Report to
THE COUSTEAU SOCIETY

EMERGY ANALYSIS PERSPECTIVES OF THE *EXXON VALDEZ* OIL SPILL IN PRINCE WILLIAM SOUND, ALASKA

M.T. Brown, R.D. Woithe, H.T. Odum, C.L. Montague, and E.C. Odum

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Center for Wetlands and Water Resources
University of Florida
Phelps Laboratory, Museum Road
Gainesville, Florida 32611-2061
Telephone: (904) 392-2424   Telefax: (904) 392-3624

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This study of Alaska and questions surrounding the Exxon Valdez oil spill and tank vessel oil transportation, resulted from ongoing collaborative research with The Cousteau Society. It is one in a series of studies, funded by The Cousteau Society, dealing with the interface between humanity and nature. As in previous studies, questions of public policy were quantitatively explored and suggestions were made for sustainable patterns of development and resource allocation.

The research support of The Cousteau Society was part of its pledge to evaluate and monitor the Valdez spill made when filming *Outrage At Valdez* in 1989. We are very much indebted to the Society, its members, and in particular, Jean-Michell Cousteau and Richard Murphy for their interest and suggestions.

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EMERGY ANALYSIS PERSPECTIVES OF THE *EXXON VALDEZ* OIL SPILL IN PRINCE WILLIAM SOUND, ALASKA

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LIST OF ABBREVIATIONS USED IN THIS STUDY

A.D.C.E.D.	Alaska Department of Commerce and Economic Development
A.D.E.C.	Alaska Department of Environmental Conservation
A.D.F.G.	Alaska Department of Fish and Game
A.D.N.R.	Alaska Department of Natural Resources
A.O.G.	Alaska Office of the Governor
A.O.S.C.	Alaska Oil Spill Commission
bbl	barrels
F.A.O.	Food and Agriculture Organization of the United Nations
N.O.A.A.	National Oceanographic and Atmospheric Administration
N.R.C.	National Research Council
N.R.T.	National Response Team
sej	solar emjoules
U.S.C.O.T.A.	United States Congress Office of Technology Assessment
U.S.D.C.	United States Department of Commerce
U.S.D.I.	United States Department of the Interior

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ERRATA

Page 33	A footnote for the "Solar Empower" column should be added and should read "Results were corrected for significant figures after all calculations were complete."
Page 33	Summary flow "R" value of "4500" should read "4100."
Page 33	In expression for summary flow "N, " term "22" should read term "29."
Page 33	Summary flow "N1" value of "270" should read "230."
Page 33	Summary flow "P1E" value of "210" should read "252."
Page 33	Summary flow "B" description "Exports transformed within" should read "Other exports."
Page 33	Summary flow "B" value of "34" should read "200" (as the following addition to the expression for "B" indicates, this is actually a change in methodology rather than an error).
Page 33	Expression for summary flow "B" should read "21 + 22 + 23."
Page 33	Expression for summary flow "FF" should read "13 + 14 + 15 + 17."
Page 34	A footnote for the "Value" column should be added and should read "Results were corrected for significant figures after all calculations were complete."
Page 34	Index "I2" value of "7600" should read "6500."
Page 34	Index "I4" value of "2400" should read "2500."
Page 34	Index "I6" value of "0.069" should read "0.087."
Page 34	Index "I7" value of "0.075" should read "0.052."
Page 34	Index "I8" value of "13" should read "19."
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EXECUTIVE SUMMARY

Emergy Analysis Perspectives of the *Exxon Valdez* Oil Spill in Prince William Sound, Alaska[a]

This study used emergy[b] analysis techniques to evaluate both the economic and environmental impacts of the March 1989 *Exxon Valdez* oil spill in Alaska. Emergy analysis allows the comparison and incorporation of environmental, economic, and social costs and benefits to provide a more comprehensive perspective for policy decisions. Impacts of the spill were estimated and the estimates used to infer the fraction of gross domestic product (macroeconomic value[c]) that was directly and indirectly impacted by the spill. The oil spill and subsequent events were placed in perspective by comparing the emergy changes associated with the spill to annual emergy budgets of the world economy, the United States, the state of Alaska, and the Prince William Sound region.

The direct economic losses, expressed in macroeconomic value, amounted to 3.2 billion macroeconomic dollars distributed as follows: 1.0% to 1.6% lost fishery harvest; 1.1% to 1.6% lost Exxon Valdez cargo; 4.0% to 6.8% fuel used in cleanup; 4.0% to 6.0% social disruption; and 56% to 80.6% human labor in cleanup.

Emergy analysis of the *Exxon Valdez* oil spill and cleanup revealed that the cleanup costs exceeded the natural resource and direct economic losses incurred by between 110% and 740%, depending on the magnitude of the actual natural resource losses. In other words, the cleanup costs were 1.1 to 7.4 times more costly than the natural resource and economic damages that actually resulted from the spill.

The annual emergy budget for the state of Alaska was calculated and compared to those of other states and nations. Alaska had a much higher proportion of free environmental emergy to purchased emergy than that other states, a condition representative of Alaska's less developed condition. Compared to Sweden, a country with somewhat similar environmental resources, Alaska has a poor pattern of emergy use. Emergy analysis of the Alaska balance of trade reveals part of the reason. When exporting environmental products, such as salmon and oil, Alaska exported ten times more emergy value to the buying states or nations than it received in exchange. It is suggested that a policy of home use would increase the long term economy and real standard of living in Alaska ten fold, while building a better pattern of environmental sustainability.

The emergy analysis of the annual environmental contributions to Alaska found an annual support of 4.5E+23 sej per year. Some of this emergy was embodied in the high levels of precipitation and wind in southern Alaska that maintain glaciers, support oceanic salinity gradients, and drive the westward ocean currents. These currents were the means for the rapid dispersal and reduced impact of the Valdez spill. The emergy of stored reserves, including oil, coal, peat, and glaciers, was estimated to have a quadrillion dollar macroeconomic value.

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[a] Report to The Cousteau Society by Mark T. Brown, Robert D. Woithe, Howard T. Odum, Clay .L. Montague, and Elizabeth C.Odum

[b] Emergy measures energy previously required to produce a product or drive a process. The concept was used from 1967 to 1982 under the name "embodied energy" and redefined in 1983. Sometimes referred to as energy memory (Scienceman, 1987), emergy is expressed in emjoules of the same form (solar emjoules; sej) to differentiate it from energy expressed in joules.

[c] Macroeconomic value of a product is the fraction of gross domestic product based on the emergy of the product. A dollar estimated from the emergy content is sometimes called an Emdollar. Solar emergy values, in solar emjoules, are divided by the solar emjoules/$ of the United States to obtain the equivalent macroeconomic dollar value (1.4 trillion solar emjoules per $ in 1992).

An evaluation of the transformities[d] of principal species in Gulf of Alaska ecosystems was performed. The higher the transformity, the higher a species is in the hierarchical chain of nature's work. In general, the high transformity species have long lives, large territories, and greater importance to the ecosystem. Transformities ranged from 10,000 sej/J for kelp to 100 million sej/J for sea otters and killer whales. Tables of transformities for species simplify future evaluations of ecologic and wildlife contributions and issues.

An evaluation of the trans-Alaskan pipeline showed a net emergy yield (over a 30-year life span) of thirteen to one. Thus, the pipeline will eventually yield ten times more emergy than was used in its construction and operation. The pipeline's emergy flow is enormous in comparison to other aspects of the Alaskan system. The emergy value of the oil flow delayed during the eight-day pipeline shutdown following the Valdez spill was greater than the oil spill damage. If political power follows in some degree from emergy, it is not likely that wildlife interests can prevent further oil drilling on the North Slope. It also follows that with such extreme emergy wealth involved, there is no reason why some of the wealth cannot be used to prevent environmental damage on the North Slope and insure continued emergy contributions of the tundra.

The value of total impact of the oil spill and associated events was between 3.3 and 4.8 billion macroeconomic dollars, 56% to 80% of which was in the cleanup effort. When expressed in emergy, the annual losses associated with the spill and cleanup represented:

1.1% to 1.3% of Alaska's emergy budget
87% to 130% of the oil spill region's emergy budget and
330% to 490% of the budget of the Prince William Sound region.

Emergy benefit-cost ratios were calculated for ten alternative methods of oil spill prevention. The benefits were calculated as the damage that would not be incurred should the method be implemented. The macroeconomic value required to implement each of the alternative prevention measures varied from 288 million to 8.8 billion macroeconomic dollars. Many measures proposed for preventing oil spills were found to divert more resources than would be saved (emergy required for prevention was greater than the losses prevented). Implementing these methods would result in a net loss. Double-hulled oil tankers were one of the alternatives found to be inappropriate. Three proposed measures for spill prevention did have positive net emergy benefits.

In order to consider minimum and maximum benefits , net emergy ratios were calculated for each prevention alternative over a range of possible conditions. None of the 10 prevention measures were a net emergy benefit for their minimum conditions, while seven had benefit ratios up to 2.4/1 under the most favorable circumstance.

An emergy analysis was conducted for the process of transforming images of environmental damage of the oil spill into the shared memory in millions of people. Based on several assumptions, the emergy of the shared information about the spill was 3.4 times that of the spill phenomena. The pressure of the unified public opinion caused Exxon to invest up to 7.4 times more emergy into Alaska (in the form of cash payments) than was in the shared information. Thus a great amplification was achieved by the information system in going from the image of disaster to the response that resulted, possibly because of the high emergy of information already in people sensitized to environmental issues. The investment of emergy created a social storm phenomenon analogous to other systems in which energy is

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[d] Transformity. The total energy, measured in one form, required to produce one unit of energy of the given product. Transformities have the dimensions of emergy/energy (sej/J). The transformity of a given product is calculated by summing all the emergy inflows to the process creating the product and dividing by the energy of the created product. Transformities are used to convert energies of different forms to emergy of the same form.

The great waste and secondary disaster produced by the television information system in the present state of American culture appears to be pathological. As a newly organizing system, global television may require trial and error before developing a pattern that contributes maximum emergy and the most prosperous sustainable economy. If confirmed with additional study, the emergy analysis of the system of environmental response by the television industry may suggest better means for finding appropriate responses.

References Cited:

Scienceman, D. 1987. Energy and emergy. Pp. 257-276 in G. Pillet and T. Murota (eds.) *Environmental Economics - The Analysis of A Major Interface.* Roland Leimgrubers, Geneva, Switzerland,

I. INTRODUCTION

This study of Alaska and questions surrounding the *T/V Exxon Valdez* oil spill resulted from ongoing, collaborative research efforts with The Cousteau Society. It is one in a series of studies, funded by The Cousteau Society, dealing with the interface between humanity and nature. As in previous studies in various regions of the world, questions of public policy were quantitatively explored and suggestions made for sustainable patterns of development and effective allocation of resources.

This study used emergy[a] analysis techniques to evaluate both the economic and environmental impacts of the *Exxon Valdez* oil spill. Emergy analysis allows comparison and incorporation of environmental costs and benefits with variables of traditional economic costs and benefits to provide a more comprehensive perspective for policy decisions. The analysis quantified, on a common basis, the environmental damage in Prince William Sound and the Gulf of Alaska, the economic costs associated with clean up, and the economic impacts of lost fishery production and tourism. Included were economic goods and services, fuels, and the fluxes of renewable energies as well as environmental changes that occurred, such as the loss of marine primary production and animals that were killed by the spill.

The spill, the cleanup that resulted, and the various alternatives that were proposed to revent oil spills following the Valdez spill offered a unique opportunity to develop perspectives for the public policy arena that might shed some light on the complex questions surrounding environmental disasters and their prevention.

Statement of the Problem

Among the most important problems facing human society today is the development of procedures for the integrated study of human and natural processes that will lead to sound management of natural resources. Increasingly, there is a need to understand both human and natural domains, each in the context of the other, and to develop management strategies and evaluation techniques which acknowledge and promote the vital interconnections between the two. Neither the discipline of economics nor that of ecology has alone adequately addressed the problems society presently faces. Faced with questions related to environmental impacts, and the costs and benefits of methods to prevent or mitigate these impacts, society often fails to adequately factor in the environment because of the inherent limitations of economic analysis. Both economic and environmental costs can be determined for most environmental disturbances. However, the two types of costs are most often accounted for in different units of measure (economic measurements in dollars and ecologic measurements in acres of impacted area or numbers of animals affected, for example). Environmental costs may be accounted for quantitatively with economic measurements if some direct "value" to humans can be determined. Otherwise, environmental costs remains in units of measure that do not combine easily with the units of economic costs. The public decision-making process is then forced to weigh impacts in different realms having differing quantitative bases, determine an equitable allocation of costs and benefits, and ultimately generate a policy decision.

To account for all costs and benefits associated with environmental disasters and to make the best policy decisions regarding the allocation of resources for the mitigation and prevention of impacts, a wider view is necessary: This view must combine the systems of humanity and nature and not treat the affairs of humans and the productive processes of the biosphere as distinct entities. A new paradigm for such an analysis is emerging, a paradigm that includes both the affairs of humans and the processes and components of the environment. It is an interface between ecology and economics. This interfacing field is "ecological economics," and among its tools is the quantitative evaluation technique of "emergy analysis."[a]

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[a] Emergy measures energy previously required to produce a product or drive a process. The concept was used from 1967 to 1982 under the name "embodied energy" and redefined in 1983. Sometimes referred to as energy memory (Scienceman, 1987), emergy is expressed in emjoules of the same form (solar emjoules; sej) to differentiate it from energy expressed in joules.

Environmental disasters such as oil spills, present a particularly difficult problem for public policy decision-makers. Such questions emerge as: for a particular disaster, what level of response is appropriate? Or, what level of prevention is appropriate to insure that environmental disasters do not occur? To answer these questions, costs to the environment and economic system must be weighed against each other and benefits related in such a way that the costs of prevention are not greater than the costs that are being prevented. Yet, most often, the problem of costs and benefits being quantified in differing units of measure - money on the one hand, and environmental deterioration and social disruption on the other - still remains.

Plan of Study

To gain perspective and understand the place of the oil spill in the economy of Alaska and the Prince William Sound region, an emergy analysis of the state and region were conducted. The environmental, economic, and social impacts of the spill were then evaluated and compared at the two scales. Finally, to provide some perspective on the relative merits of various prevention technologies, the costs of these technologies were compared to the costs of two spills; the Valdez spill in Alaska, and a hypothetical spill in a developed region of the southeast United States coast.

This final analysis (of the costs of the spill verses the costs of prevention) has extremely important implications. As is well known, but often forgotten when policy decisions are made, technology has its own environmental costs. Many oil spill cleanup technologies damage the environment they are supposed to rehabilitate. Furthermore, there is environmental damage "embodied" (from environmental disruption that results from mining, harvesting, refining, or transporting a resource) in the resources used to create and implement oil spill prevention/cleanup alternatives, technology and equipment. For instance, a proposed oil spill prevention alternative is to double-hull the tanker fleet. The double hulling of the world tanker fleet will result in a great deal of environmental impact sustained inland from the mining and transformation of the iron ore to steel plate and its installation by maritime industries. While it is nearly impossible to evaluate all the secondary impacts associated with a proposed technology, emergy analysis evaluates the relative amounts of work from the biosphere and from human economic systems that goes into the technology. Thus the emergy value of a commodity, like a second hull on a tanker, has both a global biosphere contribution of renewable and nonrenewable energy, and inputs from the human economy. Theory suggests that the environmental costs associated with a good or service are proportional to its emergy costs (Odum, 1971; 1988; Odum and Odum, 1983). A net yield ratio can be calculated if the emergy required to prevent an environmental impact is related to the emergy that is saved by preventing the impact. This net yield ratio is the ratio of emergy saved (environmental impacts diverted) to emergy spent (the costs of prevention). If the ratio is greater than one, the prevention technology has a positive net benefit. If the ratio is less than one, the prevention technology's benefit is questionable.

Emergy Analysis Perspectives

Emergy, Wealth and Value

In this analysis of the *Exxon Valdez* oil spill in Alaska, economic, environmental, and social costs were quantified and compared in common units of measure, emergy. Emergy is a relatively new concept and represents an alternative system of value from which to develop public policy options. Unlike more traditional economic theory which bases value in terms of utility and willingness to pay, emergy bases value on the amount of renewable and nonrenewable energy that is "embodied" in a commodity. This concept gives many people difficulty since they have been trained from an early age to think that value is based on utility. Something is valuable if it has utility; the more utility and the more that people perceive its usefulness, the more value it has. Thus if something has no perceived utility it has no value, regardless of how much energy may have been embodied in it. This belief system reinforces and amplifies many of the environmental dilemmas the world community now faces.

Clean air and water, productive forests and estuaries have small values in a utility-based value system until they are in short enough supply so as to make them "appear" valuable. That is to say, they were not valuable until their scarcity forced the market to price their scarcity. Yet they were always valuable, supplying air to breath, water to drink and resources for economic conversions into usable products. An emergy-based value system recognizes their value regardless of their utility at any one moment in time. There is an implicit assumption in an emergy system of value that is akin to utility value, however. Basically, it is assumed that emergy value is proportional to use value, because the biosphere does not make mistakes. Thus if a commodity (whether a natural resource, or an economic good) has embodied in it a given amount of the biosphere's energy, its value to the biosphere in its use is equivalent to that which was invested in it.

Emergy is a quantitative measure of the resources required to develop a product (whether a mineral resource that results from bio-geologic processes, a biologic resource such as wood, or an economic product that results from industrial processes) and express the required resources in units of one form of energy (usually solar). We suggest that evaluations using emergy may help to clarify policy options because the use of emergy as a measure of value overcomes four important limitations of previous attempts to quantify environmental impacts, development cost/benefits, and alternative technologies. These limitations are as follows: 1.) Mixing units of measure like weight, volume, heat capacity, or economic market price cannot lead to comparative analysis. The relative contribution to a nation's economic vitality derived from fossil fuels (measured in barrels), sunlight (measured in ergs), and phosphorus in fertilizers (measured in kilograms) is difficult to determine. 2.) Evaluations that use the heat value of resources for quantification assume that the only value of a resource is the heat that is derived from its combustion. In this way, for example, human services are evaluated as the calories expended doing work, and when compared to other inputs to a given process are several orders of magnitude smaller and often considered irrelevant. 3.) Non-monied resources and processes (i.e., those outside the monied economy) are often considered externalities and not quantified. Most processes and all economies are driven by a combination of renewable and nonrenewable energy. Renewable energies (sunlight, rain, winds, tides, etc.) are outside the monied economy and therefore are generally not accounted for in economic evaluations. Yet they are absolutely necessary in all economies and make up a large portion of most products. Economic vitality depends on the successful use of available resources, both renewable and nonrenewable (fuels, mineral resources, and the goods derived from them); thus evaluations that leave out renewable emergies because they are externalities consistently "undervalue" the total production in economies and environmental processes. 4.) Price determines value. The price of a product or service reflects human preferences often called "willingness to pay." It can also reflect the amount of human services "embodied" in a product. A valuing system based on human preference assigns either relatively arbitrary values or no value to necessary resources or environmental services.

Emergy is a measure of the real wealth of an economy (Odum 1984; Odum and Arding 1991). Since wealth is ultimately tied to resources, it is necessary to express wealth in units that reflect the resource base. Conditioned as we are, that price reflects value, we often believe that money is the measure of wealth and that price determines value. Price suggests what humans are willing to pay for something; but value to the public is determined by the effect a resource has in stimulating an economy. For instance, a gallon of gas will power a car the same distance no matter what its price; thus its value to the driver is the number of miles (work) that can be driven. Its price reflects the scarcity of gasoline and how important it is to do the work. Price is often inverse to a resource's contribution to an economy. When a resource is plentiful, its price is low, yet it contributes much to the economy. When a resource is scarce its total contribution to the economy is small yet its price is high.

Emergy may be a measure of the equivalence when one resource is substituted for another. Sunlight and fossil fuels are very different energies, yet when their heat values are used the difference is not elucidated. A joule of sunlight is not equivalent to a joule of fossil fuel in any system other than a heat engine. In the realm of the combined system of humanity and nature, sunlight and fuels are not equally substitutable joule for joule. However, when a given amount of fuel energy is expressed as solar emergy, its equivalence to sunlight energy is defined. Since emergy is a measure of the work that goes into a product expressed in units of one type of energy (sunlight), it is also a measure of what the product should contribute in useful work in relation to sunlight.

The failing of previous theories of resource-based value, and most current ones as well, has been that they did not account for different types of energy, but assumed that the heat value of energy was a common denominator by which quantification and comparisons could be made. We believe this to be incorrect. All energy types are not equivalent in their ability to do work. Without accounting for the differences in what has been termed the quality of different types of energy, erroneous conclusions can result. Use of emergy to represent all the contributions to any given product or process accounts for differences in resource quality and expresses different resources in equivalent capacity to do work.

We recognize the difficulty that these concepts present since they use new terminology and a different measure of value from those in common usage. However, the concept of value and national wealth stemming from resources is not new, but is as old as economics itself. The history of economic thought is replete with considerable discussion and analysis of national wealth as measured by resources and by attempts to measure value as it stems from resource use. Only recently has economic theory been dominated by the determination of value based on price and national wealth measured by currency. During times of resource scarcity, economic values were related most often to resources (land, labor or energy) and resource use, but during times of resource abundance, economic values were related most often to currency and price.

Theory of Maximum Empower Designs

Theory suggests (Odum 1971, 1983; Odum and Odum 1983) that economies of nature and humans organize so as to develop the maximum empower possible; and that in so doing they prevail and are sustained over alternatives. Empower is defined as the emergy measured in a flow per unit time. The theoretical basis is found in the Maximum Power Principle (Lotka 1922a, 1922b, and 1945). To maximize power, an economy develops an organization of useful processes that increases total production through positive feedback and by overcoming limiting factors. Economies, in the long run, cannot prevail in competition with others if emergy is wasted in nonproductive processes; yet in the short run, one can observe apparent contradictions. However, since observations of any system are time dependent, the real issue is not that processes exist that seem to "waste" emergy (i.e., do not reinforce productive processes) and thus violate the maximum power principle, but whether they can do so indefinitely in a competitive environment where selective processes are geared to eliminate them. This view is in contradiction to some economic theories that suggest any expenditure of money and resources leads to economic vitality, whether or not it is for unnecessary products or services.

Many scientists are used to thinking of systems as organizations of processes that are sustained by their driving energies and resources, and that competition and competitive exclusion are the means by which systems self-organize and develop sustainable patterns. Yet few believe that the criterion for survival, or sustainability, is maximum empower or that competition and competitive exclusion are selective processes that operate to maximize emergy. Other criteria for survival that have been suggested include: minimum cost, minimum risk, maximum stability, maximum efficiency, maximum production, least work, and maximum diversity, among others. The viewpoint used in this study is that economies, and processes within economies, organize and operate so as to increase real wealth and prevail according to the maximum empower principle, a refinement of the maximum power principle, and that a measure of real wealth is emergy.

Description of the Study Area

The State of Alaska

The state of Alaska system is composed of 1.49E+06 km^2 of land area and 1.68E+06 km^2 of continental shelf area (Hartman and Johnson, 1978). The land area includes large areas of tundra, 500,000 km^2 of boreal forest and 60,000 km^2 of coastal forest, and several mountain ranges (Figure I.1). Well over half the state is underlain by permafrost (Hartman and Johnson, 1978). The northern Alaskan coasts on the Bering, Chuckchi and Beaufort Seas have relatively low tidal ranges but extensive areas of tidal energy-absorbing continental shelf (Figure I.1). The Pacific coast of southeastern Alaska is dominated by deep fjords with tidal ranges up to 10 m and a continental shelf break close to shore presumably resulting in a lower proportion of tidal energy absorption than the northern coasts (Figure I.1). A significant volume of Yukon River water and therefore chemical potential energy, enters Alaska from Canada's Yukon Territory. Much of Alaskan land is held by federal and state governments in national and state parks, monuments, refuges and preserves. Only one-twentieth of a percent of the state's land is developed or altered (Smith, 1990).

