How Can We Reduce the Energy Consumption of Pulse-jet Dust Collectors in order to Reap Economic, Ecological, and Social Benefits?

By

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B.Sc., Ain Shams University, 1993

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We accept this thesis as conforming to the required standard

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ABSTRACT

An eight-step creative problem solving model, Simplex, is used as a research approach to answer the question, how can we reduce the energy consumption of pulse-jet dust collectors in order to reap economic, ecological, and social benefits? Due to the dynamic complexity of pulse-jet dust collection systems, a systems thinking approach is adopted both to present the context of the problem as well as to tackle it. The thesis reviews the major industrial air pollution control technologies with emphasis on pulse-jet systems, reviews fabric filtration theory, and then applies Simplex to tackle the thesis question arriving at the "in-situ cleaning" solution which is field-implemented. Finally, the results and the approach are evaluated from a sustainability perspective.

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GLOSSARY OF TERMS

Calender:	to press a fabric between two rollers to make it smooth and glossy.
Cyclone:	a device for separating gas from particulate based on centripetal force and angular momentum.
Felt:	a nonwoven cloth made either by needling, by matting of fibers, or by compressing with a bonding agent for permanency.
Glaze:	to press a fabric under high pressure and at elevated temperatures.
Inch of water (in. WG):	per the English system, a unit of pressure equal to the pressure exerted by a column of liquid water 1 in. high at a standard temperature.
Pressure drop:	resistance to gas flow; may refer to pressure differential across the cloth, across the baghouse, or across the entire system (in. WG).
Pulse-jet:	a generic name given to all pulsing collectors.
Singe:	to pass the fabric over an open flame, thereby removing protruding surface fibers.

ACRONYMS

A/C: Air-to-Cloth Ratio

CAA: Clean Air Act (U.S.)

CCME: Canadian Council of Ministers of the Environment

CFM: Cubic Feet per Minute

CWSs: Canada-wide Standards

ESPs: Electrostatic Precipitators

In. WG: Inch Water Gauge

NAAQOs: National Ambient Air Quality Objectives (Canada)

NAAQS: National Ambient Air Quality Standards (U.S.)

NOx: Oxides of Nitrogen

OSHA: Occupational Safety & Health Administration (U.S. Department of Labor)

PJDCs: Pulse-jet Dust Collectors

PM: Particulate Matter

PTFE: Polytetrafluoroethylene

SOx: Oxides of Sulfur

SWOT: Strengths, Weaknesses, Opportunities and Threats

TSP: Total Suspended Particulate

U.S. EPA: United States Environmental Protection Agency

CHAPTER ONE

1.0 Introduction

1.1 Study Background

> Insanity: doing the same thing over and over again and expecting different results. (Albert Einstein, as cited in Brainy Quote, 2005)

According to the U.S. Department of Energy (2004a), “the consumption of energy in the form of fossil fuel combustion is the largest single contributor to greenhouse gas emissions in the United States and the world” (Carbon Dioxide Emissions, para. 9). Under the terms of the Kyoto treaty, Canada, for its part, committed to reduce its greenhouse gas emissions[1] to six percent below 1990 levels by the period 2008 to 2012 (Jaccard, Nyboer, & Sadownik, 2002). Environment Canada (2005) estimates that in 2003, the Energy sector emitted 600 Mt CO_2 eq. (megaton carbon dioxide equivalent) of greenhouse gases, about 22% of which (134 Mt) were directly attributed to Electricity and Heat Generation (the 1990 level for the same subsector is estimated at 95.3 Mt). While in Canada about 20% of the electric power supply comes from fossil fuel combustion (primarily coal), in the U.S., fossil fuel combustion accounts for about 70% of the total electric power generation (51% from coal alone), and is responsible for about 98% of the carbon dioxide emissions (Industry Canada, 2000; U.S. Department of Energy, 2004a; U.S.

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[1] Some greenhouse gases occur naturally in the atmosphere (water vapor, carbon dioxide, methane, nitrous oxide, and ozone), while others are exclusively anthropogenic (such as various fluorocarbons).

Department of Energy, 2004b). Further, in its 2005 Annual Energy Outlook report, the U.S. Department of Energy predicts that carbon dioxide emissions from energy use will increase, on average, by 1.5% annually --from 5,789 Mt in 2003 to 8,062 Mt in 2025.

Arguably, however, carbon dioxide emissions per se are not society's worst air pollutant. Coal combustion produces a multitude of deleterious substances including sulfur dioxide, nitrogen oxides, heavy metals (especially mercury and lead), volatile organic compounds, and particulate matter (PM), besides carbon dioxide (Union of Concerned Scientists, 2001; U.S. EPA, 2004a). Since these co-pollutants are transboundary, Canada is especially vulnerable to air pollution from the U.S. For example, it is estimated that about 70% of the sulfate and nitrate deposition in Canada comes from U.S. sources (Environment Canada, 2004). Further, Environment Canada (2004) notes that "under prevalent meteorological conditions, U.S. emissions contribute significantly to $PM_{2.5}$[2] and ozone levels in some regions of Canada" (Executive Summary, para. 13). It should be noted, however, that no international treaty a la Kyoto exists for these other co-pollutants. Rather, they are regulated against end-of-pipe benchmarks.[3] The regulations pertaining to PM pollution are discussed in section 1.3. The health concerns pertinent to PM pollution are discussed in section 1.2. PM pollution is pertinent to this paper because the basic function of pulse-jet dust collectors is to mitigate PM pollution.[4] Finally, the potential reduction in greenhouse gas emissions as a consequence of reduced energy consumption in a pulse-jet dust

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[2] PM less than or equal to 2.5 µm in diameter.

[3] Though, international accords—such as the Canada/U.S. Air Quality Agreement—stressing the mitigation of such transboundary emissions exit, they are by no means global in extent or legislation.

[4] PM/dust collection efficiency in pulse-jet dust collectors is not a function of the collector's level of energy consumption, rather, the collector type and specifications, and its overall operating efficiency.

collector is presented and assessed (as carbon dioxide equivalent) in this paper as socioeconomic/environmental benefits (see subsection 5.2.1).

1.2 Particulate Matter Pollution and Health

> Air Pollution: The presence of foreign matter (gaseous or particulate or combinations of both), bacteria, sound, or other undesirable elements in air, which is detrimental to the health or welfare of man, animals, plants, or materials. (Goodfellow, 2001a, p. 1410)

Air emissions comprise two kinds of pollutants: particulates and gases (Appendix A: Characteristics of Particles). Particulate matter (PM) is "matter consisting of particulate liquid and solid substances ranging in size from 0.0002 µm to 500 µm in diameter" (Goodfellow, 2001a, p. 1465). PM includes suspended microscopic particles in the air that humans can inhale, and which are broadly divided into two size ranges: $PM_{2.5}$ and PM_{10}, where the numbers denote the particle size (diameter) of contaminants in micrometers. $PM_{2.5}$ are considered "fine" particles and are less than or equal to 2.5 µm in diameter; PM_{10} are "coarse" and are greater than 2.5 µm, but less than or equal to 10 µm in diameter. $PM_{2.5}$ is generally considered more harmful than PM_{10} (Environment Canada, 2002a).

That PM pollution has detrimental social, environmental, and economical repercussions is beyond dispute. A correlation has been established between high levels of airborne PM and increased hospital admissions, emergency room visits, respiratory and heart problems, and premature death. These effects have been established for both long-term and short-term particle exposures of both $PM_{2.5}$ and PM_{10} (Brunekreef & Holgate, 2002). For example, in the U.S., the National Mortality, Morbidity and Air Pollution Study, a national collaborative effort led by Johns Hopkins University School of Public Health, performed short-term epidemiological studies that focused on PM_{10} pollution in the 20 largest metropolitan areas in the U.S. during the period 1987-1994. All-cause mortality increased by an average of 0.5% for every 10 $\mu g/m^3$ of PM_{10} (a value close to European results). Not surprisingly, the report concluded that this effect was slightly greater for deaths due to heart and lung disease than for total deaths (ibid.). In that vein, the U.S. EPA estimates that, with respect to healthcare, the benefit-to-cost ratio of tighter PM controls is 2 – 10 times (Institute of Clean Air Companies, 2002).

The pernicious effects of PM stem from the fact that it can be inhaled deep into the lungs and enter the bloodstream, potentially triggering pulmonary and cardiovascular health problems. The prospects of adverse effects are increased by the fact that PM acts as transport vehicle for other toxic agents. Hence, scientists now believe that there is no “threshold” or safe level for exposure to PM (Environment Canada, 2002a). PM is also a major component of smog and is associated with reduced visibility and poor air quality. PM pollution can also adversely impact vegetation and material objects. Depending on their composition, PM pollutants can alter soil nutrient balance and pH, directly affecting ecosystem balance and directly damaging plants. PM pollutants can also corrode, soil and discolor inanimate materials (Environment Canada, 2002a; U.S. EPA, 2004b).

1.3 Legislative Framework

In Canada, PM pollutants are designated as toxic and are regulated under the Canadian Environmental Protection Act's National Ambient Air Quality Objectives (NAAQOs) for Total Suspended Particulate (TSP), and the Canadian Council of Ministers of the Environment's Canada-wide standards (CWSs) for $PM_{2.5}$. (As "standards," CWSs are, by definition, more legally binding than objectives.) Several provinces have also set their own standards (Table 1). The NAAQOs for PM are non-specific, lumping PM_{10} and $PM_{2.5}$ together under TSP, setting the maximum permissible TSP at 120 $\mu g/m^3$ in a 24 hour period, and 70 $\mu g/m^3$ as the annual average (CCME, 2005; Environment Canada, 2002b). CWSs for PM is established only for $PM_{2.5}$ since reductions in ambient PM_{10} levels are expected to occur as corollary benefits from reducing $PM_{2.5}$. The numeric CWS $PM_{2.5}$ target (for 2010) is 30 $\mu g/m^3$ in a 24-hour period (CCME, 2005).

Emissions from stationary sources, specifically, are regulated under the Canadian Environmental Protection Act's Thermal Power Generation Emissions National Guidelines for New Stationary Sources. In January 2003, the said guidelines were revised tightening the emissions limits for nitrogen oxides, sulfur dioxide, and PM from new fossil fuel-fired steam-driven electricity generating units based on the emissions performance achievable using current best available technologies. The revised guidelines cap the hourly mean discharge rate of PM into the ambient air from new generating units when determined over successive 720 hour rolling average periods at 0.095 kg/MWh net energy output (Environment Canada, 2003).

In the U.S., by comparison, pursuant to the Clean Air Act (CAA), the EPA Office of Air Quality Planning and Standards has established National Ambient Air Quality Standards (NAAQS) for six principal pollutants ("criteria pollutants") which, in addition to PM_{10} and $PM_{2.5}$, include lead, nitrogen dioxide, ozone, and sulfur oxides (U.S. EPA, 2005).

Table 1: Ambient Particulate Matter Standards and Objectives in Canada and the U.S.

		Permissible Pollutant Concentrations (micrograms per cubic metre ($\mu g/m^3$)) [a]			
Pollutant	**Averaging Time**	**Canadian Objectives**	**Some Provincial Standards**		**U.S. Standards Proposals**
		Acceptable Level	**Newfoundland**	**British Columbia**	
Total Suspended particulate (TSP)	24 hour	120	120	120	
	Annual	70		70	
PM10	24 hour		50	50	150
	Annual				50
PM2.5	24 hour		25		50
	Annual				15

Source: National Ambient Air Quality Standards, Environment Canada (Environment Canada, 2002b)

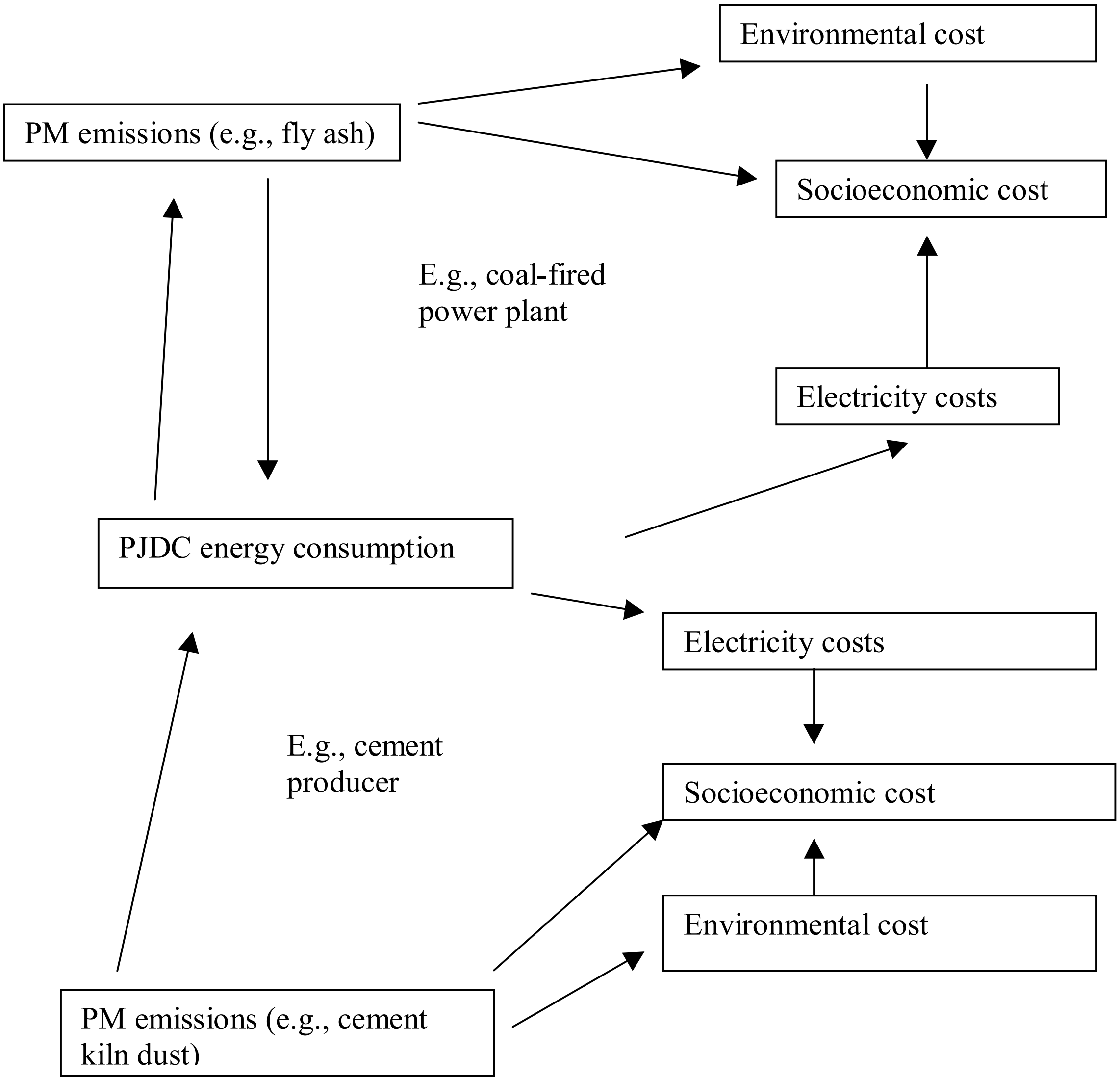
[a] "Compliance with the annual standard is determined by the average of three consecutive annual average values. Compliance with the 24-hour standard is determined by the 3-year average of annual 98th percentile concentrations." (U.S. EPA, 2004b, Primary and Secondary PM Standards, para. 2)

1.4 Research Problem

The electricity sector emits deleterious emissions from burning fossil fuels as it supplies other industries with the electrical energy they need to operate. Basic industries, such as cement, steel, and metal smelting are especially energy-intensive, and they emit emissions as production byproducts (Jaccard et al., 2002). Industries consume electrical energy to feed the dust collectors that capture their emissions. The more energy suppliers burn fossil fuels to produce energy to power up the industries, and with it the economy, the more they discharge emissions. The more they emit emissions, the more they use up energy to power their dust collectors to trap emissions. It is a vicious reinforcing cycle for which there is a social, environmental and economic price being paid. Thus, reduced energy consumption by dust collectors, which is the focus of this paper, can reduce this price, while we look for more sustainable energy supply structures (see System Diagram).

