of the F-22 organization—plus a team from the winning bidder and an MLQL representative. After a brief introduction by the convener the prime contractor opened with a compact, tightly organized overview of their design vision and a sound general argument for their approach, and then deferred to his ventilation subcontractor, who gave a lucid exposition on recirculation and its risks and benefits that included responding to questions before he presented a fairly detailed conceptual design that included 80% recirculation, and to which an activated carbon (GAC) adsorber had been added in the exhaust plenum to capture organic vapors from the circulating process air stream.

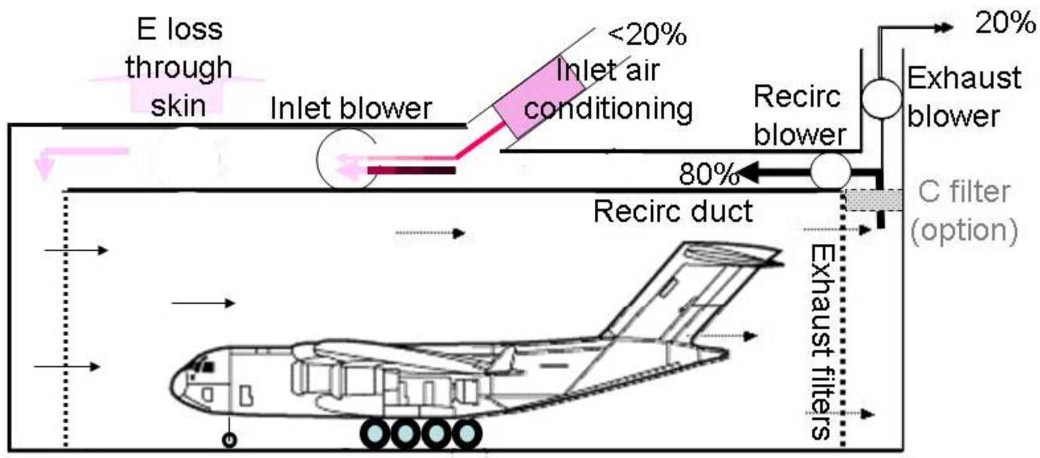
MLQL explained the importance of OSHA's defining a *de minimis* violation as a functional waiver and the necessary condition of providing "equal or better protection." The painting shop representative expressed concern about heavy metal particles in the coatings, but subsequent discussion revealed that the particle sizes in use were too large to pose a significant respiratory hazard to painting crews. CECCM addressed the limitations of the original modeling results and subsequent discussion provided missing details of process and material composition. AFRL reviewed the Air Force's history of recirculation, including many missteps, and noted that Robins' C-5 and Elmendorf's C-17 teams had assembled exemplary facilities. CO formed by the proposed direct firing of intake air was the final subject of the first session, and the BEE accepted installation of CO monitors as providing adequate protection to allow direct firing.

The conceptual drawings for the hangar were projected to open the second session, and MLQL explained that local concentrations near the painter are intrinsic to the job and extremely high because the local solvent vapors and overspray particles do not move away instantly. Thus, a background concentration of 1–2% of this local concentration is smaller than the uncertainty of the methods used to measure exposure and negligible to a reasonable engineering approximation, so it will require no increase in personal protective equipment (*i.e.*, will provide equal or better protection). The BEE accepted the argument but returned to the model results for the isocyanates and it became clear that uncertainty about reliability of the isocyanate assumptions was a matter of concern. The ventilation subcontractor's observation that the carbon bed made this a moot point shifted the focus of discussion, and it was eventually accepted that installing the GAC bed would eliminate elevations in exposure levels and that using a contractor to maintain the beds (as is being done by another Elmendorf facility) would not add to the paint shop's labor burden. The prime contractor concluded that deletion of a few options agreed to in discussion would allow his team to deliver the facility for the bid price. The BEE and the paint shop concurred with the final conceptual design.

Having reached a common resolution, the Elmendorf team was able to proceed with a construction project that should continue to completion as a routine exercise. However, that a recovery process was needed in the course of selecting this recirculating design points up the need for a policy document to guide such acquisitions in the future, and exposure measurements in these painting facilities are the final piece needed to develop a complete instruction.