Half of Alaskan citizens live in the Anchorage metropolitan area. A significant number of Alaskans live in rural villages. As a result, subsistence hunting, fishing and other subsistence activities, which are given priority over sport activities by state law, are an important subsystem used to harvest natural production for use within the state. The petroleum, mining, fishing, forestry, and tourist-related service industries, and divisions of federal government appear to be the mainstays of the Alaskan economic system. The Prudhoe Bay, Endicott, and other petroleum fields on the North Slope of the Brooks Range account for the majority of Alaskan petroleum production. This petroleum is transported to Port Valdez in Prince William Sound via the trans-Alaskan Pipeline. Two refineries amidst the Kenai Peninsula and Cook inlet oil fields and a third in North Pole, Alaska supply half the state's use of refined petroleum fuel (Smith, 1990). Crude oil and natural gas make up a large percentage of Alaskan exports, but the majority of the state's natural gas is used internally or disposed of by re-injection into the oil fields. Alaska has significant coal reserves, the majority of which are bituminous and sub-bituminous. In 1985, the year of the Alaska analysis, all of the state's coal production was used in its own power plants, though in 1990 half of an increased production was exported to Korea (Smith, 1990).

The Alaskan forest industry is almost entirely dependent upon trade with Japan. Owing to federal law, timber production from federal lands cannot be exported unprocessed and is therefore exported as rough cut lumber, wood pulp and chips. Timber exports from private lands, primarily native corporations, are generally in round log form (Smith, 1990). The Alaskan fishing industry landings are the largest in the United States. Alaska also has the largest catch by foreign vessels of any U.S. state. Japanese and Polish vessels account for over 75% of this catch. Much of the domestic catch is also exported directly to Japan. Japan is Alaska's major international trading partner, being the destination for over 70% of the state's international exports. Canada is the source of approximately half the state's international imports (Smith, 1990).

The Prince William Sound Region

The oil from the *T/V Exxon Valdez* made landfall on a diverse length of the Gulf of Alaska coast, a 1400 km arc in the North Eastern Pacific Ocean extending west from the islands of southeast Alaska and Northern British Columbia to the Aleutian Islands (Figure I.2). From the grounding sight in northeastern Prince William Sound, the oil moved southwest reaching its most distant landfall at the Chignack area of the Alaska Peninsula 900 km from Bligh Reef (Galt et al., 1991).

A coastal mountain range with peaks exceeding 4000 m stretches along the Gulf of Alaska coast restricting weather systems, resulting in high precipitation. The coastal drainage basins are narrow and most fresh water enters the Gulf from small, short streams as a disperse line source rather than concentrated point sources. The Alaska Coastal Current flows westward within 20 km of the shore driven by freshwater inputs and wind (Royer et al., 1990). The Alaska Current, a counter-clockwise deflection of the Koroshio Current, flows beyond the continental shelf, parallel to the Alaska Coastal Current. Based upon coastal relief, and the oceanography and biology of the area, the impact zone of the spill may be divided into four general regions: 1) the southwestern two-thirds of Prince William Sound; 2) the southeastern coast of the Kenai Peninsula; 3) the mouth of Cook inlet; and 4) the Kodiak Archipelago and the Shelikof Strait region of the Alaska Peninsula (Figure I.2). Because the spill occurred in Prince William Sound and this region was perhaps the most heavily impacted, and because the boundaries of Prince William Sound are identifiable for analysis purposes, the focus of this report is here. General

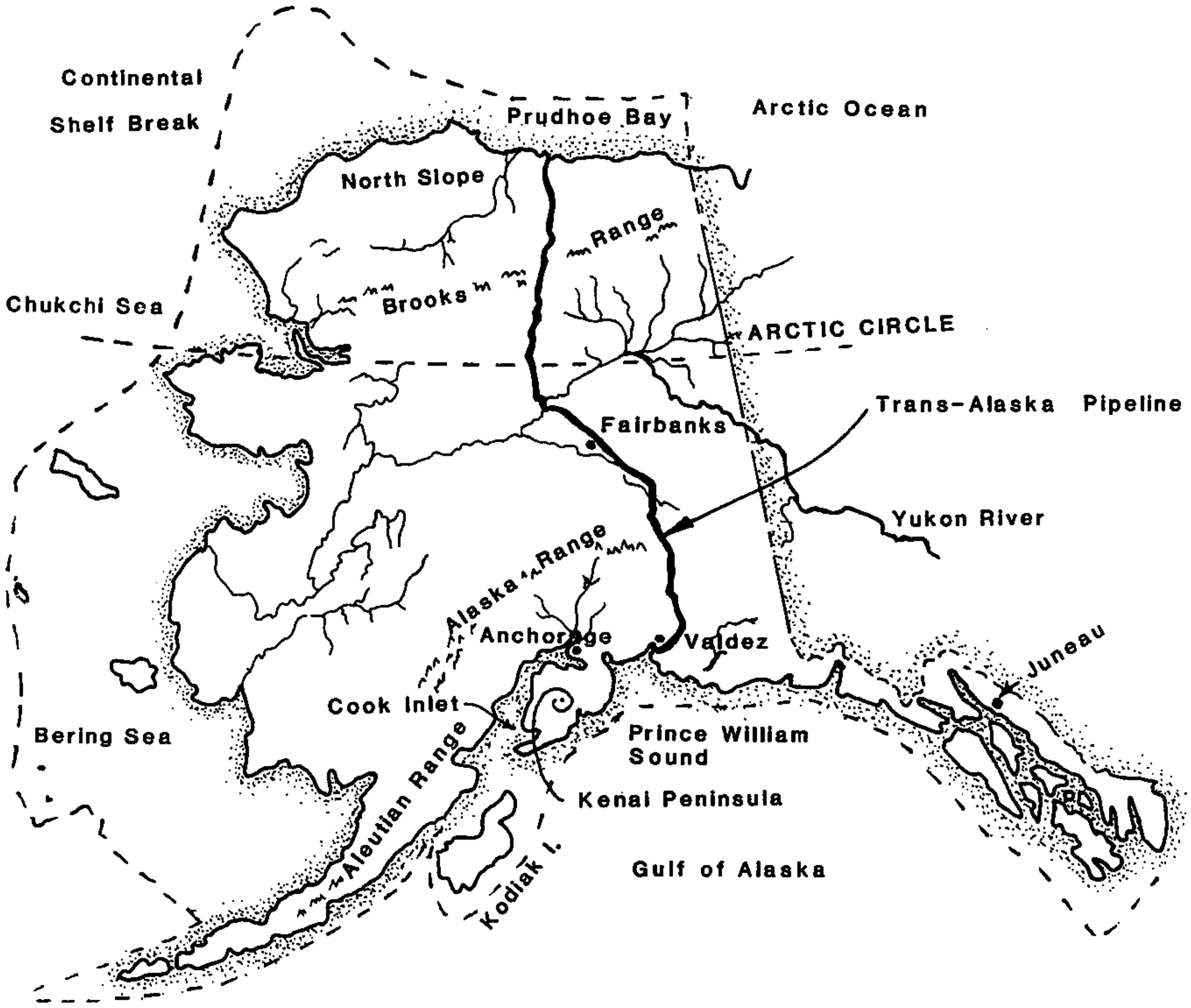

Figure I.1. A map of the state of Alaska, U.S.A.

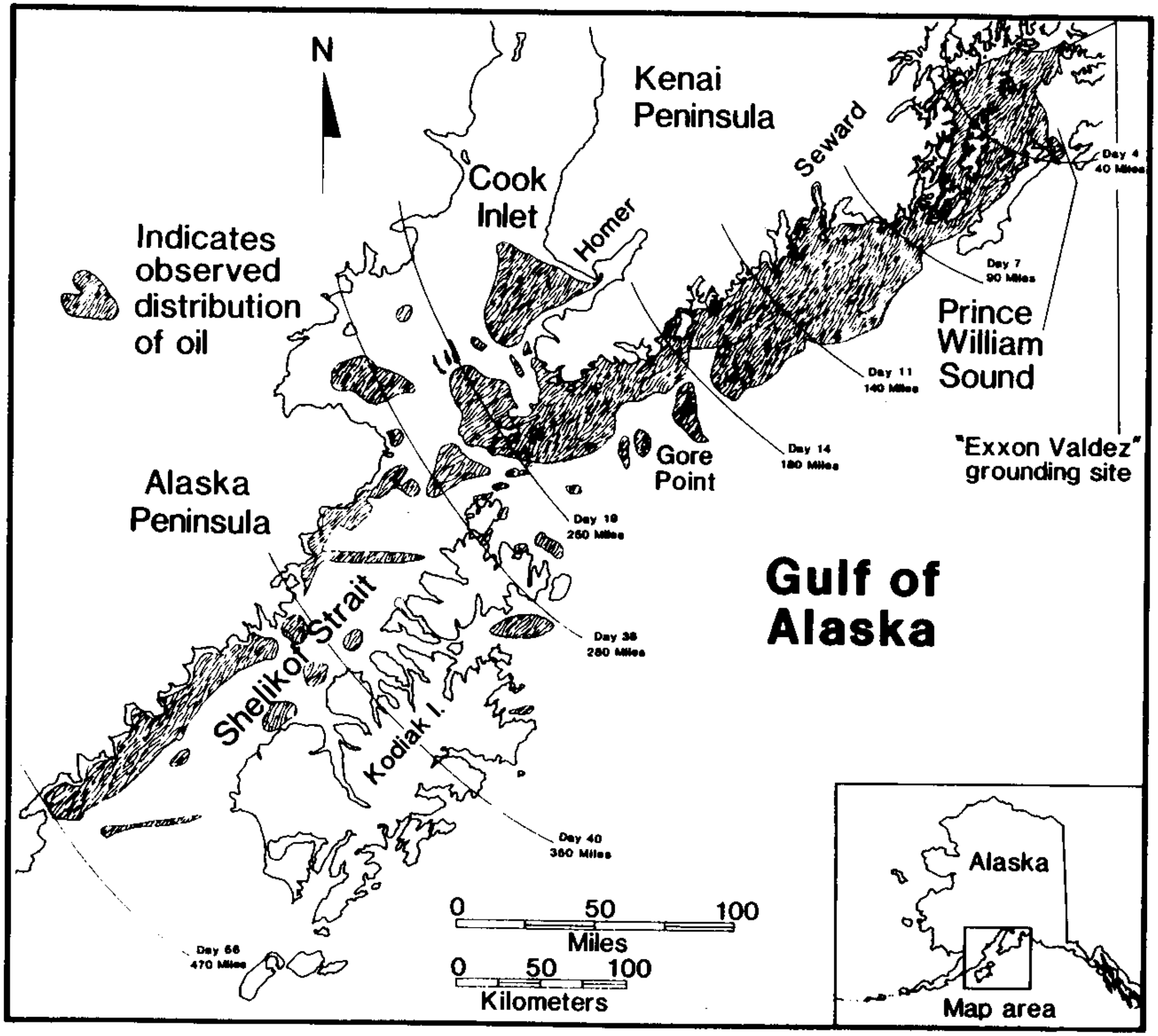

Figure I.2. A map of the 24 March 1989 T/V Exxon Valdez oil spill (A.D.E.C., Unpublished).

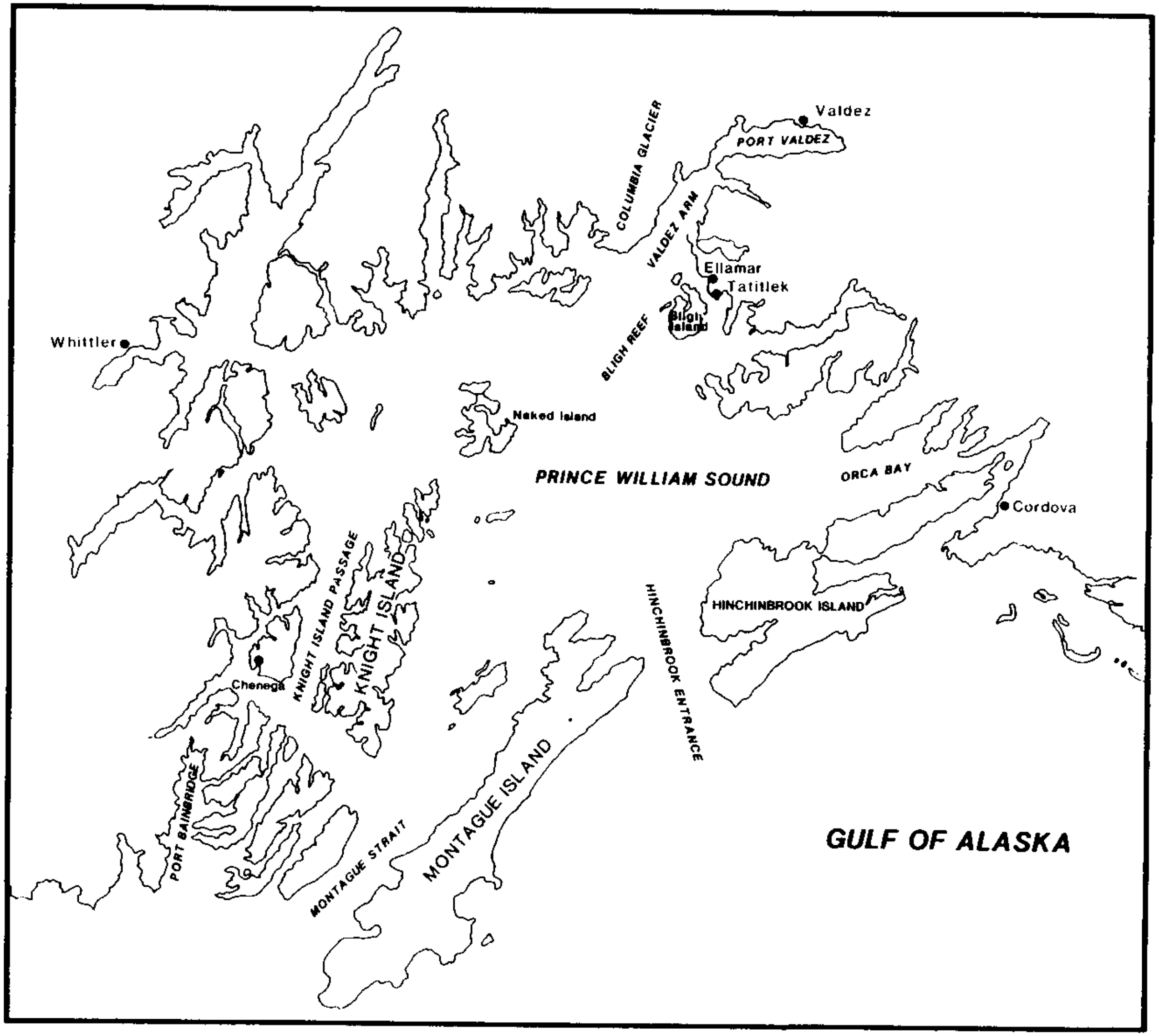

Figure I.3. A map of the Prince William Sound region of Alaska.

principles developed from analysis of Prince William Sound are to some degree pro-ratable to the other regions of impact.

Prince William Sound is a 38,000 square km embayment in the northern gulf of Alaska (Figure I.3). It includes 15 islands of over 40 km^2 in size, over 150 smaller islands, and numerous islets, sea stacks, and reefs (Mickelson, 1989). Tides within the sound are of a mixed semidiurnal type with an average range of 5 m. The area is seismicly active. On 27 March 1964, Good Friday, the largest recorded earthquake in North America, epicentered in the sound, changed shoreline elevations 10 m and damaged many of the region's towns and habitats.

The majority of Prince William Sound is within the Chugach National Forest. Prior to the spill, the destruction of salmon streams by logging was at the forefront of debate among the region's many interest groups. The towns of Valdez, Cordova and Whittier and the native American villages of Tatitlek and Chenga Bay are situated on the sound and are the base for the local fishing and transportation industries. Valdez is the southern terminus of the trans-Alaskan oil pipeline originating at Prudhoe Bay on the Bering Sea. Nine public and private salmon hatcheries within the sound produce the stock for most of the area's salmon harvest.

Most of the southwestern coastline of Prince William Sound is a steep, high wave energy, rocky shoreline with small areas of low wave energy, rocky beaches. The 5 m tides range over an intertidal area dominated by numerous algae including rockweed (*Fucus distichus*), kelps (*Laminaria* spp.), sea lettuce (*Ulva lactuca*) and filamentous green algae (*Urospora* spp.). The waters and intertidal zone of Prince William Sound support approximately 182 killer whales (*Orcinus orca*), 3000 to 5000 harbor seals (*Phoca vitulina*) (Bottini and Nicholl, 1991), 4000 to 10,000 sea otters (*Enhydra lutris*) (Calkins, 1987), dall's porpoise (*Phocoenoides dalli*), steller sea lions (*Eumetopias jubatus*), river otters (*Lutra canadensis*), brown (*Ursus arctos*) and black (*U. americanus*) bears, and black tailed deer (*Odocoileus hemionus*), along with transient species such as the humpbacked whale (*Megaptera novaengliae*). The sound serves as seasonal and permanent habitat for tens of thousands of marine birds including loons, murrelets and sea ducks (DeGrange and Sanger, 1987) as well as highly visible species like the bald eagle (*Haliaeetus leucocephalus*). Most of these animals are found throughout the area of the *Exxon Valdez* oil spill. A large number of bird and marine mammal species migrate through the region each year.

Immediately southwest of Prince William Sound is the Kenai Peninsula. The Gulf of Alaska coast of the Kenai Peninsula is an unsheltered, rocky, high energy coast cut by numerous fjords. Millions of pelagic marine birds breed in colonies on the peninsula, notably murres, puffins, kittiwakes, cormorants and petrels (Isleib and Kessel, 1989). The only town in the area is Seward, and Kenai Fjords National Park and Kachemak Bay State Wilderness Park encompass most of the region.

Beyond the Kenai Peninsula is the mouth of Cook Inlet, a large sediment-laden body of water much different in character from the areas to the north. Cook Inlet has extensive mud flats as opposed to rocky coast and consequently different intertidal communities. A number of towns are located in the lower Cook Inlet region including the towns of Homer and Seldovia and the predominantly Native American villages of English Bay and Port Graham. Cook Inlet is an area of offshore oil production and has been the site of numerous oil spills. Katmai National Park and Preserve extends from within Cook Inlet southwest down the Shelikof Strait on the Alaska Peninsula.

The Gulf of Alaska coast of the Alaska Peninsula and the offshore Kodiak Archipelago, comprise another area of rough coastline with numerous islands. This region has more kelp forests than the Prince William Sound area (Sears and Zimmerman, 1977), and presumably more of classic sea otter - kelp ecosystem interactions described by Estes and Palmisano (1974). As in the Kenai Peninsula, the rocky cliffs of this area have numerous marine bird colonies comprised of millions of birds (Isleib and Kessel, 1989). The Kodiak region contains the town of Kodiak and the villages of Ouzinki, Old Harbor, Karluk, Anhiok and Larsen Bay. The numerous public land holdings in this region include Kodiak Island, Becharof, Alaska Peninsula and Alaska Maritime National Wildlife Refuges, Aniakchak National Monument and Preserve and the Chugach National Forest.

The Prince William Sound, Kenai Peninsula, Cook Inlet and Kodiak regions contain numerous species which are the basis of commercial fisheries. Pink salmon (*Oncorhynchus gorbuscha*) accounts for the largest commercial landing in the region, though red (*O. nerka*), king (*O. tshawytscha*), silver (*O. kisutch*) and chum salmon (*O. keta*) are also harvested. Pacific herring (*Clupea harengus*) and herring roe are also harvested, particularly in Prince William Sound. Traditionally, bottom fish such as halibut

(*Hippoglossus stenolepis*) and pollock (*Theragra chalcogramma*) as well as benthic epifauana like king (*Paralithodes camtschatica*) and tanner (*Chionoecetes* spp.) and dungeness crabs (*Cancer magister*) have supported fisheries. There are also large sport fishing industries, particularly for salmon and halibut. Sea otters furs were harvested by Native and later European and U.S. fisherman. The sea otter stock is still recovering from a severe over harvest in the nineteenth century.

Historical Perspectives of the *T/V Exxon Valdez* Oil Spill

The 997-foot Tank Vessel (T/V) *Exxon Valdez* ran aground at 12:04 A.M., 24 March 1989 on Bligh Reef, a rocky shoal in northeastern Prince William Sound 25 miles south of Valdez, Alaska. The vessel struck Bligh Reef while navigating outside of the designated shipping lanes in an attempt to avoid ice flows from nearby glaciers. The ship's high momentum combined with the rocky bottom resulted in the rupture of 8 of the 11 cargo tanks (National Response Team, 1989). During the next ten hours, the *Exxon Valdez* lost an estimated 258,000 barrels of Alaska North Slope crude oil, 20% of its cargo (Harrison, 1991), creating one of the two largest oil spills in U.S. waters and the 35th largest oil spill (to that date) internationally (U.S. Congress, Office of Technology Assessment, 1990). The Valdez was outbound from the Alyeska terminal at the Port of Valdez, the southern terminus of the trans-Alaskan Pipeline from Alaska's North Slope oil fields on the Bering Sea. Factors which have been suggested to have caused the spill and increased the severity of its impact include crew error and failure; failure of Exxon Shipping Company to manage its personnel; reduced manning levels on tankers (Alaska Office of the Governor, 1989); inadequate quantities of dispersant, skimmers, booms and other response equipment at the terminal; poor response management (Kelso and Kendziorek, 1991); inadequate ship construction (Kelso, 1989); equipment failure; severe weather; and failure to meet the goals of the response plans in place (National Response Team, 1989; Alaska Oil Spill Commission, 1990).

Lightering of the remaining Valdez cargo began a day after the grounding and the vessel was surrounded with containment boom 35 hours after the grounding. Test applications of dispersant were begun the day of the spill, and the effectiveness was found to be diminished by the calm water. A small amount of oil was removed from the water by mechanical skimmers, but problems in off loading full skimmers decreased the operation's capacity (Richter, 1990). On 25 March, 15,000 to 30,000 gallons of oil were burned using fire containment boom leaving 300 gallons of residue (Allen, 1990). High winds on 27 March forced the suspension of dispersent application and controlled burning. The windstorm moved the spilled oil rapidly southwest oiling Naked, Smith and Knight Islands and breaking apart the slick increasing oil evaporation and weathering and the formation of oil-water emulsion known as mousse (Galt et al, 1991). A map showing the extent of the oil spill is given in Figure I.2.

By 30 March, the oil had moved beyond Montague Strait into the Kenai Peninsula region of the Gulf of Alaska. At a distance of 160 km from the grounding site, the leading edge of the spill began to break into isolated patches and the spill lost its contiguity. The Alaska Coastal Current moved the oil about 10 km a day so that by 1 April parts of the spill were south of Seward 225 km from Bligh Reef. The majority of the heavy oiling was limited to the offshore islands in the Kenai Peninsula region, with very little entering the major fjords (Galt et al., 1991). Mousse had reached Gore Point and a small fraction had turned into the mouth of Cook Inlet, 400 km from the spill site, on 11 April (Figure I.2).

Through the middle of April, the slick continued to break into numerous small patches composed of small chunks of mousse tar balls. Zones of converging fresh and salt water in the mouth of Cook Inlet concentrated the isolated patches along with other objects floating on the surface such as flotsam and sleeping birds (Galt et al., 1991). The vast majority of the bird mortalities were murres and other Alcids, diving birds from colonies on the rocky Gulf of Alaska coast (Piatt et al., 1990). The spill reached its greatest extent after 18 May with tarring on Trinity and Chirikof Islands and in the Chignik area of the Alaska Peninsula, over 800 km from Bligh Reef, where scattered tar balls were observed. Galt et al. (1991) estimate that 35% of the spilled oil evaporated or dispersed into the water column, 40% affected the shoreline within Prince William Sound and 25% left the sound, and 10% reached beyond Gore Point with 2% being transported to the Shelikof Strait region. Maki (1991) calculated 1752 km of shoreline had been oiled over a distance of 15,134 km of coastline.

