AN EXERGY DIAGNOSTIC METHODOLOGY FOR ENERGY MANAGEMENT IN MANUFACTURING

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Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
DOCTOR OF PHILOSOPHY
December, 2006

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ACKNOWLEDGMENTS

I wish to thank the God of my understanding with whom only in later life did I (re)establish a conscious contact. I have come to appreciate the loving sense of humor (albeit, somewhat dry) with which I am guided.

I wish to acknowledge the many people who have made this journey possible. First of all, my parents John and Nell Frazier, neither of whom survived to see me begin university work. Father graduated as a civil engineer from Oklahoma State University in 1949 and that guaranteed my attendance at this institution. Mother was interested in church affairs, science and nature. Both instilled in me the desire to learn as much as possible, thank you.

I acknowledge my major advisor, Dr. William Kolarik, who provided the right combination of support and feedback that paved the way toward completion of the research work. Dr. Kolarik's door is always open and I needed that on many occasions. Dr. Kolarik also provided my employment at the Industrial Assessment Center during my studies. I consider Dr. Kolarik a good friend and our chats about classic cars and motorcycles often provided the break I needed. Thank you.

I wish to thank Dr. Wayne Turner who first sparked my interest in energy engineering. Over the years I have come to regard Dr. Turner as a close personal friend. Whether we are fishing, talking philosophy or knee-deep in grease on an energy audit, I always enjoy our time together. Thank you, I'll see you at the fishing hole.

I extend gratitude to my doctoral committee – Dr. David Pratt, Dr. Paul Rossler and Dr. Maryanne Mowen. Over the last three and a half years I have relied on their kindness and advise which was always forthcoming. Thank you.

I am also grateful to Dr. Michael Moran, professor of mechanical engineering, The Ohio State University, Dr. Timothy Gutowski, professor and associate head of the mechanical engineering department, MIT, Dr. Kelly Kissock, associate professor, department of mechanical and aerospace engineering, University of Dayton, for their assistance on various topics.

I would also like to thank various people outside of the academic field. I express my appreciation to my dear friend Ray Bennet for always having the "best" advice and to Dr. Robert Holbrook Smith and William Griffith Wilson for their guidance.

Finally, I would like to thank the staff of the Industrial Engineering and

Management Department at Oklahoma State University. Without the help and friendship of Patsy Colemen, Janice Walters and Paulett Lauer I would not have survived. Thanks folks.

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CHAPTER I. INTRODUCTION

Introduction

The purpose of this research is to construct and describe an energy engineering methodology for the systematic characterization of the energy usage of manufacturing processes and for identifying opportunities from a simplified exergy[1] standpoint. The research methodology is herein referred to as the Exergetic Ratio Diagnostic Tool (ERDT). The ERDT is constructed to resolve energy issues in industrial process design and analysis and to extend the traditional energy audit's capabilities in analyzing manufacturing processes.

Energy audits highlight ways that firms can minimize costs by identifying energy management opportunities. The intended audiences for this research are engineers who perform energy audits on manufacturing facilities or design engineers interested in energy efficiency and costs associated with alternative processes. Additionally, others in the energy engineering field have expressed favorable interest in this methodology[2].

The ERDT methodology provides energy opportunity identification by demonstrating the gap between the theoretical minimum energy usage and actual energy usage known as bandwidth analysis (see Figure 1).

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[1] Exergy is a detailed energy analysis method and is explained later in this document. For the time being, the reader may think of "exergy" as synonymous with the term "energy".

[2] The Society of Automotive Engineers (SAE) expressed a strong interest in the research and a paper by the author explaining the methodology was presented by the author at the 2006 SAE World Conference in Detroit, MI, April 17, 2006.

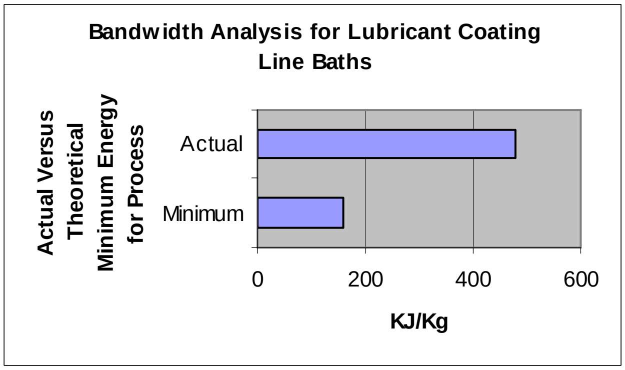

Figure 1. Example minimum versus actual energy usage for a manufacturing process (bandwidth analysis).

The ERDT methodology also demonstrates a screening function that highlights what processes have opportunities for energy usage improvement. The ERDT methodology makes recommendations to improve, redesign or replace processes that are not utilizing energy in an efficient manner. The methodology is also an integrator with accepted energy analysis techniques such as pinch analysis and thermoeconomics. In addition, the ERDT is a facilitator for the integration of process energy utilization and operation value-chain analysis.

The ERDT is composed of four pieces, namely: 1) a process energy usage characterization component, 2) a minimum energy value-added determination for the particular process 3) a project ranking mechanism with interfaces to activity based management and lean methodologies and 4) exergy analysis of the energy utilization effectiveness of the candidate processes selected in the second component.

The characterization component of the ERDT involves the identification and analysis of the energy and scientific dynamics of the product formation through processes. The second component of the ERDT is the actual energy value-added analysis of the processes used to form the products. This step demonstrates the gap between actual and minimum energy process energy usage. The third component of the ERDT ranks the processes for possible energy improvement projects and provides links to other management tools. The forth component of the ERDT is used to determine the extent to which processes are candidates for energy recovery or complete replacement with alternative processes and technology.

Both the efficiency and the effectiveness of the processes in utilizing purchased energy are examined. The economics of process energy efficiency and effectiveness is examined. The applicability of the ERDT methodology to techniques such as lean manufacturing is briefly examined. Also, a suitable accounting system for costing applications is described. The ERDT methodology has been constructed and tested in a manufacturing setting. The methodology is also compared to other contemporary energy analysis methods. Finally, the wide range of diverse applications for this methodology is discussed in the future research section.

From the applications standpoint, the ERDT provides a response to the challenges the author has faced over the course of approximately 12 years in energy engineering practice. Specifically, these challenges are:

- Increasing cost of energy
- Increasing scale of plant operations encountered
- Increasing complexity of plant operations encountered
- Potential increase in carbon emission regulations

In addition to process engineers and management who need detailed energy use and cost information for product manufacturing decisions, the ERDT will assist energy engineers in the plant energy auditing process.

Statement of the Problem

Methods for plant energy management have been in place for several decades (Capehart et al, 2003). While often effective in identifying opportunities for energy usage minimization, these energy analysis methods frequently face problems in actual field implementation. Specifically, the energy engineer often encounters problems understanding complex or new (to the engineer) manufacturing processes. While the plant personnel understand the manufacturing processes in regard to production, they may have little understanding of the energy usage details of these same processes. Therefore plant personnel may be of limited assistance to the energy engineer. The gap between the creativity brought to the energy management practice by the expert energy engineer's knowledge base and the beginning engineer or plant management will be bridged to some extent by the ERDT methodology.

A key indication that many facilities do not understand the role of energy in their operations and costs is the general lack of the most basic process energy usage information. For example, most manufacturing facilities tend to aggregate the energy usage of the various internal processes into single utility meters. This absence of energy usage detail at specific processes contributes to a lack of understanding for the energy engineer and plant management of the same process contributions to energy costs for the final product (Turner, 2001). However, the awareness of the advantages of process energy monitoring has been increasing (Plant Engineering, 2005). Additionally, many energy management studies approach single processes without consideration of the overall “systems view” of the facility. The analysis of processes in isolation may produce sub-optimal solutions (Heylighen, 1996).

From the engineer’s perspective, energy analysis of facility processes has evolved to try and cope with these limitations. Current energy auditing methods, including software tools, out of necessity tend to rely on experienced-based identification and selection of processes which have opportunities for energy savings. Often the identification of such opportunities tend to be ad-hoc, or experience-based in nature (Kissock, 2001).

Traditional energy audits are rather broad in scope and usually examine all energy utilizing systems including manufacturing process and support activities within a facility (Larsen, 1999). Subsequent analysis usually focuses on several processes identified as having opportunities for energy efficiency improvement.

Depending on the type of processing being performed on the “product”, the manufacturing processes may not be the major energy consumers in the facility. For example, an assembly plant may use little energy in the actual product assembly operations but considerable energy in the heating-cooling system and lighting for the occupants. In this case, traditional energy audits are good tools for finding opportunities. The utility billing analysis step in the traditional energy audit methodology helps to indicate whether a particular facility’s manufacturing processes are the major energy users or not (Michaels, 1984).

This research is aimed at focusing analysis on the core business processes in the manufacturing setting. For this research, the definition of a process is “A method to make or do something that involves a number of steps” (Breyfogle, p1114, 2003). In this case ‘core processes’ refer to the processes performed by the company to earn revenue. For this report, the businesses are manufacturing firms and therefore core processes refer to transformations done to materials to increase the value of the resulting product. Space heating and lighting are not considered core processes.

The traditional energy audit methodology is well suited for situations where a total facility energy audit is desired and complex core manufacturing business processes are not the primary energy usage and support systems such as heating, cooling and lighting use a greater percentage of energy in the facility. The ERDT could be employed where the core processes are complex and energy and cost intensive. Another alternative is to start with the traditional audit method and then switch to the ERDT when examining manufacturing processes (see section on integrating the ERDT and traditional energy auditing methodology in this chapter).

Existing energy audit checklists are often employed as a way of cueing the engineer to examine critical energy-using systems. The problem with checklists, whether in software or hard copy form, is that to be effective the checklist needs to be exhaustive and therefore adherence to the checklist can be quite time consuming. In addition, the checklists tend to be descriptive, not prescriptive. After using the checklist, the engineer must now decipher and analyze the gathered information to look for opportunities.

Software tools are becoming important for the energy engineer. These analysis packages are usually focused on one area of energy usage (e.g., steam or air compression). This dedicated nature of the software tools implies that the user has already determined, to some degree, the areas of opportunity or is using the tools in a search-mode to find opportunities. As an example, the Department of Energy (DOE)

"Save Energy Now" best practices tools described later are aimed at only specific energy areas such as steam or process heat (DOE Best Practices, 2006).

Energy engineers, who are successful, tend to use energy engineering education (Turner, 2003), abbreviated checklists and spot opportunities by domain expertise. These experts are using vast amounts of knowledge and experience to guide them in the energy audit. The successful energy engineer is also able to maintain a broad systems view to spot opportunities and focuses when necessary. The average engineer or plant manager does not have this experience base. Unfortunately, even the experienced energy experts may miss significant energy opportunities due to a lack of experience with a particularly new or complex process (Warfel, 1993). In other words, process understandability with respect to energy utilization is often not clear. Furthermore, obscured process-energy views typically lead to missed opportunities and limited recommendation options.

The ERDT is constructed to help the design engineer examine the energy dynamics of manufacturing core processes from a "green field" perspective. That is, the design engineer is not limited to reworking existing equipment or processes. Instead, the product and its needed transformations are examined first, and then constraints of energy costs and risks are examined in an outward flowing analysis. This "inside-out" manufacturing analysis method has been suggested (Kissock, 2001) and the ERDT is an applicable methodology for this approach.

The Exergy Diagnostic Ratio Tool (ERDT) was conceived as an *idealized* system for energy analysis of manufacturing *processes*. That is, the ERDT is designed as a significant improvement over current methods for identifying manufacturing process energy management opportunities. In addition, the ERDT produces outputs that interface with activity based management and lean methodologies.

One group of authors has termed this optimal bundling of solutions as the "solution after next" principle (Nadler and Hibino, 1994). Essentially, the idea is to think far enough into the future to consider ideal target systems. Some of the benefits of the solution-after-next method are described as:

- Recommendations for change contain provisions for continual improvement.
- Maximization of likelihood of developing creative and innovative solutions by setting aside presumed human, physical, information and financial constrains that limit vision.
- Gaining of valuable lead-time for making changes in the future.
- Solutions may be easier to implement due to clear vision of future systems.
- Breakthrough solutions are easier due to more aggressive mind-set.
- Recommendations for change are more likely to involve multiple channels developed from many options.
- Minimizes current knowledge holding back creativity.

The Research and the ERDT Relations to Other Tools

There is a need for a science-based, prescriptive energy analysis methodology that can specifically provide a framework for systematically examining the core plant processes and help determine which processes might be candidates for energy-usage improvement studies. This research should also be useful in examining processes a-priori to “improve” new facilities in the design state. The methodology should be comprehensive yet not require years of experience in order to operate. The methodology should be compatible with traditional energy audits and provide the extended analysis of manufacturing core process energy usage.

The methodology should be based, as much as possible, on accepted scientific and engineering principles rather than experiential heuristics. The research should also interface with process solution recommendation methods and cost accounting tools for economic analysis. The proposed research method is an extension and evolution of past and current energy analysis methodologies.

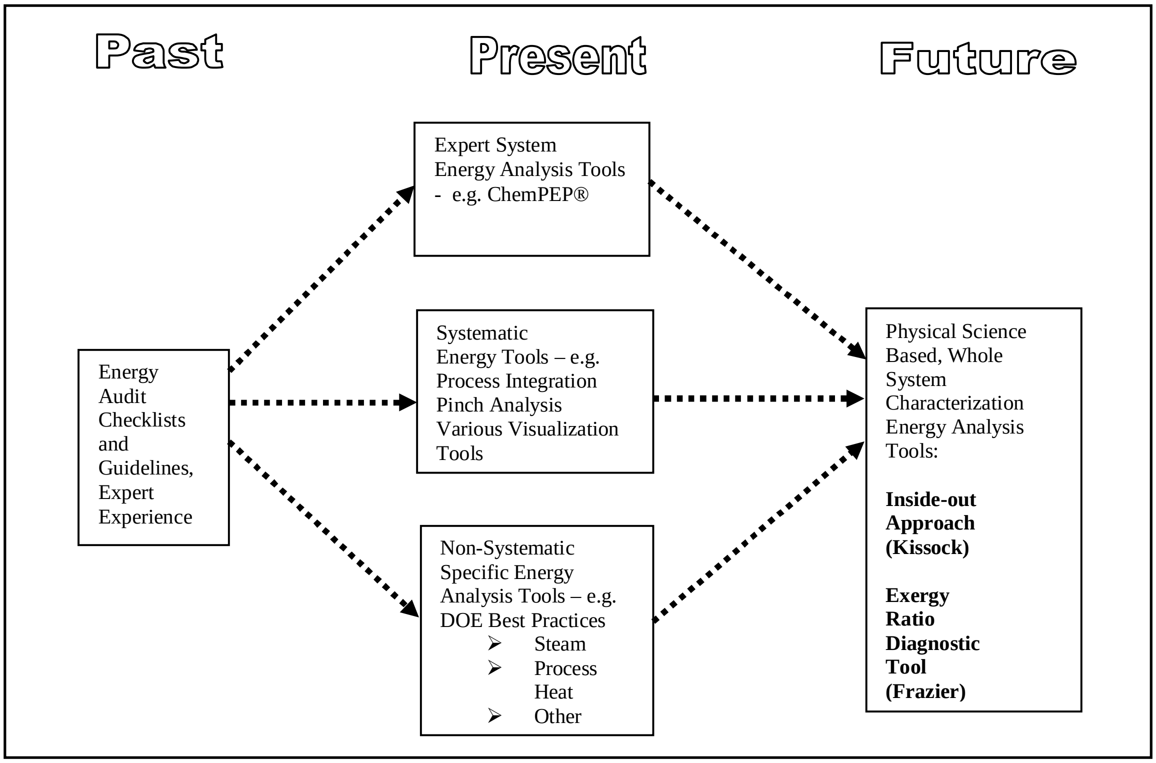

Figure 2. Chronology and relationships between energy engineering analyses methods/tools.

Figure 2 illustrates a relative chronology of energy analysis methods and tools. The early methods involved mostly checklists and guidelines implemented in a sometimes ad hoc fashion due to the high variability of facility processes (Smith, 1981). The energy management and analysis field currently has expanded to include: expert system types of analysis packages, computer driven visualization tools, and process-specific energy analysis tools. The author believes that the current expansion of energy analysis methods is a step forward however, to be manageable and useful; an integrated energy analysis approach that is flexible is needed.

The proposed Exergy Ratio Diagnostic Tool (ERDT) is designed to approach the plant core process energy analysis problem from a process physics starting point and move out to the energy analysis using accepted engineering methods. In this way the ERDT is both process specific yet hierarchical and compatible with whole plant analysis. The ERDT has been described by Moran (Personal Conversation, 2006) as an energy project screening process. The ERDT is a systems integration methodology that brings together advanced engineering techniques, accounting, engineering economics and lean methodologies.

CHAPTER II. REVIEW OF LITERATURE

Energy Management (Historical)

There has been considerable research activity in the area of industrial energy use and assessment over the past several decades. Spurred on by events such as the energy crisis of the 1970's and increased global market competition, analysis of manufacturing systems from an energy usage perspective became a needed activity on par with production control and accounting (Haman, 1999). During this time, the practice of energy management, or energy engineering, became an established methodology (Turner, 2005). Various energy-engineering tools have been constructed and are widely used. Recent increases in energy prices have brought the importance of energy management in manufacturing back into view.

Included in this research are descriptions of a traditional plant-wide energy audit and an examination of some of the more important energy engineering tools. The example set is not exhaustive but gives the reader a good representation of the types of energy engineering or analysis techniques used. Many of these tools are descriptive in nature and do not point the user toward recommendations but rather serve to illuminate the processes and energy streams. Some of the software described below is, or was, mainly intended for the commercial sectors[3] but have been included because of their historical importance to energy engineering.

General Energy Analysis and Process Design Tools

Pinch Analysis

Pinch analysis is a thermodynamic design methodology designed to integrate processes (see section below on process integration) where hot and cold fluid, or gas, streams can interact. This technique originated in the 1970's (Linnhoff et al, 1982) and is primarily used in the design and analysis of heat exchanger networks (Westphalen and Wolf Maciel, 1999).

While primarily used in the chemical industry, pinch analysis can be used when processes utilize fluid or gas streams with different thermal energy contents. The technique is also useful for establishing targets for the optimization of heat recovery systems (Mathur et al, 2006). Pinch analysis has traditionally concentrated on energy streams but has also been used in the analysis of water consumption systems (Andersen et al, 2006). Pinch analysis is designed to examine the entire thermal requirements of a facility and is therefore a systems approach. In essence, pinch analysis:

1. Identifies the "hot" and "cold" fluid streams in the plant processes
2. Determines the characteristics of the fluid streams (enthalpy, temperature, flow rates)

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[3] Office buildings, retail outlets, malls, and other non-manufacturing but non- residential spaces.

3. Using the data in 2, the analysis determines the mean heat capacity flow rates
4. The analysis compares the heat flow rates between two processes of interest
5. The analysis generates and compares the graphical representations of the “hot” and “cold” energy (Q) streams
6. The “Pinch Point” (see Figure 3) is identified as the process parameters (temperature and heat flow) where the most heat energy recovery could be attained.

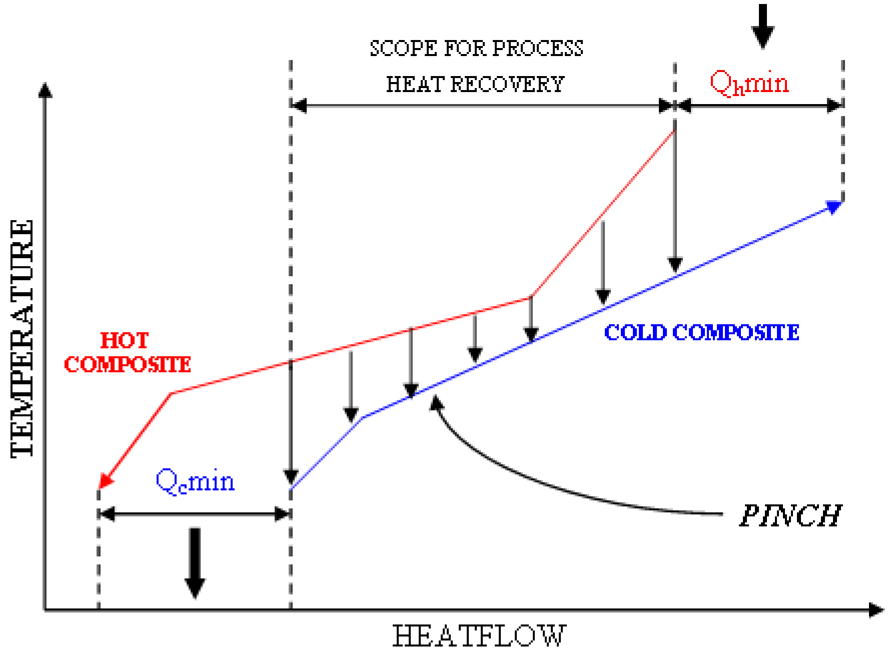


Figure 3. Pinch diagram showing “hot” and “cold” fluid (energy) flow streams in a heat exchanger (http://www.apiweb.com/products/energyTargeting.htm)

Linnhoff and Flower (1978) constructed an algorithm for determining how to select which processes to match or “***cascade***” waste energy flows to energy inputs. The steps are detailed in Westphalen and Wolf Maciel, (1999) and essentially are the following;

1. Determine the minimum temperature of all of the streams of interest
2. Set up temperature intervals for all processes
3. Evaluate the enthalpy balances for all intervals and temperatures of interest
4. Cascade the heat flows through the temperature intervals
5. Look for the largest value of heat flow and assign this as Q_H
6. Cascade through temperature intervals again and terminate with Q_C, the smallest value of heat flow (requirement)
7. Processes are matched for waste heat and input heat requirements (if possible).

Ultimately, a pinch analysis of processes will demonstrate where waste energy can be reused in other (co-located) processes. Pinch analysis is a logical recipient of the ERDT methodology identified opportunities and the integration of the ERDT and pinch analysis is suggested as an area for future research.

Process Integration

Process integration (PI) is defined as the "systematic method for the design of integrated production systems, ranging from individual processes to total sites with special emphasis on the efficient use of energy and reducing environmental effects" (IEA, 2006). Process integration can be roughly broken into mass integration and energy integration (Dunn and El-Halwagi, 2003). In the context of this research, PI is limited to energy integration.

Process integration is a further development of pinch analysis and cascading described above. As in the case with pinch analysis, PI concentrates mainly on heat exchanger networks however PI is a more systematic, integrated approach to matching various processes in a facility.

Process integration goes further than pinch analysis (IEA, 2006) in that it incorporates economic and mathematical (e.g.,, optimization) methods including:

- Artificial intelligence
- Hierarchical analysis (AHP)
- Mathematical programming
- Optimal designs
- Flexibility of operations
- Safety
- Product yield
- Operations and Maintenance

For some researchers (Gundersen, 2000), process integration is the de facto analysis of industrial energy systems. Gundersen (2000) classifies process integration methods as a two-dimensional representation (Laukkanen, 2003) shown below in Figure 4.

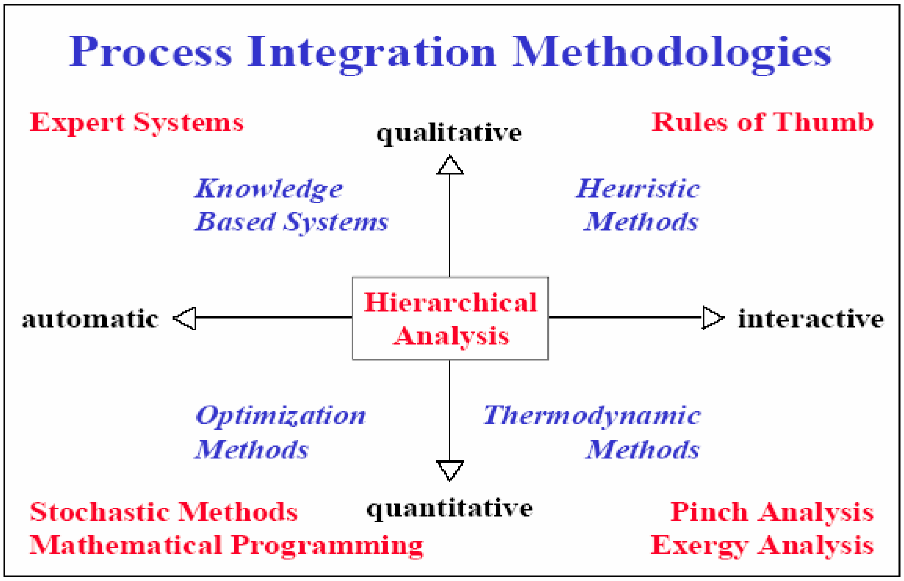


Figure 4. Representation of process integration methods (Gundersen)

The diagram in Figure 4 is showing that process integration is a combination of several approaches such as pinch analysis, expert systems, mathematical programming and heuristics.

As with pinch analysis, the relationship of the ERDT and other analysis methods will either be discussed later or suggested as future research.

Exergy Analysis

Exergy analysis is based on the "second-law" thermodynamic concept called exergy or availability analysis and has been examined for many years (Ahern, 1980) and has great potential to help the energy engineer. This concept is very useful in determining where energy "availability" is being wasted. The exergy concept examines how and where the "useful" energy in a process is being utilized or wasted (see thermoeconomic discussion below). This research describes exergy analysis in more detail later in the report however; a brief overview is presented here.

The exergy concept can be defined as the universal measure of the "usefulness" or "availability" of a particular energy flow to perform work. This is different than the concept of energy. Whereas energy cannot be destroyed, exergy can. Therefore, exergy is a resource with some value (see discussion of energy value in methodology section) that can be consumed.

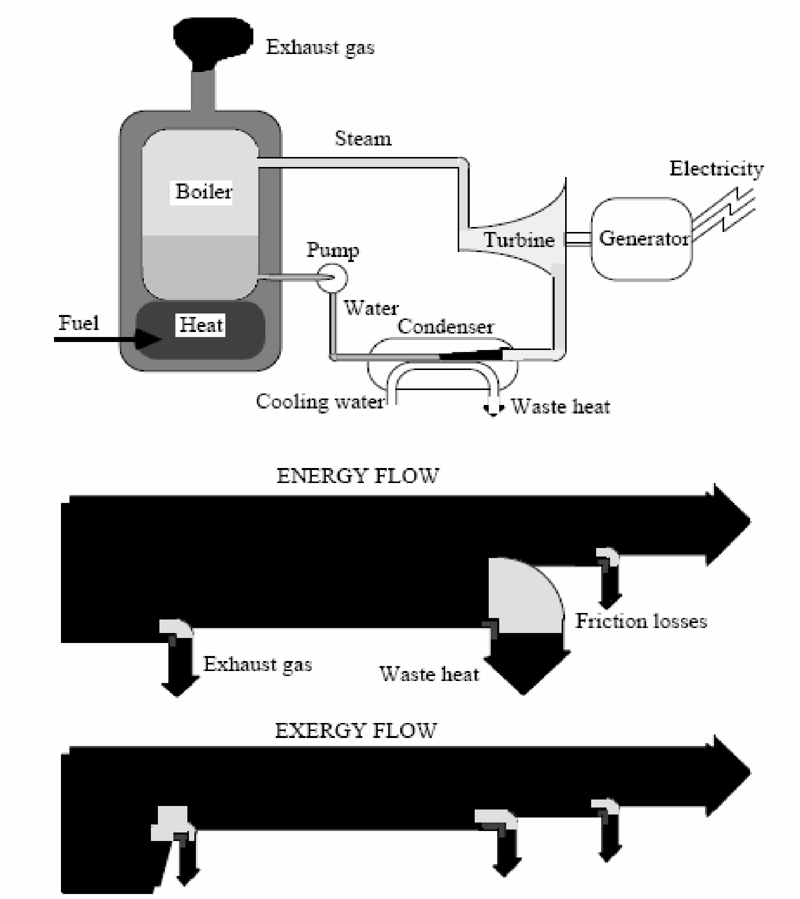


Figure 5. Exergy/energy diagrams for a condensing power plant (Wall, 1977).

The exergy concept also has been mapped out for various industries (Barclay, 1998). Figure 5 is an example of an exergy type of diagram for a condensing power plant (Wall, 1977). The width of the flows in the diagram shows the relative quantity of energy or exergy entering and leaving different parts of the process. The reader should note that the significant difference in the way waste heat energy is treated by energy versus exergy analysis. In the energy diagram, the losses add up to the same quantity as the input energy (conservation of energy – first law of thermodynamics). In the exergy diagram (bottom) of the same process, there is a loss, or destruction of exergy in the combustion and heating. This exergy, or potential for work, is permanently lost.

Exergy methods are sometimes used as analysis tools to examine current and known alternative processes (Moran, 1982). These applications are usually limited to the chemical industry where fluids and heat flows are critical aspects of the operations. Within process industries, exergy has been extensively studied and demonstrated.

In general, the exergy studies require considerable process domain knowledge and as such tend to be demonstrations of various process alternatives given domain expertise by the analyst. In the past most exergy analysis has been applied to continuous, thermal processes (e.g.,, heating of materials). However, exergy analysis can be used for any type of energy flow possible (e.g.,, electrical, chemical, thermal, kinetic, etc.) although it is not commonly done (Karakus, et al, 2002). Exergy analysis requires a good understanding of thermodynamic science fundamentals. This complexity and unfamiliarity with the technique are possibly the largest drawbacks to exergy utilization in current manufacturing settings.

For professionals in the chemical industry and thermodynamic sciences there are exergy analysis software packages available such as TEST® (Bhattacharjee, 2006). These tools require skill sets that may be too specific for energy engineers or plant management.

Thermo-Economics

The combined examination of thermodynamics and economics is described as thermoeconomics (Tribus and Evans, 1962). This concept uses exergy analysis described above and assigns costs to the thermodynamic inefficiencies (Laukkanen, 2003). A methodology for component by component analysis was first published by El-Sayed and Evans (1970).

A brief example of the thermoeconomic analysis of a co-generation plant (Valero et al, 2005) is provided for illustration (see Figure 6).

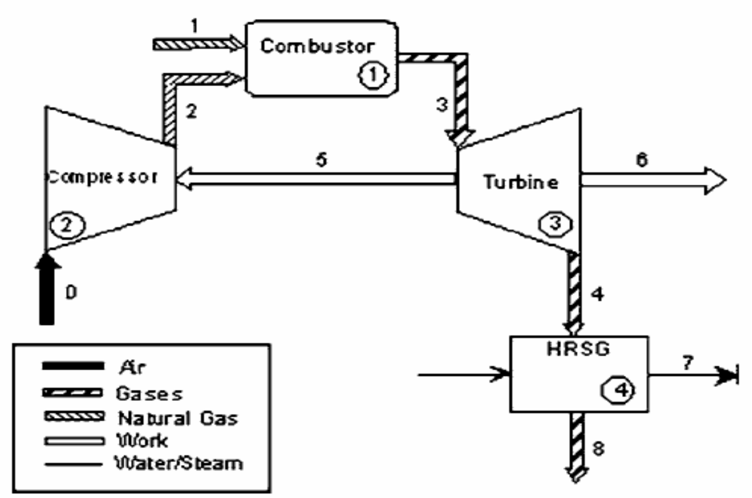
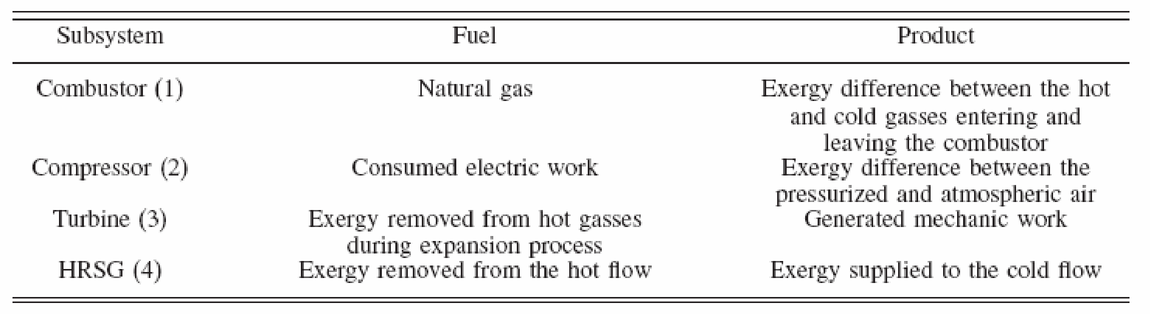


Figure 6. Schematic of co-generation plant (Valero).



Subsystem	Fuel	Product
Combustor (1)	Natural gas	Exergy difference between the hot and cold gasses entering and leaving the combustor
Compressor (2)	Consumed electric work	Exergy difference between the pressurized and atmospheric air
Turbine (3)	Exergy removed from hot gasses during expansion process	Generated mechanic work
HRSG (4)	Exergy removed from the hot flow	Exergy supplied to the cold flow

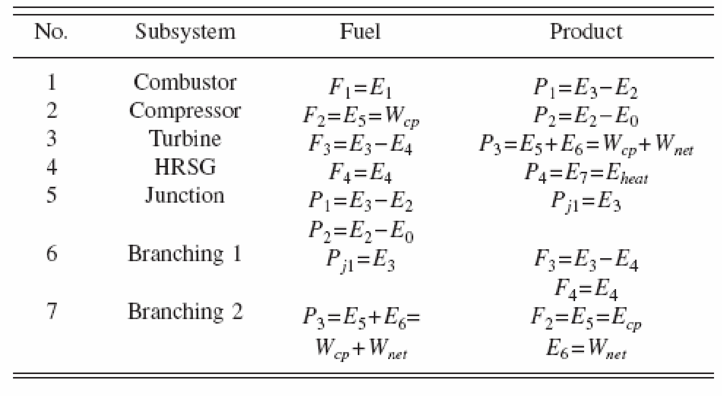
Table 1. Fuel and product definitions for the co-generation plant in Figure 5 (Valero).

Given the fuel and product definitions from Table 1, the unit exergy consumption equation is:

$$F = P + I \qquad (1)$$

Where *F* equals fuel required to generate one exergy unit of product, *P* equals the product exergy required and *I* equals the exergy destroyed in making the product.

The exergy and fuels flows for the co-generation plant are tabulated in Table 1.



No.	Subsystem	Fuel	Product
1	Combustor	$F_1=E_1$	$P_1=E_3-E_2$
2	Compressor	$F_2=E_5=W_{cp}$	$P_2=E_2-E_0$
3	Turbine	$F_3=E_3-E_4$	$P_3=E_5+E_6=W_{cp}+W_{net}$
4	HRSG	$F_4=E_4$	$P_4=E_7=E_{heat}$
5	Junction	$P_1=E_3-E_2$ $P_2=E_2-E_0$	$P_{j1}=E_3$
6	Branching 1	$P_{j1}=E_3$	$F_3=E_3-E_4$ $F_4=E_4$
7	Branching 2	$P_3=E_5+E_6=$ $W_{cp}+W_{net}$	$F_2=E_5=E_{cp}$ $E_6=W_{net}$

Table 2 . Fuels and product exergy flows for co-generation plant (Valero).

Cost equations can now be assigned to the fuel (exergy) flows for each system component such as the combustor or turbine (average or marginal costs), based on the costs of fuels for the particular facility (see Table 2) and equation 1. These cost equations can be structured as a set of linear equations for further analysis.

Various Thermodynamics Process Methodologies

A variety of models and methodologies exist for plant and process thermodynamics analysis (Hui and Ahmad, 1994). Many of these are academic research models built on the foundation of existing methods such as mathematical programming (Floudas et al, 1986), various decomposition methods, stochastic methods and simulation packages such as ARENA®.

Research Articles

An article by Dr. Kelly Kissock (Kissock, et al, 2001) of the University of Dayton titled “Energy and Waste Reduction Opportunities in Industrial Processes” describes an “Inside-Out” approach to energy audits of manufacturing facilities that is close to the research described in this report. Dr. Kissock describes examining the individual manufacturing processes and moving outward to the energy distribution system. Instead of using only first law thermodynamic analysis, the report suggests that second law, or exergy analysis, should be used (again, similar to the ERDT research). The report describes the pros and cons of using first versus second law analysis. While well written, the paper is general in nature and stops short of providing a framework for the energy audits. A DOE Plant-Wide Assessment Case Study using the methodology was conducted at the Ford Cleveland Casting plant in Cleveland Ohio (DOE PWA 2006) and appears on the website referenced. Contact with Dr. Kissock revealed that while the inside out energy audit methodology was used by the University of Dayton Industrial Assessment Center it was not documented as a set of energy audit procedural guidelines (January 3, 2006).

The Master's thesis of Wayne Bader (Bader, 2000) was the major contributor to the Kissock article mentioned above (Kissock, et al, 2001). This thesis describes the advantages of using the exergy approach to finding opportunities in industrial settings. Detailed examples are provided for examining compressed air systems, metals processing furnaces and electrical power systems. While the analysis is similar to other exergy literature included in the bibliography, Mr. Bader's conclusion section appears to have the most relevance to the ERDT. Mr. Bader briefly suggests a series of decision steps toward analyzing industrial processes using the exergy methodology. It is this suggestion for a systematic energy analysis approach that is closest to this research's core purpose. This particular exergy analysis method was suggested as future research.

An article by Gutowski (Gutowski, et al, 2006) describes the exergy analysis of metal cutting tools. The article focuses on the energy (exergy) use of the tool and the support systems such as lubricant and cooling pumps. Unlike heating processes, these manufacturing processes provide a significant challenge to exergy analysis. This article and conversations with Dr. Gutowski, proved important in the construction of the ERDT exergy analysis of these types of manufacturing systems. The analysis of metal cutting tools is explored in detail in the methodology and application Chapters (III and IV) of this report.

There are various articles describing the determination of minimum energy requirements in certain industries. The steel industry has been studied extensively to determine theoretical minimum energies (Fruehan, et al, 2000). An interesting study by Energetics, Inc. for the U.S. Department of Energy (U.S. DOE), compares theoretical minimum energy requirements for steel making processes to actual energy usage. The Energetics, Inc. study uses a bar graph method of displaying minimum and actual energy in this industry.

In general, most energy auditing articles are either older or relate to residential energy audits (McMath, 2004). A survey of energy auditing articles on the engineering article search engine COMPENDEX© reveals that approximately 70% of the energy auditing articles were written between 1975 and 1989. This timing could be explained by the energy crisis of the 1970's. As mentioned previously, it was during this time that most of the traditional energy auditing techniques were developed. Review of this older literature reveals the methodologies that have become traditional energy engineering methods.

New energy auditing research does appear from time to time in engineering literature. In general the more recent methods describe advances in monitoring technology (Pollard, 1993). The energy savings opportunities and calculations that use the monitored energy data typically are based on established engineering calculation methods as described in the methodology section of Chapter III.

Activity Based Management and Partial Productivities Economic Analysis

While not usually considered an energy analysis tool, activity based management (ABM), by nature of its attention to the details of cost allocation to proper activities and resources, has led to awareness that over-simplification can be detrimental in understanding production costs (Hansen, Mowen, 2003). In ABM, the concept of tracking value as it is created at various stages of the enterprise is fundamental and aligned quite well with the ERDT method. The ERDT methodology also examines (energy) value at various stages of a product's creation. The role of the ERDT and ABM is examined in detail later in this report.

Energy Audit Practices

The current practice of performing energy audits in industrial facilities has worked well. Millions of dollars have been saved by these energy audits and recommendations. In particular, the DOE Industrial Assessment Centers have visited over 9,800 industrial sites since 1981. In that time, savings potentials of approximately $740,000,000 have been identified with approximately 50 percent of the recommendations implemented (IAC, 2006). During this time, the practice of performing energy audits and analysis has evolved into our present methods.

As mentioned previously, there are various general guidelines for conducting energy audits (Capehart et al, 2003) however these tend to be general in scope. This generality is necessary due to the tremendous variety of processes and methods encountered in most traditional energy audits. It is very difficult to make a generic template that will easily fit into the often confusing dynamics of an industrial energy audit. It is this wide diversity of processes encountered in the field that makes the energy engineer's[4] job such a challenge and provided the impetus for this research.

In some cases there are guidelines for doing audits in specific process industries such as paper milling (Peters, 1994) and plastic forming (Farrell, 1991). There are also guidelines and checklists for specific processes such as steam systems (Siddartha, 2000).

Armed with either an energy audit checklist or guidelines, the engineer proceeds to the manufacturing facility audit. The checklists remind the auditor to examine certain critical areas. The auditor observes the various plant processes and notes which ones ***may*** have opportunities for energy efficiency improvements. Frequently, the engineer has prior knowledge that an alternative process might be more energy efficient in performing the same "task".

Often, the engineer must select the process of interest based on past experience with such systems (Oak Ridge Operations Office, 2000). Systematic engineering methods for identifying and exploring energy conservation opportunities are expected to appear however. Prescriptive tools such as the ChemPEP® tool (U.S. DOE, 2005) are beginning to emerge as described later in this report. In order to move to the next level of analysis, engineers will require system-based methods with quantitative dimensions to precisely target potential improvement points in the processes. To some degree, the ChemPEP® tool is a new generation of experienced based, expert system prescriptive tool that expands on the traditional energy audit checklists and expert knowledge.

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[4] This discussion also applies to anyone doing energy analysis on behalf of the facility. The author uses the term "energy engineer" and "auditor" interchangeably for this research. The energy auditing methodologies could also be used by knowledgeable plant management performing energy studies.

Currently, once the particular processes of interest have been selected, the engineer will perform either manual calculations or use some type of software solution (Energy Cap® Enterprise, 2005) to examine alternatives. The DOE software packages already mentioned (e.g., BLAST, DOE-2, etc.) can be employed at this point.

Therefore, a gap exists between the identification of energy management opportunities and current solution systems. Essentially, the energy engineer has to already suspect that a particular system is a candidate for improvement. However, time and resource constraints may cause the engineer to miss the opportunity. This need for a more comprehensive energy auditing methodology has led to various suggestions, such as the proposed development of structured energy audit protocols (Simon, 2001). The current tools that are used in energy audits are described below.

Energy Audit Checklists and Guidelines

Energy audit checklists and guidelines are probably the earliest and most basic of the manufacturing plant energy analysis tools. The more thorough versions are comprehensive guides that try to keep the engineer from missing important systems. These tools are an improvement over ad hoc search methods used by the inexperienced energy engineer. The guidelines and checklists do not perform analysis per se; rather they provide a receptacle for data that can be analyzed at a later time (Washington State University, 2005, Workbook Section). An example energy audit checklist is included in Appendix I of this report.

The effectiveness of the energy audit checklist tends to be contingent on the checklist being closely matched to the processes encountered in the facility (Mosier, et al, 1992). For example, if the facility is a poultry processing plant then the checklist needs to concentrate on production of hot and chilled water and other activities associated with the poultry processing industry. A metals processing plant will concentrate on delivering high temperatures to certain processes. The two plants are different enough that a generic checklist may be too broad or long to be truly useful.

The checklists must also be flexible enough to allow for the dynamic and somewhat random nature of information gathering during the energy audit. Energy audits tend to be rapid paced, confusing and complex due to the nature of the many different processes encountered and the plant personnel guiding the plant tour (Younger, 2000). A rigid checklist may completely miss opportunities simply by omission. This attribute of traditional checklist design is at odds with the former requirement of specific detail.

Over the years several energy audit checklists and guidelines have been developed. These engineering aids are very similar to each other. Usually, the checklist guides the engineer to concentrate on and obtain the following basic information (Capehart, et al, 2003):

- **Pre-Audit Information**
    - Facility Data
    - Billing Analysis
    - Facility Layout
    - Operating Schedule

Equipment Lists

Process Flowchart

- **Energy Audit Tools**

  Wattmeter, loggers, etc.

- **Facility Inspection Guidelines**

  Safety, etc.

- **Concentration on Nine Main System Families**

  i. Building envelope
  ii. HVAC
  iii. Electrical supply system
  iv. Lighting (including windows)
  v. Compressed air
  vi. Motors
  vii. Manufacturing or Service Process
  viii. Steam

- **Deliverables**

  Report guidelines, etc.

The Washington State University Energy Program website (Washington State University, 2005) provides an excellent example of a well thought-out energy-auditing checklist. An abbreviated example of this checklist is provided in Appendix I at the back of this report. This checklist and the associated workbooks on this web site are fairly comprehensive. However, if the particular process the engineer is facing is not on the checklist the checklist may not be of much assistance. Also, as mentioned above, these checklists are descriptive, not prescriptive, in nature. However, the checklists do provide guidance in energy auditing.

Once the energy engineer has examined the data contained in, or associated with, the checklists or guidelines, opportunities *may* become apparent. Often these tools lead to identification of opportunities in situ. This immediacy of opportunity identification is not a requirement of any of the energy auditing methods.

Commercial Building Energy Auditing Software

Automated energy audit software tools are appearing more frequently. Historically, this type of software was intended for simulating the heating, cooling and lighting costs associated with buildings. Some of the more comprehensive software can model manufacturing systems for overall building load analysis, however, the energy use of the individual process must already be known or estimated. The idea is that the building or system can be simulated and then sensitivity analysis with energy loads or equipment changes can be performed to look for opportunities. The following list is not exhaustive but representative.

BLAST

An early example of an energy engineering analysis tool is the Department of Energy's (DOE) software called BLAST (Building Loads Analysis and Systems Thermodynamics)[5] (University of Illinois Website, 2006). This DOE sponsored software is used mainly to calculate the energy performance (simulation) of new and retrofitted

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[5] No longer supported by DOE.

buildings. The program is useful for determining building peak (kW and Btu) usage patterns based on outdoor climate conditions and usage patterns of the building. As the acronym implies, the program mainly simulates the heating, cooling and lighting systems in commercial buildings. Therefore, use of BLAST in the manufacturing sector would be limited to calculating the facility's building envelope interaction with the heating and cooling and lighting loads in the facility.

DOE-2

This is a DOE computer simulation program that goes further than BLAST and calculates the hour by hour energy usage patterns of building and plants (ORNL Website, 2006). Like BLAST, this program is mainly used for calculating heating and cooling costs. The DOE-2 program uses ASHRAE[6] load calculations to account for building heat movement including air infiltration. The program also includes an economics module for simulating energy costs of different types of equipment and heat recovery. Both Blast and DOE-2 are useful for simulating alternative building systems. Use of DOE-2 in the manufacturing sector would be similar to BLAST (above).

EnergyPlus

Similar to BLAST and DOE-2 is the DOE Energy Efficiency and Renewable Energy's (EERE) software called EnergyPlus (EERE Website, 2006). EnergyPlus is also a building energy simulation program for modeling building heating, cooling, lighting, ventilating, and other energy flows. The software has more capabilities than the former

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[6] American Society of Heating, Refrigeration and Air Conditioning.

DOE simulation programs and includes the ability to examine renewable energy sources (e.g.,, photovoltaics). Again, use of this program is limited to the manufacturing sector.

Other Energy Analysis Software

There are a variety of software packages that simulate building and plant energy usage, one of which is MarketManager® (Abraxas Energy Consultants Website, 2006). This software is quite comprehensive and allows the user to simulate manufacturing processes to some degree by treating the processes as an energy "black boxes" with known energy usage patterns. In essence this produces a very detailed building load analysis but is of little practical use for the energy engineer doing an audit. Along the same lines, a research paper by Patlitzianas, et al, (2005) describes a proposed software package called CMIEM (Computerized Model for Intelligent Energy Management) which models industrial facilities using energy indices much the same way as MarketManager®. Both these tools are models based on residential or commercial building energy analysis packages. As a side note, programming most of these software packages to produce simple outputs can take days. There are quite a few different energy analysis packages available. See the EERE website references below for a complete list[7].

There are a variety of on-line energy tools available. A typical example is E-Bench® by Energy and Technical Services LTD (Bennet, G., 2006). This internet accessible database system takes utility, building and process data into an integrated database and produces reports that can be used for billing analysis, benchmarking and some environmental analysis.

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[7] < http://www.eere.energy.gov/buildings/tools_directory/subjects_sub.cfm>

Additionally, some companies are touting real-time, continuous energy audits using automated energy management software. Usually these systems are sophisticated monitoring and data acquisition systems (Turnbull, 2003). The systems have some on-board diagnostic and prescriptive capability but this is usually limited. Typical systems might monitor electrical demand and take action depending on pre-programmed commands.

Specific Manufacturing Process Energy Analysis Tools

There are energy analysis tools that target specific processes or machinery. For example, air compressor systems are so wide spread in manufacturing firms that several software programs are available to help diagnose problems and suggest improvements. As with the building analysis tools mentioned above, many of these packages are DOE sponsored research. A brief examination of these tools is presented in this section.

DOE Industry Tools[8] (Descriptions are taken from the DOE web site referenced)

- AIRMaster+: This tool provides information on assessing compressed air systems, including modeling, existing and future system upgrades, and evaluating savings and effectiveness of energy efficiency measures.

- Chilled Water System Analysis Tool (CWSAT): The Chilled Water System Analysis Tool (CWSAT) is used to determine energy requirements of chilled water systems, and to evaluate opportunities for energy and costs savings by

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[8] < www.eere.energy.gov/industry/bestpractices/software.html >

applying improvement measures. The tool provides basic information about an existing configuration in order to calculate current energy consumption, and then selects proposed equipment or operational changes for comparison. The results of this analysis help the engineer quantify the potential benefits of chilled water system improvements.

- Combined Heat and Power Application Tool (CHP): The Combined Heat and Power (CHP) Application Tool helps industrial users evaluate the feasibility of CHP (co-generation) for heating systems such as fuel-fired furnaces, boilers, ovens, heaters, and heat exchangers. It allows analysis of three typical system types: fluid heating, exhaust-gas heat recovery, and duct burner systems. The tool is used to estimate system costs and payback periods, and to perform "what-if" analysis for various utility costs. The tool includes performance data and preliminary cost information for many commercially available gas turbines and default values that can be adapted to meet specific application requirements.

- Fan System Assessment Tool (FSAT): The Fan System Assessment Tool (FSAT) helps to quantify the potential benefits of optimizing fan system configurations that serve industrial processes. FSAT requires only basic information about the plant’s fans and the motors that drive them. FSAT calculates the amount of energy used by the fan system, determines system efficiency, and quantifies the savings potential of an upgraded system.

- MotorMaster+ 4.0: This tool is an energy-efficient motor selection and management tool. The MotorMaster+ 4.0 software includes a catalog of over 20,000 AC motors. This software features motor inventory management tools, maintenance log tracking, efficiency analysis, savings evaluation, energy accounting, and environmental reporting capabilities.

- NOx and Energy Assessment Tool (NxEAT): The NOx and Energy Assessment Tool (NxEAT) helps plants in the petroleum refining and chemical industries to assess and analyze NOx emissions and also helps with the application of energy efficiency improvements. The tool is used to inventory emissions from equipment that generates NOx, and then compare how various technology applications and efficiency measures affect overall costs and reduction of NOx. The tool can perform "what-if" analyses to optimize and select the most cost-effective methods for reducing NOx from systems such as fired heaters, boilers, gas turbines, and reciprocating engines.

- Process Heating Assessment and Survey Tool (PHAST): The Process Heating Assessment and Survey Tool (PHAST) provides an introduction to process heating methods and methods to improve thermal efficiency of heating equipment. The tool is used to survey process heating equipment that uses fuel, steam, or electricity, and identify the most energy-intensive pieces of that equipment. The engineer can also perform an energy (heat) balance on selected equipment (furnaces) to identify and reduce non-productive energy use. The tool allows the engineer to compare the performance of the furnace under various operating conditions and test "what-if" scenarios.

- Pumping System Assessment Tool 2004 (PSAT): The Pumping System Assessment Tool helps industrial users assess the efficiency of pumping system operations. The PSAT software uses achievable pump performance data from Hydraulic Institute standards and motor performance data from the MotorMaster+ database to calculate potential energy and associated cost savings.

- Steam System Tool Suite: The Steam System Assessment Tool (SSAT) allows steam analysts to develop approximate models of real steam systems. Using these models, the engineer can apply SSAT to quantify the magnitude—energy, cost, and emissions-savings—of key potential steam improvement opportunities. SSAT contains the key features of typical steam systems.

- ASDMaster: This Windows software program helps the energy engineer, plant or operations professional, determine the economic feasibility of an ASD application, predict how much electrical energy may be saved by using an Adjustable Speed Drive (ASD), and search a database of standard drives. The package includes two 3 1/2 inch diskettes, user's manual, and user's guide.

- Plant Energy Profiler for the Chemical Industry (ChemPEP Tool): The ChemPEP Tool provides chemical plant managers with information needed to identify savings and efficiency opportunities. The ChemPEP Tool enables energy managers to see overall plant energy use, identify major energy-using equipment and operations, summarize energy cost distributions, and pinpoint areas for more detailed analysis. The ChemPEP Tool provides plant energy information in an easy to understand graphical manner that can be very useful to engineers and managers. The DOE is working on a MetalsPEP tool for the metals refining industry which has not been released as of this writing.

