CONF-9607140--2

ORAL PRESENTATION

Fourth World Congress on Environmentally Conscious Design and Manufacturing
Cleveland, Ohio
July 23–25, 1996

THE INDUSTRIAL ECOLOGY OF ASSET MANAGEMENT: A CASE STUDY*

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AUG 16 1996
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* Based on work performed at Oak Ridge National Laboratory, managed for the U.S. Department of Energy under contract DE-AC05-96OR22464 with Lockheed Martin Energy Research Corp.

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The Industrial Ecology of Asset Management: A Case Study

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Abstract

Closure of materials cycles, which is one of the key goals of industrial ecology, was shown to produce environmental and economic benefits. An interdisciplinary team of scientists and engineers at the Oak Ridge National Laboratory (ORNL) developed a life-cycle approach to examine the environmental and economic aspects of using purchased metal boxes for disposal of low-level radioactive waste versus a proposed process of fabricating boxes from metal already contaminated and destined for disposal as low-level radioactive waste. This proposal would plug a leak in the steel materials cycle in which steel is removed from the commercial cycle for permanent disposal with low-level radioactive waste. It was found that fabricating boxes out of the contaminated metal could (1) result in a direct savings of $80 million over prompt total disposal of the metal; (2) add an additional 100 jobs and about $10M/year to the regional economy compared to direct disposal; (3) result in lower particulate matter and sulfur dioxide emissions; (4) face reduced regulatory barriers; and (5) face public acceptance issues in local communities due to perceptions of risk from private sector metal recycling operations.

Introduction

One of the goals of industrial ecology is the transition from linear to cyclical materials flows in conducting our economic activities. Graedel and Allenby note that "The concept of industrial ecology is one in which the cyclization of materials at their highest possible purity and utility level is of prime importance." (Graedel and Allenby, 1995). With cyclical processes, natural resources are conserved and the volume of solid waste is reduced, with resultant costs, emissions, and effluents stemming from the processing of the materials to allow reuse in the cycle. A goal of industrial ecology is to plug the materials cycles "leaks", in which materials are irretrievably disposed and thus are unavailable for future reuse. Such goals are viewed by many as essential ingredients for achieving sustainable development: a sustainable economy would be characterized by near-total recycling of intrinsically toxic or hazardous materials, as well as materials that may not be toxic per se but due to their volume constitute environmental problems (Ayers 1994).

Although the closing of materials cycles is widely touted as the environmentally preferable, such claims are not often accompanied by rigorous analysis of the costs and benefits of the recycling activities. Many times the economic costs and environmental impacts of processing wastes to facilitate their recycling are not assessed, and seldom is the complete life cycle of the material considered when evaluating economic costs and environmental impacts. As noted by Graedel and Allenby (1995), "performing recycling should not result in a greater environmental impact than not performing recycling," and "a comprehensive analysis is often needed to determine the most sensible approach to a specific problem." A life cycle approach to evaluating the closure of materials cycles represents a "comprehensive analysis," and thus provides a number of advantages through its use in examining the economic and environmental costs and benefits of linear vs. cyclical materials flows.

Examination of global anthropogenic flows of metals indicates that the flow of steel is by far the dominant flow, with approximately 858 million tons/yr (780 Tg/yr) of flow [aluminum is in second place at 107 million tons/yr (97 Tg/yr) [Graedel and Allenby 1995]. In addition, iron/steel is also noteworthy because recycling has increased in the past two decades; in 1977, only about 30% of the total iron/steel consumption was in recycled scrap, whereas in 1987 the figure had risen to almost 50% (Ayers, 1994). Evaluating the environmental impacts of the closing of the steel materials cycle through recycling on a global or national scale would be difficult due to availability of source term and background environmental data. Regional scale evaluations, however, are more valuable to decision-making because they are done on a large enough spatial scale to provide meaningful results, yet offer the advantage of more readily accessible data. Recent programs in the U.S. Department of Energy (DOE) have provided an opportunity for a regional scale evaluation of the closing of the steel cycle.