Crude oil is a naturally occurring mixture of thousands of fossil hydrocarbon compounds which are separated in the refining process into products such as fuel oil and gasoline. An estimated 1.5 million barrels of crude oil enter the world's oceans each year from natural seeps (National Research Council, 1985), and natural, hydrocarbon-degrading organisms are ubiquitous. The lighter and more soluble compounds in crude oil are generally the most toxic and also the first to be removed or degraded during the weathering of oil (Mielke, 1990). Thus the toxicity and therefore the ecological impact of an oil spill depends on both the type of oil spilled and its state of weathering.

The oil recovery and shoreline cleaning involved numerous groups and types of equipment. Shoreline surveys were conducted by private and government groups. Weir, submersion paddle belt, disc, and sorbent belt skimmers were used as were oil containment and sorbent boom. The majority of heavily and medium oiled shorelines were treated with a warm water wash in conjunction with booms and skimmers. Mechanical treatment of shoreline with cold water as well as manual removal of oily debris and sediment was implemented as well. Following water washing treatment, some areas were treated with INIPOL and Custumblen fertilizers, in a treatment known as bioremediation, in order to increase bacterial degradation of oil (Exxon, 1990). A total of eight oiled-wildlife rehabilitation centers operating in conjunction with 140 boats and five aircraft for collection, were established and operated in 1989 (Monahan and Maki, 1991). As of March 1991 the Alaska Department of Environmental Conservation estimated that of the original 258,000 barrels of oil spilled: 350 barrels had been burned, 51,000 to 103,000 barrels had evaporated, 18,000 to 22,000 barrels were recovered as part of oil-water emulsion, and an undetermined amount had been removed as part of oiled sediments and solid waste (Alaska Department of Environmental Conservation, 1991). Local individuals also deployed containment booms for protection and collected oil and oiled sediments (Davidson, 1989; Alaska Department of Environmental Conservation, 1991).

The impact of the *T/V Exxon Valdez* oil spill on the Gulf of Alaska coastal habitat is still being determined. Preliminary results suggest 3,500 to 5, 500 sea otters, 200 harbor seals, up to 11 killer whales, 1400 bald eagles (Bottini and Nicholl, 1991), and 100,000 to 300,000 marine birds (of which approximately 70% were Alcids) and 215,000 1989 Alcid chicks (Piatt et al., 1990) died as a direct result of the oil. Houghton et al. (1991) found up to 100% decrease in plant coverage and 95% decrease in invertebrate numbers on oiled and cleaned shoreline. No massive fish die-offs were observed though preliminary analysis indicates a 50% to 70% greater mortality of pink salmon eggs laid in oiled stream intertidal areas as compared to unoiled sites in 1989 and 1990 respectively. Several species of fish showed evidence for continuing exposure to hydrocarbons, but injury has only been documented for dolly varden trout (*Salvelinus malma*), where adult mortality was found to be 32% greater in the oiled subtidal zone, and herring (*Clupea harengus*) spawning in the subtidal zone where increases in abnormal embryos and larvae, larval eye tumors and egg mortality have been documented. Intertidal fish have been found to be less abundant and those fish present had higher gill parasitism and respiration rates relative to unoiled sites (Bottini and Nicholl, 1991).

Fate and effects of Spilled Oil.

Crude oil contains a full spectrum of organic components from highly toxic and volatile low molecular weight organic compounds, such as benzene, toluene, and alkanes, to high molecular weight organics of low volatility and toxicity. When separated from the mixture the heavier components combine to form denser organics, tars, and asphalts (Mielke 1990). This process occurs intentionally in refineries, and occurs naturally following a marine oil spill. The fate of spilled oil involves the processes of spreading (slick formation), photo-oxidation, dissolution, evaporation, emulsification, sedimentation, biodegradation, and asphalt formation.

Spreading, Photo-oxidation. Immediately with the onset of a marine spill, oil spreads along the surface of the water, forming a thinner and thinner layer, vastly increases the surface area of the spill that is exposed to sunlight, air, and water, and extends the amount of shoreline potentially impacted by the spilled oil. Over a period of days to weeks, the thickness of the oil slick approaches a mono-molecular layer and breaks into patches. At this stage the maximum surface area is exposed to the sun and air and to naturally occurring oil-decomposing microbes in the water.

Dissolution and Evaporation. Within a matter of minutes of the spill, however, a separation process begins. Those low molecular weight organics that are water soluble dissolve into seawater in the first minutes and hours. Many of these are highly toxic, such as benzene. Soluble toxic components account for the acute toxicity of oil spills to marine organisms. Low molecular weight organics are also highly volatile. Those that do not dissolve in seawater evaporate. The lightest organics dissolve during the first days. Heavier volatiles evaporate over the next few weeks. Within the first few days of the *Exxon Valdez* spill, an estimated 20% to 40% of the spilled oil evaporated (50,000 to 100,000 barrels). Air quality over the evaporating spill was very poor. Pilots and aerial observers of the spill reported noxious odors, watering eyes, and skin irritation (Sale, Personal Communication)[a].

Emulsification and Sedimentation. What remains after the dissolution and evaporation processes are the heavier constituents of crude oil. In moderate seas and surf, these can emulsify, forming "mousse," a substance the consistency of a chocolate mousse and containing a relatively high water content. Some of the heavier components of crude oil that remain in open water are denser than seawater and begin to sink, being dispersed with currents eventually to settle along the bottom. Other remaining oil may be blown onto nearby shores where oil coats the surface and works into the sediment through the action of tides and waves.

Though less toxic than the original crude oil, the acute effects of a large slick of weathered oil are still devastating to animals and plants in its path as it traps them against a shoreline. Certain seabird and sea mammal populations can be damaged because of the visco-elasticity of the oil, which fouls fur and feathers, and interferes with movement, feeding behavior, and respiration. Many intertidal plants and invertebrates can be smothered by an oil coating as the oil comes ashore.

Biodegradation. Nevertheless, natural processes continue to transport and transform oil washed onto beaches and nearshore sediments. Microbes and direct sunlight, decompose oil in sediments. Tides and breaking waves, which helped mediate the initial contamination of the shore, continue to mix and re-mix sediments, re-exposing remaining oil to the weathering process. Most of the oil may eventually decompose, being incorporated into marine food chains and eventually converted to basic inorganic components -- primarily carbon dioxide and water. In the mean time, while some organisms suffer from toxic end products of hydrocarbon metabolism and perhaps bio-accumulated refractory toxins, others may benefit from the added organic "food."

Asphalt Formation. Thick accumulations of remaining oil may eventually form hardened asphalt pavements. In very heavily oiled sediments, sufficient quantities of heavy organic molecules may remain after the lighter components have decomposed, dispersed, or evaporated. If in sufficient quantity, these may combine to form tar and bind together sediments into a hard asphalt pavement. Such a pavement may be relatively long-lasting in the marine environment and will change the physical characteristics of the affected sites. These changes will likely result in a shift from infaunal communities to hard bottom communities at these sites. In the case of the *Exxon Valdez* spill, no asphalt formation has yet been detected, but several sites are being considered for re-cleaning in heavily oiled areas of Prince William Sound out of concern over possible asphalt formation (Sale, Personal Communication).[a]

Oil Spill Prevention and Cleanup Alternatives.

As long as oil is still being removed from the ground, complete prevention of spills is not possible. Spills result from accidents associated with drilling, pumping, and transporting oil and liquid petroleum products. The Alaskan oil spill has focused attention worldwide on oil spill prevention and cleanup alternatives and policies. Numerous reviews of related technologies have resulted. Especially notable among these are the Spill Report of the Alaska Oil Spill Commission (1990) and the earlier management analysis by Townsend and Heneman (1989).

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[a] David Sale, Alaska Department of Environmental Conservation, Anchorage, Alaska.

Prevention strategies are in fact risk-reduction strategies, not risk-eliminating strategies. Hence consideration of cleanup alternatives remains essential to any prevention plan. Like prevention, however, complete cleanup of an oil spill is also not possible. Cleanup is considered good if 20% of the spill can be recovered. Cleanup of larger spills has been considerably less. For example, despite the nearly $2.5 billion spent on the cleanup of the Exxon Valdez spill, less than 10% is estimated to have actually been removed from the marine environment by cleanup operations (Alaska Department of Environmental Conservation, 1991; National Response Team, 1989).

Furthermore, cleanup technologies have environmental impacts of their own (Dunford et al., 1991). In some situations, "doing nothing" is the best alternative (Foster et al., 1990). Small amounts of oil in a salt marsh, for example, might be decomposed by natural processes more effectively and with less disruption than with a cleanup procedure that involves personnel and equipment deployment in the marsh itself.

Indirect strategies for spill prevention include reducing risk through increased oil conservation (reducing global dependence on oil), and increased use of alternative methods of transporting oil (e.g., pipelines) (States/British Columbia Oil Spill Task Force, 1990). Oil conservation may not reduce the total percentage of oil spilled, but should reduce the number of spills per year. Spill prevention is not by itself, however, a compelling motivation for reducing global dependence on oil. Nevertheless, as global supplies of oil are depleted, spills will become more rare.

Prevention and cleanup strategies each have components that can be considered "hardware" and "software." Prevention hardware includes improved design of tanker cargo holds (e.g., double-hulling), improved tanker agility (e.g., bow thrusters), and improved navigational safety equipment and personnel (e.g., tanker escorts, radar, traffic controllers) (Keith, 1991; Unpublished Manuscript). Prevention "software" includes improved training and qualification criteria for personnel and more effective laws and law enforcement (States/British Columbia Oil Spill Task Force, 1990).

Cleanup "hardware" includes the equipment and personnel for mechanical spill removal in open water and on oiled shores. It also includes dispersants, burning, and bioremediation techniques (U.S. C.O.T.A., 1990). As with prevention, cleanup software includes training and qualification criteria for personnel, but it also includes other aspects of preparedness: the positioning of sufficient quantities of well-maintained spill-response equipment and personnel in proximity to spills. The spill-response capabilities of the much criticized Alyeska Pipeline Company in Valdez, Alaska were inadequate at the time of the *Exxon Valdez* spill. Today, however, they have a state-of-the-art facility able to respond to a similar spill and to help prevent spills by providing tanker escorts in and out of the Port of Valdez. This facility currently costs approximately $125,000 per day to operate (Alaska Information Service, 1989).

Major Prevention Alternatives

Double Hulls. Tanker hull design alternatives include Federal oil-spill legislation enacted in 1990 addressing prevention of spills by requiring the phasing out of all single-hulled U.S. tankers over 5000 gross deadweight tons by the year 2010. No new single-hulled tankers will be built and single-hulled vessels will be decommissioned or retrofitted with double hulls. This legislation does not apply, however, to foreign tankers operating in U.S. waters.

Double hulls currently exist on 26 of the 93 tankers registered for Alaska trade (State of Alaska 1990). The single-hulled tankers range in size from 16,000 to 265,000 deadweight tons. The *Exxon Valdez* was 211,000 deadweight tons. To retrofit single-hulled tankers with double hulls will cost perhaps $65,000 to $70,000 per 1000 deadweight tons. New construction of double-hulled tankers is roughly $1 million per 1000 deadweight tons (Keith, Unpublished Manuscript).

Other hull designs are also possible, such as an intermediate oil-tight deck to separate oil cargo carried above the waterline from that carried below the waterline. Oil below this deck will have a negative head pressure compared to the water outside, thus creating a natural vacuum in the event of a hull puncture which should prevent a spill by allowing water pressure to hold oil the tanker (Ost 1991, Husain and Koepenick, 1990).

Bow Thrusters and Ballast Controls. Some tanker spills could be avoided if tankers were more agile. Smaller tankers can turn to avoid catastrophes that can be seen but not avoided by larger tankers. Installing bow thrusters and automated ballast controls on tankers would increase the ability of tanker operators to turn and control tanker stability (Keith, Unpublished Manuscript).

Escorts, Preparedness, and Navigational Equipment. In addition to double-hulling the tanker fleet, the federal oil spill legislation of 1990 requires a two-tug escort for all tankers going in and out of Alaska's oil ports, a new light on Bligh Reef and upgrades of other navigational equipment, and stiffer licensing requirements for tanker pilots. Such prevention measures have undoubtedly resulted in considerable reduction in spill likelihood in Prince William Sound and elsewhere, though estimates of the magnitude of this reduction have not been publicized.

Exclusive Use of Overland Oil Pipelines. An extreme alternative is simply not to ship Alaskan oil over water, but rather to ship all Alaskan oil to the United States via a network of oil pipelines. A similar proposal was considered prior to the construction of the Alaskan oil pipeline. This alternative is not a practical option at present, but is included for analytical comparison to give perspective on the problem. Pipelines also have spills and maintenance problems.

Cleanup Alternatives

Perhaps the most significant cleanup "software" is embodied in the individual responsible for making on-sight decisions about what to protect given the circumstances of a spill. Since it is impossible for humans to completely clean up a spill, someone has to make moment-to-moment decisions about what to protect with the available tactics on site. Generally this is the responsibility of an on-scene coordinator with the U.S. Coast Guard, but this person may not always in practice be allowed much autonomy (Westermeyer 1991).

Open-Water Cleanup Techniques. Weather permitting, oil on the water can be herded and contained with booms (sometimes assisted by herding and gelling chemicals), then skimmed from the water surface and stored in containment vessels. Oil recovered by these mechanical means can be reprocessed for sale to help minimize economic losses.

Several physical variables determine the efficacy and desirability of mechanical cleanup procedures in open water. These include the size of the slick, which is a function of local currents and the time between the onset of a spill and the onset of an effective response; the toxicity and viscosity of the spilled oil, which affect safety as well as mechanical efficiency of the cleanup; and weather, sea state, and the location of the spill, which affect the logistics of cleanup operations (Westermeyer 1991, U.S. Congress 1990).

When mechanical recovery is not possible in open water, other techniques are often considered which attempt to enhance the natural processes of dispersal and decomposition of oil before oil reaches sensitive areas. Most of these are controversial, however, because of concern over possible damaging side effects. Burning an oil slick, for example, can rapidly decompose and evaporate spilled oil that is concentrated and not emulsified, but concerns over resulting air pollution prevented its timely use in Prince William Sound (Allen 1991). Timely burning, however, could reduce the impact of oil threatening sensitive shorelines. As can be imagined, on-site decisions are genuinely difficult.

Perhaps the most controversial technique is the use of dispersal agents. These are chemical agents that break up an oil slick into smaller, more dense particles that generally sink. Some wind energy must be available for the dispersants to work. Application in calm weather is ineffective (Alaska Department of Environmental Conservation, 1991). If the water is deep and the sinking rate is low relative to horizontal transport, the dispersed oil particles are spread over a large area of marine bottom. The impact of the spill is thus diluted over an extensive area. Controversy arises over the toxicity of many dispersal agents and the potential impact on bottom-dwelling organisms. The approach has been criticized as simply cosmetic: by causing the spill to disappear from the surface, the fate and effects of the dispersed oil may be ignored. If the alternative, however, is to allow damage nearshore, the decision may not be easy. Are shores more valuable to protect than the sea bottom? The answer depends on what is on the bottom compared to the shore and how concentrated and toxic the oil will be once it reaches the bottom or the shore.

Another tactic is bioremediation. This is a set of techniques for enhancing biodegradation of oil either by adding populations of cultured or genetically-engineered oil-consuming bacteria or simply by adding nutrients (e.g., nitrogen and phosphorus) in an attempt to stimulate natural oil decomposition by relieving a growth-limiting factor. Concerns about bioremediation involve uncertainty about the efficacy of these techniques in open water. While waiting to see if they are working, proven techniques are not being deployed at that site.

Shoreline Cleanup. In the *Exxon Valdez* oil spill, the greatest problem by far was the oiling of the ecologically productive and biologically spectacular southwestern shore of Alaska. In the lower two thirds of Prince William Sound, approximately 36% of the shoreline was oiled, 6% heavily, 21% lightly, and the remainder intermediate (Exxon, 1990). Dying seabirds, bald eagles, and sea otters produced a public relations nightmare. A public outcry arose to punish Exxon. People demanded removal of the oil by whatever means possible, perhaps feeling that this was the natural punishment for Exxon. Hundreds of millions of dollars were spent in shoreline cleanup. Unfortunately, intensive cleaning of the beach was not necessarily beneficial to those shore organisms that happened to have survived the spill.

Shoreline cleanup procedures include physical removal by manual or hydro-mechanical means. Manual cleanup involves crews on the shore using shovels and rakes to bag oily flotsam (mousse "patties"), and small accumulations of tar and asphalt. Manual use of sorbents may be included to hand-wipe or dab the affected shore (Exxon, 1990; 1991). Manual operations are recommended for small areas of contamination. Pooled oil can be vacuumed from the shore and large accumulations of tar or asphalt may require large digging machinery.

Hydro-mechanical techniques were commonly used along the affected Alaskan shoreline to remove oil from contaminated sediments. These included washing the surface with ambient temperature or pressurized warm water (100 psi and 140^{o}F) to drive surface oil downslope where it was trapped by booms and picked up by skimmers.

A method that was tested but not employed on a large scale, perhaps due to logistical problems, was a high-pressure subsurface injection of warm water or air during incoming tides. Oil at depth in contaminated sediments was loosened and floated to the surface for removal. Current techniques for loosening oil at depth involve tilling the shoreline by hand or with machinery. Because of the potential for disruption of shoreline ecosystems, however, this technique is used only in areas of high recreational value.

Solvents were tested for loosening subsurface oil prior to warm-water washing. They were found to significantly increase the amount of oil removed. One (Corexit 9850) was proposed but has not received approval for wide-spread use partly because of uncertainty about its disruption of shoreline ecosystems.

Intertidal and subtidal ecosystems areas will naturally clean themselves (Foster et al, 1990; Jahns et al., 1991; Michel et al., 1991; Baker et al., 1990). Interference in this process by using high-pressure, warm water, and solvents is counterproductive as learned both in the *Exxon Valdez* spill of 1989 and previously in the *Torrey Canyon* spill of 1987 (Kerr, 1991).

Bioremediation by adding limiting nutrients (nitrogen and phosphorus) was tested with encouraging, but not entirely consistent, results on shores (Pritchard and Costa, 1991; U.S.C.O.T.A., 1991; Environmental Protection Agency, 1990; Chianelli et al., 1991). Although found to be most effective when water-soluble fertilizers were applied on affected shores through sprinkler systems, this technique was not practical for most affected shores. Broadcast of fertilizer granules (i.e., Customblen) and oleophilic sprays (i.e., Inipol EAP 22) were more practical and were often effective if applications were repeated every three to five weeks. In well aerated sediments, enhancement of biodegradation was detected to 50 cm depth. Tilling has been proposed to prepare some contaminated sediments for bioremediation by fertilizer additions.

The federal oil spill legislation of 1990 required pre-positioning of spill cleanup facilities capable of removing a 200,000 bbl spill in Prince William Sound and a Coast Guard oil-spill strike team for Alaska. Moreover it created a 5 cent per barrel tax on crude oil which will raise $1 billion to pay for cleanup costs of future oil spills. The cleanup preparedness for another spill in Prince William Sound is now considerable. Plans are for the Petroleum Industry Response Organization to construct similar oil-spill response facilities in five regions around the United States where the risk of oil spills are great (National Response Team, 1990). The maintenance costs of these will likely be in the tens or hundreds of millions of dollars per year.

II. METHODS

General Methods for Emergy Analysis

This section gives general methods of emergy analysis for the evaluations that follow in the results section. The general methodology for emergy analysis is a "top-down" systems approach. The first step is to construct systems diagrams that are a means of organizing thinking and relationships between components and pathways of exchange and resource flow (systems symbols and brief definitions are given in Figure II.1). The second step is to construct emergy analysis tables directly from the diagrams. The final step involves calculating several emergy indices that relate emergy flows of the economy with those of the environment, and allow the prediction of economic viability and carrying capacity. Additionally, using the results of the emergy analysis, comparisons between the emergy costs and benefits of proposed developments as well as insights related to international flows of money and resources can be made.

Before presenting detailed descriptions of each step in the methodology, definitions are given for several key words and concepts.

Definitions

Energy. Traditionally referred to as the ability to do work. Energy is a property of all things which can be turned into heat and is measured in heat units (BTUs, calories, or joules).

Emergy. An expression of all the energy used in the work processes that generate a product or service in units of one form of energy. Solar emergy of a product is the emergy of the product expressed in equivalent solar energy required to generate it. Sometimes its convenient to think of emergy as energy memory.

Emjoule. The unit of measure of emergy. It is expressed in the units of energy previously used to generate the product; for instance the solar emergy of wood is expressed as joules of solar energy that were required to produce the wood. Solar emjoule is abbreviated "sej."

Empower. The emergy value of a flow of energy per unit time, expressed as sej/time.

Empower density. Empower per unit area, expressed as sej/time*area.

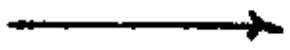
Macroeconomic dollar. A measure of the money that circulates in an economy as the result of some process. In practice, to obtain the macroeconomic dollar value of an emergy flow or storage, the emergy is divided by the ratio of total emergy to Gross National Product for the national economy.

Nonrenewable Energy. Energy and material storages such as fossil fuels, mineral ores, and soils that are consumed at rates that far exceed the rates at which they are produced.

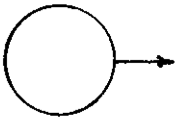
Renewable Energy. Constant and reoccurring energy flows of the biosphere that ultimately drive the biological and chemical processes of the earth and contribute to geologic processes.

Resident Energy. Renewable energies that are characteristic of a region.

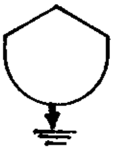
Transformity. The total energy, measured in one form, required to produce one unit of energy of the given product. Transformities have the dimensions of emergy/energy (sej/J). The transformity of a given product is calculated by summing all the emergy inflows to the process creating the product and



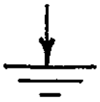
ENERGY CIRCUIT: a flow of energy, often with a flow of materials.



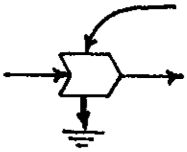
SOURCE: outside source of energy; a forcing function.



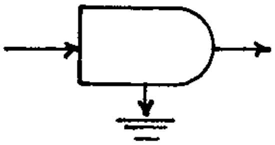
STORAGE: a compartment of energy storage within the system storing a quantity as the balance of inflows and outflows.



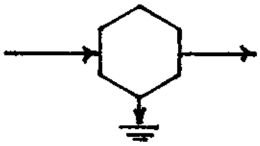
HEAT SINK: dispersion of potential energy into heat that accompanies all real transformation processes and storages.



INTERACTION: process which combines different types of energy flows or material flows to produce an outflow in proportion to a function of the inflows.



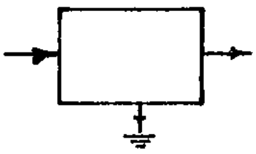
PRODUCER: unit that collects and transforms low-quality energy under control interactions of higher quality flows.



CONSUMER: unit that transforms energy quality, stores it, and feeds it back autocatalytically to improve inflow.

TRANSACTION: a unit that indicates the sale of goods or services (solid line) in exchange for payment of money (dashed line).

SWITCHING ACTION: symbol that indicates one or more switching functions where flows are interrupted or initiated.



BOX: miscellaneous symbol for whatever unit or function is labeled.

Figure II.1. Symbols of the Energy Circuit Language (Odum, 1971; 1983).

dividing by the energy of the created product. Transformities are used to convert energies of different forms to emergy of the same form.

Further Elaboration on the Methods Used for Emergy Analysis

Step 1: Overview System Diagrams. A system diagram in "overview" is drawn first to put the system of interest into perspective, combine information about the system from various sources, and to organize data-gathering efforts. The process of diagramming the system of interest in overview ensures that all driving energies and interactions are included. Since the diagram includes both the economy and environment of the system, it is like an impact diagram which shows all relevant interactions.

Then a second simplified (or aggregated) diagram which retains the most important essence of the more complex version is drawn. The final, aggregated diagram of the system of interest is used to construct a table of data requirements for the emergy analysis. Each pathway that crosses the system boundary is evaluated.