- Others: FLEX v. 3.0[9] and ProjectKalc v. 3.02[10]

While quite useful for examining processes and possible alternatives for energy utilization improvement, most of the tools described above tend to rely on considerable prior knowledge or suspicion that a particular system deserves attention. That is, the energy engineer has already suspected (domain expertise perhaps) that a problem exists. Some of the tools point the engineer towards possible problems by using heuristics such as the ChemPEP® tool, and will be examined below. Possibly the largest drawback to using the above tools is that they are not integrated into a single application or methodology and are used piece-meal.

This software list is a representative example and has few large scale[11] equivalents in the commercial software world for specific manufacturing process

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[9] www.eere.energy.gov/buildings/tools_directory/software/flex.htm

[10] <208.254.22.6/index.cfm?c=business.bus_projectkalc>

[11] There may be small, dedicated applications for specific manufacturing processes that are not widely disseminated.

analysis. However, individual engineers and researchers have developed some systems to examine certain families of processes such as steam and motors (Siddartha, 2000).

ChemPEP® Tool:

As mentioned in the DOE industry tools section above, a slightly different approach has been taken with a recent addition to the facility energy assessment tools: the Plant Energy Profiler for the Chemical Industry (ChemPEP®). This prototype tool will be used to profile a particular chemical industry facility and help determine "overall plant energy use, identify major energy-using equipment, review cost distributions, and locate areas of improvement" (EERE - ChemPEP, 2006). This tool helps guide the engineer toward the areas of opportunity and is therefore prescriptive in nature (and descriptive).

The tool uses an interesting combination of general facility process descriptions, utility data and an operator or manager questionnaire. In many ways it resembles an expert system or fuzzy logic decision tool in that it quantifies the subjective questionnaire input into data and uses various heuristics to make prescriptive recommendations.

The ChemPEP® tool uses the facility process or system information and utility billing data to establish the general size of the plant and its operating characteristics. Once the tool has simulated or estimated the operations in the chemical plant, it uses the plant management questionnaire to estimate the overall operating efficiencies of the systems. Answers to questions such as: "Do you have a systematic steam trap maintenance program?" drive heuristics that assign process efficiencies to the processes.

Once the process efficiencies are estimated, the tool compares these to benchmarked chemical processes in its database. Deviations are noted and highlighted as possible areas for improvement. Improvements in the estimated processes to meet the benchmarks are calculated as possible energy savings.

This software tool is qualitative in nature and uses survey information as the input data in an expert-system to help in the analysis. While this tool uses a systematic method to calculate savings etc., the selected areas or processes for improvement are based on plant personnel surveys and as such, require considerable domain expertise on the part of the user. This also implies subjectivity in the process selection method for energy evaluation. The ChemPEP® system is well designed, however, there are drawbacks as well as benefits as listed by the author below:

ChemPEP® Benefits:

- Better than guessing for overall system performance
- Tool and benchmarks are logical and well thought out
- Can essentially perform energy assessments over the phone
- Uses expert knowledge base

ChemPEP® Drawbacks:

- Relies on survey for main data that may not be answered correctly (qualitative assessment)
- Relies on plant management contact person’s understanding of processes
- Assumes many aspects of existing facility system (does this reflect reality?)

General Energy Usage Visualization Tools

There are quite a few tools or methods used to graphically depict energy flows in processes and industries. As such, these methods are purely descriptive. However, the area of visual management tools such as value stream mapping (Parry, G., and Turner, C., 2006) has demonstrated that these tools can help plant managers find areas for improvement. The graphical representation of energy flows is a useful tool for understanding manufacturing energy system dynamics.

A good example of one of the tools used for visualization purposes is the US Department of Energy's Manufacturing Energy Footprint studies (DOE EERE, 2005). This methodology breaks down the energy use at each major process activity (e.g., welding, tempering, etc.) for a particular category of manufacturing (e.g., steel, chemical, textiles, food, etc.). Figure 7, shown below, is the overall average breakdown for metals manufacturing energy streams in the United States.

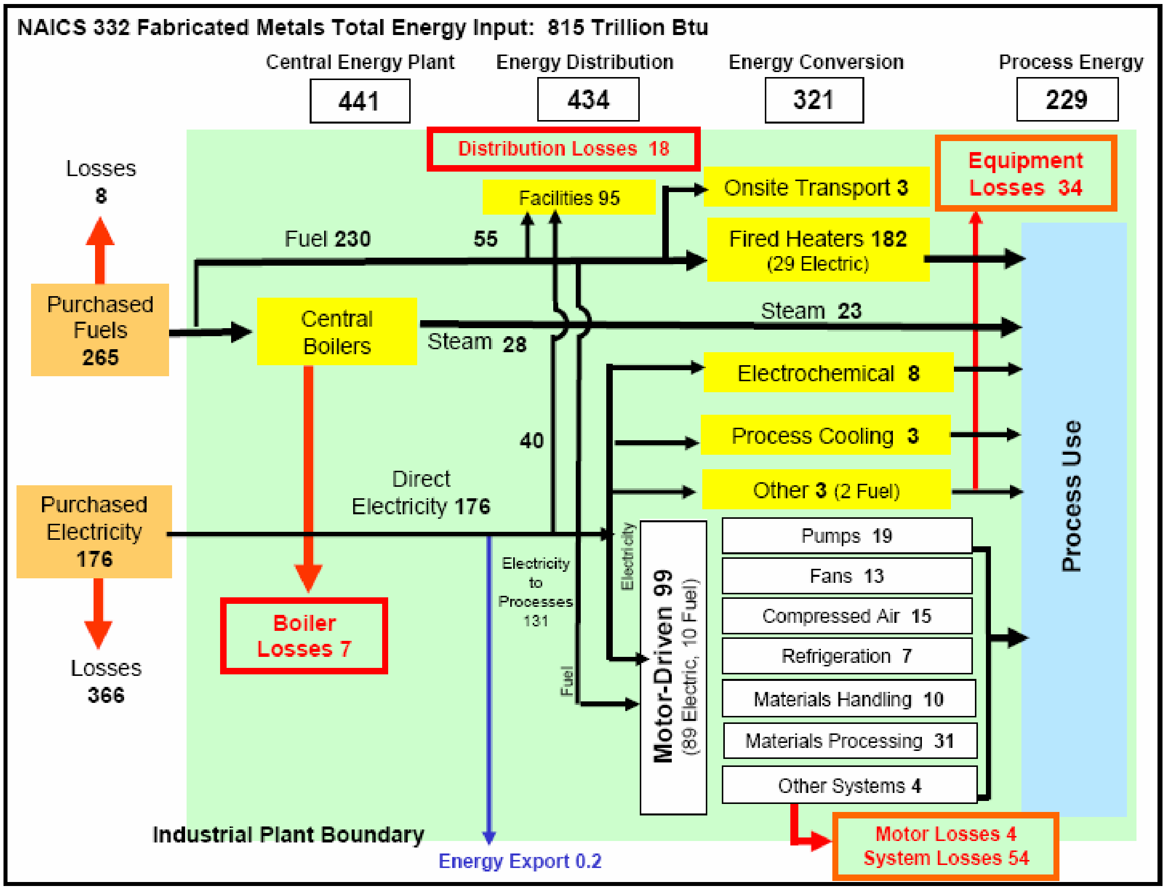

Figure 7. DOE Energy Footprint for U.S. fabricated metals manufacturing. Similar aggregated diagrams exist for different types of manufacturing (DOE EERE 2005).

While these “footprint” diagrams are good for demonstration and comparison purposes, they are too general to be useful to the energy engineer who is examining processes and sub-processes in a particular facility and seeking energy usage improvement areas. However, for demonstrating energy flows in general, they are well designed.

CHAPTER III. METHODOLOGY

Specific Objectives and Assumptions

The goal of this research is to develop and evaluate a systematic, logic-based energy analysis tool and methodology that is useful in complimenting and expanding the capabilities of traditional energy audits (improving existing systems) as well as process design work (creating new systems).

For example, the ERDT can be used in conjunction with traditional U.S. DOE Industrial Assessment audits to specifically analyze manufacturing core processes. As such, it provides a powerful analytic tool in identifying energy management opportunities.

The proposed methodology is science-based and can be extended to analyzing process transformations down to the molecular level if needed. As such, it provides a thorough process view and provides process-related detail with respect to energy usage here to fore unavailable with conventional methods.

The ERDT research will be validated from a technical perspective using established mathematical and physical science methods and methodological reductionism or “Occam’s Razor” (Hooft, 2001). The ERDT will also be validated from an operational perspective by demonstrating the method’s compatibility and augmentation of existing energy audit methodologies (face validity). In addition, the research provides a comparison of opportunity identification and energy saving potential as compared to existing energy auditing methodologies. The operational validation is therefore directly linked to contextual *usefulness* or *relativist validation* (Olewnik and Lewis, 2005). Finally, an expert opinion will be obtained to provide an outside view of the operational merit and applicability of the ERDT methodology.

The challenge is to measure, bound, characterize and analyze the "value-added" of the process energy flows used to produce a product or service. To this end, the research is meant as a structured approach to:

- Build an energy value stream characterization method to visualize, present and understand the role of energy, value and process alternatives in a manufacturing setting.
- Determine the actual value-added (VA) amount of the purchased energy[12] at the process level compared to the total amount of energy used at the particular process (ratio of VA to total energy used at process via bandwidth analysis).
- Demonstrate integration of energy partial productivities from bandwidth analysis into activity accounting methods.
- Isolate and identify selected processes for investigation via various ranking methods including decision matrix analysis.
- Examine the selected processes with an exergy ratio analysis to help determine possible courses of action for energy usage and economic opportunities.

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[12] For this analysis we examine only the energy flows into the facility, not energy from point of extraction, etc.

Because the concept of energy value-added is important for the ERDT, the definition of "value" in this research must be established. A traditional definition of a value index (Kolarik 1999, 522) is defined as:

Value Index = Worth/Cost (2)

A value index is analogous to a productivity index. Value can also be expanded as:

Value = Worth – Cost (3)

In these definitions "worth" is associated with customer benefits and cost is associated with customer burdens. The ERDT research is interested in the particulars of energy use associated with product production and therefore, energy value-added.

For the "value" portion of the value relationship, the research will use the Value Engineering definition (Parker, 1977) of "the least cost to provide a given function." This least cost will be linked to the least amount of energy needed to provide the given function (described below).

The "Cost" denominator portion of the value index definition is the actual amount of energy (cost) being currently employed to provide the given function. Notice that this produces a dimensionless value-index. For the ERDT, the "value" is the minimum (theoretical) energy required to produce the process transformation.

By including the energy value-added metric in a value stream structure, examination of various types of resource waste can be studied along with the energy inputs. The role this research could play in lean production methodology will also be examined.

Borrowing from the thermoeconomics concept, it can be shown that thermal energy has more worth as the temperature of the working fluid gets higher. Intuitively, this makes sense. Hot water is more useful than cold water and steam is even more useful than hot water. Various studies have demonstrated the increasing worth or value of hotter temperatures (ITP, 2003).

Using data from a steam system optimization study (Laukkanen, 2003), the relative cost of water in steam and liquid states can be determined (see Figure 8).

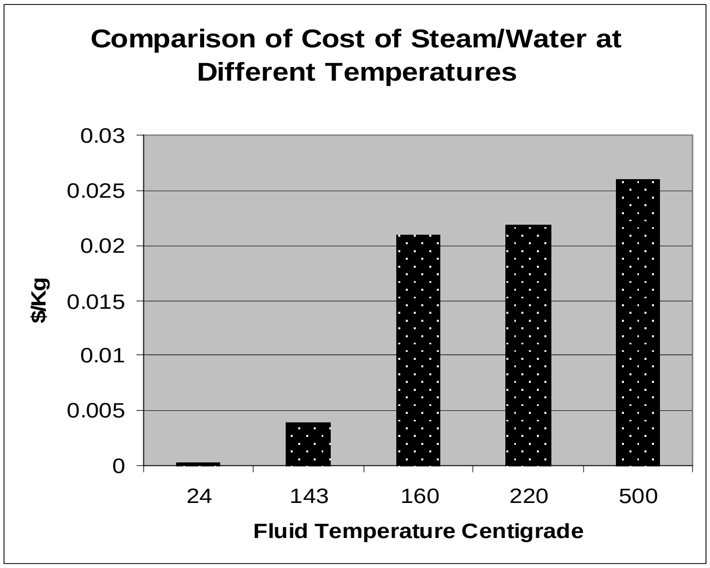

Figure 8. Chart showing increasing cost of working fluid (water and water vapor) at different temperatures (see footnote).

The implications of the charted data above are two-fold: 1) There is a definite economic relationship corresponding to increased fluid temperature (and pressure[13]), and associated thermal energy content and 2) The relationship of energy value to temperature

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[13] The 500 °C steam was at 100 Bar, the 220 °C steam was at 10 Bar and the 160 °C steam was at 4 Bar pressure.

is not constant, the value of 160°C water drops dramatically. The value drop of the 160 °C water corresponds directly to the drop in enthalpy (Kilojoules per Kilogram (KJ/Kg) energy per unit mass) of the fluid at that temperature. Therefore, market dynamics have determined that not all energy has the same unit value. There are aspects of energy that give one type a higher value than another. For example, electricity is more expensive than natural gas per KJ of energy. Electrical energy can be completely converted to mechanical work; natural gas cannot and is therefore less “valuable”.

A better way to examine the thermal energy/worth relationship would be to examine only the steam portion of Figure 7 (see Figure 8).

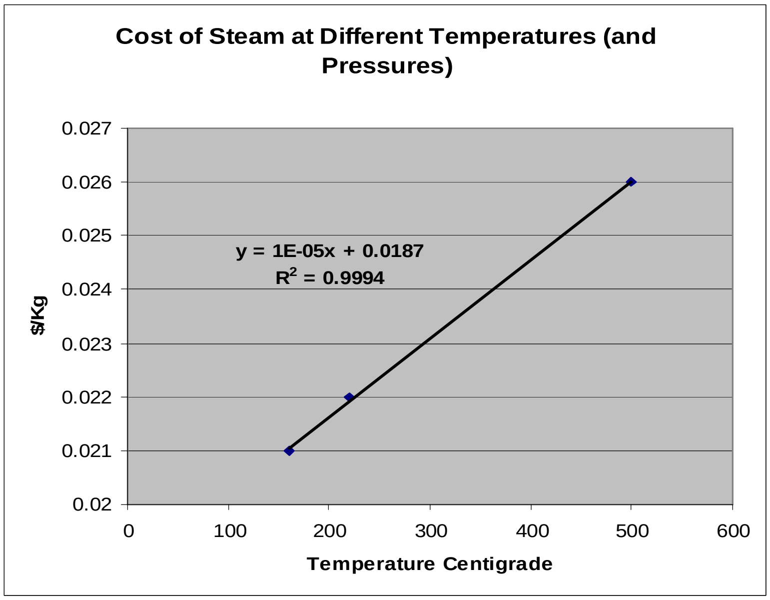

Figure 9. Chart showing increasing cost of steam at different temperatures.

The linear regression line in Figure 8 gives an approximation of the value (for the particular steam system of the Laukkanen study) of the increasing temperature of the steam. The implication of being able to calculate the different values of energy is expanded further in this chapter.

From the information in Figure 8, a value function could be derived (Conversation, Wong, 2006) for the thermal energy value given this particular facility and associated energy costs:

$$f(T, \Delta T)\alpha(\mathrm{Pr}\, ocessTemperature) = \text{Thermal Energy Value Function} \qquad (4)$$

Where: T = *function value at an operation temperature*

ΔT = *increment between processes at different temperatures*

For this case: $f(T) = (0.00001(T) + 0.0187)$ = *Energy Value (\$/Kg product)*

Limitations and Assumptions

The limitations and assumptions (L&A) for this research report are broken into two sub-categories. The first category corresponds to general L&A for the methodology. The second category pertains to L&A for the specific examples demonstrated in the report.

General L&A:

1. Only manufacturing processes that produce transformations in the product are considered. For example, the plant heating and cooling or lighting systems in the manufacturing plant are not considered in the research. All such processes can be identified and studied however. The assumption is

that the exergy concept can be applied to any process but this study concentrates on core manufacturing processes.

2. A “process” is defined from a hierarchical energy point of view and thus the process boundaries may actually describe what would normally be considered sub-processes. For example, a specific metal cutting operation such as countersinking a bore is the “process” of interest for the ERDT. This (sub) process may be part of a larger machining cell operation in the metal-working section of the plant called “CNC operations at machine-N” by plant management.
3. All processes are performed in-house. That is, the question of whether or not to purchase pre-processed material is not relevant to this research.
4. The starting point for all energy studies (ERDT, ChemPEP® and Traditional Methods) is the existing system in the particular manufacturing plant of interest.
5. For minimum energy (bandwidth) calculations, only the energy involved in the actual material transformations is considered. Support system energy usage, such as pumps, is not included. This assumption allows for the determination of the absolute minimum theoretical energy utilization needed.
6. Energy units will be normalized to Kilo Joules (KJ) for uniformity in the analysis. The assumption is that KJ is an appropriate unit for normalizing exergy units.

7. Energy rates are determined at the point of usage not back to extraction (fuel) or point of generation (electricity). This eliminates variance in efficiencies of extraction, generation and distribution of energy.
8. Only the exergy flows of energy in and out of the core processes are examined. The exergy flows of raw material streams are not analyzed and this is left for future research.
9. Minimum energy calculations assume perfect insulation (resistance to heat energy loss) and other conditions. It is understood that this is not realizable but forms the basis of the bandwidth analysis.
10. The importance of time to produce material "energy value" changes is not addressed directly in this study unless specified by the facility on existing processes. Time constraints for process bottlenecks and issues such as "pushing" a process are left for future study.

Specific Example L&A:

1. For the machining examples: The tools are assumed to be sharp. The material feed, speed rates and depths of cut are based on observation of the actual process or recommendations from the Machinery's Handbook (Oberg, 1996) for the particular process. Estimated machine efficiencies are 80%. Machine load factors (when unknown) are assumed at 80%. Some tool dimensions are assumed (e.g.,, saw widths, abrasive material

diameter) based on observation. For machines with multiple tools (e.g.,, de-scale nozzles) an average number of tools employed is used based on observation or worker interviews.

2. It is assumed that some processes, such as the air compressor, operate in the "ideal" state (i.e., no heat recovery is occurring). This is an accepted simplification used in various thermodynamic studies (Cengal, Boyles, 1998).
3. The drop in water temperature for the chemical rinse baths when loaded/unloaded is estimated based on infrared thermographic measurements taken during site visits.
4. The carburization and draw open analysis is assumed to be at steady-state. This assumption is a simplification and is based on the long residence times (24 hours) of the pins at steady temperature. The oven manufacturer's literature also assumes steady state conditions. The potential and kinetic energy in some steady state systems are assumed to be zero.
5. Material specifications for a particular steel are sometimes taken from accepted analog steels (e.g., AISI 5120 – SAE 4340) when data is missing.
6. For simplification, the combustion processes assume ideal gas dynamics and air is also assumed to behave as an ideal gas in the temperature ranges studied.

7. The amount of heat energy (fuel) that escapes out of the carburization and draw oven flues is assumed to be the “energy provided” minus the detailed “energy losses” listed in the manufacturer’s[14] literature for the case examples in Chapter IV.

Research Plans and Procedures

Methodology

The methodology will be explained using both established physical science and mathematics. Worked examples of the above steps will be provided during this explanation. This portion of the research will provide the basis for the technical approach validation described later in Chapter V.

For the application portion (Chapter IV) of the research, the ERDT will be applied in a case study using an actual energy audit at a manufacturing facility where a traditional OSU-IAC audit had been recently performed. The compatibility of the ERDT either as an extension of the traditional energy audit approach or to produce results comparable to (or better) than the traditional audit will be examined. In addition, the ability of the ERDT methodology to provide additional energy engineering perspectives to the standard energy audit will be demonstrated.

The resulting process opportunity identification set (POI) generated by the ERDT will be compared to the traditional audit POI set for this manufacturing facility. The two POI sets will be compared and discussed with regard to usefulness of the outputs.

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[14] Atmosphere Furnace Co., no longer in business.

Finally, the methodology will be demonstrated to energy experts for their opinions and comments on the operational applicability of the method to actual field use. As stated previously, the main contributions of this research are expected as follows:

- The development of a systematic, logic-based energy analysis methodology that opens the possibilities of exploring the many energy management opportunities for a particular manufacturing facilities core processes.
- The development of an energy analysis methodology which yields process visibility and can direct the engineer toward the energy using processes with the greatest potential for improvement.
- The development of an analysis methodology that promotes both divergent and convergent thinking with regard to the analysis of processes for both experienced and novice energy professionals.
- The development of an energy analysis methodology that is a logical progression to the current methodology of energy engineering analysis.
- The development of an energy analysis methodology which can be integrated with other management tools and provides promise for a bundled solution set.

The Energy Ratio Diagnostic Tool Steps (Demonstration)

The background example used in this section’s explanation is a metal drawing facility audited by the OSU-IAC in 2003 that produced radial tire and welding wire. A full case study using another IAC audited facility comparing the ERDT with an IAC method is examined later in the report.

Step 1: Process Energy Use Characterization

Principle: A Manufacturing enterprise's energy use can be described by a hierarchical sequence of processes, sub processes, activities and tasks.

Discussion:

Manufacturing processes usually involve the application of energy to produce a transformation in the raw material or unfinished component at that particular process. For example, metal plates may need to be welded together in a particular process. This involves the application of electrical energy sufficient to produce temperatures high enough for metals to liquefy and fuse. Other processes may involve the removal of material by cutting or grinding. Still other processes involve the heating of chemical baths by steam or combustion. Process energy is typically one of the following forms:

- Electrical (I^2R)
- Thermal (Btu, joule, etc.)
- Internal (Chemical) Energy ($\Delta U = Q +/- W$)
- Mechanical ($KE=1/2mv^2$ and $E_p = mgh$)

The first step in the proposed ERDT methodology is process characterization from an energy perspective. This is done to determine the logical points from which to measure the process energy inputs to the value chain of the product as it experiences transformations in the manufacturing process. This step also helps to isolate which processes will be analyzed which in turn, establishes the "system boundaries" that are crucial in the later thermodynamic analysis. This step also highlights logical points to attach energy monitoring sensors and submetering for various studies.

Traditional process characterization from the engineer's point of view usually involves physical characterization of the manufacturing processes (Rother, et al, 1999). In addition, newer areas of interest such as lean manufacturing techniques characterize the processes based on attributes such as time and work-in-process quantities.

Traditional forms of process characterization (Kolarik, 1999) are designed with regard to the desire to produce a product. Therefore, the focus of these traditional studies revolves about the attributes of the finished product (e.g.,, dimensions, time to market, etc.). In the ERDT energy process characterization, the research is interested in a slightly different view (in addition to the finished attributes of the product). In the energy analysis case, engineers are interested in the ability of the processes to utilize energy efficiently and effectively to accomplish the designated tasks already specified by the traditional process design.

The ERDT process energy characterization (Step 1) borrows from the process characterization methodology described by Kolarik (1999, 69-73). The concept of particular interest used by Kolarik is the idea of process "leverage" or "leverage points". These leverage points are areas in the identified processes where small changes in process parameters (e.g.,, force, speed) tend to produce dramatic changes in the outputs of the processes. The implication is that these points need to be located and deserve special attention because they illustrate insight into what is occurring in the processes. The author believes there is an analogy in the importance of identifying energy usage leverage points. What follows is the ERDT methodology for process energy characterization.

This first step in the ERDT methodology involves identification and documentation of the process hierarchy. This identification and documentation is accomplished via a walk-through energy survey of the manufacturing facility or some form of detailed knowledge of the processes in the plant. The energy engineer is identifying the individual process groupings and sub-groupings at this step.

Step 1 Example Process Characterization Analysis

The ERDT steps are illustrated by providing an example with the wire drawing facility mentioned previously. This first process characterization grouping will examine the major categories of processing. In the wire drawing plant used as the example case there were five major processing category areas:

- Decoiling
- Drawing
- Patenting (heat treat)
- Surface treat
- Coiling

The major processing categories provide the first major subdivisions of overall work performed in the facility. This view is sometimes used by the facilities accounting department as cost centers and may be the lowest level of detail used for that purpose.

Within the major processing categories identified above, are various sub-processes usually arranged in a hierarchical division of sub-processes. For the ERDT, the engineer continues to identify sub-processes until a boundary is reached that reflects the logical point for analysis and submetering. For example, within the Patenting category there are the sub-processes of the patenting oven and the lead bath quenches (see Figure 9). Depending on the level of detail desired, the engineer may conclude that within each of these sub-processes there is no further practical subdivision of energy addition.

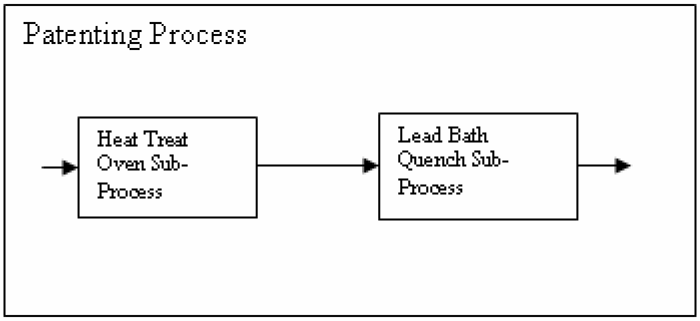

Figure 10. Diagram showing hierarchical nesting of sub-processes within processes for ERDT methodology

This step also produces a matrix of processes and associated energy parameters (see Table 3). The first column (Processes) lists the processes identified above in the characterization step (Figure 10). The next column (Principle) describes generally what the process is trying to accomplish. The third column (Technology) explains in more detail which physical principle the process is using to accomplish the process task. The forth column (Energy Type) describes what energy source is currently used to accomplish the process task. The fifth column (Energy Application) describes what machinery is employed that uses the energy type described to accomplish the process task. The sixth column (Desired Process Outcome) identifies what is the desired physical transformation or value transformation from the process. The seventh column (Process Physical Leverage) describes the physical leverage variables of the parameters of the process. For example, the original diameter of the metal rod to be drawn is an important variable in the rod mill reduction process. The eighth column (Fundamental Energy Task) describes how the current process applies energy in order to achieve the desired process outcome. The final column (Current Energy Leverage) describes the energy leverage variable in relation to energy efficiency of the particular process. For example, the efficiency of any motor used in an operation requiring one will directly impact the energy usage and energy efficiency of that process.

Processes	Principle	Technology	Energy Type	Energy Application	Desired Process Outcome	Process Physical Leverage	Fundamental Energy Task	Current Energy Leverage
Process #1								
Process #2								
Process #3								
Process #4								
Process #5								
Process #6								
Process #7								

Table 3. Process Matrix for process characterization step of ERDT

Completing the process matrix guides the engineer toward highlighting the energy usage areas. This step also helps to clarify where process energy measurement boundaries exist. These boundaries are logical locations for energy submetering measurements and form the system boundaries used for the subsequent thermodynamic analysis in Steps 2 and 4. Completion of the process matrix also identifies the physical and energy leverage points. The physical leverage points are used in later steps of the ERDT methodology while the current energy leverage points can be used for intermediate uses such as traditional energy usage analysis or incorporated into later parts of the ERDT analysis. An example ERDT process matrix with possible expansion to “recommendations” and “energy units” is shown in Table 4.

Activities	Principle	Technology	Energy Type	Energy Application	Desired Activity Outcome	Activity Physical Leverage	Fundamental Energy Task	Current Energy Leverage	Possible Recommendation Opportunity	Energy Unit Cost for Process (at time of study)
Decoiling	Un-wind from shipping spool	Un-wind with 19 KW motor through sets of straighteners	Electrical	19 KW AC Motors	Straighness of wire off of spools	Diameter of initial wire. Physical properties of wire. Speed of un-wind	Overcoming surface and internal structural energies of steel wire on spools	Motor Efficiency, de-coil machine design, wear	More efficient motors	$2.22E-5/KJ
Rod Mill Diameter Reduction	Pass through various rod mills	Stretch wire through series of spools (rod mills)	Electrical	DC Motors driving spools (rod mills)	Proper wire diameter reduction without breaking wire	Diameter of initial wire. Physical properties of wire. Speed of un-wind	Overcoming surface and internal structural energies of steel wire on spools	Motor Efficiency, machine design, machine wear	VFD drives on AC motor conversions, harder die material	$2.22E-5/KJ
Heat Treat Patenting Oven	Pass through 982 C Oven for 10-20 seconds	Heat wire to restore desired physical properties (initial process)	Natural Gas	NG Burners direct firing into oven space	Returning desired metal characteristics (initial)	Desired physical properties of wire. Speed of wire through activity	Heating mass of steel to desired temparature for desired residence time	Insulation levels, burner efficiency, oven design	Electric induction furnace	$7.58E-6/KJ
Lead Bath Quench	Pass through molten lead bath(s)	Quench wire to restore desired physical properties (final process)	Natural Gas	NG Burners heating bottom of tanks	Returning desired metal characteristics (final)	Desired physical properties of wire. Speed of wire through activity	Cooling mass of steel to desired temperature (but not lower)	Insulation levels, heat source design and efficiency, temperature needed	Smaller, insulated baths	$7.58E-6/KJ
Chemical Baths	Pass through various chemical cleaning baths	Surface treatment and cleaning	Natural Gas	Steam from NG Boiler	Clean wire	Amount of contaminants on wire. Speed of wire through activity	Providing sufficient heat in chemical baths to produce desired chemical reactions	Insulation levels, heat source design and efficiency, temperature needed	Waste heat recovery from patent oven using economizer	$2.22E-5/KJ
Air Knife Drying	Pass through blown air drying apparatus	Remove moisture from wire to avoid corrosion	Electrical	0.69 MPa air from 149 KW air compressor	Dry wire	Amount of moisture (water) on wire. Pressure of air across wire. Speed of wire through activity	Removal of excess water (from chemical rinse baths). Currently done by kenetic energy of high speed air across wire.	Air pressure and CFM needed, compressor and motor efficiency	Switch to mechanical wiping process	$2.22E-5/KJ
Coiling (Packaging)	Coil into final packaging	Wire feed and wrapped onto final spools	Electrical	19 KW motors	Final coiling of wire	Size of final spools. Speed wire through activity.	Overcoming surface and internal structural energies of steel wire on spools	Motor Efficiency, de-coil machine design, wear	More efficient motors	$2.22E-5/KJ

Table 4. Example ERDT process matrix for metal drawing operation.

Step 1 Summary:

While this characterization step is simply the first of four major components of the ERDT method, the results of this step can be used as a stand-alone analysis tool. By identifying the current energy leverage points, considerable insight is gained as to where the energy engineer should search for energy reduction opportunities.

Step 2: Calculation of Minimum versus Actual Energy Requirements (η) of Processes Identified in Step 1 using First Law of Thermodynamics Analysis

Principle: For each process element which requires energy for its transformation (identified in Step 1) there is a scientific minimum energy threshold and an actual energy consumed level (first law based analysis).

Discussion:

In this step, the theoretical minimum energy requirements to produce the desired process transformations identified in Step 1 are calculated and compared to the actual energy used to produce the transformation. This technique is also sometimes referred to as bandwidth analysis (ITP, 2006) because of the graphical bars or bands that can be visually compared. The resulting efficiency ratios are described as the task energy ratios. This section also expands the concepts of energy-value-added and energy-non-value-added.

Bandwidth Analysis

The idea of determining minimum energy values in industry is not new (Tanzil, et al, 2002) and (Fruehan, et al, 2000). However, the incorporation of this technique into a systematic, predictive energy audit and exergy analysis tool is a new approach to energy engineering.

Step 2 of the ERDT methodology first examines the physics of the material changes desired then uses energy balance and thermodynamic techniques to perform the energy accounting. A short discussion on material science is introduced to establish the material transformation information required from the processes. The conservation of energy is the central theme in this step and is introduced by a short explanation of the first law of thermodynamics.

Material Science

In order to determine the minimum energy requirements, an understanding of the physics of the material properties associated with the desired transformations is needed. The mechanical properties of materials can be traced to physical properties at the atomic and molecular level (Van Vlack, 1989, 229).

For example, to anneal metal, the required temperatures and dwell times are crucial. To evaporate a liquid, the specific heat and heat of vaporization parameters of the fluid are required. Similarly, all processes or transformations have underlying physical requirements. However, determining the minimum required energy to effect the material transformation may, or may not, be a trivial activity. For example, heating a material until it melts is straightforward. However the minimum energy required for various shaping, forming and coating operations may be more difficult to determine. For this research, it is assumed that these physical requirements can be determined (Podesta, 1996).

In manufacturing, the engineer is usually dealing with three categories of materials: (1) metals, (2) ceramics, and (3) polymers. Besides manufacturing, there are also industrial transformations involving: minerals, petroleum products, food materials, etc.

This report concentrates on manufacturing processes only. Manufacturing processes are typically broken into processing and assembly operations (see Figure 10). While assembly operations do use energy, it is the processing operations that typically are the most energy intensive and are the focus of this research.

Processing operations are normally composed of: shaping processes, property enhancing processes and surface processing operations. From these three branches of processes, the major energy consuming transformations[15] occur such as casting, forming, cutting, heat treating, etc. (see Figure 11). Non-traditional processes such as electrical discharge machining have also gained acceptance for some requirements (Groover, 2002). These transformation processes, such as forming, are the main focus of this section.

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[15] These "transformations" are the value added operations referred to in other parts of this report.

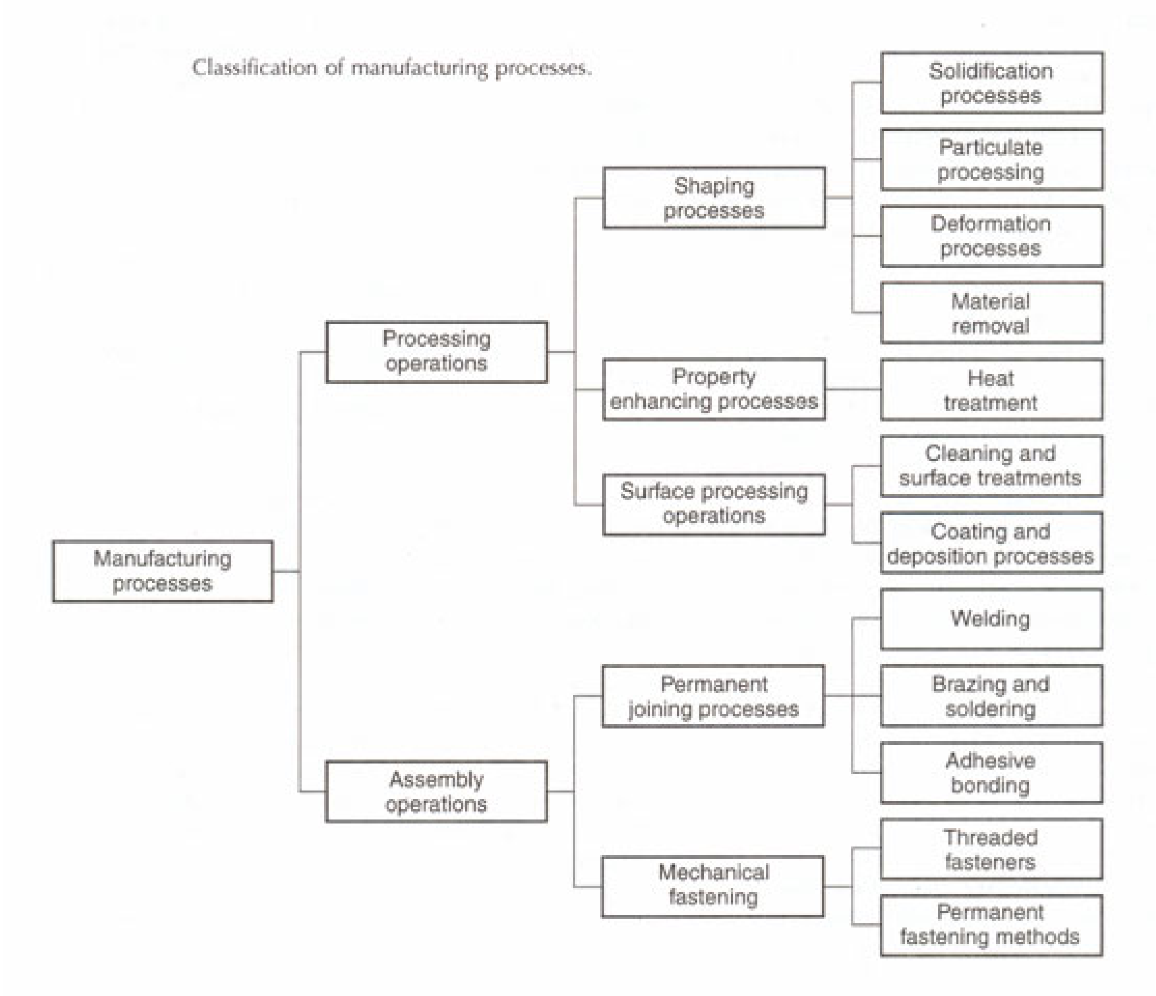

Figure 11. Hierarchy of manufacturing processes [Groover, 12]

Different materials and different transformations will require different scientific analysis methods. This background detail is part of the information needed to use the ERDT. The research's example involves patenting or heat treating metal; therefore a short description of some of the science behind the phases of metal forming will give the needed insight. Many material transformations that ultimately add value that occur in the course of manufacturing involve the addition of heat to the materials. Examples of typical heat energy addition are melting and heat treating.

Once the sciences (physics and chemistry) of the transformation are understood, the minimum energy requirements can be measured, calculated or found in empirical tables (Kalpakjian, 2001, 547, 599-605). For this research, the ERDT methodology will demonstrate how to calculate the minimum energy requirements. However, it would not be unusual for the manufacturing plant engineering personnel to actually know these values as part of the physics or chemistry of running the processes.

An important issue in this section regards the definition of the efficiency equations used to calculate the minimum energy requirements for a process such as metal forming. What is the appropriate baseline against which to compare and establish the minimum energies for the bandwidth analysis? There are several difficulties associated with such studies:

1. What is the appropriate process hierarchy level to determine the absolute minimum energy? (e.g.,, atomic level analysis, machine-part interface, total machine, machining center, etc.)
2. What are the appropriate system boundaries for the energy and thermodynamic analysis?
3. When examining process energy use, should the support equipment associated with the task be included? (e.g.,, pumps for lubricating oils, conveyors, etc.)
4. Load factor or time issues associated with processes.

Appropriate process hierarchy level to determine the absolute minimum energy

It is the author's opinion that the minimum energies required to accomplish the process tasks can ultimately be determined at the atomic or quanta level. For example, the machining of metal ultimately depends on breaking molecular bonds between atoms on two surfaces of metal (Podesta, 1996). However, the energies required to accomplish these bond separations are extremely small and there are no technologies existing today that can selectively break one layer of atomic bonds on a metal part and allow the resulting pieces of metal to separate from each other. Hence, the usefulness of this type of minimum energy calculation is suspect.

Therefore, for this ERDT study, the author will sometimes use a practical minimum energy calculation based on the existing process technology to keep the analysis manageable. For example, if the facility is currently using metal cutting machines such as lathes or mills, the engineer may elect to use the specific energy calculations for such processes (Machinery's Handbook, 1996) to determine the practical minimum energies required for the process. The problem with such an approach is that there may be technologies that require even less energy to accomplish the same process task such as electrical discharge machining. In that case there may be a lower theoretical minimum energy value. Therefore, another possibility is to benchmark all processes for energy use per unit. This is an area for possible future research (see Chapter V).

It should be noted that even by using the practical minimum energy calculations, the overall task efficiencies for many processes calculated by the ERDT are quite small (<5% of applied energy is utilizes for actual task). At first glance it may seem counter-intuitive that long established processes such as metal cutting are fairly energy inefficient however, this has been previously noted by various engineers, researchers and scientists (Astakhov, 2005).

Appropriate process system boundaries for analysis

A fundamental concept in all thermodynamic and energy studies is the determination of the system boundaries for the particular study. The efficiency calculations for processes are very sensitive to boundary selection. For example, the first law efficiency of a gas turbine to produce shaft power alone may be 30%. If the waste heat is used to heat water for a process, the first law efficiency for the gas turbine *and* water heater may raise to 45%. This difference of efficiency depending on boundary location, points to the importance of process boundary placement.

For the ERDT process boundaries, the study examines the utility energy source (gas or electric), the prime consumer (primary process) of the utility energy source and the direct application of the energy to the product transformation (process). Support systems such as lubrication pumps are not included.

In the case of electricity, energy is examined as it enters the process, not back to the point of generation. The section on assumptions points out the reasons for not tracing energy sources back to origination for this analysis. For a more detailed explanation of boundaries and thermodynamic analysis see the section below on thermodynamic techniques.

Another primary reason for selecting the system boundary where the utility energy enters the process is that this simulates the logical location for process energy submetering. A key determinant to the accuracy of the ERDT methodology is the ability to measure and record the energy streams entering the processes of interest. In lieu of having actual submetering, the ERDT may depend on estimates of energy flows. One of the outcomes of the ERDT methodology is suggestions for the future placement of submetering equipment on processes of interest (determined by the ERDT).

For the ERDT methodology to be applicable, the facility should be able to monitor and record the energy flows going into the processes. At a minimum, good estimates of the energy flow rates should be available. In addition, the flow of material (parts, mass of material, etc.) passing through the processes must also be recorded or estimated. Submetering of the current energy flows combined with product mass flow rates give the energy density of each product.

Support equipment accounting in minimum energy calculations

As has been pointed out by various researchers and engineers (Dahmus, Gudowski, 2004), the energy use of support equipment on many fabrication processes can overwhelm the energy use of the actual process. For example, the actual energy used for cutting metal at the tool and work piece interface may be only 0-15% of the total energy usage of the metal cutting machine (see Figure 12).

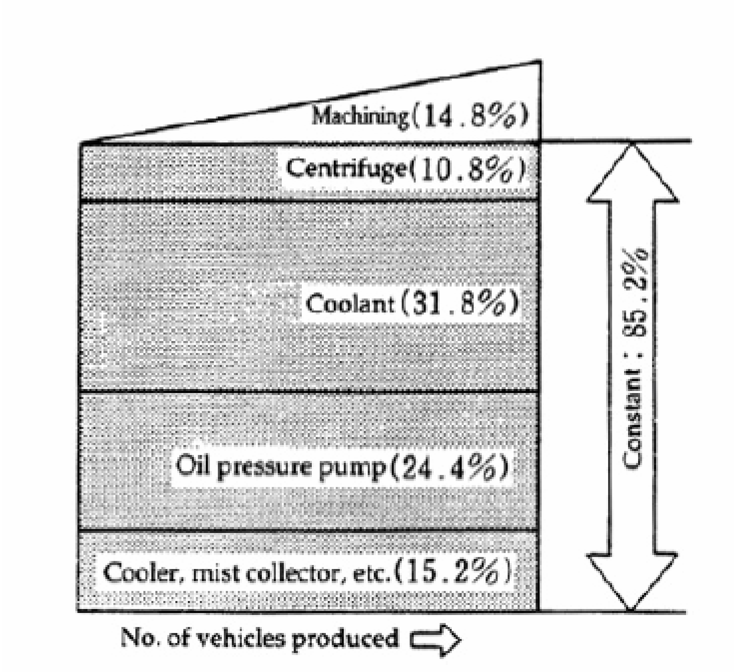

Figure 12. Diagram showing relative energy use of various metal cutting machine components in the automotive industry (Gutowski).

In order to minimize the complexity of energy calculations by going to the minimum energy process task analysis, the ERDT does not include the support equipment in the minimum energy calculation. Besides trying to demonstrate a true minimum energy requirement, the inclusion of the support equipment would be very machine and manufacturer dependent. For consistency, the support equipment is not examined in the actual energy used (denominator) of the energy ratio.

Process load factor (time factors)

In actual manufacturing, temporal requirements may also strongly influence energy requirements for processes. At certain bottleneck areas of the manufacturing value chain (Hansen and Mowen, p. 498), excess energy may be utilized to speed these constraining processes up in order to increase overall throughput. In this case, the economics of overall throughput dominate the particular process dynamics. This can be accounted for in the ERDT's AHP Decision Matrix ranking scheme for the processes. However, time constraints are not specifically addressed in the research report and are an additional subject for further research (see section on future research in the Chapter V).

Problematic Processes

There are three classes of processes that present a challenge for Step 2. The ERDT methodology is capable of examining all manufacturing processes, however, for some processes it is difficult to calculate the minimum energy usage due to their nature. These processes are the following:

- Subtractive Processes -- such as milling, sawing and grinding.
- Net Shape Processes -- such as extruding and forging
- Additive Processes -- such as various deposition operations

As demonstrated by Dahmus and Gutowski (2004), these processes can be analyzed for energy and exergy efficiency, however they are complex due to several factors:

- The energy use of these processes is highly variable, going from idle to some load factor in fractions of a second. Idle portions of processing time can be significant.
- The energy use strongly correlates to throughput.

- The definition of energy usage or specific energy in machining is directly linked to amount of material processed (e.g.,, removed, displaced, added, etc.) over time. Lower specific energy is generally better (more efficient).
- The energy usage of the support systems associated with these processes (e.g.,, coolant and oil pumps) are sometimes many times greater than the actual material processing.
- Tool wear increases energy use per unit of material processed and is a significant factor in efficiency calculations.
- Energy usage is directly related to the shape and geometry of the tool.

In the case of process heating, the benchmark is simply the amount of heat needed. For material forming processes this research uses a type of task efficiency. That is, if the operation is a metal cutting operation, the baseline is the theoretical energy consumed for simply removing metal by cutting using established tool equations. The energy usage of a real system will include support processes such as coolant pumps and feed motors. The discussion regarding some of the details of the ERDT method and material forming operations are included in the case study presented later in the report.

Thermodynamic Science Techniques

The first-law thermodynamic equations discussed in Appendix II are the basic energy accounting tools used for the bandwidth analysis in Step 2. Traditional energy engineering relies almost exclusively on the first law relationships to determine the *quantity* of energy utilization. In this capacity the first law equations are very useful.

The first law equations demonstrate how much heat energy is lost up the stack of a boiler or how much energy is converted to shaft work in an internal combustion engine. As described later, first-law equations tell little about how *useful* energy streams are.

Using the first-law relationships, energy efficiencies of systems can be calculated. There are various forms of efficiency ratios depending on the desired description. For this research the ratio of the minimum energy needed to accomplish a process or task is compared to the actual (total) energy used by the process:

Step 2: Calculation of Minimum versus Actual Energy Use, Bandwidth Analysis Example

This section demonstrates the steps of the minimum energy calculation with the annealing oven example identified in the process matrix of Step 1. This is a simplified view of this process but sufficient for this demonstration. For example, the methodology is concentrating only on the fuel consumption aspects of the oven. There are several other sub-systems that are part of this process such as the electric blowers that supply outside air to the combustion process etc. A complete analysis would include the details of the support systems if desired.

This example process heats steel to a high enough temperature to affect a desired transformation. The process is called patenting and is a type of metal heat treating. The desired temperature and other process specifics can either be given by plant engineering or determined by material science. This example assumes the patenting temperatures are known in advance.

The analysis for this example uses the thermodynamic concept of specific heat capacity C_p. Specific heat capacity is the energy that must be added to a unit of mass to raise the temperature one degree. For simplification, specific heat capacities of solids are usually considered at constant pressure. Therefore, the amount of heat energy needed to raise the temperature of steel for patenting $Q_{patenting}$ is given by:

$$Q_{patenting} = \Delta u = \int_{T_{ambient}}^{T_{patenting}} c_p dT + \Delta u_{latent} \tag{5}$$

The term Δu_{latent} represents the change in internal energy and c_p is the specific heat. The change in internal energy term Δu_{latent} is included to account for the latent heat associated with the recrystallization from austenite to pearlite that occurs in the patenting process between 700-750°C (ASM, 1998).

The ASM Metals Handbook provides data on the mean apparent specific heat for SAE 1078 steel (see Table 1). These values account for any latent heat occurring within each discrete temperature interval. This piecewise approach is needed mainly because of the jump in the mean apparent specific heat for the 700-750°C temperature range where the austenite to pearlite phase transformation occurs. When materials undergo phase transitions, additional energy is required (Bradey and Holum, 1993) to continue heating the material.

This example is a good demonstration of the need to understand the physics of the process transformation in order to have accurate calculations. By summing the product of the mean apparent specific heat and the corresponding temperature interval over the entire temperature range, the total change in internal energy can be determined. Thus,

$$\Delta u = \sum \overline{c}_p \Delta T \tag{6}$$

where $\bar{c}_p$ is the mean apparent specific heat.

The mass of the steel rod entering the furnace per unit time, $\dot{m}$ is given by

$$\dot{m} = N\rho\dot{V} = N\rho A v \tag{7}$$

where N is the number of wire strands, ρ is the density of steel, $\dot{V}$ is the rate of volume of a single strand of steel rod entering the furnace, A is the cross-sectional area of a single strand of steel rod, and v is the speed that the steel rod travels through the furnace. Using equations (6) and (7), the rate energy that must be supplied to the steel rod to heat it to the patenting temperature, $\dot{Q}$, is thus

$$\dot{Q} = \dot{m}\Delta u = N\rho A v \Sigma \bar{c}_p \Delta T \tag{8}$$

Theoretical Minimum Energy Requirements

This step calculates the ratios of minimum to actual energy usage at the particular process for the wire drawing heat treat example. For this process, the known material and process data include:

Steel Specific Heat	See Table 5
Steel density	7,849 Kg/m^3
Required patent temperature	800 °C
Steel wire speed through oven	1,464 m/hour
Wire diameter in oven	3.96 mm
Number of wire strands in oven simultaneously	8-12 (10 avg.)

Estimated existing Patent oven heat capacity[16]………. 26,380 MJ/hr

Estimated load factor of oven…………………………… 25%

Table 5 utilizes equation (8) to calculate the minimum energy required to patent a unit mass of steel.[17]

Temp Range °C	J/Kg°C	CpΔT = J/Kg
50-100	490	24,500
100-150	511	25,550
150-200	532	26,600
200-250	548	27,400
250-300	565	28,250
300-350	586	29,300
350-400	607	30,350
400-450	639	31,950
450-500	670	33,500
500-550	691	34,550
550-600	712	35,600
600-650	741	37,050
650-700	770	38,500
700-750	2,081	104,050
750-800	615	30,750
	delta u =	537,900

Table 5. Minimum energy required to patent steel calculation.

The value of 537.9 KJ/Kg is the minimum energy needed to patent the steel wire in the oven ($E_{TheoreticalMin}$). This value is now compared to an estimate of the actual energy used per kilogram to patent the wire (E_{Actual}). Using the average value of 10 strands of 1078 steel rod coming into the oven and equation 7:

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[16] Provided by plant personnel.

[17] Mean apparent specific heat data for the 100-150°C, 400-450°C, 500-550°C, and 600-650°C were linearly interpolated from the presented data.

$$\dot{m} = N\rho\dot{V} = N\rho Av = (10strands)(7{,}849Kg/m^3)(\pi(0.002m)^2)\left(1{,}464\frac{m}{hour}\right)$$
$$= 1{,}415.3\frac{Kg}{hour} \tag{9}$$

The estimated actual patent oven heat energy capacity[18] is given by:

(26,380MJ/hr)(0.25) = 6,595 MJ/hr. (10)

The specific actual energy used by the patent oven is:

$$E_{Actual} = \frac{6{,}595\frac{MJ}{hour}}{1{,}415\frac{Kg}{hour}} = 4{,}661\frac{KJ}{Kg} \tag{11}$$

Note that the particulars of the current process (large natural gas oven) have been simplified and the fuel input rate was estimated by the plant personnel. In an actual implementation of the methodology, these parameters should be determined with sensors or submeter.

Calculation of First Law Efficiency (Minimum Energy Required to Patent Steel in Example versus Process Actual Energy Usage) for Patent Oven

The bar chart displayed as Figure 13 demonstrates the difference between the minimum energy needed and the actual energy usage of the patenting oven example. This is an example of bandwidth analysis.

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[18] Burner rating of oven times 25% load factor depicts burner throttling and was estimated by plant personnel.

$$\eta = \frac{Energy_{TheoreticalMinimum}}{Energy_{Actual}} \tag{12}$$

$$\text{Energy Value Ratio} = \frac{537.9\frac{KJ}{Kg}}{4{,}661\frac{KJ}{Kg}} = 0.115 = (\eta) \tag{13}$$

The above calculation (13) is the 1st law efficiency for this product in this process (η). The first law energy efficiency ratio is low for this thermal process. The author is more accustomed to task efficiencies in the 70 to 90 percent range for these types of heating operations. With an energy efficiency value ratio this low (12%), the engineer is clued to the possibility that the company should investigate improving the efficiency of the process or should use another process altogether. Subsequent analysis of this process in the ERDT provides guidance and is addressed in the second law based Step 4, or the exergy analysis, portion of the methodology.