Due to budgetary pressures and changes in programmatic missions, DOE is examining ways to reduce costs of managing its assets and to stimulate economic growth in the areas of DOE facilities. This in turn has resulted in proposals to empty unused facilities of equipment and to transfer the facilities to the private sector. In Oak Ridge, Tennessee, one of three DOE facilities, the K-25 Site, is being studied as a resource in asset management activities. The K-25 site, formerly known as the Oak Ridge Gaseous Diffusion Plant, was placed on standby in 1985 following termination of uranium enrichment activities at the site. K-25 was permanently shut down as an enrichment facility in 1987. DOE has announced plans to sell or lease surplus materials, equipment, and facilities at the K-25 site; besides the buildings themselves, there are thousands of tons of valuable metals, including nickel, aluminum, stainless steel, and copper available for recycle or salvage. In addition, thousands of electric motors and companion switch gears, controls, and cabling are also salable assets at the K-25 site.

As part of the asset management initiative, a recycling scenario has been proposed in which the metals present in unused process equipment at the K-25 site would be "mined" to use in fabricating containers for shipping low-level radioactive waste to the Nevada Test Site (NTS) for disposal. Currently, NTS waste is placed in purchased boxes made from virgin or recycled steel, which represents a leak in the steel cycle because once the commercial steel is used for these boxes, it is effectively removed from future use due to its disposal with low-level radioactive waste. Manufacturing boxes from low-level contaminated metal would plug the "leak" in this cycle, and could reduce DOE's waste disposal costs if the costs of manufacturing boxes from low-level waste are less than the costs of purchasing new boxes.

Managers at DOE and at Lockheed Martin Energy Systems were considering this proposed use of contaminated metal in late FY 1995 when they identified a need for a framework for quantifying the energy, environmental, and economic aspects of the proposed recycling (as well as other proposed asset management policies and practices), as well as a need for order-of-magnitude estimates of the overall costs and benefits of the proposed recycle scenario. In order to meet these needs, an interdisciplinary team of scientists and engineers from the Oak Ridge National Laboratory, the K-25 site, and the Y-12 Plant in Oak Ridge was quickly assembled to develop and test this framework. In order to provide a complete perspective of the costs and benefits of the proposed recycling, it was decided to use a life cycle assessment approach that incorporated direct economic costs, regional economic benefits, and health and environmental costs (including externalities where possible) (Hill et al., 1996). Consequently, this initiative resulted in an opportunity to examine the environmental and economic implications of closing a materials cycle. For the purposes of this study, only one building at the K-25 Site was used (Building No. K-31).

Building K-31 has 60 "cells" that were used in uranium enrichment. Each cell contains about 731 tons (663 metric tons) of metal. Figure 1 shows the breakdown of the metal content by major component of

the cell. Note that iron and nickel dominate the composition in most of the components; exceptions are the heat exchangers and motors, where copper makes significant contributions, and compressors and converters, where aluminum makes a significant contribution.