Step 2: Emergy Analysis Tables. Emergy analysis of a system of interest is usually conducted at two scales. First the system within which the system of interest is embedded is analyzed and indices necessary for evaluation and comparative purposes are generated. Second, the system of interest is analyzed. Both analyses are conducted using an emergy analysis table organized with the following headings:

1	2	3	4	5	6
Note	Item	Raw Units	Transformity	Solar Emergy	Macro-economic $

Each row in the table is an inflow or outflow pathway in the aggregated systems diagram; pathways are evaluated as fluxes in units per year. An explanation of each column is given next:

Column 1	The line number and footnote number that contains sources and calculations for the item.
Column 2	The item name that corresponds to the name of the pathway in the aggregated systems diagram.
Column 3	The actual units of the flow, usually evaluated as flux per year. Most often the units are energy (joules/year), but sometimes are given in grams/year or dollars/year.
Column 4	Transformity of the item, usually derived from previous studies.
Column 5	Solar Emergy (sej), is the product of the raw units in Column 3 with the transformity in Column 4.
Column 6	The result of dividing solar emergy in Column 5 by the emergy-to-money ratio (calculated independently) for the economy of the nation within which the system of interest is embedded.

Step 3: Calculation of Emergy Indices. Once the emergy analysis tables are completed, several indices using data from the tables are calculated to gain perspective for and aid in public policy decision-making. The principles used in judging development alternatives are as follows: 1.) When alternative investments are compared, the investment that contributes the most emergy value to the public economy in the long run is most likely to be successful; and 2.) When a single system is analyzed, the emergy intensity of the development should match that of the local economy. Two ratios are calculated: Emergy Investment Ratio (IR), and the Environmental Loading Ratio (ELR). Several other indices help in gaining perspective about processes and are necessary precursors to the IR and ELR; they are: Emergy Money Ratio, Emergy Per Capita, Emergy Density, Emergy Exchange Ratio, Net Emergy Yield Ratio, and Solar Transformity.

Emergy-money ratio. The ratio of total emergy flow in the economy of a region or nation to the GNP of the region or nation. The emergy money ratio is a relative measure of purchasing power when the ratios of two or more nations or regions are compared.

Emergy per capita. The ratio of total emergy use in the economy of a region or nation to the total population. Emergy per capita can be used as a measure of the average standard of living of the population.

Emergy density. The ratio of total emergy use in the economy of a region or nation to the total area of the region or nation. Renewable and nonrenewable emergy density are also calculated separately by dividing the total renewable emergy by area and the total nonrenewable emergy by area, respectively.

Net emergy yield ratio. The ratio of the emergy yield from a process to the emergy costs of that process. The ratio is a measure of how much a process will contribute to the economy. Primary energy sources have yield ratios in the range of 3 to 1 to as high as 11 to 1; thus they contribute much to the wealth of the economy. Figure II.2a shows the method of calculating the net emergy yield ratio.

Emergy exchange ratio. The ratio of emergy exchanged in a trade or purchase (what is received to what is given). The ratio is always expressed relative to one or the other trading partners and is a measure of the relative trade advantage of one partner over the other. Figure II.2a shows the relationship and calculation of the emergy exchange ratio.

Net emergy yield ratio. The ratio of the emergy yield from a process to the emergy costs. The ratio is a measure of how much a process will contribute to the economy. Primary energy sources have yield ratios that range from 3 to 1 to as high as 11 to 1; thus, they contribute much to the wealth of the economy. Figure II.2a shows the method of calculating the net emergy yield ratio.

Determining the Intensity of Development and Economic Competitiveness: EMERGY INVESTMENT RATIO

Given in Figure II.3 is a diagram illustrating the use of nonrenewable and renewable emergies in a regional economy. The interaction of indigenous emergies (both renewable (I) and nonrenewable (N) with purchased resources from outside (F)) is the primary process by which humans interface with their environment. The investment ratio (IR) is the ratio of purchased inputs (F) to free emergies derived from local sources (the sum of I and N) as follows:

$$IR = F/(I+N) \tag{1}$$

The name is derived from the fact that it is a ratio of "invested" emergy to resident emergy. The Investment Ratio is a dimensionless number; the larger the number the greater the amount of purchased emergy per unit of resident emergy. When the ratios of two developments of like kind are compared, an indication of their economic competitiveness is derived. The investment ratio can also be used to indicate if a process is economical in its utilization of purchased inputs in comparison with other alternative investments within the same economy. Comparison between a regional investment ratio and the ratio for a proposed development may also be used as an indicator of the intensiveness of the development within the local economy.

Determining Environmental Impact: ENVIRONMENTAL LOADING RATIO

Nearly all productive processes of humanity involve the interaction of nonrenewable emergies with renewable emergies of the environment, and in so doing the environment is "loaded" (meaning to strain, stress, or pressure). Figure II.3 shows environmental loading as the interaction of purchased emergy and nonrenewable storages of emergy from within the system with the renewable emergy

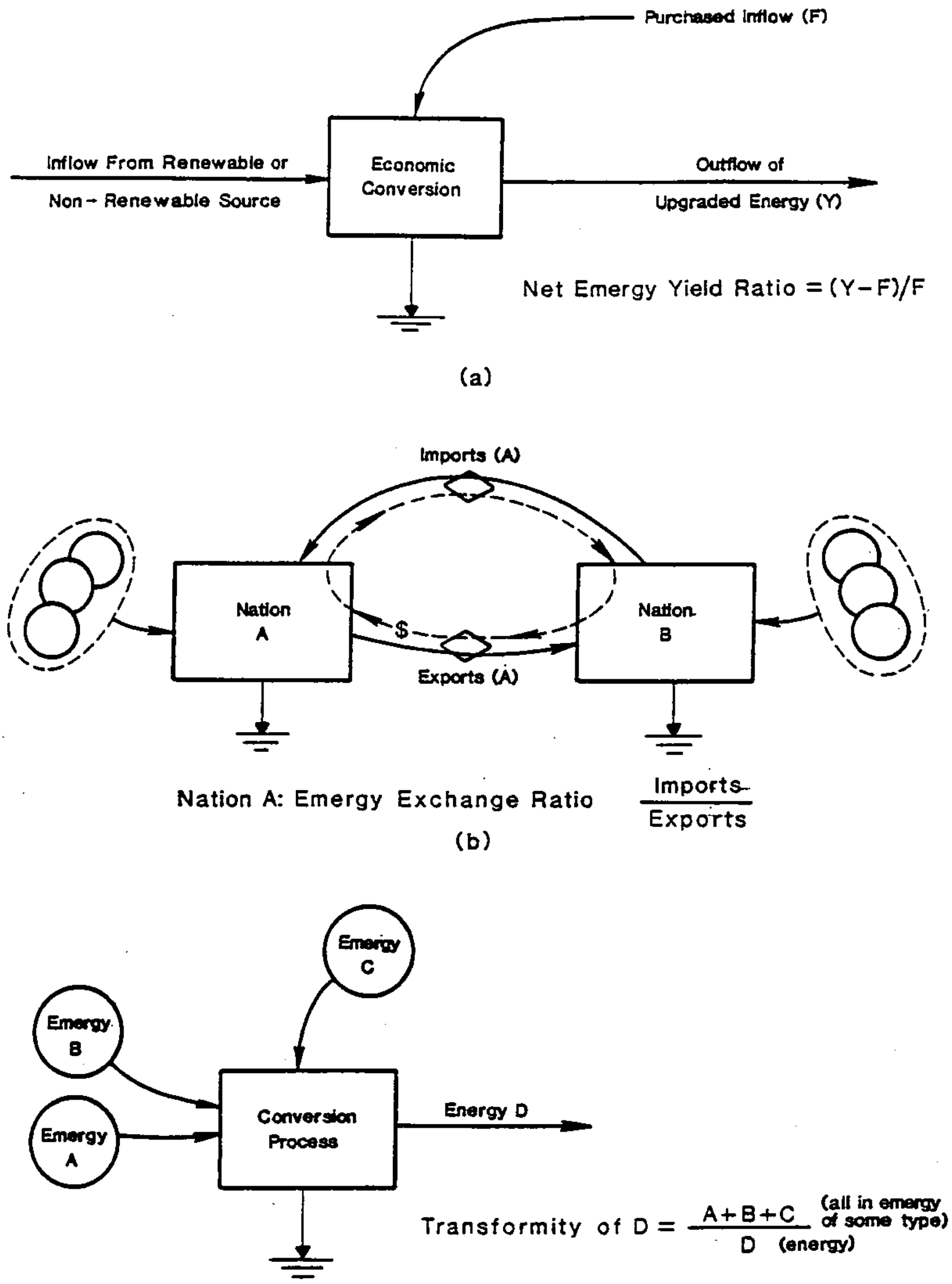
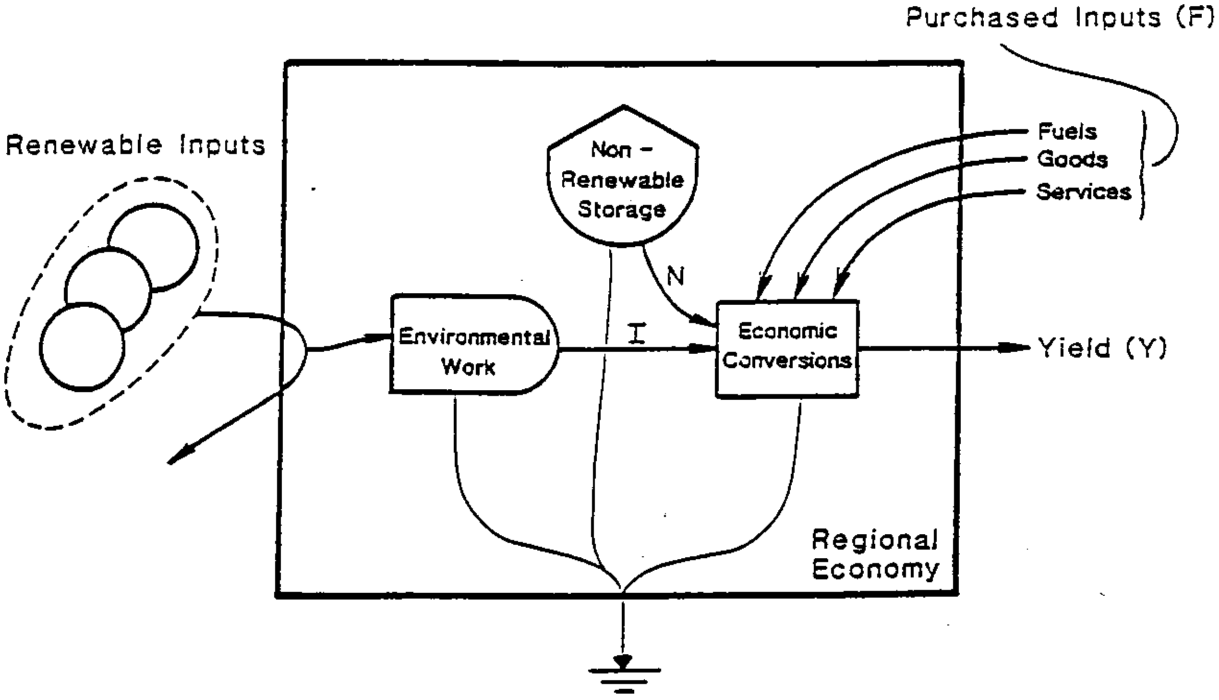


Figure II.2. Simplified diagrams illustrating: a.) the calculation of Net Emergy Yield Ratio for an economic conversion where purchased energy is used to upgrade a lower grade resource; b.) the calculation of an Emergy Exchange Ratio for trade between two nations; and c.) the calculation of a Transformity for the flow D that is a product of the process that requires the input of three different sources of emergy (A, B, and C).



Investment Ratio of Regional Economy: $IR = F/I+N$

Environmental Loading Ratio of Regional Economy: $ELR = F+N/I$

Yield Ratio of Regional Economy: $YR = Y/F$

Figure II.3 A diagram illustrating a regional economy that imports (F) and uses resident renewable inputs (I) and nonrenewable storages (N). Several ratios used for comparisons between systems are given below the diagram and explained in the text. The letters on the pathways refer to flows of emergy per unit time, thus the ratios of flows are dynamic and changing over time.

pathway through environmental work. An index of environmental loading, the Environmental Loading Ratio (ELR) is the ratio of nonrenewable emergy (N + F) to renewable emergy (I) as follows:

$$ELR = (N+F)/I \tag{2}$$

Low ELRs reflect relatively small environmental loading, while high ELRs suggest greater loading. The ELR reflects the potential environmental strain or stress of a development when compared to the same ratio for the region and can be used to calculate carrying capacity.

Criteria for Alternative Public Policies

Public policy alternatives that involve decisions regarding the development and use of resources are guided by two criteria in this study: 1.) the alternative should increase the total emergy inflow to the economy, and 2.) the alternative should be sustainable in the long run.

Development alternatives that result in higher emergy inputs to an economy increase its vitality and competitive position. A principle that is useful in understanding why this is so is the Maximum Empower Principle (which follows from the work of Lotka (1922), who named it the "maximum power principle"). In essence, the Maximum Empower Principle states that the system that will prevail in competition with others is the one that develops the most useful work with inflowing emergy sources. Useful work is related to using inflowing emergy in reinforcement actions that insure, and if possible increase, the inflow of emergy. The principle is somewhat circular. That is, processes that are successful maximize useful work, and useful work is that work which increases inflowing emergy. It is important that the term useful is used here. Energy dissipation without useful contribution to increasing inflowing emergy is not reinforcing and thus cannot compete with systems that use inflowing emergy in self-reinforcing ways. Thus drilling oil wells and then burning off the oil may use oil faster (in the short run) than refining and using it to run machines, but it will not compete in the long run with a system that uses oil to develop and run machines that increase drilling capacity and ultimately the supply of oil.

Alternatives that do not maximize emergy cannot compete in the long run and are "selected against." In the trial and error processes of open markets and individual human choices, the patterns that generate more emergy will tend to be copied and will prevail. Recommendations for future plans and policies that are likely to be successful are those that go in the natural direction toward maximum emergy flow.

A second guiding criterion for many alternatives is that they be sustainable in the long run. Ultimately sustainable development is an activity that uses no nonrenewable energy, for once supplies have dwindled, development that depends on them must also dwindle. However, the criteria for maximum empower would suggest that energy be used effectively in the competitive struggle for existence. Thus when energy is available, its use in actions that reinforce overall performance is a prerequisite for sustainability. To do otherwise would suggest that the development would not be competitive, and would not be sustainable in the short run. This alternative (no use of nonrenewable energy) provides the lower boundary for sustainability. The upper bound is determined by the maximum empower principle as well. Sustainable developments are those that operate at maximum power, neither too slow (efficient) nor too fast (inefficient). The question of defining sustainability becomes one of defining maximum power. Investment ratio and the environmental loading ratio are used as the criteria for sustainability. By matching the ratios of a development with those of the economy in which it is imbedded, a proposed development is as sustainable as the economy as a whole.

Analysis of Public Policy Options

The emergy analysis procedure is designed to evaluate the flows of energy and materials of systems in common units that enable one to compare environmental and economic aspects of systems. Questions concerning development policy and the use of resources usually involve environmental impacts that must be weighed against economic gains. Most often impacts and benefits are quantified in different units and result in a paralyses of the decision-making process because there is not a common means of evaluating the trade-offs between environment and development. Emergy provides a common basis, the energy of one form that is required by all productive processes.

While "Ecological Economics" and the methods of Emergy Analysis are comparatively new and still evolving, we believe they offer an important step in developing a quantitative basis for public policy decision making.

Analysis of the Ecologic and Economic Costs of the Exxon Valdez Oil Spill

Environmental Costs

The emergy losses that occurred as the result of damage to natural ecological systems in Prince William Sound and the Gulf of Alaska (A, Figure II.4) from the *Exxon Valdez* oil spill included any natural resource damage for which there was not an equal, corresponding gain by another natural resource (for example increased prey availability to a competitor of damaged resource). If a specific natural resource damage resulted in both an emergy gain and loss, the net gain was subtracted from, or the net loss added to, the total emergy loss.

Net decreases in primary production (LPP_i) of phytoplankton resulting from the Valdez oil spill were calculated as the product of the following four components: 1.) the annual net production of phytoplankton per m^2; 2.) the fraction of this production that was lost (estimated from decreases observed in phytoplankton populations following other spills (Trudel, 1978; National Research Council, 1985)); 3.) the maximum area covered by the Valdez spill at any one time; and 4) a duration for this maximum extent (time, estimated by integrating the time of coverage for smaller extents normalized for their respective areas). Lost primary production by intertidal algae was calculated as the product of the: 1.) sum of the differences between post-spill standing stock biomass of intertidal algae and pre-spill standing stock biomass of intertidal algae (for a recovery assumed to be a linear increase from post-spill standing stock to pre-spill standing stock over 5 to 10 year period); and 2.) the annual production per unit biomass.

Zooplankton and phytoplankton mortalities measured as biomass were calculated as the product of: 1.) the pre-spill standing stock per unit area; 2.) estimated percent mortality, and 3.) the maximum area of the Valdez spill. Intertidal producers, herbivores, meiofauna, and macrofauna mortalities in units of biomass were estimated as the product of the initial standing stock per unit area, estimated percent mortalities, and the total area of shoreline oiled.

Natural resource damage estimates that were reported in numbers of individuals killed were converted into dry-weight biomass and a general value for the ratio of dry weight to live body weight for vertebrates (H_i = 0.30 g-dry wt./g-live wt. (Carter, 1969)) was used where a specific H_i is not given. The biomass mortalities were converted to energy losses using biomass to energy conversion factors to generate energy losses as the result of different types of natural resource damage.

The emergy values of specific components and flows of the ecosystem were calculated using transformities given in Appendix A. Appendix C gives details of the calculations of trophic levels and transformities of individual species for the Prince William Sound ecosystem. The emergy losses of individual species and groups were added to determine the total emergy of natural resource damages (VNRL). A sensitivity analysis was performed by halving and doubling components of the loss calculations to determine their effect on the individual and total natural resource damage emergy losses.

Economic Costs

The emergy lost by the economic systems of Alaska and the United States as a result of the *Exxon Valdez* oil spill (F and G, Figure II.4) included lost fishery harvests, human labor and material expenditures for the oil recovery and shoreline cleaning operations, and other perturbations and changes

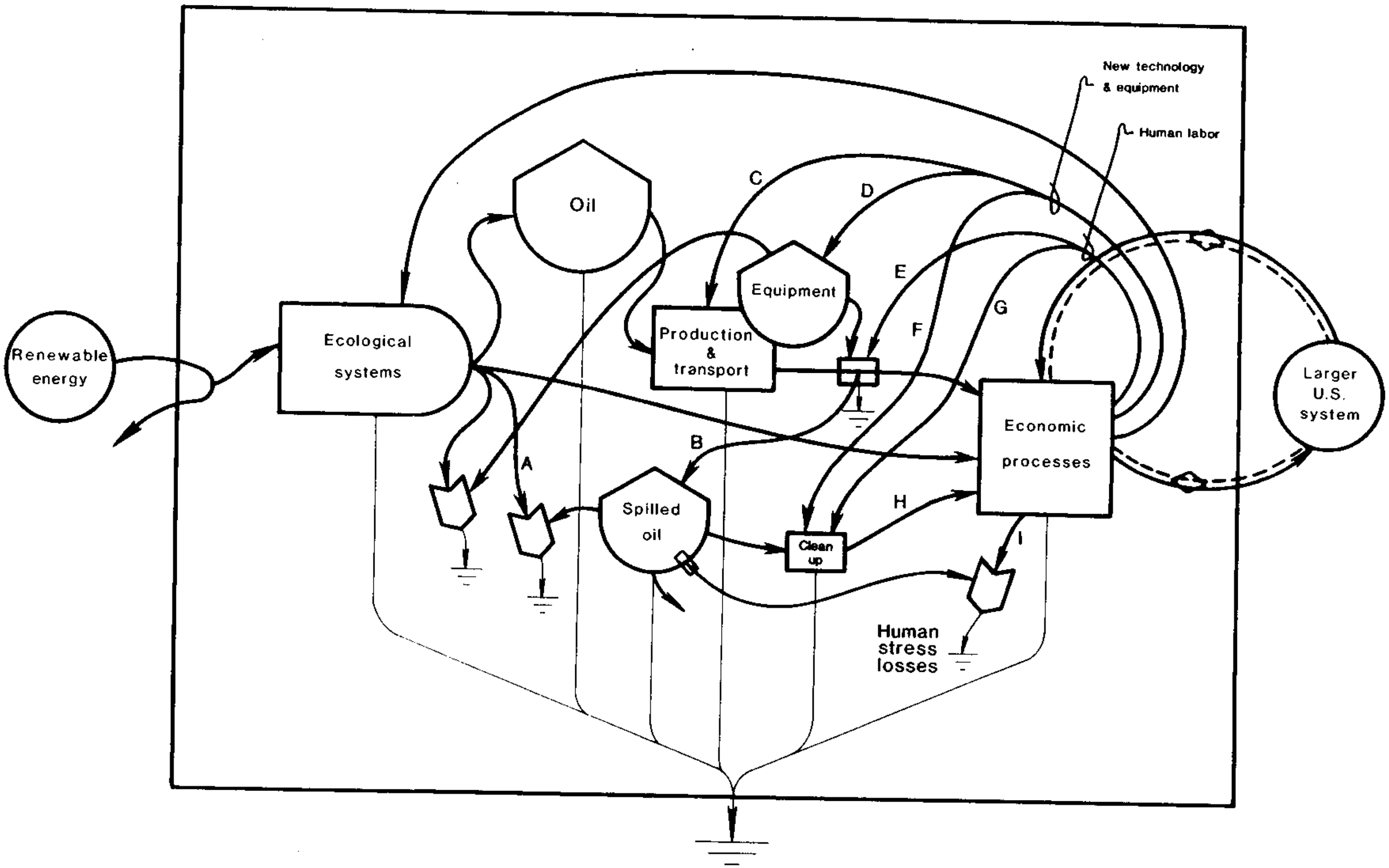


Figure II.4. A model of the costs and benefits of oil spill damage and oil spill prevention methods for the U.S. oil transportation system. the total loss from an oil spill is defined as: A + B + F + G + I - H, and the investment required to implement a prevention alternative is defined as: C + D + E, where, A = natural resource damage resulting from the oil spill, B = spilled oil, C = new technology invested in transport systems, D = new equipment invested in transport systems, E = additional human labor invested in transport systems, F = equipment and technology used in oil spill cleanup, G = human labor used in oil spill cleanup, H = spilled oil recovered during cleanup, I = human productivity losses due to stress as a result of the oil spill of flows in the human system that resulted from the spill. The emergy loss associated with the oil that was not shipped out of Port Valdez as a result of the oil spill (National Response Team, 1989) was calculated, but not added into the total economic system losses as there was no evidence that the United States used less oil in 1989 as a result of the spill. As in the natural resource damage assessment, where an emergy loss was associated with an emergy gain, the net loss was added to, or the net gain was subtracted from, the total loss.

The emergy values of the economic system losses were calculated using transformity values referenced in Appendix A. The total economic system emergy loss (VESL) resulting from the spill was calculated as the sum of: 1.) the economic losses; 2.) labor costs in cleanup; 3.) social disruption; 4.) the loss of *Exxon Valdez* crude oil cargo; and 5.) the fuel used in cleanup operations. A sensitivity analysis was performed by halving and doubling the individual values used to calculate losses in order to determine the values' effects upon the economic system losses as a result of the spill. Emergy values for human stress losses as a result of the spill were estimated from social and cultural impact studies of the Valdez and other spills by Brown and Owen (Unpublished Data)[a].

Analysis of Oil Spill Prevention Alternatives

An emergy analysis of oil spill prevention alternatives (C, D, and E in Figure II.4) was conducted to determine the net emergy benefits of seven tank vessel designs and three spill prevention system modifications analyzed by the National Research Council (1991) and Keith et al. (1990). These net emergy benefits were calculated separately for: 1.) the tanker fleet serving the United States and 2.) the fleet licensed for Alaska.