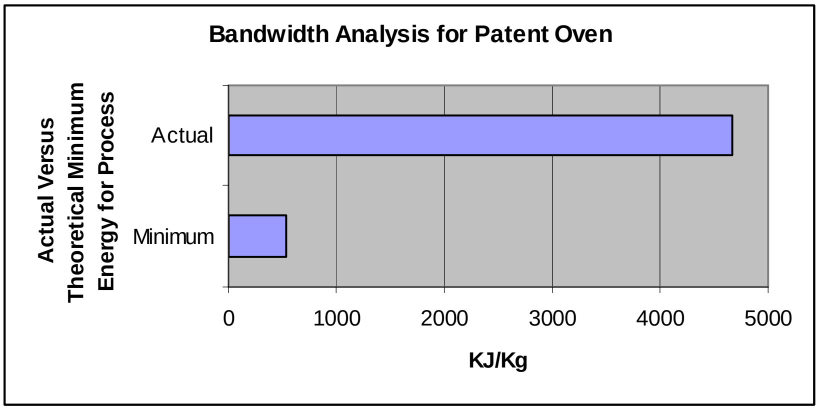

Figure 13. Bandwidth analysis comparison of minimum energy (bottom bar) required to patent steel versus process actual energy usage (top bar) for the natural gas patenting oven.

The example above was a thermal problem. Other processes might require different analysis. For example, the wire drawing operation examines the energy requirements to draw wire to a particular diameter. This information would come from strength of materials calculations involving modulus of elasticity, percentage of elongation, or other parameters. The work provided to this process is composed of the electric motor power (kW). Under these circumstances, the calculations would involve the energy equations associated with the particular process being investigated (e.g.,, electrical, mechanical or thermal). Fully worked examples of different processes are demonstrated in Chapter IV.

In summary, a general first law equation for energy flowing in and out of a process can be shown as:

$$\frac{gz_1}{J} + \frac{V_1^2}{2gJ} + u_1 + \frac{p_1 v_1}{J} + Q = \frac{gz_2}{J} + \frac{V_2^2}{J} + u_2 + \frac{p_2 v_2}{J} + W \qquad (14)$$

where:

$\frac{gz_i}{J}$ are the potential energy terms (in and out)

$\frac{V_i^2}{2gJ}$ are the kinetic energy terms

u_i are the internal energy terms

$\frac{p_i v_i}{J}$ are the flow work terms

Q is the work into the system

W is the work out of the system

For many problems some of the terms can be eliminated. For simplification of steady state problems the potential energy and kinetic energy terms are often assumed to be zero.

Step 2 Summary:

In this Step (2) the engineer designates the minimum energy requirements as the energy value added component of the energy input. Any energy input above and beyond the calculated minimum is considered by definition as non-value added energy. Figure 14 demonstrates the bandwidth analysis for all of the major energy using manufacturing processes for the example facility.

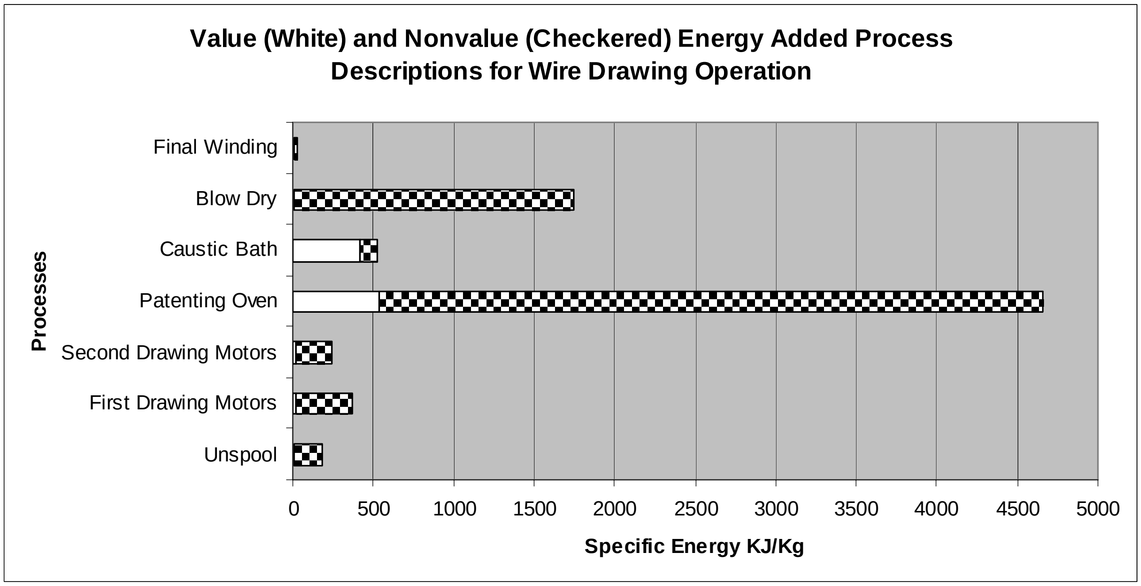

Figure 14. Value added (white bar) versus non-value added (checkered bar) process energy inputs. Note that the natural gas and electrical units have been combined and converted to a common energy unit.

Once the minimum energy requirements (bandwidth analysis) for all the critical processes have been compared to the actual energy use for the same processes, valuable information can now be generated and transferred to other management tools. The next step demonstrates that the ERDT does not operate in isolation but can be a component in a suite of management decision methods.

Step 3: Ranking of Processes by Energy Value Added Partial Productivity Ratios (η), Interface to Activity Based Management and Lean Methodologies

Principle: The process elements can be ranked by Criteria to Prioritize Energy Improvement Projects. The ERDT also Provides Input to Other Management Tools.

Discussion:

Examination of Figure 14 (Bandwidths) above highlights some interesting observations. Because of the visual nature of bandwidth analysis, it is obvious which processes use the most overall energy (the oven and baths). Another observation is that the ratio of value versus non-value added (η) is significantly different between processes.

An important question in any facility energy audit is: which processes should the engineer concentrate on for improvement? That is, what energy improvement projects should the organization fund? For this report, the energy projects are directly linked to the facility processes. The energy usage bands in Figure 14 remind the reader that process selection for analysis is more than simply picking the processes with the worst (smallest) energy value to nonvalue ratios. Conversely, the magnitude of energy usage by itself is also not sufficient information to warrant process analysis. Issues such as the varying costs of alternative fuels also complicate energy decisions.

Process selection for detailed energy analysis is dependent on some combination of criteria. In addition to the value-nonvalue and magnitude criteria, there are management criteria such as ease (cost) of process replacement, production interruption to replace a process, management/labor training concerns and others.

To address the concerns mentioned, the ERDT introduces a three-part process project ranking methodology. The process ranking engine is composed of the following sections:

1) Process ranking by percentage of energy nonvalue added. The data for this section comes directly from the bandwidth analysis computations.
2) Process ranking by Energy Partial Productivities (PPe) or cost of energy nonvalue added per unit of product produced. The calculations for this section are based on the NVA amount from the bandwidth analysis times the energy cost for the particular fuel or electrical energy.
3) Process ranking by use of a decision matrix. The decision matrix uses inputs from sections 1 and 2 above along with additional criteria that plant management deems important.

It would be naïve to assume that there is no experience based subjectivity involved with management decision making. To accommodate this aspect of project selection, the ERDT process ranking section includes methods from the decision sciences.

The author prefers a combined ranking technique known as a decision or Pugh matrix, shown as the last column in Table 6 (UMass, 2006), for examining both the amount of non-value-added energy and the percentage of non-value-added energy This allows the manager and engineer to examine the large potential improvements (cost savings) and the most probable savings projects (% non-value-added). Additionally, the decision matrix includes the ability to include weighted ranking variables based on the manager's expertise, which may not be completely objective (e.g., staff resistance to new technology). This ability to add flexibility to the decision matrix adds the advantages of ownership in the projects and may overcome internal inertia to process change (Breyfogle, p.941, 2003). With an unlimited budget the company would obviously examine all of the activities, however, the author has not encountered this situation to date.

The decision matrix was borrowed from RFP Evaluation Centers, Inc. (RFP http://www.rfp-templates.com/RFP-Evaluation-Centers.html) and includes the following description: "A *decision matrix* is basically an array presenting on one axis a list of ***alternatives***, also called *options* or *solutions*, that are evaluated regarding, on the other axis, a list of ***criteria***, which are *weighted* depending on their respective importance in the final decision to be taken. The decision matrix is, therefore, a variation of the 2-dimension, ***L-shaped matrix***".

'The decision matrix is an elaborated version of the *measured criteria technique* in which options are given, for each criterion. Satisfactory or compliance point (values) up to a maximum (usually from 0 to 100) that are predefined per criterion and may vary between criteria depending on its relative importance in the final decision are assigned'.

The case study example in the methodology Chapter (IV) includes a detailed decision matrix example.

For the example used in this chapter, the ranking and decision matrix output is demonstrated in Table 6. The reader should notice that the three columns produce different results. In all cases, the processes are listed as top-most-important. That is, the processes would likely be selected from the top-down until the process improvement budget was exhausted.

Ranked by Percent Energy Nonvalue Added	Ranked by Cost of Nonvalue Added	Decision Matrix Ranking
99% Blow Dry	Patenting Oven	Patenting Oven
94% First Drawing Motors	Blow Dry	Blow Dry
93% Unspool	First Drawing Motors	Caustic Bath
92% Second Drawing Motors	Second Drawing Motors	Unspool
87% Patent Oven	Unspool	Final Winding
75% Final Winding	Final Winding	First Drawing Motors
20.5% Caustic Bath	Caustic Bath	Second Drawing Motors

Table 6. Different ranking schemes using energy value ratios and total energy usage (η).

As the engineer moves from the left to the right in the process ranking Table 6, the emphasis shifts from engineering importance to economic importance.

Value Stream Mapping

Because the ERDT places a great emphasis on energy value identification and tracking, a logical extension of the ERDT is a visual management methodology showing various aspects of value in the production chain. The method most commonly used for this visualization task is the value stream map (Rother, et al, 1999).

The ERDT builds an energy value stream map using the accepted protocol of Rother, et al., and specifically the "learning to see" workbook. Two new parameters are added to the traditional value stream map (VSM) in the form of energy-non-value-added (waste), energy value-added and energy partial productivities (see gray shaded legend boxes in Figure 15). The legend boxes under each process may include:

- C/T – Cycle Time, a traditional VSM parameter
- L/T – Lead Time, a traditional VSM parameter
- Non-Value Added KJ/Kg – a new ERDT parameter (energy waste/unit mass)
- Value Added KJ/Kg – a new ERDT parameter (energy value/unit mass)
- (PPe) Partial Productivity of Energy

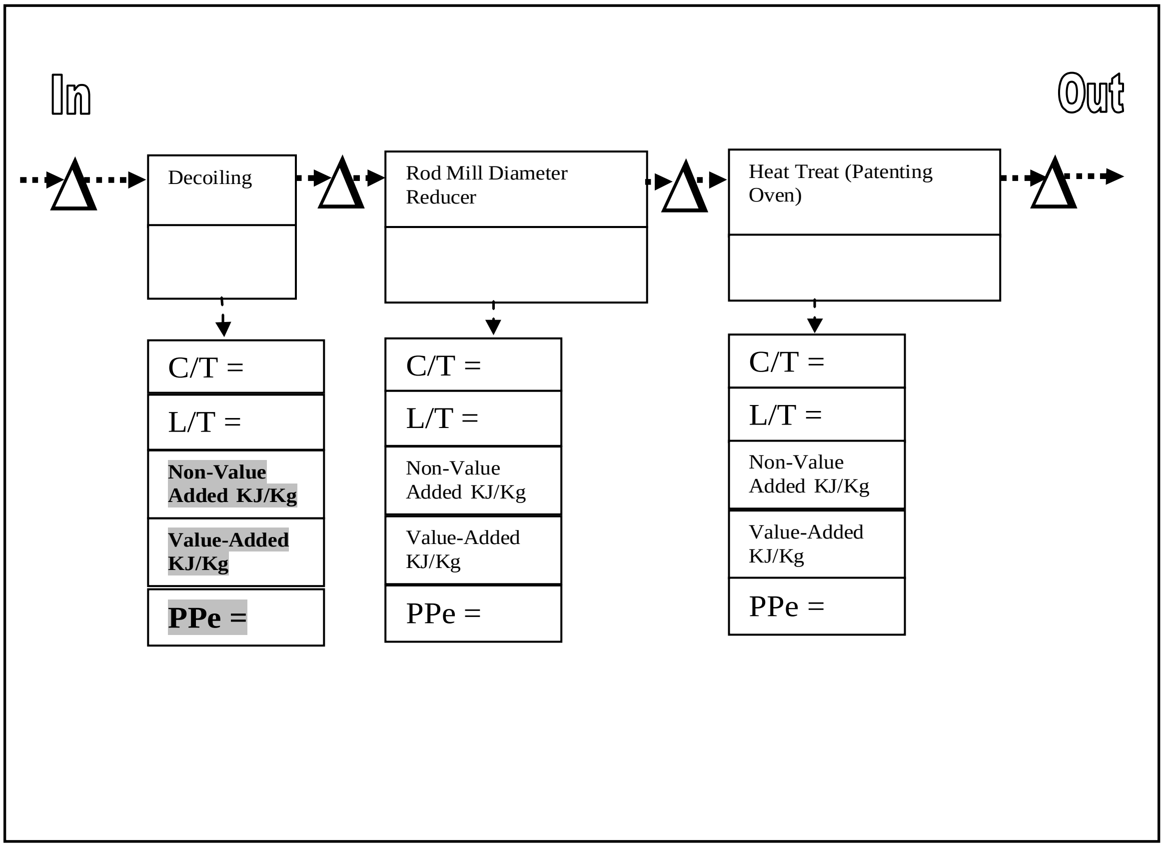

Figure 15. ERDT Value Stream Map with energy value/waste parameters and Energy Partial Productivities (gray shading).

Beyond functioning as a visualization tool, the VSM is also the logical interface between the ERDT and a lean production methodology. The ERDT-VSM is also a logical interface to an activity based management or cost system (ABM) using the energy partial productivities (see Figure 16).

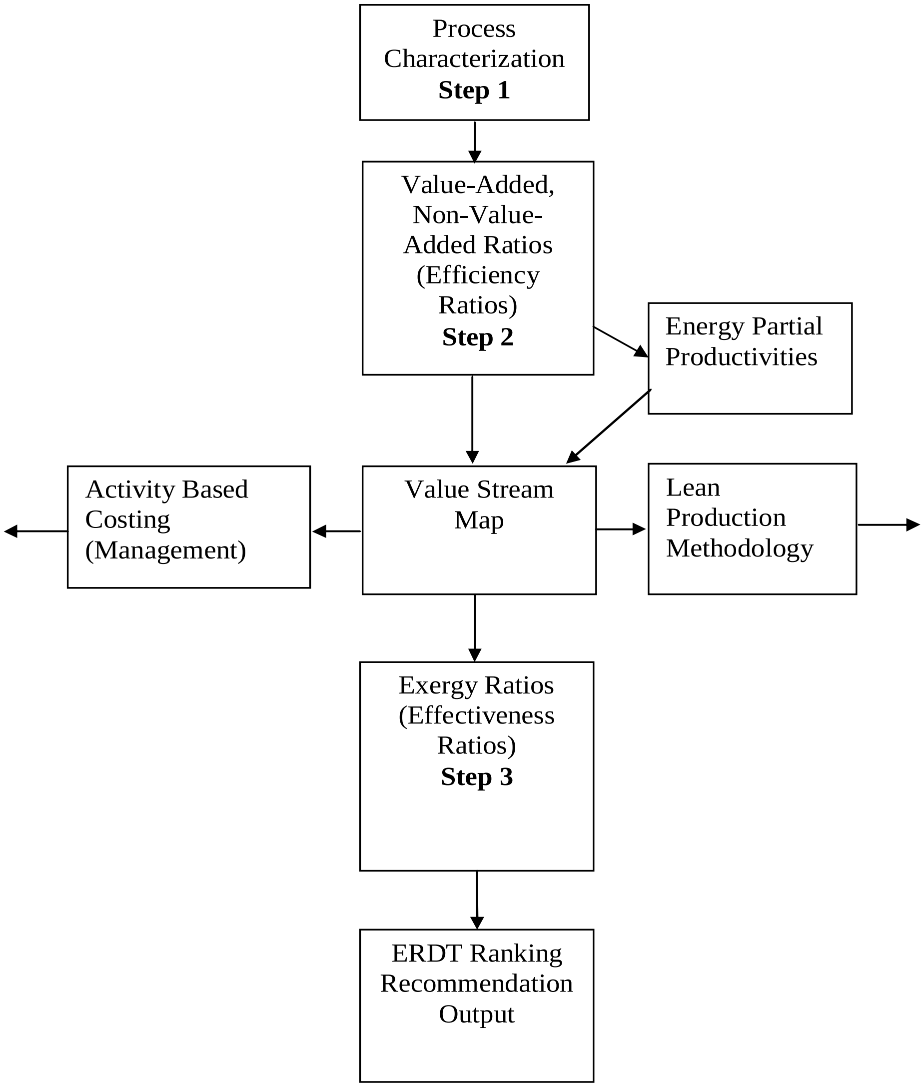

Figure 16. ERDT interface with lean methodologies and activity based management system.

Energy Value and Non-Value-Added Interface to Lean Production Methodology

Lean practice methodologies come in various forms and most literature agrees that the concept originated with Taichi Ohno for the Toyota Production System (Ohno, 1988). Central to most lean methodologies is the concept of waste reduction or the elimination of non-value-added activity. Lean literature typically lists seven (sometimes eight) types of waste to be eliminated in systems (IFS, 2004):

1. Excess or early production
2. Delays
3. Transportation to and from processes
4. Inventory
5. ***Processing***
6. Defects
7. Movement (excess within process)

The ERDT method has significant applicability to the fifth type of waste – Processing. This type of waste has been described as "doing more work on workpiece than is necessary". An extension of this statement could be "having the processes perform more work than is necessary", which is a subtle difference. While there is certainly energy waste associated with delays, transportation, etc., it is the within processing energy waste that the ERDT concentrates on specifically. Therefore, there appears to be a direct link, from the energy engineering perspective, to the ERDT methodology and lean practices.

Partial Productivity Ratio Interface to Activity Based Management Accounting System

One of the main areas of interest to management in a manufacturing facility involves the aspects of production that influence profitability. As demonstrated above, a decision matrix is employed as a selection filter to select certain processes for examination. Up to this point, the ERDT has concentrated mainly on the engineering aspects of energy usage. However, the model is capable of providing energy cost information for management. This ERDT-ABM interface cost information is a useful management tool for the analysis of profitability – a direct link to top management.

As demonstrated in the proceeding sections, the ERDT produces energy value added and non-value added information in the form of energy partial productivities (PPe). These PPe indices are a logical input for a value and nonvalue-added cost report (Hansen, Mowen, p556, 2003) used in activity based management (ABM). The tables below (7 and 8) demonstrate the type of information available to management from this section of the ERDT. Tracking productivity changes allows management to determine the relative efficiency of operations, efficient use of resources and provides the information needed for strategic decisions such as lot sizing, make/buy and product mix.

Drawing Wire	Energy Type	Energy Cost $/MJ	Partial (1/PP) Productivity KJ/Kg	Total 1/PP Energy Cost $/Kg	Partial Energy Value Productivity MJ/hr/Kg (1/PP)	Value 1/PP Energy Cost $/Kg/hr	Partial Energy Nonvalue Productivity MJ/hr/Kg (1/PP)	Non-Value 1/PP Energy Cost $/Kg/hr	Percent % Non-VA	Cost of Energy Nonvalue Added
Unspool										
First Drawing Motors										
Second Drawing Motors										
Patenting Oven										
Caustic Bath										
Blow Dry										
Final Winding										

Table 7. Energy value and nonvalue added cost report (ABM) output from ERDT[19].

Drawing Wire	Energy Type	Energy Cost $/MJ	Partial (1/PP) Productivity KJ/Kg	Total 1/PP Energy Cost $/Kg	Partial Energy Value Productivity MJ/hr/Kg (1/PP)	Value 1/PP Energy Cost $/Kg/hr	Partial Energy Nonvalue Productivity MJ/hr/Kg (1/PP)	Non-Value 1/PP Energy Cost $/Kg/hr	Percent % Non-VA	Cost of Energy Nonvalue Added
Unspool	Electrical	0.022	180.5	$0.0040	12.4	$0.0003	168.1	$0.0037	93	$0.0040
First Drawing Motors	Electrical	0.022	372.2	$0.0082	22.6	$0.0005	349.6	$0.0077	94	$0.0082
Second Drawing Motors	Electrical	0.022	245.6	$0.0054	18.3	$0.0004	227.3	$0.0050	93	$0.0054
Patenting Oven	Natural Gas	0.0095	4,661.0	$0.0443	537.9	$0.0051	4,123.1	$0.0392	88	$0.0443
Caustic Bath	Natural Gas	0.0095	523.4	$0.0050	416.2	$0.0040	107.2	$0.0010	20	$0.0050
Blow Dry	Electrical	0.022	1,740.8	$0.0383	12.8	$0.0003	1,728.0	$0.0380	99	$0.0383
Final Winding	Electrical	0.022	27.8	$0.0006	5.6	$0.0001	22.2	$0.0005	80	$0.0006

Table 8. Example value added (minimum) versus nonvalue added (actual – minimum) process energy inputs (KJ/Kg) for subset of processes.

The energy value and nonvalue-added cost report can either be used independently for management decisions regarding product production cost decisions; or can serve as decision variable input into the decision matrix (See Figure 17) employed in the next section to rank the manufacturing processes for investigation. This report will examine the later scenario. Assuming limitations of budget or time constraints, the facility management may only be able to select a subset of processes for improvement studies. Under this scenario, the question often becomes one of: Which processes, if improved from an energy usage standpoint, would increase profitability?

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[19] Values shown for PPe's are actually reciprocals.

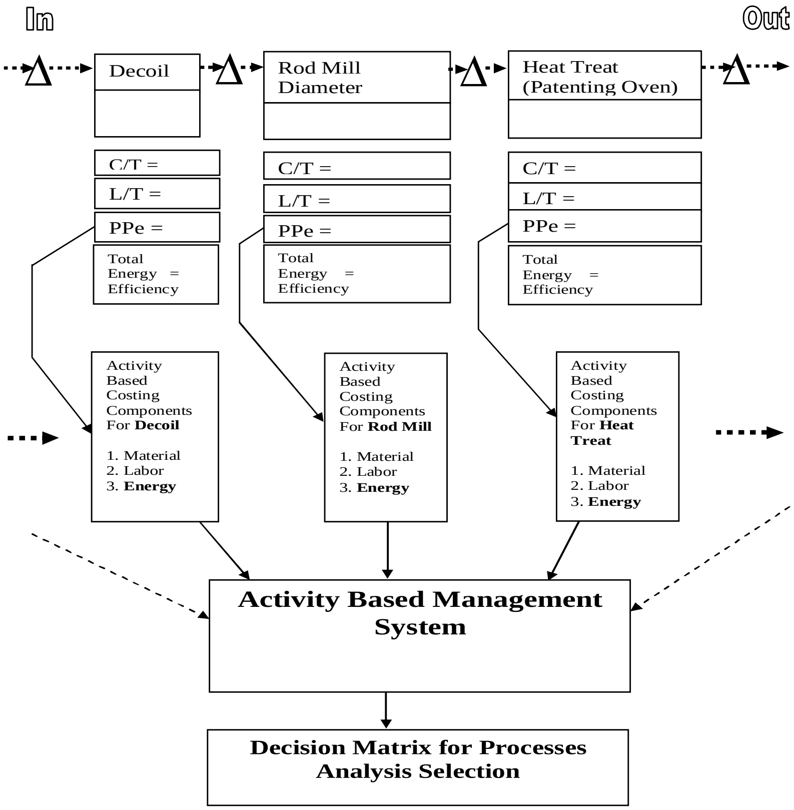

Figure 17. Interface between ERDT Value Stream Map and Activity Based Management (ABM) Accounting system.

In Steps 2 and 3 the methodology used gross energy calculations in a fairly straightforward manner to demonstrate relative energy efficiencies. For many manufacturing plants just this identification step would be quite helpful. However, a tool that is more prescriptive regarding energy improvement recommendations is more desirable for the energy engineer.

Step 3 Summary:

It would be useful to have a methodology that could indicate whether processes were utilizing energy in an ***effective*** manner. Considering the minimum energy requirements identified versus energy input into the process ($\boldsymbol{\eta}$) in Step 2, does the current process utilize the purchased energy (fuel, etc.) efficiently? Does the process utilize energy in such a way that some useful energy can be recovered, or is the process completely "wrong" for the type of process energy/transformation that is required? Such a methodology exists (that can point the engineer in this direction) and has been used for some time. This method is known as "exergy analysis", "availability analysis", or "second law analysis".

Step 4: Examination of Ranked and Selected Processes from Step 3 Using Exergy Analysis (ε)

Principle: For each process element identified and highlighted in Step 3 there is a thermodynamically determined exergy efficiency; demonstrating the match between energy source and process (second law based analysis).

Discussion:

Central to this step in the ERDT methodology is the concept of exergy or available energy. While the first law of thermodynamics is useful in energy accounting it does not explain something very fundamental that most readers will recognize. When a fuel or energy is used to produce work or heat, "something" has been lost. When a match is burned it can not be reignited. What is lost when energy is utilized is a measure of its usefulness or value. It is a measure of the "something" lost that is the focus of exergy analysis.

Exergy Analysis

The first law of thermodynamics states that the energy may have been transformed into a lower temperature effluent or other form of waste heat however the total amount of energy has not changed (Cengal, Boyles, 1998). The “something” that has changed is the capacity to do *work*. This capacity to do work or the “availability” or “exergy” of the resulting energy is a very important concept. The term “exergy” has become accepted world-wide recently while the term “availability” is still used in the United States.

In reality, when most people use the term *energy* they are describing the usefulness of the energy. This is a definition of exergy. As demonstrated in the Step 2 section above, energy is actually somewhat difficult to describe. Exergy is easier to describe and understand in that it is the usefulness one expects from purchased energy. Exergy or availability are described by the second law of thermodynamics and are sometimes referred to as second-law analysis. Exergy has the same units as energy, work and enthalpy (e.g., KJ/Kg) and is directly related to the concept of entropy.

Exergy examines systems in relationship to some ambient state (dead state). For many processes the dead state is the average earth-based ambient conditions of temperature (15.6 °C) and pressure (100 KPa). The notation for temperatures, pressures and other parameters at environmental conditions are usually subscripted with the $({}_0)$ (e.g., T_0 and P_0). As will be shown later, the ambient conditions may be different than earth surface conditions. This is a key concept with regard to the usefulness of some types of energy versus others. Consider how much work 5,000,000 cubic meters of an inert ideal gas at 500 °C and 20 MPa could do on the surface of the earth. What if this gas system were placed on a planet where the ambient conditions were already 500 °C and 20 MPa? In this case the gas system would simply be at ambient conditions and essentially useless from an exergy or energy point of view. On earth however, at ambient (dead state) conditions, this high temperature and pressure gas could turn a turbine, produce electricity, heat water and do other tasks.

Therefore, exergy, usefulness or availability depends on the process's relation to ambient or dead state conditions (T_0) (Cengal, Boyles, p. 420, 1998). This is why some forms of waste heat are practically useless even though there is considerable "energy" in the heat – the process temperatures are too close to dead state (ambient) conditions.

A classical example of exergy versus energy is the tremendous amount of waste heat that is produced by electric power generating stations. This waste heat is usually carried away from the turbine condenser in the form of hot water. This water is discharged into ponds, rivers or lakes. A 1,000 Megawatt coal fired generator may discharge 1,700 Megawatts of heat energy into a lake (Masters, 1991). People have tried for some time to recuperate this large amount of warm water waste energy however the temperature of the waste water is so low (typically 30 °C) that little can be done with it. It could be said that while the amount of energy is high, the availability or exergy of the waste heat is low or poor.

A very important exergy concept for the ERDT is exergy utilization efficiency (ε_u). This type of efficiency is significantly different from energy efficiency (η). Energy efficiency measures the amount of energy applied to the task. Exergy utilization efficiency measures how effectively the energy was applied to the task. The difference between the two definitions appears subtle but is profound and easily seen in a comparison of the two types of flow for the same processes.

In Figure 18 the oil furnace may have an energy efficiency (η) of 85%, but the exergy utilization efficiency (ε_u) is only 4%. This indicates that 96% of the available energy in the fuel oil is wasted in producing low temperature space heating. However, the energy efficiency only indicates that the burners and insulation are 85% efficient. Exergy utilization efficiency tells how well the task is matched to the type of energy and is described in detail later in this report.

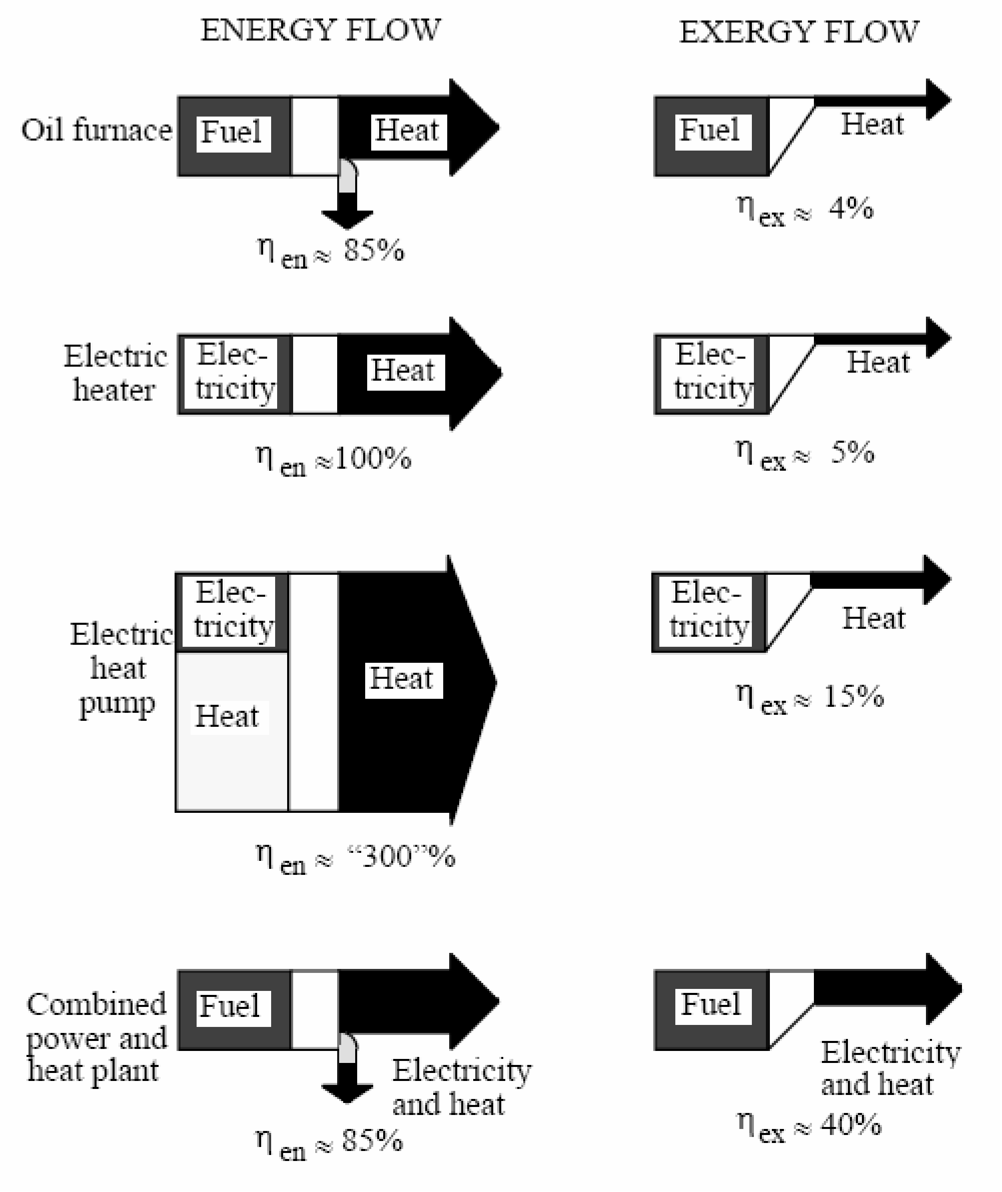

Figure 18. Comparison of exergy flow versus energy flow for the same processes (Wall, 1977).

For this research, specialized exergy (second law) ratios are developed for the processes under investigation. As will be demonstrated later, once the first and second law ratios have been determined for a process, they can be combined to give real insight into process efficiency and effectiveness.

There are various types of energy as noted previously. These types of energy can be converted into work and are described by various first law equations:

- Potential Energy (mechanical)– gz/J
- Kinetic Energy (mechanical) – $V^2/2gJ$
- Internal (Chemical) Energy – u
- Flow Work (mechanical) – pv/J
- Electrical Energy – I^2R
- Heat Flow (thermal) – Q

Potential energy can be used by mechanical systems such as hydro-electric power generation facilities using water change of elevation (head pressure). Likewise, kinetic energy can be used by mechanical systems to turn crankshafts or turbines with high velocity gases. Fuel cells use internal energies of chemicals to produce electric current. Electrical energy is used to produce mechanical shaft power via electric motors. Both mechanical and electrical energy could be completely converted into work if not for losses or irreversibility such as friction. Heat energy is different in that only a portion of the energy content can be converted into work and therefore, heat is treated a little differently as will be demonstrated below.

Reversibility is the ability of a system to return to its initial state. Usually, this is described as the system's working fluids and surroundings being returned to the original state and is used as a conceptual benchmark. In the real world there are no completely reversible systems (Kay, 1989). Irreversibilities are the aspects that keep systems from being able to return to their original states – without added energy. Examples of irreversibility's are electrical resistance (ohms), friction in mechanical systems, and turbulence in fluids and gases. Irreversibilities can also be described as the production of entropy in a system (see the discussion of equation 24 below).

The discussion that follows is a brief introduction to second law analysis of thermal, mechanical and chemical systems. While the ERDT method uses a specialized form of exergy ratios, all exergy calculations can be performed using the foundations of second law analysis.

Thermal Energy Second Law Calculations (Thermal Exergy)

Thermal energy (exergy) is one of the main energy types of interest to this research. Many industrial processes use heat for a variety of tasks such as heat treating, forming or drying. Additionally, thermal energy is the most common type of waste energy encountered in systems (Creyts, Carey, 1999). Thermal waste energy is often an indicator of the irreversibility's mentioned above. Most processes that utilize natural gas are thermal and therefore conservation of natural gas resources will involve examination of thermal systems.

Unlike mechanical and electrical work mechanisms, which have the theoretical potential to approach 100% conversion of energy into work, thermal systems are greatly constrained by the phenomenon of heat flow and entropy described below in the second law of thermodynamics.

Thermal energy can only be converted to mechanical (useful) work by using a heat engine (Cengal, Boyles, 1998). The most familiar heat engine is probably the internal combustion engine. The definition of work for the heat engine is the ability to perform mechanical work such as turn a crankshaft. Heat engines take thermal energy from a high temperature heat reservoir (HTER or Q_H), produce some useful work (see Figure 19 below) and reject waste heat to a low temperature energy reservoir (LTER or Q_C). An example of an LTER is the cooling pond water used by the power generation station mentioned above. Notice that if there were no losses in the system, there would be no waste heat to go to the LTER. Conversely, in a no loss system, the work output *could* be converted back into high temperature energy and fed in the HTER. This would lead to a perpetual motion machine based on the first law of thermodynamics, sometimes called a PMM1 (Cengal, Boyles, p.271, 1998). All real world systems have irreversibility's and therefore some heat in a heat engine is always rejected to the LTER[20].

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[20] This is, in essence, the proof against a PMM1 by the complete empirical lack of a reversible heat engine.

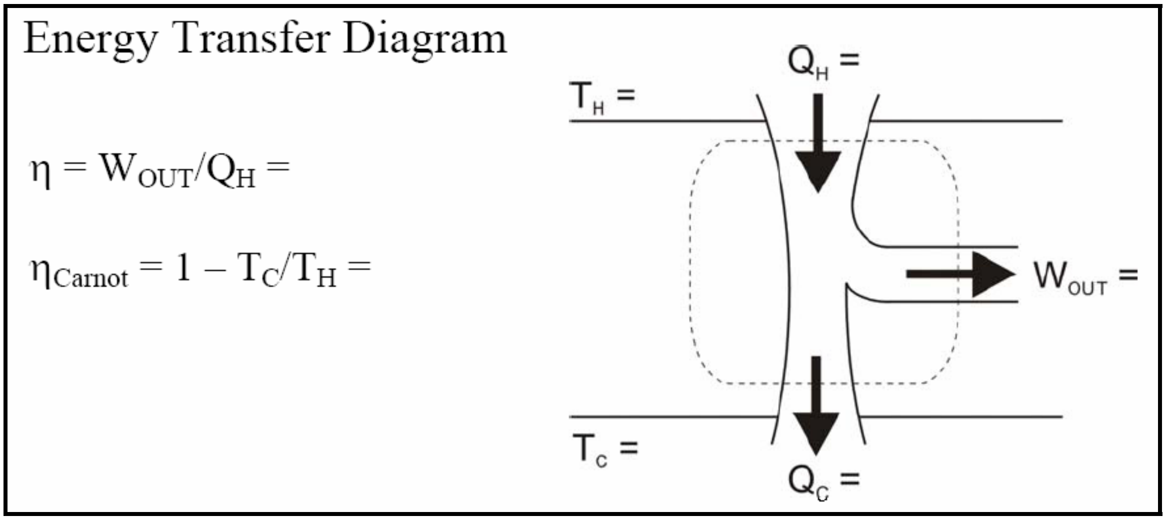

Figure 19. Diagrammatic representation of a heat engine with energy reservoirs (http://sitemason.vanderbilt.edu/files/aZzjaM/HeatEngineWorksheet.pdf.)

The idealized (perfect) heat engine was first described by Sadi Carnot in 1824 (Erlichson, 1998). The efficiency of such a hypothetical engine is useful in that it sets the upper limit on efficiency for any heat engine. The Carnot efficiency is typically given by:

$$\eta_{Carnot} = \frac{T_H - T_C}{T_H} \tag{15}$$

Where T_H is the high temperature reservoir and T_C is the low temperature reservoir.

While this equation seems simple, its implications are profound. For example, for a heat engine to produce work there must be a temperature difference between the reservoirs. However, if there is any temperature difference in the reservoirs, the efficiency of the heat engine cannot be 100%. As the temperature difference between the reservoirs goes up, the amount of work possible increases. At the same time, the potential for a worse efficiency also increases. Attempts to ignore the second law limitations for heat engines leads to misguided proposals for perpetual thermal machines sometimes called PMM2's. A less obvious misuse of first law efficiencies is the often stated high efficiencies of thermal processes such as water heaters (Moran, 1982).

In general, a heat engine's efficiency can be expressed by:

$$\eta_{HE} = \frac{Q_1 - Q_2}{Q_1} = \frac{W}{Q_1} \tag{16}$$

Where T_H for the Carnot cycle and Q_1 (Q_{Hot}) for the general heat engine are the higher energy heat flows entering the heat engine and T_C and Q_2 (Q_{Cold})is the waste heat leaving the heat engine and W is the mechanical work output of the heat engine. These models are sometimes called the reservoir models because they describe heat flowing from a higher temperature reservoir, doing work, and then flowing into the low temperature reservoir (sink).

By combining the Carnot and general heat engine equations the following relationships are derived:

$$1 - \frac{Q_{Cold}}{Q_{Hot}} = 1 - \frac{T_{Cold}}{T_{Hot}} \tag{17}$$

$$\frac{Q_C}{T_C} = \frac{Q_H}{T_H} \tag{18}$$

$$\frac{Q_H}{T_H} - \frac{Q_C}{T_C} = 0 \tag{19}$$

For the Carnot cycle:

$$\sum_i \frac{Q_i}{T_i} = 0 \tag{20}$$

This equation can be restated as an integral around a reversible cycle. The resulting relationship is known as the Clausius Theorem for the reversible cycle:

$$\oint \frac{dQ}{T} = 0 \tag{21}$$

Unlike the perfect reversible cycle, the real-world irreversible cycles are less efficient than the Carnot cycle. Considerable empirical observation has shown that some heat always flows out of real systems and cannot perform work. This is expressed as the Clausius Inequality and is the central point of the second law of thermodynamics and by direct association, the exergy concept:

$$\oint \frac{dQ}{T} \leq 0 \tag{22}$$

Equation 23 examines the amount of heat energy (Q) that flows in a reversible cycle at a constant temperature (T). From experiment it is known that no true reversible cycles exist, therefore "something" must be changing.

$$S(B) - S(A) = \int_A^B \frac{dQ}{T} \tag{23}$$

The concept of entropy (S) can now be introduced. Entropy is a measure of the amount of energy in a system that is *unavailable* to perform work and was first introduced by Rudolf Clausis in 1850. Entropy is a state function and is also a measure of the relative randomness and chaos in a system. Entropy is also a measure of the irreversibility's in a system.

Equation 23 stated in differential form at any point in a heat cycle is:

$$dS = \frac{dQ}{T} \quad \text{or} \quad dQ = TdS \tag{24}$$

Using the example of gas and a piston, the relationships of heat, energy and entropy can be expanded.

The first law energy balance equation can be written as:

$$\delta Q - \delta W = dU \tag{25}$$

where U is the internal energy of the system.

Work (W) is a path function and can be expressed as the boundary work of moving a piston:

$$\delta W = PdV \tag{26}$$

If PdV and TdS are substituted into equation 26, a fundamental form of the Gibb's relation is derived:

$$TdS = dU + PdV \tag{27}$$

By introducing the concept of enthalpy, where enthalpy (H) is defined as:

$$H = U + PV \tag{28}$$

$$dH = dU + PdV + VdP$$

The final Gibb’s relation is derived below. This equation will be used at later times in this report.

$$TdS = dH - VdP \tag{29}$$

The classical equation form for the calculation of exergy or available work is:

$$Available\_Work = \left(\left(U + KE + PE\right) - U_0\right) + p_0\left(V - V_0\right) - T_0\left(S - S_0\right) = Exergy \tag{30}$$

Assuming kinetic and potential energy can be ignored and using equation 29 gives:

$$Available\_Work = \left(H - H_0\right) - T_0\left(S - S_0\right) \text{ or} \tag{31}$$

$$Change\_in\_Available\_Work = \left(H_2 - H_1\right) - T_0\left(S_2 - S_1\right) \tag{32}$$

A complete form of the exergy equation (equation 33) would be in the following form where all types of available energy are included:

$$Exergy = \left(u - u_0\right) - T_0\left(s - s_0\right) + \frac{P_0}{J}\left(v - v_0\right) + \frac{V^2}{2gJ} + \left(z - z_0\right)\frac{g}{g_c J} + \sum_c\left(\mu_c - \mu_0\right)N_c + E_i A_i F_i\left(3T^4 - T_0^4 - 4T_0 T_3\right)\ldots$$

internal entropy work momentum gravity chemical radiation

First and second law (exergy) efficiencies are an integral part of the ERDT methodology. The next section discusses and demonstrates the specialized exergy utilization task efficiencies. However, the exergy or availability changes, efficiency ratios and other second law metrics for any process can be derived from the above equations. In future extensions of this research, complete exergetic analysis of all the components in the production chain would lead to complete engineering solutions (see section on future research in Chapter V).

Exergy Utilization Efficiencies or Effectiveness Ratios

Efficiencies are common metrics for engineers and provide a clear representation of how well a process is performing. One needs to exercise caution when using or interpreting efficiencies because the definition of the denominator and numerator terms determine what the ratio is actually describing. Thermodynamic and exergy efficiencies are heavily dependent on the definition of systems boundaries and desired scope of study.

In general, exergy efficiencies can be divided into two main categories (Moran, p.86-87, 1982):

1) Classes of efficiencies where:

$$\eta = \frac{EnergyOutIn\,\mathrm{Pr}\,oduct}{EnergyIn} = 1 - \left(\frac{Loss}{Input} \right) \tag{34}$$

$$\varepsilon = \frac{ExergyOutIn\,\mathrm{Pr}\,oduct}{ExergyIn} = 1 - \left[\frac{Loss + Destruction}{Input} \right] \tag{35}$$

The class of these efficiencies is determined by the user. The definition of what is a product, input, or output may be arbitrary but should be consistent.

2) Task efficiencies where:

$$\eta = \frac{TheoreticalMinimumEnergyInput}{ActualEnergyInput} \tag{36}$$

$$\varepsilon = \frac{TheoreticalMinimumExergyInput}{ActualExergyInput} \tag{37}$$

The ERDT methodology uses a specialized form of exergy task efficiency herein called the “exergy utilization efficiency” (ε_U). This form of exergy ratio is similar to equation 34 but measures the exergy (percentage) required for the process task versus the exergy available in the task input energy stream (e.g., fuel, electricity).

$$\varepsilon_U = \frac{Task\%Exergy\,\mathrm{Re}\,quired}{Task\%ExergyAvailable} = \left(1 - \frac{Task\%ExergyDestroyed}{Task\%ExergyAvailable}\right) \tag{38}$$

Some traditional exergy efficiencies (Moran, 1982) will use the form:

Exergy Efficiency = (First law efficiency) x (Second Law Efficiency) or

Exergy Efficiency = $(\eta_I)\ x\ (\eta_{II})$ (39)

This form is sometimes called the “Total Energy or Exergy Efficiency”. This form is convenient and allows the system first law efficiency to be substituted for the heat energy input and loss values. However, the aggregating of the efficiency terms looses a degree of freedom of information contained in the second law term (η_{II}). The ERDT de-couples and highlights the exergy efficiency term separate from the first law efficiency term and calls it the exergy utilization efficiency (ε_u). This type of exergy efficiency ratio is demonstrated in some literature (Ahern, p.77, 1980) but is not specifically labeled.

This separation of the efficiency terms leads to some informative relationships between the first law and exergy efficiency ratio terms. For example, it is now possible to have an exergy utilization efficiency ratio with a value higher than the first law efficiency. This is because the exergy utilization efficiency is now simply describing how *well* the task utilizes energy, not the *quantity* of energy (exergy). This does not violate the fact that the *process* second law efficiency will still always be equal to, or lower than, the *process* first law efficiency[21]. The ERDT needs this independence of the two efficiency terms for the prescriptive deliverables described later.

Within the task efficiency category the engineer could use the practical (existing technology) minimum theoretical energy or the absolute minimum physical energy needed to accomplish the task. The ERDT analysis is sometimes used with practical minimum energy and exergy coming from existing technologies (processes) when the absolute (theoretical) physical minimum energies become very small (<1.0E-6 joules) and are difficult to calculate. This is a compromise but makes the task efficiency calculations manageable and more realistic for this research.

Steady State Thermal Systems

These systems basically are assumed to be operated at one set of temperatures that do not change throughout the process[22]. A typical example would be a furnace processing parts. The parts are loaded into the furnace and heated for some time at constant temperature and then removed.

As mentioned above, comparison of thermal efficiencies against the optimum possible involves comparing the process under question against the Carnot cycle. Revisiting equations 15 and 16, the relationship for the amount of work possible in a completely reversible (Carnot) cycle is given by:

$$W_{REV} = Q\left(1 - \frac{T_{OUT}}{T_{IN}}\right) \tag{40}$$

---

[21] Notice that when the terms are coupled, the second law efficiency is forced to be either equal to, or less than the first law efficiency.

[22] This assumption is a simplification that would not hold for some furnace systems.

Examination of equation 38 shows that even for the perfectly reversible Carnot cycle, a heat engine will not be able to produce 100% work for the heat energy added if there is any difference in temperature between the higher temperature source and cooler sink (which there will always be). Another way of stating this is if there is any heat rejected at T_{OUT} the cycle will be less than 100% efficient in producing work. The closer the input and output temperatures become the less work the system can produce. Intuitively, this makes sense. A heat engine needs a ΔT to produce work.

Delivery of thermal energy at a (use) temperature T_u from an energy source at temperature T_s, while both T_u and T_s may be different than T_0.

This is the thermal exergy equation usually used by the ERDT for process heating system descriptions. Both use (e.g., oven temperature) and source (e.g., natural gas flame) temperatures are different than the dead state T_0 (usually ambient temperatures). An example of this type of system (Moran, p. 92, 1982,) would be a boiler with an adiabatic flame at T_s producing steam at a saturated temperature of T_u. The steam is then used in the manufacturing process. Because this is a thermal transfer system there is no shaft work, just heat transfer and therefore:

$0 = \dot{Q}_s - \dot{Q}_u - \dot{Q}_l$ expanding terms

$$0 = \left(1 - \frac{T_0}{T_s}\right)\dot{Q}_s - \left(1 - \frac{T_0}{T_u}\right)\dot{Q}_u - \int_{\wp}\left(1 - \frac{T_0}{T_l}\right) q_l \, d\wp - \dot{I} \tag{41}$$

where $\dot{Q}_l$ equals heat energy losses

Because this system is at steady state, the expression reduces to:

$$\varepsilon = \frac{\left(1 - \frac{T_0}{T_u}\right)\dot{Q}_u}{\left(1 - \frac{T_0}{T_s}\right)\dot{Q}_s} \tag{42}$$

The first law efficiency for this system is simply:

$$\eta = \frac{\dot{Q}_u}{\dot{Q}_s} \tag{43}$$

The exergy efficiency (equation 65) now reduces to:

$$\varepsilon = \eta \frac{\left(1 - \frac{T_0}{T_u}\right)}{\left(1 - \frac{T_0}{T_s}\right)} \tag{44}$$

The exergy utilization efficiency for this type of process is:

$$\varepsilon_U = \frac{\left(1 - \frac{T_0}{T_u}\right)}{\left(1 - \frac{T_0}{T_s}\right)}$$

Time-Dependent or Compound (Non-Steady State) Thermal Energy Problems

In this case the amount of heat energy entering or leaving the control surface is changing over time. A classic thermodynamic textbook example (Cengel, Boles, 1998) of this situation is a hot mass of metal left in a room to provide heat in the space. From a first law perspective all of the heat from the cooling metal mass above the dead-state temperature is transferred into the space and therefore η = 100%:

$$\eta = \frac{Q_{out}}{Q_{in}} \tag{45}$$

However, from a second law or exergy point of view, the availability of the heat energy is decreasing over time as the metal mass's temperature begins to approach the ambient temperature. Recalling that second law heat efficiencies are compared to the reversible Carnot cycle as the quantitative measurement of how much work *could* have been done, a rate based analysis is used with the Carnot cycle.

$$\delta W_{rev} = \eta_{thermal} \cdot Q_{in} = \left(1 - \frac{T_{\sin k}}{T_{source}}\right)\delta Q_{in} = \left(1 - \frac{T_0}{T}\right)\delta O_{in} \tag{46}$$

$$W_{rev} = \int \left(1 - \frac{T_0}{T}\right)\delta Q_{in} \tag{47}$$

The exergy ratio efficiency would be:

$$\varepsilon = \frac{W_{rev}}{Q_{in}} \tag{48}$$

The exergy utilization efficiency is:

$$\varepsilon_U = \frac{\Delta Availability}{W_{total}}$$

As has been discussed, exergy calculations involving thermal energy are compared to the reversible Carnot cycle as the reference standard for calculating efficiencies. Some authors have suggested the possibility of using heat pumps with high coefficients of performance (COP) as a reference (Cengel, Boyles, 1998) for exergy efficiency ratios. This research acknowledges this possibility but keeps the Carnot cycle as the reference system.

Electrical (Non-Thermal Primary Tasking)

In theory, electrical and mechanical energy can be completely converted to useful work (Cengal, Boyles, 1998). The efficiency equations are comparing an electrical work process against a theoretically perfect electrical motor. In the case of electrical motors, this is not a significant stretch of the imagination. Large electrical motors can have first law efficiencies approaching 99% (Lobodovski, et al, 1989).

In the case of electrical and mechanical devices, the second law efficiency is essentially the first law efficiency. However, exergy analysis examines the losses (irreversibilities) such as heat loss due to wire resistance for better engineering analysis and optimization.