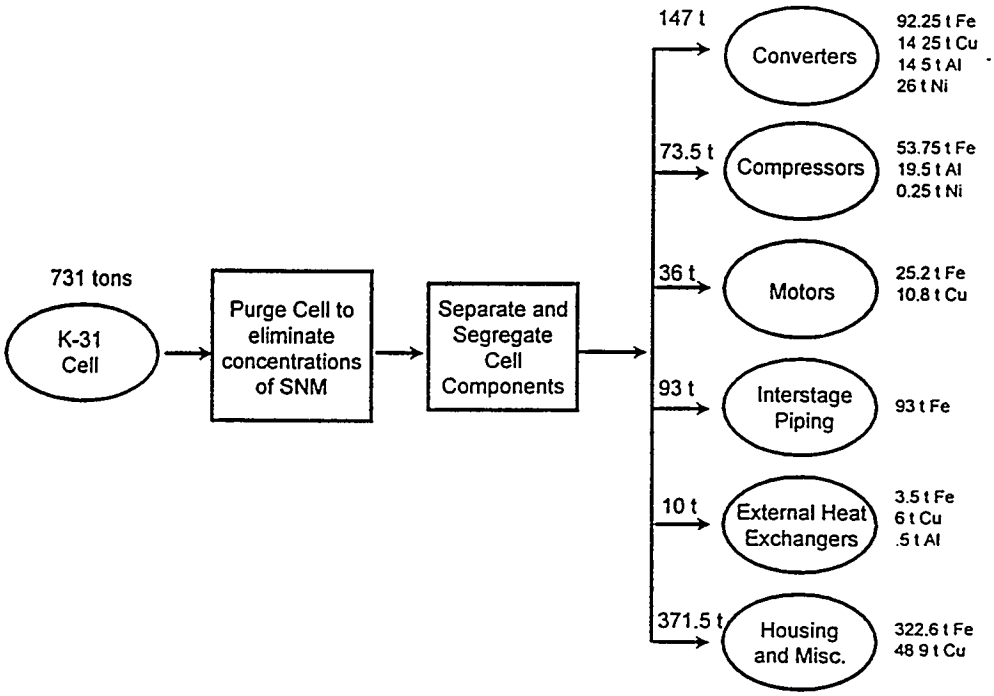

Figure 1. Metals composition of cells found in Building K-31

This assessment considered two alternatives for scrap metal disposition: (1) disposal of the Building K-31 scrap metal as low-level waste or (2) recycle of the Building K-31 scrap metal to the maximum extent; both alternatives require dismantlement, separation, segregation, and disassembly of the equipment in Building K-31. Under the recycle option, some of the metal could be decontaminated for sale, some could be remanufactured into waste containers, and the remainder disposed of as low-level waste. Table 1 gives the disposition of the metal under the recycle alternative. Under the disposal alternative, all of the low-level contaminated metal was disposed of as low-level waste. Disposition of the scrap metal is assumed to require five years, leaving the building structure available for re-use.

Table 1. Disposition of metals in the recycle alternative

Metal	Sell (%)	Dispose (%)	Fabricate Products (%)
nickel in converters	0	0	100
ferrous metal	0	5	95
copper	90	10	0
aluminum	30	70	0

The metals were assumed to be removed from Building K-31 by DOE contractor personnel. For the recycle alternative, metals were assumed to be transported by truck to local private sector treatment facilities that would melt the metal, fabricate sheet steel, and construct boxes. No construction and operation of DOE facilities were assumed to occur for the fabrication of the boxes out of the low-level waste. Restricted use stainless steel and carbon steel B-25 containers were assumed to be fabricated using the nickel and ferrous metal. Virgin chromium in the form of 70Cr/30Fe Ferrochrome was assumed to be purchased for production of stainless steel in amount sufficient to liquidate all of the nickel in the converters. The remaining recyclable ferrous metal was assumed to be fabricated into carbon steel boxes. The fabricated boxes were then assumed to be transported back to the K-25 site for loading with low-level radioactive waste for shipment by truck to the NTS for disposal.

Approach

The life cycle assessment approach that was developed in this case study incorporates the following principal steps:

Objectives Setting. This stage of the analysis includes identifying programmatic objectives, defining performance measures, assessing the data required to perform the analysis, defining the principal alternatives to be considered, and identifying the criteria for the quality and efficiency of the analysis.

Materials and Resource Quantification. This step includes assessing the information available to perform the analysis, identifying and creating an inventory of assets and resources, and determining data collection programs useful in enhancing the available information.

System Characterization. In this stage, models are developed for carrying out the analysis on the proposed alternatives from two major perspectives: direct costs and external factors (local economic impacts, environmental and health impacts, social/institutional issues, and market issues.

Impact Assessment. This step involves application of the system models to assess impacts. Direct cost impact assessment includes costs of dismantling, operating costs for facilities and equipment, maintenance costs, transportation costs, manufacturing costs, salvage costs, investment costs and risks, financing costs and disposal costs, and sensitivity and uncertainty analyses to determine the impacts of key parameters. External factor impact assessment includes analyses of external costs and benefits (e.g., supply and demand, local economic impacts, etc.) and potential impacts to human health and environmental resources. Additional integrating analyses are conducted, including the impacts on programmatic budgets and the impacts on program schedules. Strategic alternatives are reviewed in relation to the initial assumptions, objectives, and scope that were developed in the first stage.