ENERGY CONSERVATION AND EXHAUST FLOW REDUCTION

The figure below illustrates the movement of air, energy and volatile contaminants in an aircraft hangar operating at 80% recirculation and in which the aircraft is assumed to be at the same temperature as the workspace. Slightly starved (to minimize effusion of contaminated process air) inlet air is heated or cooled and moistened or dried to bring it into the *T* and *RH* window required by the coating and to compensate for heat passing through the skin of the structure. The exhaust contains 20% of the energy investment and 20% of the volatile contaminants entering the exhaust plenum, while the recirculating duct returns 80% of both. Because process air is exhausted, process air conditioning costs will be nearly linear with the exhaust rate. In principle heat recovery devices can enhance energy conservation by recovering part of the energy invested in the spent air, but first it must be demonstrated that the exchanger surfaces do not accumulate contamination by overspray particles. And decreasing the exhaust rate would decrease the size of and associated costs to operate such an energy recovery system.



Vapor capture is a second matter of possible interest. Low-observable (LO) coatings are not water based so, if application rates were to reach the regulatory threshold specified in 40 CFR 264 for aircraft spray painting, volume reduction would become an economic factor in designing an exhaust emission treatment system. As shown as an option in the figure, a GAC bed was incorporated in the recirculating duct of Elmendorf's F-22 CRF to decrease contaminant concentration in the circulating process air. The exhaust concentration—and potential to emit—will be reduced by the same amount, an amelioration that should be negotiated with regulators in the event that usage is ever predicted to approach the regulatory threshold.

For present technology, however, energy calculations are straightforward if one neglects heat loss through the skin and heat release from lighting and electric-powered equipment. A dilution calculation determines the smallest airflow rate consistent with concentrations of contaminants that can be tolerated, and a weather table provides the temperature and relative humidity from which process air must be adjusted to the nearer limit of *T* and *RH* specified for the coatings to be used. From these the amount of sensible and latent heat required to adjust a unit volume of outside air into the *T* and *RH* conditions. Multiplying this unit cost by the net volume exhausted during a full-volume and a reduced-volume paint-and-cure cycle give the respective process energy costs, and the difference is the reduction realized. Summing these calculations over a working year gives the respective annual values, or one can perform a single calculation with annual average values.

Thus,

$$AEC = VFR \text{ x } \{(SHL + LHL)/HSE\} \text{ x } \%Y$$

Where *AEC* is the estimated annual energy consumption in Btu
VFR is the exhaust volume flowrate in cfm
SHL is sensible heat load in Btu/cfm-yr
LHL is latent heat load in Btu/cfm-yr
HSE is heating system efficiency (80% for indirect fired systems) and
%Y is the fraction of the year that the air treatment system operates

And one is able to dissect the savings associated with individual design factors by estimating *AEC* for a condition with and without that factor. Compared to standard designs the C-17 CCF reduced cross section and linear air flowrate, and recirculated. However, the decrease in cross section is independent of the mode of ventilation so only linear flowrate and recirculation will be parameters in the calculations.

Four conditions are considered for the C-17 CCF: (Using Air Force 30-year average weather data[9] and 2006 energy prices; the ventilated area cross section is 10,000 sq.ft.)

1. Baseline (0% recirculation, 90 ft/min [1.2 x 75 ft/min to allow for increasing resistance to airflow as filters fill]):

$$AEC = 900{,}000 \text{ cfm x } \{(303{,}559 \text{ Btu-cfm/yr} + 48{,}581 \text{ Btu-cfm/yr})/0.800\} \text{ x } 0.200 \text{ yr}$$
$$= 80{,}000 \text{ MBtu/yr consumed}$$

2. 80% recirculation (90 ft/min, *VFR* = 0.200 x 900,000 cfm = 180,000 cfm)

$$AEC = 180{,}000 \text{ cfm x } \{(303{,}559 \text{ Btu-cfm/yr} + 48{,}581 \text{ Btu-cfm/yr})/0.800\} \text{ x } 0.200 \text{ yr}$$
$$= 16{,}000 \text{ MBtu/yr consumed}$$
$$\Delta AEC = 80{,}000 \text{ MBtu/yr} - 16{,}000 \text{ MBtu/yr} = 64{,}000 \text{ MBtu/yr saved}$$

3. 0% recirculation, 60 ft/min (*VFR* = 600,000 cfm)

$$AEC = 600{,}000 \text{ cfm x } \{(303{,}559 \text{ Btu-cfm/yr} + 48{,}581 \text{ Btu-cfm/yr})/0.800\} \text{ x } 0.200 \text{ yr}$$
$$= 53{,}000 \text{ MBtu/yr consumed}$$
$$\Delta AEC = 80{,}000 \text{ MBtu/yr} - 53{,}000 \text{ MBtu/yr} = 27{,}000 \text{ MBtu/yr saved}$$