For a cement manufacturer, for example, reduced energy consumption translates into tangible financial benefits from reduced electricity costs. Reduction of emissions from the primary source manifests in social and environmental benefits. (There is also the potential for emissions trading.) Finally, as more companies use triple bottom line reporting, or adopt formal environmental management systems (such as ISO 14001), the need to reduce emissions will increase (H. Johannesen, personal communication, January 20, 2005). One type of dust collectors widely used in dust-emitting industries is pulse-jet dust collectors (PJDCs), a type of fabric filter representing the most efficient dust removal technology available.

System Diagram



1.5 Research Objectives

The primary objective of this research is to investigate ways to make the operation of pulse-jet dust collectors more sustainable, to reap economic, ecological, and social benefits. Specifically, to answer the question: how can we reduce the energy consumption of pulse-jet dust collectors? As this paper will attempt to demonstrate, especially in chapters 2 and 3, optimized energy consumption is achieved by proper design, sizing, and operation of the collector. A second objective is to introduce Simplex (Basadur, 1998) as a creative problem solving model. A third objective is to introduce Simplex as an exploratory research tool. A fourth objective is to introduce Simplex as an environmental management model.

1.6 Research Approach

According to Homer-Dixon (2001), ingenuity is the ability to continually generate implementable solutions to the emerging challenges, both technical and social. Technical ingenuity, according to Homer-Dixon, is the “kind used to create new technologies, like irrigation systems that conserve scarce water…” Social ingenuity is the “kind used to reform old institutions and social arrangements and build new ones, including efficient markets, competent and honest governments, and productive schools and universities” (p. 22). Homer-Dixon concludes, not surprisingly, that social ingenuity is a critical prerequisite to technical ingenuity.

One can infer from this argument that the conventional “if it ain’t broke, don’t fix it” approach to managing our affairs is anti-progress, and that creative approaches to solving our emerging problems are the only way to close the ingenuity gap between our needs (sustainable solutions) and current supply (unsustainable technologies/inefficient systems). Simplex is a social ingenuity tool that will be used in this endeavor, i.e., to answer the question, how can we reduce the energy consumption of pulse-jet dust collectors? Simplex is a structured approach to creativity comprising: (1) Problem Finding, (2) Fact Finding, (3) Problem Definition, (4) Idea Finding, (5) Evaluate and Select, (6) Plan, (7) Acceptance, and (8) Action (Appendix B: Simplex). On his website (www.basadur.com, accessed 30 November, 2004), its author, Min Basadur, informs that his approach has helped numerous industry leaders, including Procter & Gamble, Frito-Lay, PepsiCo, Goodrich and Pfizer, “generate hundreds of millions of dollars in new revenues and cost savings.” The website cites numerous scientific articles which establish the Simplex methodology (Basadur, Graen, & Green, 1982; Basadur, 1994; Basadur & Gelade, 2003).

Basic industries, such as cement producers, are typical clients of Albarrie Canada Limited, the organization with which this writer works and which is sponsoring this thesis. Albarrie, based in Barrie, Ontario, Canada, is a manufacturer and supplier of technical fabrics and engineered fabric solutions, including filter bags for use in pulse-jet dust collectors. The extent to which this fact has influenced the direction of this research will be assessed in the final chapter. While chapter one highlighted the importance of the research subject and furnished its social, environmental, economical, and legislative context, chapter two will review the most common air pollution control technologies, including a section on system design and selection relevant to fabric filters.

Chapter three will cover fabric filtration and cleaning theory, adopting a systems thinking approach in its analysis and presentation of the information. In this writer's opinion, pulse-jet dust collection systems are complex in that not only is there a great number of different parts (detail complexity), but there is also a great number of possible connections between these parts, because each part may have a number of different states (dynamic complexity). Further, these parts are interconnected and interrelated in non-linear ways, and are maintained via a complex network of feedback loops. Hence, pulse-jet systems can be best understood through a systems thinking spectacles, and this fares well with Simplex, which is a systems approach.

Chapters two and three together comprise the technical context necessary to apply the Simplex model. Chapter four will apply the Simplex methodology to the thesis question after discussing its conceptual framework first. This culminates in a field-implemented solution, i.e., in-situ cleaning. Finally, chapter five will assess the Simplex approach results against the thesis objectives, i.e., the sustainability ramifications of in-situ cleaning, and the effectiveness of Simplex as a creative problem solving, research, and environmental management approach.

CHAPTER TWO

2.0 Air Pollution Control Technologies

2.1 Background

> Prevention is the best cure.
>
> —Maxim

The first tenet of waste management is prevention --even before looking for ways to "reduce, reuse, recycle and recover." However, given our insatiable appetite for cheap energy resources and yet fledgling appreciation for the sustainability paradigm[5], prevention of dust emissions altogether remains unrealistic. As Croom (1995) puts it:

> Zero discharge is the ultimate source reduction goal and may be achieved by a closed loop or other process recovery change; a change of fuels, raw materials, or neutralization treatment; maintenance or design improvements; reuse or conversion of the pollutant; and other possibilities. Next best would be reduction of the discharge to a level below the required limits. Failing that…meet emission limits. (p. 4)

He further notes that the U.S. manufacturing industry spent approximately US$2.6 billion in 1990 on air pollution control, 71% of which went for end-of-pipe solutions rather than source

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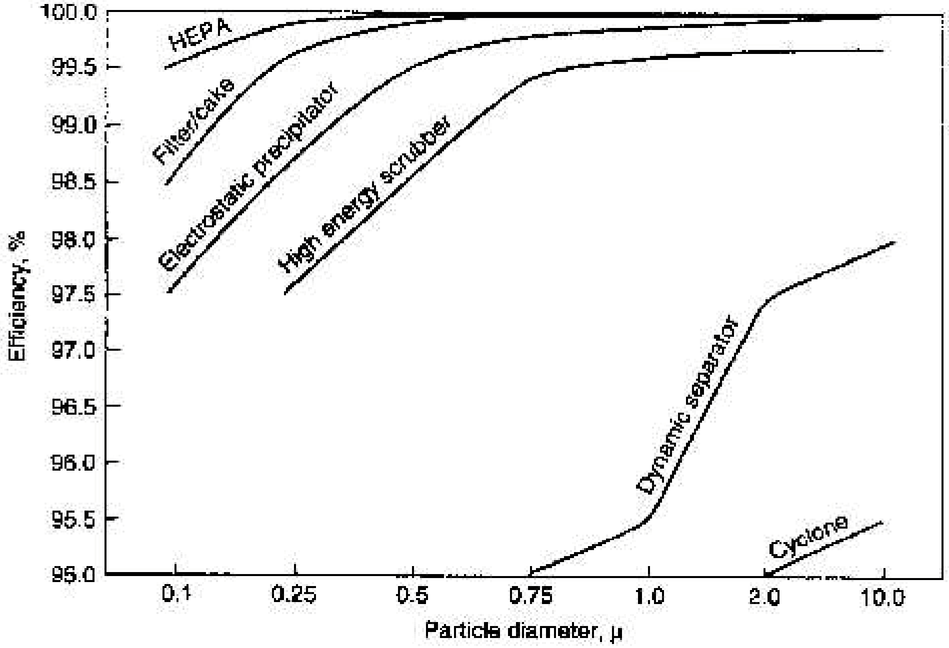
[5] In practical terms, prevention would mean we either exclusively use renewable energy resources, or we adopt a new "cradle to cradle" working paradigm where the concept of waste is entirely eliminated because goods and services are designed from the outset as feedstocks for future beneficial use.

reduction techniques. The quality of feed coal in coal-fired power plants, for example, determines to a large extent the level of toxic emissions at the exhaust. High pyrite coal, a high sulfur coal, is likely to produce more sulfur emissions, which in turn is likely to raise the cost of air pollution management. Prevention also entails increasing the overall efficiency or the optimization of processes. In a dust collector, that would be through design modification for the aim of reducing emissions—whether from the primary energy source or from a particular application—and for reducing operating costs.

This chapter reviews the most common end-of-pipe air pollution control technologies, but discusses in more detail fabric filters (baghouses). Efficient baghouses—those properly designed, sized and maintained—are able to conserve energy and reduce emissions to a level well below the required limit. Pulse-jet dust collectors, which are one of the more common types of baghouses, are studied in more detail, especially from a systems thinking perspective (i.e., by giving special consideration to the interrelationships between the various factors—operational, functional and structural—that affect the collectors' performance).

2.2 Technologies Overview

Several technologies exist for removing particulate matter (PM) from exhaust gases or for removing fugitive dust. These include wet scrubbers, electrostatic precipitators (ESPs), and fabric filters. Following is a basic review of these technologies highlighting the comparative advantage and disadvantage and field of application for each kind (other technologies not discussed here include inertial separators). Selection of the appropriate air pollution control technology will depend on, first and foremost, the required efficiency level (Figure 1), in addition to budgetary and space limitations (Croom, 1995; Goodfellow, 2001b; McKenna & Turner, 1993).



Source: Miles L. Croom, Filter Dust Collectors: Design and Application, 1995

Figure 1: Collection Efficiency vs. Particle Size by Collector Type

2.2.1 Wet Scrubbers

Wet scrubbers use water spray to collect PM from an air stream passing through the spray. As water falls through the upward-flowing gases, it collides with and removes the PM. The tainted water that accumulates in the bottom of the scrubber is pumped from the scrubber and treated to remove the solids as wet sludge (Croom, 1995; Dickenson, 1992). High-energy venturi scrubbers can reach efficiencies up to 99.5% on particles as small as 0.5 micron. Appropriation cost will be around US $1.00 to $2.00 per cubic feet per minute (CFM) (Croom, 1995).

Hybrid systems allow for the mitigation of multiple pollutants concurrently. Wet scrubbers are used in conjunction with flue-gas desulfurization (FGD) technology (removal of SO_2) where the flue gas enters a large vessel (spray tower or absorber), and is sprayed with water slurry (approximately 10 percent lime or limestone). The calcium in the slurry reacts with the SO_2 to form calcium sulfite or calcium sulfate. The gypsum produced from FGD waste is a useful by-product used in the manufacture of various plaster products, fertilizers, etc. (Croom, 1995; “World Bank Group,” n.d.).

2.2.2 Electrostatic Precipitators

Electrostatic precipitators (ESPs) can efficiently remove fly ash and hence are widely used in coal-fired power plants at temperatures up to 1000º F (537º C). The dust collection efficiency can be as high as 99.9% and for a wide range of particle sizes, with an initial cost of US$1.5 to $4.00 per CFM (Croom, 1995; Heumann, 1997).

The dust-laden air stream passes through electrically charged grids of wires or plates where dust particles are charged. The air stream then passes through a second set of wires or plates with an opposite charge, attracting the charged dust particles. Depending on whether the collected particles are "rapped" off (i.e., dislodged from the collection plates by mechanical agitation) or whether they are cleaned by water sprayers, the ESP is considered either dry or wet (U.S. EPA, 2002a). ESPs can handle large gas volumes with a wide range of inlet temperatures, pressures, and acid gas conditions. In new compact hybrid particulate collector (COHPAC) systems, to achieve outstanding PM collection targets, ESPs are being used as a pre-filter to baghouses, especially pulse-jet filters (Croom, 1995). COHPAC systems offer the opportunity for multi-pollutant control. For example, pursuant to the U.S. Department of Energy's Clean Coal Technology initiative, which aims to pioneer approaches for complying with the CAA, COHPAC technology is being tested since March 2001 at Alabama Power for effectiveness to remove mercury (a byproduct of coal combustion) from the air stream. Pulverized activated carbon is injected downstream of the ESP and is then collected by a fabric filter (Monroe & Miller, 2003).

2.2.3 Fabric Filters

Under the CAA, permits for emission sources in attainment areas (areas where criteria pollutants meet NAAQS) mandate the installation of pollution controls that represent the best available control technology (BACT)[6] (U.S. EPA, 2004c). The U.S. EPA (2004c) defines BACT as "an emission limit based on the maximum degree of reduction of each pollutant subjected to regulation under the Clean Air Act" (Air Quality Management, para. 2). Similarly, in Canada,

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[6] Permits in nonattainment areas must meet the lowest achievable emission rate (LAER).

"certificates of approval" from the provincial ministries of environment for emission sources stipulate use of the best available technologies (BAT). Fabric filters are the most efficient air pollution control devices and represent BACT/BAT for several criteria pollutants. Though fabric filters and ESPs both have comparable dust removal efficiencies, fabric filters outperform ESPs when the PM size drops below 0.9 micron (Croom, 1995).

> When high collection efficiency on small particle size is required…the most widely used method consists of separating the dust from the air by means of fabric filter. —U.S. EPA, "Air Pollution Control Equipment for Particulate Matter." (As cited in Croom, 1995, p. 17)

A baghouse is a "house" full of filter bags, in either envelope or, more commonly, tube shape. The Industrial Gas Cleaning Institute defines a fabric filter as follows:

> A Fabric filter is one in which the dust-bearing gas is passed unidirectionally through a fabric in such a manner that the dust particles are retained on the dirty gas side of the fabric, while the cleaned gas passes through the fabric to the clean gas side, where [they are] removed by natural and/or mechanical means. (Goodfellow, 2001b, p. 1232)

Baghouses are diverse—structurally, operationally, and functionally—and a comprehensive review of their designs, applications, and maintenance is beyond the scope of this paper. This paper only examines the energy-related aspects of baghouse operation with emphasis on pulse-jet systems, and from a systems perspective. The extensive nature of this field compels this writer to generalize, except where inappropriate. This is because not only is every type of baghouse unique (structurally, operationally, and functionally), but also because every installation is unique in its requirements and operating conditions. There are three types of fabric filters, based on the cleaning method: shaker, reverse air, and pulse-jet. In cleaning, the captured dust on the dirty side of the fabric is knocked down to the bottom hoppers (where it can be removed, and either recycled or disposed) by one of three methods. In shaker systems, bags are cleaned by mechanical shaking; in reverse air systems, by blowing clean air backwards through them; and in pulse-jet systems, by bursts of pressurized air (Croom, 1995; McKenna & Turner, 1993).