Summary of Performance Measures. This stage summarizes the results of the analysis for use by decision makers. With the data and the models developed through the life cycle analysis methodology, these decision parameters can be varied and presented in any form desired by decision makers for use in decision support systems.

Figure 2 illustrates these elements from the standpoint of three types of impacts: market and socioinstitutional issues; direct costs and benefits; and environmental, safety and health impacts.

Application of this generic approach to the evaluation of recycle vs disposal of the scrap metal at Building K-31 is described below in further detail. Each of the above steps was conducted to varying degrees depending upon the availability of data and time for analysis.

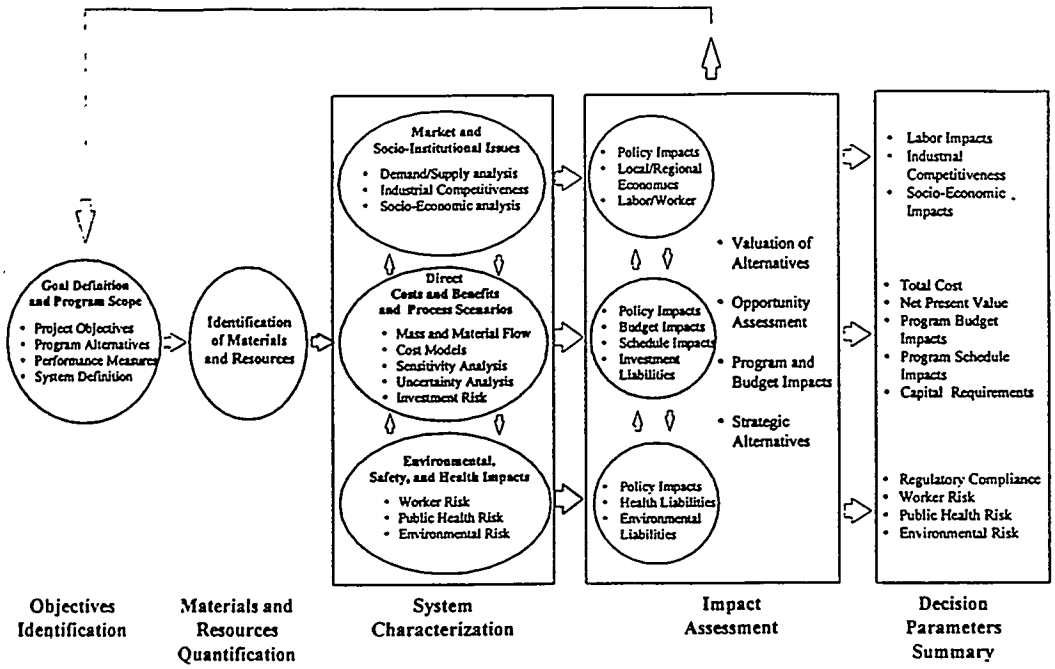

Figure 2. Elements of the life cycle analysis methodology

Direct Costs

The assessment of the direct costs of the two alternatives (total disposal, maximum recycle) was conducted by developing a process flow model to simulate material flow and produce material balances for both alternatives and by developing a financial spreadsheet to calculate costs for various process scenarios. The materials flow model was developed using FLOW, a process simulation model developed at ORNL. The model allows users to simulate various program alternatives; allows for efficient analysis of sensitivities of key parameters; and provides process costs based on assumptions on the cost-per-pound for extraction, decontamination, processing of metals, and disposal of waste. The cost-per-pound assumptions were based on engineering estimates and expert opinion that are used to assess the total materials stock and estimate some of the manufacturing unit costs, and on cost estimates developed for separation, segregation, and disassembly of Building K-31.

External Factors

External factors are those outside of the direct costs of implementing the alternatives. Four key areas of external factors were evaluated during this study: local economic impacts, environmental and health impacts, social/institutional issues, and market impacts.