The first law equation is:

$$\Delta U(energy) = W_e - Q_l \qquad (49)$$

The second law equation demonstrates that the change in availability (exergy) is the electrical work input W_e (first law) minus the heat transfer Q_l given off by electrical wire resistance. The irreversible losses I_e within the device during operation such as copper and iron losses (Sakamoto, et al, 1994) are broken out separately for analysis:

$$\Delta Availability = W_e - \int \left(1 - \frac{T_0}{T_l}\right) \delta Q_l - I_e \tag{50}$$

Therefore, the exergy utilization efficiency equation for electrical/mechanical devices is:

$$\varepsilon_{eU} = \frac{\Delta Availability}{W_e} \tag{51}$$

Some research has indicated that digital information, as the product, could also be analyzed with exergy analysis methods. The concept of information entropy (Lin, 1991) has been suggested. This definition however is outside the scope of this research.

Mechanical Energy

Mechanical energy, in theory, can be completely converted into work. Therefore the first and second law analyses and efficiencies are essentially the same except for the breakout of the process irreversibilities in the exergy analysis. Irreversibilities such as friction-generated heat are highlighted for analysis. Mechanical energy follows the same logic as the electrical energy example above:

The first law mechanical energy equation is:

$$\Delta U(energy) = W_m - Q_l \tag{52}$$

The second law mechanical energy equation is:

$$\Delta Availability = W_m - \int \left(1 - \frac{T_0}{T_l}\right) \delta Q_l - I_m \qquad (53)$$

Combining the first and second law equations gives the exergy efficiency term for the mechanical systems:

$$\varepsilon_{mU} = \frac{\Delta Availability}{W_m} \qquad (54)$$

Chemical Energy

The chemical availability analysis is complex and is based on the detailed analysis of the energies and availabilities of products and reactants. Chemical exergies are determined using entropies and enthalpies of the many species involved before and after chemical reactions. The derivations follow the same logic as the Thermal Second Law Calculations above. In general, the equation for exergy or available energy at a particular state is (Ahern, 1980):

$A_i = (U + P_0 V_i - T_0 s_i) - (U_0 + P_0 V_0 - T_0 s_0)$, where " X_0 " is the property at the dead state (Ahern, 1980). (55)

Neglecting kinetic and potential energies and letting $h_i = U_i + P_i V_i$ gives the familiar exergy equation (31):

$$A_i = (h_i - h_0) - T_0 (s_i - s_0)$$

This expression must be analyzed for all species involved in the chemical reaction. For example methane C_2H_4 reacts exothermically with oxygen in the presence of air (O_2, N_2). To perform a detailed exergy analysis on this reaction the availability of all the corresponding chemical species before and after the reaction would need to be calculated. For this simple example the species would be:

C_2H_4

CO_2

O_2

N_2

H_2O

Fortunately, many industrial chemical reactions involve producing thermal energy as the main desired effect (e.g., combustion). For these problems the Carnot exergy relationship can provide the ERDT the needed information. It is left for future research to examine detailed chemical exergy relations.

This section now uses the combustion of a fuel to generate thermal energy as a simplified example to show the derivation of exergy efficiency ratios central to the ERDT methodology. An example is worked below in the Examples of Typical Industrial Process Exergy Efficiency Analysis.

A restated form of the traditional first law efficiency for fuels can be written as:

$\eta =$ (mass flow rate of media x change in enthalpy)/(fuel flow rate x fuel heating value)

$$\eta = \frac{\dot{m}_s\left(h_e - h_i\right)}{\dot{E}_f} \tag{56}$$

Additionally, the second law efficiency for the fuel problem would have the following form:

$\varepsilon =$ (mass flow rate of media x change in availability) / (fuel flow rate x fuel heating value) or

$$\varepsilon = \frac{\dot{m}_s \left(\dot{a}_{fe} - \dot{a}_{fi}\right)}{\dot{A}_f} \qquad (57)$$

The exergy utilization efficiency is:

$$\varepsilon_{cU} = \frac{\left(\dot{a}_{fe} - \dot{a}_{fi}\right)}{\dot{a}_{fe}}$$

Examples of Typical Industrial Process Exergy Efficiency Analyses

The following are general second law efficiency ratios for several processes frequently encountered in manufacturing plants. For the detailed derivation of these forms, the reader is directed to Moran (1982).

Mechanical cutting of material from stock using electrical power

As mentioned above, electrical, mechanical (kinetic and potential) and some types of chemical energies are fully available to do work. Therefore, for these energy types, their energy content is equal to the exergy content. As in all such system descriptions, the placement of the system boundary is important.

For electro-mechanical systems in a manufacturing facility analyzed by the ERDT, the system boundary will include the electric motor, the mechanical working device, and the workpiece. The analysis does not consider the conversion of fuel or nuclear power to the electricity (point of generation).

The first law equation is:

$$\Delta U(energy) = W_e - Q_l \tag{58}$$

The second law (exergy) equation is:

$$\Delta Availability = W_e - \int\left(1 - \frac{T_0}{T_l}\right)\delta Q_l - I_e \tag{59}$$

Therefore, the exergy efficiency equation for electrical/mechanical devices is:

$$\varepsilon_{eU} = \frac{\Delta Availability}{W_e} \tag{60}$$

Because availability with electrical and mechanical systems is the same as the applied energy:

$$\varepsilon_{eU} = \frac{\Delta Availability}{W_e} = \frac{W_e - Q_l}{W_e} \tag{61}$$

The term Q_l is the loss associated with electrical resistance in the wiring and mechanical losses such as friction in the mechanical portion of the electro-mechanical device.

Heating of water with electric resistance heating

Energy is added to the water in the amount W_e. Some heat is invariably lost in heat transfer Q_l. The first law energy equation for this process is:

$$\Delta U = W_e - Q_l$$

A first law efficiency is described by:

$$\eta = \frac{\Delta U}{W_e} \quad \text{or} \quad \eta = \frac{mc\Delta T}{W_e} \tag{62}$$

The general exergy equation is:

$$A = (E - U_0) + p_0(V - V_0) - T_0(S - S_0) \tag{63}$$

The *change* in availability for a control mass has been derived as:

$$\Delta A = \int_1^2 \left(1 - \frac{T_0}{T_S}\right)\delta Q - (W - p_0\Delta V) - I \tag{64}$$

where $\int \left(1 - \frac{T_0}{T_S}\right)\delta Q$ is the flow of availability associated with heat transfer

and $(W - p_0\Delta V)$ is the flow of availability associated with work interaction

and I is the reversibility associated with the destruction of availability or creation of entropy for the control mass and environment $I = T_0((S_0 - S) + \Delta S^0)$.

Because the availability of the work input with electricity is 100%, the W_e term is included in the availability equation. Therefore, the availability or second law equation for the water heating process is:

$$\Delta A = W_e - \int \left(1 - \frac{T_0}{T_l}\right) \delta Q_l - I \tag{65}$$

The second law efficiency form is:

$$\varepsilon = \frac{\Delta Availability}{W_e}$$

(61)

Evaluating ΔA for an incompressible fluid gives the following expression for ε:

$$\varepsilon = \frac{mc\{\Delta T - T_0 \ln[(T_i + \Delta T)/T_i]\}}{W_e} \qquad \text{or}$$

$$\varepsilon = \eta \left[1 - \frac{T_0}{\Delta T} \ln\left(\frac{T_i + \Delta T}{T_i}\right)\right] \tag{66}$$

The exergy utilization efficiency is:

$$\varepsilon_U = \left[1 - \frac{T_0}{\Delta T} \ln\left(\frac{T_i + \Delta T}{T_i}\right)\right]$$

(67)

Combustion (fuel chemical) availability

In-depth exergy analysis of the combustion process involves examining the various chemical availabilities of the products and reactants involved. Typically, hydrocarbon fuels mixing with air or oxygen and producing exothermic reactions with by products are the activities involved in these processes. As discussed later, complete break down and analysis of the various exergy streams of reactants and products is justified once potential opportunities are identified. For example, the physics and chemistry of combustion produces irreversibilities (losses) on the order of 10-20% of the incoming fuel energy content (Ahern, p.74-75, 1980). However, for the initial ERDT methodology, the following simplified exergy analysis will suffice. The engineer will need to keep in mind that the actual second law exergy efficiencies will be even lower than calculated due to the combustion irreversibilities.

An accepted simplification in combustion exergy analysis is the use of a fuel's lower heating value (LHV) as an approximation of the fuel's chemical availability for processes not recovering the latent heat of water vaporization (Moran, 1983).

If $\overline{Q}$ is the heat transfer per mole of fuel consumed at T_s then the first law efficiency for the combustion heat energy source is:

$$\eta = \frac{\overline{Q}}{LHV} \qquad (68)$$

The exergy efficiency will be the ratio of the availability of the combustion process to availability of the fuel consumed:

$$\varepsilon = \frac{\left(1 - \frac{T_0}{T_s}\right)\overline{Q}}{Avail_{fuel}} \quad \text{where } Avail_{fuel} \approx LHV \quad \text{Therefore:}$$

$$\varepsilon = \eta\left(1 - \frac{T_0}{T_s}\right) \tag{69}$$

The exergy utilization efficiency for this class of processes is:

$$\varepsilon_U = \left(1 - \frac{T_0}{T_s}\right) \tag{70}$$

Comparison of Minimum Exergy (Availability) Required to Patent Steel in Example (Exergy Task Ratio)

The patent oven is using a natural gas flame to heat treat the metal at a temperature different from the ambient temperature (obviously). Examination of the various exergy ratio equations shows that equation 71 is suitable for this process.

$$\varepsilon_U = \frac{\left(1 - \frac{T_0}{T_u}\right)}{\left(1 - \frac{T_0}{T_s}\right)} \tag{71}$$

For the patent oven, η = 0.115 from the 1st law analysis in Step 2 above. The engineer simplifies the oven analysis by assuming the adiabatic flame for methane is 2,200 °K (T_s = supply temperature), the annealing processes (T_u = utilization temperature) is 1,243 °K, and ambient (T_0 = ambient temperature) is 306 °K. In addition the analysis assumes an ideal gas.

Therefore: $$\varepsilon_U = \frac{\left(1-\frac{306K}{1,243K}\right)}{\left(1-\frac{306K}{2,200K}\right)} = \frac{0.75}{0.86} = 0.87$$

This exergy **(** ε_U **)** calculation indicates that 87% of the initial available energy (exergy) of the incoming fuel is available for the task of annealing. The remainder of the availability is wasted in the combustion process, heat escaping the oven, and other irreversibilities. An interesting note is that the first law *(*η*)* efficiency term from Step 2 for this process is very low (11.5%). While the first law analysis points to the inefficiency of the process, the exergy analysis indicates the natural gas is a good energy source selection for the task. That is, the use of natural gas (or methane) to provide the high temperature needed for the process is a good use of this fuel. However, the oven is so poorly designed, constructed and operated that the process is significantly inefficient overall. This is a good example of why the second law or exergy term is separated from the first law term. In this case the first law efficiency is very low and would drag down the product of the first and second law terms. By separating the terms the engineer can observe that the fuel (energy type) selection is good for the processes, however, the implementation of the technology is poor.

Step 4 produces an exergy efficiency ratio that relays considerable information to the engineer. Specifically, the following benefits are derived from the exergy analysis:

1) The degree to which the energy source is matched to the energy need (process). The exergy ratio analysis quantifies this matching and demonstrates where fuels and energy sources are possibly misapplied.
2) Construction of a process ranking scenario based on magnitude of exergy ratio. This second ranking (after the Step 3 ranking) leads the engineer to decisions regarding the handling of the processes.
3) Possible matching of waste energy streams to other process energy input streams. During the exergy efficiency calculation the engineer is aware of the quality, or availability, of various waste energy streams. Only with this information can waste energy be matched to energy needs of other processes in the plant. First law analysis does not provide this information.

Final Ranking and Decision Support Analysis

After completion of the first three steps of the ERDT, the engineer now has a set of ranked processes and two energy indicators ($\boldsymbol{\eta}, \boldsymbol{\epsilon_u}$) which can be used in combination to make specific determinations regarding energy usage project selections. While this early incarnation of the ERDT is an energy characterization and energy project selection diagnostic method, the final goal of energy management auditing is usually the improvement of process profitability and effective energy utilization. Therefore, an examination of how the ERDT can lead to actual process improvement recommendations is examined below.

The combined first and second law analysis and ranking information leads to the final phase of the ERDT in which the engineer is directed toward possible energy usage opportunities such as waste energy recovery or determination that entirely new process designs should be considered (e.g., replacement). The methodology should also be of interest to design engineers wishing to match processes as effectively as possible. From the patent (heat treat) oven example in which the first law efficiency is low but the second law efficiency is relatively high (see Table 9) the engineer might draw several conclusions about this process from Steps 2 and 4:

1) Using a hydrocarbon fuel for this task is effective from an availability (exergy) point of view (Step 3).
2) The current design of the oven does not utilize the energy or exergy efficiently (Step 2).
3) Recovering waste heat, while certainly abundant, is probably not the ultimate solution for this process (Step 3).
4) A complete process redesign or alternative process is indicated (Steps 2 and 3).

Using conclusion number four above, the engineer and company might decide to examine an alternative process. Considering the volatility of natural gas prices and the gross inefficiency of the oven, a good solution may be to examine a completely different technology for the annealing process such as induction heating.

Using the ERDT analysis the engineer can examine the other processes identified in the process characterization piece (Step 1). Demonstrated below is an example of what such an analysis might present to the engineer (Table 9). Most of the values are estimated and used for demonstration only. See the conclusion for a further explanation of Table 9.

Activities	Energy Type	1st Law Energy Efficiency (η) Percentage	2nd Law Exergy Utilization Efficiency (εu) Percentage
Decoiling	Electrical	6.9	5.3
Rod Mill Diameter Reduction	Electrical	6.1	5.1
Heat Treat Anneal Oven	Natural Gas	11.5	87.2
Lead Bath Quench	Natural Gas	25.3	18.8
Chemical Baths	Natural Gas	79.5	8.4
Air Knife Drying	Electrical	0.7	7.0
Coiling (Packaging)	Electrical	20.1	18.1

░ Low 1st Law
▨ Low 2nd Law

Table 9. (η & ε_U - Efficiency Table) Comparison of the processes and their respective efficiencies.

Step 4 Summary:

Example Process Energy Project Selection and Recommendations

Given the processes that were ranked as important in Step 3; the engineer now examines the exergy efficiency table generated in Step 4. Not surprisingly, the three processes with the lowest overall exergy efficiencies are also the top ranked opportunities identified previously in Step 3.

The efficiency table (Table 9) gives additional clues as to what to do with the identified opportunities (processes). The table was constructed to show how the individual efficiencies such as the first law (η), and the second law exergy utilization ratio (ε_U) do not give complete energy opportunity recommendations by themselves.

For example, the first law efficiency column (η) indicates that the patent heat treat oven is very inefficient and that the chemical baths are very efficient. This conclusion is only partially correct. The second law efficiency column indicates that the anneal oven is actually a good match between fuel/energy type and task while the chemical baths are not.

The final selection process is to identify the energy project opportunities by examining the combination of energy and exergy efficiency ratios. Where there is a large discrepancy between the energy and exergy ratios – opportunities exist.

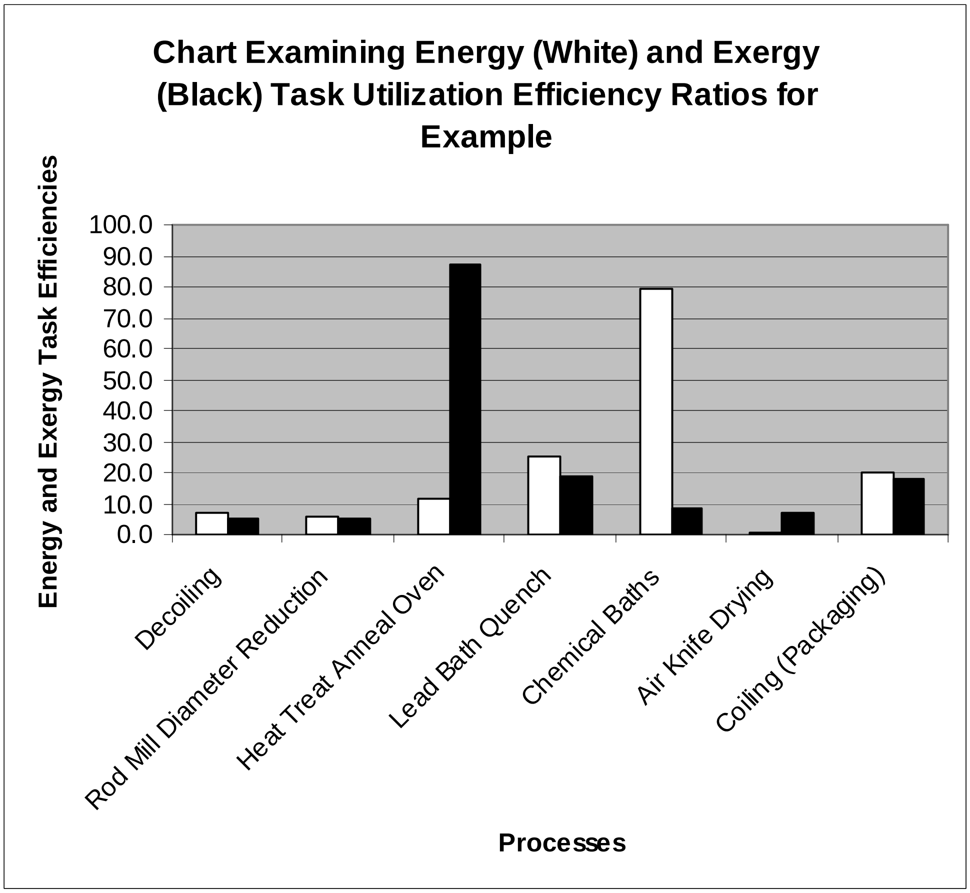

Figure 20. Top process candidates for energy management action based on exergetic efficiencies.

The task is now to decide how to approach the examined processes (Figure 20) for improvement. In this case, the first and second law efficiencies noted in Table 9 provide direction. Specifically, rules for process opportunities appear as follows:

ERDT Decision Rules

1) If 1st law efficiency is low:
    a. And 2nd law efficiency is high – Consider alternative process or redesign. (Process is matching energy effectively but design or implementation is poor) – ***Patent Oven***.

    b. And 2nd law efficiency is low – Consider new process.(Poor process design is wasting high quality energy/exergy) – ***Air Knife Drying***

2) If 1st law efficiency is high:
    a. And 2nd law efficiency is high – Process may be adequate for task – (Relatively) ***Coiling/Decoiling***
    b. And 2nd law efficiency is low – Process is wasting high quality energy (Consider using waste energy/exergy recovery and improvement of current process) – ***Chemical Baths***

An interesting observation of the above analysis is that the air knife drier is a process much in need of complete process change. While the air knife drier doesn't use nearly the energy that the patent oven does (see Table 9), it is such an inefficient process from both the efficiency and energy use effectiveness, it should be addressed immediately. In the original IAC energy audit at this facility, this process was not addressed with a recommendation due to time work-load constraints.

While the patent oven is properly matching an energy source (high temperature flame from natural gas) to the transformation task, the operation is so poorly designed, or operating in applying the energy to the product, that the operation needs to be dramatically redesigned or the plant should consider using an alternative process altogether.

The chemical baths are a classic example of why the second law and exergy analysis tell the engineer more about what is happening in a process than just first law energy analysis. In this case, the burner efficiency on the chemical baths is relatively high (79.5%). However, the low temperatures required for the baths (approximately 77°C) is much lower than the adiabatic 1,649°C flame provided by the burners. Exergy analysis and the ERDT point the engineer to investigate a better match between energy source and end-use. The chemical baths would be good candidates for using lower exergy waste heat from another process instead of high quality fuel (see next section below). Therefore, the three processes the ERDT has highlighted for further study are:

1. Patent Heat Treat Oven
2. Chemical Baths
3. Air Knife

Matching Process Exergy Waste Streams to Needed Exergy Inputs in Other Processes via Pinch Analysis and Process Integration

One of the advantages of using exergy or second law analysis is the ability to match waste exergy streams of some processes with exergy input requirements of other processes. Unlike first law energy analysis that simply describes the energy content of a waste stream, exergy analysis describes the energy "value" or availability of the waste stream.

This is the point at which the ERDT would hand off the calculations to process integration or pinch analysis. Once the candidate processes have been identified by the ERDT methodology, the processes can now be further matched (output waste energy and required input energy) by the "cascading" method of pinch analysis mentioned in the literature review section. This research will not provide a full pinch analysis but will use an abbreviated version to demonstrate the technique. Full integration of the ERDT and Pinch/Process Integration is left for further research.

As mentioned previously, all heat streams have some energy content. However, exergy analysis demonstrates that for the thermal energy to have value, it must be at some temperature above a reference condition. For example, there may be a waste heat energy stream coming off of a process air drier that can be recovered at 65 °C. This air stream may have sufficient mass flow rate to provide many kilojoules of energy per hour. Consider the possibility of using this significant source of waste energy to heat the chemical baths. In this example, the chemical baths operate at 70 °C (reference temperature). It should be quickly apparent that even though the energy content of the waste stream is significant, the quality, or value of this energy with respect to the chemical baths is zero (actually negative) because the temperature of the waste stream is cooler than the temperature requirement of the chemical baths. This is easily demonstrated using the exergy equation (31) for the two air streams[23]:

$$Exergy = \left(h - h_0\right) - T_0\left(s - s_0\right)$$

Where:

h = Air stream enthalpy at temperature T (65 °C, 338 °K)

h_0 = Air stream enthalpy at temperature T_0 (reference 70 °C, 343 °K)

T_0 = Temperature at reference conditions

s = Air stream entropy at temperature T (65 °C)

s_0 = Air stream entropy at temperature T_0 (reference 70 °C)

---

[23] Results would be the same for fluids.

Using air as the working fluid and air properties tables (Cengal, 1998, p923):

Exergy Avail. = (338 KJ/Kg – 343 KJ/Kg) – (343 °K)(1.83 KJ/Kg-K – 1.80 KJ/Kg-K)

= - 5 KJ/Kg – 10.3 KJ/Kg = **-15 KJ/Kg**

The negative answer indicates there is a net exergy (energy) loss in this energy stream exchange. Therefore, the waste energy from the driers *cannot* be used to heat the chemical baths. However, waste heat energy streams with recoverable temperatures above 70 °C are viable candidates. A first law analysis would not have indicated this energy value or quality problem.

Because the ERDT uses second law analysis, it is also capable of matching waste energy to input energy requirements in other processes. This allows the engineer to examine the ERDT processes analyzed and determine if there is a possibility for waste energy re-use within the facility.

In the case of the three processes identified by the ERDT for further study, the engineer may wish to determine if there are any opportunities to use waste exergy from one process to run one of the other processes. Examination of Figure 15 and the ERDT decision rules for this example show that the patent heat treat oven has a high exergy potential that is being largely wasted (exhausted gases) due to equipment inefficiencies (first law analysis), while the chemical baths have fairly efficient equipment but are using a high quality fuel (natural gas) ineffectively (low exergy ratio). Therefore, a potential match exists between the patent oven’s waste heat as an energy source for the chemical baths. An expanded analysis of the exergy input and output of these processes is used to make this determination. A worked example of this type of analysis is provided with the case study example in Chapter IV.

The use of exergy analysis to match process exergy waste and requirements can be visually displayed in simplified form using exergy flow diagrams (Wall, 2003). As shown in Figure 20 below, there may be an opportunity to recover the waste exhaust gas exergy from the heat treat oven to use as the exergy source for the chemical baths.

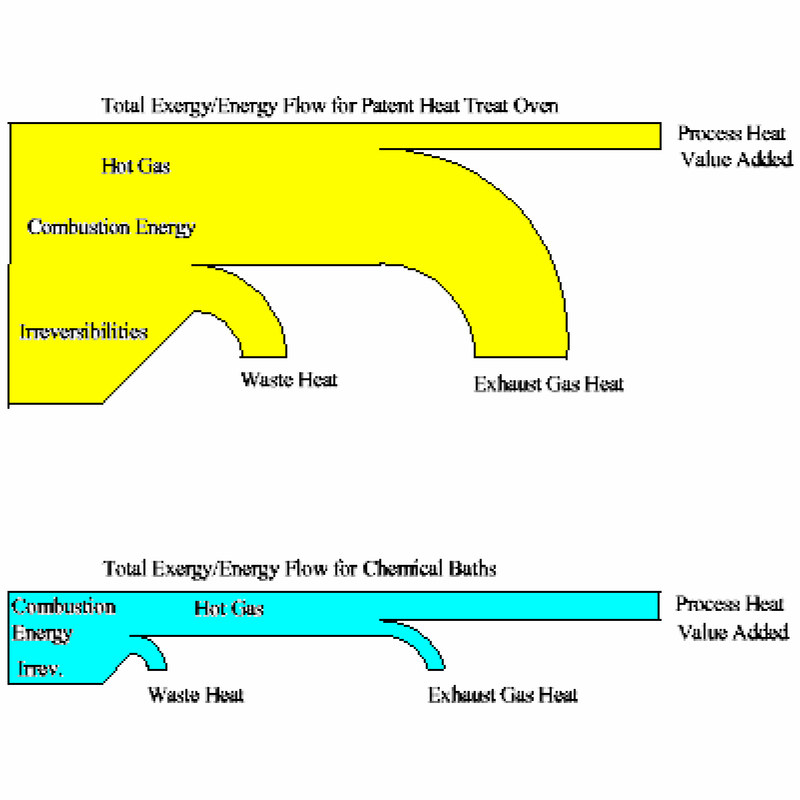

Figure 21. Total exergy flow diagrams for two heat processes

Expansion of ERDT Methodology

In the expanded form of the ERDT's method (see Chapter V on further research) the engineer would actually calculate the exergy components of the energy streams in detail. For example, in the combustion process, the energies of all of the inputs and output (chemical species) would be calculated (Barclay, 1998). This information would then point the engineer directly to the specific areas of opportunity (even within the process). This analysis of waste streams also points to environmental studies using exergy and the ERDT. As expanded in the future research section, the extension of the ERDT to include environmental analysis is logical.

CHAPTER IV. APPLICATION OF METHODOLOGY

Introduction

In order to demonstrate the technical and operational perspectives for validation of the ERDT, the research methodology is applied in an actual manufacturing plant setting. The selected facility had a traditional OSU-IAC audit with recommendations performed previous to the application of the ERDT. The traditional IAC audit for this plant will be briefly described after the demonstration of the ERDT. The ERDT methodology and identification of energy management opportunities at this particular plant are then compared to the traditional IAC audit and results.

In addition, the compatibility of the ERDT with the traditional IAC energy audit is examined. This coupling of older and newer techniques is done to illustrate the usefulness of the ERDT.

Application of ERDT to Manufacturing Facility

The manufacturing facility in Claremore, Oklahoma, manufactures piston pins for a variety of applications, and was selected for the ERDT case study because of several factors:

- The plant had a combination of electrical and natural gas energy utilizing processes
- The processes include thermal and mechanical applications

- The process’s energy usage was significant (compared to assembly operations which have comparatively low energy requirements, for example)
- The plant management was receptive and helpful with the research
- Some of the processes are metered or have fuel flow indicators
- Most of the processes and equipment are well documented
- A previous OSU-IAC audit exists with which to compare audit methodology results

The same facility had received a traditional energy audit by the Oklahoma State University Industrial Assessment Center in February 26, 2003, which is described later.

Site Visit Plant Tour

The site visit begins in the same manner as a typical OSU-IAC energy audit. The ERDT can be considered an extension of the traditional energy audit as the plant tour and billing analysis portions of the methodologies are the same.

The author met with the plant manager and explained the nature of the research. The author discussed the basic processes of manufacturing the finished piston pins starting with blank steel rods. The plant manager verbally explained the flow of the material as it proceeded from process to process while using plant floor layouts to demonstrate the location of major processes.

After the verbal facility flow description the plant manager gave the author a walk-through plant tour. The manager would stop at each major process and explain some of the salient characteristics of the process or equipment. The author would take notes as needed. The plant manager and author returned to the office spaces to discuss and clarify parts of the tour.

This company makes a wide variety of piston pins. However, one type of pin makes up the majority of the product sold. It was agreed to track the manufacture of this "representative" pin through the processes in order to simplify the case study.

Process Details

At this point, the author was allowed to return to the shop floor to make detailed observations of the processes, equipment and material flows. The author would measure energy flows where possible for the various processes or take enough observation notes to be able to make viable estimates. The author also used this opportunity to take physical measurements of equipment. The author recorded energy-related data for the processes such as:

- Infrared images of thermal systems
- Natural gas sub-meter reading for carburization oven
- Natural gas and air flow measurements for carburization oven
- Power ratings for electric motors driving:
- Air Compressor
- Metal Working Equipment
- Blowers
- Loading information for various pieces of equipment (Digital Loggers)

Product Details

In a subsequent visit the author visited with the plant process engineer and quality manager. One key to using the ERDT is a detailed understanding of the science of the material transformations occurring to the work-piece as it becomes a finished product. The author was given a verbal description of the various transformations and directed to literature describing the details of others (Atmosphere Furnace Company, 1975).

Once equipped with the material science information and the process descriptions, the author was ready to apply the ERDT methodology. What follows is the actual case study starting with a brief description of the company, a description of the product, the science of the transformations, a process description, and finally application of the ERDT. In the next chapter the ERDT results will be compared to the previous OSU-IAC energy audit performed at this facility.

Facility Background

This company, located in Claremore, Oklahoma, primarily produces piston pins for diesel engines in the automotive and truck markets. The plant, with 70 employees, is in production 24 hours per day, seven days per week. The company's annual sales are estimated at $16 million and annually produce 6 million piston pins.

The facility covers approximately 9,569 square meters and is composed of the following areas:

- 9,290 square meters of plant area
- 186 square meters of administration area
- 93 square meters of waste storage area

Process Description

Raw material is received in the form of solid steel bars (AISI 5120[24]) and stored on the bar steel racks in the loading bay area. When a customer order is received, the steel bars are moved from the storage racks into the adjacent machining department where they begin the processing. For this report, the processes begin at the first process beyond storage. In the actual plant, there are four alternative machining operations for the different types of piston pins. For this report, a "typical" pin is tracked through the process for simplification.

The machining processes begin by sawing the long steel bars into the appropriate size piston pin blank at the cold cut-off saw station(s). Here, the 244 cm long blank bars are cut to 9 cm length slugs. The accumulated slugs are then taken to the coating area on the East side of the plant. In this area, the pin blank slugs are coated with a zinc-phosphate chemical by immersion in a series of heated chemical and rinse tanks. This coating is used as a dry lubricant for the subsequent forging process.

The coating process also imparts a slight surface annealing to the blank slugs. The coated slugs are transported to the holding queue for the extrusion process. The zinc-phosphate coated pins are then extruded in the extrusion press. In this operation, two large end holes are placed horizontally through the center by opposing dies of the pin as the pin's overall length increases. This extrusion process also imparts a strong grain structure in the pins. The piston pins are then processed through the web drilling and end-pointing stations.

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[24] American Iron and Steel Institute

After the machining operations, the pins are transported to the heat treat department for further hardening, strengthening and stress relief. The first of the heat treat processes is carburization treatment. In this operation, the pins are heated to approximately 900°C in the presence of a controlled carbon-rich atmosphere. The carbon diffuses into the outer layer of steel giving the desired hardness and other characteristics. The carburizing furnaces have integral oil quench baths. The entire movement of pins on racks through the carburization oven and quench bath is automated. The typical residence time for a batch of pins in the oven is 24 hours. On average, one rack of pins is added and discharged from the oven every 20 minutes.

The carburized pins are transported to the draw furnaces. This operation relieves surface stresses that build up in the pins from the carburization process. The pins residence time in the draw ovens is 8 hours.

The pins are next sent to the de-scaling operation. In this process, the ends of the pins are shot-peened by high pressure air streams delivering abrasive steel media. The pins are then transported to the lap line area where the surfaces of the pins are lap honed by high-precision finish grind machines to a mirror finish. The finished piston pins are inspected before being automatically packaged and stocked in finished goods inventory. Figure 22 demonstrates a basic flow diagram of the processes. Table 10 demonstrates a partial processes matrix for the same processes shown in Figure 22.

Step 1: Process Characterization

Facility Process Flow Diagram

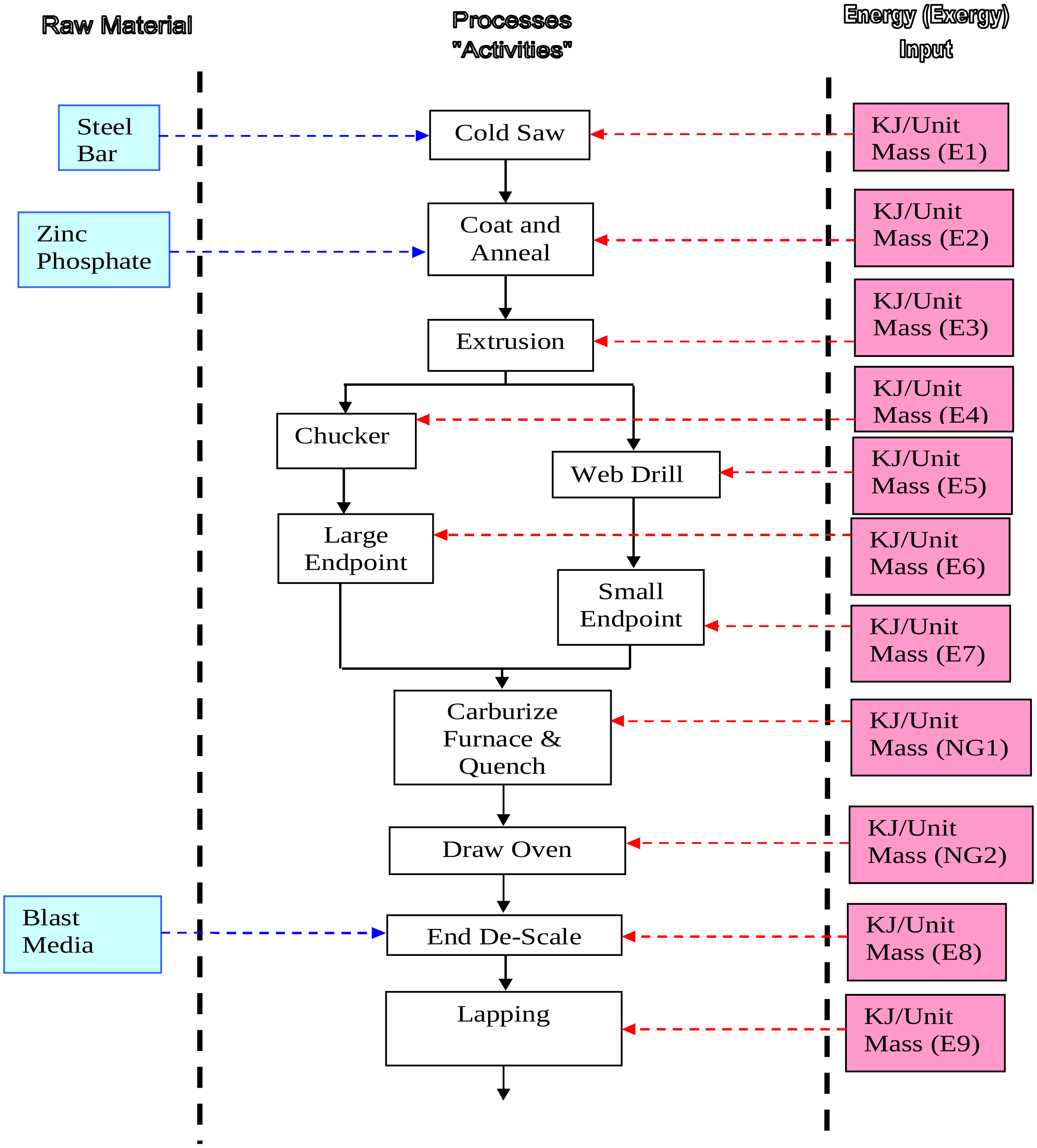

Figure 22: Process flow chart

Process Matrix

Activities	Principle	Technology	Energy Type	Energy Application	Desired Activity Outcome	Activity Physical Leverage	Fundamental Energy Task	Current Energy Leverage	Possible Recommendation Opportunity	Energy Unit Cost for Process (at time of study)
Decoiling	Un-wind from shipping spool	Un-wind with 19 KW motor through sets of straighteners	Electrical	19 KW AC Motors	Straighness of wire off of spools	Diameter of initial wire. Physical properties of wire. Speed of un-wind	Overcoming surface and internal structural energies of steel wire on spools	Motor Efficiency, de-coil machine design, wear	More efficient motors	$2.22E-5/KJ
Rod Mill Diameter Reduction	Pass through various rod mills	Stretch wire through series of spools (rod mills)	Electrical	DC Motors driving spools (rod mills)	Proper wire diameter reduction without breaking wire	Diameter of initial wire. Physical properties of wire. Speed of un-wind	Overcoming surface and internal structural energies of steel wire on spools	Motor Efficiency, machine design, machine wear	VFD drives on AC motor conversions, harder die material	$2.22E-5/KJ
Heat Treat Patenting Oven	Pass through 982 C Oven for 10-20 seconds	Heat wire to restore desired physical properties (initial process)	Natural Gas	NG Burners direct firing into oven space	Returning desired metal characteristics (initial)	Desired physical properties of wire. Speed of wire through activity	Heating mass of steel to desired temparature for desired residence time	Insulation levels, burner efficiency, oven design	Electric induction furnace	$7.58E-6/KJ

Table 10. Partial process matrix

It is the belief of the author that any physical process can be examined in the ERDT methodology. However, as mentioned in the ERDT Step 2 methodology section, some processes are difficult to analyze.

Metal working is a difficult process to analyze. With metal removal through cutting, grinding or other metal working processes, the minimum power requirements can be determined from long established tool equations such as (Machinery's Handbook, 1996):

$$P_c = K\ CQW \tag{72}$$

and

$$P_m = \frac{P_c}{E} = \frac{K_p CQW}{E} \tag{73}$$

Where the power required to cut, or machine, a material is dependent on the rate at which the material is being cut and upon an experimentally determined power constant K_p (unit power constant). The power is measured in Kilowatts. The power is equal to the kilowatts required to cut material at a rate of one cubic centimeter per second. The values calculated are for sharp tools. The K_p is unaffected by the cutting speed, depth of cut or the cutting tool material.

- The power constant (K_p) for carbon steel of Brindel hardness 150 is 2.02. (Oberg, page 1043, 1996)
- The feed factor (C) is between 0.72 and 1.70

- The machine tool efficiency factor (E) is between 0.70 and 0.90 depending on type of drive, belt, gears, etc. ((Oberg, page 1045, 1996)
- The tool wear factor (W) is between 1.00 and 1.60 depending on the type of operation ((Oberg, page 1044, 1996)
- The material removal rate (Q) equation and parameters depend on the type of operation.

While the various metal working equations can predict the minimum energy (power) needed to remove or process material, the analysis is hampered by the extremely variable load profiles of the metal working processes. Additionally, metal working operations consist of tool idle time while the component is positioned in the machine. Therefore, metal cutting and other forms of material working tie energy efficiency, or specific energy, to throughput. High throughput increases the amount of time the machining operations are actually cutting material versus standing idle.

Another important aspect of material working processes is that the support systems almost always use more energy than the actual transformation process. However, these support systems should be considered in a detailed analysis of the overall material transformation process. Examples of support systems include lubricating oil, coolant pumps and centrifuges. For simplification, these support systems were not examined in this study and left for further research.

As described by Gutowski and Dahmus (Dahmus, Gutowski, 2004), the actual energy consumed by the metal processing (e.g., cutting or grinding) can be less than 15%

of the total machining operation for a large machining center at Toyota. An energy breakdown for an automated milling machine is provided in Figure 23.

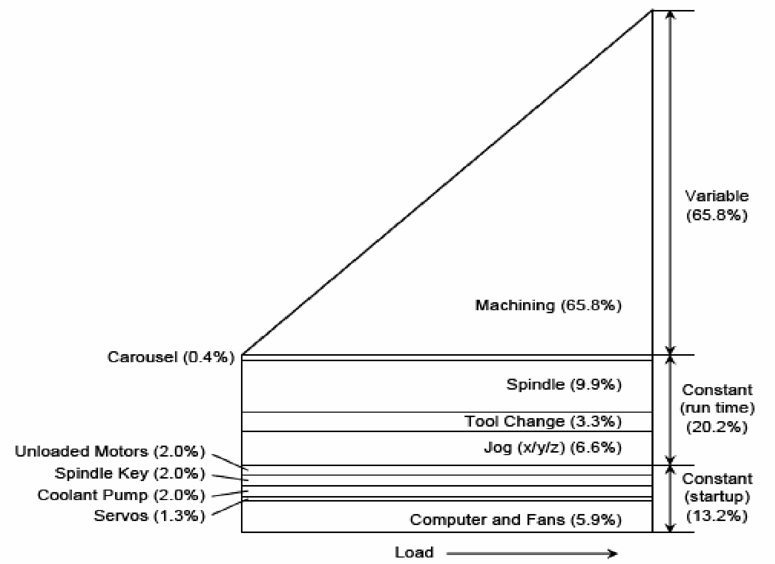

Figure 23: Machining energy use breakdown for a 1998 Bridgeport automated milling machine with a 5.8 kW spindle motor. Figure from Gutowski et al, 2006.

The important point from the above figure is that the support system's energy usages are constant while the machining energy is variable, dependent on throughput or load.

Case Study

Cold Saw:

Desired Activity Outcome – Single cut to produce slug

Activity Physical Leverage –	Diameter of steel rod	35 mm
	Length of steel slug	90 mm
	Mass of slug	0.67 Kg
	Slug Material	AISI 5120 Chrome Alloy Steel

AISI 5120 Chrome Alloy Steel Mechanical properties (Harvey, 1982):

Tensile Strength	2,240 Mpa
Yield Strength	2,030 Mpa
Compression Yield Strength	2,584 Mpa
Elongation in 50.8 mm	5%
Reduction in area	8%
Modulus of elasticity	203,300 Mpa
Density	7.74 g/cc
Hardness	HRC 60-66 regardless of size or grade Brinell 230

Cold Saw Machine Parameters:

Motor power: 8 KW

Cutting Fluid Pump: 1/3 HP = 0.249 KW

Support Systems (Lighting, various small motors) = 1 KW (estimated)

Total Cold Saw Potential Energy Demand: 9.3 KW

Process Rate: 1 cut every 9 seconds = 6.67 cuts per minute = 400 cuts per hour

Process Description

The cold saw operation cuts the piston pin blanks (slugs or billets) out of the AISI 5120 steel rods. These rods are approximately 5.5 meters long and 35 mm in diameter.

The rods are loaded onto the feed conveyor of the cold saw. The saw cuts one blank at a time. The blank length is approximately 90 mm. The saw takes approximately 9 seconds to perform an individual cut.

Energy Requirements for Cold Saw:

The main power source for the cold saw operation is an 8 KW alternating current electric motor determined from site visit nameplate inspection. This motor powers the band saw and part of the saw feed-conveyor mechanism.

Various other small motors, power fans, fluid pumps, and clamping devices contribute to a machine energy base load that is not considered for this report (see methodology Chapter III). In addition, there is limited task lighting available on the machine. The estimated power requirement for these support systems is 1 kW.

Calculation of energy requirements for Cold Saw:

- 1 each: Alternating current electric bandsaw drive motor, 8 KW.
- 1 each: Alternating current electric support motor, 0.5 KW.
- Various support systems (lighting, etc.), 0.5 kW.
- Estimated process load factor of cold saw: 50%
- Estimated loading of motor while cutting: 80%
- Estimated machine efficiency: 80%

Minimum Energy Requirement Calculation for Cold Saw:

The calculation of minimum energy requirements for the cold saw is based on the steel bar material properties and tool equations from a variety of accepted sources (Machinery's Handbook, 1996). Some of the parameters are assumptions and are stated as such.

All mechanical cutting tools share certain similarities in energy and power calculations. The characteristics or parameters that must be determined are:

- Empirically determined power constants (Kp) based on the type of material being removed
- Material removal rate (MRR, Q)
- Feed rate or feed factors (C), (mm/second, mm/minute, mm/tooth, etc.)
- Tool wear factors (W), (new-sharp, older-dulling)
- Cutting times

The equation for power at the cutting tool (saw) is:

$$P_c = K_p CQW = kW \tag{74}$$

and

$$Q = \frac{V}{60} w n_c d_t = {cm^3}\!\!\diagup_{\sec ond} \tag{75}$$

Where:

P_c = Power at Cutting tool

K_p = 1.91 for AISI 5120 steel

C = Feed Factor = 1.00 (assumed median value for sawing)

V = Cutting Speed = 67.1 m/s (MHB page 1061)

w = Saw width = 1.5 mm (assumed)

Average saw tooth spacing = 4.66 mm

n_c = Number of teeth engaged in work = number of teeth in parallel = 1

d_t = Depth of cut per tooth = 0.25 mm (assumed)

W = Tool wear factor = 1.0 (assumed sharp)

Q = (67.1/60)(1.5)(1.0)(0.25) = 0.42 cm^3/sec

P_{cmin} = (1.91)(1.0)(0.42)(1.0) = 0.80 kW = Theoretical minimum power needed for cold saw

E_{cmin} = Theoretical minimum energy needed for single cut = (0.80 kW)(9sec/3,600 sec/hr) = 0.0020 kWh/cut = 7.2 KJ[25]/0.67 Kg[26]= **10.7 KJ/Kg**

Estimated Actual Energy Usage for Cold Saw:

P_{cact} = Actual minimum power needed for cold saw = [(8 kW)(0.8)]/(0.8) = 8 kW

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[25] Converted from kWh

[26] Mass of slug

E_{cact} = Actual minimum energy needed for single cut = (8.0 kW)(9sec/3,600 sec/hr) = 0.020 kWh/cut = 72 KJ/0.67 Kg = **107.5 KJ/Kg**

First law efficiency for Cold Saw Process:

$$\eta_{ColdSaw} = \frac{E_{c\min}}{E_{cact}} = \frac{(10.7KJ/Kg)}{(107.5KJ/Kg)} = \mathbf{0.10}$$

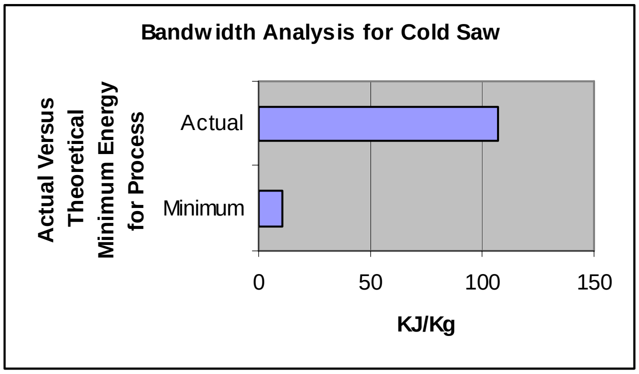

Figure 24. Bandwidth graph for cold saw process:

Lubricant Coating Line Baths:

Desired Activity Outcome – Coat slug with Zinc phosphate Coating

Activity Physical Leverage – Surface area of slug

Heat transfer rate to slug

Chemical properties of bath

Desired Speed of Operation

Diameter of steel rod = 35 mm

Process Description:

Cut steel alloy slugs are placed in permeable baskets. Each basket is a cylinder made of mesh steel that holds approximately 600 slugs. The basket is suspended on an automated overhead trolley that dips the slugs into various baths and rinses. As the basket is lowered into a particular bath, a chain drive mechanism slowly rotates the basket to agitate the steel slugs. After a programmed residence time, the basket is lifted and transported to the next chemical or rinse bath. The basket is again lowered and agitated. The heated baths use a combination of electric resistance heating elements, large electric water heater and portable circulating water heating/pump units. A typical sequence of baths would be:

1. Soap bath (remove cutting fluids)
2. Neutralizer Bath
3. Water Rinse Cold (ambient +)
4. Zinc Phosphate (coating bath)
5. Chemical Cleaner Bath

6. Hot Water Rinse
7. Hot Water Rinse
8. Sulfuric Acid Cleaner
9. Final Cold Water Rinse

After the final cold water rinse the slugs are uniformly coated with zinc phosphate and are placed in the queue for the extrusion press.

Energy Requirements for Lubricant Coating Line Baths:

- ➢ 18 each: Electric resistance heating elements (Process Tech., Inc.), 5 KW, 480 volts at 15 amps.
- ➢ 5 each: Electric resistance heating elements (Process Tech., Inc.), 15 KW, 480 volts at 25 amps.
- ➢ 1 each: 80 gallon vertical water heater, with two 4.5 KW electric resistance heating elements.
- ➢ 4 each: Portable circulating water heaters (Micro Therm, Inc.®), with 24 KW resistance heating elements and 0.75 HP (0.56 KW) pump motor.

  - Estimation of heater cycle times from data loggers: (25%)[27]
  - Process Rate: 4.4 minutes residence time per basket in each of the nine baths
  - Overall chemical bath cycle time: 40 minutes

---

[27] Data loggers were installed on bath heaters and load factors were determined from logger outputs.

- Process runs 24 hours a day.

Bath Container Specifications: (tanks #6 and #12 are unused)

Average heated chemical or rinse bath temperature = 170 °F = 77 °C

Average unheated chemical or rinse bath temperature = 80 °F = 27 °C

Assumed temperature drop of slugs between heated baths = 5%

Dimensions for tanks #2,3,4,7,8,9,10,11,13: 86.4 cm wide x 91.4 cm high x 124.5 cm deep

Fluid volumes in tanks #2,3,4,7,8,9,10,11,13: 86.4 cm x 81.2 cm x 124.5 cm = 873,452 cm^3 = 873.4 liters

Dimension for tank #5: 152.4 cm wide x 91.4 cm high x 124.5 cm deep

Fluid volumes in tank #5: 152.4 cm wide x 91.4 cm high x 124.5 cm deep = 1,734,205 cm^3 = 1,734.2 liters

Total chemical bath fluid volume: (8 tanks)(873.4 liters/tank) + (1 tank)(1,734.2 liters/tank) = 8,721.4 liters

With an assumed 5 percent temperature drop of the slugs between tanks, only the first tank (#2) experiences a significant drop in temperature due to the ambient temperature metal slugs (27 C) being introduced to the hot bath (77 C). The remaining heat loss in the tanks is due to heat loss transfer to the ambient air (environment) from the metal tank walls and exposed fluid surface. Only one of the tanks (#10) is insulated. The remaining tanks are bare metal walled with open tops.