In shaker systems, tubular bags are suspended from horizontal beams at the top and fastened onto a tube sheet at the bottom of the baghouse such that the open end of the bag is at the bottom and the closed end is at the top. Dust-laden gas enters from the bottom of the baghouse (under pressure or suction from a fan) and is retained inside the bags. The tube sheet (or cell plates) separates the clean air and dirty air plenums of the baghouse. Bag cleaning is achieved by mechanical shaking action of the top horizontal bars from which the bags are suspended. The mechanical shaking causes the dust on the fabrics to dislodge to the hopper. However, during cleaning, the collector must be taken “offline” or “off-stream” (i.e., the airflow through the baghouse stopped). If the installation requires continuous cleaning, a compartmented baghouse would be need, where when one compartment is being cleaned, the airflow can be diverted to other compartments (Greiner, 1993; McKenna & Turner, 1993; OSHA, n.d.).

Similarly, in reverse air systems, tubular bags are suspended from an adjustable hanger frame at the top and fastened onto a tube sheet at the bottom of the baghouse such that the open end of the bag is at the bottom and the closed end is at the top. Again, dust-laden gas enters from the bottom of the baghouse and is retained inside the bags. Reverse air baghouses are compartmented to allow continuous airflow. The compartment to be cleaned is taken off-stream and the bags are cleaned by reversing the direction of airflow. This pressurizes the compartment which causes the bags to partially collapse causing the dust cake to crack and fall into the hopper. (Metal rings are sewn into the bags at intervals to maintain the shape of the bags.) Once the cleaning cycle is over, reverse airflow is discontinued and the compartment is put back on stream. The gentle cleaning mechanism of reverse air systems makes them especially suitable for high temperature applications (Heumann, 1997; McKenna & Turner, 1993; OSHA, n.d.).

In pulse-jet (reverse-jet) systems, tubular bags supported by metal cages are suspended from a tube sheet at the top of the baghouse with their open end upwards. Dust-laden gas enters from the bottom of the collector and flows through the bags in the outside-in direction, leaving the retained dust outside the bags. To clean the bags, bursts of compressed air, usually at pressures of 70 to 100 lb/in^2 (header pressure), are injected into the bags via nozzles from blow tubes fixed above the bags which are aligned in rows. The air bursts cause the bags to flex, which causes the dust cake to crack, and the dust is dislodged to the hopper below. This cleaning mechanism permits pulse-jet systems to remain on stream even during cleaning, because the rapid (0.05 – 0.1 seconds) high pressure bursts do not interfere with normal airflow; hence, reverse-jet systems need not be compartmented, and space requirements are reduced, and fewer bags are used. Potential savings, therefore, include lower capital costs, and reduced bag change-out expenses

(Croom, 1995; Heumann, 1997; McKenna & Turner, 1993; Turner, McKenna, Mycock, Nunn, & Vatavuk, 1998).

One fundamental structural difference between shaker and reverse air systems on the one hand, and pulse-jet systems on the other, is that pulse-jet systems exhibit outside-in filtering mode, where the dust is retained outside the bags, leaving the upper plenum of the baghouse clean. This offers a major health benefit (advantage over shaker and reverse air systems) since the dirty bags can be removed with nominal health risks. Another major difference, also considered a pulse-jet system advantage, is that pulse-jet systems can operate online (on-stream). The fact that they have an effective cleaning mechanism allows them to operate at a higher air-to-cloth ratio (A/C), which allows for significant capital and operating cost savings and significant reductions in space layout requirements. Further, given that in reverse air and shaker systems bags are unsupported (in contrast to pulse-jet systems where bags are supported by cages), the bags must have high resistance to sagging (high tensile strength) (Croom, 1995; McKenna & Turner, 1993). Hence, in reverse air and shaker systems, filter bags from woven fabrics are normally used and the A/C is low (on the order of 2 ft/min); in pulse jet systems, felted fabrics are normally used and the A/C is high (on the order 4-6 ft/min) (McKenna & Turner, 1993). Croom (1995), however, suggests that using non-woven felt in reverse air can help reduce system pressure drop, energy cost, and possibly raise the collection efficiency. The bags are usually made of synthetic fibers such as Polyethylene Terephthalate (polyester), glass fibers, etc., and there may be hundreds of bags within one structure.

In its review of dust control technologies, the U.S. Department of Labor, Occupational Safety & Health Administration (n.d.) suggests that “space requirements for a reverse-air baghouse are comparable to those of a shaker baghouse; however, maintenance needs are somewhat greater” (Fabric Collectors, Reverse Air, para. 4). For pulse-jet collectors, the biggest tradeoff for reduced space requirements is a higher operating pressure drop and the added cost of compressed air consumption. Installation cost for baghouses commensurate with air volume. Standard systems can range from US$1.25 to $6.00 per CFM, and can go up to US$12.00 for special designs (Croom, 1995). Typical industrial applications of fabric filters include coal utility boilers, industrial boilers (coal, wood), metals processing (foundries), mineral products processing (e.g., cement manufacturing), asphalt manufacturing, and grain and feed milling (U.S. EPA, 2003).

2.3 Design and Selection Considerations

The three performance criteria for a filter are dust collection efficiency, operating costs (especially energy costs), and maintenance costs (Croom, 1995; Goodfellow, 2001b; McKenna & Turner, 1993). Therefore, filter design and selection must commensurate with these general performance goals no matter what is the application. In other words, optimum performance hinges on optimum design and selection. As Croom (1995) posits, “the levels of collection system efficiency, pressure drop, energy use, physical size, and costs will be fairly well determined after the filter collector design has been decided on, the filter material has been chosen, accessory functions have been defined, and the performance and construction specifications have been written" (p. 33). However, he notes that subsequent fine-tuning can optimize overall filter performance sometimes significantly.

According to Goodfellow (2001b), "the selection and sizing of fabric filters are complex issues because of the many variables and the range of applications. The selection depends primarily on judgement based on experience" (p. 1239). McKenna and Turner (1993) opine that the endeavor may involve more art than science, but they agree with Goodfellow that the main technique is probably application history. They suggest that there are two ways an engineer can "design" a baghouse for a specific application. He can actually design a system if he has the expertise and the resources, or he can select a commercially available system that meets a set of specifications or design goals. A detailed review of a baghouse selection process is outside the scope of this paper. This section reviews the basics of the selection process from a systems perspective. Having defined the design objectives from a strategic angle, especially emissions goals, the selection process cannot be consummated without factoring budgetary and space limitations. Depending on the application, there are generally six key baghouse design objectives, which are outlined in Appendix C: Key Items to Consider in Collector Design.

Therefore, before deciding on the type of collector, all field and application information should be gathered first and studied. In addition to emission limits, these include dust data (particle size distribution, bulk density, expected dust loading, physical and chemical properties, etc.), air stream data (airflow volume, temperature, expected pressure drop, etc.), and other application-specific considerations (safety issues, expected hours of operation, etc.) (Croom, 1995). This basic data is then used to evaluate the various design alternatives which would deliver a system that is as economical and as efficient as possible and which meets the design objectives. In this regard, McKenna and Turner (1993) categorize design features into optional and application-specific. The latter include capacity (small: <10,000 CFM, medium: 10,000 - 100,000 CFM, and large: >100,000 CFM), filtering temperature (low: under 200ºF (93ºC), medium: 200-300ºF (93 - 149ºC), and high: above 300ºF), and operating duty (continuos or intermittent). Optional design features include cleaning method (pulse-jet, reverse air, and shaker), filter media (woven or felted), and filtering mode (outside or inside dust collection).

One of the critical design features is sizing or deciding the size of the collector, which is based on the A/C (filtration velocity). The cloth area is determined by dividing the airflow volume in CFM by the filtration velocity in ft/min. Determining the right A/C is an art, as there are a multitude of interrelated factors involved, the more obvious of which include the cleaning method, operating duty, filter media, dust properties, flow volume, gas temperature, and dust loading (McKenna & Turner, 1993; Turner et al. 1998). The A/C in its turn will affect the operating pressure drop, cleaning efficiency, and bag life. Turner et al. (1998) detail three methods for determining the A/C, and McKenna and Turner (1993) offer an additional method. The reader is advised to consult these references for the details. One method to note here, however, is the reference table method, which is a listing of nominal filtration velocities for selected dust materials based on empirical findings.

McKenna and Turner (1993) prescribe the following procedure for a baghouse selection: (1) Review dust source operation, (2) Define emission problem, (3) Select cleaning method, (4) Size collector, (5) Select filter media, (6) Identify materials of construction, and (7) Identify auxiliary equipment needs. Besides the main baghouse, auxiliary components needed for normal operation include fans and motors, dampers and flow valves, ducts, dust handling systems, etc. Because it is the single largest contributor to operating costs, fan selection is critical and should be strategic, specifically in terms of type, size, location (downstream or upstream) and efficiency, to achieve maximum performance and minimum problems (Croom, 1995; McKenna & Turner, 1993).

Capacity and dust source operation are the two biggest factors that influence fan selection. For example, if the dust source is not corrosive, an upstream fan can save on a considerable amount of ductwork, and less energy would be required to draw the gas through the system (compared to negative pressure systems). The most commonly used type of fan for operating static pressures of up to 25 WG and air stream volumes of up to 100,000 CFM are centrifugal fans (Croom, 1995). An efficiency range of 65-85% is typical for most fans. Finally, it is important to remember that the fan is a constant volume machine. Constant volume is maintained by speed (rpm) control and resistance (energy to overcome resistance to flow) manifested in operating pressure drop. According to fan laws, volume $\propto$ (rpm), pressure $\propto$ $(\text{rpm})^2$, and horsepower $\propto$ $(\text{rpm})^3$; hence, when speed is reduced by half, fan output is also reduced by half (pressure one fourth and horsepower one eighth). A variable speed control fan drive system, therefore, can minimize energy loss associated with changes in the volume discharge rate (Croom, 1995; McKenna & Turner, 1993).

CHAPTER THREE

3.0 Fabric Filtration Theory and Interrelationships

3.1 Background

> Intellectuals solve problems, geniuses prevent them. (Albert Einstein, as cited in Brainy Quote, 2005)

Leibinger (2003) gives us the sub-components of the “flange-to-flange” differential pressure for the filter: (1) pressure drop in the raw gas duct, (2) inlet flow loss in the filter housing, (3) pressure drop across the filter bags (tube sheet pressure drop), and (4) pressure drop in the clean gas chamber. (It is thus clear that in compartmented systems, the total pressure drop is accumulative.) Noting that the pressure drop across the bags accounts for the largest proportion, and further to the premise that pulse-jet filters are assessed vis-à-vis their dust removal efficiency and their operating costs (especially, fan power consumption), and given that the total energy input requirements for the filter are primarily a function of the operating pressure drop, we shall focus hereinafter on the factors that affect the dust collection efficiency and the pressure drop across the filter and the interrelationships among them.

3.2 Fabric Filtration Theory

3.2.1 Dust Cake Formation

Whether it is woven or felt fabric, the useful life of a filter fabric begins when the dust particles accumulate within and upon its surface creating a semi-permanent deposit or residual dust cake (Donovan, 1985; McKenna & Turner, 1993). It is this dust cake layer that performs most of the filtration and which makes this technology efficient. It takes hours or days of operation to reach fabric-system stabilization and that is when efficiency peaks. However, as time passes, during normal operations, an excess of dust accumulates on the fabric that hampers the airflow and elevates the pressure drop, and at one point it becomes necessary to remove this excess dust. Cake filtration is believed to be the predominant dust collection mechanism, especially in reverse air and shaker systems; however, depth filtration is also believed to play an important role in pulse-jet systems (ibid.). Turner et al. (1998) note that the longer a pulse-jet compartment remains on-line without cleaning, the more its filtration modus operandi switches to cake filtration:

> A complete model of pulse-jet filtration must account for the depth filtration occurring on a relatively clean pulse-jet filter, the cake filtration that inevitably results from prolonged periods on-line, and the transition period between the two regimes. (p. 17)

This statement begins to highlight the complexity of the theoretical science of fabric filtration, especially for pulse-jet systems. Many researches have developed pressure drop and filtration efficiency equations, but the uniqueness of every installation leaves generalized equations in the theoretical realm. Nonetheless, this is an area of continuing research. Membrane fabrics, i.e., fabrics laminated with expanded polytetrafluoroethylene (e-PTFE), are a creative invention in that they optimize surface filtration and so gain efficiency (however, there may be a tradeoff here, as lamination inevitably reduces permeability). Koch, Seville, and Clift (1995) suggest, in addition to the filter medium type and geometry, filtration behavior also relies on the chemical and physical nature of the dust and its size distribution, the gas properties, and the operating filtration velocity.

3.2.2 Separation Mechanisms

> Several particle collection mechanisms are responsible for filter efficiency. Each mechanism may contribute to the collection of particles on fibers, or particles on fabrics, or particles on dust cakes; and theoretical equations exist for the capture efficiency of each mechanism based on single particles approaching single fibers. For an operating fabric filter, however, there is more to consider. The particles approach in swarms…the fabric is covered with dust cake and the dust cake is of continually varying thickness. (McKenna & Turner, 1993, p. 2-11)

McKenna and Turner (1993) posit that sieving becomes the dominant filtration mechanism once a dust cake is reformed following a cleaning cycle. Depending on the relative sizes, a dust particle attempting to penetrate the porous cake might be able to penetrate, or is sieved out.

Cleaning, however, is inconsistent in its extent and leaves "patches" and pores of various sizes across the fabric which are subject to above average dust loading (according to the path of least resistance principle) (Koch et al., 1995). Importantly, the pore velocity through the more open pores reaches several thousand feet per minute which causes the pores to dilate and dust "leaks" to the clean side (these are the potential emissions) at the rate of one out of a thousand, or one out of ten thousand particles (McKenna & Turner, 1993). This leakage phenomenon explains the counterintuitive finding that leaked particles are of average dust particle size, and not necessarily from the lower end of the size distribution scale. Since pore velocity is dependent on face velocity, this explains the relationship between A/C and filtration efficiency.

The fate of particles that are not sieved out is one of several:[7] interception, which occurs when the streamline on which the particle is riding allows for direct collision with the fiber; inertial impaction, which occurs when the dust particle, due to its inertia, travels straight ahead rather than follow the streamline around the fiber resulting in "side" impaction; and diffusion, which occurs when dust particles in the 0.2 μ size range and below collide with the filter elements through random Brownian movement (Dickenson, 1992; Heumann, 1997; McKenna & Turner, 1993).

3.3 Fabric Cleaning Theory

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[7] Authors are not in universal agreement on the terminology to describe these mechanisms. One Scientist's impaction is another scientist's interception. Impingement has also been used to denote impaction or interception.

Leibinger (2003) reminds us that the premise for operating at high A/C (>4 $ft^3/min/ft^2$ or $1m^3/min/m^2$) is a very effective cleaning system. The idea of cleaning is that enough energy is imparted to the dust-loaded fabric to overcome the adhesion and cohesion forces between fabric and cake. Koch et al. (1995) explain that the dust cake deposited on a fabric could be detached by applying a tensile stress which is equal to either the cake cohesive strength or the strength of the adhesive bond between the cake and the medium, whichever is smaller. (In practice, detachment is at least partially cohesive.) There are two ways to apply the stress: either by a reverse flow of gas or by imposing an acceleration on the filter cake. However, it is believed that fabric acceleration is the primary mechanism of dust removal, which occurs when bags are inflated by the reverse pulse.