Local economic impacts. Any new activity introduced into a region will affect the local economy through the direct infusion of funds as well as the indirect multiplying effect as local businesses, governments, and residents spend their share of the added funds in the local economy. A five county regional input/output model called the Oak Ridge Social Accounts Matrix was used to model the perturbation to the local economy due to recycling or disposal of Building K-31 metals. The matrix characterizes and allows for the financial flows among major sectors of a regional economy. The model

was modified to estimate the local direct and indirect economic impacts of recycle versus disposal options for Building K-31 metals. Five key activities were defined and were analyzed using the matrix: (1) removal of the metals from Building K-31, (2) melting the metal, (3) rolling steel/fabricating containers, (4) local trucking, and (5) long-haul trucking. Economic indicators used to evaluate effects were: business shipment, gross local product, household income, net government revenues, and employment levels.

Environmental and Health Impacts. To address the life cycle health and environmental issues associated with the two alternatives in the limited time available for this study, an abbreviated life cycle assessment (LCA) approach was developed that begins with a comparative screening level analysis to identify life cycle stages of the two alternatives that offer the potential for significantly different adverse environmental impacts (note that an impact could be potentially significant but not analyzed in this method if it is common to both options). Potentially notable differences between the two alternatives were identified in three major areas: mining, metal production, and waste disposal. Under the disposal option, additional iron, coal, and other mineral must be mined to manufacture the waste containers that would otherwise be manufactured from the recycled metal under the recycle option. In addition, smelting of the steel from these mined materials has a potentially significant impact on environment and health. Further, the disposal option would ultimately dispose of more material because of the additional "clean" steel used for the containers.

Social/Institutional Issues. Federal regulations regarding waste treatment and transport were consulted, as were reports describing stakeholder perceptions of waste treatment in the Oak Ridge region. Contacts were made with a number of parties involved in waste treatment operations in the region.

Market Issues. Volumes of steel processed in the world market were evaluated, as was the demand for radioactive scrap metal. The volumes of steel and the numbers of containers that could be fabricated using Building K-31 steel were compared against these markets.

Results

Direct Economic Effects

The findings of the direct cost analysis support the recycle alternative. The costs of separation, segregation, and disassembly were found to be the major cost drivers for both the recycle and total disposal alternatives. The recycle alternative is seen to significantly reduce the number of shipments to a disposal facility: an estimated 2900 shipments under the total disposal alternative are reduced to approximately 500 shipments to a disposal facility under the recycle alternative. It was also noted that the cost-effective packing method is a function of the cost of disposal--it was found to be cost effective to melt the metal for both the recycle and total disposal alternatives. Recycle of the Building K-31 metals was found to produce an estimated direct cost savings of about $80 million over total prompt disposal based on the market price of products and a disposal cost of $45/cubic foot.

A sensitivity analysis was performed on the disposal of the metal. It was found that as the cost of disposal rises, the recycle alternative becomes more attractive because of the reduced volume of material for disposal. However, total cost variations were still small due to the dominance of total costs by the separation, segregation, and disassembly costs that are common to both alternatives. A sensitivity study was also conducted on the stainless steel recovery value; it was found that recycle becomes more attractive as the recovered value for stainless steel increases. Each $1/lb increment in recovery value for stainless steel reduces the cost of the recycle option by $35 million.

Local Economic Impacts

The direct local expenditures in the disposal scenario were found to result in a 1.1% increase in economic activity in the Oak Ridge economic area. The increase in gross local product for the Oak Ridge area in this case would be about $85 million. Local employment would increase by about 2100 jobs. Under the recycle option, the direct local expenditures would result in an additional 1.3% increase in local economic activity. The increase in the gross local product for the Oak Ridge economic area under recycle would be $97 million, and local employment would increase by more than 2200 jobs. Thus, compared to disposal, recycle would result in an increase of about 100 jobs for the region compared to disposal, and an increase of about $12 million in gross local product.