Minimum Energy Requirement Calculation for Heating Metal Slugs in Tank #2:

45360 Slug Material: 5120 Steel Alloy

Change in temperature (ΔT) = 77 – 27 °C = 50 °C

Slug Dimensions: 90 mm Length, 35 mm diameter

Slug Volume: (90 mm)(17.5 mm)^2(3.1415) =86,590 mm^3 = 86.6 cc

Slug mass: (slug volume)(slug density) = (86.6 cc)(7.74 g/cc) = 670.3 g = 0.67 Kg

Specific heat (c_p) of steel in the 50-100 C temperature range: 490 J/Kg °C

Change in energy required for heating using specific heat: $\Delta u = \sum \bar{c}_p \Delta T$

Mass flow rate into baths: $\dot{m} = N\rho\dot{V} = N\rho A v$

Heat energy needed to heat slugs: $\dot{Q} = \dot{m}\Delta u = N\rho A v \Sigma \bar{c}_p \Delta T$

$\dot{m}$ = (600 slugs)(7.74 g/cc)(86.6 cc/slug)(1 Kg/1,000 g) = 402.2 Kg

Δu = (490 J/Kg °C)(50 °C) = 24.5 KJ/Kg

$\dot{Q}_{MIN}$ = (402.2 Kg)(24.5 KJ/Kg) = 9,853.9 KJ = 2.72 kWh

Estimated Actual Energy Usage for Heating Metal Slugs in Tank #2:

Heating element power rating: 15 kW

Estimate of percentage of time electrical resistance element on (Load Factor) from logger data: 75%

Time #2 Tank heated for 1 load cycle: 40 minutes = 0.67 hour

Tank #2 energy usage per batch = $\dot{Q}_{ACTUAL}$ = (15 kW)(0.75)(0.67 hour) = 7.54 kWh = 27,144 KJ = **67.5 KJ/Kg**

Minimum Energy Requirement Calculation for Heating Metal Slugs in Tank #5:

Because the slugs have been cooled in rinse tank #4 at 27°C, the energy requirement is the same as the initial energy utilized in tank #2 = 9,853.9 KJ = **24.5 KJ/Kg**

Minimum Energy Requirement Calculation for Heating Metal Slugs in Remaining Seven Tanks:

Using the assumption of 5% heat loss when switching tanks and the heating of the additional fresh makeup water at 15 °C (288.6 °K) for three of the rinse tanks, the heat needed would be:

ΔT = (0.05)(77°C) = 3.9°C

Δu = (490 J/Kg °C)(3.9 °C) = 1.9 KJ/Kg x 7 tanks = 13.3 KJ/Kg

Volume and mass of makeup water: 124.5 cm x 91.4 cm x 2.5 = 28,448.3 cm^3

= 28.4 Liters = 28.4 Kg

$\dot{Q}_{MakeUpWater} = \dot{m}_{MUW}\Delta u = \dot{m}_{MUW} C_p \Delta T$ = (28.4 Kg)(4.186 J/gm-°C)(1,000gm/Kg)

(350.0 – 288.6 °K) = 7,427.9 KJ x 3 tanks = 22,283.7 KJ = 55.4 KJ/Kg

$\dot{Q}_{MIN\,\mathrm{Re}\,mainingTanks}$ = (13.3 KJ/Kg) + (55.4 KJ/Kg) = **68.7 KJ/Kg**

Total Minimum Energy Requirement Calculation for Heating Metal Slugs in Tanks:

$\dot{Q}_{MINTOTAL}$ **=** 67.5 KJ/Kg + 24.5 KJ/Kg + 68.7 KJ/Kg = **160.7 KJ/Kg**

Estimated Actual Energy Usage for Heating Metal Slugs in Remaining Tanks:

Total electrical resistance load:

18 elements @ 5 kW = 90 kW

5 elements @ 15 kW = 75 kW

2 elements @ 4.5 kW = 9.0 kW

4 units @ 24 kW = 96 kW

4 units @ 0.56 kW = 2.2 kW

TOTAL HEATING LOAD = 272.2 kW

Estimated average load factor based on logger output = 0.25

Total estimated average energy usage for heating tanks = (272.2 kW)(0.25)(0.67 hour) = 45.6 kWh = 164,160 KJ

Total Estimated Actual Energy Usage for Heating Metal Slugs in Remaining Tanks:

$\dot{Q}_{ACTUALTOTAL}$ = 27,144 KJ + 164,160 KJ = 191,604 KJ = **476.4 KJ/Kg**

First Law Efficiency and Bandwidth Analysis for Chemical Tanks:

$$\eta = \frac{\dot{Q}_{MINTOTAL}}{\dot{Q}_{ACTUALTOTAL}} = (160.7)/(476.4\ \text{KJ}) = \mathbf{0.34}$$

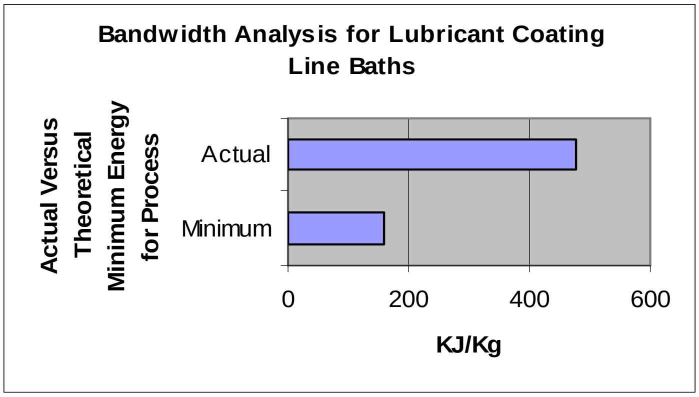

Figure 25. Bandwidth graph for chemical tanks:

Press – Extrusion Forge:

Desired Activity Outcome – Impart new shape and grain structure to slug

Activity Physical Leverage –

Diameter of steel rod = 35 mm

149.2 kW (200 HP) motor loading = 90%

Press efficiency = 80%

Process Description

The press operation uses a cold forge or press to change the shape of the slug. The outside diameter of the slug remains approximately the same (33 mm) while two 17 mm holes are introduced at either end of the slug and these holes come within about 13 mm of connecting in the center of the pin to form a continuous internal diameter hole through the pin. The holes are formed by two opposing rams with circular dies (17 mm diameter) on the respective ends of the rams pushing toward the center of the slug or billet. The remaining material in the center of the billet is referred to as the “web”. The billet material displaced by the formation of these bores is extruded via plastic deformation backward along the length of the ram and billet and, therefore, the overall billet length increases approximately 19 mm. This process is called backward extrusion and is a type of indirect extrusion (Groover, 2002, p.415). Once through this process, the billet will be referred to as the “pin”.

This operation introduces the beginning of the internal bore of the pin and gives the pin a desired grain structure for strength. The zinc phosphate applied to the slug in the coating operation is used as a die lubricant in this cold forge/extrusion operation.

Slugs are conveyed to the press. A vibrating table helps to position the slugs as they are introduced to the dies. The slugs or billets are cold forged (pressed) individually at a rate of approximately one slug every two minutes.

Energy Requirements for Press Forge:

The main power source for the forging operation is a 200 HP (149 KW) direct current electric motor. This motor applies the clamping and pressing force needed to extrude the billet into the pin.

The press uses a ¼ HP (0.19 KW) loading motor. There is a 0.19 KW motor used on a conveyor vibrator to position pins in the loading section of the press as well.

Compressed air is used to assist in lifting and balancing the dies during and after the press operation.

Calculation of energy requirements for Press Forge:

Minimum Energy Requirement Calculation for Press Forge:

The calculation of minimum power and energy to perform the backward extrusion of the press forge come from the analysis of indirect extrusion in Groover, pages 416 through 419.

The first calculation for the extrusion energies is the extrusion or reduction ratio:

$$r_x = \frac{A_o}{A_f} \tag{76}$$

Where A_o the cross-section of the original starting is billet in mm^2, and A_f is the cross-section of the extruded section in mm^2.

The true strain value can be determined by:

$$\varepsilon = \ln(r_x) = \ln\frac{A_o}{A_f} \tag{77}$$

The average flow stress during deformation is:

$$\bar{Y}_f = \frac{K\varepsilon^n}{1+n}$$

where K is the material strength coefficient and n is the strain-hardening exponent. Both values are found in empirical tables.

Specifically for extrusion calculations, the extrusion strain is determined by:

$$\varepsilon_x = a + b\ln(r_x) \tag{78}$$

where *a* and *b* will typically have values (empirical) of 0.8 and 1.2 to 1.5, respectively.

The ram pressure to perform indirect extrusion is:

$$p = \bar{Y}_f \varepsilon_x \tag{79}$$

The ram force (Newtons) for indirect extrusion is given as:

$$F = pA_o \tag{80}$$

The ram power (J/s) needed for indirect extrusion is given as:

$$P = Fv \tag{81}$$

where v is the ram velocity in m/s.

Note: For the press calculations the strength coefficient and strain-hardening exponents for SAE 4340 steel were used as the author could not find these values for AISI 5120 steel. SAE 4340 is an analog to AISI 5120 (J404) but has approximately 10% less tensile yield strength (Metal Suppliers Online, 2006). A lower steel yield strength should produce incrementally more elongation and therefore a higher r_x value, however the author uses the SAE 4340 analog numbers and leaves study of the sensitivity of energy calculations to material property differences as a topic for future study.

$$r_x = \frac{(35/2mm)^2 \pi}{(35/2mm)^2 \pi - (17/2mm)^2 \pi} = (962.1 \text{ mm}^2) / (227.0 \text{ mm}^2) = 1.31$$

$$\varepsilon = \ln(r_x) = \ln (1.31) = 0.27$$

$$\varepsilon^n = (0.27)^{0.15} = 0.82$$

$$\bar{Y}_f = \frac{K\varepsilon^n}{1+n} = [(641.2 \text{ MPa})(0.82)]/(1.15) = 458.1 \text{ MPa}$$

$$\varepsilon_x = a + b\ln(r_x) = (0.8) + (1.5)(0.27) = 1.21$$

$$p = \bar{Y}_f \varepsilon_x = (458.1 \text{ MPa})(1.21) = 554.3 \text{ MPa}$$

$$F = pA_o = (554.3 \text{ MPa})(0.000962 \text{ m}^2) = 533.2 \text{ KN}$$

$$P_{\min} = Fv = (533.2 \text{ KN})(0.048\text{m/s}) = 25.6 \text{ kW}$$

Energy$_{\text{min}}$ = power x time = (25.6 kW)(2 min/60 min/hr) = 0.85 kWh/pin = 3,060 KJ/0.67 Kg = **4,567.2 KJ/Kg**

Estimated Actual Energy Usage for Press Forge:

Power$_{\text{actual}}$ = [(149.2 kW)(0.9)]/(0.8) = 167.6 kW

Energy$_{\text{actual}}$ = (167.6 kW)(2 minutes/60 min/hour) = 5.59 kWh/pin = 20,124 KJ/0.67 Kg

= **30,035.8 KJ/Kg**

First law efficiency for Forge Press Process:

$$\eta_{Forge\ \Pr ess} = \frac{E_{c\,\min}}{E_{cact}} = \frac{(4{,}567.2 KJ / Kg)}{(30{,}035.8 KJ / Kg)} = \mathbf{0.15}$$

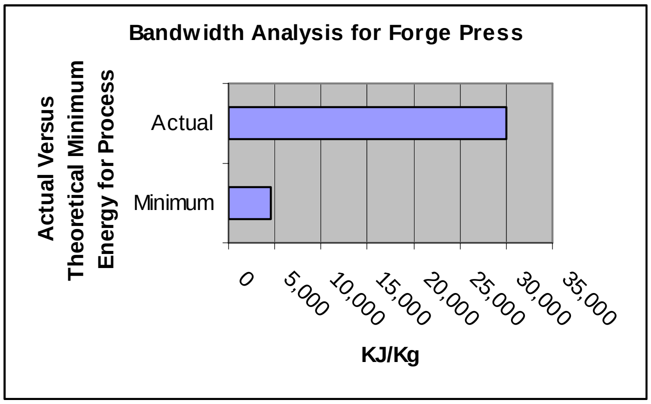

Figure 26. Bandwidth graph for forge press:

Web Drill – Metal Removal:

Desired Activity Outcome –	Remove remaining “web” material in the internal bore of the pin
Activity Physical Leverage –	Volume of material to be removed Physical Properties of Steel Desired Speed of Operation

Volume of material removed = $(3.1416)(8.5\text{ mm})^2(13\text{ mm}) = 3.0\text{ cm}^3$

Process Description

The web drill operation rapidly removes the remaining 3 cc of “web” material in the center of the pin. This produces a pin with a continuous bore from end to end.

The pins are conveyed to the web drill where two pins are drilled simultaneously. For each pin a rapid position motor brings the pin into position where a spindle motor is used to drill out the web. The web drilling operation takes approximately 16 seconds per pin. An air brake is used to stop the drilling and the rapid position motors retract the pins and drops them onto the exiting conveyor.

Energy Requirements for Web Drill:

Rapid Position Motor: 2 HP (1.5 KW)

Spindle Cutting Motor: 7.5 HP (5.6 KW)

Calculation of energy requirements for Web Drill:

- Estimated loading of motor while cutting: 80%
- Estimated machine efficiency: 80%

Minimum Energy Requirement Calculation for Web Drill:

The calculation of minimum power and energy to perform drilling, web removal of the pressed pin comes from the analysis of drilling power requirements from the Machinery's Handbook, 25th edition pages 1047 through 1049.

The first calculation for the drilling energies is:

$$P_c = \frac{MN}{9{,}550} \tag{82}$$

where:

Pc = Power required for drilling (cutting)

M = Torque required for drilling material

N = Spindle speed; rpm estimated as 320 rpm

$$M = 0.000025 K_d F_f F_M AW \tag{83}$$

where:

K_d = Work material factor (material dependent) = 24,000

F_f = Feed factor (from MHB table 31) = 0.219 (based on 13 mm/85.3 rev/pin = 0.15 mm/revolution feed rate)

F_M = Torque factor for drill diameter (from MHB table 32) = 164.2

A = (Standard drill from MHB table 33) = 1.085

W = (Tool wear factor from MHB table 27) = 1.00 assume sharp

M = 0.000025(24,000)(0.219)(164.2)(1.085)(1.0) = 23.4 Nm

Powercut$_{min}$ = [(23.4 Nm)(320 rpm)]/(9,550) = 0.78 kW

Energy$_{min}$ = power x time = (0.78 kW)(16 sec/3,600 sec/hr) = 0.00347 kWh/pin = 12.5 KJ/0.66 Kg[28] = **18.9 KJ/Kg**

Estimated Actual Energy Usage for Web Drill:

Power$_{actual}$ = [(7.5 kW)(0.8)]/(0.8) = 7.5 kW

Energy$_{actual}$ = (7.5 kW)(16 seconds/3,600 sec/hour) = 0.033 kWh/pin = 1,188 KJ/0.66 Kg = **1,800.0 KJ/Kg**

First law efficiency for Web Drill Process:

$$\eta_{WebDrill} = \frac{E_{c\min}}{E_{cact}} = \frac{(18.9KJ/Kg)}{(1,800.0KJ/Kg)} = \mathbf{0.011}$$

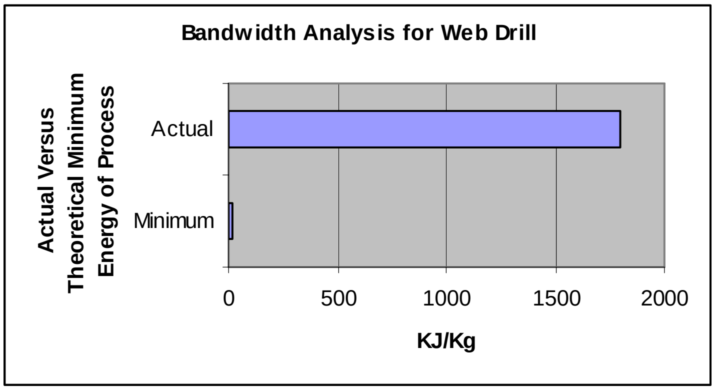

Figure 27. Bandwidth Graph for Web Drill

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[28] Average of new pin weight after material removal

End Pointer – Metal Removal:

Desired Activity Outcome –	Produce chamfer in ends of pin internal bores. Mill ends of pin to near finished overall length.
Activity Physical Leverage –	Volume of material to be removed Physical Properties of Steel Desired Speed of Operation

Volume of material removed = $\frac{\pi r^2{}_{cone} h}{3} - \pi r_{bore}^2 h$

= [(3.1416)(12.5 mm)^2(25 mm)]/3 – [(3.1416)(8.5 mm)^2 (25 mm)] = 12.3 cc – 5.7 cc = 6.6 cc

Material volume of pin: 86.6 cc – 3.0 cc – 6.6 cc = 77 cc

Mass of pin = (77 cc)(7.74 g/cc) = 596.0 g = 0.60 Kg

Process Description

The end pointer operation is a counter sink process where a decreasing taper is added to the internal bores at the end of the pin. The operation increases the internal diameter of the end bores from about 17 mm to 24.7 mm and tapers down to the original 17 mm bore in about 25 mm. Simultaneous to the introduction of the bore chamfers is the removal of 1.4 mm of material from both ends of the pin to bring the overall length to near finished dimensions.

The pins are brought into position via magnetic conveyors. Like the web drill, the end pointer processes two pins simultaneously. Each pin's material is removed by a cutting tool on a spindle motor. The operation takes approximately 5.5 seconds per pin.

Energy Requirements for End Pointer:

Magnetic Conveyor Motor: 5 HP (3.7 KW)

Spindle Cutting Motor: 20 HP (14.9 KW)

Calculation of energy requirements for End Pointer:

- Estimated loading of motor while cutting: 80%
- Estimated machine efficiency: 80%
- Assumed spindle speed = 320 rpm

Minimum Energy Requirement Calculation for End Pointer:

The calculation of minimum power and energy to perform the end pointer operation is complicated by the geometry of the cut. This is basically a countersinking operation into a pin with an existing bore, or hole. The material removed was calculated using cone and cylinder geometries. The power calculation uses the standard machine cutting equation (I) from the Machinery's Handbook, 25th edition page 1,044.

$$P_c = K_p CQW = kW \tag{84}$$

and

Q = (6.6 cm^3)/(5.5 second/pin)(2 ends) = 2.4 cm^3/sec

where:

P_c = Power at Cutting tool

K_p = 1.91 for AISI 5120 steel

C = Feed factor = 0.97 (based on 10.2 mm/29.3 rev/pin = 0.35 mm/revolution feed rate)

Q = 2.4 cm^3/sec

W = Tool wear factor = 1.0 (assumed sharp)

P_{cmin} = (1.91)(0.97)(2.4)(1.0) = 4.45 kW = Theoretical minimum power needed for end pointer(s)

E_{cmin} = Minimum energy needed for single cut = (4.45 kW)(5.5 sec/3,600 sec/hr) = 0.0068 kWh/cut = 24.5 KJ/0.60 Kg = **40.8 KJ/Kg**

Estimated Actual Energy Usage for End Pointer:

P_{cact} = Actual power needed for end pointers saw = [(14.9 kW)(2)(0.8)]/(0.8) = 29.8 kW

E_{cact} = Actual energy needed for single cut = (29.8 kW)(5.5 sec/3,600 sec/hr) = 0.046 kWh/cut = 165.6 Kg/0.60 Kg = **276.0 KJ/Kg**

First law efficiency for End Pointer Process:

$$\eta_{EndPo\text{int}\,er} = \frac{E_{c\min}}{E_{cact}} = \frac{(40.8KJ/Kg)}{(276.0KJ/Kg)} = \mathbf{0.15}$$

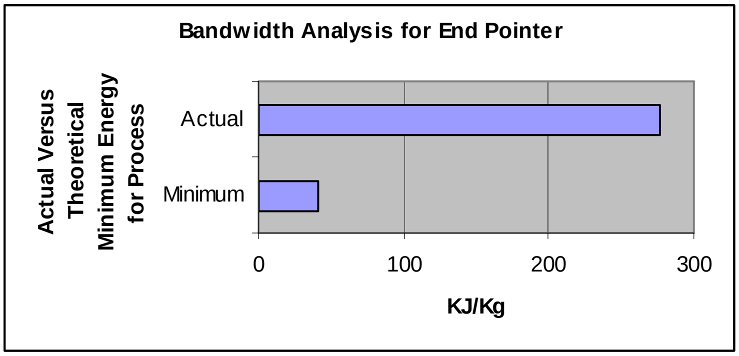

Figure 28. Bandwidth graph for end pointer:

Carburization Oven (and Quench):

Desired Activity Outcome –	Provide sufficient heat over time for desired phase changes and diffusion of carbon into steel pin
Activity Physical Leverage –	Volume (mass) of Pin Metal Properties Heat Level Needed Desired Speed of Operation Percentage of Carbon in Endo-gas

Mass of pin = (77 cc)(7.74 g/cc) = 596.0 g = 0.60 Kg

Process Description

Carburizing is the addition of carbon to the surface of low-carbon steels at temperatures generally between 850 and 950°C, at which austenite, with its high solubility for carbon, is the stable crystal structure. Hardening is accomplished when the high-carbon surface layer is quenched to form martensite so that a high-carbon martensitic case with good wear and fatigue resistance is superimposed on a tough, low-carbon steel core (Van Vlack, 1989).

Case hardness of carburized steels is primarily a function of carbon content. The carbon content is supplied by endothermic carbon gas generators with a resulting steel surface carbon content of 0.4%. The pins are carburized to a case depth of about 1.5 mm

The company uses a pusher-type carburizer/quench manufactured by the Atmosphere Furnace Company. An abbreviated sequence of the process is described below.

The pins are placed in heat resistant trays. These trays are about 61 x 61 cm and hold a load of about 45 pins or about 27 Kg total. The trays are pushed into the carburizing oven automatically by pneumatic pistons at about 23 minute cycles. As a new tray is introduced, it pushes the previous tray ahead. The oven holds a total of 41 trays. The total residence time of each tray in the oven is about 19 hours. During this time, the pins are maintained at about 900°C in the carbon rich atmosphere.

There are three heating zones in the oven that are automatically controlled by motorized air valves. The interior of the furnace is heated by 20 vertically mounted U-type radiant tubes.

Before pushing the last batch of pins out of the oven, the pins are cooled in an oil quench located within the oven. After the quench, the pins are pushed out of the oven onto a conveyor waiting for the drawing oven.

Energy Requirements for Carburizing Oven (provided by Atmosphere Furnace Company literature specific to particular oven):

The following specifications are for the oven heating 386 Kg of steel pins per hour. It should be noted that the oven is currently set up to heat much more than this amount, but these figures will provide relative data and suffice for the ERDT calculations.

The following is the approximate fuel consumption when the furnace is heating 386 Kg per hour of steel pins (644 pins), gross work, to a temperature of 927°C and thermal equilibrium has been reached.

Fuel: Natural Gas having a heating value of 1,000 Btu/ft^3 = 1,055 J/ft^3 = 37,242 J/m^3
Heating Work = 425 CFH = 448.4 KJ/hr = 1.16 KJ/Kg/hr = 0.70 KJ/pin/hr
Radiation Losses from Walls = 450 CFH = 426.5 KJ/hr = 1.11 KJ/Kg/hr
Black Body Losses = 278 CFH = 263.5 KJ/hr = 0.68 KJ/Kg/hr
Heating Atmosphere = 112 CFH = 106.2 KJ/hr = 0.28 KJ/pin/hr
Total = 1,270 CFH = 1,340 KJ/hr = 3.12 KJ/Kg/hr
Provided = 3,600 CFH = 3,412.3 KJ/hr = 8.84 KJ/Kg/hr

It is assumed that the natural gas provided is a measure of the total fuel delivered to the oven during this steady-state operation. This implies that 8.84 KJ/Kg – 3.12 KJ/Kg = 5.72 KJ/Kg is the waste heat that escapes out of the furnace flues.

The following electric motors are used in carburizing furnace:

- 100% Load Factor
- Combustion Air Fan: 7 HP (5.2 KW)
- Circulation Fans (3 each): 7.5 HP (5.6 KW)

< 1% Momentary Load Factor
Pusher Motor (2 each): 3 HP (2.2 KW)
Rack Pusher Motor: 5 HP (3.7 KW)
Wash Circulation Pump: 5 HP (3.7 KW)

Various Smaller Motors

Calculation of energy requirements for Carburizing Oven:

Minimum Energy Requirement Calculation for Carburizing Oven:

Because the steel alloy will experience a phase change in the range of temperatures of the carburization process, a numerical integration (summation) of the energy changes at 50 degree increments, based on empirical specific heat data is used (Table 11).

45360 Slug Material: 5120 Steel Alloy

Change in temperature (ΔT) = Incremental 25 – 900 °C

Slug Dimensions: 90 mm Length, 35 mm diameter

Slug Volume: (90 mm)(17.5 mm)^2(3.1415) =86,590 mm^3 = 86.6 cc

Slug mass: (slug volume)(slug density) = (86.6 cc)(7.74 g/cc) = 670.3 g = 0.67 Kg

Specific heat (c_p) of steel in the 0-900 °C temperature range: Varies (see ASM Metals Reference Book)

Change in energy required for heating using specific heat: $\Delta u = \sum \bar{c}_p \Delta T$

Mass flow rate into baths: $\dot{m} = N\rho\dot{V} = N\rho A v$

Heat energy needed to heat slugs: $\dot{Q} = \dot{m}\Delta u = N\rho A v \Sigma \bar{c}_p \Delta T$

$\dot{m}$ = (600 slugs)(7.74 g/cc)(86.6 cc/slug)(1 Kg/1,000 g) = 402.2 Kg

5120 Alloy Steel

Temp Range °C	J/Kg°C	CpΔT = J/Kg
50-100	494	24,700
100-150	509	25,450
150-200	523	26,150
200-250	536	26,800
250-300	553	27,650
300-350	574	28,700
350-400	595	29,750
400-450	626	31,300
450-500	657	32,850
500-550	699	34,950
550-600	741	37,050
600-650	789	39,450
650-700	837	41,850
700-750	1499	74,950
750-800	934	46,700
800-850	754	37,700
850-900	574	28,700
	SUM	528,300

Table 11. Incremental energy requirements to heat AISI 5120 steel in carburizing oven.

$\dot{Q}_{MIN}$ = **528.3 KJ/Kg**

In a perfect oven (minimum energy use), there would be no heat loss through the walls and once the steel pins were up to temperature they would stay at this temperature indefinitely until the oven doors were opened and the pins removed.

Estimated Actual Energy Usage Requirement Calculation for Carburizing Oven:

The oven fuel (energy) usage data from the equipment specifications sheet is used to show the hourly energy usage of the oven once at thermal equilibrium. This is the heat (energy) loss by convective, radiation and other losses (see oven specification discussion above). To reach thermal equilibrium, the oven must provide the same 528.3 KJ/Kg of heat needed to raise the temperature of the pins to 900 °C as the minimum energy calculation. The residence time needed for the carbon migration into the pins is[29] = 19 hours.

Total Estimated Actual Energy Usage for Heating Metal Slugs in carburization oven:

$\dot{Q}_{ACTUALTOTAL}$ = ($\dot{Q}_{MIN}$) + (3.12 KJ/Kg/hour equilibrium heat loss)(19 hours) + (5.72 KJ/Kg/hour heat loss out flues)(19 hours)

= 528.3 KJ/ Kg + 59.3 KJ/Kg + 108.7 KJ/Kg

= **696.3 KJ/Kg**

First Law Efficiency and Bandwidth Analysis for Carburization Oven:

$\eta = \dfrac{\dot{Q}_{MINTOTAL}}{\dot{Q}_{ACTUALTOTAL}}$ = (528.3 KJ/Kg)/(696.3 KJ/Kg) = **0.76**

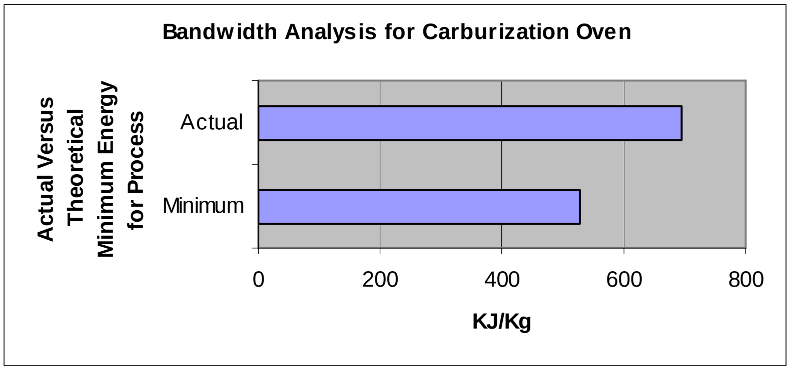

Figure 29. Bandwidth graph for carburization oven:

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[29] Manufacturer process requirements for migration of carbon into steel.

Draw Oven:

Desired Activity Outcome – Provide sufficient heat over time for desired material changes (stress relief)

Activity Physical Leverage – Volume (mass) of Pin
Metal Properties
Heat Level Needed
Desired Speed of Operation

Mass of pin = (77 cc)(7.74 g/cc) = 596.0 g = 0.60 Kg

Process Description

The carburizing process hardens the steel alloy pin’s metal surface significantly, and this introduces stress in the micro-structure of the metal. These stresses can lead to brittle cracking. The draw oven is used to relieve the residual stresses in the metal surface of the pins.

The draw oven operates at a temperature of 171°C. The nominal residence time for a batch of pins in the oven is 8 hours. Like the carburization ovens, the batch oven uses the trays full of pins to push trays in the oven, in and out of the oven.

Energy Requirements for Draw Oven (Estimated by Atmosphere Furnace Company literature specific to particular oven):

The following specifications were estimated for the draw oven heating pins for eight hours. Unlike the carburization oven that had detailed specifications, the draw oven literature only has the maximum gross heat input of 800,000 Btu/hr (844 KJ/hr) listed. The temperature operating range of the draw oven is adjustable from 0 to 427°C. Normal operating temperature range is 149 °C to 288 °C.

All ovens, or furnaces, have a firing curve which shows the relationship between energy input and internal temperature. Most oven curves are slightly convex-up but must be determined by empirical data (Ohio State University, 2006). In the absence of such oven data, the author has assumed a linear relationship between operating temperature and gross heat energy input, a linear interpolation can be performed to estimate the heat energy input needed to maintain 171 °C (temperature required by this facility).

The following is the approximate fuel consumption when the furnace is heating 455 Kg per hour of steel pins (758 pins), gross work, to a temperature of 171°C and thermal equilibrium has been reached.

Fuel: Natural Gas having a heating value of 1,000 Btu/ft^3 = 1,055 J/ft^3 = 37,242 J/m^3

Heating Work = 114 CFH = 120 KJ/hr = 0.26 KJ/Kg/hr = 0.16 KJ/pin/hr

Radiation Losses from Walls = 120 CFH = 127 KJ/hr = 0.28 KJ/Kg/hr

Black Body Losses = 74 CFH = 79 KJ/hr = 0.17 KJ/Kg/hr

Heating Atmosphere = 30 CFH = 32 KJ/hr = 0.07 KJ/pin/hr

Total = 340 CFH = 359 KJ/hr = 0.79 KJ/Kg/hr = 0.47 KJ/pin/hr

Provided = 800 CFH = 844 KJ/hr = 1.85 KJ/Kg/hr = 1.11 KJ/pin/hr

It is assumed that the natural gas provided is a measure of the total fuel delivered to the oven during this steady-state operation. This implies that 1.11 KJ/Kg – 0.47 KJ/Kg = 0.64 KJ/Kg is the waste heat that escapes out of the furnace flues. It is also assumed that the pins have cooled down to ambient temperature prior to being placed in the draw oven.

The following electric motors are used in draw oven:

100% Load Factor

- Combustion Air Fan: 7 HP (5.2 KW)
- Exhaust Fans (2 each): 3 HP (2.2 KW)
- Blower Fan: 1/3 HP (0.25 KW)

< 1% Momentary Load Factor

- Conveyor Motor: 1 HP (0.75 KW)
- Rack Pusher Motor: 5 HP (3.7 KW)
- Wash Circulation Pump: 5 HP (3.7 KW)
- Various Smaller Motors

Calculation of energy requirements for Draw Oven:

Minimum Energy Requirement Calculation for Draw Oven:

Because the steel alloy will experience a phase change in the range of temperatures of the carburization process, a numerical integration (summation) of the energy changes at 50 degree increments, based on empirical specific heat data is used (Table 12).

45360 Slug Material: 5120 Steel Alloy

Change in temperature (ΔT) = Incremental 25 – 171 °C

Slug Dimensions: 90 mm Length, 35 mm diameter

Slug Volume: (90 mm)(17.5 mm)^2(3.1415) =86,590 mm^3 = 86.6 cc

Slug mass: (slug volume)(slug density) = (86.6 cc)(7.74 g/cc) = 670.3 g = 0.67 Kg

Specific heat (c_p) of steel in the 0-900 °C temperature range: Varies (see ASM Metals Reference Book)

Change in energy required for heating using specific heat: $\Delta u = \sum \bar{c}_p \Delta T$

Mass flow rate into baths: $\dot{m} = N\rho\dot{V} = N\rho Av$

Heat energy needed to heat slugs: $\dot{Q} = \dot{m}\Delta u = N\rho Av\Sigma\bar{c}_p\Delta T$

$\dot{m}$ = (600 slugs)(7.74 g/cc)(86.6 cc/slug)(1 Kg/1,000 g) = 402.2 Kg

5120 Alloy Steel **Draw**

Temp Ran	J/Kg°C	CpΔT = J/Kg
50-100	494	24,700
100-150	509	25,450
150-171	223	11,150
	SUM	61,300

Table 12: Incremental energy requirements to heat AISI 5120 steel in draw oven.

Residence time needed in draw oven = 8 hours

$\dot{Q}_{MIN}$ = **61.3 KJ/Kg**

As in the carburization oven, in a perfect draw oven (minimum energy use), there would be no heat loss through the walls and once the steel pins were at temperature they would stay at this temperature indefinitely, until the oven doors were opened and the pins removed.

Estimated Actual Energy Usage Requirement Calculation for Draw Oven:

The oven fuel (energy) usage data from the equipment specifications sheet is used to show the hourly energy usage of the oven once at thermal equilibrium. This is the heat (energy) loss by convective, radiation and other losses (see oven specification discussion above). To reach thermal equilibrium, the oven must provide the same 159.5 KJ/Kg of heat needed to raise the temperature of the pins to 350 °C as the minimum energy calculation. The residence time needed for the surface stress relief of the pins is[30] = 8 hours.

Total Estimated Actual Energy Usage for Heating Metal Slugs in Draw Oven:

$\dot{Q}_{ACTUALTOTAL}$ = ($\dot{Q}_{MIN}$) + (0.79 KJ/Kg-hour equilibrium heat loss)(8 hours) + (0.64 KJ/Kg heat loss out flues)(8 hours) = 61.3 KJ/ Kg + 6.3 KJ/Kg + 5.1 KJ/Kg

= **72.7 KJ/Kg**

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[30] Manufacturer process requirements for migration of carbon into steel.

First Law Efficiency and Bandwidth Analysis for Draw Oven:

$$\eta = \frac{\dot{Q}_{MINTOTAL}}{\dot{Q}_{ACTUALTOTAL}} = (61.3\ \text{KJ/Kg})/(72.7\ \text{KJ/Kg}) = \mathbf{0.84}$$

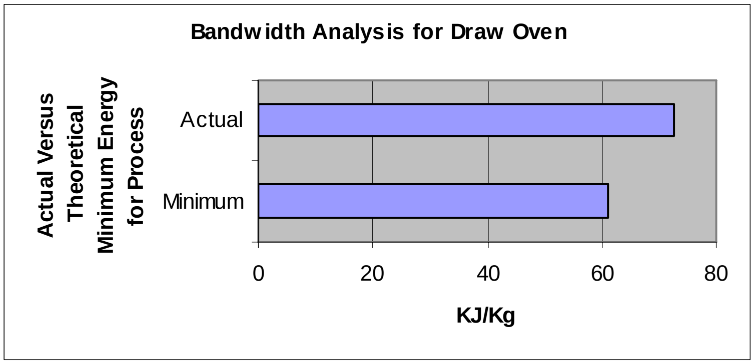


Figure 30. Bandwidth graph for draw oven:

End De-Scale:

Desired Activity Outcome – Remove end scale by abrasive blasting

Activity Physical Leverage – Exposed surface area of pin ends

Physical Properties of Steel

Desired Speed of Operation

Exposed area of steel pin end: A1 = $\pi\ (17.4mm)^2 = 951.1mm^2$

A2 = $\pi(12.3mm)^2 = 475.3mm^2$

A1 – A2 = 475.8mm^2 x 2(ends per pin) = 951.6mm^2

Assumed steel shot abrasive particle diameter = 0.2mm

Process Description

The steel pins are removed from the draw ovens and transported via fork truck to the end de-scaler. This operation is a combination scale removal and surface hardening technique for the ends of the pins. An abrasive is introduced into a high velocity air stream and is guided to impact the ends of the pins. The typical residence time of the pin in the de-scaler is 30 seconds.

The de-scaler box is enclosed and contains the conveyor system and sixteen 6.4mm air guns operating at 65 psig (3,112 Pa). The guns are arranged such that the abrasive media completely processes both ends of the pin. A 7.5 KW dust collector also runs coincidentally with the de-scaler. The de-scaler, and associated dust collector run an average of 14 hours per day.

Calculation of energy requirements for De-Scale:

Minimum Energy Requirement Calculation for De-Scale:

In theory, the energy requirement for abrasive blast cleaning or shot-peening is the sum of the kinetic energies of the abrasive particles as they collide with the work piece. While compressed air is used as the vehicle for the particles in this facility, it is not the only means of accelerating the media to the required velocity (e.g., centrifugal blasting). In all cases however, the abrasive particle is accelerated to a proper velocity. Therefore, using the kinetic energy of the particles as the minimum energy requirement is appropriate.

The kinetic energy equation is: $KE = \frac{1}{2}mv^2$

where m= particle mass and v = particle velocity

Using an industry article (Kondo, et al, 1979) gives the following process parameters:

Individual Abrasive Particle Mass: 2.05 x10^{-6} Kg

Average Abrasive Particle Velocity: 76.2 m/sec

Number of Particles Delivered per minute per mm^2: 2,691

Total Mass of Particles Delivered per Minute per mm^2: 0.0055 Kg

Total Pin Surface Area to be de-scaled: 951.6mm^2

Total Mass of Particles Delivered per Minute per Pin: 5.23 Kg

Total Mass of Particles Delivered per Pin: (0.087 Kg)(30 seconds) = 2.61 Kg

Total Kinetic Energy Required to de-scale per Pin:

E_{MIN} = KE = ½(2.61 Kg)(76.2 m/sec)^2 = 7,577 Kgm/s^2 = 7,577 Joules = 7.6 KJ/0.60 Kg = **12.7 KJ/Kg**

Estimated Actual Energy Usage Requirement Calculation for De-Scale Process:

The horsepower requirements for compressed air media blasting depends on the specific gravity of the abrasive media and the quantity of media per time. Somewhat counter intuitively, the less blast particles in the air stream, the more the air consumption and therefore the higher the power (energy) requirements.

By assuming the steel abrasive occupies roughly 10% of the air volume, and due to steel's higher density than air, a 70% correction factor will be applied to 100% air nozzle calculations. That is, the amount of air will be decreased by 30% to account for the abrasive particles in the air stream.

- Number of Air/Abrasive Nozzles: 16 (assume 8 used at any one time)
- Operating Pressure: 65 psig (3,112 Pa)
- Nozzle Orifice Smoothness (assumed): Medium
- Air Leak Power Calculations (Parekh, 2006): Note: Calculations are in English units and converted to SI at final answers

Air flow Through Nozzles (air leak):

$$V_f = \frac{NLx(T_i + 460)x\frac{P_l}{P_i}xC_1xC_2xC_dx\frac{\pi D^2}{4}}{C_3\sqrt{T_l + 460}} \qquad (85)$$

where:

V_f = Volumetric flow rate of free air (Leak) – cubic feet per minute

NL = Number of leaks (nozzles) – no units = 16 (assume 50% usage at a time)

T_i = Temperature of air at compressor inlet (F) = 80 F

P_l = Pressure at leak (nozzle) = 65 psia

P_i = Inlet (Atmospheric) pressure, 14.7 psia

C_1 = Isentropic sonic volumetric flow constant, 28.37 ft/sec-R(0.5)

C_2 = Conversion constant, 60 sec/minute

C_d = Coefficient of discharge for square edged orifice (0.6)

D = Leak diameter (inches) = 0.25”

C_3 = Conversion constant, 144 in2/ft2

T_l = Average line temperature = (80 F)

$$V_f = \frac{8x(80 + 460)x\frac{65}{14.7}x28.37x60x0.6x\frac{\pi(0.28)^2}{4}}{144\sqrt{80 + 460}}$$

V_f = (286.2 CFM) = 8.1 Cubic Meters per Minute Total Air Loss through Nozzles

Horsepower Requirement to supply Nozzles:

$$LeakHP = \frac{P_ixC_4xV_fx\frac{k}{k-1}xNxC_5x\left[\left(\frac{P_0}{P_i}\right)^{\frac{k-1}{kxN}} - 1\right]}{E_axE_m} \qquad (86)$$

where:

k = Specific heat ratio of air (1.4) – no units

N = Number of stages – no units = 1

V_f = Volumetric flow rate of free air (Leak) – 286.2 cubic feet per minute

C_4 = Conversion constant, 144 in2/ft2

C_5 = Conversion constant, 3.03 x 10-5 HP-min/ft-lb

P_0 = Compressor operating pressure at nozzles = 65 psia

P_i = Inlet (Atmospheric) pressure, 14.7 psia

E_a = Air compressor adiabatic efficiency – no units = 0.82 (Screw)

E_m = Compressor motor efficiency – no units = 0.97

$$NozzleHP = \frac{14.7x144x286.2x\frac{1.4}{1.4-1}x1x3.03x10^{-5}x\left[\left(\frac{65}{14.7}\right)^{\frac{1.4-1}{1.4x1}}-1\right]}{0.82x0.97}$$

$NozzleHP =$(42.8 HP) = 31.9 KW Total Power to Operate De-Scale Nozzles

$W_{Actual} = E_{Actual}$ = 31.9 KW x 0.00833 hour = 0.266 kWh per pin = 957,600 Joules =

957.6 KJ/0.60 Kg = **1,596 KJ/Kg**

First Law Efficiency and Bandwidth Analysis for De-Scale Operation:

$\eta = \frac{E_{MIN}}{E_{Actual}}$ = (12.7 KJ/Kg)/(1,596 KJ/Kg) = **7.91 x 10^{-3}**

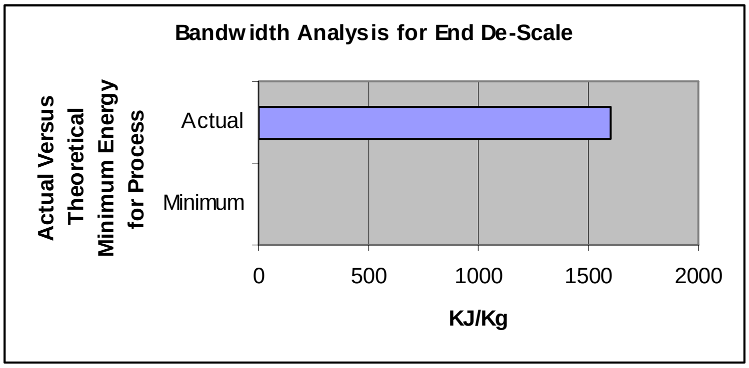


Figure 31. Bandwidth graph for de-scale operation:

Finish Grinding/Lapping:

Desired Activity Outcome – Fine (final) grinding and honing down to desired dimensions and surface finish

Activity Physical Leverage – Surface Area (and volume) of pin to be reduced
Physical Properties of Steel
Desired Speed of Operation

Diameter of pin = 34.8 mm

Volume of Removed Material: V1 = $\pi\ (17.40mm)^2\ x90mm = 85{,}603.5mm^2$

V2 = $\pi(17.40 - 0.03mm)^2\ x90mm = 84{,}308.4mm^2$

V1 –V2 = 295.1mm^3 = Total volume of material removed in grinding and lapping per pin

Process Description

This is the last of the pin manufacturing processes. The diameters of the pins are brought down to specifications, and a fine finish is applied by a series of honing operations. The honing starts at a 100 HP (75 KW) lap grinder and proceeds down to a 75 HP (56 KW) lap grinder, then a 60 HP (45 KW) lap grinder and a 20 HP (15 KW) grinder. Finally, the pin is passed through 2 final lap machines at 7.5 HP (5.6 KW) each. The amount of material removed is very small in these operations. As the pin proceeds toward the finishing lap grinders, the amount of material removed is almost zero. Plant personnel estimated that about only 0.025 mm of pin diameter was removed in the first three lap grinders with very little removed in the final polish grinders.

The grinders are a centerless operation in which the work piece rides between the grinding roller and a regulating wheel. Usually, the regulating wheel is inclined at a slight angle (I) which provides a feed force that moves the work piece along the length of the grinding wheel. Gravity provides the feed force of the work piece into the abrasive grinding wheel.

The author will use the published (Kalpakjian, Schmid, 2001) specific energy data for abrasive machining based on volume of material removed. The specific energy is interpolated to meet the Brinell hardness of 220. The value of 61 W*s/mm^3 will be used for the specific energy to grind AISI 5120 steel. It should be noted that some literature (Marinescu, 2003) has suggested that lapping specific energy may exceed 100 W*s/ mm^3 in some operations.

For simplification, only the first three grinders (56 kW, 45 kW and 15 kW) will be examined. The author will use a decreasing depth of cut and amount of material removed (50%-30%-20%) for each grinder starting with the 56 kW grinder. The break down of material removed will be:

Energy Requirements for Finish Grinding:

- Estimated loading of motor while cutting: 70%
- Estimated machine efficiency: 80%

Minimum Energy Requirement Calculation for Finish Grinding:

Finish Grinder #1 (75 HP (56 KW)): (0.5)(295.1mm^3) = 147.6 mm^3

Specific energy 56 kW = (147.6 mm^3)(61 W*s/mm^3) = 9.0 KJ/pin

Finish Grinder #2 (60 HP (45 KW)): (0.3)(295.1mm^3) = 88.5 mm^3

Specific energy 56 kW = (88.5 mm^3)(61 W*s/mm^3) = 5.4 KJ/pin

Finish Grinder #3 (20 HP (15 KW)): (0.2)(295.1mm^3) = 59.0 mm^3

Specific energy 56 kW = (59.0 mm^3)(61 W*s/mm^3) = 3.6 KJ/pin

Total specific energy for finish grinding = 9.0 KJ/pin + 5.4 KJ/pin + 3.6 KJ/pin =

18.0 KJ/0.60 Kg = **30.0 KJ/Kg**

Estimated Actual Energy Usage for Finish Grinding:

Finish Grinder #1 (75 HP (56 KW)):

$P_{gactual}$ = [(56 kW)(0.7)]/(0.8) = 49.0 kW

$E_{gactual}$ = (49.0 kW)(5 sec/3,600 sec/hour) = 0.068 kWh/pin

Finish Grinder #2 (60 HP (45 KW))

$P_{gactual}$ = [(45 kW)(0.7)]/(0.8) = 39.4 kW

$E_{gactual}$ = (39.4 kW)(5 sec/3,600 sec/hour) = 0.055 kWh/pin

Finish Grinder #3 (20 HP (15 KW)):

$P_{gactual}$ = [(15 kW)(0.7)]/(0.8) = 13.1 kW

$E_{gactual}$ = (13.1 kW)(5 sec/3,600 sec/hour) = 0.018 kWh/pin

Total $P_{gactual}$ = 49.0 kW + 39.4 kW + 13.1 kW = 101.5 kW/pin

Total $E_{gactual}$ = 0.068 kWh + 0.055 kWh + 0.018 kWh = 0.14 kWh/pin = 504 KJ/pin =

504 KJ/0.60 Kg = **840.0 KJ/Kg**

$$\eta = \frac{E_{MIN}}{E_{Actual}} = (30.0\ \text{KJ/Kg})/(840.0\ \text{KJ/Kg}) = \mathbf{0.036}$$

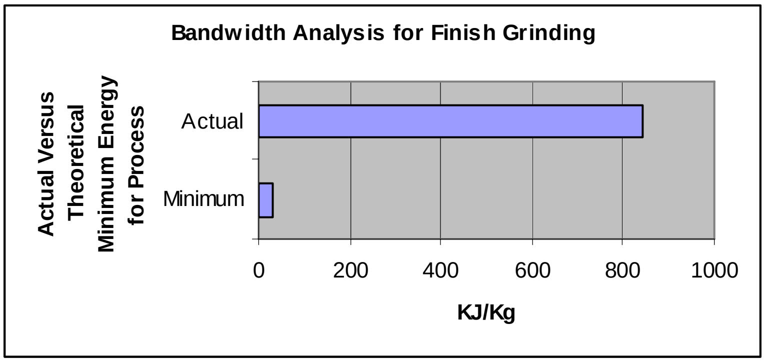


Figure 32. Bandwidth graph for finish grinding:

The following figures and tables are resulting products of Step 3 for the case study. A discussion is included after Table 15.

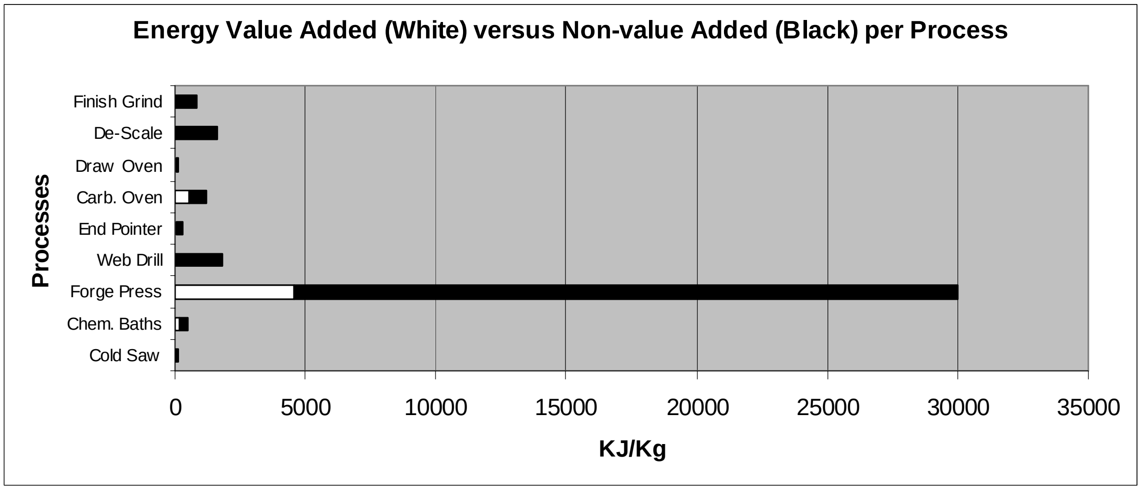


Figure 33. Bandwidth graph for all processes

Existing Process Piston Pin Manufacture	**Energy Type**	**Energy Cost $/KJ**	**Total 1/PPE KJ/Kg**	**Total 1/PPE Cost $/Kg**	**Total 1/PPE (Value) KJ/Kg**	**Total 1/PPE (Value) Cost $/Kg**	**Total 1/PPE (Non-Value) KJ/Kg**	**Total 1/PPE (Non-Value) Cost $/Kg**	**Percent Energy Non-Value Added**	**Max/Min**
Cold Saw	Electrical	$2.22E-5/KJ	107.5	$0.0024	10.7	$0.0002	96.8	$0.0021	90.0	
Chemical Baths	Electrical	$2.22E-5/KJ	476.4	$0.0106	160.7	$0.0036	315.7	$0.0070	66.3	
Forge Press	Electrical	$2.22E-5/KJ	30,035.8	$0.6668	4,567.2	$0.1014	25,468.6	$0.5654	84.8	
Web Drill	Electrical	$2.22E-5/KJ	1,800.0	$0.0400	18.9	$0.0004	1,781.1	$0.0395	99.0	
End Pointer	Electrical	$2.22E-5/KJ	276.0	$0.0061	40.8	$0.0009	235.2	$0.0052	85.2	
Carburization Oven	Nat. Gas	$7.58E-6/KJ	1,224.6	$0.0093	528.3	$0.0117	696.3	$0.0155	56.9	
Draw Oven	Nat. Gas	$7.58E-6/KJ	134.0	$0.0010	61.3	$0.0014	72.7	$0.0016	**54.3**	**Best**
De-Scale	Electrical	$2.22E-5/KJ	1,596.0	$0.0354	12.7	$0.0003	1,583.3	$0.0351	**99.2**	**Worst**
Finish Grind	Electrical	$2.22E-5/KJ	840.0	$0.0186	30.0	$0.0007	810.0	$0.0180	96.4	
	Total			**$0.7902**		**$0.1206**		**$0.6895**		

Table 13. Partial productivities[31] and ABM cost report interface for case study example

---

[31] Values shown for PPe's are actually reciprocals

						ALTER													
		De-Scale		**Web-Drill**		**Finish Grind**		**Chemical Baths**		**End Pointer**		**Forge Press**		**Draw Oven**		**Carburization**		**Cold Saw**	
CRITERIA	**Weight**	Rating	Score(1)	Rating	Score(1)	Rating	Score(1)	Rating	Score(1)	Rating	Score(1)	Rating	Score(1)	Rating	Score(1)	Rating	Score(1)	Rating	Score(1)
C1 = Subjective Concerns	1	4	**4**	2	**2**	1	**1**	5	**5**	1	**1**	1	**1**	3	**3**	2	**2**	1	**1**
C2 = % of Energy NVA	2	5	**10**	5	**10**	4	**8**	4	**8**	3	**6**	3	**6**	2	**4**	2	**4**	1	**2**
C3 = Production interuption to Install Solution	3	3	**9**	2	**6**	1	**3**	3	**9**	1	**3**	1	**3**	3	**9**	3	**9**	1	**3**
C4 = Ease to Provide Solution	4	4	**16**	1	**4**	1	**4**	5	**20**	1	**4**	1	**4**	4	**16**	4	**16**	1	**4**
C5 = Amount of Energy NVA	5	5	**25**	5	**25**	4	**20**	4	**20**	3	**15**	3	**15**	3	**15**	3	**15**	1	**5**
C6 = Waste Exergy Available for Use	6	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	1	**6**	4	**24**	5	**30**	0	**0**
Total	21	21	**64**	15	**47**	11	**36**	21	**62**	9	**29**	10	**35**	19	**71**	19	**76**	5	**15**

C5 = Amount of Energy NVA	Greater Quantity = Higher	Higher implies Improve/Repair/Replace
C4 = Ease to Provide Solution	Probable = Higher	Lower implies Status Quo/Option Zero
C3 = Production interuption to Install Solution	Probable = Lower	
C2 = % of Energy NVA	Greater % = Higher	
C1 = Subjective Concerns	More Conserns = Lower	

Higher = Important
Lower = Not Important

Ranking from AHP Decision Matrix

1	**Carburization**
2	**Draw Oven**
3	**De-Scale**
4	**Chemical Baths**
5	**Web-Drill**
6	**Finish Grind**
7	**Forge Press**
8	**End Pointer**
9	**Cold Saw**

Table 14. AHP decision matrix ranking

Ranked by % Energy Non-Value Added	Ranked by Amount of Non-Value Added Energy	AHP Decision Matrix
De-Scale 99.2%	Forge Press 25,486.6 KJ/Kg	Carburization Oven
Web-Drill 99.0%	Web Drill 1,781.1 KJ/Kg	Draw Oven
Finish Grind 96.4%	De-Scale 1,583.3 KJ/Kg	De-Scale
Cold Saw 90.0%	Finish Grind 810.0 KJ/Kg	Chemical Baths
End Pointer 85.2%	Carb. Oven 696.3 KJ/Kg	Web-Drill
Forge Press 84.8%	Chemical Baths 315.7 KJ/Kg	Finish Grind
Chem Baths 66.3%	End Pointer 235.2 KJ/Kg	Forge Press
Carb. Oven 56.9%	Cold Saw 96.8 KJ/Kg	End Pointer
Draw Oven 54.3%	Draw Oven 72.7 KJ/Kg	Cold Saw

Table 15. Case study example processes ranked by various methods for improvement studies

Step 3 Results Discussion:

The combined bandwidth graph in Figure 33 visually demonstrates the relative value versus non-value added energy utilization for the processes. The graph also provides a good view of the relative magnitudes of the process energy usage per product unit mass.