The United States Tanker Fleet

For the United States tanker fleet, the monetary implementation and operation costs and oil spillage prevention estimates for the three prevention systems of Keith et al., originally developed for Cook Inlet and Prince William Sound, Alaska, were extrapolated to national cost and prevention estimates by determining the cost and prevention per metric ton of oil transported through each of the two Alaskan sites and then multiplying by a representative annual oil transport of 600 million metric tons in United States waters (National Research Council, 1991). The emergy investment required to implement each alternative was measured in units of human services and steel required to implement and operate the alternative. The steel required to implement an alternative for the U.S. fleet was calculated in two ways. The maximum estimate was calculated as the amount of steel required to refit the 1500 different tankers which use the 15 major U.S. ports each year, assuming each tanker was of average size in the world fleet, 78,700 lightweight tons (lightweight denotes the weight of a vessel without cargo, crew, fuel or stores) (National Research Council, 1991). The minimum estimate was calculated as the amount of steel required to refit the 257 U.S. flag tankers (National Research Council, 1991), assuming each was of world fleet average size.

The Alaskan emergy-money ratio was used with the monetary cost estimates of Keith et al. (1990) for oil spill prevention methods. Odum's (1992) 1.6E+12 sej/$ U.S. emergy-money ratio (Appendix A) was used with the National Research Council (1991) estimates. The two different ratios were used because the Keith et al. data were for Alaska while the National Research Council data were for the United States as a whole. The sum of the natural resource emergy loss (VNRL) and the economic system emergy loss (VESL) *per metric ton* of oil spilled in the *Exxon Valdez* oil spill, were used as an estimate for total damage *per metric ton* of oil spilled for all U.S. spills. Loss estimates were given as ranges. The highest loss estimates were used in best-case prevention estimates and lowest loss estimates were used in worst-case prevention estimates.

The emergy benefits as the result of natural resource (ecologic) damage and economic system losses that would not occur as a result of an implemented oil spill prevention alternative, were also given

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[a] M.T. Brown and P. Owen. University of Florida, Center for Wetlands and Water Resources.

as a range. Each alternative's best-case (highest) and worst-case (lowest) net emergy benefits were calculated as the sum of emergies of economic system losses and natural resource damages that did not occur as a result of implementing the alternative, less the emergy used in implementing the alternative. The National Research Council (1991) reported a range of oil spillage prevention estimates for tanker designs. Lowest emergy in implementation and highest spillage prevention estimates were used with highest natural resource loss prevention estimates to calculate best-case net emergy benefits.

The human stress and productivity losses as a result of the *Exxon Valdez* oil spill were not included in this analysis because the low human populations of Prince William Sound, the Kenai Peninsula and Kodiak Island were not typical of much of the United States coastline. As such, the human stress losses from the Valdez spill may not have been indicative of a general U.S. oil spill. Thus, the emergy benefit of a given prevention alternative that results from prevented human stress losses in Alaska may underestimate that for the United States in general. Since coastal ecosystems are different, and population density and economic activity are greater along much of the coast of the contiguous U.S., estimates of damages were adjusted to include these additional losses. Best- and worst-case additional loss estimates were calculated using coastal ecosystems typical of the southeastern United States. Ecologic loss per metric ton of oil spilled was derived using data for oil spilled and area oiled estimates for salt marshes and mangroves from: the *Amazon Ventura* oil spill in Georgia (Brown, 1989); the 1985 Nairin, Louisiana, Shell pipeline spill (Fischel et al., 1989); the 1986 Naval Air Station Roosevelt Roads jet fuel spill in Puerto Rico (Ballou and Lewis, 1989); and the Refineria Panama spill in Panama (Cubit et al., 1987; Teas et al., 1989). Standing stock biomass and primary productivity estimates for Atlantic and Gulf of Mexico wetlands were used to estimate losses in oiled areas. The highest and lowest ecological system loss estimates calculated for southeastern coastal ecosystems were then added to the highest and lowest ecological loss estimates calculated for the Valdez spill.

Additional economic losses in the continental U.S. were estimated using Florida beach tourism industry data of Bell and Leesworthy (1986) and tourist visit declines following the 1978 *Amoco Cadiz* oil spill in Brittany, France (Bonnieux and Rainelli, 1978). Annual coastal tourist industry receipts and employees per kilometer of Florida beach were used with the length of shoreline oiled per metric ton of *Exxon Valdez* cargo and one- and four-year tourism declines to generate lowest and highest loss estimates. These additional loss estimates were summed with the economic loss estimates of the Valdez spill to calculate economic loss estimates per metric ton of oil spilled adjusted for a spill off the contiguous U.S. Tourism receipt declines were taken as an emergy loss under the assumption that the lost income would result in a corresponding decrease in goods and services imported into the coastal region.

The Alaskan Tanker Fleet

The net emergy benefits of modifications to the Alaskan tanker fleet were calculated in the same manner as for the U.S. fleet. The data of Keith et al. (1990) were used for monetary costs of system and tanker modifications. The steel required for implementing tanker modifications was estimated from the characteristics of the 93 vessel Alaskan tanker fleet described by the Alaskan Oil Spill Commission (1990) and the dead weight of vessels described by other sources. Steel requirements were estimated assuming a 0.1 to 1 light weight to dead weight ratio and a weight of steel equal to a vessels light weight required to double hull a single-hulled tanker. High monetary cost and steel estimates assumed double hulling of all 70 single hulled vessels of the fleet, while low estimates assumed double-hulling of only half of these vessels. The oil spillage prevention estimates used for each system modification and the low prevention estimates used for tanker modifications were those given by Keith et al. The high prevention values for tanker modifications were estimated at three times the Keith et al. values, as spillage prevention was assumed to occur not only in Alaska, but along the remainder of each tanker's route as well.

III. RESULTS & DISCUSSION

Emergy Analysis of Alaska

The state of Alaska energy systems model is diagrammed in Figure III.1. The major natural emergy sources are the chemical potential energies of rain ($J_{204\text{-}B}$) and inflowing Canadian river water ($J_{208\text{-}B}$), and the energy absorbed from tide ($J_{205\text{-}B}$). These natural, driving energy flows support the ecologic-economic system of Alaska through both economically valued and economically unvalued processes. The resources harvested in economically valued processes ($J_{209\text{-}223}$ through $J_{212\text{-}223}$, $J_{213\text{-}223}$ through $J_{215\text{-}223}$, and $J_{212\text{-}219}$, Figure III.1) include minerals, oil, natural gas, coal, timber, and fish. The Prince William Sound region model is diagrammed in Figure III.2. The major natural emergy sources were chemical potential energy of fresh water (from rain, runoff, and glaciers ($J_{403\text{-}B}$)), the absorption of tidal energy ($J_{404\text{-}B}$) and a smaller value associated with input of seismic energy ($J_{406\text{-}B}$).

State Economic System

The emergy signature derived from the state of Alaska analysis is given in Table III.1. The emergy of each major, long-term storage is shown in Table III.2. Energy conversion factors used in this analysis are given in Appendix B. Table III.3 gives a summary of several categories of related flows. The sum of the major renewable emergy sources (the chemical potential energies of rain and inflowing Canadian river water, and the energy absorbed from tides) (R) is given in Table III.3. These natural, driving energy flows support the ecologic-economic system of Alaska through both economically valued and unvalued processes. The emergy values of resources that were harvested in economically valued processes are estimated in the indigenous renewable energy section of Table III.3.

The Alaskan system used and exported emergy from its reserves of coal, natural gas, and oil at a rate much greater than they are replaced through natural formation in geologic processes . These flows are included under the heading of nonrenewable sources (Table III.3). Fishery products exported to the remainder of the United States (U.S. Fishery products, Table III.1) were assumed to be processed within the Alaskan system and are therefore included in the summary flow of exports transformed within the system (B, Table III.3). The emergy values of the mineral exports reported by the U.S. Department of the Interior (1988) in 1985 were insignificant with the exception of those for silver and gold (Table III.3).

Several indices derived from Table III.3 are given in Table III.4. These indices serve to characterize Alaska with respect to its driving forces, emergy flux per person, emergy flux per dollar of economic transactions, and fossil fuel and electric use. Very little of the emergy used was imported. Ninety-seven percent of total emergy use was derived from indigenous sources (I2, Table III.4). Ninety-two percent of Alaska's emergy use resulted from non-economic, locally renewable processes (I5, Table III.4) and was calculated as free in monetary terms. The ratio of emergy in exports to emergy in imports was 13 to one (I8, table III.4). Only small fractions of the state's emergy use were derived from electricity (0.60%) and fossil fuel (5.0%). The Alaskan emergy-money ratio was calculated as 2.3E+13 sej/$ for 1985 (I16, Table III.4). The emergy flux per unit area was 3.0E+11 sej/m^2.

Alaska is probably unique among U.S. states for its high percent emergy use from within, high emergy use per capita, and high emergy-money ratio. Emergy indices for Alaska are distinctly different from those of the United States as a whole as well as from other developed countries such as the Netherlands, Taiwan, and Switzerland (Table III.5). Alaska's 97% emergy use from within compares with those of Australia, Liberia, Brazil, and India. These values result largely from Alaska's small population and large area relative to other U.S. states and most developed countries. The state includes some more densely populated regions, particularly the Anchorage area, which probably have emergy signatures more typical of the United States. Sparsely populated regions with small, often isolated towns and villages comprise over 99% of the Alaskan landscape (Smith, 1990).

Ninety-eight percent of Alaska's emergy support comes from within. The economic system this emergy supports is characterized by pulses or as a "boom and bust" system. This may be related to the

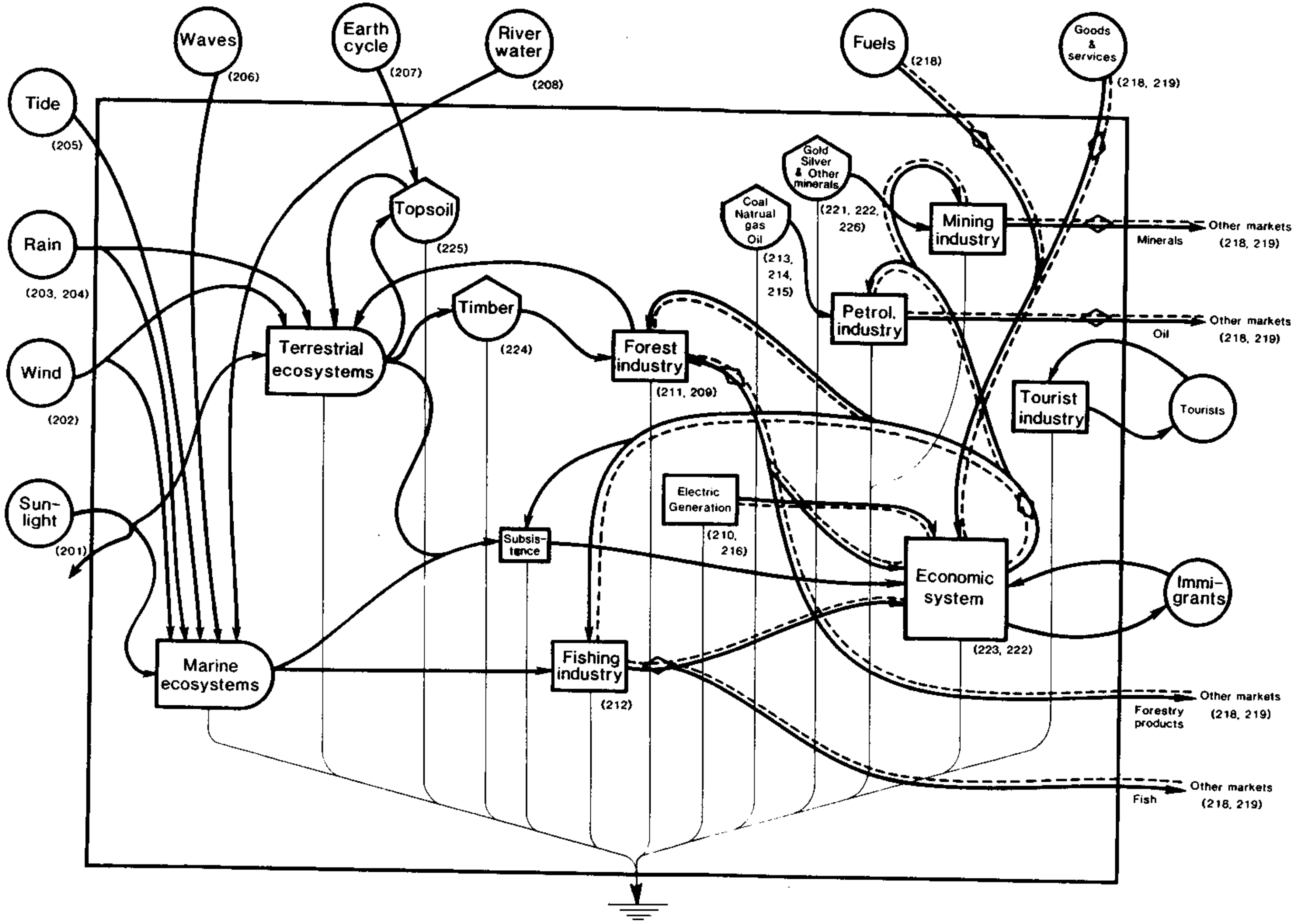

Figure III.1. The state of Alaska model.

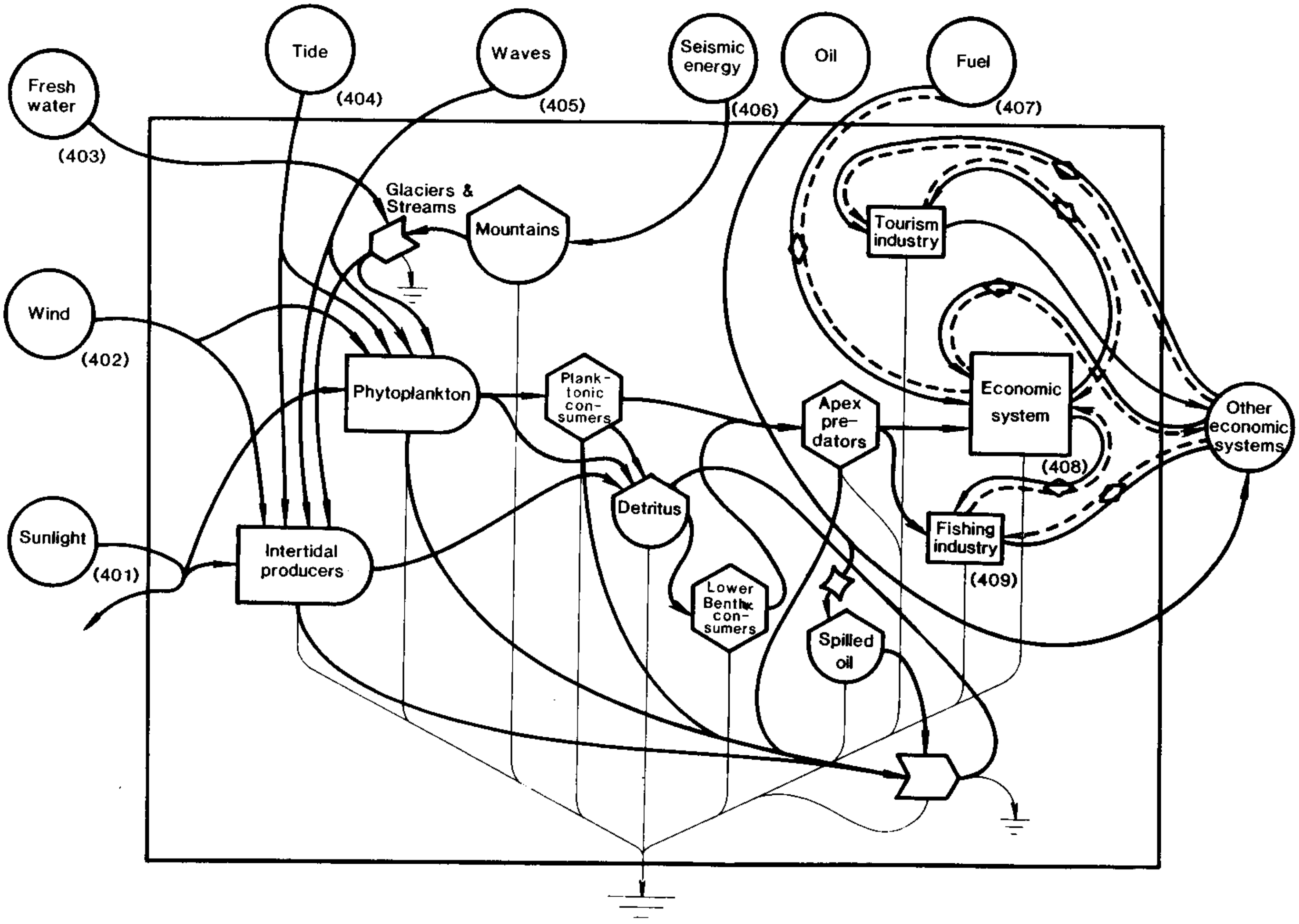

Figure III.2. The Prince William Sound regional model.

Table III.1. Emergy analysis of the state of Alaska (Figure III.1) in 1985. Data and calculations are given in Appendix B.

Note	Name	Raw Units J,$,g or people/y		Solar Transformity sej/unit	Solar Emergy E20 sej/y
RENEWABLE SOURCES					
1	Sunlight	6.5E+21	J/y	1	65
2	Wind, kinetic	2.6E+19	J/y	620	160
3	Rain, geopotential	7.8E+18	J/y	8900	700
4	Rain, chemical	1.2E+19	J/y	15000	1800
5	Tide	8.2E+18	J/y	24000	1900
6	Waves	2.7E+18	J/y	26000	700
7	Earth cycle	3.6E+18	J/y	29000	1000
8	River water	8.3E+17	J/y	41000	340
INDIGENOUS RENEWABLE ENERGY					
9	Fuelwood production	7.5E+15	J/y	3.5E+04	2.6
10	Hydroelectricity	2.8E+15	J/y	1.6E+05	4.4
11	Forest extraction	1.2E+15	J/y	3.5E+04	0.42
12	Fisheries	6.2E+11	J/y	5.0E+06	0.031
NONRENEWABLE SOURCES FROM WITHIN SYSTEM					
13	Coal	1.8E+16	J/y	4.0E+04	7.1
14	Natural gas	2.2E+17	J/y	4.8E+04	110
15	Oil	2.1E+17	J/y	5.3E+04	110
16	Fuel derived electricity	1.5E+16	J/y	1.6E+05	24
IMPORTS AND OUTSIDE SOURCES					
17	Fuel	7.1E+16	J/y	5.3E+04	38
18	International services	5.6E+08	$/y	1.6E+12	8.9
19	U.S. services	5.1E+09	$/y	1.6E+12	82
20	Net immigration	5250	p/y	9.4E+16	50
EXPORTS					
21	International fishery products	3.4E+15	J/y	5.0E+06	170
22	U.S. fishery products	6.7E+14	J/y	5.0E+06	34
23	Forestry products	5.9E+15	J/y	3.5E+04	2.1
24	Natural gas	2.9E+17	J/y	4.8E+04	140
25	Oil	3.4E+18	J/y	5.3E+04	1800
26	Service in exports to Intrntl.	2.6E+09	$/y	1.6E+12	42
27	Service in exports to U.S.	1.3E+10	$/y	1.6E+12	210
28	Silver	7.5E+05	g/y	3.0E+14	2.2
29	Gold	5.0E+06	g/y	4.4E+14	22

Table III.2. Emergy value of major, long-term emergy storages (Q_i) of Alaska in 1985. Calculations and data are given in Appendix B.

Note Q_i	Storage	Raw Units J, g or $		Solar Transformity sej/unit	Solar Emergy E20 sej
1	Timber	3.5E+18	J	35000	1200
2	Coal	1.6E+20-1.6E+23	J	40000	64000-64000000
3	Natural Gas	1.3E+20-1.6E+20	J	48000	62000-77000
4	Crude Oil	3.4E+19-6.7E+19	J	53000	18000-36000
5	Topsoil	1.2E+21	J	63000	760000
6	Other Minerals (Au, Ag, Zn, Pt, Pb, etc.)	Unknown	g		Unknown
7	Capital Assets	5.7E+10	$	1.6E+12	920

Table III.3. Summary of annual emergy flux and money in the Alaskan economy from Table III.1. All expressions are from Odum (1992). Numerical terms in expressions refer to values associated with line numbers in Table III.1.

Summary Flow used in Table III.4		Solar Empower (E20 sej/y)
R	Renewable sources (chemical rain, tide, river water) 4 + 5 + 8	4500
N	Nonrenewable sources from within Alaska 13 + 14 + 15 + 24 + 25 + 28 + 22	2200
N1	Nonrenewable sources used within Alaska 13 + 14 + 15	270
N2	Nonrenewable sources exported without use 24 + 25 + 28 + 22	2000
F	Imported fuels 17	38
P2I	Emergy value of human services embodied in imports 18 + 19	91
P1E	Emergy value of human services embodied in exports 26 + 27	210
B	Exports transformed within 22	34
EL	Emergy in electricity use 10 + 16	28
FF	Emergy in fossil fuel use 13 + 14 + 15	270
H	Net human immigration 20	50
U	Emergy value of total Alaskan energy use R + N1 + F + P2I	4500

Table III.4. Alaskan 1985 emergy indices derived from Table III.1. All expressions are from Odum (1992). Terms in expressions are from Table III.4.

Index	Name	Expression	Value	Units
I1	Flow of Imported Emergy	F+P2I	130E+20	sej/y
I2	Total Emergy Inflows	R+N+F+P2I+H	7600E+20	sej/y
I3	Economic Component	U-R	360E+20	sej/y
I4	Total Exported Emergy	N2+B+P1E	2400E+20	sej/y
I5	Percent Locally Renewable & Percent of Emergy Use Which is Free	R/U	92	percent
I6	Economic/Environment Ratio	(U-R)/R	0.069	
I7	Ratio of Imports to Exports	(F+P2I+H)/(N2+B+P1E)	0.075	
I8	Ratio of Exports to Imports	(N2+B+P1E)/(F+P2I+H)	13	
I9	Net Imports	(F+P2I+H)-(N2+B+P1E)	-2200E+20	sej/y
I10	Percent of Emergy Use Purchased	(F+P2I)/U	2.9	percent
I11	Fraction of Emergy Use That is Imported Services	P2I/U	0.020	
I12	Percent of Emergy Use Derived From Indigenous Sources	(N1+R)/U	97	percent
I13	Use Per Unit Area	U/(area)	3.0E+11	sej/m^2
I14	Use Per Person	U/AK population[a]	9.1E+17	sej/person
I15	Renewable Carrying Capacity at Present Living Standard	(R/U)*(AK population[a])	4.5E+05	people
I16	Alaskan Emergy-Money Ratio	U/GNP	2.3E+13	sej/$
I17	Fraction Electric	EL/U	0.0060	
I18	Fraction Fossil Fuels	FF/U	0.050	
I19	Fuel Use Per Person	FF/AK population[a]	5.1E+16	sej/person

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[a] 1985 Alaskan Population = 4.9E+05 people (U.S.D.C., 1989)

Table III.5. A comparison of emergy indices of Alaska in 1985 to those for 12 other nations in 1980 given by Huang and Odum (1991).

System	Empower Density, E11 sej/m^2-y	Emergy Use From Within %	Per Capita Emergy Use E15 sej/person-y	Emergy-Money Ratio E12 sej/$
Netherlands	100.0	23	26	2.2
Taiwan	37.0	24	8	2.5
Switzerland	18.0	19	12	0.7
Poland	11.0	66	10	6.0
Dominica	8.8	69	13	15.
U.S.A.	7.0	77	29	2.3
Liberia	4.2	92	26	35.
Spain	3.1	24	6	1.6
ALASKA	**3.0**	**97**	**910**	**23.**
New Zealand	2.9	60	26	3.0
Brazil	2.1	91	15	8.4
India	2.1	88	1	6.4
Australia	1.4	92	59	6.4

13 to 1 emergy export to import ratio (I8, Table III.4) and to the less than 2% of exports that are transformed within. Many of the most important Alaskan industrial functions are extraction for export. Most of these industries are seasonal in nature resulting in annual production and employment pulses.