In pulse-jet filters, the ephemeral compressed-air burst (0.1s) acts as a rapidly moving air bubble traveling through the entire length of the bag causing the bag surfaces to flex. The acceleration force of the rebounding fabric is greater than the fabric/cake adhesion forces, which affects cleaning (McKenna & Turner, 1993). Where necessary, venturis are installed at the top of the bags to accelerate the compressed air. This process is influenced by the dust properties, fabric properties (both of which have characteristic electrical properties that affect collection and adhesion), and the collector operating conditions (Koch et al., 1995). In the three types of baghouses, cleaning is initiated by timer or photohelic differential pressure gages. The latter technique, also referred to as “on-demand,” is deemed more economical and should be used whenever possible “to automatically maintain the most effective filter cake and filtration efficiency, as well as to achieve the most economical energy use in fan and cleaning power”

(Croom, 1995, p. 46). Two adjustable photohelic switches are used to control pressure settings: a high differential pressure setting is used to trigger the cleaning cycle, and a low pressure setting to stop the cycle. Further, use of on-demand cleaning, can reduce compressed air consumption (in pulse-jet systems) and wear on the filters (Croom, 1995; McKenna & Turner, 1993).

3.4 Factors Affecting Filtration Efficiency and Pressure Drop

This account is by no means exhaustive nor is it intended to be as such; rather, this section reviews what this writer considers major factors and which have not been covered hitherto at the necessary level of detail.

3.4.1 Dust Collection Efficiency

Dust collection efficiency represents the principal design goal. It is a measure of the relative ability to separate or collect the inlet dust load (Croom, 1995). Stated differently, efficiency is the collected dust divided by the inlet dust load, or:

$$\text{Efficiency (ų)} = Ci - Co/Ci \tag{3-1}$$

Where Ci = inlet dust concentration

Co = outlet dust concentration

For example, if the inlet dust load is 50 gr/ft^3, and the allowable emissions level is 0.02 gr/ft^3, then the required collection efficiency is 99.96% (collection efficiencies in excess of 99.9% are routinely achieved in well-operated fabric filter units). Penetration, (1 - ų), is also used as a performance measure. McKenna and Turner (1993) assert that there is no satisfactory set of published equations that allows a designer to calculate efficiency for a prospective baghouse. (However, they offer one example, an equation developed by Dennis and Klemm for a computer model describing one specific system for filtration of fly ash by glass fabrics.) Collection efficiency and pressure drop are directly proportional, up to a point. As dust filter is formed, filtration efficiency increases as the pressure drop increases. However, a point will come when excessive differential pressure will cause the dust cake to compress or collapse, at which point the dust particles will rearrange into a denser structure. This rearrangement does not alter the mass of the cake (W), but it affects its specific resistance coefficient (K_2). Therefore, the denser structure will cause the pressure drop to elevate further, and the filtration efficiency begins to drop (McKenna & Turner, 1993).

3.4.2 Air-to-Cloth Ratio (A/C)

A/C (or gas-to-cloth ratio) in feet per minute (FPM) is a major baghouse deign factor. It is a measure of the amount of gas in cubic feet per minute (CFM) driven through each square foot of fabric in the baghouse. A distinction should be made between gross A/C and net A/C. Gross A/C is the total gas inlet volume divided by the total collector cloth area, whether or not part of it is off-stream. Net A/C is the total gas inlet volume divided by the on-stream cloth area. The result is the superficial gas velocity, or face velocity, not the actual velocity through the openings in the fabric (Greiner, 1993; McKenna & Turner, 1993).

Excessive A/C can cause elevated pressure drops which can cause compaction of the filter cake, which in turn affects dust collection efficiency (McKenna & Turner, 1993; Turner et al., 1998). Dennis and Wilder studied fabric filter cleaning in pulse-jet and shaker pilot scale systems and found that in pulse-jet systems, the outlet dust concentration decreased five-fold when the face velocity was reduced by 25%. This is an interesting finding; however, it is not clear whether it was due to reduced re-entrainment or whether it was due to reduced A/C, or both. They also found that outlet concentration decreased when pulse pressure was reduced and pulses damped, but was little affected by extended pulse duration or by pulse frequencies over time intervals from 0.4-4 min. Equally interesting, they found that outlet dust loading is more dependent on inlet loading in pulse-jet collectors than in shaker collectors. Pulse-jet systems tended to give constant efficiency, whereas shaker systems tended to give constant outlet loading (McKenna & Turner, 1993).

3.4.3 Pressure Drop and Drag

Much of the formulae that attempt to express the pressure drop in mathematical terms are based on the work Darcy performed in the early nineteenth century. Envisioning a bed composed of a variety of geometrical arrangements through which a fluid wades, Darcy formulated his equation (McKenna & Turner, 1993):

$$\Delta P = L\mu_f V/K \qquad (3\text{-}2)$$

Where ΔP = pressure difference across the bed

L = bed thickness

μ_f= fluid viscosity

V = superficial fluid velocity

K = bed permeability

Assuming that the fluid is essentially incompressible, flow is steady, fluid viscosity is Newtonian, and the velocity is low enough so that only viscous effects occur, McKenna and Turner (1993) suggest that the equation is intuitive: "[Pressure] loss of a normal fluid flowing relatively calmly through the resistance of a porous bed is proportional to the bed depth, the velocity of the fluid, and the internal resistance to shear of the fluid; and is inversely proportional to the openness of the bed" (p. 2-3).

In baghouses, the concern is fluid flow through an accumulating mass of filter cake entrenched in cloth matrix. The dust properties (physical and chemical), cloth characteristics and geometry, and operating conditions create dynamism that defies theoretical equations. Nonetheless, theoretical equations for gas filtration, in which an equilibrium state is assumed, can help us predict the pressure drop for an operating fabric filter. Building on Darcy's equation, McKenna and Turner (1993) present the following pressure drop equation for an operating fabric filter with residual dust accumulating on it:

$$\Delta P = P_E + K_2VW \qquad (3\text{-}3)$$

Where ΔP = total pressure drop, in. H_2O

P_E = effective residual pressure drop across the fabric with its residual dust loading, in. H_2O

K_2 = specific resistance coefficient of the freshly deposited dust, [in. H_2O/(ft/min)]/(lb/ft^2)

V = superficial fluid velocity, ft/min

W = areal dust loading on the fabric, lb/ft^2

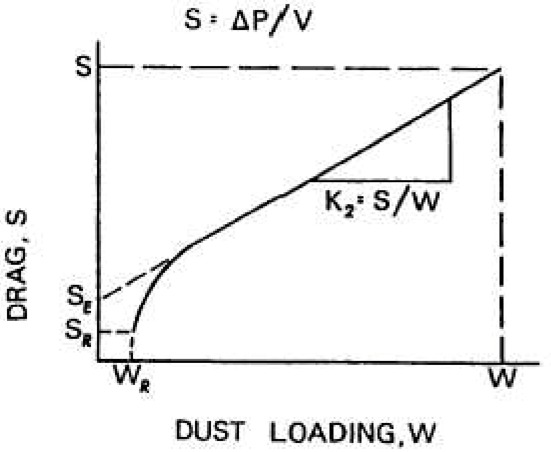
Equation (3-3) can be presented in a linear form:

$$S = S_E + K_2W \qquad (3\text{-}4)$$

Where $S = P/V$ = drag, in. H_2O/(ft/min)

S_E = effective residual drag of the fabric and its residual dust loading, in. H_2O/(ft/min)

Filter drag is the measure in inches water gauge of the pressure drop across a filter at the filtration velocity in feet per minute at the operating conditions with dust cake present. This linear form makes it possible to estimate the values of K_2, S_E, and resistance through the cake (K_2 W) from a plot of S vs. W (Figure 2):



Source: John McKenna and James Turner, Fabric Filter-Baghouses I: Theory, Design, and Selection, 1993

Figure 2: A Plot of Drag vs. Dust Loading

The filtration cycle begins at point (S_R, W_R) where there is only a residual dust mass, W_R, on the fabric that is associated with resistance to gas flow (drag), S_R, that is peculiar to the particular fabric, dust, and cleaning mechanism at a given set of operating conditions. As dust accumulates on the fabric, drag increases rapidly at first, then linearly as the cake builds up uniformly. Dust loading can be estimated as follows (McKenna & Turner, 1993):

$$W = C_i Q \Delta t / 7000A \qquad (3\text{-}5)$$

Where C_i = inlet concentration, gr/ft^3

Q = volume flow through filter, ft^3/min

Δt = accumulated filtration time since the last cleaning, min

A = area of filtration fabric, ft^2

7000 = conversion factor, grains to pounds

Substituting for W in equation (3-4):

$$S = S_E + K_2 C_i V \Delta t \tag{3-6}$$

Multiplying both sides by V results in what McKenna and Turner (1993) offer as a "practical pressure drop equation," suitable for reverse-air and shaker systems:

$$\Delta P = S_E V + K_2 C_i V^2 \Delta t \tag{3-7}$$

To account for the re-entrainment phenomenon relevant to online pulse-jet systems (re-entrainment is normally greater than 90%):

$$\Delta P = S_E V + (K_2)_c W_c V + K_2 C_i V^2 \Delta t \tag{3-8}$$

Where $(K_2)_c$ = specific resistance coefficient for the recycling fraction of the total dust load alternately dislodged and redeposited on the fabric, [in. H_2O/(ft/min)]/(lb/ft²)

W_c = the cycling portion of the dislodgeable dust loading, lb/ft²

Goodfellow (2001b) offers the following practical equation for estimating "approximately" the operating pressure drop in pulse-jet filters:

$$\Delta P = 2C_i^{1.4}\rho^{-2}R^{-0.5} \tag{3-9}$$

Where ΔP = operating pressure drop across the filter (mm WG)

C_i = inlet dust concentration (g/m³)

ρ = reservoir compressed air pressure (Pa)

R = reservoir pulse rate (pulses per bag per minute)

Though not evident from this empirical equation, Goodfellow notes that, as in shaker and reverse-air filters, ΔP is proportional to the square of the filtering velocity.

3.4.4 Can Velocity

In on-stream systems, as the dust is dislodged following the pulsing action, the forward gas velocity can result in re-entrainment of the dust particles back onto the fabric. When redeposition approaches 100%, the functionality of the filter is impaired. This velocity, which is the upward vertical flow or the air stream velocity passing around the filters, is referred to as can velocity (V_c) and can be expressed as follows (Croom, 1995):

$$V_c = \frac{\text{air stream volume}}{(\text{housing cross sectional area} - \text{filter cross sectional area})} \qquad (3\text{-}10)$$

High V_c is especially problematic in the case of fine/low density dust particles (recommended V_c then is less than 150 ft/min), and the only remedy seems to be switching to offline cleaning mode.

3.4.5 Dust Particle Characteristics

Relevant characteristics include particle size distribution, shape, agglomerating properties, chemistry, electrical conductance, and hygroscopic property. Dust properties must be investigated from the outset because they are a major design consideration. This is a huge subject outside the purview of this effort; but its importance can be stressed with a couple of examples. On the relevance of adhesion forces, McKenna and Turner (1993) relay that smaller particles tend to have higher adhesion forces per unit of surface area. It would seem then that for this kind of dust, off-stream cleaning, and not on-stream cleaning, would be more apt. On the other hand, conductive dust tends to have lower adhesion forces; hence on-stream cleaning might be a more viable option. On the relevance of cohesion forces, Klimczak (1988) suggests that some cohesion forces may help in the cleaning process, especially for low density dust. If the dust totally deagglomerates following the pulse, it will likely be redeposited on the fabric in online cleaning; hence the solution may be switching to the off-line mode. He notes, however, that some dusts with very low densities, such as fume dusts, will blow apart in any reverse jet or reverse-air dust collector, and even filter media changes will not remedy the de-agglomeration situation. Hence, a shaker system would be more apt.

3.4.6 Gas Characteristics

Characteristics to consider include temperature, humidity and acidity. For example, if water vapor entering the collector condenses, usually due to operating at a reduced temperature, dew point excursions can occur, and this can be very detrimental to both the filter media and collector components (Greiner, 1993; McKenna & Turner, 1993). When sulfur trioxide is present in the gas stream, acid dew point can occur. Klimczak (1988) cautions that since acid-water condensate has no surface tension, it can readily spread over the dust cake turning it into mud.

3.4.7 Filter Media

The good news about fabrics is that they can be changed and the most suitable type installed. The "best" filter medium is the one that fulfils the emissions goals and collector design objectives as efficiently and economically as possible. The tube sheet pressure drop, which is the largest component of the flange-to-flange pressure drop, as well as the filtration efficiency are primarily a function of the fabric/dust interaction or filter drag [S_E in equation (3-8)]. Related to drag is permeability, which is the volumetric airflow in CFM per square foot of new or clean filter at a pressure differential of 0.5 in. WG per ASTM standard D-737. Drag for a new fabric equals 0.5 divided by its permeability (ASTM test D-737) (McKenna & Turner, 1993).

The fabric's primary role is a support medium for the layer of dust cake that performs most of the filtration. There is an array of designs, treatments and finishes for fabrics available, and making the right choice requires extensive knowledge and skills. Felted fabrics generally allow for a reduced filter drag and increased filtration efficiency especially for finer dust (Croom, 1995; Greiner, 1993). However, each application is unique. Felted media may not be suitable for hygroscopic or sticky dust, for example, as it can clog the media pores (U.S. EPA, 2002b). Every aspect of the application—operating parameters, dust properties, gas properties, and the required mechanical strength—must be considered before a fabric can be selected.

The three performance criteria for a filter are filterability, cleanability, and durability (an industrial axiom), and the three are interrelated. Filterability refers to filtration efficiency, cleanability refers to how well a fabric cleans, and durability refers to its service life. Together, these three criteria form a continuum of reinforcing loops. For example, when a filter cleans well (dislodges the dust effectively), it is likely to have a healthy dust cake and is efficiently collecting dust, and it is likely be less pulsed (assuming on-demand actuation), and hence its service life is enhanced.

Fabric properties can be traced down to the micro and nano levels (i.e., fiber shape and molecular composition) as well as to the macro level (manufacturing/finishing procedures). It is found that lobular and micro-fibers trap dust more effectively than conventional uniform fibers. One theory is that such fibers provide higher surface area. A second is that they accumulate static charges which help capture dust. A third is that their high differentiation allows for smaller interstitial voids which supports surface filtration. The end result is that they generally provide lower pressure drop and higher filtration efficiency (but tend to be more costly). Treatments are added to enhance cake release, chemical, and mechanical properties (McKenna & Turner, 1993). Media selection charts are ubiquitous and offer general selection guidelines. Bench-scale filtration tests can help the selection process by investigating ab initio the interrelations among medium type, pressure drop, and filtration efficiency. Alternatively, computer modeling can be used.

3.4.8 Baghouse Design Considerations

Croom (1995) argues that an optimum hood or inlet design that is located as close as possible to the dust source is a major design factor that is too often overlooked: “Working to achieve good inlet design without interference with the process results in the minimum size duct, collector, and fan, as well as a reduction in costs and emissions” (p. 161). Failing this, “the entire system must then be overpowered to achieve adequate dust control. Thereby a higher initial investment along with a higher energy cost is incurred throughout the operating life of the system” (pp. 161-162). Another area of major significance is the air stream inlet designs and corollary inlet velocities.

Reduced pressure losses can result from appropriate transmission from a conveying duct size and velocity into the collector enclosure at a gradual 15° to 30° flare. Croom (1995) recommends that velocity be reduced to below 2000 ft/min on entering the hopper, and to the 200 ft/min range at the filter passage area (can velocity). In between these two regions, a baffle can be used to even out flow velocity and thus help reduce dust re-entrainment on the bags. Further, certain inlet designs seem more appropriate for certain dust types.