The partial productivities and ABM cost report shown in Table 13 demonstrates the relative energy costs (value and non-value) associated with the plant processes. This table is the interface to the activity based management costing system.

Table 14 demonstrates the AHP decision matrix used to produce the right-hand ranking column in Table 15 (energy project ranking). Examination of Table 15 highlights some of the mechanics of the ERDT ranking methodology. The first column on the left of the table demonstrates the processes that have the greatest percentage of wasted energy utilization per process. However, this ranking does not indicate whether a particular process is a large energy consumer in relation to the total energy purchases for all the processes. That is, are some of the processes worth studying? The second, or middle, ranking shows the processes ranked by amount of energy utilization wasted per kilogram of product produced. This ranking may be more important to plant management considering improvement studies because of the link to economics. Finally, the far right column is the result of the decision matrix (Table 14) that takes the first two rankings into account and adds management concerns (whatever they may be).

The next set of figures (Figures 34, 35 and 36) demonstrates the partial productivity cost of energy included in a value stream map. This map can interface these econometrics with an activity based management accounting system.

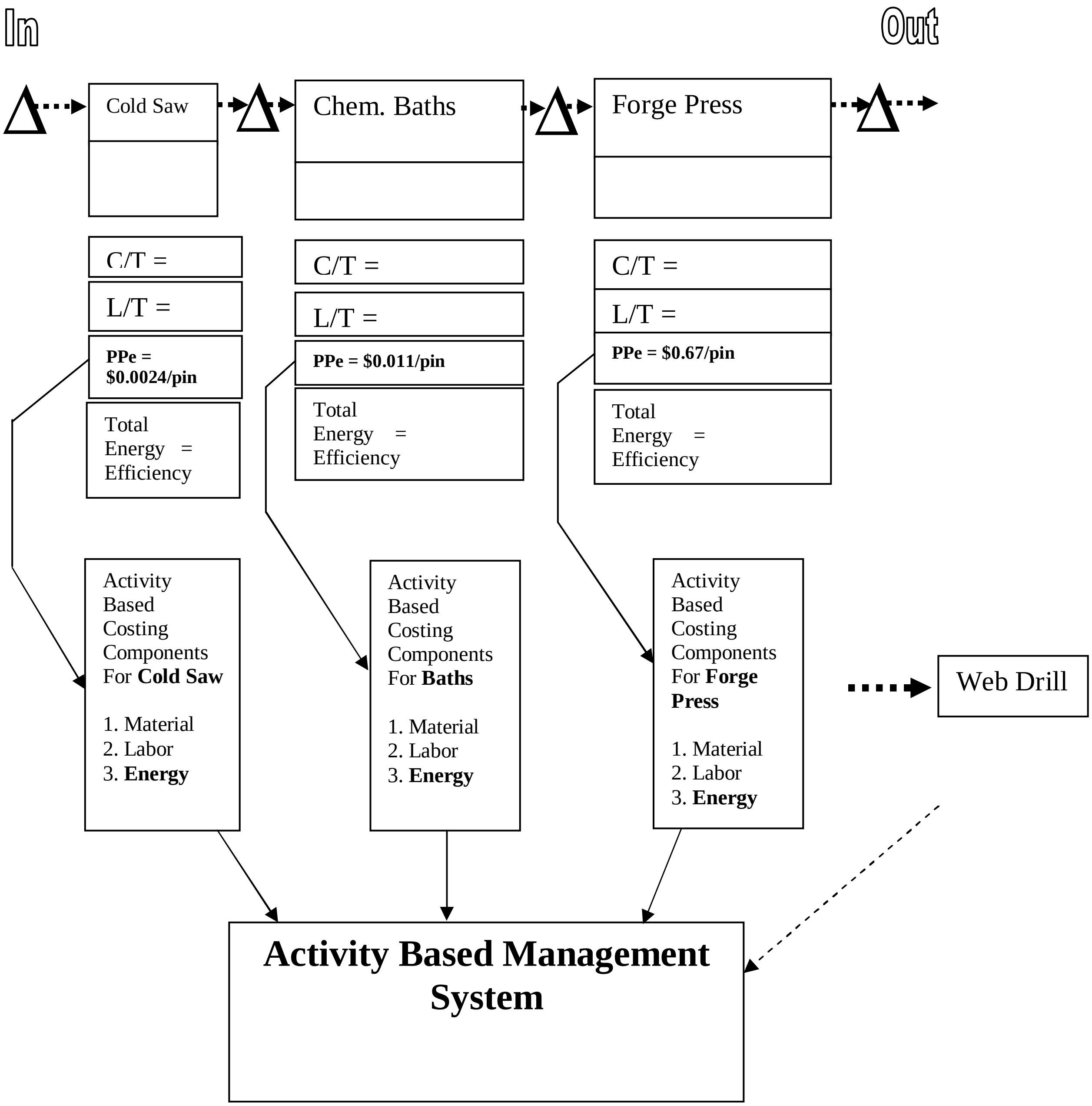


Figure 34. Value stream map with partial productivity/ABM interface for first three processes of case study example.

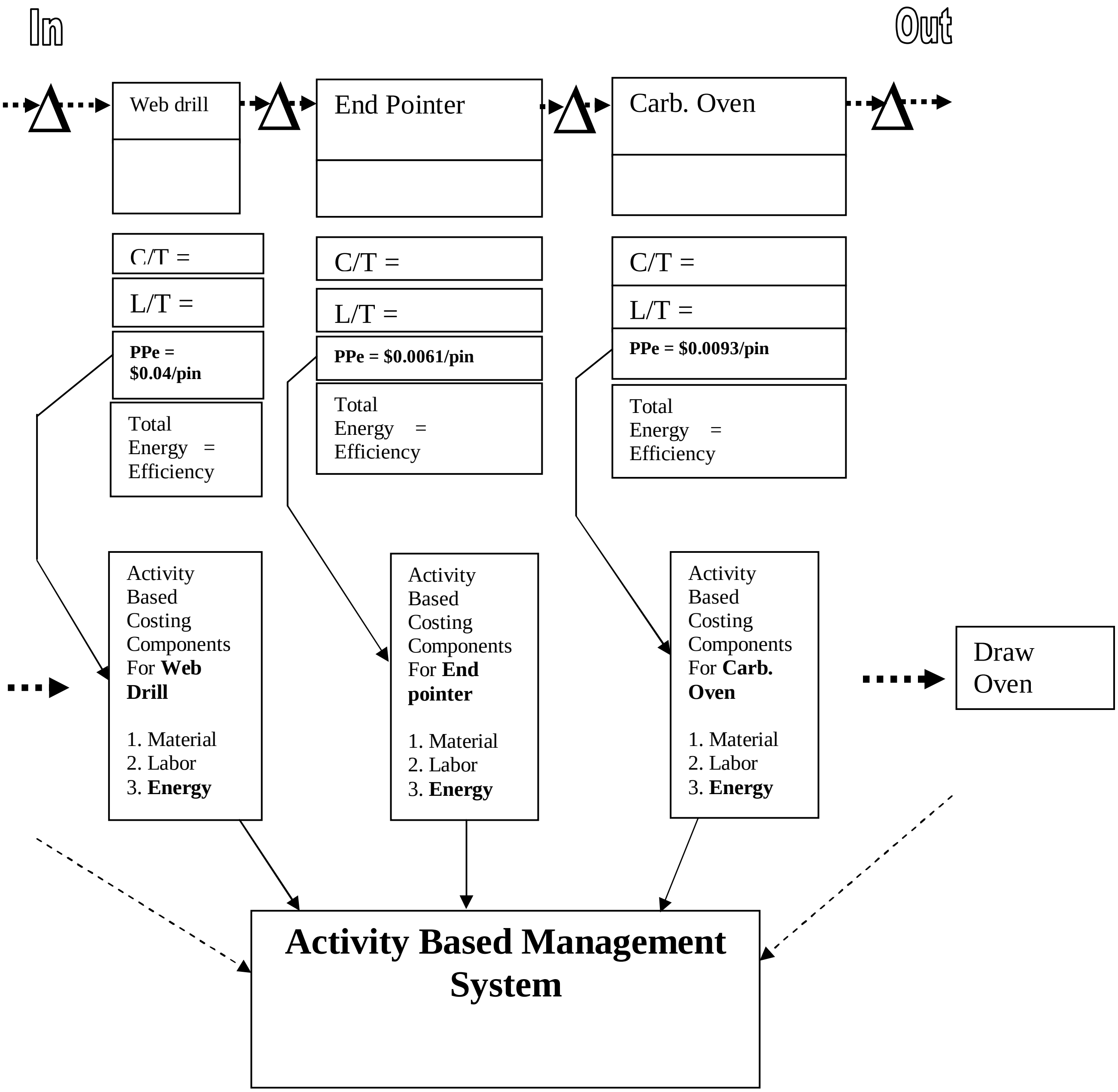


Figure 35. Value stream map with partial productivity/ABM interface for processes four through six of case study example.

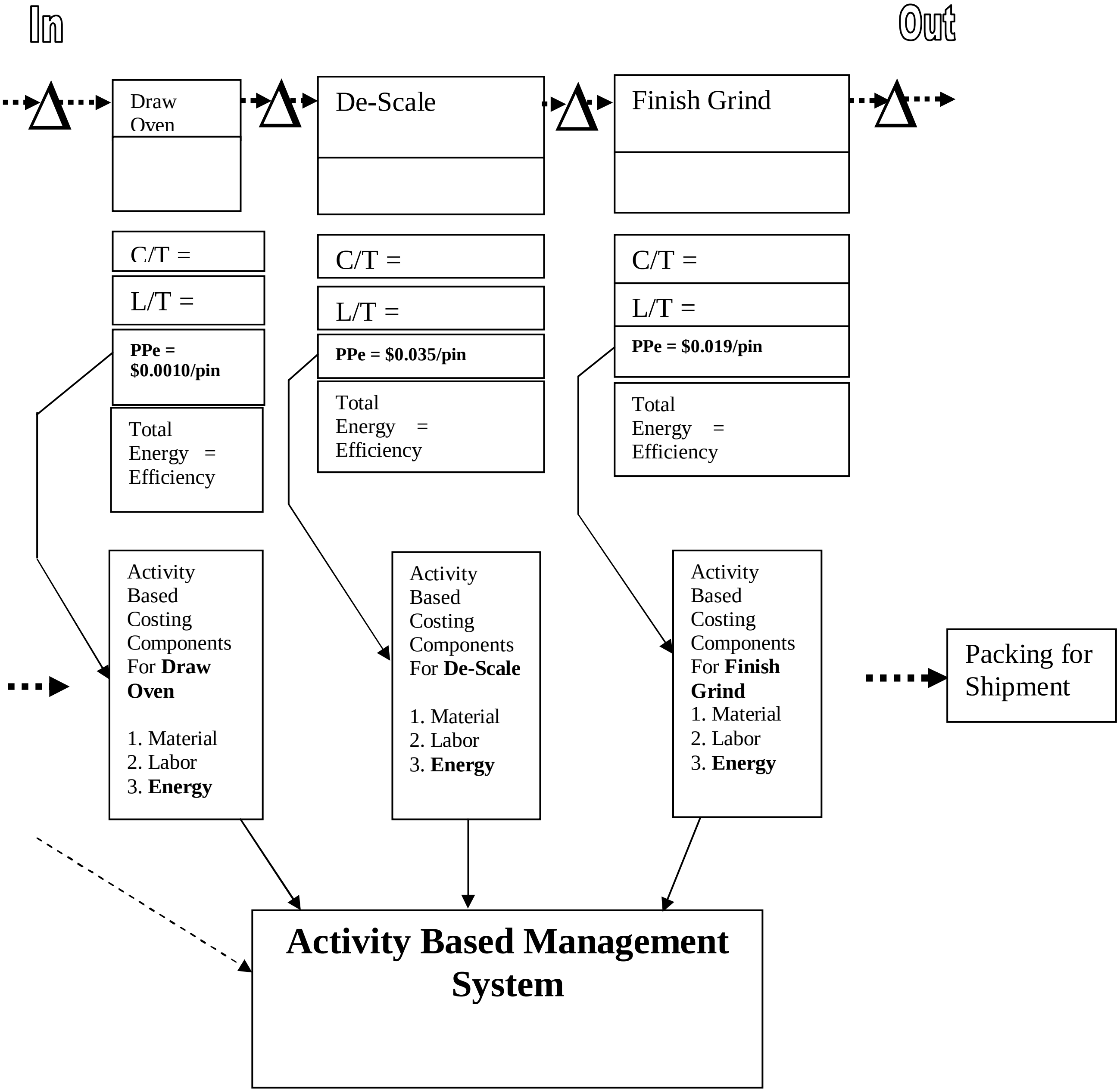


Figure 36. Value stream map with partial productivity/ABM interface for last three processes of case study example.

Exergy Analysis

Comparison of Minimum Exergy (Availability) Required for Processes in Case Study Example (Exergy Ratio)

As described in the methodology Chapter (III), the ERDT uses task exergy utilization efficiency ratios. For mechanical and electrical processes (other than thermal processes), the ERDT uses the practical theoretical minimum energy information described in the first law analysis.

Process: Cold Saw

This is an electro-mechanical metal cutting or subtractive process. From the discussion regarding exergy analysis of mechanical systems in Chapter III, the kinetic and potential energy in such systems can be converted directly to the energy equivalents. This significantly simplifies the first law analysis, however, for second law analysis the irreversibilities in such processes must be accounted for.

In metal cutting, the tool is overcoming the plastic deformation and frictional energies of the work piece (see Figure 37). The plastic deformation or shear specific energy is useful and produces the actual work of shearing and chip removal while the frictional energy (heat) is a useless by-product of the process (Kalpakjian, 2001, p883). The total specific energy (u_t) is expressed as:

$$u_t = u_s + u_f \tag{87}$$

where: u_s is the specific energy of plastic deformation or shearing and u_f is the specific energy of friction (Vaz, 2000).

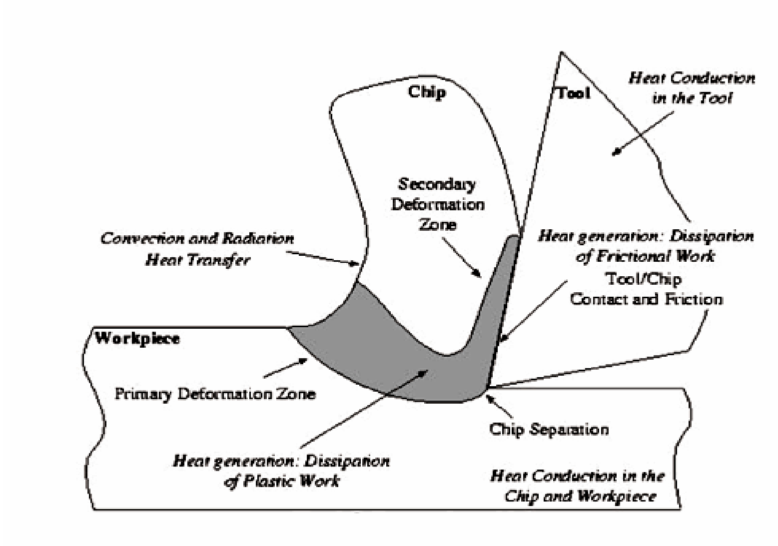
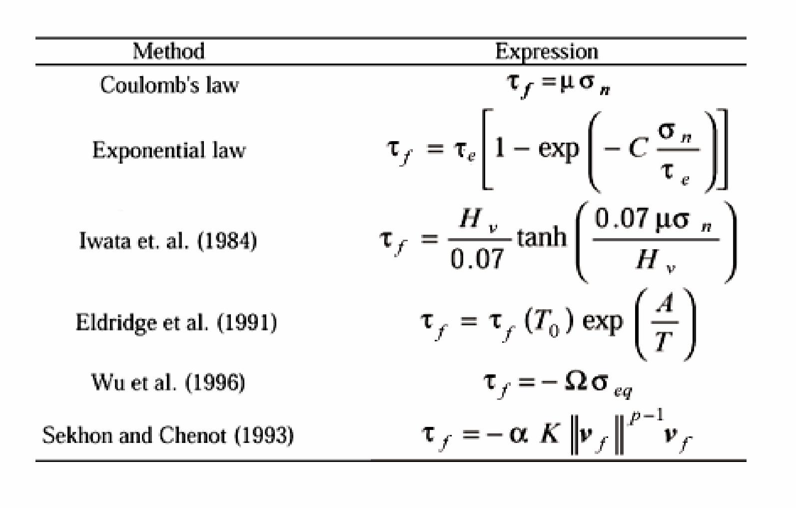


Figure 37. Diagram showing plastic deformation and friction heat (energy) zones in metal cutting operation (M. Vaz Jr.)

The friction energy (heat) generated in the metal cutting operation can be calculated or simulated using a variety of models (see Table 16).



Method	Expression
Coulomb's law	$\tau_f = \mu \sigma_n$
Exponential law	$\tau_f = \tau_e \left[1 - \exp\left(-C \frac{\sigma_n}{\tau_e} \right) \right]$
Iwata et. al. (1984)	$\tau_f = \frac{H_v}{0.07} \tanh\left(\frac{0.07 \mu \sigma_n}{H_v} \right)$
Eldridge et al. (1991)	$\tau_f = \tau_f (T_0) \exp\left(\frac{A}{T} \right)$
Wu et al. (1996)	$\tau_f = - \Omega \sigma_{eq}$
Sekhon and Chenot (1993)	$\tau_f = - \alpha K \left\| \boldsymbol{v}_f \right\|^{p-1} \boldsymbol{v}_f$

Table 16. Various friction temperature models for metal cutting operations (M. Vaz Jr.)

In order to simplify the analysis for the cutting examples, the author will use a typical percentage of the total specific energy that is the specific energy of friction. Some literature (Keopfer, 2006) indicates that 18% of the cutting tool heat waste energy is created at the tool/chip secondary shear zone and another 2% is generated at the tool tip. Kalpakjian demonstrates a detailed example of metal cutting where the specific energy of friction is 32% of the total cutting energy (Kalpakjian, p.549, 2001). Dr. Tim Gutowski estimates that 30-40% of the total specific energy at a metal cutting tool is frictional energy. Therefore, the author will use a value of 30% of the total specific energy of cutting as frictional energy ($u_f = 1 - 0.30$).

The plastic deformation work in metal cutting for this report can be expressed as:

$$W_{Plastic} = \left(u_t x(1 - 0.3)\right) \tag{88}$$

Conversations with Dr. Gutowski at MIT (Gutowski – phone conversation) indicated that an acceptable exergy analysis of the motor/tool/workpiece system boundary could be described as the ratio of the plastic deformation work divided by the electrical work input in to the workpiece.

$$\varepsilon_{MetalCutting} = \frac{PlasticWork_{Cutting}}{W_e} \text{ and } \varepsilon_{MetalWorking} = \frac{\left(u_t x(1 - 0.3)\right)}{W_{ActualInput}} \tag{89}$$

Therefore, the exergy efficiency ratio for all types of metal cutting and forming will be the energy needed for plastic deformation. The electric motor efficiency is not used in the exergy utilization efficiency for the same de-coupling of 1st law efficiency from exergy utilization discussed in the thermal problems.

For the total specific energy of the cold saw, the first law minimum energy requirement will be used:

E_{cmin} = Theoretical minimum energy needed for single cut = (4.01 kW)(9sec/3,600 sec/hr) = 0.010 kWh/cut = 36 KJ/0.67 Kg = **53.7 KJ/Kg =** u_t

For the total work input to the saw the actual energy input will be used:

E_{cact} = Actual minimum energy needed for single cut = (8.0 kW)(9sec/3,600 sec/hr) = 0.020 kWh/cut = 72 KJ/0.67 Kg = **107.5 KJ/Kg**

$$\varepsilon_{ColdSaw} = \frac{(u_t x(1-0.3))}{W_{ActualInput}}$$

Therefore the exergetic efficiency for the cold saw is:

$$\varepsilon_{ColdSaw} = \frac{(53.7KJ(1-0.3))}{107.5KJ} = \mathbf{0.35}$$

Process: Lubricant Coating Line Baths

This is a thermal energy process and will not have the same exergy quantities as the first law energy analysis of the same process and consequently, the exergetic efficiency ratios will also be different. The exergetic efficiency equation 43 from Chapter III gives the following analysis:

$$\varepsilon = \frac{mc\{\Delta T - T_0 \ln[(T_i + \Delta T)/T_i]\}}{W_e} \tag{90}$$

$$\varepsilon_U = \left[1 - \frac{T_0}{\Delta T}\ln\left(\frac{T_i + \Delta T}{T_i}\right)\right] \tag{91}$$

where: $T_0 = T_i$ = 25 °C = 298 °K

$\Delta T = 50$ °K

$$\varepsilon_U = \left[1 - \frac{298}{50}\ln\left(\frac{298+50}{298}\right)\right] = \mathbf{0.076}$$

Process: Press Forge

This is also an electro-mechanical process. Therefore, the exergy utilization efficiency ratio calculations will be similar to the first law energy efficiency ratio calculations with the exception of the friction forces. The energy efficiency was described as the ratio of the theoretical minimum energy needed for a single forging/extrusion to the actual minimum energy needed for forming a single pin. The exergy efficiency ratio is the ratio of the minimum available exergy needed to transform the product to the amount of exergy actually input into the process:

Using the same percentage of friction heat generated (30%) for the press forge, the plastic deformation work in indirect or reverse extrusion for this report can also be expressed as:

$$W_{Plastic} = \left(u_t x(1-0.3)\right) x \eta_{ElectricMotor} \tag{92}$$

However, as described in the exergy utilization efficiency description in Chapter III, the first law efficiency term (η) is removed so that the exergy term can be examined in isolation. For the total specific energy of the press forge, the first law minimum energy requirement will be used:

Energy$_{\text{min}}$ = power x time = (25.6 kW)(2 min/60 min/hr) = 0.85 kWh/pin = 3,060 KJ/0.67 Kg = **4,567.2 KJ/Kg**

Energy$_{\text{actual}}$ = (167.6 kW)(2 minutes/60 min/hour) = 5.59 kWh/pin = 20,124 KJ/0.67 Kg = **30,035.8 KJ/Kg**

$$\varepsilon_{\Pr essForge} = \frac{(u_t x(1-0.3))}{W_{ActualInput}} \tag{93}$$

Therefore, the exergetic efficiency for the cold saw is:

$$\varepsilon_{\Pr essForge} = \frac{(4{,}567.2KJ(1-0.3))}{30{,}035.8KJ} = \mathbf{0.11}$$

Process: Web Drill

This is also an electro-mechanical process. Therefore, the exergy utilization efficiency ratio calculations will also be similar to the first law energy efficiency ratio calculations with the exception of the friction forces. The energy efficiency was described as the ratio of the theoretical minimum energy needed for the drill to cut and remove the center web section from the forged pin to the actual energy usage. The exergy efficiency ratio is the ratio of the minimum available exergy needed to drill the web to the amount of exergy actually input into the drill chuck (electric motor):

Using the same percentage of friction heat generated (30%) for the other metal working examples, the plastic deformation work in drilling for this report can also be expressed as:

$$W_{Plastic} = (u_t x(1-0.3))$$

For the total specific energy of the press forge, the first law minimum energy requirement will be used:

Energy_{min} = power x time = (0.78 kW)(16 sec/3,600 sec/hr) = 0.00347 kWh/pin = 12.5 KJ/0.66 Kg[32] = **18.9 KJ/Kg**

Energy_{actual} = (7.5 kW)(16 seconds/3,600 sec/hour) = 0.033 kWh/pin = 1,188 KJ/0.66 Kg = **1,800 KJ/Kg**

$$\varepsilon_{WebDrill} = \frac{(u_t x(1-0.3))}{W_{ActualInput}}$$

Therefore the exergetic efficiency for the cold saw is:

$$\varepsilon_{WebDrill} = \frac{(18.9KJ(1-0.3))}{1{,}800KJ} = \mathbf{0.007}$$

Process: End Pointer – Metal Removal

This is also an electro-mechanical metal removal process. Therefore, the exergy utilization efficiency ratio calculations will also be similar to the first law energy efficiency ratio calculations with the exception of the friction forces. The energy efficiency was described as the ratio of the theoretical minimum energy needed for the cutting tool to cut and produce the counter-bored relief on both ends of the piston pin compared to the actual energy used to accomplish the task. The exergy efficiency ratio is the ratio of the minimum available exergy needed to produce the countersink to the amount of exergy actually input into the cutting tool (electric motor):

E_{cmin} = Minimum energy needed for single cut = (4.45 kW)(5.5 sec/3,600 sec/hr) = 0.0068 kWh/cut = 24.5 KJ/0.60 Kg = **40.8 KJ/Kg**

P_{cact} = Actual power needed for end pointers saw = [(14.9 kW)(2)(0.8)]/(0.8) = 29.8 kW

---

[32] Average of new pin weight after material removal

E_{cact} = Actual energy needed for single cut = (29.8 kW)(5.5 sec/3,600 sec/hr) = 0.046 kWh/cut = 165.6 Kg/0.60 Kg = **276.0 KJ/Kg**

$$\varepsilon_{EnPo\,\mathrm{int}\,er} = \frac{\left(u_t x(1-0.3)\right)}{W_{ActualInput}}$$

Therefore the exergetic efficiency for the cold saw is:

$$\varepsilon_{EndPo\,\mathrm{int}\,er} = \frac{\left(40.8KJ(1-0.3)\right)}{276.0KJ} = \mathbf{0.10}$$

Process: Carburization Oven – Metal Heat Treat

This is a thermal energy process and will have unique exergy calculations as compared to the mechanical processes.

The carburization process is assumed to be occurring at steady state. The author points out that this is a simplified analysis of a combustion process. A more detailed analysis would include the destruction of availability by the combustion processes itself where different chemical species are destroyed and created (Moran, 1983, p 93). For example, a considerable amount of exergy is lost in simply heating the nitrogen in the combustion air to the flame temperature. Suffice it to say, a more detailed exergetic task efficiency ratio will probably be lower than the simplified version shown here.

This is a case where the oven's supplied fuel - natural gas is supplying a flame at the adiabatic flame temperature (T_s). The adiabatic flame temperature is calculated based on the enthalpies of the reactants and products (Cengal, Boles, 1998, p.781). For natural gas, the value of 2,200 °K for methane is used as the adiabatic flame temperature. The temperature of utilization (T_u) is the temperature maintained in the carburization oven to treat the pins. The temperature of utilization is 900 °C or 1,173 °K. The ambient, or dead-state, temperature is 25 °C or 298 °K.

Using the exergetic utilization efficiency equation (64) from Chapter III gives the following analysis:

$$\varepsilon_U = \frac{\left(1-\frac{T_0}{T_u}\right)\dot{Q}_u}{\left(1-\frac{T_0}{T_s}\right)\dot{Q}_s} \tag{64}$$

Delivery of thermal energy at a (use) temperature T_u from an energy source at temperature T_s, while both T_u and T_s may be different than T_0.

Both use and source temperatures are different than the dead state T_0. An example of this type of system would be a boiler with an adiabatic flame at T_s producing steam at a saturated temperature of T_u. The steam is then used in the manufacturing process. Because this is a thermal transfer system there is no shaft work, just heat transfer and therefore:

$0 = \dot{Q}_s - \dot{Q}_u - \dot{Q}_l$ expanding terms

$$0 = \left(1-\frac{T_0}{T_s}\right)\dot{Q}_s - \left(1-\frac{T_0}{T_u}\right)\dot{Q}_u - \int_{\wp}\left(1-\frac{T_0}{T_l}\right)q_l\,d\wp - \dot{I}$$

where $\dot{Q}_l$ equals heat energy losses

Because this system is at steady state, the expression reduces to:

$$\varepsilon = \frac{\left(1 - \frac{T_0}{T_u}\right)\dot{Q}_u}{\left(1 - \frac{T_0}{T_s}\right)\dot{Q}_s}$$

The first law efficiency for this system is simply:

$$\eta = \frac{\dot{Q}_u}{\dot{Q}_s}$$

The exergy efficiency (equation 65) now reduces to:

$$\varepsilon = \eta \frac{\left(1 - \frac{T_0}{T_u}\right)}{\left(1 - \frac{T_0}{T_s}\right)}$$

The exergy utilization efficiency for this class of process is:

$$\varepsilon_U = \frac{\left(1 - \frac{T_0}{T_u}\right)}{\left(1 - \frac{T_0}{T_s}\right)}$$

$$\varepsilon_{U-CarburizationOven} = \frac{\left(1 - \frac{298}{1{,}173}\right)}{\left(1 - \frac{298}{2{,}200}\right)} = [(0.75)/(0.87)] = \mathbf{0.86}$$

Process: Draw Oven – Metal Heat Treat

This is also a thermal energy process and will have unique exergy calculations as compared to the mechanical processes.

Like the carburization process, the draw oven is assumed to be occurring at steady state. The draw oven also utilizes natural gas therefore the adiabatic flame temperature of methane (T_s) will be used again (2,200 °K). The temperature of utilization (T_u) is the temperature maintained in the draw oven further heat-treat the pins. The temperature of utilization is 171 °C or 444 °K. The ambient, or dead-state, temperature is 25 °C or 298 °K.

Again, using the exergetic efficiency equation (64) from Chapter III gives the following analysis:

$$\varepsilon = \frac{\left(1 - \frac{T_0}{T_u}\right)\dot{Q}_u}{\left(1 - \frac{T_0}{T_s}\right)\dot{Q}_s}$$

$$\varepsilon_{DrawOven} = \frac{\left(1 - \frac{298}{444}\right)\dot{Q}_u}{\left(1 - \frac{298}{2{,}200}\right)\dot{Q}_s}$$

The exergy utilization efficiency for this class of process is:

$$\varepsilon_U = \frac{\left(1 - \frac{T_0}{T_u}\right)}{\left(1 - \frac{T_0}{T_s}\right)}$$

$$\varepsilon_{U-DrawOven} = \frac{\left(1 - \frac{298}{444}\right)}{\left(1 - \frac{298}{2,200}\right)} = [(0.67)/(0.87)] = \mathbf{0.77}$$

Process: End De-Scale

The end de-scale process is a pneumatic abrasive blasting operation where steel shot media is transported to the workpiece at high speed via a jet of compressed air. This process requires a compound, or two part, exergy analysis. Because the system boundary for the ERDT process analysis is designed to interface with utility submetering, the analysis of the de-scale operation must include the electric power supplied to the air compressor (not simply the supply air to the jet nozzles).

Therefore, the overall exergy task efficiency will be of the form:

$$\varepsilon_{TaskTotal} = \varepsilon_{Compressor}\varepsilon_{AbrasiveNozzles} \quad (94)$$

Because the exergy efficiency of the nozzles will simply be the kinetic energy of the abrasive steel particles divided by the supplied air horsepower, this value will be the same as the first law efficiency for this process. The compressor in this case is assumed to be ideal with no heat recovery and no difference in inlet and outlet air temperature (isothermal process). Various cooling strategies used by air compressor designs make this assumption reasonable.

The exergy efficiency of the compressor however includes a term for the change in entropy as the gas (air) is compressed. Recall that the change in entropy can be described by:

$$s_2 - s_1 = C_p \ln\left(\frac{T_2}{T_1}\right) - R \ln\left(\frac{P_2}{P_1}\right) \tag{95}$$

By assuming that the inlet and outlet temperatures are the same, the first term disappears and the remaining term describes the change in entropy and exergy destroyed:

$$\text{Exergy Lost} = \dot{m} R T_0 \ln\left(\frac{P_2}{P_1}\right) \tag{96}$$

Therefore, the exergy efficiency term for the compressor would be the exergy lost divided by the electrical input to the compressor motor:

$$\varepsilon_{Compressor} = \frac{\dot{m} R T_0 \ln\left(\frac{P_2}{P_1}\right)}{\left(\frac{W_{CompressorElectricInput}}{\eta_{Compressor}}\right)} \tag{97}$$

The first term to be calculated is the compressor mechanical efficiency ($\eta_{Compressor}$). This is different than the first law task efficiency for this process calculated earlier. The efficiency of the compressor is a function of the reversible work possible versus the actual electrical work input into the device.

$$\eta_{Compressor} = \frac{W_{\mathrm{Re}\,vCompressor}}{W_{ElecCompressor}} \tag{98}$$

The compressor reversible work is given by (Cengal, Boles, 1998):

$$W_{RC} = \frac{nRT_1}{(n-1)}\left[\left(\frac{P_2}{P_1}\right)^{\frac{(n-1)}{n}} - 1\right] \tag{99}$$

where:

n = 1.4 (isentropic compression exponent)

T_1 = 298 °K

R = 0.287 KJ/Kg-K

P_2 = 758 kPa

P_1 = 101 kPa

$W_{RC} = 233.5$ KJ/Kg

To calculate the compressor power requirements, the mass flow of air through the nozzles is needed ($\dot{m}$).

$$\dot{m}_{Air} = C_{Disch\arg e}\left(\frac{2}{k+1}\right)^{\frac{1}{k-1}}\frac{P_{Line}}{RT_{Line}}A_{Nozzles}\sqrt{kR\left(\frac{2}{k+1}\right)T_{line}} \tag{100}$$

where:

C $_{\text{Discharge}}$ = Discharge loss coefficient for flow interruptions at nozzle assumed = 0.8

k = Specific heat ratio for air = 1.4

P & T $_{\text{Line}}$ = Pressure and temperature of the compressed air lines = 758 kPa, 298 °K

R = 0.287 KJ/Kg-K

$\dot{m}_{Air}$ = 0.368 Kg/second

Power at compressor needed for nozzles = $(\dot{m}_{Air})(W_{RC})$

= (0.368 Kg/s)(233.5 KJ/Kg) = 85.9 kW

Estimated horsepower at compressor to supply 4 CFM per horsepower[33] at 286.2 CFM = 141 HP = 105.2 kW

Air compressor system efficiency = $\eta_{Compressor}$

= Power (Supplied to Nozzles) / Power (Supplied to Compressor) = $\frac{85.9kW}{105.2kW}$ = 0.82

The exergy efficiency of the compressor is calculated next: $\varepsilon_{Compressor}$

$$\varepsilon_{Compressor} = \frac{\dot{m}RT_0 \ln\left(\frac{P_2}{P_1}\right)}{\left(\frac{W_{CompressorElectricInput}}{\eta_{Compressor}}\right)} = \frac{(0.368)(0.287)(298)\ln\left(\frac{758}{101}\right)}{\frac{85.9kW}{0.82}} = 0.61 \qquad (101)$$

From the bandwidth analysis, the exergetic ratio for the abrasive nozzles is $\varepsilon_{AbrasiveNozzles}$ = 0.008

The overall exergy utilization task efficiency is:

$\varepsilon_{U\,TaskTotal} = \varepsilon_{U\,Compressor}\varepsilon_{U\,AbrasiveNozzles} = (0.61)(0.008) = 4.9 \text{ x } 10^{-3}$ = **0.0049**

Process: Finish Grinding/Lapping

This is also an electro-mechanical process. Therefore, the exergy utilization efficiency ratio calculations will be similar to the first law energy efficiency ratio calculations with the exception of the friction forces. The energy efficiency was described as the ratio of the theoretical minimum energy needed to finish grind a single pin versus the actual minimum energy needed for finish grinding. The exergy efficiency

---

[33] Industry estimate of typical CFM/HP (http://www.ecompressedair.com/library/compressedairsystems.shtml)

ratio is the ratio of the minimum available exergy needed to transform the product to the amount of exergy actually input into the process:

$$\varepsilon_{FinishGrind} = \frac{(u_t x(1-0.3))}{W_{ActualInput}} \tag{102}$$

Total specific energy for finish grinding = 9.0 KJ/pin + 5.4 KJ/pin + 3.6 KJ/pin = 18.0 KJ/0.60 Kg = **30.0 KJ/Kg**

Total E_{gactual} = 0.068 kWh + 0.055 kWh + 0.018 kWh = 0.14 kWh/pin = 504 KJ/pin = 504 KJ/0.60 Kg = **840.0 KJ/Kg**

Therefore the exergetic utilization efficiency for the cold saw is:

$$\varepsilon_{U\,FinishGrind} = \frac{(30.0KJ\,(1-0.3))}{840.0KJ} = \mathbf{0.025}$$

Now that the ERDT has generated the energy and exergy process task efficiencies, the model will now demonstrate the prescriptive functions. Starting with the maximum and minimum energy and exergy ratios in Table 17, the ERDT now makes recommendations to the engineer for further analysis. The combined bandwidth charts shown in Figure 38 are generated as a visual aid. This prescriptive set of deliverables for the case study using the ERDT decision rules are demonstrated after the bandwidth chart below.

Activities	Energy Type	1st Law Energy Efficiency (η)	2nd Law Exergy Utilization Efficiency	Exergy U to Energy Ratio (εu/η)
Cold Saw	Electrical	0.100	0.063	0.630
Lubricant Chemical Baths	Electrical	0.340	0.020	0.059
Forge Press	Electrical	0.150	0.100	0.667
Web Drill	Electrical	0.011	0.006	0.582
End Pointer	Electrical	0.150	0.095	0.633
Carburization Oven	Natural Gas	0.900	0.250	0.278
Draw Oven	Natural Gas	0.960	0.160	0.167
De-Scale	Electrical	0.008	0.005	0.620
Finish Grind	Electrical	0.036	0.024	0.667

▒	Low 1st Law
░	Low 2nd Law
▨	Low ε/η

Table 17. Case study η & ε - Efficiency Table) Comparison of the processes and their respective efficiencies.

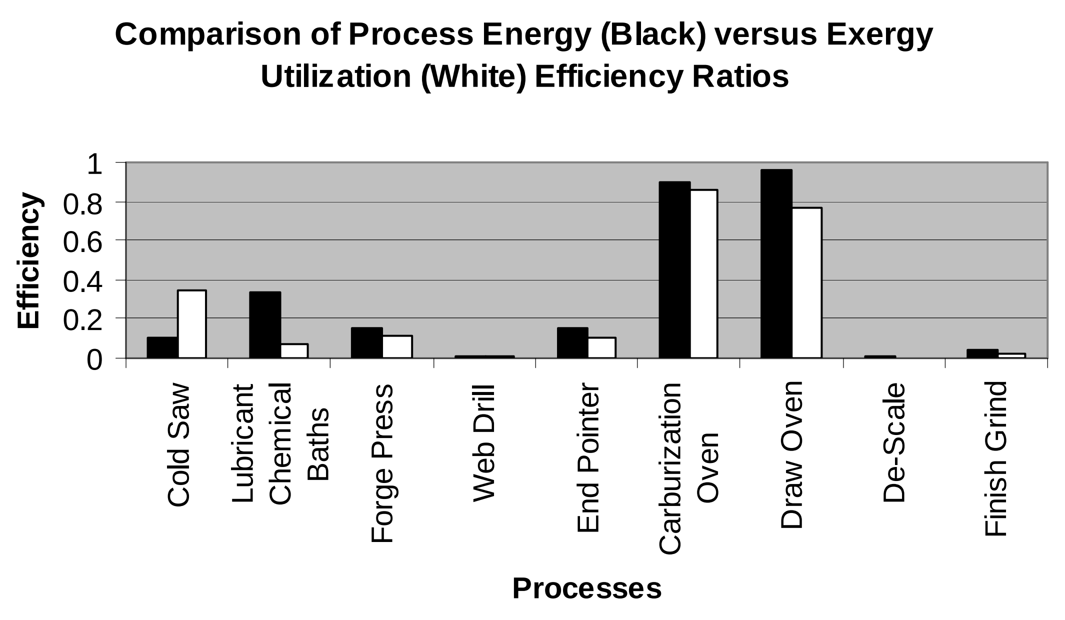


Figure 38. Process comparison of exergetic versus energy efficiencies.

ERDT Decision Rules

3) If 1st Law efficiency is low:
    a. And 2nd Law efficiency is high (relatively) – Consider alternative process or redesign. (Process is matching energy effectively but design or implementation is poor) – ***No Examples in this Particular Case***
    b. And 2nd Law efficiency is low – Consider new process.(Poor process design is wasting high quality energy/exergy) – ***De-scale***
4) If 1st Law efficiency is high:
    a. And 2nd Law efficiency is high or equal– Process may be adequate for task – (Relatively) – ***Ovens and Forge Press (relatively)***
    b. And 2nd Law efficiency is low – Process design or inefficiency is wasting high quality energy (Consider using waste energy/exergy recovery and improvement of current process) – ***Chemical Baths***

The metal working machines have low efficiencies but are probably the only current methods to achieve the desired product transformations practically. Therefore, metal working tools are not considered for improvement. This is not to say there is not an energy management opportunity with these processes, only the issue is not further explored in this research.

Based on the AHP decision matrix ranking and the exergy/energy efficiency ratios shown in Table 17 and the ERDT decision rules, a set of recommendations might be as follows:

1) Try to match the waste heat energy coming from the carburization oven to provide the heat energy for the chemical baths.
2) If there is sufficient heat energy remaining in the carburization oven exhaust stream after recommendation #1, use this heat energy/exergy to supply or supplement the draw oven.
3) While the de-scale operation has smaller energy usage than the thermal processes in recommendations #1 and #2, the extremely low exergy and energy ratios indicate a need to search for a completely different process to accomplish this task (e.g., centrifugal shot dispenser).

Matching Process Exergy Waste Streams to Needed Exergy Inputs in Other Processes

As mentioned in the methodology chapter, future versions of the ERDT will include interfaces and integration with pinch analysis and process integration in order to match waste energy streams to needed energy inputs in other co-located processes. In order to demonstrate some of this promise of this capability, an abbreviated pinch "type" analysis is provided below.

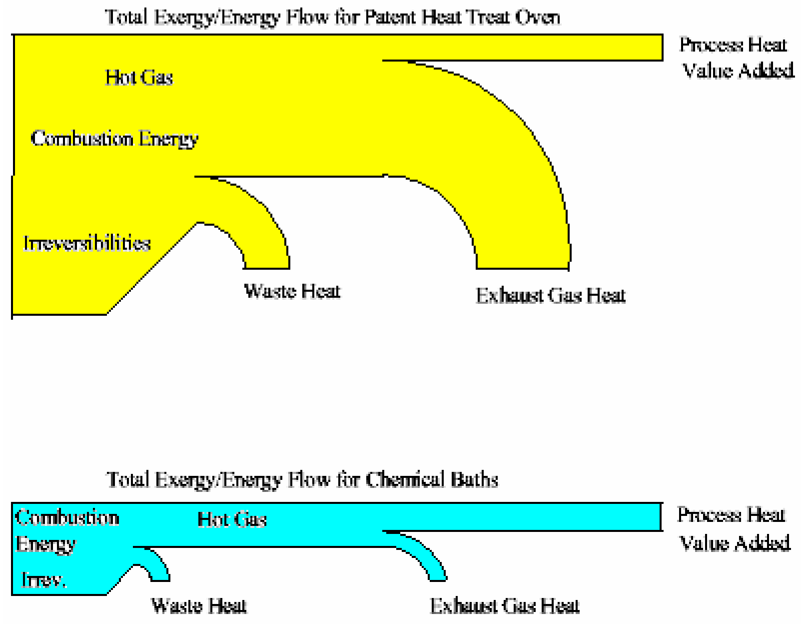


Figure 39. Exergy stream diagrams for heat treat oven and chemical baths.

Examination of the ERDT bandwidth data reveals a possible potential to recover waste heat exergy for use elsewhere in the other processes (Figure 38). The carburization oven, and to a lesser degree the draw oven, have large amounts of high value exergy (high temperature gases) for use in their process. Unfortunately, the lower energy (first law) efficiencies indicate that a significant amount of this high quality exergy is escaping as heat energy loss through the flue exhaust.

By searching the other processes, and based on the ERDT decision rules above, the energy engineer decides that the chemical baths are a good recipient candidate for this waste exergy. By performing an additional set of exergy calculations (pinch analysis) on the carburization oven and the chemical baths, this opportunity can be confirmed or denied.

Exergy Content of the Carburization Oven Exhaust Stream

The carburization oven exhausts a steady stream of hot gases at 900 °C or about 1,173 °K. The chemical tanks require hot water and aqueous solutions at 77 °C or about 350 °K. For simplification the properties of air will suffice as the ideal gas in this estimate. Assuming an air to water heat exchanger efficiency, or pinch, of 75%, the temperature needed for the chemical baths would be (350 °K)/0.75 = 467 °K. Therefore, 467 °K will be the reference temperature for the carburization oven waste exergy calculation:

$$Exergy = (h - h_0) - T_0(s - s_0)$$

where:

h = Air stream enthalpy at temperature T (1,173 °K)

h_0 = Air stream enthalpy at temperature T_0 (reference 350 °K)

T_0 = Temperature at reference conditions (350 °K)

s = Air stream entropy at temperature T (1,173 °K)

s_0 = Air stream entropy at temperature T_0 (reference 350 °K)

Using air as the working fluid and air properties tables (Cengal, 1998, p923):

Exergy Avail. = (1,246.14 KJ/Kg – 350.49 KJ/Kg) – (350 °K)(3.15216 KJ/Kg-K – 1.85708 KJ/Kg-K) = 895.65 KJ/Kg – 453.28 KJ/Kg = **442.37 KJ/Kg**

The fact that this calculation produces a positive number indicates that there is available exergy in the carburization oven exhaust that can be used to heat the chemical baths. A similar calculation is performed for the chemical baths, except water is the working fluid. Note that now the reference temperature is 300 °K and the tank water temperature is 350 °K.

$$Exergy = (h - h_0) - T_0(s - s_0)$$

Where:

h = Water enthalpy at temperature T (350 °K)

h_0 = Water enthalpy at temperature T_0 (reference 300 °K)

T_0 = Temperature at reference conditions (300 °K)

s = Water entropy at temperature T (350 °K)

s_0 = Water entropy at temperature T_0 (reference 300 °K)

Using water as the working fluid and saturated water properties tables (Cengal, 1998, p904):

Exergy Needed = (322.32 KJ/Kg – 113.25 KJ/Kg) – (300 °K)(1.0394 KJ/Kg-K – 0.3952 KJ/Kg-K) = 209.07 KJ/Kg – 193.26 KJ/Kg = **15.81 KJ/Kg**

Because the heat is being transferred from different fluids with different densities (air and water), the mass flows must be considered:

An estimate of the mass flow rate of gas leaving the carburization oven is 1,305 Kg/hour based on the expansion rate and fuel inputs rates given by the manufacturer (Atmosphere Furnace Company, 1975). Therefore, the oven has the potential to transfer:

(442.37 KJ/Kg)(1,305 Kg/hour) = 577,293 KJ/hour

The chemical baths have 8,721 liters of water or 8,721 Kg of water. Therefore, the chemical baths will require:

(15.81 KJ/Kg)(8,721 Kg) = 137,879 KJ

(577,293 KJ/hour)/(137,879 KJ) = 4.18/hour

The Carburization oven's exhaust exergy can supply the amount of heat exergy needed by the chemical baths every 14.3 minutes. Considering that the chemical bath heat requirement is on a 40 minute cycle, this is ample. Therefore, using the carburization oven's exhaust heat to supply the chemical baths in lieu of the electrical resistance heaters appears to be a viable project.

Traditional IAC Energy Audit at Facility

The energy auditing method used by most industrial assessment centers is based on the established method of billing analysis followed by identification of opportunities during the facility site visit. The traditional energy audits successfully identify areas for improvement. While the actual performance of the energy audit method varies somewhat between IAC's, the underlying framework is similar. The University of Dayton industrial assessment center is an exception that uses an inside-out analysis approach similar to the ERDT method (Kissock Conversation, 2006).

The manufacturing facility which is the focus of the main ERDT case study in this dissertation was audited by the OSU-IAC team on February 26, 2003. The audit methodology used at that time was a traditional auditing approach described below.

While the facility product throughput numbers had increased slightly in the span of three years since this initial audit, the processes remained the same except for changes to two major energy users.

In 2003, the plant used a steam boiler and heat exchangers to heat the zinc phosphate lubricant chemical and rinse tanks. This boiler was removed in 2005 and the chemical and rinse tanks were outfitted with electric resistance heaters (see Lubricant Coating Baths process description in ERDT methodology above). A dedicated annealing oven was used for a particular product line. This furnace was also removed. Other than these major changes, the plant is generally the same as when the 2003 IAC audit was performed.

The traditional one-day IAC audit at the Burgess Norton facility followed the normal procedures for such audits, namely:

1) Initial contact with request for following information via fax or mail:
    a. Principal products
    b. Production per year
    c. Number of employees
    d. Number of buildings
    e. Plant floor space
    f. Facility layout
    g. Twelve month billing history for electric, water and gas utilities
    c. Annual sales
    d. Number of shifts
    e. Primary energy users (Boilers, chillers, furnaces, air compressors)

    f. HVAC notes
    g. Lighting notes
    h. Other energy consumers
    i. Process flow chart (if available)

2) Plant site visit
    a. Introduction meeting
    b. Verbal plant process description by plant personnel
    c. Walk-through audit
    d. Team brainstorming meeting to select areas (processes) of concentration
    e. Team break-up to examine selected areas of concentration
    f. Assignment of engineers to particular areas of interest
    g. Recording details of processes
    h. Installing and recording process particulars (energy related) via loggers and monitoring devices
    i. Meeting with plant personnel during audit for further clarification
    j. Closing meeting with plant personnel and audit team to clarify and select processes to perform energy management opportunity calculations

3) Post-Audit Analysis and Delivery
    a. Assembling all relevant data into coherent information base

b. Assignment of Assessment Recommendation (AR) analysis and write-up to appropriate engineers
c. Analysis of AR's phase
d. Re-contact with plant personnel where needed and appropriate
e. Assembly of AR's into coherent report
f. Proof reading of report
g. Report delivery to client

Recommendations from IAC audit at facility:

AR #1 IMPLEMENT DUTY CYCLING OF ROOF TOP A/C UNITS

AR #2 INSTALL OCCUPANCY SENSORS IN LESS OCCUPIED AREAS

AR #3 INSTALL VARIABLE FREQUENCY DRIVE ON 15 HP COOLING TOWER MOTOR

AR #4 INSULATE BOILER FEED WATER TANK

AR #5 REPLACE T12 FLUORESCENT LIGHTING WITH T8 LAMPS

AR #6 INSTALL REACTIVATE ECONOMIZERS ON ROOF TOP UNITS

AR #7 INSULATE ANNEAL HEAT TREAT FURNACE

AR #8 SOFT GRIND PINS BEFORE HARDENING PROCESS

Discussion:

What follows is a discussion and comparison of the traditional IAC audit to the ERDT methodology. It should be pointed out that the comparison is for the illustration of differences. As discussed in the introduction, the ERDT method compliments and extends the traditional audit for process analysis.

The traditional IAC audits are usually hampered by having a time limit of one to two days on-site for the plant tour and process evaluation. Because of this, complicated processes are sometimes not examined (plant personnel may not be available to explain the processes or enough energy savings potential exists in other more accessible systems in the facility).