The effect of a catastrophic event like an oil spill may be small in a system adapted to historical patterns of pulsing compared to a system normally immune to pulses. Historically, large outside inputs, such as those occurring during gold rushes and construction of the trans-Alaskan pipeline, have initiated pulses within the state's relatively small economic system (Smith, 1990). The pipeline construction caused a large demand for labor and a boom in employment and immigration that was followed by an unemployment bust when construction was finished and the less labor-intensive extraction processes began. The elastic demand for Alaskan exports, because other sources are easily substituted, ties the Alaskan system to fluctuations in the world markets, perhaps reinforcing the pulsing behavior. An example of this was the collapse of the 1991 Alaskan salmon market as a result of competition from farm-raised fish in the Japanese market (Gay, 1991).

Prince William Sound Regional Economic System

The Prince William Sound region energy systems model is diagrammed in Figure III.2. The emergy signature derived from the Prince William Sound regional model is given in Table III.6. Conversion factors used to calculate the energy flows in the analysis are given in Appendix B. A summary of several related flows for the region is given in Table III.7. The major natural emergy sources were the chemical potential energy of fresh water (from rain, runoff, and glaciers), the absorption of tidal energy and a smaller value associated with input of seismic energy. These sources yielded a 9.5E+10 sej/m^2 natural, annual emergy flux for Prince William Sound (R in Table III.7). Table III.8 gives several emergy indices for the Prince William Sound region. Imports comprised 35% (I10, Table III.8) and fossil fuels accounted for 27% of the emergy in the region's energy use. The per capita emergy use of the region was 1.7E+17 sej/person-year (I14, Table III.8).

Because of their similarity to the emergy indices of United States in general, the indices of the Prince William Sound region allow the use of the *Exxon Valdez* spill as a case study for U.S. oil spills in general, where those of Alaska as a whole would not support this use. The emergy in the fossil fuel support for the Prince William Sound region (27%) is an order of magnitude greater than that for Alaska (5.0%). The 35% of Prince William Sound emergy support derived from imports is also an order of magnitude greater than the state's 2.9%. The ratio of imports to export is 0.86 to 1, again an order of magnitude larger than the 0.075 to 1 value calculated for Alaska. The region's emergy support derived from imports, is similar to that of the United States as a whole which derives 33% of its support from imports. Largely as the result of the greater population density of Prince William Sound with respect to Alaska as a whole, the emergy characteristics of the sound region appear to fall between those of Alaska and the United States, being closer to the remainder of the United States. A comparison of the emergy signatures of the Prince William Sound region and the state of Alaska is shown in Figure III.3.

Analysis of the Costs of the *Exxon Valdez* Oil Spill

Emergy Analysis of Ecologic and Economic Losses

The components of the natural resource and economic system loss analyses are defined in Appendix D. The emergy values of the natural resource (ecologic) and economic system losses resulting from the *Exxon Valdez* oil spill are given in Table III.9. Biomass loss estimates and conversion factors used to calculate the energy values in Table III.9 are given in Tables IIID.1 and IIID.3. The distribution of emergy values for the natural resource loss is graphed in Figure III.4 and the distribution of emergy losses among ecologic and economic components is graphed in Figure III.5. The total economic system losses were 2 to 21 times greater than the natural resource losses. The major loss in both the highest and

Table III.6. Emergy analysis of the Prince William Sound region of Alaska (Figure III.2) in 1988. Data and calculations are given in Appendix B.

Note	Name	Raw Units J or $/y		Solar Transformity sej/unit	Solar Emergy E20 sej/y
RENEWABLE SOURCES:					
1	Sunlight	3.9E+19	J/y	1	0.39
2	Wind, kinetic	8.6E+15	J/y	620	0.22
3	Fresh water, chemical	2.6E+16	J/y	15000	4.0
4	Tide	1.9E+16	J/y	24000	4.5
5	Waves	6.3E+14	J/y	26000	0.68
6	Seismic energy	7.3E+11	J/y	3.7E+07	0.27
IMPORTS:					
7	Fuel	7.1E+15	J/y	53000	3.8
8	Services	9.2E+07	$/y	1.6E+12	1.5
EXPORTS:					
9	Fishery products	9.1E+13	J/y	5.0E+06	4.6
10	Services	9.1E+07	$/y	1.6E+12	1.5

Table III.7. Summary of annual Prince William Sound empower and money flows from Table III.6. All expressions are from Odum (1992) except R2. Numerical terms in expressions refer to values associated with line numbers in Table III.6.

Summary Flow		Solar Empower (E20 sej/y)
R	Renewable sources (chemical fresh water, tide, seismic) 3 + 4 + 6	9.8
R2	Renewable sources exported without use 9	4.6
F	Imported fuels 7	3.8
P2I	Emergy value of human services embodied in imports 10	1.5
P1E	Emergy value of human services embodied in exports 8	1.5
U	Emergy value of total Prince William Sound energy use R + F + P2I	15

Table III.8 Prince William Sound region 1988 emergy indices derived from Table III.6. All expressions are from Odum (1992) except I4, I7, I8, and I9. Terms in expressions are from Table III.7.

Index	Name	Expression	Value	Units
I1	Flow of Imported Emergy	F+P2I	5.3E+20	sej/y
I2	Total Emergy Inflows	R+F+P2I	1.5E+21	sej/y
I3	Economic Component	U-R	5.2E+20	sej/y
I4	Total Exported Emergy	P1E+R2	6.1E+20	sej/y
I5	Percent Locally Renewable & Percent of Emergy Use Which is Free	R/U	65	percent
I6	Economic/Environment Ratio	(U-R)/R	0.54	
I7	Ratio of Imports to Exports	(F+P2I)/(R2+P1E)	0.86	
I8	Ratio of Exports to Imports	(R2+P1E)/(F+P2I)	1.2	
I9	Net Imports	(F+P2I)-(R2+P1E)	-8.0E+19	sej/y
I10	Percent of Emergy Use Purchased	(F+P2I)/U	35	percent
I11	Fraction of Emergy Use That is Imported Services	P2I/U	0.10	
I13	Use Per Unit Area	U/(area)	1.6E+10	sej/m^2
I14	Use Per Person	U/PWS population[a]	1.9E+17	sej/person
I15	Renewable Carrying Capacity at Present Living Standard	(R/U)*(PWS population[a])	5200	people
I19	Fuel Use Per Person	F/PWS population[a]	4.6E+16	sej/person

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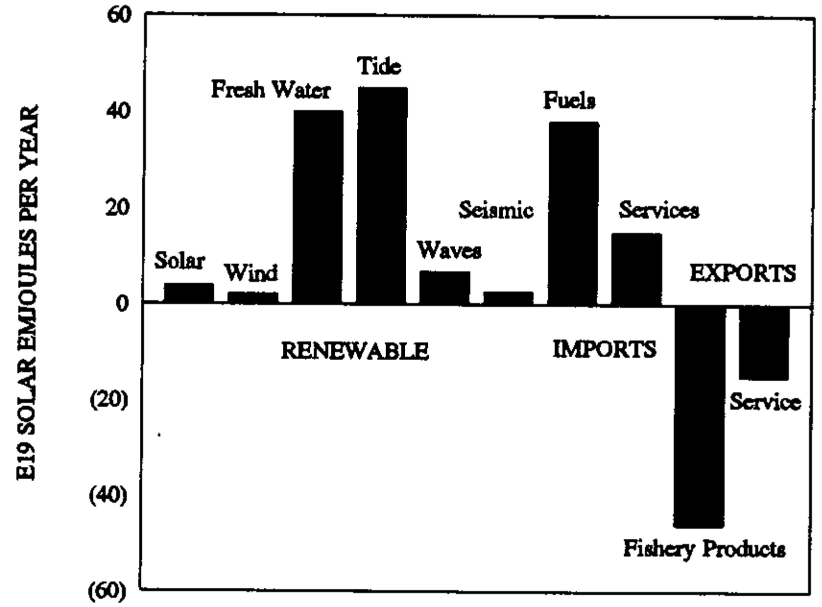
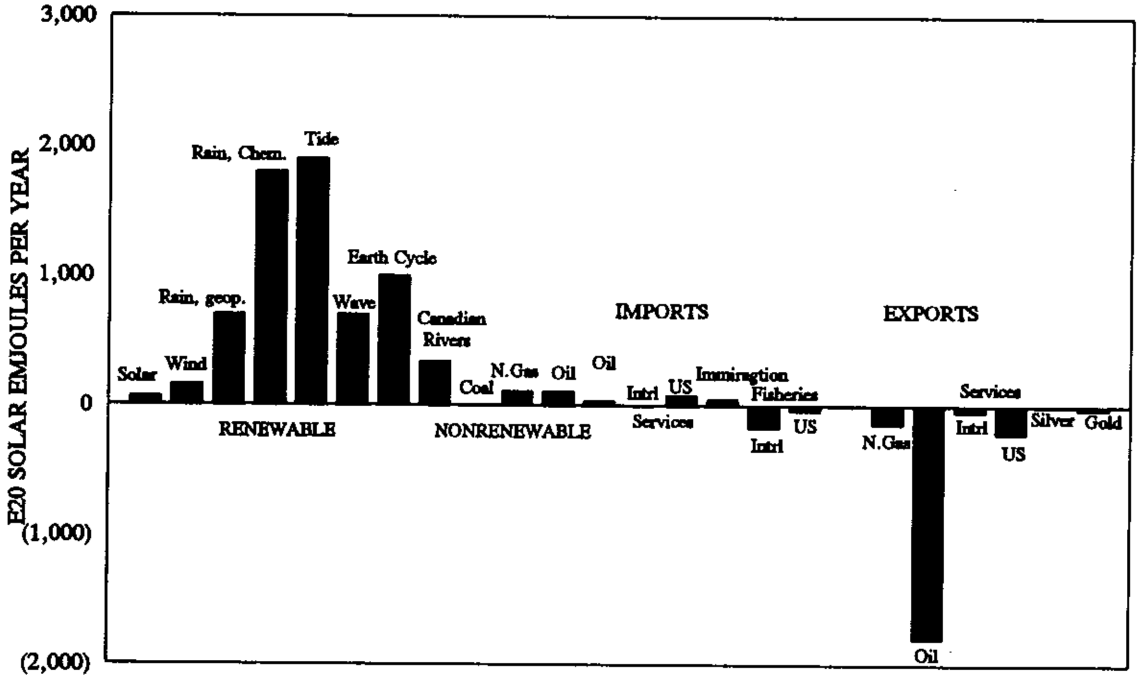
[a] 1988 Prince William Sound region Population = 8,000 people (A.D.C.E.D., 1984; Michelson, 1989)



a. Prince William Sound Region



b. State Of Alaska

Figure III.3. A comparison of emergy signatures of:
a). the Prince William Sound region of Alaska circa 1988 (Table III.6)
b). the state of Alaska circa 1985 (Table III.1).

Table III.9. Emergy losses (L_j, LPP_j, and M_j) of the *Exxon Valdez* oil spill. Sources and descriptions for natural resource losses are given in Appendix D.

Loss	Form	Energy J	Solar Transformity sej/J	Solar Emergy 1E+19 sej	Macro-economic $ 1E+07 m$
NATURAL RESOURCE LOSSES					
M_2	Zooplankton	0.53-16E+15	1.5E+05	5.8-170.	3.6-110
M_{33}	Bald Eagles	8.0E+10	2.5E+07	0.20	0.13
M_{37}	Harbor Seals	6.0E+11	1.1E+07	0.66	0.41
M_{38}	Sea Otters	5.3-8.4E+11	9.2E+07	4.9-7.6	3.1-4.8
M_{39}	Killer Whales	0-5.3E+11	1.7E+08	0.0-8.9	0.0-5.6
M_{40}	Phytoplankton biomass	0-2.9E+16	1.1E+04	0.0-32.	0.0-20.
LPP_{40}	Phytoplankton production	0-3.7E+15	1.1E+04	0.0-4.1	0.0-2.6
M_{41}	Intertidal Producer biomass	5.2-15E+15	1.1E+04	5.6-17.	3.5-11.
LPP_{41}	Intertidal Producer production	1.4-7.5E+14	1.1E+04	0.14-0.83	0.09-0.52
M_{43}	Intertidal Herbivores	2.7-5.3E+13	1.1E+05	0.30-0.58	0.19-0.36
M_{44}	Intertidal Mieo- & Microfauna & Microflora	0-2.3E+14	2.9E+05	0.0-6.8	0.0-4.3
M_{45}	Intertidal Macrofauna	0-1.3E+14	8.1E+05	0.0-11.	0.0-6.9
$M_{46}+M_{46a}$	Murres	1.5-1.7E+12	4.7E+07	7.2-8.1	4.5-5.1
M_{47}	Procellarids	1.6-1.8E+11	2.3E+07	0.36-0.41	0.23-0.26
ECONOMIC SYSTEM LOSSES					
L_{10}	Herring Fishery Harvest	7.5E+13	1.1E+06	8.3	5.2
L_{AKNS}	AK North Slope Oil Production Loss	7.8E+16	5.3E+04	410.	260.
L_{fuel}	Fuel	5.9E+15	5.3E+04	31.	19.
L_{oil}	*Exxon Valdez* cargo	1.6E+15	5.3E+04	8.5	5.3
		person-y	sej/person-y		
L_{people}	Social Disruption	1.6E+04	1.9E+17	30.	19.
		$	sej/$		
$L_{services}$	Human Labor In Cleanup	2.7E+09	1.6E+12	430.	270.
EMERGY LOSS TOTALS					
	Primary Producers			5.6-53.	3.5-33.
	Intertidal Invertebrates			0.30-18.	0.19-11.
	Zooplankton			5.8-170.	3.6-110.
	Vertebrates			13.-19.	8.1-12.
VNRL	Natural Resource Losses:			25.-260.	16.-160.
VESL	Economic System Losses (excluding L_{AKNS})			508.	320.
	Total Loss (excluding L_{AKNS})			533.-768.	330.-480.

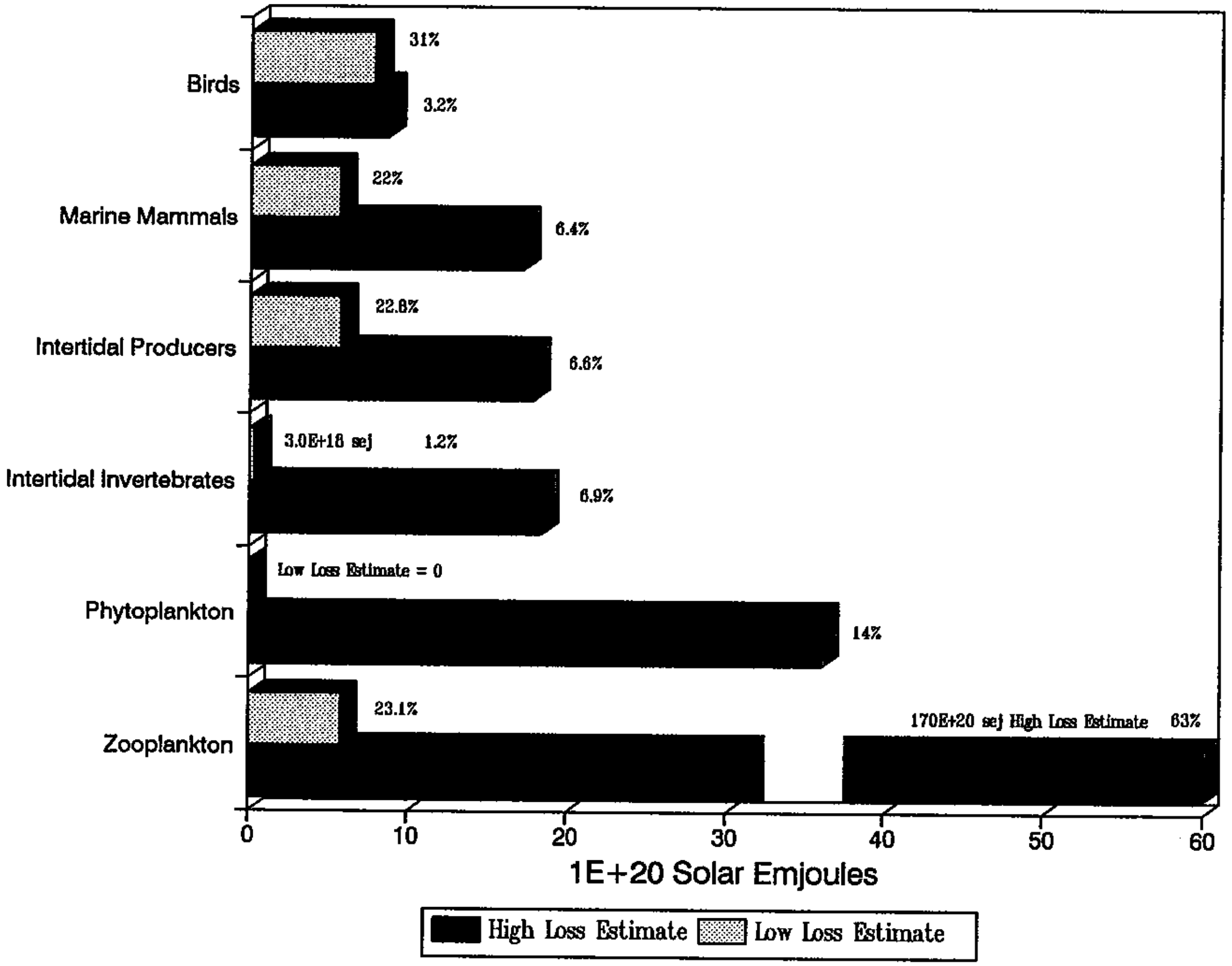
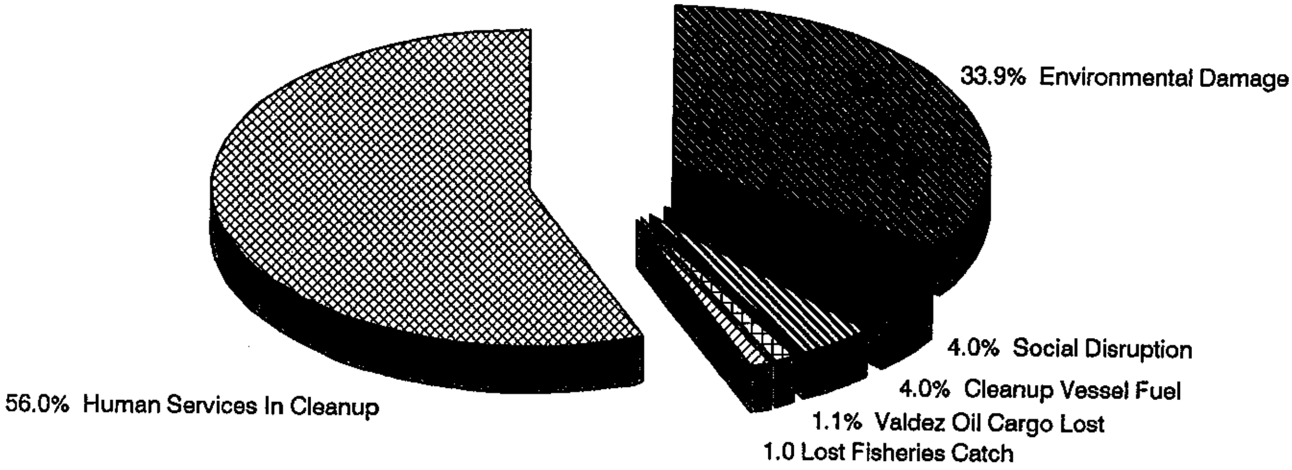
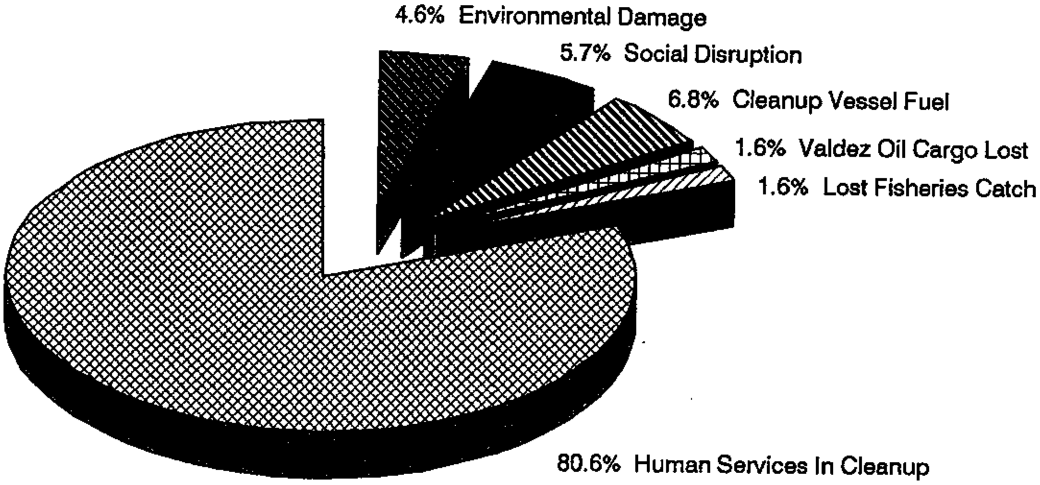


Figure III.4. The distribution of emergy values for natural resource losses resulting form the *Exxon Valdez* oil spill in sej and percent of total natural resource emergy loss for the highest (2.6E+21 sej) and lowest (5E+20 sej) loss estimates (Table III.9).



a.) distribution of the 7.7E+21 sej highest total emergy loss estimate



b.) distribution of the 5.3E+21 sej lowest loss total emergy loss estimate

Figure III.5. The distribution of the emergy values for the highest (a) and lowest (b) estimates for total emergy loss resulting from the *Exxon Valdez* oil spill (Table III.9).

lowest estimates was the human services (embodied labor) involved in the response and cleaning operations (Figure III.5). The emergy value of the actual oil spilled was 8.5E+19 sej, less than two percent of the total loss.

The value of the total ecologic and economic system losses (VESL, Table III.9) were not sensitive to halving and doubling the component values used in the natural resource and economic system loss analyses. Doubling planktonic variables (zooplankton fractional mortality and area of the Valdez spill, Table III.10 increased the highest loss natural resource loss estimate (VNRL) 65% to a maximum of 430E+19 sej, while halving it decreased the lowest loss natural resource loss estimate by 20% to 5.0E+19 sej. Halving and doubling other variables resulted in changes in natural resource loss of less than 10E+19 sej (4%) for the high estimate and 1.0E+19 sej (4%) for the low estimate. The economic system loss analysis was only sensitive to changes in the estimate of services invested by Exxon in the cleaning operations (Table III.9). Halving and doubling this variable halved and doubled the economic system loss.

The highest natural resource emergy losses were found in widely distributed and relatively immobile classes of organisms such as plankton, intertidal producers, and intertidal invertebrates. These classes of organisms and oil have similar transformities of between 1.1E+04 and 1.1E+05 sej/J. This observation may suggest that the trophic levels which will be most impacted by a pollutant may be predicted from the transformity of the pollutant. However, the mobility and distribution of these organisms is also similar to that of the spilled oil. Phytoplankton, zooplankton, and floating oil are all widely distributed and moved by wind and ocean currents. Intertidal organisms and oil stranded on shorelines have limited mobility and are concentrated in the intertidal zone. The distribution and mobility of planktonic and intertidal organisms and spilled oil may, however, be related to their transformities. Hence, the similarity between pollutant and impacted trophic level transformities may yet warrant further investigation.

Assuming an equal amount of emergy passes through all levels in the trophic hierarchy as in the canonical trophic levels of Ulanowicz and Kemp (1979), there should be an equal storage of emergy at each level (Odum, 1987a). Thus, the emergy in standing stocks of plankton trophic levels is equal to that in vertebrate trophic levels, yet, emergy losses due to vertebrate mortality only comprise 10% to 53% of the total natural resource loss (Table III.9). This suggests differing responses to oil spills among trophic levels. The difference between emergy losses for plankton and for vertebrates may reflect different life history strategies, the differences between r and K strategist classes of organisms (MacArthur and Wilson, 1967). The r strategy of adapting to environmental variability with rapid growth and reproduction, small body size, and numerous offspring may be manifest in increased production following the spill, thereby replacing mortality losses relatively fast. The K strategy of slower growth and reproduction, larger body size, and fewer, larger offspring may result in a high metabolic investment by these strategists in avoiding the spilled oil in order to keep mortality to a minimum.