3.4.9 Other Important Parameters

The influence of the system design on the performance cannot be exaggerated. From a systems perspective, it is the system structure that defines the causal relationships between its various elements. Hence, the complexity of the operation of pulse-jet dust collectors can be traced to their designs and the dynamic relationships they foster within them. Other important parameters that contribute to optimized filtration efficiency and pressure drop include cage integrity, bag-to-cage fit, and bag-to-tube-sheet fit. The reader is advised to consult the primary references for further information. Finally, inefficient collector operation could be due to worn out parts, non-calibrated equipment or readout devices, or a host of other mechanical or design defects.

CHAPTER FOUR

4.0 Research Activities

4.1 Conceptual Framework

> That a cause may have several effects and an effect may be a result of many causes is conceded by all. Yet in management of practical affairs and in attempts at problem solving, this truism is often lost sight of. (Anatol Rapaport, 1986, as cited in Spruill, Kenney, & Kaplan, 2001)

Rather than logical[8] and linear, systems thinking is lateral (non-linear) and circular (De Bono, 1972; O'Connor & McDermott, 1997). In dynamic complexity systems, a change in one part of the system will ripple out and affect other parts in unforeseeable ways, and since all parts are interconnected, the ripple effect will eventually reach the original part, which will respond in turn. Hence, systems are maintained by feedback loops, which could be either reinforcing or balancing (O'Connor & McDermott, 1997). Because the effect could appear at an unexpected location and time, the system management style must be flexible to allow for continuous revision, according to the feedback signals. But maintaining an efficiently functioning system may not necessarily be a prudent strategic objective: sometimes proactive change is necessary, before an external balancing feedback loop brings the system to a standstill, or worse. To affect positive change, therefore, in addition to adaptive management, creative management is needed.

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[8] Logical: based on earlier or otherwise known statements, events, or conditions (The American Heritage Dictionary of the English Language, Fourth Edition, 2000).

This is especially important when dealing with a rapidly changing and competitive world, and during a paradigm shift (Proctor, 1999).

4.1.1 I Think Therefore I am Creative

The online WordNet® 2.0 dictionary defines creativity as "the ability to create [syn: creativeness, creative thinking]." Gilliam defines creativity as "a process of discovering what has not been considered —the act of making new connections" (as cited in Proctor, 1999). An online source[9] defines it as "the act of originating novel associations that are useful"; and defines innovation as "the result of applying creativity to an explicit product or service." Basadur (1998) suggests that creativity is an integration of curiosity, knowledge, imagination, evaluation, implementation, and process. Proctor (1999) points out that because creativity is a multifaceted concept, it is difficult to define; however, the various definitions seem to agree that creativity entails an in-depth thought of a subject and an ability to come up with new viewpoints or ideas.

Ideas are the building blocks of creativity and innovation (Proctor, 1999). Sometimes, they come by accident, as flashes of insight. And it would seem that an idea is a manifestation of an association established at the preconscious level between two subjects. However, an idea in and of itself is mere neural traffic if not taken up at the conscious level, and this is something applied creativity teaches. For simplification purposes, one can divide creativity into two streams (MindTools.com, 2004): artistic and technical. Artistic creativity is manifested in aesthetic sensibility, emotional resonance and a gift for expression (De Bono, 1972). Such abilities are innate and are not the subject of applied creativity. Technical creativity, on the other hand, is manifested in new theories, technologies and procedures; it is driven by generative or lateral thinking and it can be nurtured. By comparison, vertical thinking is selective; it fosters a logical approach, which is indeed needed for efficiency, but it cannot foster innovation.

In their review of creativity and problem solving techniques, Souder and Ziegler (1988) warn that ideas generating techniques "need to be combined with organizational methods which provide the necessary care, feeding, and implementation of embryonic ideas" (p. 267). In order to be innovative, therefore, both linear (systematic) and lateral (systemic) faculties are needed simultaneously.

4.1.2 It's a Patterned, Patterned, Patterned, Patterned World

It is hypothesized that our brains are pattern recognition systems (Proctor, 1999). The cognitive problem solving process can be explained with the index metaphor as follows. The first step in the cognitive problem solving process is perception of the problem. O'Connor and McDermott (1997) explain that we each have a set of established mental models that have become entrenched in our subconsciousness through years of socialization. We take ownership of these models, we maintain them and use them as a basis on which future models are constructed. They are also the "filter" through which we perceive information. Subconsciously, we use deletion (we

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[9] The Creative Problem Solving Group, Inc., http://www.cpsb.com/cps101_sample/4-2-6-1.html Accessed

are selective as to what information we notice), construction (we “fill in the blanks” where information is missing), distortion (we may amplify certain aspects and diminish other aspects), and generalization (we tend to form stereotypes) to conceptualize a problem. Once we perceive a problem, we identify its main theme and look it up in the index of our metaphorical mental book, where all past life experiences are stored. Themes contain scripts, or packets of information pertaining to each theme. If no reference exists in our mental book for a particular problem, the brain attempts to find cross-references under various headings to construct a new script. If this fails, we can get stuck (Proctor, 1999).

Mental models can be thought of as fractals organized in a certain way that corresponds to our past individual socialization and education. However, when we shake things up, we break the pattern and new patterns emerge, just as in a Kaleidoscope (H. Johannesen, personal communication, January 2005). Patterned thinking is a double-edged sword. On the one hand, it allows us to quickly recognize faces and objects and solve minor problems; on the other hand, we tend to get stuck in these patterns, which stifles creativity. Applied creativity attempts to break the patterned thinking routine thus offering us the social ingenuity tool we need to foster technical ingenuity.

December 16, 2004.

4.2 The Simplex Approach

4.2.1 Quality Results

Cooper (2001) argues that, just like in warfare, launching a new product successfully to market requires both strategy and tactics. He notes that without tactics, strategy is nothing but words; tactics are the tools by which strategy is implemented. In other words, what to be done (the strategy, for example, launch a media blitz) and how to do it (the tactics, for example, hire PR pundits) are both requisites to achieving a goal or a vision (for example, winning an election). Basadur (1998) agrees that both content (what to be done) and process (how to do it) are requisites for achieving quality results but distinguishes between process (how) and process skills (how to do the "how" well). This breakdown of process components helps us manage project variables and identify weak spots and critical links. It further concurs with the TQM principle that a quality product (result) is only guaranteed when quality is built into each step of the manufacturing process. However, Basadur argues that it is not sufficient for an organization to have efficient processes. Both flexibility and adaptability are needed to ensure sustainability. Simplex focuses on adaptability, which is a manifestation of creativity, to generate innovative results. The following expression represents the conceptual framework of Simplex:

Quality (innovative) results = Content (the challenge; the relevant knowledge) + Process (Simplex) + Process skills (divergence, convergence, deferral of judgement, and vertical deferral of judgement)

Like a computer, our brain can absorb and retain knowledge. However, what gives us the ability to be creative is our ability as humans to ideate and evaluate. Basadur (1998) captured this concept in his creativity equation: Creativity = Knowledge X Ideation X Evaluation. However, this formula requires a delivery mechanism, or it will remain a strategy without tactics. Simplex is such delivery mechanism that teaches people the tactics that enable them to animate the creativity formula. The first tactic, “the big secret,” to applied creativity is the ability to separate the ideation and evaluation processes. As Basadur explains it, imagine pressing both the accelerator and brake of your car simultaneously: energy is expended but no meaningful result would be attained. In the same way, if we cannot separate divergence and convergence as two discrete thought processes, i.e., if we cannot defer judgement, we cannot produce innovative results. The second biggest secret is to follow the process faithfully, i.e., practice vertical deferral of judgement.[10]

An online source, www.mindtools.com (accessed 30 November 30, 2004), lists Simplex under “Practical Creativity” and describes it as “an industrial-strength creativity tool,” which rather than seeing creativity as a linear process, sees it as “the continuous cycle it should be.” On his website, www.basadur.com (accessed 30 November, 2004), its author, Min Basadur, describes it as a “method of applied creativity that interconnects a process of creative problem solving with skills and tools to make that process work...[it] is simple, experiential and inclusive.”

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[10] Min Basadur (personal communication, June 16, 2005) explains, “This means to avoid leap-frogging steps in the process, such as jumping to solutions before open-mindedly discovering and probing for facts and defining the problem in many new ways. Often, the final problem definition is surprisingly different from that originally believed.”

The “problem” to be tackled is not necessarily one that is manifested in a formal manner; a problem is a perceptual discrepancy between “what is and what should be” (Proctor, 1999). In fact, a problem could be as simple as a perceived lack of one (De Bono, 1972). Further, sometimes what we perceive as a problem is only the symptom of the problem and we end up “solving the wrong problem.” Simplex takes this complexity into account in two ways. First, by its “why-what’s-stopping” analysis (see subsection 4.2.2 Step 3) during the problem definition phase which allows us to conceptualize the interrelationships and interconnectedness among the various system components on one level, and between the system and the larger system, i.e., the ecosystem, on another. Second, the circular structure of Simplex stresses the fact that when one “problem” is solved, the change it causes to the system will likely appear in another location, creating a new “problem.”

The secret to successful divergence is unrestrained imagination. Here, what counts is quantity rather than quality of ideas. During evaluation (or convergence), judgment and decision making skills are practiced. Finally, throughout the process, we are advised to use simple, specific, clear, and action-oriented statements, as ambiguity will only keep the situation “fuzzy.”

4.2.2 The Eight Steps

Step 1: Problem Finding (The “fuzzy situation”)

The Simplex process begins with searching for opportunities for creative problem solving, selecting one, and then stating what you think may be the issue or the problem. It is referred to as a "fuzzy situation" at this point in order to emphasize that you should not assume anything about it yet. Thus, the first step in the Simplex process is to generate opportunities. In his book, *Simplex: A Flight to Creativity*, Basadur (1998) suggests a host of provocative questions to aid personal or corporate problem finding.

- How can we reduce the energy consumption of pulse-jet dust collectors?

Step 2: Fact Finding

In many ways, this step is "laundry" to any assumptions you might have had so far regarding your dilemma. For divergence, Basadur (1998) suggests six fact finding questions (only five are explored here) that are designed to scope out the relevant facts regarding the fuzzy situation. For convergence, select a few of the most intriguing facts which seem especially pertinent or novel.

A. Diverge

1. What do you know, or think you know, about this fuzzy situation?

- Overall efficiency improvements (achieving the same or more output with less input) would reduce operating and maintenance costs.

- Basic performance starts with design; therefore, retrofit improvements would have a limited effect and would be principally attained through process adjustments, system modifications or upgrade.

- Increased pressure drop may reduce system airflow. A dust collector may or may not be process-dependent. In process-dependent systems, such as cement kiln baghouses, reduced airflow can slow down normal production throughput and thus can be very costly. If the daily cement production of a cement manufacturer is 2350 tons, for example, then 1% decrease in production represents 23.5 tons, or a daily loss of $1,410.00 in sales assuming the selling price of cement is $60 per ton.

- The total annualized cost of a pulse-jet dust collector can be estimated as follows (McKenna & Turner, 1993):

$$T = G + X + Y \tag{4-1}$$

Where T = Total annualized cost ($/year)

G = Annual costs for operation and maintenance ($/year)

X = Annualized capital costs ($/Year)

Y = Depreciated capital investment ($/year)

Where G can be further expressed as:

$$G = E + M \tag{4-2}$$

Where E = Electrical cost ($/year)

M = Maintenance cost ($/year)

Electrical costs would include the power of the main baghouse system fan, the power for the compressor, and other system controls, dust discharge, lighting, etc. employed at the baghouse. Maintenance costs would include compressed air consumption and replacement of expended filter media (Leibinger, 2003; McKenna & Turner, 1993).

- The largest three contributors to operating costs are, in descending order of magnitude, fan power consumption (about 70% of the total costs), replacement of filter media, and compressed air consumption (Leibinger, 2003).

- More and more systems are being dimensionized for constant flow and pressure drop is the integrated value, making the energy input requirements a direct function of the operating pressure drop for the filter (Goodfellow, 2001b).

- The relationship between fan power, system pressure drop, and volumetric airflow can be expressed as follows (McKenna & Turner, 1993):

Fan brake horsepower (hp) = $\Delta PS/6356E_f$ (4-3)

Where ΔP = Baghouse pressure drop (sum of ductwork system static pressure plus filter system static pressure), in. WG

S = Design capacity of fabric filter, ACFM (actual cubic feet per minute)

6356 = Air Horsepower constant

E_f = Fan mechanical efficiency (percentage)

- Equation (4-3) can be further modified to directly calculate annual electricity costs:

$E = (0.746)\ \Delta PSHK/6356E_f$ (4-4)

Where E = Electricity costs ($/year)

H = Annual operating time (hours)

K = Power cost (dollars per kilowatt-hour)

0.746 = Conversion factor, horsepower to Kilowatt-hour

From equations (4-3) and (4-4), it is clear that reduction in ΔP and/or increase in E_f would lower the energy consumption.

2. What do you not know about this fuzzy situation (but you would like to know)?

- How to reduce ΔP
- How to increase fan efficiency
- How to reduce energy consumption
- How to increase overall system efficiency
- Whether we can find a way to reduce energy consumption without lowering the dust collection efficiency

3. Why is this a problem for you?

- We need more sustainable dust collection systems (i.e., with an improved economical, ecological, and social footprint)

4. If this problem were solved, what would you have that you don’t have now?

- Economic, environmental, and social benefits

5. What might you be assuming that you don’t have to assume?

- Most dust collectors are not optimized and overall system efficiency could be improved
- Conservation of energy would help make dust collectors more sustainable
- Electricity must be purchased

B. Converge

- The energy input requirements are a function of the operating pressure drop for the filter
- Most dust collectors are not optimized, and efficiency could be improved
- G = E + M
- We need more sustainable dust collection systems

Step 3: Problem Definition

The maxim “a problem well defined is a problem half solved” highlights the significance of this milestone step. It is critical such that divergence and convergence are each performed twice. In the initial divergence, based on the facts from step 2, list as many creative challenges as possible using the format “how might we?” (or “how might I?”). Using the how might we (HMW) format prevents the problem-solver from using facts as roadblocks by invoking cliches such as “that’s not how we do it around here” or “we can’t because…” Then, converge by choosing one challenge that seems most pertinent and take it over to the final divergence stage.

In the opinion of this writer, Final Divergence is the most enlightening step in the Simplex process.[11] Done properly, the problem solver will be able to discern the interconnectedness of his seemingly isolated challenge with the other parts of the system, and the interrelationships (cause and effect) between them. And on another level, he will be able to discern the interconnectedness between his problem and his system with other larger societal systems. The final divergence stage tries to break down the challenge into smaller more manageable parts. It thus incorporates other creative problem solving techniques such as the “Drill-Down” technique by default. In the final convergence, from the problem definition map, select one challenge that seems most actionable and creative.

A. Initial Divergence

- HMW optimize ΔP?
- HMW find a more sustainable way to operate pulse-jet collectors?
- HMW extend the service life of the filter bags?
- HMW optimize the fan operation?
- HMW optimize the dust collector operation?
- HMW reduce G (the annual operation and maintenance costs)?
- HMW increase the dust collection efficiency?

B. Initial Convergence

- HMW optimize ΔP?

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[11] This step is fully documented and explained in three journal articles by Basadur and his colleagues: Basadur,

The above selection was based especially on the fact that a reduction in ΔP will lower the energy consumption, as explained in Fact Finding, and as is evident from equations (4-3) and (4-4).