The ERDT methodology requires the engineer to gather enough detail about the processes that the methodology can work. The ERDT information gathering may require several site visits. This raises the possibility that the traditional energy audits may also perform better if given enough days on-site. This is a legitimate concern, however the systematic inside-out analysis method of the ERDT should perform better at spotting core process opportunities than the traditional auditing method regardless of time on-site. It is the opinion of the author that the ERDT can also be accomplished in a one day audit assuming the following (also see Chapter V – Future Research):

1. The client (facility personnel) are knowledgeable and willing to provide the level of detail needed (this is not usually the case in one day audits).
2. The manufacturing facility is not so complex and/or large that it is difficult to grasp the major energy utilizing systems.
3. The energy engineers possess enough skills to identify and select the appropriate systems.

The 2003 IAC energy audit provided at this facility identified approximately $20,000 per year in energy related savings for a $33,000 investment. Due to a change in management personnel who worked with the IAC team, it is uncertain what ultimate impact the IAC audit report had on decisions in the plant, however, two of the systems highlighted in the report as needing improvement were subsequently removed and replaced with other technologies (annealing furnace and steam boiler).

Of the eight recommendations in the old report, four deal with non-core process energy consumption such as building heating and cooling or lighting. Therefore, the report concludes that the facility heating and cooling is a major area for energy management opportunities.

One of the recommendations is for a process support activity, namely, controlling the cooling tower motor with a variable speed drive. The report concludes that this cooling tower's 15 HP (11.2 KW) motor is a significant opportunity.

The remaining three recommendations are core process specific. Upgrading or repairing the insulation on the boiler make-up water tank and the anneal furnace are process recommendations that would affect the energy value added component to the product. The report concludes that the boiler make-up water tank and the anneal furnace are major opportunities for energy management. As pointed out above, about two years after the IAC report, these systems were removed and replaced with different technologies or processes.

The last AR is a process change recommendation that could save time and energy utilization by switching the order of processing the pins. This recommendation (if feasible and implemented) could affect the energy value added to the product. This recommendation implies that process sequence changes could provide significant opportunities in energy management.

In summary, the opportunities highlighted by the traditional IAC audit for investigation of energy savings are:

1) Facility Heating and Cooling
2) 11.2 KW cooling tower motor
3) Insulation installation or repair on
    i. Boiler Make Up Water Tank
    ii. Anneal Oven
4) Process sequence change

While the recommendations in the IAC audit have merit and could save the facility energy costs, there is limited attention on the core business processes. That is, the processes that directly impact the manufacturing of the product. The importance of concentrating on core processes is:

- Core processes at manufacturing firms are often the largest energy users and likely the largest energy savings opportunities.
- Core processes often directly impact the revenues of the company.
- Interactions between product quality and reduced resource use may be significant (positively correlated).
- Because core processes are connected to revenue, investment in improvements may be viewed more favorably by management.

Compatibility of ERDT and Traditional IAC Audit

As discussed in the introduction, the ERDT should be viewed as a logical extension or strengthening of the traditional IAC audit. The ERDT could be integrated into the existing audit template and may provide some insight into the best use of time and resources during a one day audit.

Another evolution of energy audits is the ability to recommend and track longer term impacts of recommendations. Many recommendations have longer payback periods but the impacts for energy management are also significant. Volatile energy prices are trending up, not down, and recommendations made with an eye toward this uncertainty could payoff quiet well.

Because the ERDT examines processes from their physical basis, many diverse recommendations can be examined from the “ground up”. The ERDT combined into the traditional energy audit template would provide a means of identifying and examining novel opportunities. This is one of the main reasons for using the minimum (practical) energy as the benchmark of the bandwidth analysis. This minimum may clue the engineer to the possibility that other processes may exist for performing the same task. As an example, the minimum energies required for metal removal are often quite small. This indicates there may be processes that can remove metal using much lower energies. This is the case with chemical and electrical discharge machining (CDM and EDM). These alternative processes may not be applicable for other reasons (e.g., time constraints etc.) but they do exist.

CHAPTER V. CONCLUSION

Overview of Methodology

As previously discussed, the ERDT methodology is a detailed, systematic methodology suitable for energy engineers to use in identifying and selecting energy management opportunities in manufacturing plants. The ERDT brings the following benefits to energy audit practices:

1) The ERDT is more systematic and therefore repeatable
2) Is based on fundamental scientific principles
3) Stands as an integration platform for various engineering methods
4) Provides greater process energy visibility
5) Concentrates on core business processes

Partially based on the traditional DOE Industrial Assessment Center and energy professional's audits, the ERDT describes a science based energy opportunity screening process. In this process, the energy opportunities become evident via the methodology and are less subjective in their selection.

As shown in Figure 40, the ERDT is a synthesis and advancement of past energy analysis techniques such as IAC audit guidelines, visualization methods, and various process specific techniques. The ERDT also is designed to integrate the techniques of energy analysis, economics, accounting, lean methods and process integration.

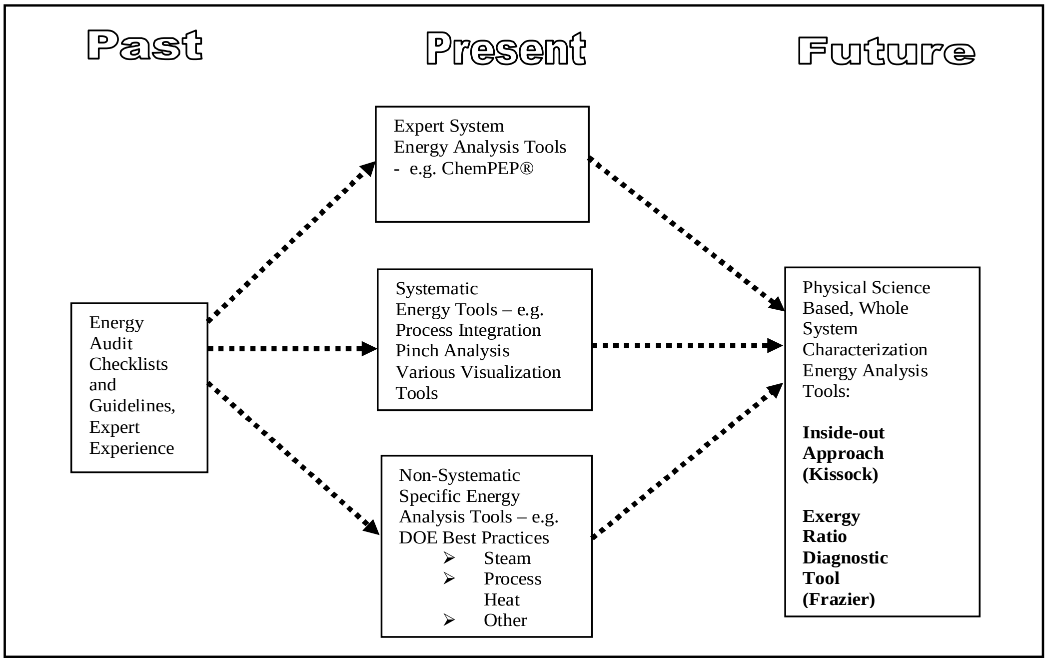


Figure 40. Chronology of energy auditing techniques.

The ERDT highlights the energy (cost) contributions to a product at various stages of manufacture. This energy costing of intermediate process steps is a useful feature for management costing decisions. The ERDT interfaces with various manufacturing management initiatives such as lean and activity based costing. The visibility of the value stream mapping corresponds to lean techniques, while the partial productivity outputs provide data directly for activity based costing. Both interfaces provide plant management with the added opportunities such systems provide. For an expanded discussion of these features see the section on future research and applications below.

The ERDT research methodology is composed of four main components:

1) A process energy usage characterization component
2) A minimum energy value-added determination for the particular process
3) A project ranking mechanism with interfaces to activity based management and lean methodologies
4) Exergy analysis of the energy utilization effectiveness of the candidate processes selected in the second component.

Summary of ERDT Constructs (Outputs):

The ERDT produces several useful outputs for the energy engineer. The most significant of the outputs is listed below:

1) Energy characterization of the various sub-processes (activities) used in the manufacture of the product. This activity matrix is the method by which the sub-processes are identified and described from both a physical science and energy perspective.
2) Identification of sub-process physical and energy leverage points during the activity (process) characterization. The physical leverage points highlight the physical aspects of the material that strongly influence the quantity and type of energy needed to accomplish the

sub-process task. The current energy leverage points highlight the current process's attributes that strongly contribute to energy usage.

3) Calculation of the sub-process's theoretical minimum energy needed to accomplish the process task per unit mass of product. This minimum number (value-added) is compared to the actual (current) energy used in the sub-process. The difference between these two numbers is the theoretical non-value added energy usage. This comparison is a form of bandwidth analysis. From the bandwidth analysis, 1st Law efficiency ratios are calculated for each sub-process. This is examining the *efficiency* of the current processes. The bandwidth analysis is the interface point for a Lean Practices program.
4) Calculation of the sub-process's energy partial productivities including: Partial Value Productivities, Partial Non-Value Added Productivities, Partial Productivity Energy Cost. These Partial Productivities are also the interface point for an Activity Based Costing system.
5) Construction of a Value Stream Map for the Sub-Processes. This is a visualization methodology borrowed from Lean Methodologies (visual management or control). The value stream map is also the interface into a lean manufacturing program from the energy perspective.

6) Exergy analysis of existing sub-processes identified in the process characterization phase of the ERDT. This second law analysis produces sub-process exergy ratios based on the theoretical exergy use of the process versus the total exergy available from the energy source. This is examining the *effectiveness* of the current processes.

7) The ranked processes are compared with both the 1st Law efficiencies and the exergy ratios (effectiveness) in tabular form. This matrix visually allows grouping of the sub-processes into categories including:
   a. Low 1st Law ratio, low exergy ratio
   b. Low 1st Law ratio, high exergy ratio
   c. High 1st Law ratio, low exergy ratio
   d. High 1st Law ratio, high exergy ratio

   These categories point the energy engineer toward one of several recommendations including:

   - a. Consider new process.(Poor process design is wasting high quality energy/exergy)
   - b. Consider process redesign or improvement. (Process is matching energy to use effectively but design or implementation is poor)

    - c. Consider alternate process or using waste energy/exergy recovery. (Process design is good but there is a misuse or waste of high quality energy)
    - d. Process may be adequate for task. (Process design is good and energy type is matched to use)

8) Hand-off point for Process Integration/Pinch Analysis for matching waste energy streams to input requirements in co-located processes.

Evaluation of the Research Results or Application

The ERDT methodology is evaluated from two standpoints; a demonstration of the validation of the concept (technical perspective) and a discussion of the usefulness (operational perspective) of the new methodology. Each perspective is described below.

ERDT Validation (Technical Perspective)

The ERDT began as an idea, or conceptualization, that a more systematic method of examining manufacturing facilities for energy opportunities could be constructed. Such a methodology would provide considerable usefulness or utility to the energy engineer. From this initial desire came the realization that a variety of useful deliverables could be gained by such an engineering methodology. These are the constructs, or outputs of the ERDT. The constructs in turn are built on accepted science and engineering methods. The science and engineering methods are, in turn, based on accepted, fundamental equations (see Figure 36 below). The constructs are validated based on content validity which draws from content domain and face validity which demonstrates the usefulness or utility of the construct (Trochim, 2006).

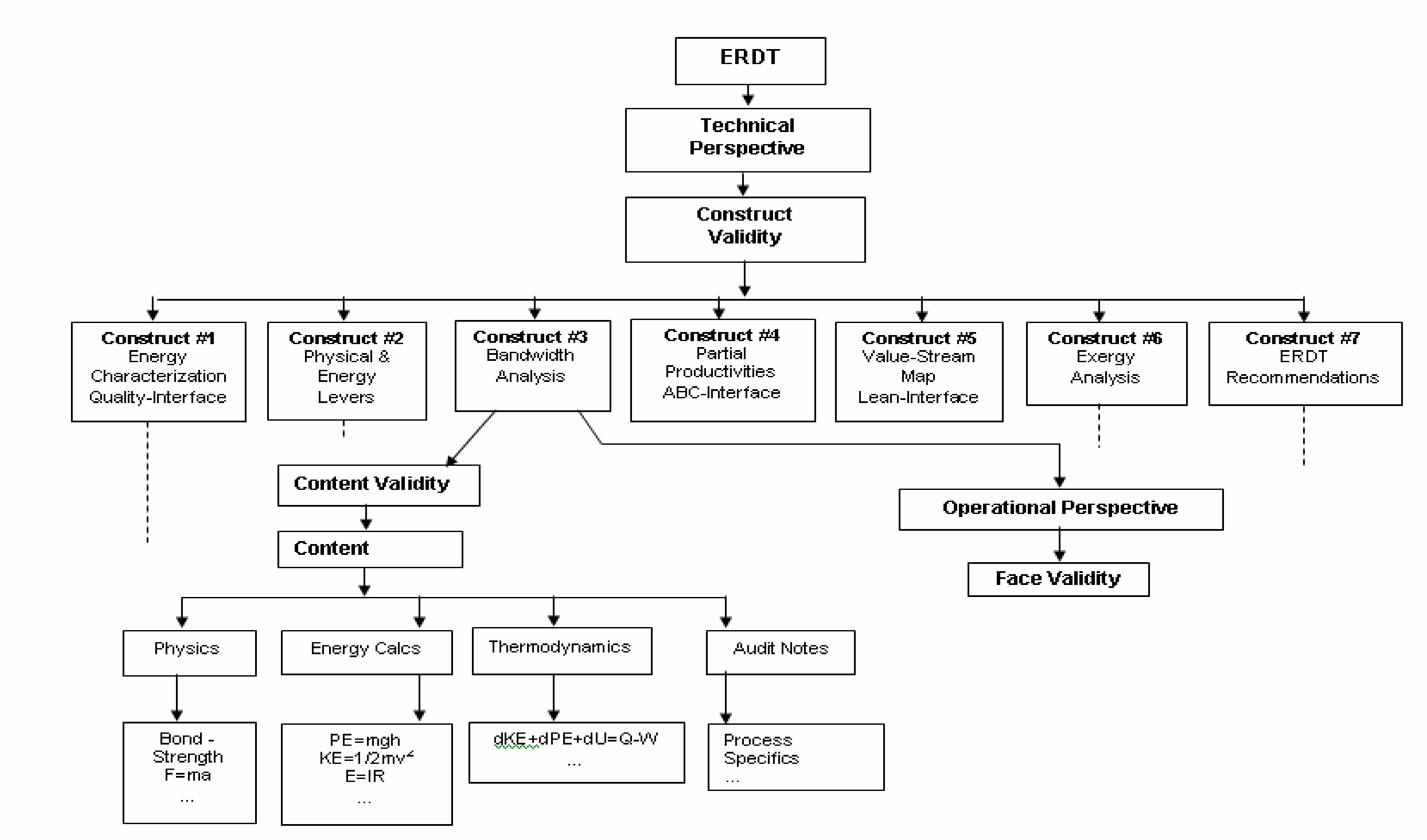


Figure 41. Diagram of the Construction and Validation Methodology for the ERDT

In order to demonstrate the validity of the ERDT, each construct will be examined separately from conceptualization to referenced basic equations or methodologies and operational usefulness.

Construct #1 (Energy characterization of the various sub-processes (activities) used in the manufacture of the product): This construct is the beginning of the ERDT process and is built based on the information gathered from the manufacturing facility site visit(s). Various tools are utilized to build the rows of the energy characterization activity matrix shown in Table 4 in Chapter III. This construct systematizes the entire ERDT from the beginning.

Content Validity and Content Domain (Technical Perspective): The energy characterization component draws directly from industrial process characterization in literature. Initial depiction of the different processes is built using the techniques of processes mapping (Damelio, 1996) or From-To charts (Nahmias, 1989). Unlike some production control techniques such as material requirements planning (MRP) described by Vollmann et al (Vollmann, 1997), this process analysis is simply a description and annotation of the product flow through the various existing processes.

Kolarik (1999) suggests a systematic method for characterization of manufacturing processes based on observation and the process value chain (PVC) model (Porter, 1985). The result is a matrix of activities, technology, principle, mechanism, leverage (described later) and levers/variables for each sub-process. Kolarik's PVC characterization is designed to concentrate on the quality aspects of the processes. That is, what influences do the processes have on quality parameters such as dimensions to specification? The ERDT borrows from this methodology with the emphasis of the description being energy usage instead of quality parameters.

Face Validity/Usefulness (Operational Perspective): The energy characterization construct has several useful features for the user. The processes identified serve as conceptual boundaries for the remainder of the methodology, but also serve as a logical location for the installation of energy submetering equipment. The very act of systematically mapping out the processes highlights opportunities sometimes otherwise missed (Parry, Turner, 2006) and (Meyer, 1997). The characterization also produces a written record of processes that often does not exist in a single, convenient source. Because this construct is based on a quality methodology, the ERDT could interface with efforts such as Six Sigma, TQM or Baldrige at this point (see discussions on Lean Methodologies interface also).

Construct #2 (Identification of sub-process physical and energy leverage points during the activity (process) characterization): This construct is a product of using Kolarik's process characterization methodology (Kolarik, 1999). The physical and energy levers identified are logical extensions of construct #1. This construct begins the identification of factors affecting the energy usage of the various processes.

Content Validity and Content Domain (Technical Perspective): Based on the information gathered in construct #1, Ishikawa diagrams (Ishikawa, 1981) are used to highlight factors that:

1. Identify physical leverage points which are parameters of the *product* that influence what processes will be needed to accomplish the sub-process task.
2. Identify how the current process applies energy to the physical leverage points.
3. Identify the energy leverage points which are parameters of the *process* that influence how much energy is used to accomplish the sub-process task.

Face Validity/Usefulness (Operational Perspective): This construct begins the process of removing the energy engineer from the outside-in view (Kissock, 2004), and forces him or her to consider the fundamental task that is being asked of the sub-process (inside-out). This systemization reduces the myopic tendency to concentrate on processes with which the engineer is familiar. All processes will have an initial equal chance of examination until later ranking and selection techniques possibly cull the list.

By identifying the process energy levers such as need for more insulation, tune equipment, etc., this construct is almost as far as many energy-auditing techniques go in total. The first two constructs, by themselves, can be (and are) used as an abbreviated energy audit methodology.

Construct #3 (Calculation of the sub-process's theoretical minimum energy required to accomplish the process task per unit mass of product, Bandwidth Analysis): This construct is the first of the energy analysis techniques. The minimum energy requirements needed to accomplish the tasks (per unit mass) identified in the first construct are determined. These minimum values are compared to the actual energy usage per unit mass in the current processes. This methodology is also called bandwidth analysis.

Content Validity and Content Domain (Technical Perspective): The determination of minimum energy requirements for the task is based on accepted scientific and engineering methods.

Materials Science/Strength of Materials/Chemistry: Depending on the transformation desired at a particular sub-process, different methods are used to determine the minimum energy requirements. In all cases, a basic understanding of the changes required of the materials must be understood. Typically, this information comes from the realm of materials science, strength of materials or chemistry. The equations and empirical tables used for different materials and techniques come from accepted literature relevant to the transformation and the material (references previously cited).

Thermodynamics/Physics: The energy calculations for this construct come from the first law of thermodynamics and physics (references) and are widely accepted for this purpose. Relativistic effects are not considered.

Face Validity/Usefulness (Operational Perspective): Bandwidth analysis bridges the gap between analytic and visual tools. The difference between minimum and actual energy usage for a sub-process (task) is often much greater than estimated. By providing efficiency ratios, this construct provides an immediate gauge of the process efficiency. This efficiency points toward possible equipment improvements. However, the engineer should proceed through all the constructs before making a determination of energy opportunities (references previously cited).

Construct #4 (Calculation of the sub-process's energy partial productivities): This construct is a logical extension of the bandwidth analysis performed in construct #3. The energy partial productivities (PPE) can interface with an activity based management (ABM) system in order to gain the advantages of the accounting methodology (described in detail in Chapter III).

Content Validity and Content Domain (Technical Perspective): The construction of the energy partial productivities is straightforward and derived from similar techniques used for material and labor partial productivities. Borrowing from the description of partial productivity (PP) calculation of Hansen and Mowen (pages 696-699), the energy PP is calculated by determining the energy utilized, in Kilojoules, at a particular process per unit mass of product (in that process). These PPE's can now feed the ABC methodology.

Face Validity/Usefulness (Operational Perspective): The advantages of having an interface to an ABC system is that now the business can use accounting techniques, inclusive of energy, in their management decision processes. Activity based costing using energy inputs gives more visibility to energy cost issues during planning and allows all personnel involved in the planning to see the impacts of energy costs and usage on product economics. In addition, sensitivity analysis can now be performed using stochastic energy prices and the impacts on different product mixes, production and equipment selections.

Construct #5 (Construction of an Energy Value Stream Map for the Sub-Processes): As demonstrated by Womack et al, value stream mapping (VSM) can be a useful method in the analysis of manufacturing or value-chain systems (Womack et al, 2003). Value stream mapping is an accepted and powerful tool in lean practices.

Content Validity and Content Domain (Technical Perspective): The construction of the energy value stream map is based closely on the method described by Womack in his "Learning to see" workbook. The symbols, legend boxes and arrows are used exactly as described in the workbook. The main difference for the ERDT-VSM is that symbols for energy input and waste have been designed and added to the traditional VSM by the author.

Face Validity/Usefulness (Operational Perspective): The ERDT energy VSM is a methodology used in visual management. Visual management is usually associated with lean or quality programs and is a clear, concise method of communicating operational processes and dynamics via visual symbols. Energy value stream mapping is a form of clear communication to management of the dynamics of energy usage of manufacturing processes. This form of visual management conveys vital information quickly and can assist managers who are confronted by masses of information (references previously cited).

Specifically, the ERDT energy VSM helps to introduce the concept of energy management into the area of lean practices where it has not previously been examined (Mize, 2005). For example, the ERDT VSM would allow the visual examination of the energy use and waste impacts of changing production line structures (e.g., series/sequential to cellular).

Construct #6 (Exergy analysis of existing sub-processes identified in the process characterization phase of the ERDT): This construct is one of the cornerstones of the ERDT methodology. In this construct, the effectiveness of the various processes in utilizing the purchased energy is examined. Essentially, this construct determines to what degree the purchased energy is matched to the process task at hand. This type of second law energy "effectiveness" analysis is a clear break from the more traditional energy analysis methods of the past.

<u>Content Validity and Content Domain (Technical Perspective)</u>: The determination of exergy efficiency (effectiveness) ratios for the process task is based on accepted scientific and engineering methods.

Thermodynamics/Physics: The energy calculations for this construct come from the second law of thermodynamics and physics and are widely accepted for this purpose. The exergy calculations follow accepted methods and examples from literature. The exergy ratios are determined as the task effectiveness (exergy efficiency) for the supplied available energy for the sub-process under consideration.

Face Validity/Usefulness (Operational Perspective): The construction of the exergy ratios provides an immediate determination of the matching between process energy types and matching of the energy to the task. In essence, these ratios demonstrate that the processes themselves may be "incorrect" for the process task. The resulting exergy ratios can be benchmarked to other similar processes using different energy sources.

The exergy calculations are also the beginning of a powerful analysis that has applications in sustainability and waste management. While not specifically addressed in this research, the usefulness of exergy analysis and sustainability studies is significant (Ayers, et al, 2001). See the section on future research below.

Construct #7 (Selection and recommendations for processes based on 1st Law, exergy ratios and ranking methods): This construct is terminus for this research report and is the final deliverable of the ERDT methodology in its current form. By examining constructs #3 and #6 in a systematic manner, a simple energy management decision set is arrived at regarding for the various processes in the plant. Unlike an expert system's use of prior knowledge to make recommendations, the ERDT has worked up to this point by starting at the process's fundamental tasks and examination of the process's effective (or not) use of energy. The resulting selection and ranking of processes for examination and possible recommendations, short of specific solutions, is a very useful deliverable for the energy engineer.

Content Validity and Content Domain (Technical Perspective): The energy and exergy ratio magnitudes of interest are derived from suggestions in engineering literature (Ayers, et al, 2001) - that is, what would be considered poor, medium and good efficiencies. The recommendations of improve process, redesign, reuse waste energy, or go to completely new process, are based on the straightforward implications of the First and Second Law analyses.

Face Validity/Usefulness (Operational Perspective): The final deliverable of the ERDT is very useful in that is removes any doubt as to which and how certain processes should be examined. The prospect of completely missing a significant process energy saving opportunity is minimized by the systematic ERDT method and this final highlighting of recommendations. By combining the traditional IAC audit framework and the ERDT's ability to concentrate on processes, the energy engineer has a powerful tool for energy management analysis.

Expansion of ERDT Usefulness (Operational Perspective)

The operational perspective portion of the ERDT validation involves the more objective aspects of the methodology evaluation. As stated in the Goals and Assumptions in the beginning of Chapter III, the ERDT will be evaluated on its "usefulness" for performing energy audits.

Usefulness in the case of engineering methods can be defined as providing a measure of utility or improvement for the engineer toward the analysis of the systems of interest (U.S. Patent Office, 2006). In this case, the systems of interest are the energy utilizing processes within a manufacturing facility. The author uses the following criteria in order to demonstrate that the ERDT is potentially useful:

1. The ERDT shows applicability for field work (utility)
2. The ERDT provides process energy usage visibility previously lacking (utility)
3. The ERDT is compatible with accepted improvement methodologies such as Activity Based Management and Lean methods (utility and new perspective)
4. The ERDT provides solutions to deficiencies in the existing energy audit methodology identified by experts in the subject area. (utility and new perspective)

Amplification of the Usefulness Criteria:

The ERDT shows applicability for field work: Because the ERDT is designed to utilize data gathered from a field audit, the method is, by its own definition, a field work application. In general, the ERDT method is designed to assist the energy engineer in the task of performing an effective energy audit.

Where the traditional energy audit makes something of a leap from the walk-through plant tour to the decision as to which processes to concentrate on, the ERDT systematically guides the engineer toward which processes deserve attention. This utility of the ERDT potentially saves time, money and energy.

Future Research

The ERDT research has many extensions for further study. As with many research topics, a larger scale topic was first imagined and reduced for manageability. The larger vision for the methodology is still very relevant. The first two extensions of the research have already been demonstrated in reduced form in the report, namely: Integration of the ERDT into activity based costing (ABC) and the use of the ERDT's value stream map in a lean methodology. The remaining extensions are described but not elaborated on in detail at this time. The author will pursue these topics in the future.

Expansion of the ERDT to Detail Economic Analysis of Potential Energy Savings and Implementation Costs

As stated previously, a next logical step in the energy management study is to examine the economics of the above suggestions. For example, if natural gas were relatively inexpensive as was the case 10 years ago, the economics would point toward using natural gas for all heating processes regardless of efficiencies or energy-task matching. This sensitivity analysis (EPA, 2006) of energy price volatility would be a useful tool for project selection. Exergy and economics, known as thermoeconomics in some circles (Tsatsaronis, 1993); (Gaggioli, 1980), is an established methodology that examines the cost of destroying available energy.

As discussed in the energy value section of the methodology chapter, given the economic energy value function relating the relative value of thermal energy streams, it would be possible to quantify the avoided energy cost by reusing energy streams versus buying new energy. Therefore the avoided energy costs between all energy projects could be calculated. These opportunity costs could be attached as an extra column[34] in Table 4 to show the potential economic resources available as waste energy (see example Table 18 below). Additionally, economic analysis opens several options for management considering energy improvement projects:

1) Increase process efficiency
2) Reuse waste energy in other processes
3) Sell waste energy
4) Do nothing

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[34] Waste energy values are estimated for this example

Activities	Energy Type	1st Law Energy Efficiency (η) Percentage	2nd Law Exergy Utilization Efficiency (εu) Percentage	Example Economic Energy Value of Waste Energy
Decoiling	Electrical	░ 6.9	▨ 5.3	0
Rod Mill Diameter Reduction	Electrical	░ 6.1	▨ 5.1	0
Heat Treat Anneal Oven	Natural Gas	░ 11.5	87.2	$0.30/Kg Product
Lead Bath Quench	Natural Gas	25.3	18.8	$0.09/Kg Product
Chemical Baths	Natural Gas	79.5	▨ 8.4	$0.0003/Kg Product
Air Knife Drying	Electrical	░ 0.7	▨ 7.0	0
Coiling (Packaging)	Electrical	20.1	18.1	0

░ Low 1st Law
▨ Low 2nd Law

Table 18. Example ERDT ratio table with waste energy opportunity costs

While economic analysis of the ERDT project recommendations is not examined in detail in this research, it is suggested as an area for future research.

Integration of the ERDT and Pinch Analysis/Process Integration

to include matching of Energy Waste Streams to Other Sub-Process Inputs

Currently, the ERDT analysis acts as a screening device to identify, rank and qualify processes for improvement. Some recommendations are made regarding examining the use of waste energy within the manufacturing facility, however, the ERDT model stops short of analyzing the energy streams and making further recommendations.

The next logical step is to expand the detail of the exergy analysis to identify and quantify the various exergy streams entering and leaving the sub-processes.

Previous discussions highlighted that exergy is a measure of the quality of energy. This indicates that exergy is a good methodology to match one process’s waste energy (exergy) to another process’s energy input requirements. Straight energy stream descriptions do not give this needed information. For example, moist, low temperature waste energy from flashing steam may contain the needed KJ of energy for another process input, however the receptor process needs the KJ’s of energy at high temperature and low humidity. Exergy stream analysis can provide this.

Equipped with such expanded exergy analysis, the ERDT would be a complete analysis and recommendation generating engineering methodology. This type of exergy analysis requires considerably more process detail in order to quantify the exergy streams. In order to demonstrate the potential of such exergy matching analysis, a simplified example was provided in the case study in Chapter IV.

Use of ERDT as a Design Methodology for New Manufacturing Facilities or Processes

Another interesting aspect of the ERDT is the manner in which it could be employed by different parties. The manufacturing engineer might want to view the analysis as it is presented in this research from a first law to exergy order as shown in the example (after the fact analysis). The process design engineer might wish to use the methodology from an exergy first, then first law perspective. This would allow a more effective matching of energy source to process at the beginning of the design phase.

While not specifically addressed in this research, the ERDT has the potential to be a design tool. Because of the ERDT's inside-out analysis of processes beginning with the desired physical transformations in the product, the ERDT would be useful in prescribing minimum energy screening criteria for candidate processes.

If the methodology were expanded to include the ability to match waste energy streams to other process inputs (described above) along with economic analysis, the ERDT could be used in the design phase of multiple-facility industrial parks. Manufacturers could be screened and co-located in order to take full advantage of waste energy streams and the (assumed) associated economic discounts.

Compatibility and Integration of the ERDT into Lean Practices (Expanded)

Historically, lean methodologies have not looked specifically at energy as value and non-value components. However, the ERDT specifically these energy-value definitions during the characterization phase of the methodology. Inclusion of energy value parameters into lean practices may produce different workplace designs than without considering energy.

Discussions with Dr. Joe Mize (Mize, 2005) regarding the inclusion of ERDT energy value parameters into lean practices raised some interesting observations. Dr. Mize pointed out that some lean practices may actually be counter to energy conservation. For example, lean manufacturing often strives for integrated cellular manufacturing operations. These cells will tend to produce completed, individual product units. Components that require energy inputs often achieve energy efficiency by being processed in batches. To start and stop a heat treating operation for individual parts in a manufacturing cell is inefficient. Likewise, heat treating one part at a time within a manufacturing cell would be inefficient as well. Therefore, tradeoffs need to be made to ensure cellular and energy efficiency. How lean practices and energy efficiency interact in the manufacturing environment needs to be studied.

The ERDT is positioned to become a powerful systems integrator methodology. By combining the ERDT with traditional energy auditing, accounting, value economics, pinch analysis and process integration, a complete facility systems analysis methodology is available. This suite of tools would be effective at identifying and eliminating energy waste[35]. This systematic reduction of waste is the very definition of lean methodology (Womack, Jones, 2003).

ERDT Use in Environmental and Sustainable Manufacturing Studies

Within the environmental engineering field, second law or exergy analysis is recognized as a valuable tool (Chamchine, 2003). The exergy content of materials and processes has been suggested as a prime environmental indicator (Creyts, 2000). This concept is fairly easy to understand. Because all real processes are irreversible (see section on second law analysis in Chapter III), they generate waste. Waste energy is almost always manifested as waste heat and/or pollutants. Because exergy analysis is a direct measure of the relative amount and type of waste energy given off by materials or processes, it is also an indicator of waste pollutants given off by these processes.

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[35] Waste in lean methods is often referred to as “muda”.

For example, the low exergy efficiency of the gas fired water heater is directly related to the amount of pollutants given off by the combustion process. The heating of various chemical species (mostly nitrogen) contribute nothing to the combustion process but do contribute to pollutants. Additionally, because the water only needs to be heated to 60 °C from a 1,600 °C flame, the resulting exergy waste streams account for the usefulness destruction. In turn, these lower exergy waste materials describe pollutants. For materials, as the exergy content of the material decreases through chemical reactions they tend to transform from useful materials (e.g., fuels) into waste material.

The ERDT would be an excellent methodology to begin the accounting and tracking of wastes for the individual processes in the plant. Decisions regarding waste generation, environmental liability and associated costs would be greatly assisted by a modified and expanded ERDT providing exergy waste stream data.

Compatibility of ERDT with DOE-IAC energy audits and Best Practices tools

As mentioned previously, the ERDT is a good fit into the existing IAC audit methodology. Future effort could be directed into developing an abbreviated version of the ERDT method that could be used in the one or two-day IAC audits. This combining of the two methods could be advantageous. Traditional IAC audits are already saddled with the task of trying to determine what systems to investigate in a very short time. A version of the ERDT method could provide direction needed by rapidly highlighting what sub-processes have the greatest opportunities for improvement and payback. Therefore, time would not be wasted examining processes with limited opportunities.

In its present manifestation, the ERDT does not make specific recommendations regarding hardware changes. The methodology identifies and selects certain processes and suggests avenues of opportunity. The actual engineering calculations to determine energy and cost savings are outside of the ERDT. However, this is a perfect interface, or hand-off, for the DOE best practices software tools mentions in Chapter I.   By combining the decision science capability of the ERDT with the computational ability of the dedicated best practices tools, the engineer would have a complete energy auditing analysis package. Examples might include:

1) ERDT suggests using waste heat to produce steam – Interface – Combined Heat and Power Application Tool.
2) ERDT identifies compressed air as major opportunity – Interface – Compressed AIRMaster+.
3) ERDT suggests keeping steam system but improve efficiencies – Interface – Steam System Assessment Tool.

Abbreviated ERDT Methodology for One-Day IAC Audits

In the current state of construction, the ERDT requires process information detail that may be difficult to acquire in a one-day energy site visit (audit). As mentioned previously, if the plant personnel are not aware of the process details, the engineer will need to search out this data.

However, it may be possible to build templates for commonly occurring processes such as heat treating, chemical baths, air compressor systems, etc. These templates might only require estimates of the power requirements and frequency of the loads. For the

ERDT to be a viable methodology for the DOE Industrial Assessment Center's use, such one-day site visit capability would greatly enhance the utility of the method.

Examine Interactions between Different Processes

The current demonstration of the ERDT examines individual processes without examining the interactions of processes within the plant. This was done to keep the analysis manageable in the conceptual stage. In reality, many processes are interconnected either by batch size, timing of operations or other parameters. This raises the importance of temporal aspects in production and processes and the possibility of suboptimization problems. One cannot necessarily assume that these time-issue interactions are linear in nature (Hardt or Tsz-Sin-Siu, 2004). Therefore, the process interaction studies will probably be non-trivial analysis.

While this is beyond the scope of this report, it is certainly an important area for future research. The combination of an ERDT analysis methodology with processes interaction modeling and waste/input exergy availabilities would be a step closer to the overall energy use dynamic of a manufacturing facility.

Expansion of Process Details and Sensitivity Study of Some Material and Process Parameters

For simplification, some assumptions were made in the study that merit further study. For example, sensitivity analysis of the energy and exergy calculations to different material properties should be examined. In some cases, conservative values for process parameters were used (e.g., specific energy of finish grinding) due to a lack of measurement data. Sub metered process equipment would provide better data and associated calculations would reflect actual conditions to a higher degree.

Summary

This report has demonstrated a new methodology (ERDT) for use in energy engineering for energy auditing and new process design. The ERDT has demonstrated the following advantages:

- The ERDT performs the systematic characterization of manufacturing process energy use.
- The methodology provides identification and screening of energy management opportunities.
- The methodology produces energy waste stream recovery and reuse recommendations.
- The ERDT methodology provides the opportunity for integration with other systems improvement methodologies.

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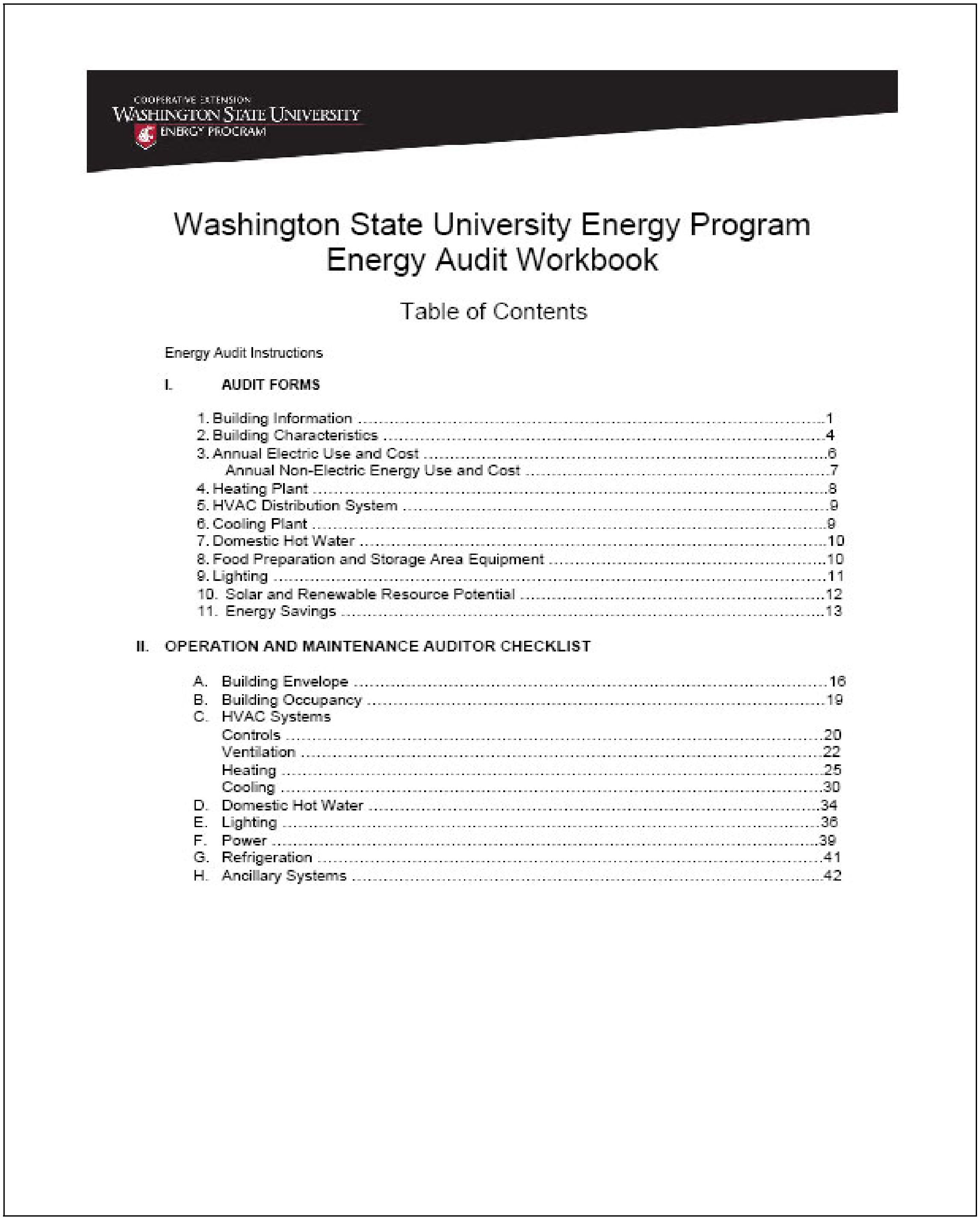
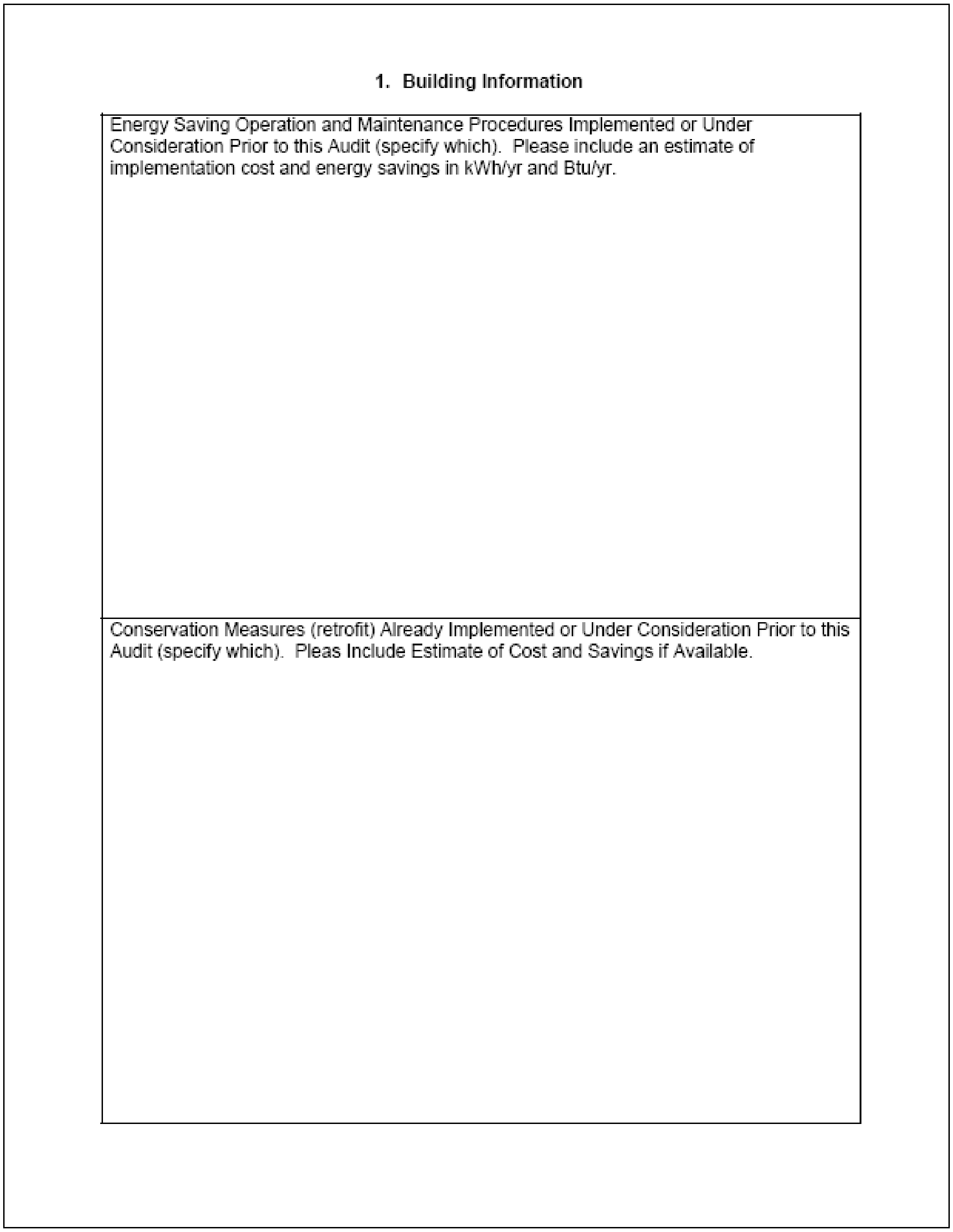
Appendix I
WSU Energy Audit Checklist



COOPERATIVE EXTENSION
WASHINGTON STATE UNIVERSITY
ENERGY PROGRAM

Washington State University Energy Program
Energy Audit Workbook

Table of Contents



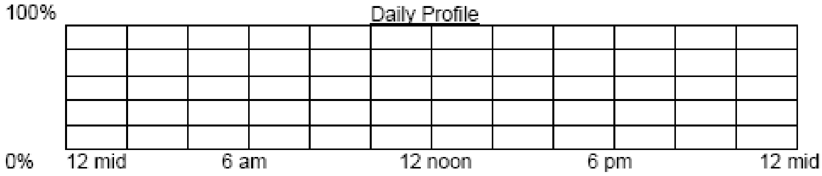
1. Building Information

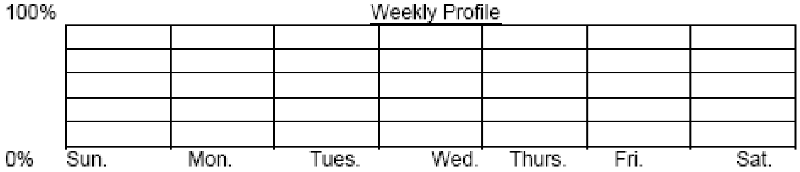
Energy Saving Operation and Maintenance Procedures Implemented or Under Consideration Prior to this Audit (specify which). Please include an estimate of implementation cost and energy savings in kWh/yr and Btu/yr.

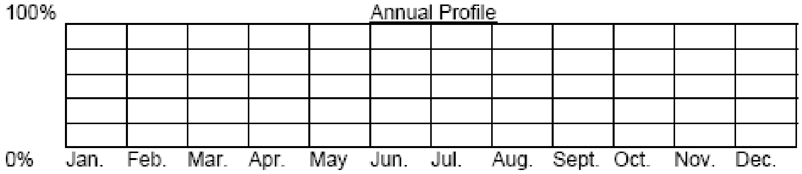
Conservation Measures (retrofit) Already Implemented or Under Consideration Prior to this Audit (specify which). Pleas Include Estimate of Cost and Savings if Available.

1. BUILDING INFORMATION

Building Occupancy Profile







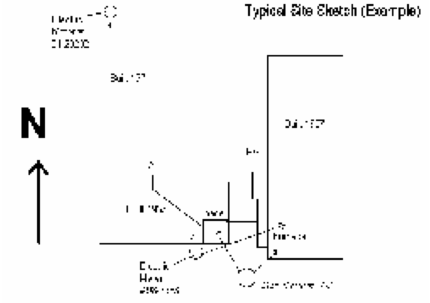
Building Occupancy Schedule

Area/Zone	# of Sq.Ft.	**Week Days**			**Weekends, Holidays**		
		hours		# of People	hours		# of People
		from	to		from	to	

BUILDING INFORMATION

On the following page, prepare a site sketch of your building or building complex which shows the following information:

1. Relative location and outline of the building(s).
2. Building Age
3. Building Number (Assign numbers if buildings are not already numbered.)
4. Building Size
5. Fuel Type
6. Location of heating and cooling units
7. Heating plants
8. Central cooling system, etc.
9. North orientation arrow



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2. BUILDING CHARACTERISTICS

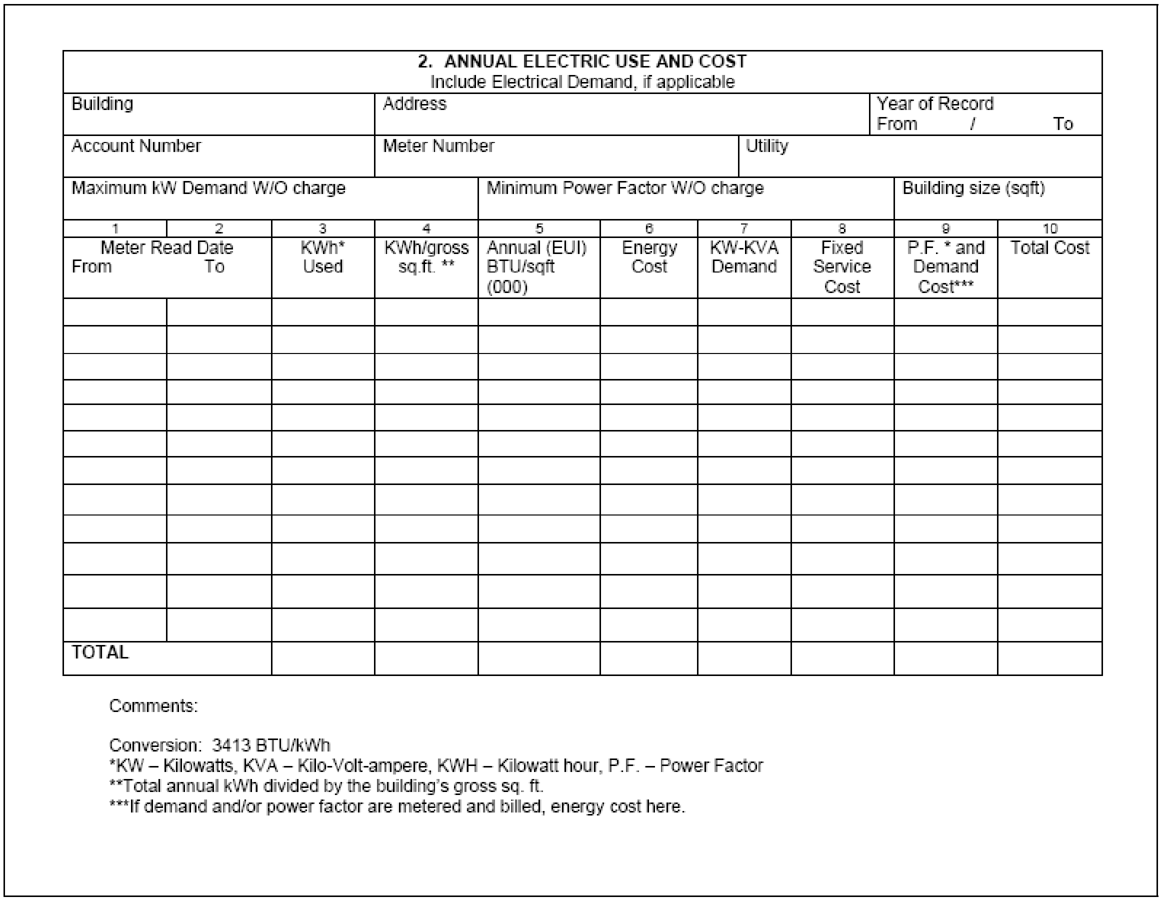
a. **Gross Floor Area**: ______ Gross Sq.Ft. x Ceiling Height _______ Ft. = volume ____Cu.Ft.
b. **Conditioned Floor Area:** _______ (if different that gross floor area)
c. **Total door Area:** __________ Sq.Ft. Glass doors _______sq.ft. Wood doors _____sq.ft.
Metal doors _______ sq.ft. Garage doors ________ sq.ft.
d. **Total Exterior Glass Area:** __________sq.ft. Single Panes _______sq.ft. Double panes ____sq.ft.

	North	**South**	**East**	**West**
Total Area	________sqft	_________sqft	________sqft	_________sqft
Single Pane	________sqft	_________sqft	________sqft	_________sqft
Double Pane	________sqft	_________sqft	________sqft	_________sqft

e. **Total Exterior Wall Area:** ___________ sqft Material: [ ]Masonry [ ]Wood
[ ]Concrete [ ]Stucco [ ]Other
f. **Total Roof Area:** __________sqft Condition: [ ]Good [ ]Fair [ ]Poor
g. **Insulation Type**: __________Roof ____________Wall ______________Floor
h. **Insulation Thickness:** __________Roof ____________Wall ___________Floor
i. **Metering**: Is this building individually metered for electricity? [ ]Yes [ ]No
Is this building individually metered for natural gas? [ ]Yes [ ]No
Is this building on a control boiler system with other buildings? [ ]Yes [ ]No
j. **Describe general building condition**:

SITE SKETCH

Indicate compass direction with a north arrow.