Non-lethal metabolic losses as a result of the *Exxon Valdez* oil spill have not been reported and were not analyzed in the emergy loss calculations. Most quantitative reports of natural resource damage from oil spills consist solely of mortality estimates. The small emergy value of lost primary production relative to the value of primary producer mortality losses suggests non-lethal metabolic losses may be small for r strategists. As suggested above, the same might not be true for K strategists.

A factor influencing the ratio between the emergy in non-lethal stress losses and mortality losses is the distribution of stress over the impacted area. Oil spills produce patches of high intensity stress and damage which many K selected organisms often appear to avoid (National Research Council, 1985). Thus, these organisms may avoid the majority of non-lethal stress losses by avoiding oil slicks all together, and the majority of the losses would be mortality losses from the small fraction of their populations that fail to avoid slicks. If this is true, non-lethal stress losses should not be important to the outcome of the analysis.

Though non-lethal stress losses for higher transformity K strategists may not be significant, these losses are potentially significant for lower transformity, shorter generation time, organisms intermediate between r and K strategists, such as herring, capelin, and sandlance. Neither non-lethal metabolic losses nor mortalities in the Valdez spill are reported for this group, and no estimate for these losses was included in this analysis. Hence, the value for the lowest estimate may underestimate the total emergy loss. Improving the estimate would require estimates for individual organisms, non-lethal stress losses during an oil spill, and the total number of organisms affected. While standing stocks of some species are known for the Prince William Sound and Gulf of Alaska area, most are not, particularly those of fish species. While estimates of standing stocks and metabolic losses could improve understanding of oil spill impacts, even if the emergy value of vertebrate metabolic losses in the Valdez spill were found to be five times the emergy value of vertebrate mortalities, the overall damage estimates would not be significantly changed.

Impacts of Losses at Three Scales

The relative impact of the *Exxon Valdez* oil spill measured as a percent of annual emergy use at three scales, local, regional, and state, is shown in Figure III.6. The oil spill may have had the positive effects upon the Alaskan economy suggested by Smith (1990) because the effect of the oil spill was noticeable, but small (1.1% to 1.3%) relative to the system's total emergy use. In the Prince William Sound region, where much of the spill damage and loss occurred and where the emergy loss was 330% to 490% of the region's annual emergy use, the Valdez spill was almost certainly a catastrophe. The calculated emergy losses from the spill were between 87% to 130% of the annual emergy use of the region from Prince William Sound to Kodak Island effected by the spill. The Alaskan system may have adjusted to the relative small change and made use of the additional outside support, whereas the Prince William Sound system may have been overwhelmed by the large, intense perturbations to which it could not adjust.

The value of total emergy loss from the Exxon Valdez oil spill was equal to 1.1% to 1.3% of the total emergy in Alaska's annual energy use (U, Table III.3). The values of total natural resource loss and total economic system loss were equal to 0.046% to 0.47% and 0.78% of U, respectively. A 1.9E+17 sej/person-year per capita emergy use (I14, Table III.8) was calculated from the Prince William Sound regional model. When this was multiplied by the population of the entire oil spill region, it yielded an emergy value for annual energy use of 5.7E+21 sej/y. Using this value, the total loss was equal to 87% to 130%, the natural resource losses equal to 4.4 to 46%, and the services invested in response were equal to 84% of the emergy value of the region's annual emergy use. The total loss was equal to 330% to 490% of the Prince William Sound region's 1.5E+21 sej/y emergy use (U, Table III.7). The heaviest, and possibly the majority of the oil spill damage occurred in this region.

The actual effect of the spill on a local area within the spill region depended upon the amount of ecological damage in that area as well as the area's proximity to bases for cleanup operations like Valdez and Seward. The spill was a catastrophe in areas sustaining heavy ecological damage and areas that were the staging sites and bases for the cleanup operations. Areas that were not heavily damaged by the spill and that supplied labor to cleanup operations, such as much of the Kenai Peninsula, reaped the economic benefits of the spill without sustaining the extent of severe social disruption that accompanied the large influxes of people, material, and money into the staging areas.

Analysis of Oil Spill Prevention Alternatives

Descriptions of prevention alternatives that were analyzed for the United States and Alaskan tanker fleets are given in Appendix E. The analysis of prevention alternatives were performed and presented in two ways. The first was based on the costs and benefits for the United States tanker fleet, assuming the costs and benefits were proportional to those experienced in Alaska from the *Exxon Valdez* spill, and adjusted for an oil spill in the contiguous U.S (see Appendix E). The second was based on the costs and benefits for the Alaskan tanker fleet, using the costs and benefits calculated from the Valdez spill alone. Net emergy benefits for each alternative are given in Tables III.10 and III.11 and Figures III.7 and III.8.

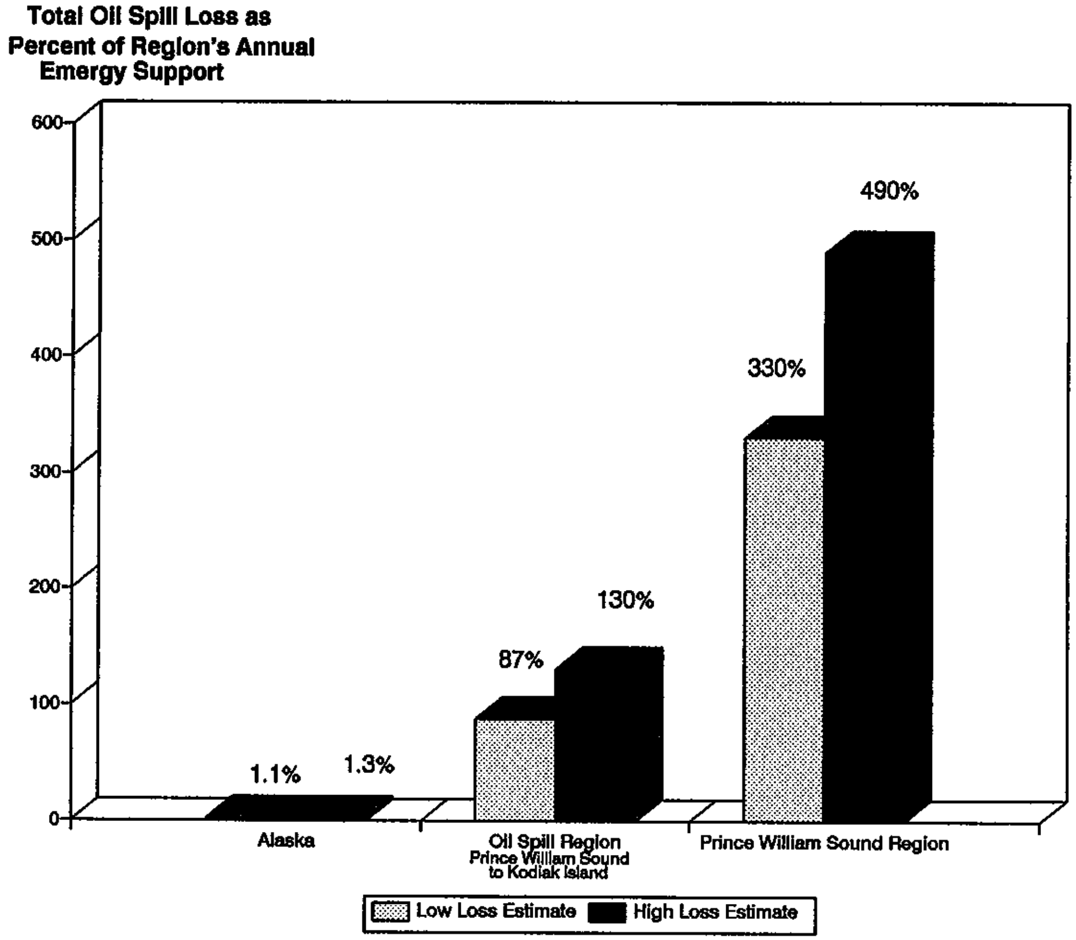


Figure III.6. The relative impact of the *Exxon Valdez* oil spill as a percent of annual emergy use of each of three regions: the state of Alaska, the region from Prince William Sound to Kodiak Island impacted by the oil spill, and the Prince William Sound region.

Table III.10 . The emergy investments in implementation, natural resource damage prevented, economic system losses prevented, and preliminary net emergy benefits for 10 spill prevention alternatives for the U.S. tanker fleet adjusted for an oil spill in the continental U.S. Notes, calculations, and alternative descriptions are given in Appendix E.

	Alternative	Emergy Investment In Implementation	Natural Resource Emergy Benefit	Economic System Emergy Benefit	Net Emergy Benefit	Ratio of Net Emergy Benefit
		A	B	C	B+C-A	(B+C)/A
		E20 sej/y	E20 sej/y	E20 sej/y	E20 sej	sej/sej
1	Group I System Modifications:	29.	0.13	1.3	-25.	0.14
		0.66	25	1.5	+0.76	2.2
2	Group II System Modifications:	110.	0.38	3.7	-100.	0.10
		4.6	7.4	4.3	-0.40	0.91
3	Group I & II System Modifications:	140.	0.44	4.7	-130.	0.10
		5.2	8.8	5.1	-0.31	0.94
4	Double-Hulled Vessels W/ Hydrostatic Vacuum:	53.	0.51	5.1	-47.	0.11
		37.	15.	8.7	-13.	0.64
5	Double-Sided Vessels W/ Hydrostatic Vacuum:	23.	0.51	5.1	-18.	0.24
		16.	15.	8.5	-7.7	1.5
6	MARPOL Vessels With Hydrostatic Vacuum:	18.	0.51	5.0	-14.	0.31
		18.	11.	6.6	+0.59	1.0
7	Vessels With Intermediate Oil-tight Deck & Double Sides	19.	0.54	5.3	-13.	0.32
		15.	14.	8.4	+7.4	1.5
8	Double-Hulled Vessels:	30.	0.44	4.4	-25	0.16
		15.	14.	8.2	+7.2	1.5
9	Vessels With Small Tanks:	16.	0.28	2.8	-13.	0.19
		8.5	7.2	4.2	+2.9	1.3
10	Double-Bottomed Vessels:	12	0.24	4.9	-6.9	0.29
		8.2	4.3	15	+11.	2.4

Table III.11. The emergy investments in implementation, natural resource damage prevented, economic system losses prevented, and preliminary net emergy benefits for Alaskan tanker fleet spill prevention alternatives. Notes, calculations, and alternative descriptions are given in Appendix E.

Alternative		Emergy Investment In Implementation A E20 sej/y	Natural Resource Emergy Benefit B E20 sej/y	Economic System Emergy Benefit C E20 sej/y	Net Emergy Benefit B+C-A E20 sej	Ratio of Net Emergy Benefit (B+C)/A sej/sej
11	Group I System Modifications:	0.45 0.45	0.099 1.0	1.9 1.9	+1.6 +2.5	4.4 6.4
12	Group II System Modifications:	4.7 4.7	0.29 3.0	5.6 5.6	+1.2 +3.9	1.3 1.8
13	Double-Hulled Vessels (Group III Modifications):	21. 12.	0.39 4.0	7.4 7.4	-14. -0.60	0.37 0.95
14	Group I & II System Modifications:	5.1 5.1	0.35 3.6	6.6 6.6	+1.9 +5.1	1.4 2.0
15	Group I, II & III System Modifications:	27. 16.	0.54 5.7	7.4 7.4	-19. -2.8	0.29 0.82

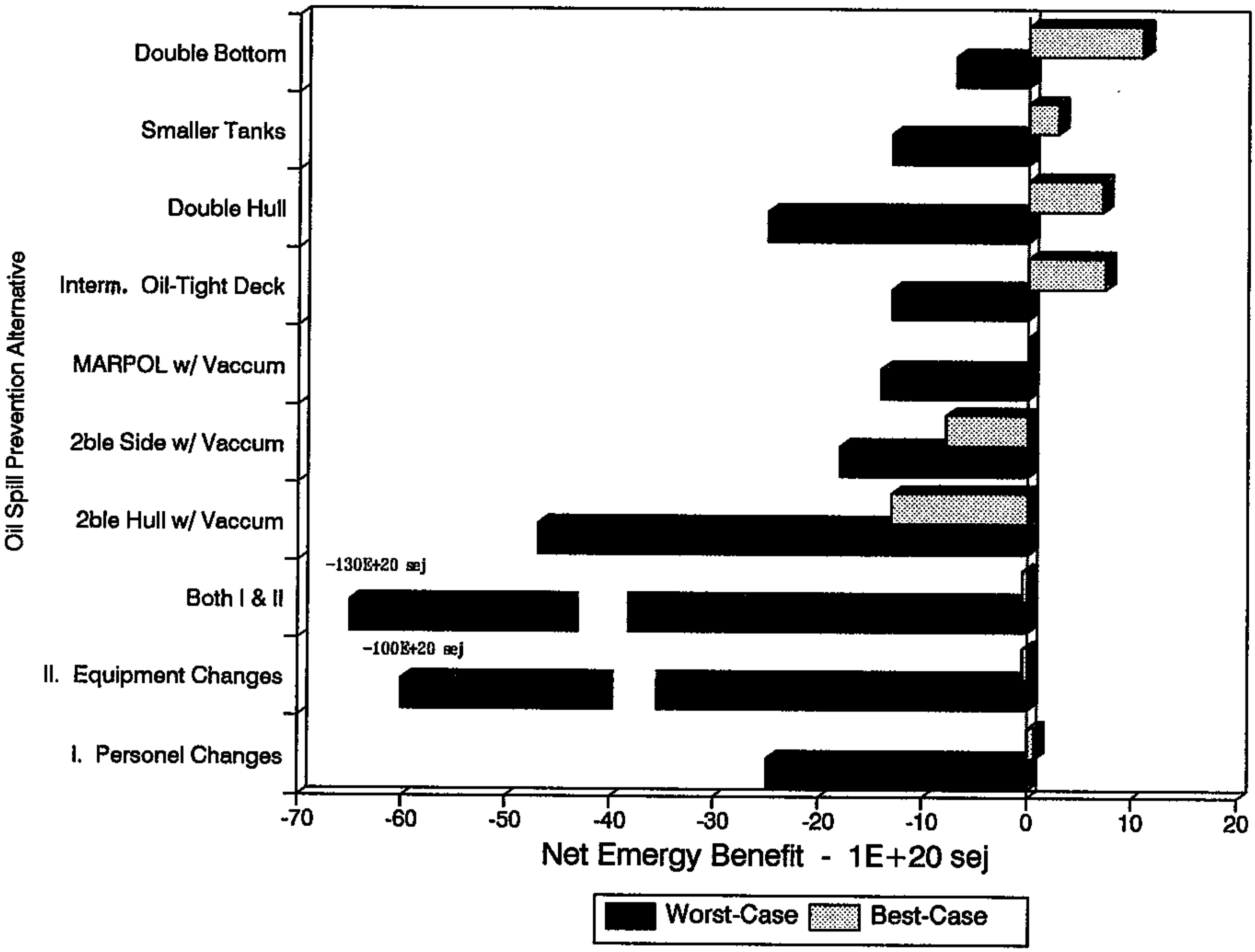


Figure III.7. A comparison of the net emergy benefits of the ten oil spill prevention methods for the U.S. tanker fleet adjusted for an oil spill in the continental U.S. from Table III.10

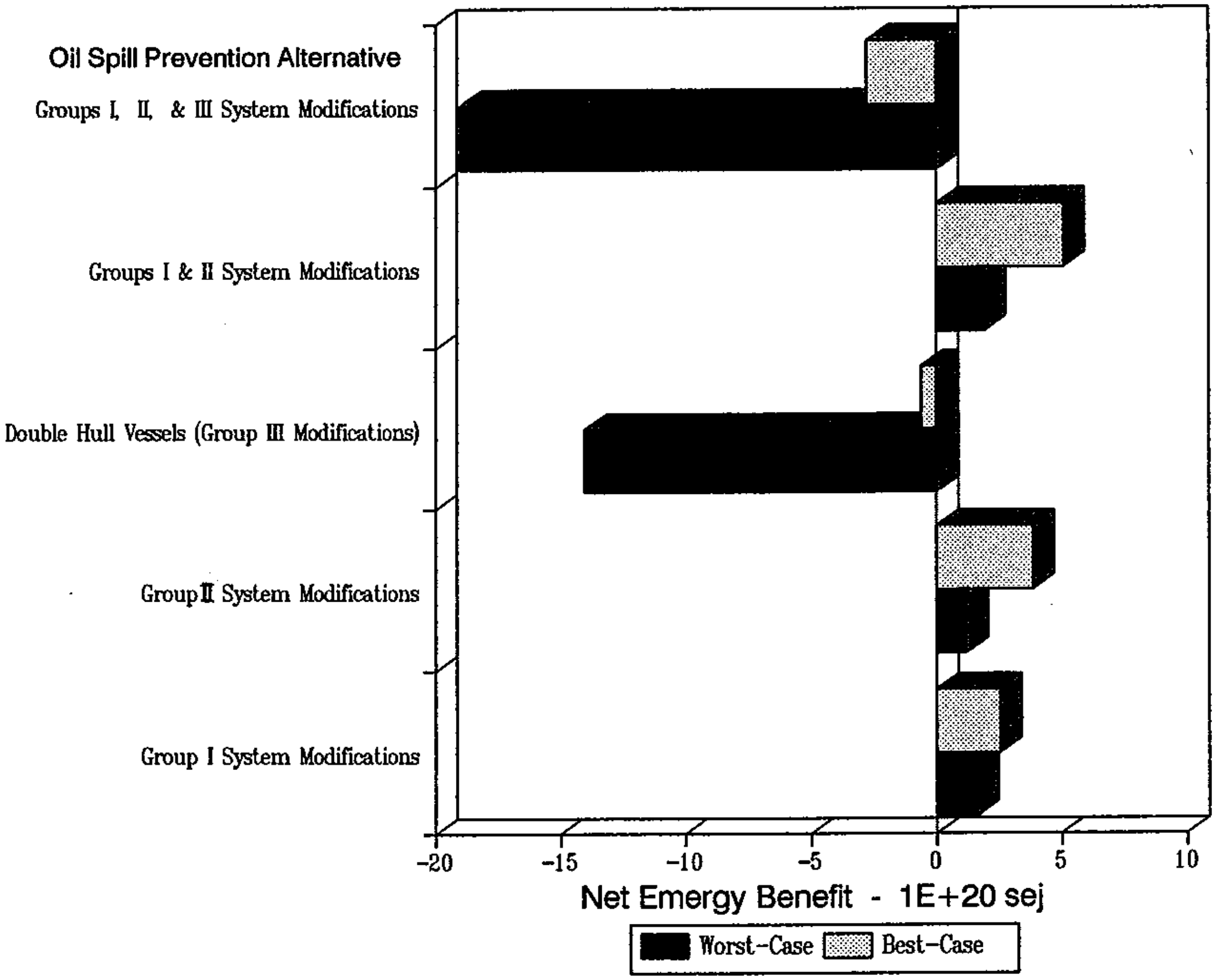


Figure III.8. A comparison of the net emergy benefits of the ten oil spill prevention methods for the Alaskan tanker fleet from Table III.11.

United States Tanker Fleet

Net emergy benefits for the United States tanker fleet are given in Table III.10 and summarized in Figure III.7. The fraction of the emergy investment in prevention alternative implementation that was from steel accounted for approximately half of the total emergy investment in implementation for each of the tanker design alternatives. Human services used directly in, and embodied in materials used in tanker design implementation accounted for the other half. The human service estimates account for most of the range in emergy investment in implementation values. The magnitude of the contiguous 48 states' adjustments to the *Exxon Valdez* losses suggest that the Valdez spill may have resulted in lower losses because of its location. The increased tourism losses and coastal wetland damage occurring if the case study spill took place in the continental U.S. instead of Alaska have a significant effect on the results of the oil spill prevention analysis. These adjusted loss estimates are still not enough to cause any alternative to have both positive best- and positive worst-case net emergy benefits.

The net emergy benefit and necessary human stress loss results were most sensitive to changes in human labor investment in implementation, steel investment in implementation, and spillage prevention estimates. Halving and doubling the investment estimates changed the net emergy benefits by less than 25%. Halving and doubling the emergy-money ratio and steel transformity variables produced the same behavior. Halving and doubling the spillage prevention estimates changed net emergy benefit by less than 10%. Halving and doubling other variables resulted in net emergy benefit changes of less than 5%. None of the halving and doubling trials resulted in additional positive net benefits for any of the alternatives

An analysis of the emergy investment in implementation for each of the individual system modifications within the categories of groups I and II (Appendix E) would likely show some of these individual modifications to have better net emergy benefits than others. These changes would result from the differing investments of labor and materials in each of the individual modifications. It is difficult to anticipate how many of these would be positive without a more detailed analysis. Better net emergy benefits may also be possible for all the prevention alternatives if they were optimally implemented. At some point, each alternative reaches a point of diminishing returns (benefits) for additional investment. If only the individual tankers that can be refitted for the least emergy investment are refitted, and only the most successful, lowest emergy investment system modifications are made, the net emergy benefits should be higher. For example, establishing tanker exclusion zones only in critical areas with high ecological value, may yield a positive net emergy benefit. However, sweeping legislative mandates that require specific designs of all tankers and specific system modifications in all ports and on all shipping routes will probably produce negative net emergy benefits similar to those given in Table III.10.

Though some inaccuracy was introduced by using dollar costs as a measure of human labor in each alternative, this method still appears to be the best way of integrating the human services embodied in the hierarchy of agricultural, extraction, manufacturing, distribution, and other processes that support the people implementing the prevention alternatives (given the specific lack of data for these processes). Other inaccuracies may have resulted from applying simple percentage estimates of steel use in the tanker design alternatives. Though these inaccuracies may be significant for any one year, the world tanker fleet is extremely heterogeneous (National Research Council, 1991), and as a result the tanker fleet calling at U.S. ports varies both in size and design composition from year to year. This variability seems large enough to justify the use of the percentage estimates discussed above.

Alaskan Tanker Fleet

The net emergy benefits for group I, group II, and concurrent groups I and II system modifications for the Alaskan fleet were all positive (Table III.11). The net emergy benefits for double hulling the Alaskan fleet (group III modifications) were all negative (Table III.11). As with the U.S. tanker fleet, approximately half the emergy investment in implementation for tanker modifications was from steel. Also similar to the U.S. fleet, the net emergy benefits were most sensitive to changes in the estimates for the human labor investment in implementation and for steel investment in implementation (Appendix E). Halving and doubling the investment estimates, emergy-money ratios, and steel transformity values changed the net emergy benefits by a little less than 25%. Halving and doubling spillage estimates changes net emergy values by less than 10%. All other halving and doubling trials resulted in net emergy benefits by less than 5%.

Oil Spill Clean Up

While quantitative data on the relationship of the investment in, and benefits from, shoreline cleaning are lacking, there appear to be several emergy thresholds related to the intensity of shoreline cleaning. The first series of thresholds are those points at which the total emergy invested in shoreline cleaning will produce a larger net emergy benefit if allocated to another process, for instance, if energy and money that were to be used for cleaning were allocated to purchase and preserve local forests from damaging exploitation. There also appears to be a point at which emergy invested in cleaning produces no additional ecological benefit, followed by a situation in which additional cleaning emergy produces additional ecological damage. This behavior has been documented in monetary terms by Dunford et al. (1991). But at a larger scale, cleaning that produces some additional, local ecological damage may lower or mitigate total losses in the larger system. For example, the closure of Prince William Sound and Gulf of Alaska fisheries following the *Exxon Valdez* oil spill was mandated by government regulations whenever fishing gear was fouled with oil. Under these circumstances, additional cleaning may be justified, since the losses resulting from closure of the fishery may be greater than the costs of shoreline cleaning.