C. Final Divergence (Problem Definition Map)

In the final divergence, Basadur (1998) recommends using the questions “Why?” and “Why else?” to broaden the scope of the selected challenge, and “What’s stopping” and “What else is stopping?” to narrow it. The following lines explain how the “why-what’s stopping” analysis is performed (refer to the Problem Definition Map). In Initial Convergence, the challenge “HMW optimize ΔP?” was chosen. Then, this question was placed in the center of the Problem Definition Map and other challenges based on/derived from it were deduced using two questions: Why/Why else (i.e., why/why else do we want to do such as such?), and What’s stopping/What else is stopping (i.e., what’s stopping/what else is stopping us from doing such and such?).

For the “why” analysis, which progressively gives more strategic insights, first, the question Why? is asked of the challenge. Thus, for “HMW optimize ΔP?” the question posed is “Why do we want to optimize ΔP?” (This step can be completed cerebrally). Second, the answers to the why question are stated as new HMW challenges in the Problem Definition Map (following the direction of the arrow). Thus, the question “Why do we want to optimize ΔP?” triggered four answers that were further restated as new HMW questions: in order to pulse bags less frequently, became “HMW pulse bags less frequently?” In order to maintain flow (through the filter unit),

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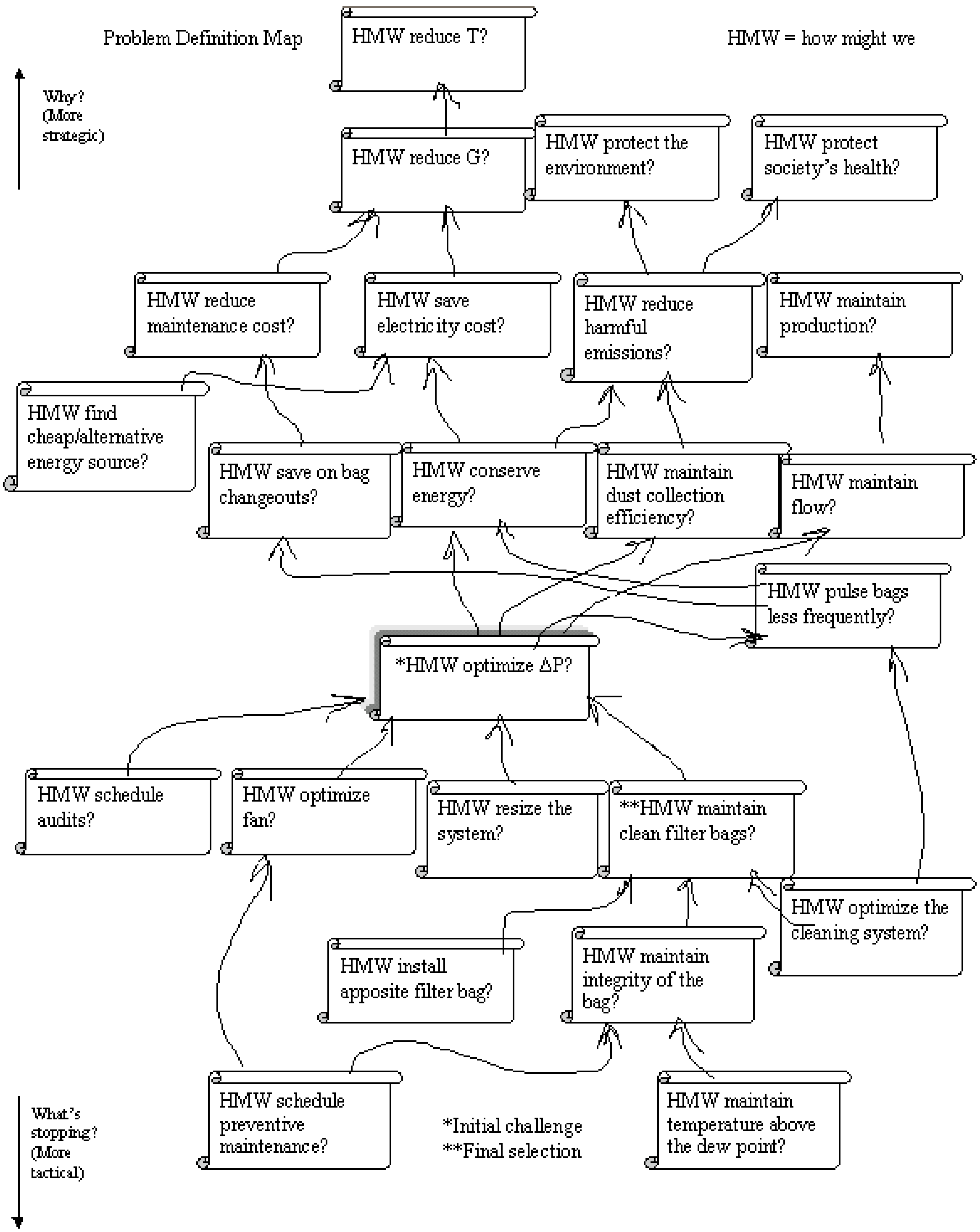
Ellspermann, & Evans (1994); Basadur, Potworowski, Pollice, & Fedorowicz (2001); and Basadur (2003).

became “HMW maintain flow?” And so on. To further process “HMW pulse bags less frequently?” the question was asked, “why do we want to pulse bags less frequently?” The answer, “so that we can save on bag changeouts,” was restated as “HMW save on bag changeouts?” And so on.

To conduct the “what’s stopping” analysis, which progressively produces more tactical insights, following our example for the challenge “HMW optimize ΔP?” the question was “What’s stopping us from optimizing ΔP?” The answers, four in this case, were restated as new HMW challenges. For example, the answer “maintaining clean filter bags,” became “HMW maintain clean filter bags?” And so on.


Problem Definition Map
HMW = how might we
Why? (More strategic)
HMW reduce T?
HMW reduce G?
HMW protect the environment?
HMW protect society's health?
HMW reduce maintenance cost?
HMW save electricity cost?
HMW reduce harmful emissions?
HMW maintain production?
HMW find cheap/alternative energy source?
HMW save on bag changeouts?
HMW conserve energy?
HMW maintain dust collection efficiency?
HMW maintain flow?
HMW pulse bags less frequently?
*HMW optimize ΔP?
HMW schedule audits?
HMW optimize fan?
HMW resize the system?
**HMW maintain clean filter bags?
HMW optimize the cleaning system?
HMW install apposite filter bag?
HMW maintain integrity of the bag?
HMW schedule preventive maintenance?
*Initial challenge
**Final selection
HMW maintain temperature above the dew point?
What's stopping? (More tactical)

D. Final Convergence

- HMW maintain clean filter bags?

The above option was selected because it seemed most actionable (also see section 5.3: Limitations and Potential Biases, para. 2).

Step 4: Idea Finding

The solution formulation phase of the Simplex process begins with idea finding. Letting your imagination loose, generate ideas (Basadur proposes the generation of at least twenty ideas) that might solve the problem. List your ideas as short specific action items. Techniques for generating ideas include brainstorming, blitzing, forcing relationships, and Provocation. In brainstorming, while focusing on a problem, diverge and come up with as many radical solutions as possible. Basadur (1998) notes, “brainstorming involves following four rules: do not criticize ideas; go for quantity of ideas; hitchhike on ideas; and practice freewheeling” (p. 142). During convergence, select the most promising ideas (say, four of them) to take over to the next step (evaluation and selection).

A. Diverge

1-Install new bags

2-Install other types of bags

3-Change length of bags

4-Change area of bags

5-Work baghouse without bags

6-Install an alternative cleaning system

7-Install a complementary cleaning system (e.g., cyclone pre-filter)

8-Perform in-situ cleaning[12]

9-Punch holes in filter bags

10-Pre-coat bags with a residual dust layer

11-Deflect dust-laden gas away from the dust collector inlet

12-Treat fabrics with chemicals that reduce the surface energy of fabrics such as fluorochemicals or silicone (stain/water repellants)

13-Treat fabrics with anti-static chemicals (especially for low-density dust)

14-Resize the filter unit

15-Reduce the can velocity

16-Flush the bags periodically with soap and water (as in a drive thru car wash)

17-Pulse via a perforated air hose suspended into each bag

18-Suspend a high voltage electrode into each bag, perhaps synchronized with pulsing

19-Permanently reverse the direction of airflow through the dust collector

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[12] In-situ (in place) cleaning -or high efficiency cleaning (HEC)- is a proprietary filter bag cleaning technology that was developed in Germany by Albarrie's partner Josef Heimbach GmbH & Co. Filtration Group, and which Albarrie has exclusive rights to its commercial use in North America. HEC technology uses calculated high-pressure bursts applied to each individual bag inside the dust collector, which effectively dislodges the dust accumulated on the filter fabric that normal pulsing action fails to dislodge. By using this service, the filter-media's service life can

20-Remove the system fan

21-Install venturis where there is none

22-Use sonic horns[13]

23-Use fabrics made from multi-lobular fibers or micro-fibers or both

24-Use PTFE laminated fabrics

25-Use fabrics made from 100% PTFE fibers

26-Use other percentages of PTFE fibers

27-Change fabric density

28-Calender/glaze/singe fabrics

29-Change purge mode (e.g., alternate between high-pressure low-volume, low-pressure high-volume, low-pressure low-volume, and high-pressure high-volume)

30-Change purge pressure

31-Change pulsing frequency (e.g., change from on-demand to timer initiation)

32-Change cleaning mode (e.g., from online to offline)

33-Change cleaning sequence (e.g., pulse bag rows randomly)

34-Use layered "peel-off" fabrics

35-Use a combination of cleaning mechanisms in tandem (e.g. pulsing with shaker or reverse air)

36-Use reverse air baghouse design but with bags that have caps that open during cleaning

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be extended significantly. The service is performed with minimal shutdown time. For more information see http://www.albarrie.com/Task%20Canada/index.html (accessed December 2, 2004).

[13] As the name implies, sonic horns emit sonic waves -high intensity waves that vibrate dust-containing fabric with sufficient energy to loosen or detach patches of dust that fall to the hopper. They are indeed used by the baghouse industry -usually suspended inside the baghouse structure- as an aide to the main cleaning mechanism, and that is one way to help keep the bags clean. However, divergence has led me to envision using a sonic horn device a la the in situ HEC device, i.e., modified for use on individual bags. However, the validity of this idea remains left to investigation.

37-Change the inlet dust properties

38-Optimize the cleaning mechanism

39-Mist dust particles with water at inlet to “trap” and drop in hopper

40-Install a sieve/mesh before the bags

41-Install IR lamps inside the dust collector to eliminate dew point excursions and help keep the dust dry

42-Use microwaves to periodically evaporate excess humidity

43-Install dehumidifiers inside the dust collector

44-Use gamma rays to ionize the dust particles at inlet, then allow the ionized stream to pass through electrically charged plates to capture the ionized dust particles

45-Spray inlet dust with hot steam to trap the dust particles then allow the dust-water aerosol to condensate on a cold surface (e.g. with aid of liquid nitrogen)

46-Install cheap disposable filters at dust inlet (e.g., paper filter)

47-Install controlled vacuum suction immediately beneath the bags and synchronize it with the pulsing cycle so that it is activated immediately following the pulse (especially in online systems, where more than 90% of dislodged dust is redeposited on the fabric)

48-Alternatively, as above but operate vacuum concurrently with purging (suck and blow at the same time)

49-Install a separator (impervious baffle) that extends horizontally across the baghouse and prevents the dislodged dust from being redeposited on the filter bags immediately following the pulse

50-Employ VDI[14] (e.g., VDI 3926) laboratory simulation tests to determine the apposite filter medium

51-Employ LD-Mobile technology[15] (in-situ bag permeability/static pressure testing) to determine the apposite filter medium

52-Use multiple pulsing at short intervals

53-Switch main fan off and pulse

54-Test different fabric types in a pilot scale system to determine the apposite type

B. Converge

1-Install new bags

2-Perform in-situ cleaning

3-Use sonic horns

4-Optimize the cleaning mechanism

5-Employ VDI 3926 laboratory simulation tests to determine the apposite fabric medium

6-Employ LD-Mobile technology to determine the apposite fabric medium

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[14] VDI or "Verein Deutscher Ingenieure" is German for the Association of German Engineers. VDI 3926 "Testing of Filter Media for Cleanable Filters under Operational Conditions" is a standard filter fabric performance evaluation test method using the "VDI instrument" which simulates conditions of a real dust collector. It is slowly becoming the global standard for assessing the filterability and cleanability of filter fabrics.

[15] The LD-Mobile and HEC devices were both invented by the same inventor.

Step 5: Evaluate and Select

Begin the evaluation and selection process by first ideating for some twenty evaluation criteria (record them in specific, clear and simple statements), then begin converging by choosing few (say, four) of them that seem most pertinent. On a grid, such as the following one, list your selected solutions vertically on the left, and your chosen selection criteria across the top. You can then rate each solution against each criterion in turn. To avoid ranking the solutions (as opposed to rating them), complete the evaluation process vertically. In the following example, a simple numerical rating scale (as suggested by Basadur) was used: 3 for excellent, 2 for good, 1 for fair, and 0 for poor. Also, in the following example, several criteria deemed more pertinent were weighed by a multiplication factor (2X, in this case to denote that they were twice as important compared to other criteria). Complete converging by choosing one solution to carry forward to the implementation stage.

A. Diverge

1-Financial benefit (for the service buyer, i.e., the customer)
2-Environmental benefit (for society)
3-Health benefit (society)
4-Profit margin (for the vendor; for the purpose of this effort, Albarrie Canada Limited)
5-Effort needed (vendor)
6-Time needed (vendor)

7-Ethical considerations (vendor)

8-Ease of implementation (vendor)

9-Probability of success (vendor)

10-Salability (vendor)

11-Human resources needed (vendor)

12-Investments needed (vendor)

13-Legal considerations (vendor)

14-Corporate Social Responsibility (vendor)

15-Corporate image (vendor)

16-Opportunity cost (vendor)

17-Degree of interest (vendor)

B. Converge

1-Financial benefit (buyer)

2-Environmental benefit (society)

3-Health benefit (society)

4-Profit margin (vendor)

5-Ease of implementation (vendor)

6-Probability of success (vendor)

The evaluation grid:

	Financial benefit (buyer)	Environmental benefit (society)	Health benefit (society)	Profit margin (vendor)	Ease of implementation (vendor)	Probability of success (vendor)	Total (weighted)
	2X	1X	1X	2X	1X	2X	
Install new bags	0	3	3	1	3	3	13 (17)
Perform in-situ cleaning	3	3	3	3	2	3	17 (26)
Use Sonic horns	1	3	3	3	2	1	13 (18)
Optimize the cleaning mechanism	3	3	3	1	0	2	12 (18)
Employ VDI 3926 tests	2	2	2	2	1	1	10 (15)
Employ LD-Mobile technology	2	2	2	1	2	2	11 (16)

- Selected solution: Perform in-situ cleaning

Step 6: Planning Action

Begin the implementation phase of the Simplex process by diverging on the following seven planning action questions (the purpose is to ensure that all angles are covered). Converge by translating these thoughts into an action plan --a “what-how-who-when-where” grid as follows.