Health and Environmental Effects

Recycling Building K-31 metals would eliminate the need to mine iron, coal, limestone, nickel, aluminum, and copper, in addition to the various secondary resource requirements necessary to generate the electricity, create the fuel for transportation, etc. Mining would have the highest impacts in land use, waste disposal, and human health. Every ton of steel recycled would eliminate the need for roughly 3-6 tons (2.7-5.4 metric tons) of iron ore, 0.8 tons (0.7 metric tons) of coal, and 0.15 tons (0.14 metric tons) of limestone. Nickel ore contains only around 2% nickel metal on average, so 50 tons of ore are required for every ton of metal (approximately 98% of the ore materials become waste). For the purposes of quantifying environmental impacts, it was decided to focus on air pollutant emissions (particulate matter and sulfur dioxide). Computed emissions are summarized in Table 2.

Table 2. Summary of estimated air pollutant emissions (lb of emissions per ton of steel produced)*

Alternative	Particulate Matter	Sulfur Dioxide
Disposal	2.5-12.3	6.9-11.8
Recycle	0.6	3.0**

* Multiply by 0.5 to convert to kg/metric ton

**The technology assumed to be used for melting the contaminated scrap metal is electricity intensive. Value reflects recycle process only and does not include emissions from electricity generation. Production of electricity from a coal-fired power plant could increase the total sulfur dioxide emissions by a factor of 2-3.

Mining in various forms presents various health hazards to the workers involved, e.g., black lung disease, radon exposure, and accidents. Additionally, runoff from the waste piles can be a significant polluter of area streams. To further carry out the analysis of impacts in terms of assigning dollar values to the health and environmental effects, the emissions noted above in Table 2, as well as the worker health and safety impacts, were analyzed using previous life cycle assessment work conducted at ORNL (ORNL and RFF, 1994). Based on these two emission and non-emission type issues alone (particulates and sulfur dioxide and accidental death and injury in coal mining), the external damages ranged from 0.5 cents/lb to 2 cents/lb of recycled material (external damages for disposal were not computed, but would be higher if the same damage function were applied to the higher emission rates of these pollutants from disposal).

Social/Institutional Issues

It was found that a lack of certification and opposition from other states would severely limit disposal options for contaminated metal generated at the DOE Oak Ridge facilities. Recycling would likely face fewer regulatory burdens because of the reduction in net waste, but the extra handling and shipping

involved may increase the total burden above the disposal option. The Oak Ridge region and vicinity must decide if it is willing to become a national center for recycling scrap metals. A key to public acceptance will be continued public involvement in the decisionmaking process. At present there is some opposition to private-sector-based waste treatment operations due to perceptions of risk.

Market Issues

The annual amount of metal from Building K-31 [approximately 7600 tons/year (6900 metric tons/yr) over five years] is much smaller than the U.S. or world demand; therefore, this volume of metal would not impact prices. However, a key issue to the recycle option is identifying markets that are available for the metal. Potential markets include low-level waste containers for DOE, transuranic waste cans, vitrified high-level waste cans, multipurpose canisters for high-level waste, and low-level waste containers for commercial use. The largest of these is the DOE low-level requirements, at somewhere between 3000 and 10,000 tons/year (2700 and 9100 metric tons/year). The transuranic, vitrified waste and multipurpose canisters would require stainless steel for which the nickel from K-25 could be used. However, demand for these containers is not expected to become significant until after the year 2008 due to the initiation of major DOE programmatic initiatives.

Conclusions

Key parameters that affect the amount of cost savings from recycle are the disposal costs and the demand and price for the products. Recycle is also favored from a health and environmental standpoint, as well as from the standpoint of local economic benefits.

Future work includes expanding this preliminary analysis to more thoroughly analyze the costs and benefits of scrap metal recycling. Extraction of costs currently "hidden" in overhead and the assessment of future liabilities should be examined; health and environmental effects should be more thoroughly examined for the two alternatives. Further work is needed to identify the optimum strategy for disposition of the assets at the K-25 site; this study only examined two extremes, and the optimum strategy may lie in between disposal and recycle. Future work should also include development of an up-to-date, quality-assured data base on emissions and effluents and energy use from metal production.

Lastly, this preliminary study demonstrated that the closing of materials cycles can produce environmental and economic benefits on a regional scale. Disposition of DOE's assets represents an excellent living laboratory for further study and exploration of many of the underlying tenets of industrial ecology.

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