4. 80% recirculation, 60 ft/min (VFR = 0.200 x 600,000 cfm = 120,000 cfm)

$$AEC = 120{,}000 \text{ cfm x } \{(303{,}559 \text{ Btu-cfm/yr} + 48{,}581 \text{ Btu-cfm/yr})/0.800\} \text{ x } 0.200 \text{ yr}$$
$$= 11{,}000 \text{ MBtu/yr consumed}$$
$$\Delta AEC = 80{,}000 \text{ MBtu/yr} - 11{,}000 \text{ MBtu/yr} = 69{,}000 \text{ MBtu/yr saved}$$

Cost savings = Estimated Energy savings x Cost/unit of fuel
= 69,000 MBtu/yr x $5.61/MBtu
= $387,000/yr

CONCLUSIONS

From the analysis above it is clear that at bases operating LO CRFs and at bases in the Northern and Southern tiers that adjust *T* and *RH* in painting operations, process air treatment consumes a sizable fraction of the installation's energy budget. It follows immediately that conversion of these facilities to recirculate part of their exhaust and/or to decrease the linear ventilation rate to values compliant with 29 CFR 1910.94(c)(6)(ii) offers many bases a single-step approach to complying for at least one year with executive order EO13423, which directs installations to decrease basewide energy consumption by 3% annually.

The experience of the F-22 CRF design teams points up the need for a guidance document to ensure that—from the outset of each facility acquisition or major modification project—proper consideration is given to safety and regulatory compliance in the design selected for construction. The guidance will also have to recommend a criterion for interpreting predicted concentrations of isocyanates and other toxic risk drivers.

REFERENCES

1. Wander, J.D.; Adams, B.A.; Gibbs, S.T.; Williston, C.A. "Recirculating Ventilation System in an Integrated Maintenance Hangar Supporting B-1B and KC-135 Aircraft," *Air & Waste Management Association 94th Conference*, Orlando, Florida, abstract #710; AFRL-ML-TY-TP-2001-0031, Air Force Research Laboratory, Tyndall AFB, Florida

2. Hughes, S.; Ayer, J.; Sutay, R. *Demonstration of Split-Flow Ventilation and Recirculation as Flow-Reduction Methods in an Air Force Paint Spray Booth*, AL/EQ-TR-1993-0002 /EPA/600/R-94/214a and b, Armstrong Laboratory, Tyndall AFB, Fla.

3. Wander, J.D.; Belser, W.B.; Smith, M.H.; Palmer, G.R. "Comparison of Time-Averaged Concentrations Measured at Fixed Locations and Painters' Breathing Zones During Aircraft Spray Painting in Conditions of Straight-Through and Recirculating Ventilation," *Air & Waste Management Association 94th Conference*, Orlando, Florida, abstract #711; AFRL-ML-TY-TP-2001-0033, Air Force Research Laboratory, Tyndall AFB, Florida

4. Shepich, T.J. Letter from DoL-OSHA to Wyatt, S.R., EPA-OAQPS, reproduced as Appendix A of ref. 2, pp. 100–102.

5. Miles, J.B. Jr. *Interpretation for questions related to compliance with NFPA 33 (1995 Edition)*, http://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=INTERPRETATIONS&p_id=22163; Plummer, J.E., (1997) *The airflow rate required*

for a spray painting area, http://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=INTERPRETATIONS&p_id=22383

6. LaPuma, P.T. "Recirculation Model for Industrial Air," *Air & Waste Management Association 94th Conference*, Orlando, Fla., June 2001, abstract #xxx; *idem., Recirculating Industrial Air: The Impact on Air Compliance and Workers' Safety. Case Study: Hill Air Force Base C-130 Painting Operations*, AFRL-ML-TY-TR-1998, Air Force Research Laboratory, Tyndall AFB, Florida; download the model from http://nersp.nerdc.ufl.edu/%7Elapuma/index.html

7. LaPuma P.T.; Bolch W.E. *Applied Occupational and Environmental Hygiene*, **1999**, *14(10)*: 682–690; LaPuma P.T., *ibid.*,, **2001**, *16(4)*: 443–454

8. Wander, J.; Deaver, W.H. III; Thovson, J.K.; Hurley, T.; Doddington, G. "Cost-Effective Ventilation of a Large-Aircraft Painting Facility at Robins AFB, Georgia," *Air & Waste Management Association 97th Conference*, San Diego, Calif., abstract #431; AFRL-ML-TY-TR-2004-4518, Air Force Research Laboratory, Tyndall AFB, Fla.

9. https://notus2.afccc.af.mil/SCIS/