A. Diverge

1. What new problems might this idea create?

- In-situ cleaning might lower the filtration efficiency temporarily until a new dust cake is formed at stabilization
- In-situ cleaning may not be helpful where dust particles have migrated deep into the depth of the filter media

2. Where might you encounter difficulties with this idea?

- Convincing the customers to buy the service (as it is a novel technique)
- Internal (corporate) conflict of interest could stifle enthusiastic promotion of the technology (as the vendor traditionally sells filter media)

3. Who might be negatively affected by this idea?

- Competitors

- The business traditionalists who resist change

4. Who would benefit from this idea?

- Service vendor, service buyers, the environment, and society as a whole (as a result of reduced emissions and reduced waste, i.e., less bags to landfill or to incinerate)

5. How might you introduce this idea?

- Through promotional literature, calls, and presentations

6. When might be the best time to introduce this idea?

- To clients, when their bags are nearing their normal life expectancy
- To senior management, as soon as a business plan is completed

7. What specific steps might I take to get the ball rolling?

- Review current promotional literature to decide whether new material should be developed and/or the current material revised
- Review/gather list of potential customers to determine potential market size
- Review case histories to identify trends, and any operational faux pas

- Perform SWOT analysis (identify the relevant strengths, weaknesses, opportunities and threats)
- Develop a call questionnaire draft
- Develop a follow-up questionnaire draft
- Call for a meeting to discuss the next steps
- Identify the persons who should attend the meeting
- Draft a tentative meeting agenda
- Draft a preliminary business plan, marketing strategy, and goals to present at the meeting

B. Converge (Action Plan)

What will be done	*How it will be done*	*By whom*	*By When*	*Where*
1. Set preconsult appointment with department head[16]	Phone call	Me	August 02	My desk
2. Draft preconsult discussion points	Typed on paper	Me	2 days ahead of preconsult meeting	My desk
3. Conduct preconsult with department head	Using Simplex steps 1-3	Me and departmental head	August 16	As agreed

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[16] Basadur (1998) opines that a successful meeting is a three phase process: 1-Preconsult, a pre-meeting session between the process facilitator and content owner during which the meeting objective, agenda, participants and pre-work are defined; 2-Meet; and 3-Debrief, a post-meeting session during which the process is assessed.

4. Draft meeting agenda and send out to identified participants[17]	Email	Me	August 18	My desk
5. Meet with ad hoc committee	Simplex	Participants	August 24	Meeting room
6. Debrief the meeting	By asking what helped and what hindered our meeting; and what did we learn	Participants	August 24	Meeting room

Converging in this step produced the action plan and culminated in the debrief meeting. Thus, a business plan for implementing the in-situ cleaning solution was formulated with the participation (and to the satisfaction) of mid-level management, the support of whom was necessary for taking this project further to senior management and/or to action.

Step 7: Gaining Acceptance

This step is about creatively selling your idea to its intended clients. Diverging using some anticipatory questions, as follows, allows you to identify your selling points and your weak points and proactively build arguments to handle them. Converge by building these arguments.

A. Diverge

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[17] Basadur (1998) recommends that participants fill four roles: facilitator and coach, as process roles, and owner and participants as content roles.

1. Whose approval is needed to proceed?

- For the business plan, senior management
- For the service, the clients identified in the business plan

2. One major problem the solution (in-situ cleaning) solves?

- For the vendor, competitive advantage
- For the buyer, system shut down due to high pressure drop or bag-change maintenance

B. Converge

1. Three benefits from solution implementation:

	A. Diverge	B. Converge
	Benefits	Clarify benefits
Vendor:	Increased profitability	Profit = revenue - costs
	Positive corporate image	A “total solution provider” image
	Access to new markets/clients	The service will have its unique market (will “open doors”)
Client (buyer):	Direct savings	Delay in bag change or reduced electricity consumption, and compressed air consumption

	Reduced maintenance downtime	Bags are “regenerated” on site; service is especially rewarding if performed as part of a preventive maintenance schedule
	Reduced pressure drop	Maintained airflow and throughput

2. Three possible objections to the proposed solution:

	A. Diverge	B. Converge
	Objections	Overcoming the objections
Vendor:	None anticipated	
Client (buyer):	It may not work	Bags will be pre-qualified in a laboratory simulation test; further, one compartment could be serviced as a pilot project
	We don’t do it that way (we just purchase new bags)	With this technology, you will realize immediate financial and operational benefits
	Why is this technique better than regular laundering?	With this technique, bags are cleaned on site; hence it takes a fraction of the time needed for regular laundering

Step 8: Taking Action

Now that you have “planned your work, work your plan,” as the adage goes. If, however, at this stage, there are impediments to implementing the first item in the action plan, Basadur (1998) recommends that you write down these impediments, i.e., diverge. Then, isolate the biggest impediment and list at least three ideas for overcoming it, i.e., converge. Finally, put these ideas into action. For the purpose of this study, there were no impediments. Based on the preceding steps, the in-situ cleaning solution was field-implemented as detailed in Action.

4.2.3 Action

This subsection details the action taken to implement the in-situ cleaning solution for a pulse-jet dust collection system at a non-ferrous metals foundry in London, Ontario. According to the information obtained from the filter manager, the filter collects sub-micron sized dust particles generally containing metals, semi-volatile and volatile organic compounds that mainly come from the melting process. It is a compartmented design comprised of 4 modules, with 165 bags in each module. Each bag has a diameter of 6 inch and is 12 feet long, giving a total cloth area of 12,434 ft^2. The fan has a capacity of 35,000 ft^3/min. The filtration velocity is 35,000 CFM/12,434 ft^2 = 3 ft/min, which is considered well below the nominal value of 6 ft/min which is suggested for metallurgical fumes (Croom, 1995).

The system operating temperature is 190ºC (374ºF) with possible surges up to 210ºC (410ºF), employing aramid type bags, which are suitable for this temperature range (whether the type of fabric used, or whether the operating parameters in totality are suitable for such application is a subject for an entirely different endeavor, namely, a system audit, and is beyond the scope of this study). No emissions data was obtained. The bags are 500 grams per square meter (14 ounces per square yard) with no surface treatment. Dust loading and dust properties vary with scrap quality. The latter also affects the service life of the bags, but which is nonetheless two months on average. Cleaning is normally on-demand, however, when the pressure drop increases, they switch to a timer controller. Normal flange-to-flange operating pressure drop is 5-7 in. WG; shutdown is at 9 in. WG. On the advice of the filter manager, before the in situ cleaning, the pressure drop had reached 9 in. WG and the system was shutting down intermittently.

Following the in-situ cleaning, six flange-to-flange pressure drop readings were collected from the photohelic gauge roughly ten days apart as shown in Figure 3. The first reading (day one) will be ignored because the system had not stabilized yet. The simple arithmetic mean for the following six readings was estimated as 6.3 in. WG, but for practical purposes it will be assumed as 6.0 in. WG. It is apparent that after 60 days the pressure drop had reached 9 in. WG, marking the end of the filter material functionality. Analysis of the results is discussed in chapter five.

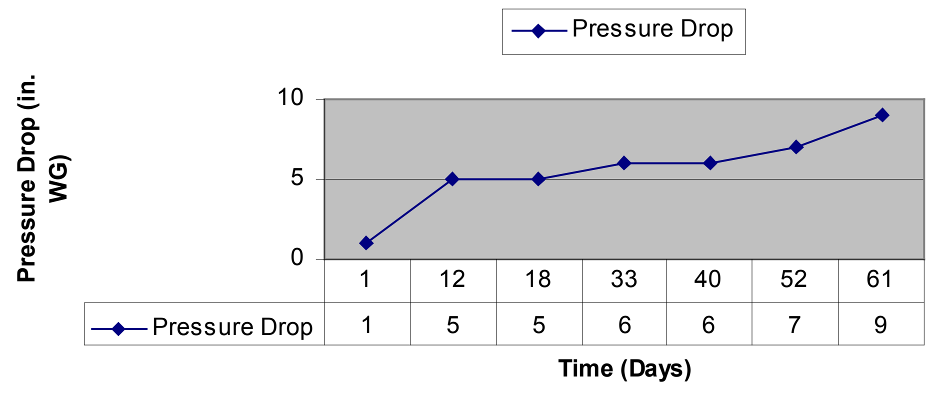

Figure 3: Pressure Drop vs. Time

CHAPTER FIVE

5.0 Conclusions

5.1 Introduction

> A decision is only as good as the process used to produce it. (O'Connor & McDermott, 1997)

Meeting the ever-tighter ambient air quality standards defining the post-Rio era demands a paradigm shift towards, initially, enhanced efficiency—in both managerial and manufacturing processes—and, ultimately, ecological economics (i.e., fair distribution and efficient allocation of resources within a sustainable scale). Coping with paradigm shifts—and, indeed, fostering them—requires holistic and creative approaches and mechanisms to help us redefine our priorities and reengineer our technologies and processes. In that vein, this paper applied an industrial-strength creative problem solving model, Simplex, to tackle a technical challenge, how can we reduce the energy consumption of pulse-jet dust collectors? This led to a simple yet innovative solution, i.e., in-situ cleaning.

5.2 Process Results

The success of the Simplex approach will be assessed by its results (process results), which are bipartite: results of the solution (in-situ cleaning) implementation (as detailed in Action) from a sustainability perspective (i.e., by assessing the potential economic, ecological and social benefits of in-situ cleaning), and Simplex as a creative problem solving, research, and management approach. Then, limitations of the Simplex approach and potential personal biases that might have influenced the direction of this research will be assessed. The chapter will conclude with a statement of personal learnings.

5.2.1 Action Results

5.2.1.1 Potential Economic Benefits

a. Potential energy consumption savings

Equation (4-4) can be used to estimate the potential savings in electricity consumption by the main baghouse fan due to 3 in. WG reduction in pressure drop for two months. However, it should be noted that the differential pressure gauge reading inevitably varies from day to day and from hour to hour. The writer acknowledges that a more reliable statistical gathering and treatment of the data would have entailed the daily monitoring of the flange-to-flange pressure drop at a fixed daily hour for at least 100 consecutive days. Then the pressure drop mean at the 95% confidence limit (or, if the variance is seemingly significant due to frequent disruptions in the operating conditions, at the 68% limit) is used in the said equation.

Hence, applying equation (4-4), assuming 75% fan efficiency, 100% motor efficiency, \$0.07 electricity cost per kilowatt-hour, and continuous operation for 60 days:

E = (0.746) X 3 X 35000 X 60 X 24 X 0.07/6356 X 0.75 = CAD\$1,656.32

b. Potential bag replacement savings

The purchase price of a new aramid bag is approximately CAD\$40.00/bag. Hence, bag replacement costs for two months can be estimated as follows:

Costs per 2 months = (\$40.00/bag) X (660 bags) = CAD\$26,400.00

To estimate the potential savings offered by in-situ cleaning, subtract the in-situ cleaning service charges, which are about CAD\$6,600.00. Therefore, the total customer savings for a 2 months period is CAD\$19,800.00. If the customer chooses to repeat the service, assuming the same performance pattern (i.e., two months average bag life), his yearly potential savings would be CAD\$19,800.00 X 3 = CAD\$59,400.00.

For this particular client, the savings were mainly attained for bag replacement costs and not for energy consumption. However, where the savings will lie depends on the baghouse capacity and bag change frequency. For example, in a different hypothetical scenario that is not uncommon in the cement industry, where often the bags are changed every few years, assuming a fan capacity of 250,000 CFM, continuous yearlong operation, and similar assumptions regarding fan efficiency, motor efficiency, electricity cost per kilowatt, and average pressure drop reduction, the annual electricity consumption savings can be estimated as follows:

$$E = (0.746) \times 3 \times 250000 \times 365 \times 24 \times 0.07/6356 \times 0.75 = \text{CAD\$}71{,}970.92$$

There is a lesson here. It was generalized earlier that fan power consumption is the largest contributor to operating costs followed by bag replacement costs. While this remains generally true, we are reminded that every application is unique. At any rate, the savings attained are either reduced energy consumption or bag replacement costs, or possibly a bit of both. Finally, these estimates ignore the cost of labor for bag replacement, which in our case would be approximately 2 men 2 days, and the associated maintenance downtime (these are savings for the foundry).

5.2.1.2 Potential Environmental and Social Benefits

Most of North American solid waste—both municipal and industrial—is dumped in landfill sites. Pollution prevention or source reduction remains the most sustainable waste management technique. Prolonging the life of filter bags is a way to reduce solid industrial waste volume which relieves the stress on our landfill sites, which in turn relives the stress on our environment –because “landfills” are essentially sinks and ecosystems that are themselves dynamically interconnected with other ecosystems. Landfill sites may leak—even if after thousands of years—and contaminate the groundwater which is a major source of drinking and irrigation water for many communities. The contamination could be carried by the groundwater aquifers to nearby rivers and water streams disrupting the local aquatic life. Secondly, vendor profit should be considered a social benefit, as it contributes to the financial sustainability of the corporation, which secures jobs, and contributes to the overall national economic performance. Thirdly, reduced PM pollution means reduced health risks especially for those working in the vicinity of an emissions source. As this potentially means reduced sick leaves, downtime, and increased productivity, it should be counted as social and economic benefits (H. Johannesen, personal communication, January 2005).

To get an approximation of the amount of carbon emissions associated with 3 in. WG reduction in pressure drop during the two months, we can use the greenhouse gas emission coefficient for electricity to convert energy consumption data into carbon dioxide equivalent, which is the standard greenhouse gas measurement unit. Carbon coefficients relate the mass of oxidized carbon (emissions) to combustion energy released from a specific fuel type. There are several factors devised, including the list generated by the Intergovernmental Panel on Climate Change (IPCC), and they are continuously being updated (they depend on fuel quality/chemical composition which in turn depends on source, exploration method, etc.). Though in our case the bags were nearing the end of their service life and hence the reduction in greenhouse gases is more theoretical than practical, this service can be used as part of a preventive maintenance program for filter bags that are in service to enhance their performance with respect to drag and dust collection efficiency. If we use the U.S. EPA (2001) national average emissions factor for electricity (1.64 pounds CO_2 per kilowatt-hour), which corresponds to a typical American fuel mixture:

CAD$1,656.32/$0.07 = 23,661.71 kilowatt-hour
23,661.71 X 1.64 = 38,805.20 pounds CO_2 eq.

By comparison, the U.S. EPA (2001) estimates that an average household emits 20,000 pounds of CO2 eq. annually. The emissions are cumulative and we each have a role to play in cutting emissions by reducing our energy consumption –if we are serious about sustainable development. The benefits of reduced energy consumption far exceed mere reduction in carbon dioxide emissions. While we have concentrated on PM pollution in this paper, in fact, fossil fuel combustion emissions include, in addition to carbon dioxide and PM, sulfur dioxide, nitrogen oxides, mercury, and other heavy metals such as arsenic and lead. Sulfur dioxide contributes to acid rain which damages forests, lakes, and material possessions. Nitrogen oxides also contribute to acid rain, and lead to the formation of ozone, which is the primary component of smog, and which has been linked to a host of respiratory diseases including aggravated asthma and lung diseases (Union of Concerned Scientists, 2001).

The good news is that we are slowly becoming aware of the overreaching harmful effects of fossil fuel combustion, and we are legislating ever-tighter emissions reduction objectives and putting efforts into developing advanced multi-pollutant filter collectors, such as the “SOx-NOx-Rox-Box” which can mitigate sulfur dioxide and nitrogen oxides concomitantly using sorbents

(Croom, 1995). While this awareness is welcomed, perhaps we should be thinking outside the "Rox-Box" altogether and concentrating more on prevention and source reduction rather than on end-of-pipe solutions. Perhaps we should be asking, how might we find alternative and more sustainable energy resources?