2. ANNUAL ELECTRIC USE AND COST

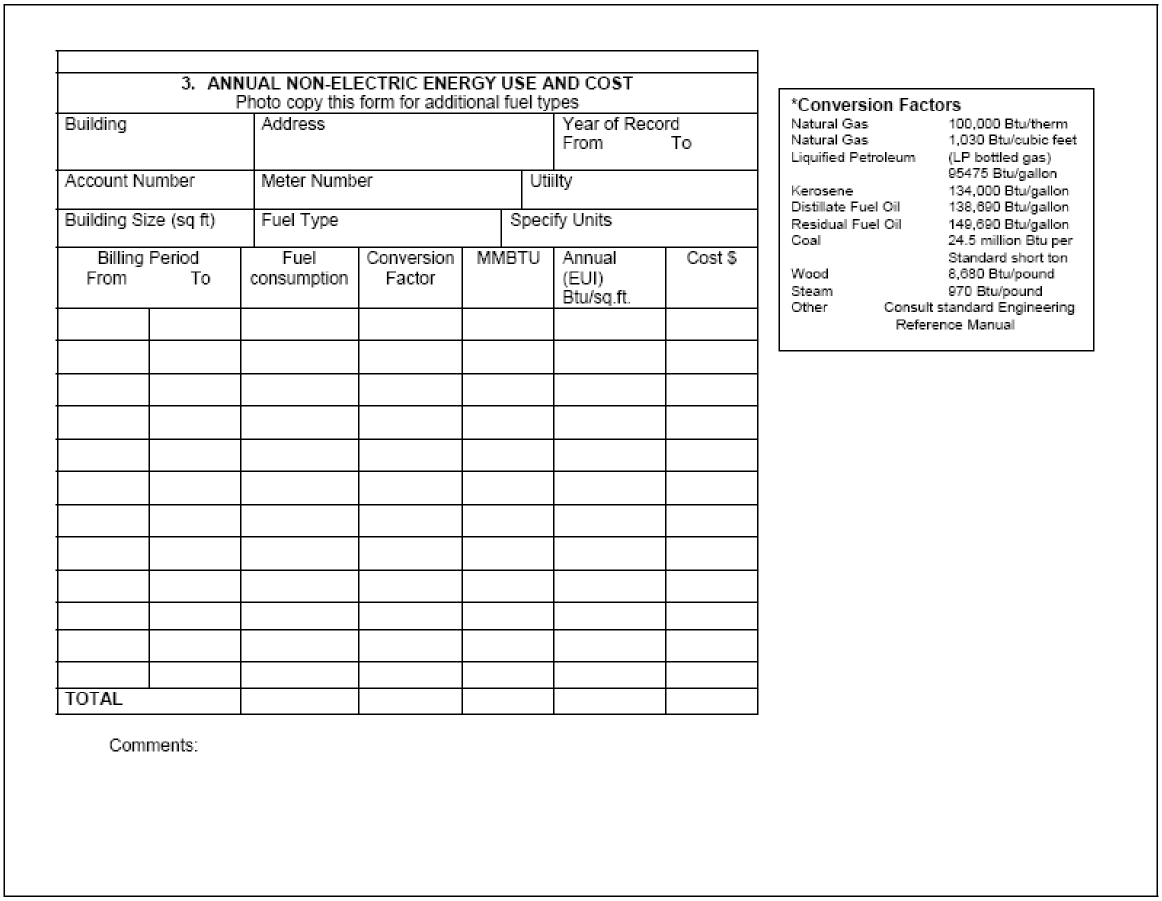
Include Electrical Demand, if applicable

Building
Address
Year of Record From / To
Account Number
Meter Number
Utility
Maximum kW Demand W/O charge
Minimum Power Factor W/O charge
Building size (sqft)

1	2	3	4	5	6	7	8	9	10
Meter Read Date From	To	KWh* Used	KWh/gross sq.ft. **	Annual (EUI) BTU/sqft (000)	Energy Cost	KW-KVA Demand	Fixed Service Cost	P.F. * and Demand Cost***	Total Cost
TOTAL									

Comments:

Conversion: 3413 BTU/kWh
*KW – Kilowatts, KVA – Kilo-Volt-ampere, KWH – Kilowatt hour, P.F. – Power Factor
**Total annual kWh divided by the building's gross sq. ft.
***If demand and/or power factor are metered and billed, energy cost here.



3. ANNUAL NON-ELECTRIC ENERGY USE AND COST

Photo copy this form for additional fuel types

Building

Address

Year of Record From To

Account Number

Meter Number

Utiilty

Building Size (sq ft)

Fuel Type

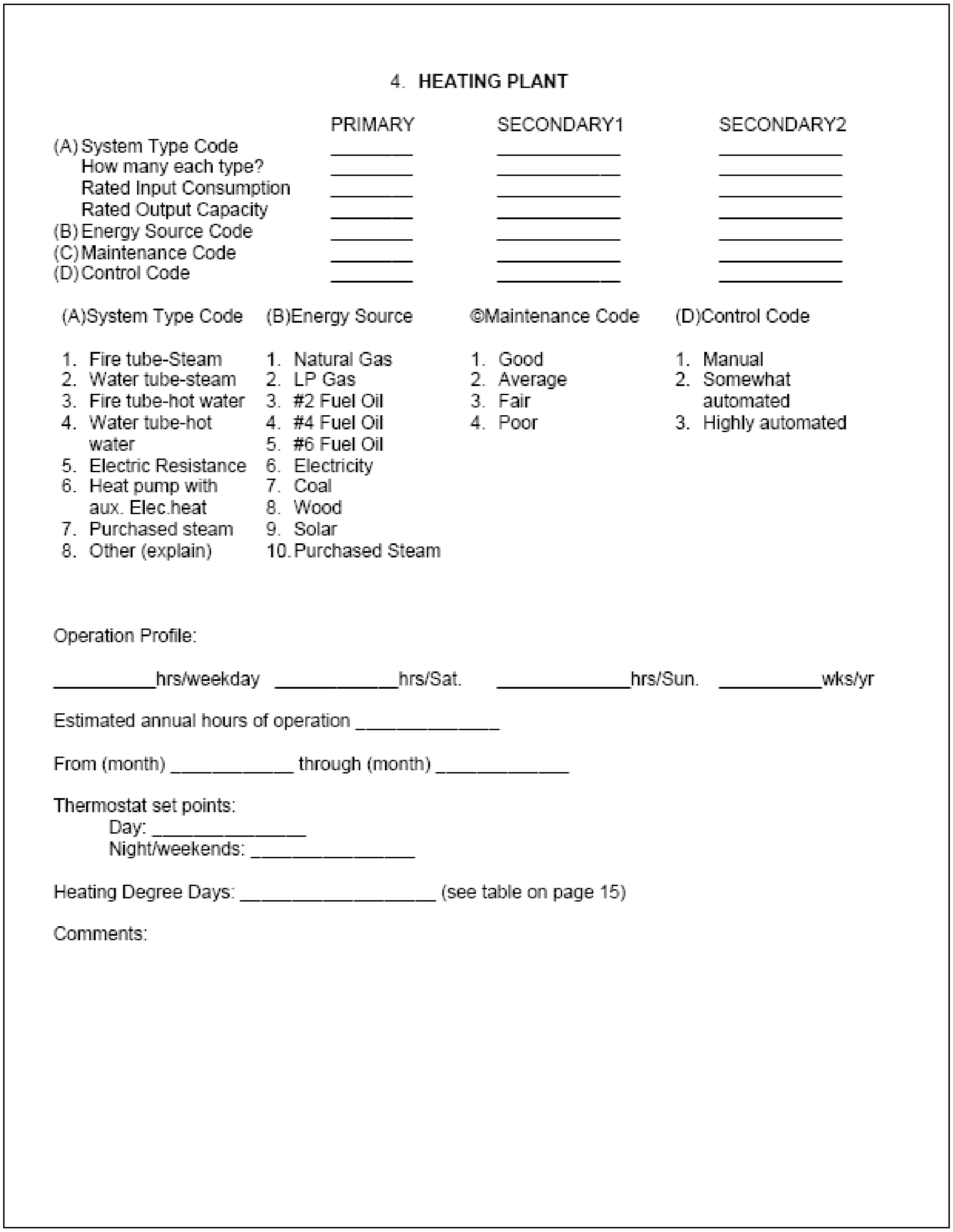
Specify Units

Billing Period		Fuel consumption	Conversion Factor	MMBTU	Annual (EUI) Btu/sq.ft.	Cost $
From	To					
TOTAL						

Comments:

***Conversion Factors**

Natural Gas	100,000 Btu/therm
Natural Gas	1,030 Btu/cubic feet
Liquified Petroleum	(LP bottled gas) 95475 Btu/gallon
Kerosene	134,000 Btu/gallon
Distillate Fuel Oil	138,690 Btu/gallon
Residual Fuel Oil	149,690 Btu/gallon
Coal	24.5 million Btu per Standard short ton
Wood	8,680 Btu/pound
Steam	970 Btu/pound
Other	Consult standard Engineering Reference Manual



4. HEATING PLANT

	PRIMARY	SECONDARY1	SECONDARY2
(A) System Type Code	________	____________	____________
How many each type?	________	____________	____________
Rated Input Consumption	________	____________	____________
Rated Output Capacity	________	____________	____________
(B) Energy Source Code	________	____________	____________
(C) Maintenance Code	________	____________	____________
(D) Control Code	________	____________	____________

(A)System Type Code

1. Fire tube-Steam
2. Water tube-steam
3. Fire tube-hot water
4. Water tube-hot water
5. Electric Resistance
6. Heat pump with aux. Elec.heat
7. Purchased steam
8. Other (explain)

(B)Energy Source

1. Natural Gas
2. LP Gas
3. #2 Fuel Oil
4. #4 Fuel Oil
5. #6 Fuel Oil
6. Electricity
7. Coal
8. Wood
9. Solar
10. Purchased Steam

©Maintenance Code

1. Good
2. Average
3. Fair
4. Poor

(D)Control Code

1. Manual
2. Somewhat automated
3. Highly automated

Operation Profile:

__________hrs/weekday ____________hrs/Sat. _____________hrs/Sun. __________wks/yr

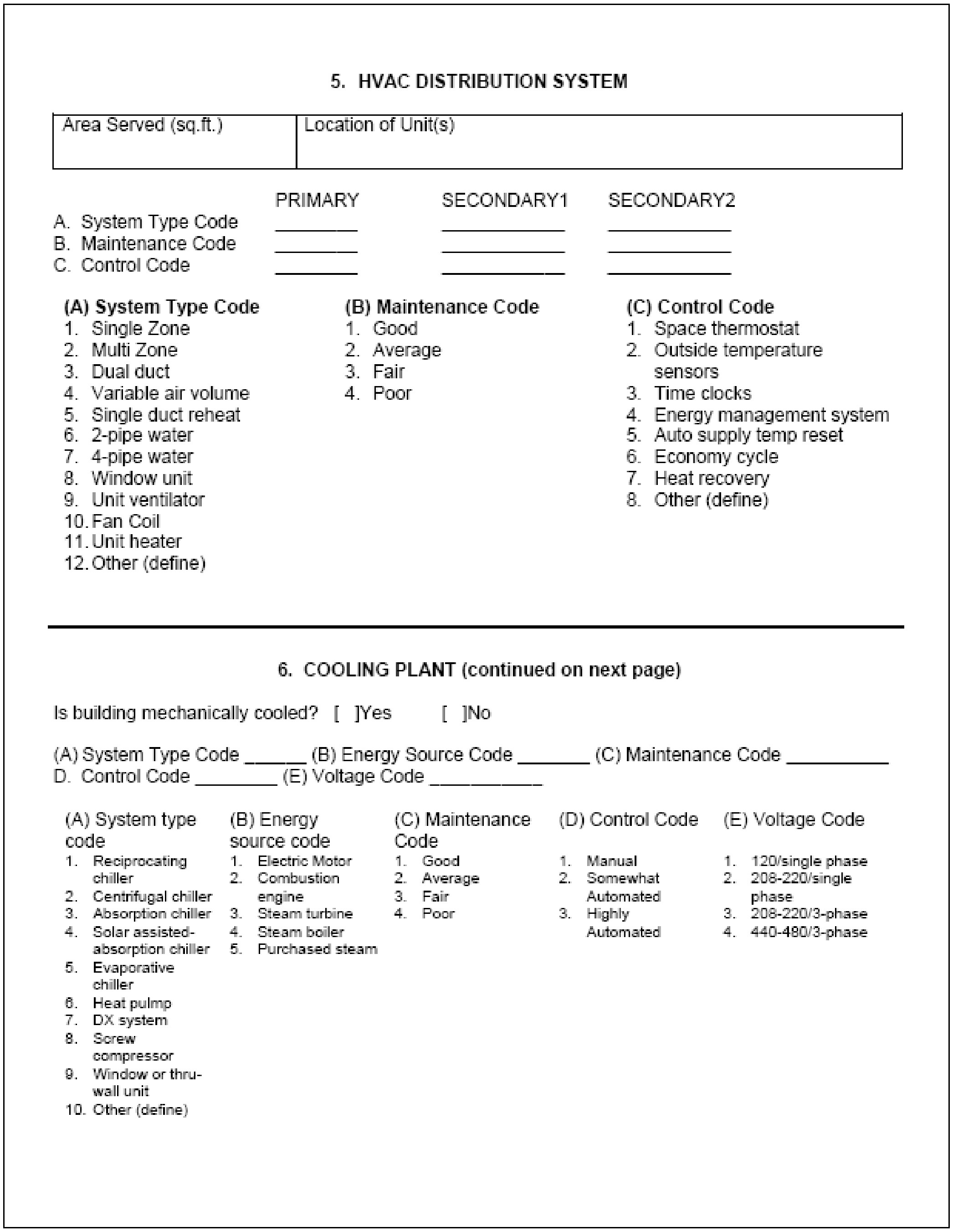
Estimated annual hours of operation ______________

From (month) ____________ through (month) _____________

Thermostat set points:
Day: _______________
Night/weekends: ________________

Heating Degree Days: ___________________ (see table on page 15)

Comments:



5. HVAC DISTRIBUTION SYSTEM

Area Served (sq.ft.)	Location of Unit(s)

	PRIMARY	SECONDARY1	SECONDARY2
A. System Type Code	________	____________	____________
B. Maintenance Code	________	____________	____________
C. Control Code	________	____________	____________

(A) System Type Code
1. Single Zone
2. Multi Zone
3. Dual duct
4. Variable air volume
5. Single duct reheat
6. 2-pipe water
7. 4-pipe water
8. Window unit
9. Unit ventilator
10. Fan Coil
11. Unit heater
12. Other (define)

(B) Maintenance Code
1. Good
2. Average
3. Fair
4. Poor

(C) Control Code
1. Space thermostat
2. Outside temperature sensors
3. Time clocks
4. Energy management system
5. Auto supply temp reset
6. Economy cycle
7. Heat recovery
8. Other (define)

---

6. COOLING PLANT (continued on next page)

Is building mechanically cooled? [ ]Yes [ ]No

(A) System Type Code ______ (B) Energy Source Code _______ (C) Maintenance Code __________
D. Control Code ________ (E) Voltage Code __________

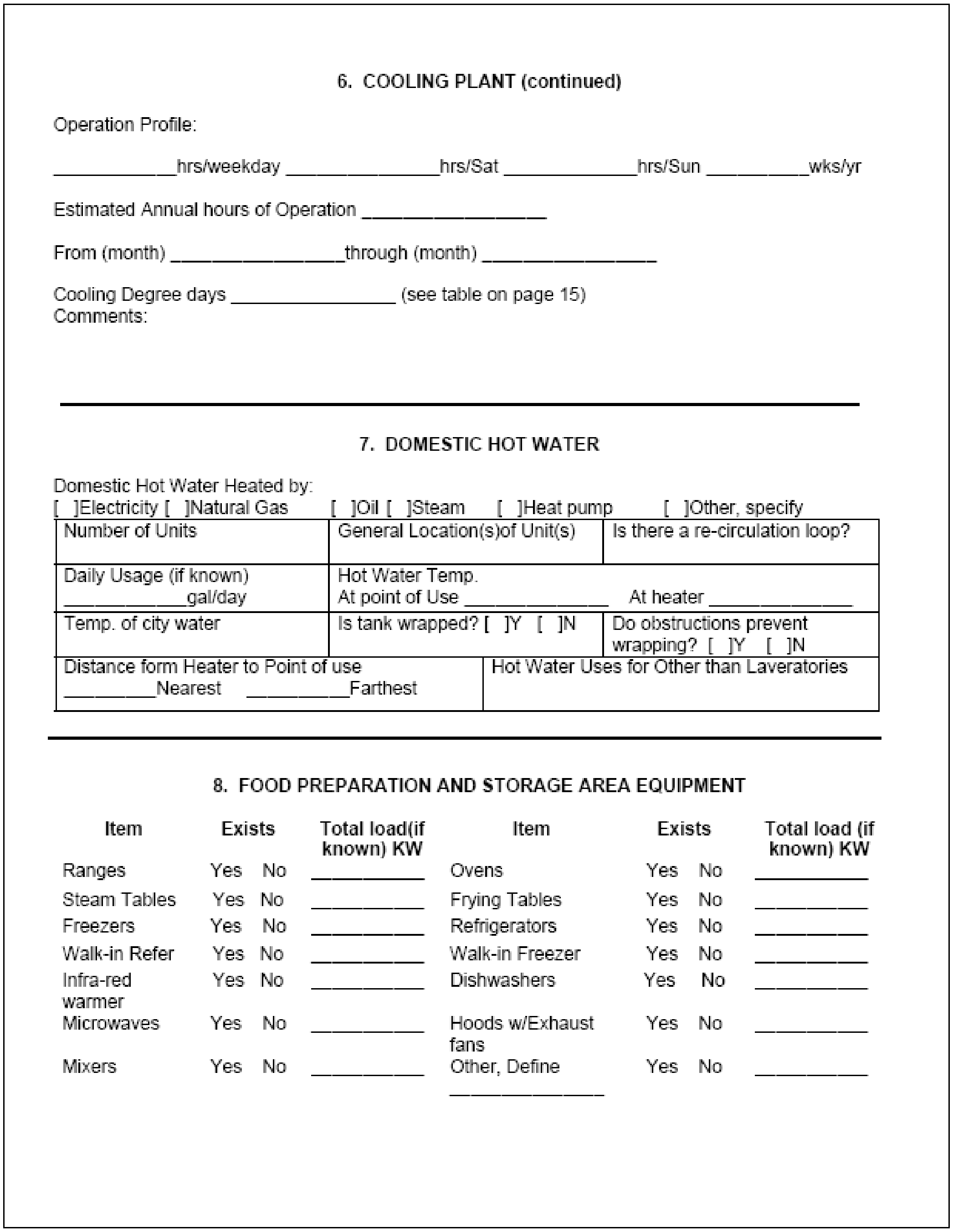
(A) System type code
1. Reciprocating chiller
2. Centrifugal chiller
3. Absorption chiller
4. Solar assisted-absorption chiller
5. Evaporative chiller
6. Heat pulmp
7. DX system
8. Screw compressor
9. Window or thru-wall unit
10. Other (define)

(B) Energy source code
1. Electric Motor
2. Combustion engine
3. Steam turbine
4. Steam boiler
5. Purchased steam

(C) Maintenance Code
1. Good
2. Average
3. Fair
4. Poor

(D) Control Code
1. Manual
2. Somewhat Automated
3. Highly Automated

(E) Voltage Code
1. 120/single phase
2. 208-220/single phase
3. 208-220/3-phase
4. 440-480/3-phase



6. COOLING PLANT (continued)

Operation Profile:

___________hrs/weekday ______________hrs/Sat _____________hrs/Sun __________wks/yr

Estimated Annual hours of Operation _________________

From (month) ________________through (month) _________________

Cooling Degree days _______________ (see table on page 15)
Comments:

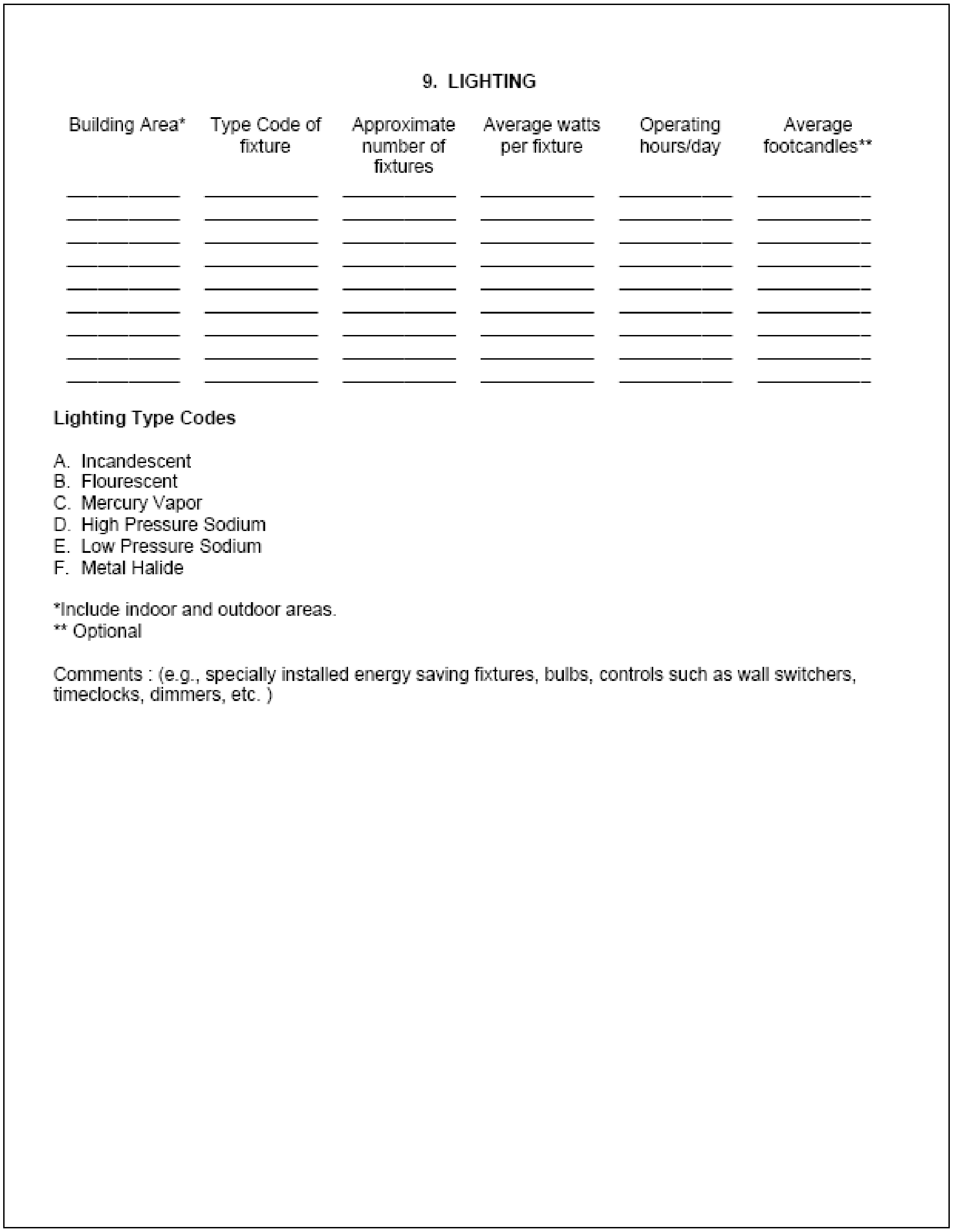
7. DOMESTIC HOT WATER

Domestic Hot Water Heated by:
[ ]Electricity [ ]Natural Gas [ ]Oil [ ]Steam [ ]Heat pump [ ]Other, specify

Number of Units	General Location(s)of Unit(s)	Is there a re-circulation loop?
Daily Usage (if known) ___________gal/day	Hot Water Temp. At point of Use ______________ At heater ______________	
Temp. of city water	Is tank wrapped? [ ]Y [ ]N	Do obstructions prevent wrapping? [ ]Y [ ]N
Distance form Heater to Point of use _________Nearest _________Farthest	Hot Water Uses for Other than Laveratories	

8. FOOD PREPARATION AND STORAGE AREA EQUIPMENT

Item	Exists	Total load(if known) KW	Item	Exists	Total load (if known) KW
Ranges	Yes No	__________	Ovens	Yes No	__________
Steam Tables	Yes No	__________	Frying Tables	Yes No	__________
Freezers	Yes No	__________	Refrigerators	Yes No	__________
Walk-in Refer	Yes No	__________	Walk-in Freezer	Yes No	__________
Infra-red warmer	Yes No	__________	Dishwashers	Yes No	__________
Microwaves	Yes No	__________	Hoods w/Exhaust fans	Yes No	__________
Mixers	Yes No	__________	Other, Define ______________	Yes No	__________



9. LIGHTING

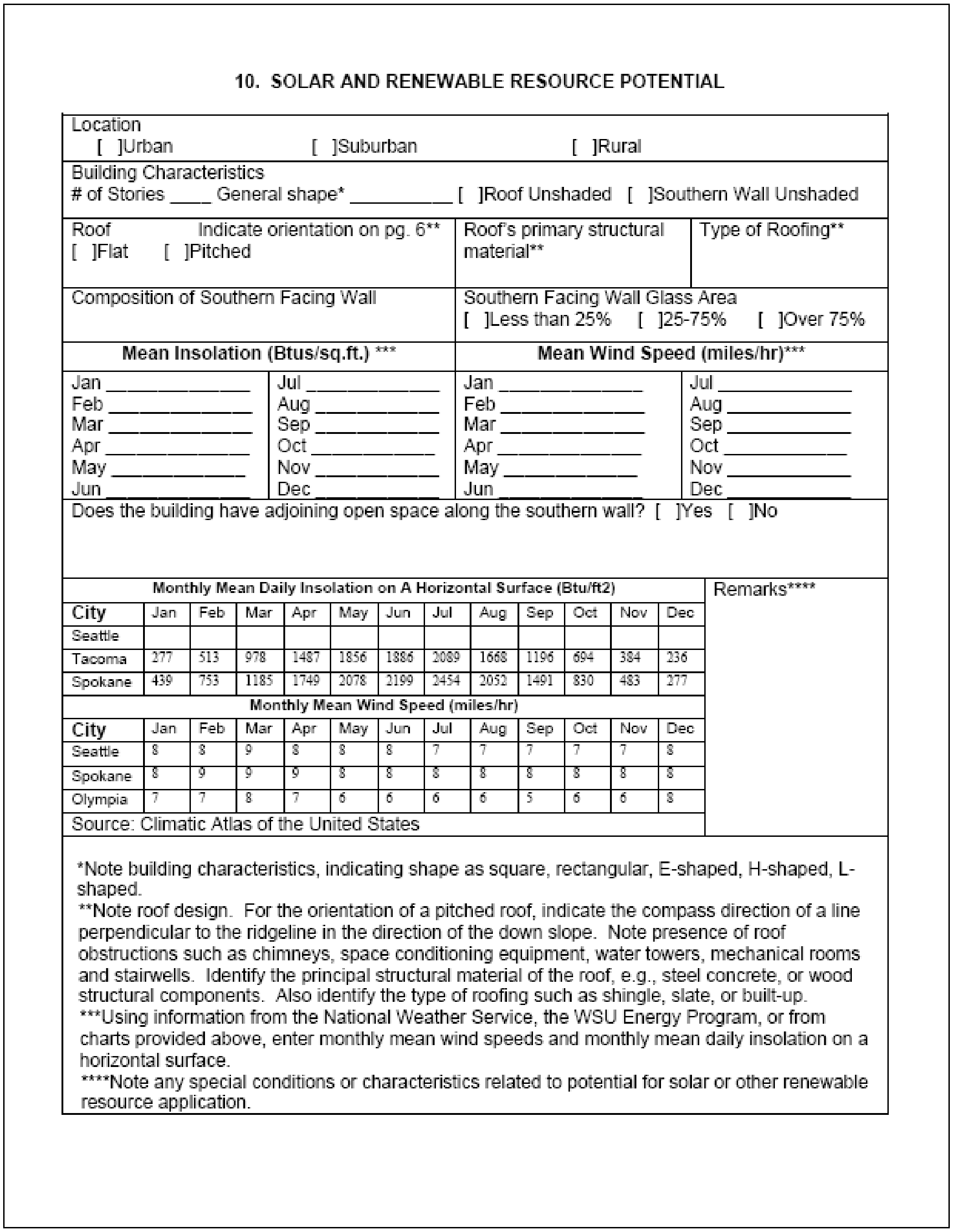
Building Area*	Type Code of fixture	Approximate number of fixtures	Average watts per fixture	Operating hours/day	Average footcandles**
___________	___________	___________	___________	___________	___________
___________	___________	___________	___________	___________	___________
___________	___________	___________	___________	___________	___________
___________	___________	___________	___________	___________	___________
___________	___________	___________	___________	___________	___________
___________	___________	___________	___________	___________	___________
___________	___________	___________	___________	___________	___________
___________	___________	___________	___________	___________	___________
___________	___________	___________	___________	___________	___________

Lighting Type Codes

A. Incandescent
B. Flourescent
C. Mercury Vapor
D. High Pressure Sodium
E. Low Pressure Sodium
F. Metal Halide

*Include indoor and outdoor areas.
** Optional

Comments : (e.g., specially installed energy saving fixtures, bulbs, controls such as wall switchers, timeclocks, dimmers, etc.)



10. SOLAR AND RENEWABLE RESOURCE POTENTIAL

Location
[ ]Urban [ ]Suburban [ ]Rural

Building Characteristics
# of Stories ____ General shape* __________ [ ]Roof Unshaded [ ]Southern Wall Unshaded

Roof Indicate orientation on pg. 6**
[ ]Flat [ ]Pitched

Roof's primary structural material**

Type of Roofing**

Composition of Southern Facing Wall

Southern Facing Wall Glass Area
[ ]Less than 25% [ ]25-75% [ ]Over 75%

Mean Insolation (Btus/sq.ft.) ***

Jan ____________
Feb ____________
Mar ____________
Apr ____________
May ___________
Jun ____________

Jul ___________
Aug ___________
Sep ___________
Oct ___________
Nov ___________
Dec ___________

Mean Wind Speed (miles/hr)***

Jan ____________
Feb ____________
Mar ____________
Apr ____________
May ___________
Jun ____________

Jul ___________
Aug ___________
Sep ___________
Oct ___________
Nov ___________
Dec ___________

Does the building have adjoining open space along the southern wall? [ ]Yes [ ]No

Monthly Mean Daily Insolation on A Horizontal Surface (Btu/ft2)

City	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Seattle												
Tacoma	277	513	978	1487	1856	1886	2089	1668	1196	694	384	236
Spokane	439	753	1185	1749	2078	2199	2454	2052	1491	830	483	277

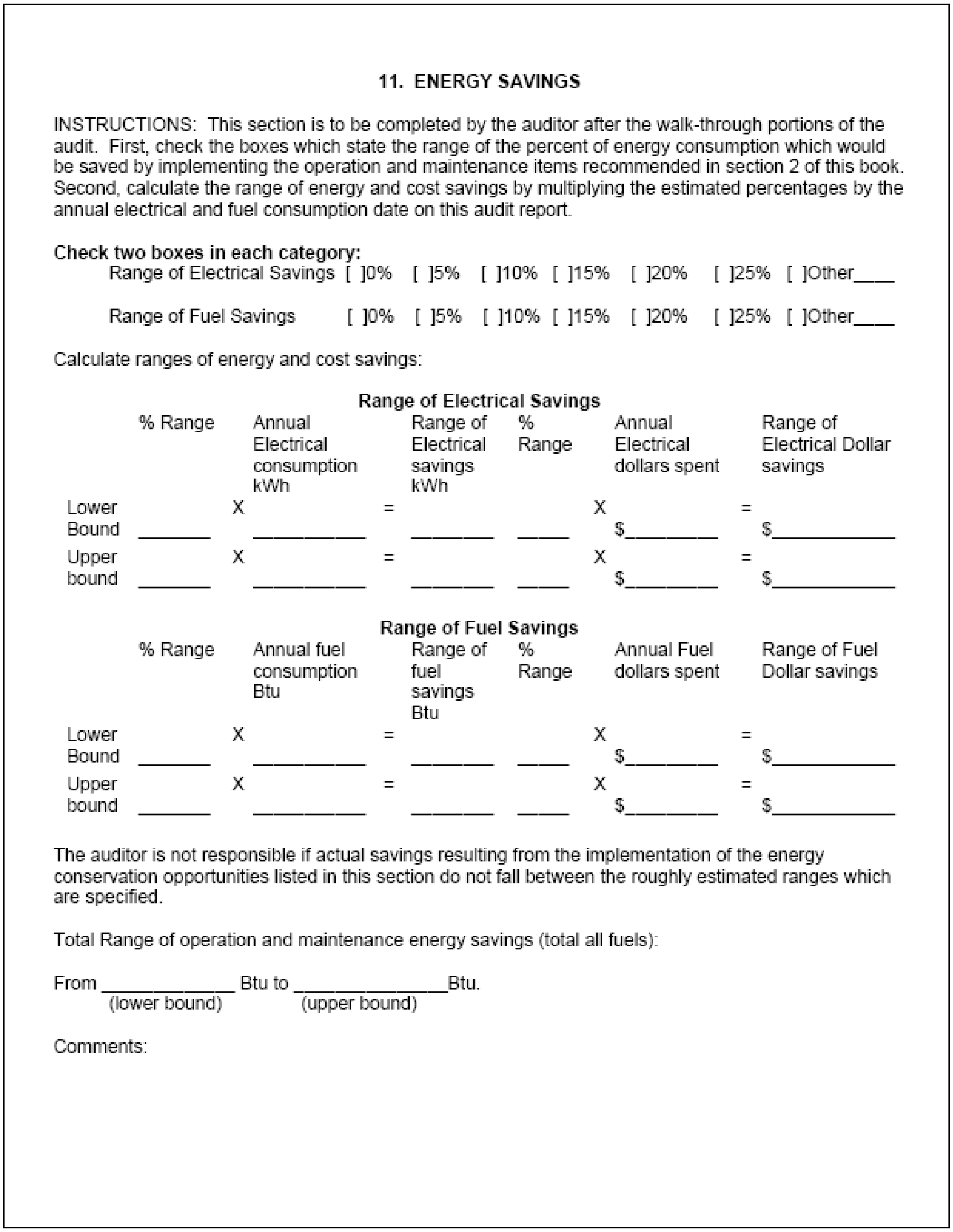
Monthly Mean Wind Speed (miles/hr)

City	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Seattle	8	8	9	8	8	8	7	7	7	7	7	8
Spokane	8	9	9	9	8	8	8	8	8	8	8	8
Olympia	7	7	8	7	6	6	6	6	5	6	6	8

Source: Climatic Atlas of the United States

Remarks****

*Note building characteristics, indicating shape as square, rectangular, E-shaped, H-shaped, L-shaped.
**Note roof design. For the orientation of a pitched roof, indicate the compass direction of a line perpendicular to the ridgeline in the direction of the down slope. Note presence of roof obstructions such as chimneys, space conditioning equipment, water towers, mechanical rooms and stairwells. Identify the principal structural material of the roof, e.g., steel concrete, or wood structural components. Also identify the type of roofing such as shingle, slate, or built-up.
***Using information from the National Weather Service, the WSU Energy Program, or from charts provided above, enter monthly mean wind speeds and monthly mean daily insolation on a horizontal surface.
****Note any special conditions or characteristics related to potential for solar or other renewable resource application.



11. ENERGY SAVINGS

INSTRUCTIONS: This section is to be completed by the auditor after the walk-through portions of the audit. First, check the boxes which state the range of the percent of energy consumption which would be saved by implementing the operation and maintenance items recommended in section 2 of this book. Second, calculate the range of energy and cost savings by multiplying the estimated percentages by the annual electrical and fuel consumption date on this audit report.

Check two boxes in each category:

Range of Electrical Savings [ ]0% [ ]5% [ ]10% [ ]15% [ ]20% [ ]25% [ ]Other____

Range of Fuel Savings [ ]0% [ ]5% [ ]10% [ ]15% [ ]20% [ ]25% [ ]Other____

Calculate ranges of energy and cost savings:

Range of Electrical Savings

	% Range		Annual Electrical consumption kWh		Range of Electrical savings kWh	% Range		Annual Electrical dollars spent		Range of Electrical Dollar savings
Lower Bound	_______	X	__________	=	_______	____	X	$________	=	$___________
Upper bound	_______	X	__________	=	_______	____	X	$________	=	$___________

Range of Fuel Savings

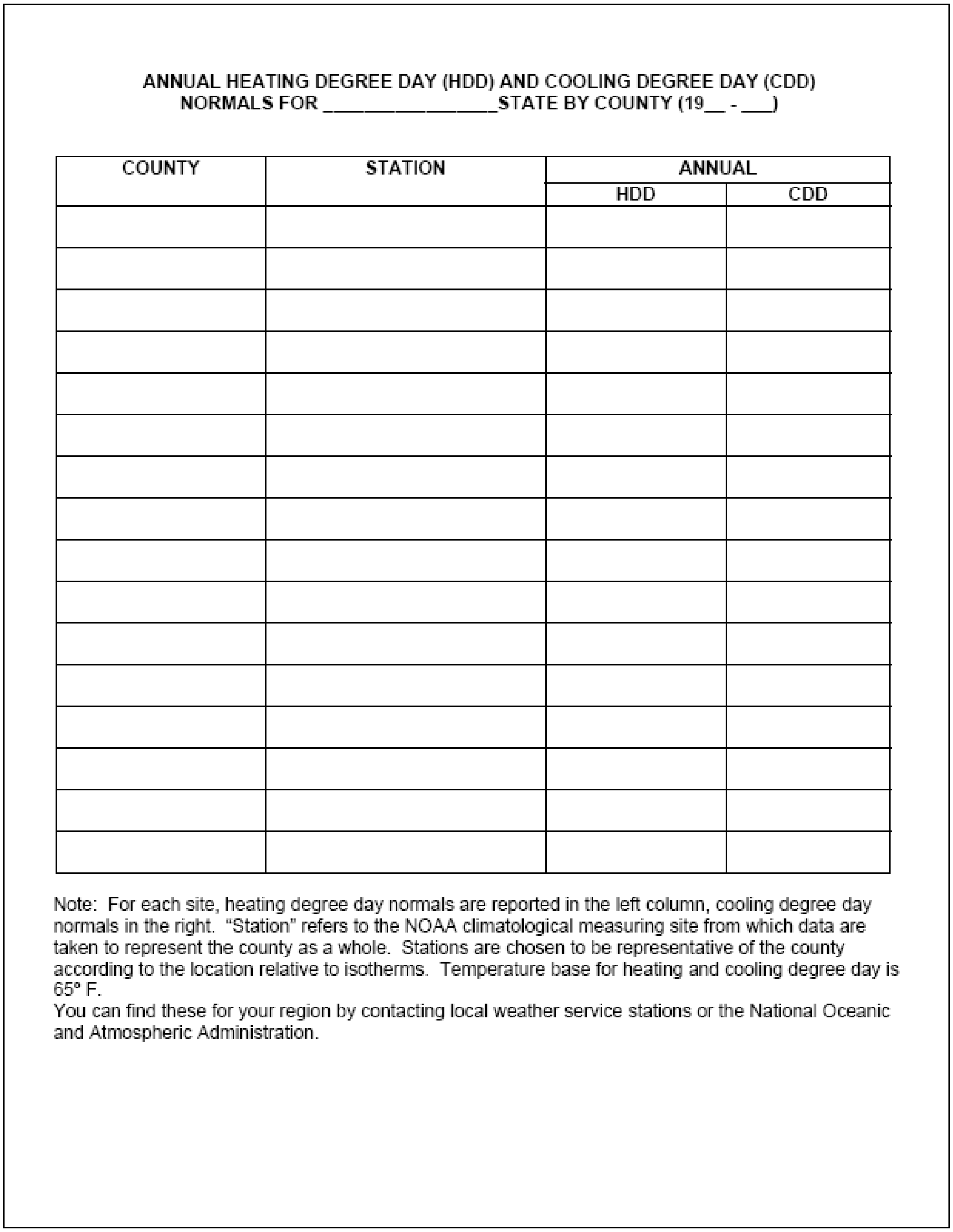
	% Range		Annual fuel consumption Btu		Range of fuel savings Btu	% Range		Annual Fuel dollars spent		Range of Fuel Dollar savings
Lower Bound	_______	X	__________	=	_______	____	X	$________	=	$___________
Upper bound	_______	X	__________	=	_______	____	X	$________	=	$___________

The auditor is not responsible if actual savings resulting from the implementation of the energy conservation opportunities listed in this section do not fall between the roughly estimated ranges which are specified.

Total Range of operation and maintenance energy savings (total all fuels):

From ____________ Btu to ______________Btu.
(lower bound) (upper bound)

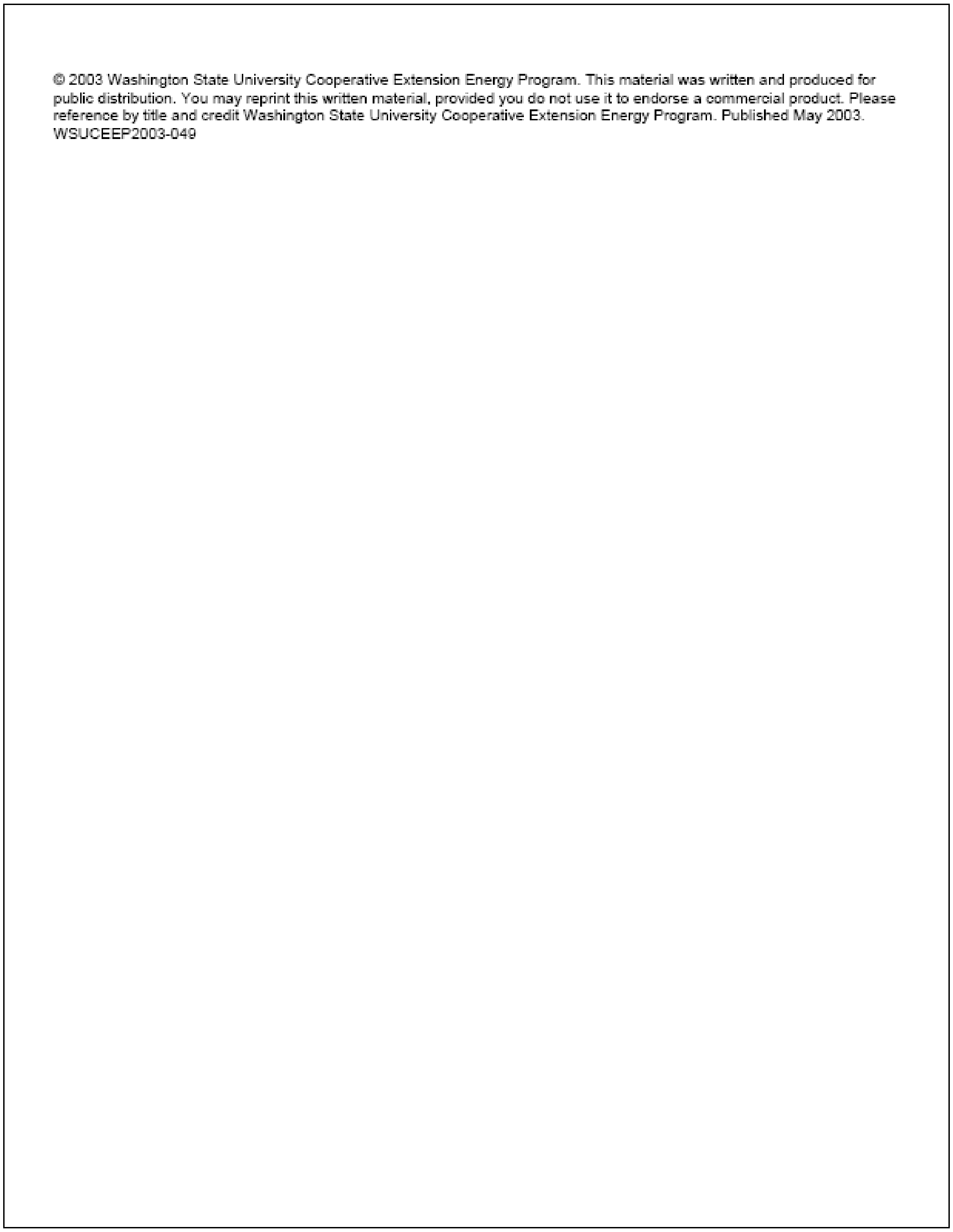
Comments:



ANNUAL HEATING DEGREE DAY (HDD) AND COOLING DEGREE DAY (CDD) NORMALS FOR ________________STATE BY COUNTY (19__ - ___)

COUNTY	STATION	ANNUAL	
		HDD	CDD

Note: For each site, heating degree day normals are reported in the left column, cooling degree day normals in the right. "Station" refers to the NOAA climatological measuring site from which data are taken to represent the county as a whole. Stations are chosen to be representative of the county according to the location relative to isotherms. Temperature base for heating and cooling degree day is 65° F.
You can find these for your region by contacting local weather service stations or the National Oceanic and Atmospheric Administration.



Appendix II

Thermodynamics Fundamentals

Because the addition of heat to a product in processes is such a ubiquitous part of manufacturing, one of the key components of the ERDT analysis is the use of thermodynamics to perform many of the main calculations in the second step. Specifically, the methodology uses the first law of thermodynamics or, the conservation of energy, to calculate the minimum versus actual energy task ratios. As such, a basic review of thermodynamic fundamentals with respect to the ERDT method is presented below.

The science of thermodynamics examines energy and heat flows. Most industrial processes involve energy and heat in some combination and therefore thermodynamics is the good tool to analyze these systems.

To set the stage for this subject, the following terms are defined:

System – In thermodynamics, the system is whatever is being studied. For the ERDT methodology a system usually means the particular process under investigation such as the heat treat oven or the air compressor. Everything outside of the system is considered the surroundings. In a manufacturing plant there are other systems as part of the surroundings to a particular process under investigation. Therefore, systems can have other systems contained within. For example the heat treat area could be considered a system. Within heat treat there are furnaces, each of which could also be considered a system. For this study, individual processes, or systems, are analyzed as a simplification.

When there are strong interactions between systems this is addressed in the methodology. Systems can either be closed systems with fixed quantities of matter or control volumes in which mass passes through.

Boundary – A system is separated from its surrounding by a boundary. Placement of the boundary is determined by what the engineer wishes to study. Constructing the boundary too large can complicate analysis by including systems that are not part of the problem. Making the boundary too small runs the risk of eliminating energy or mass flows that are a critical part of the problem. This is an important concept in thermodynamics and energy analysis. Energy and mass can cross the boundary or control surface.

Equilibrium –When an isolated system is in equilibrium it will not spontaneously change states such as temperature, pressure or volume. For second law or exergy analysis the distance a system is from being in equilibrium with ambient conditions is very important (Step 3).

Force – Force is defined as the ability to accelerate a mass. In SI units the Newton (Kg*m/s^2) is defined as the force needed to accelerate a mass of 1 Kg at the rate of 1 meter per second per second.

$$F = ma \quad \text{or} \quad F = m\frac{dV}{dt} \tag{A1}$$

Energy – While most people appear to have a subjective concept of energy, the term is difficult to describe in isolation. Energy is best described by describing other phenomenon.

Kinetic Energy – Using the analysis of forces acting on a body over some distance results in the well-known equation:

$$\Delta KE = KE_2 - KE_1 = \frac{1}{2}m\left(V_2^2 - V_1^{\,2}\right) = \int_{s1}^{s2} F \cdot ds \qquad \text{(A2)}$$

The kinetic energy (KE) equation describes the energy of moving bodies. A hammer striking a surface is an example that could be analyzed using the kinetic energy equation. A fluid or a gas striking and turning a turbine to produce work is another example of kinetic energy.

Potential Energy – Potential energy (PE) is a concept that deals with stored energy. Examples of stored energy are: compressed springs, mass in a gravity field and chemical energy. A body at some height above the ground has the potential to do work as it is released and falls. The PE equation is:

$$\Delta PE = PE_2 - PE_1 = mg\left(z_2 - z_1\right) \qquad \text{(A3)}$$

Both KE and PE are extensive properties in that their value depends on what is being done to the mass (e.g., position or velocity). The two types of energy are quite often used together as in the case of hydroelectric-power where the PE of the higher elevation water turns the generator turbines via KE as it falls to a lower elevation.

Work – The definition of work is when a force acts through a distance. Work has meaning in the relm of mechanics but for the study of thermodynamics the term is expanded to include: Work is done by a system on its surroundings if the sole effect on everything external to the system could have been the raising of a weight (Moran, Shapiro, 32). Work can be expressed as the integral:

$$W = \int_{s1}^{s2} F \cdot ds \tag{A4}$$

Work is a path function and does not depend on the end states of the system rather the continuous path of the interactions. Work is often examined in pressure/Volume systems such as piston and cylinder assemblies. In this case the work integral is:

$$W = \int_{V1}^{V2} pdV \tag{A5}$$

Other Examples of work include shaft work, electrical work and magnetism.

First Law of Thermodynamics

The change in energy of an adiabatic closed system between two equilibrium states can be described by ΔE as work:

$$E_2 - E_1 = -W_{adiabatic} \quad \text{or more specifically} \tag{A6}$$

$$\Delta E = \Delta KE + \Delta PE + \Delta U \tag{A7}$$

The symbol ΔU refers to the remaining energy changes not associated with kinetic or potential energy changes and is called internal energy. Internal energy is often associated with chemical energy due to activity at the atomic and molecular level in a substance.

Closed systems can also interact with their surroundings in one other way that is not classified as work. This interaction is called a heat interaction Q. From experimental evidence it is known that energy is conserved in systems regardless of the type of activity occurring with the system. Therefore, the total change in energy of a system can be described as a relationship between work and heat transfer:

$$\Delta E = Q - W \tag{A8}$$

The sign convention for heat transfer is:

Q > 0 for heat transferred into the system

Q< 0 For heat transferred from the system

Like work, heat is not a property and is described as the integral of the interactions over time, area, etc.:

$$Q = \int_1^2 \delta Q \tag{A9}$$

As will be examined in the Step 3 section on the second law of thermodynamics, heat energy cannot be completely converted into mechanical work in the way the kinetic, potential or internal energy can.

The energy balance equation for a closed system can now be described as:

$$\Delta KE + \Delta PE + \Delta U = Q - W \tag{A10}$$

In essence, this is the main equation used to describe the first law of thermodynamics. This equation is also called the conservation of energy equation. A rate form for this equation is:

$$\frac{dE}{dt} = \dot{Q} - \dot{W} \qquad \text{(A11)}$$

Typically the first law equation is used as a mathematical system of known and unknown terms. For example, knowing the changes in energy and the work, the heat interaction can be found.

V ITA

Robert Scott Frazier

Candidate for the Degree of

Doctor of Philosophy

Thesis: AN EXERGY DIAGNOSTIC METHODOLOGY FOR ENERGY MANAGEMENT IN MANUFACTURING

Major Field: Industrial Engineering and Management

Biographical:

Personal Data: Born in Phoenix, Arizona, On December 18, 1957, the son of John (OSU Civil Engineering - 1949) and Nell Frazier.

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Experience:

- ➢ Project coordinator and engineer for Oklahoma State University Industrial Assessment Center (IAC), 2003 - present.
- ➢ Industry Energy Engineering Consulting Work and teaching, 1995-present.
- ➢ United States Naval Reserves: Intelligence Specialist, USNR, mobilized veteran of operation Noble Eagle/Enduring Freedom (2001-2002).
- ➢ Mantech Systems Engineering Corp. Project Engineer, Project Manager and Lead Certification Tester for Navy aircraft (2000-2001).
- ➢ Southern Maryland Electric Cooperative Inc. Hughesville, Maryland, Commercial Energy Analyst for all industrial and commercial customers in the Southern Maryland area (1995-2000).
- ➢ School of Industrial Engineering and Management, OSU, Stillwater, Oklahoma, Energy Engineer, Consultant, and Graduate Research and Teaching Assistant, 1993-1995).

Professional Memberships: Society of Professional Engineers, Society of Automotive Engineers, Association of Energy Engineers, Associate Environmental Professional (AEP 1379), Alpha Pi Mu Industrial Engineering Honors Fraternity.

Name: Robert Scott Frazier   Date of Degree: December, 2006

Institution: Oklahoma State University   Location: Stillwater Oklahoma

Title of Study: AN EXERGY DIAGNOSTIC METHODOLOGY FOR ENERGY MANAGEMENT IN MANUFACTURING

Pages in Study: 280   Candidate for the Degree of Doctor of Philosophy

Major Field: Industrial Engineering and Management

Scope and Method of Study: The focus of this study was the creation of a systematic characterization and identification methodology for potential energy management projects in the industrial manufacturing setting. The current methods of selecting processes for energy improvement processes tend to be experience-based in nature. Most energy improvement software either begins with the notion that the particular processes to be improved have already been identified or that some form of a-priori domain knowledge is needed to identify these processes. The methodology proposed in this study begins with the product value transformations and works outward to establish metrics of process performance (efficiency and effectiveness). The methodology presented in this research can be used as both a process design system and an energy auditing aid.

Findings and Conclusions: A systematic methodology is described that gives the engineer an understanding of the energy use of individual processes at a systems level and uses a more quantitative means for the identification of candidate energy improvement projects. The method suggested uses a combination of an exergy (second law) based analysis and energy value stream mapping to visualize the entire plant process for systems optimization (process integration). The sub-processes with potential for energy conservation are highlighted and may be ranked or otherwise selected by the engineer and management for action. The methodology also is poised to act as an integrator with other process analysis methodologies such as activity based management, lean manufacturing and sustainability studies. The expansion of this integration role is suggested for further research.

ADVISOR'S APPROVAL: Dr. William Kolarik________________________