5.2.2 Simplex as a Creative Problem Solving, Research, and Management Paradigm

> Improving energy efficiency both by reducing quantities of energy consumed and by changing processes, offers a powerful tool for achieving sustainable development by reducing the need for investment in energy infrastructure, by cutting fuel costs, by increasing competitiveness for businesses and welfare for consumers. It can create environmental benefits through reduced emissions of greenhouse gases and local air pollutants. It can offer social benefits in the form of enhanced energy security (through reduced reliance on fossil fuels, particularly when imported) and enhanced energy services. (The International Energy Agency, 2004, para. 1)

In our ideation, especially in steps 3 (Problem Definition) and 4 (Idea Finding) we came up with several creative and implementable methods to improve the energy efficiency of pulse-jet systems. In the final divergence of Problem Definition, for example, we came up with techniques such as optimizing the cleaning system, optimizing the fan operation, performing a system audit, etc. We then selected one strategy, namely, maintaining clean filter bags, to carry forward to Idea Finding where we came up with many more implementable tactics. Then, besides the practical tactics, we also came up with several novel ideas, such as the use of sonic horns a la the high efficiency cleaning instrument, the use of IR lamps to help prevent dew point excursions, and the extending plate following pulsing to prevent the re-entrainment of dust particles, to name a few.

The Simplex creativity promise is self-evident in Problem Definition. When pondering what's stopping us from saving electricity costs, we realized that we needed a cheaper or an alternative energy source. Had we selected this challenge for Idea Finding, we would have found some innovative solutions such as co-generation techniques with renewable energy resources—such as windmills or solar cells—or perhaps processes integration. Many of the ideas generated at Idea Finding make material for research and development. Further, the Simplex process itself is a powerful tool to use in the problem formulation stage of a research project, and for the development of the research design and method, as this thesis attempted to demonstrate. Simplex is also a change management model. By finding new and improved processes, and by planning action to implement these new processes, we are managing change effectively. Finally, since every individual has a different thought process, behavior, and attitude, a structured approach that harnesses synergy is needed to manage organizational change.

5.3 Limitations and Potential Biases

Tactical limitations may include time constraints, budgetary or human resource constraints, organizational structure inadequacies including incompetent management or staff. Process related constraints include inadequate content (relevant knowledge) and unpolished process skills. Finally, even though "thinking is a skill [which] can be developed and improved if one knows how" as De Bono, who pioneered applied creativity, contended in 1972, the significance of variation in learning abilities, cognitive skills, etc. among individuals cannot be ignored (P. Kuziw, personal communication, January, 2005). Following the process with others, in a team setting, however, can alleviate many of these constraints.

Biases in using existing company core competencies cannot be underestimated. For example, selection of the challenge, how might we maintain clean filter bags, at Problem Definition might relate to the writer's professional occupation. The same may have influenced the generation and selection of technological solutions at Idea Finding (for example, LD-Mobile, VDI testing and in-situ cleaning).

5.4 Personal Learnings

Mainstreaming Simplex can foster a creative and learning environment. As a process, it has helped me (1) gain tactical and strategic insights into the various aspects of the thesis' technical dilemma, (2) generate novel solutions/approaches to solve that dilemma, and (3) evaluate, select, and action-plan for the solution implementation. I quickly realized that I was embarking on an expedition of mind-stimulating experiential learning. The structured approach of Simplex has tremendously helped me manage this project efficiently, and served as a yardstick for measuring progress, which was motivational. But there is a catch: while Simplex can equip us with vision and leadership tools, it cannot make our decisions for us. It cannot give us moral strength or courage. After action planning, it is up to us to take action.

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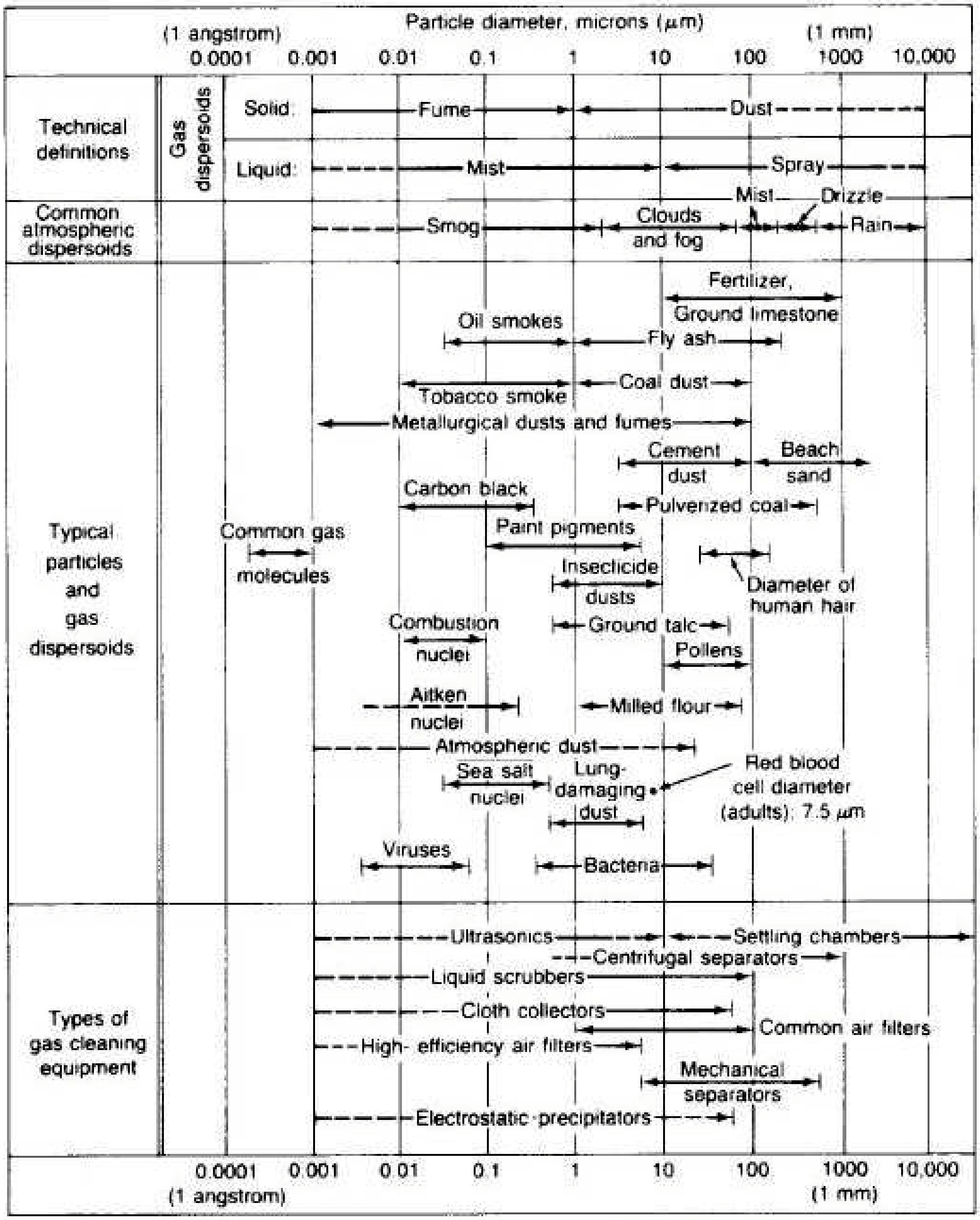
APPENDICES

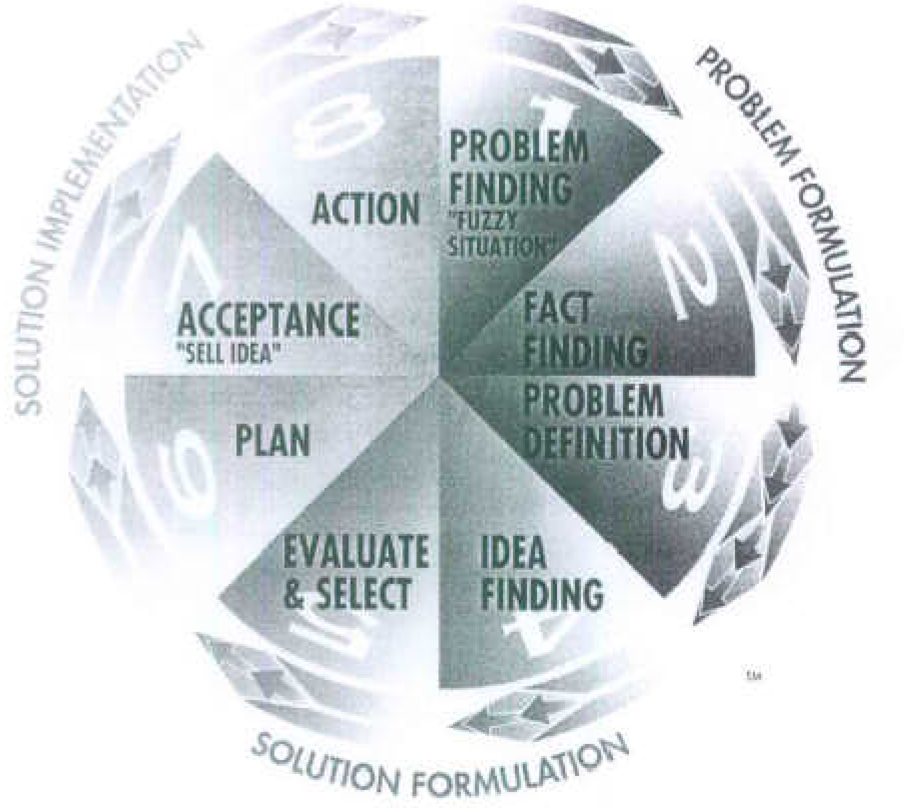
Appendix A: Characteristics of Particles

Source: http://www.continuingeducation.com (adapted from Lapple, 1961). Retrieved January 21, 2005.



Appendix B: Simplex

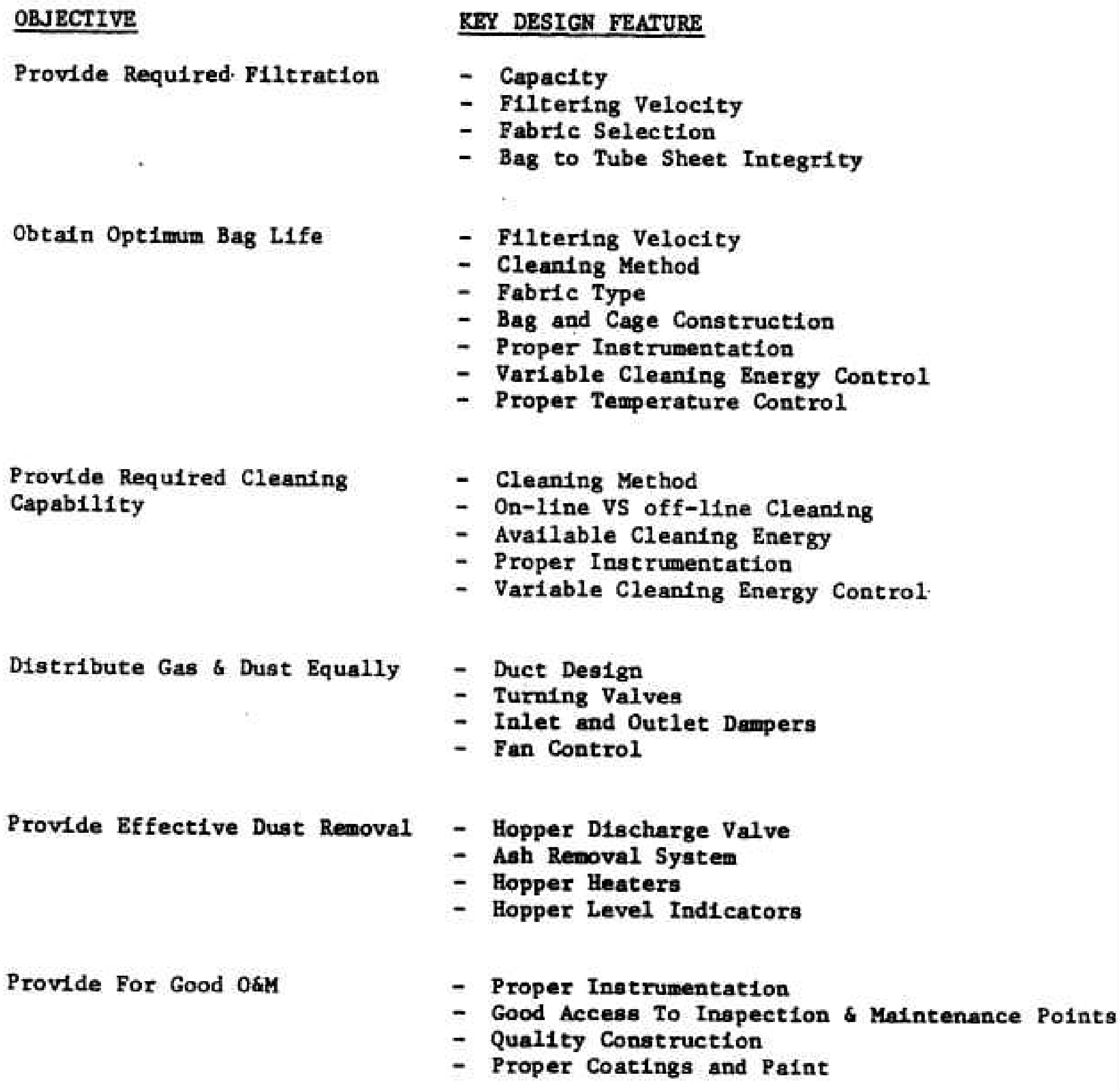
Source: Min Basadur, Simplex Innovative Thinking Skills Introductory Workshop: “Innovative Thinking and Problem Solving” study material, McMaster University, 1999.



A complete process starting with "problem finding" and ending in "action".

Appendix C: Key Items to Consider in Collector Design

Source: John D. McKenna and James H. Turner, Fabric Filter-Baghouses I: Theory, Design, and Selection, 1993.



OBJECTIVE	KEY DESIGN FEATURE
Provide Required Filtration	- Capacity
	- Filtering Velocity
	- Fabric Selection
	- Bag to Tube Sheet Integrity
Obtain Optimum Bag Life	- Filtering Velocity
	- Cleaning Method
	- Fabric Type
	- Bag and Cage Construction
	- Proper Instrumentation
	- Variable Cleaning Energy Control
	- Proper Temperature Control
Provide Required Cleaning Capability	- Cleaning Method
	- On-line VS off-line Cleaning
	- Available Cleaning Energy
	- Proper Instrumentation
	- Variable Cleaning Energy Control
Distribute Gas & Dust Equally	- Duct Design
	- Turning Valves
	- Inlet and Outlet Dampers
	- Fan Control
Provide Effective Dust Removal	- Hopper Discharge Valve
	- Ash Removal System
	- Hopper Heaters
	- Hopper Level Indicators
Provide For Good O&M	- Proper Instrumentation
	- Good Access To Inspection & Maintenance Points
	- Quality Construction
	- Proper Coatings and Paint