Conclusions

Variability in loss estimates may be enough to cause additional prevention methods to have positive best-case net benefits. The data and sensitivity analyses, however, suggest that the worst-case net benefits will remain negative. Consequently, each prevention method is a break-even proposal with no substantial increased net emergy yield when implemented at the national level. Odum (1992) reports a 6 to 1 emergy yield ratio for current, economically successful processes in developed countries. Though coastal areas are of great ecologic and economic importance, it is apparent that analyses of other natural resource management strategies should be conducted before implementing the alternative oil spill prevention methods discussed here. The MARPOL tanker - already the product of a pollution control treaty - is currently designed to prevent oil spillage (National Research Council, 1991). MARPOL tankers may be currently preventing oil spills in the most optimal fashion for some transportation routes. However, the results of the U.S. and Alaskan tanker fleet analyses suggest that management strategies employing the lowest investment prevention methods in the highest yielding situations will produce the largest positive net emergy benefits, while sweeping, industry and nation-wide regulations would appear to have very low or negative benefits.

Two specific series of additional analyses are required to generate the information needed to identify the best oil spill prevention alternatives. The first of these is detailed analyses of the equipment intensive and labor intensive prevention options assembled in the Group I and Group II prevention categories (Appendix E). These analyses require data on the resource investment required for implementation and operation and predictions for spillage prevention for each prevention technology. The second series of analyses is required for tank vessel routes. In order to calculate the effect of selective implementation of tanker design changes for regions with particularly high value or sensitive coastal resources, the number of tankers that pass through these areas and amount of time they are in the areas must be estimated. These two series of analyses can then be combined with the results of this study to identify the specific conditions under which oil spill prevention technologies can be implemented with the highest net emergy benefits.

Information Frenzy and the Valdez Oil Spill Disaster

Currently, advances in global information processing, particularly in the television industry, are causing the people of the world to increasingly share information. The sharing of information joins people and makes certain groups immensely influential. As the result of the numerous energy transformations required to develop, copy, distribute, and maintain shared information in large human populations, shared information has a high emergy value. Following trial-and-error selection, which sorts useful information from noise or useless information, the influence of useful information may be proportional to its emergy value. As the people of the world become more and more conscious of the inherent symbiosis of humanity and nature, information related to the environment is emerging as a major component of global sharing, however, both the system of global information and of environmental management are new, rapidly changing, and little understood. The extraordinary "information storm" that followed the *T/V Exxon Valdez* oil spill in Prince William Sound, raised questions about the relationship between environmental policy and information. An emergy analysis was conducted for the spill, its effects, the information storm that developed, and the responses that followed. Innovations (detailed in the following pages) were developed to evaluate the emergy of information in order to consider the way amplification of disaster images amplified the response to the Valdez spill and diverted global resources.

Emergy of Television in the United States

Using data assembled by Morton (1991), the inputs used by television were evaluated as items 1 through 4 in Table III.12. Transmission inputs included the electricity, assets (buildings and equipment), and the services of the people of the industry. Items 5 through 8 evaluated the television reception, its electricity, equipment and especially the audience of people watching the received television signals. The audience's time engaged in television interaction was evaluated as the time of watching multiplied by their metabolism and by the transformity of their level of education. This involves the hypothesis that the delivery of information to a person can be evaluated by using the emergy per unit energy accumulated with their education and experience (Odum, 1988). An energy systems diagram of the relationships evaluated is shown in Figure III.9.

Previous evaluations provided an estimate of the whole emergy use of the United States. People are at the top of the energy hierarchy of the nation, and their information processing is at the top of human activity (Odum, 1988). Thus in an aggregated overview, the information flow in the whole country depends both directly and indirectly on the entire national emergy budget. The hours of human interaction with television each day were used to assign the fraction (7/24) of the national emergy supporting the system that culminates in information. These approximations were used to evaluate the magnitude of emergy in the television broadcast of Valdez oil spill news (Table III.13).

Damage and its Extraction and Transmission as Information

Figure III.10 shows the type of images shown on television in the aftermath of the Valdez spill. Evaluations of the Valdez oil spill (Table III.9; Woithe, 1992) included the oil loss, the damages to sea otters, sea birds, shore life, fisheries, and other marine organisms. As shown in Figure III.11 (from left to right) the images of damage are extracted by television journalists, and successively transmitted, then received by television watchers, causing a group response that resulted in responses by Exxon Corporation and government agencies. At each step, more emergy comes in, further contributing to the emergy value of the information and actions. The evaluations are given in Table III.13 and summarized in Figure III.11.

The emergy of the damage phenomenon given in Table III.13 is based upon the assumption that the journalistic reporting was an honest and successful effort to capture the magnitude of the disaster. The emergy of the damage was taken as the emergy required to collect, sort, and assemble the damage information (item 2). Line 4 gives the emergy of copying and transmitting the information, based on

Table III.12. Line 5 is the emergy of operating television receivers. Line 6 includes the emergy of people watching television broadcasts for an assumed total of 30 minutes per person over the course of the many weeks of oil spill news coverage. The cumulative total emergy (equivalent to 490 million macroeconomic dollars) in developing the shared oil spill information among the people of a nation, was several times larger than the spill's environmental damage (16 to 160 million macroeconomic dollars).

Amplified Oil Spill Response

As indicated by item 8 of Table III.13, the response by Exxon and government agencies was approximately 3 billion dollars, much of it paid into the small Alaskan economy area as part of oil spill cleanup. Part of the money bought fuels, goods, and services within Alaska where the emergy per dollar is large and part was used to purchase goods and services from the other states where the emergy per dollar was small. The magnitude of this payment expressed in emergy terms was huge compared to the spill itself (Table III.9). A shared information emergy of 490 million macroeconomic dollars had elicited a response 2 to 20 times larger than the environmental damage caused by the spill. Questions raised by this response include: 1.) Should we expect emergy response to be in proportion to emergy used in developing the shared information? 2.) Would this much amplification have occurred if people were not already environmentally sensitized with earlier information inputs?

The many assumptions in this calculation make the results very approximate, but the results do show the large magnitude of information involved, the way information sharing cascades, and the information needed for this kind of calculation to be improved in the future.

A "Storm" From Emergy Dumping

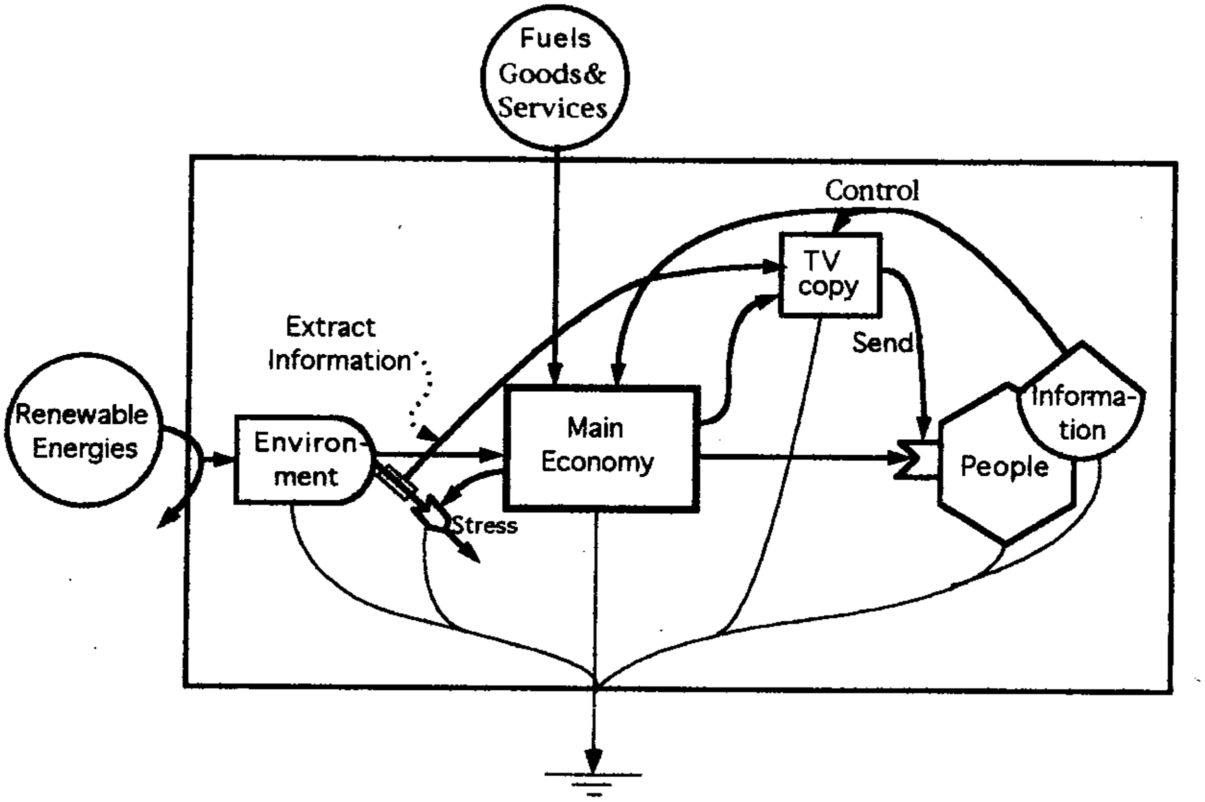
The surge of local buying power, followed by goods, services, and fuels rushing into the oil spill region, was equivalent to the storms of disasters such as hurricanes, earthquakes, volcanic activity, and wars. All of these events develop secondary storms of destruction when emergy is released suddenly. The dumping of emergy into the Valdez spill region produced a social storm. A few items of oil spill disruption that comprised this storm are evaluated in Table III.14

Disruptions and spill damage included the loss of normal livelihood of fishing and fish processing, extra people coming in to do cleanup, and added costs of services like police, counseling, and garbage collection. While the concentration was on the cleanup of the spill and the rescue of the wildlife, much was happening to the people. Similar to certain areas impacted by Hurricanes Hugo (South Carolina and the Caribbean (1989)) and Andrew (Florida and Louisiana (1992)), Alaska experienced an economic boom, bigger than anything since the building of the trans-Alaskan pipeline. As was also the case following the two hurricanes, both direct, actual damage, and damaged public perceptions completely shut down some local industries. The Cordova and Kodiak herring fisheries, which earned $14 million in 1988, were closed in 1989. The fish processing industry that depended on these catches was also out of business. (N.R.T., 1989). In Prince William Sound and Kodiak, 8 million salmon of the 14 million projected salmon were caught (Townsend & Heneman, 1989). The price of salmon fell by half. This was partially the result of consumer suspicion of possible impurities because of the spill. (Alaska Oil Spill Reporter, 1989). As in the case of the two hurricanes, there was also a boom in short-term employment. The unemployment rate in the state dropped to 7.7%, and to 5.5% in the Valdez-Cordova area. This was about a 1% drop. It is estimated that half of the decrease was due to the spill. (Alaska Oil Spill Reporter, 1989). This effect was so great that seasonal jobs outside of the spill region went unfilled, and state-wide labor shortages in retail and service businesses developed.

The effect on native villages was economic disruption; from an economy based on subsistence fishing, they became one of day laborer for the cleanup. More cash was available, but it was accompanied by a stressful change in customary lifestyle. There was no harvest of some fish like herring and salmon, and there was worry that other subsistence foodstocks were oil-tainted. Others were more concerned with their livelihoods and routines. Children were upset, traffic increased, and there was more overtime work.

Table III.12. Emergy analysis of the U.S. television industry.

Note	Item	Solar Emergy Flux 1E+22 sej/y
1	Television Transmission:	
2	Electricity	20.3
3	Assets Cost	0.28
4	People	22.1
	Total to Extract, Copy and Transmit	42.7
5	Television Reception, 1.62E+08 Sets:	
6	Electricity	4.5
7	Assets Cost	9.5
	Total to Receive	14.0
8	People Watching	263
9	Annual Emergy Support for the United States	900
10	Reception (Emergy per Television Set per year)	7.1E+14 sej/set-y



Television processing of environmental stress information.

Figure III.9. An emergy systems diagram of the processing of environmental stress information by the U.S. television industry.

Table III.13. Emergy aspects of the *Exxon Valdez* oil spill based on one hour television transmission and 0.5 hour reception per person.

	Process	E20 sej	Macroeconomic Value[a] million m$
1	Emergy of phenomenon (oil spill)	4.0	250.
2	Emergy of damage	2.3	140.
3	Emergy of the assembled information about that damage	2.3	140.
4	Emergy of copying and transmitting that information	0.49	31.
5	Emergy of receiving	0.55	34.
6	Emergy of watching and sharing, U.S.A.	5.1	320.
7	Cumulative total	7.9490	
8	Response by Exxon and Government	132.	8250.
9	Oil flow interrupted	47.7	2981.

[a] Expressed in 1989 U.S. macroeconomic dollars using an emergy-money ratio of 1.6 E12 sej/$ from Odum (1992)

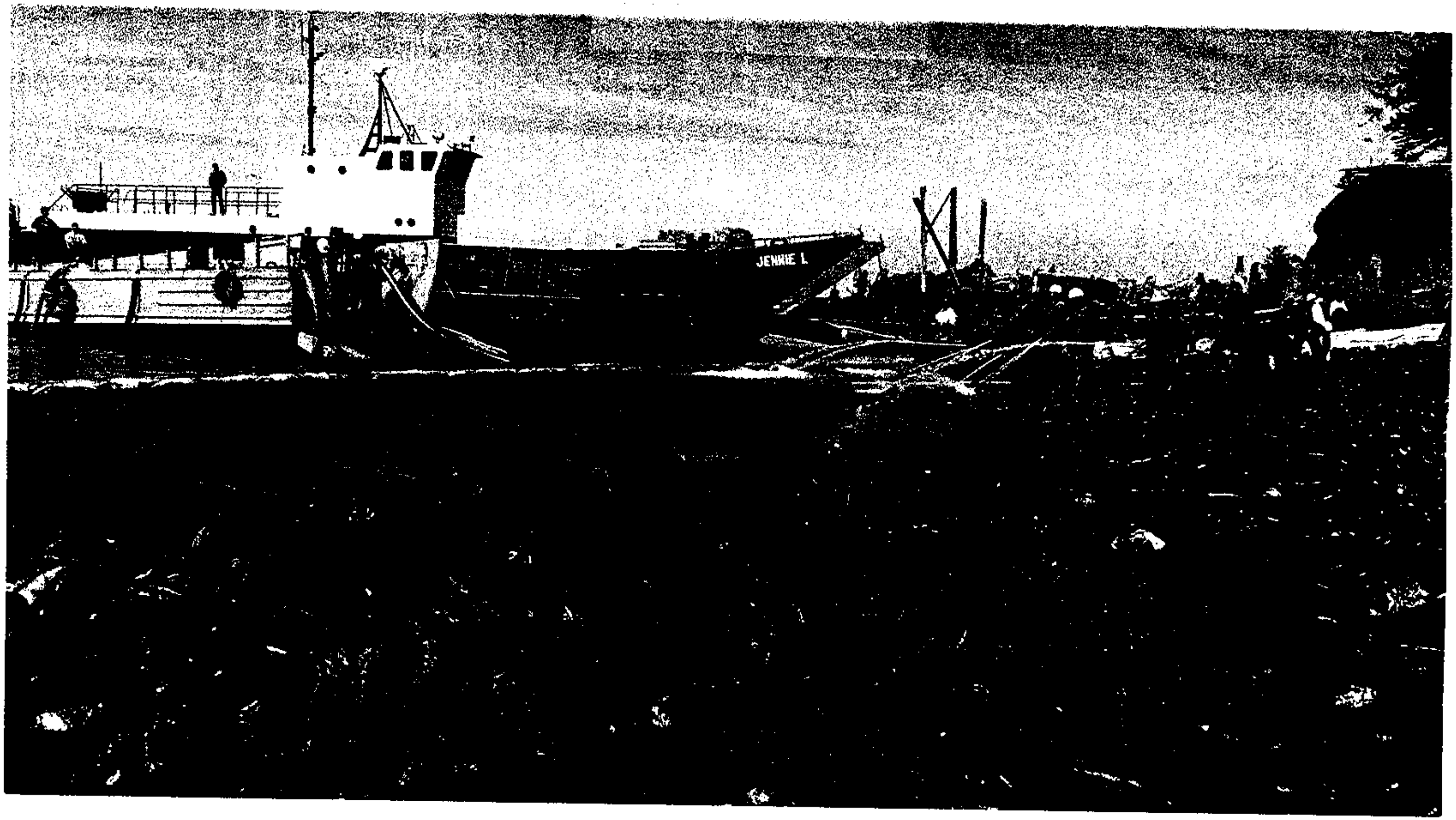


Figure III.10. An example of oil spill images broadcast by television in the aftermath of the *Exxon Valdez* oil spill (Photograph: Alaska Sea Grant Program, Fairbanks, AK).

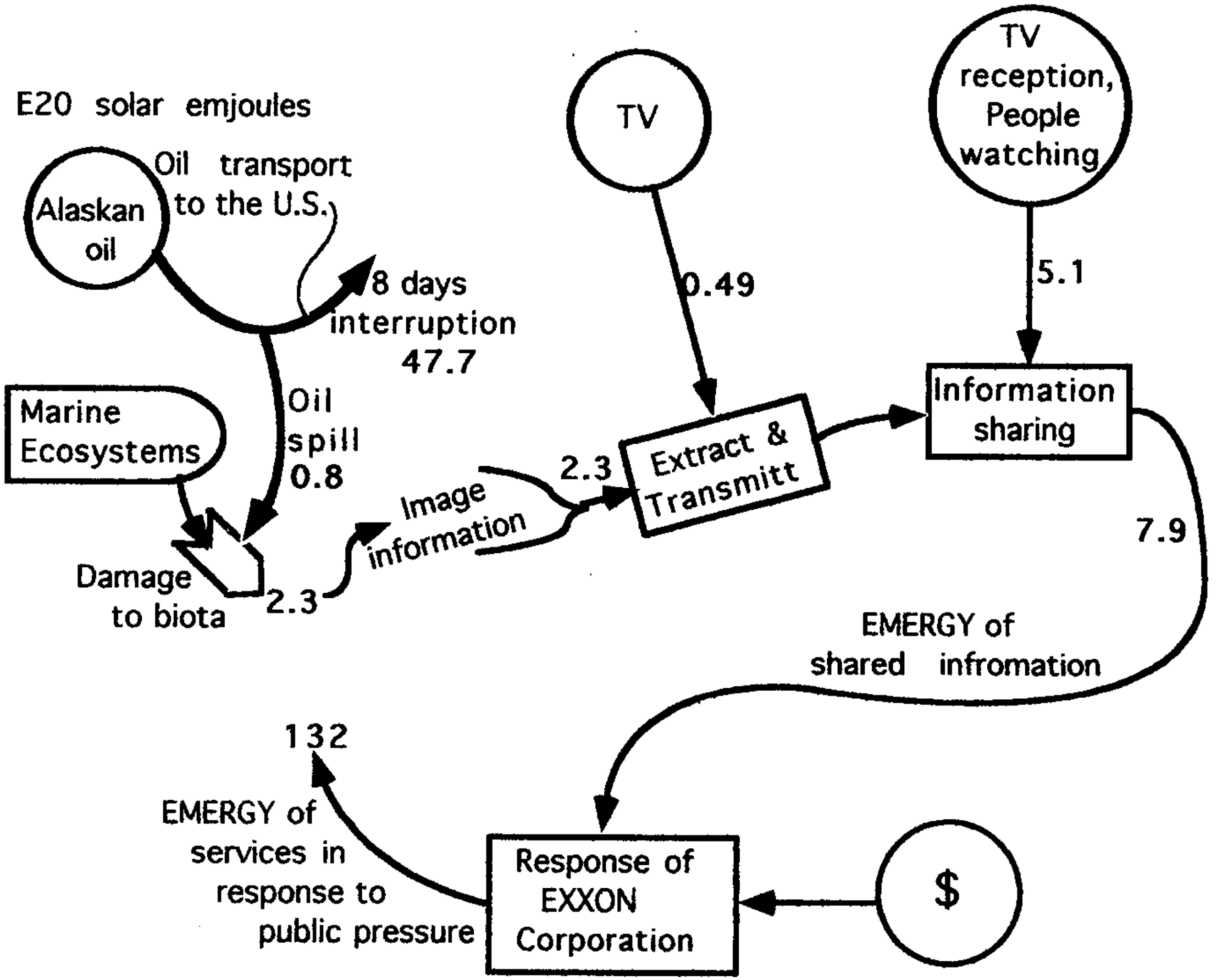


Figure III.11. Solar emergy inputs in the transformations that convert environmental damage to shared information and human group response.

Table III.14. Emergy analysis of human disturbance from the *Exxon Valdez* oil spill.

	Item	Value	Transformity	Emergy value E20 sej
1.	Unemployment decrease	31 people	8.4E+17 sej/person	0.26
2.	Increase in alcohol- and drug-related crime	$4.0E7	10E+12 sej/$	4.0
3.	Population increase	1045 people	8.4E+17 sej/person	8.8
4.	State assistance to communities	$1.3 E6	10E+12 sej/$	0.13
5.	Increase in money earned	$130 E6	10E+12 sej/$	13.0
6.	Evaluations of crime, bankruptcy, and stress are incomplete			

The population of the city of Valdez grew to double the 3,000 permanent population. Arrests rose by 500%, double those at the time of the pipeline population boom of 10,000 people. The increased crimes included domestic violence, depression, fights, divorces, alcoholism and drug use (Townsend & Heneman, 1989). The Valdez counseling center caseload was three times the normal size; and 1/2 the residents of Valdez and 2/3 the residents of Cordova had "significant post-traumatic stress."

Overview

The effect of the emergy amplification of disaster images from the *Exxon Valdez* oil spill may have benefited general, global, environmental progress, but the ill conceived responses to the spill were disastrous. From both national and world points of view, a very large amount of emergy was diverted from normal productive processes and dumped to make a second useless frenzy at the impacted site (the first frenzy being the oil spill). The closing of the trans-Alaskan oil pipeline for eight days had a larger impact than the environmental damage of the oil spill (Table III.13). The pipeline closing reduced the economic production of the western United States, and even affected the price of oil. Oil not used was production not made.

Although Alaska experienced a small scale economic boom, the state's long range processes of general emergy production and use were disrupted. The payments by oil companies after the spill were not so different from the state's annual payments to each Alaskan citizen (approximately $800 in the year of the Valdez spill) from the Permanent Fund (a fund established and supported by mineral lease rentals and royalties). Emergy analysis showed these payments to be tiny compared to the potential in the oil stream moving out of the state (Table III.1). The emergy analysis of the whole state shows it to have the characteristics of under-developed countries (Table III.5). Because of policies forced on Alaska by the U.S. and world economic systems, the state exports its resources like oil, timber, and fish. Our analysis of the fish sold to Japan, shows a net emergy benefit to Japan of more than 10 to 1 (M.T. Brown, Unpublished Data). An analysis of the trans-Alaskan Pipeline as a whole by M.T. Brown shows the net export of emergy to the mainland to be more than 9 times the emergy received by Alaska. If these resources were kept and used at home, the economy would be stimulated to 9 to 10 times the present pattern. Prices would eventually fall, standards of living would rise, and total productivity and consumption would increase. Sweden, with the same kind of climate and environmental resources, keeps its resources and supports a prosperous, balanced economy; while Alaska strips and sells its emergy with only the exporters profiting.

The attitudes that prevail in Alaska, holding that economic benefit comes from sale rather than use of resources, are frontier oriented and have been deeply ingrained since pioneer times. These attitudes readily play into the hands of other economies that want the resources. To be fair, without emergy analysis, the buyers in these other economies think they have given fair value for the resources they purchase. In Alaska, the misuse of information in education perpetuates attitudes that cause a bountiful state to operate at a fraction of its potential. The oil spill and other issues of conservation have galvanized environmental concerns about Alaska. Without emergy perspectives, however, the information these concerns are based upon is unbalanced and diverts people from the real need to develop a better balance of humanity and nature in Alaska in which symbiosis and sustainability replace strip and sell.

Better Uses of Global Storms of Shared Information

The frenzy of media attention following the Valdez oil spill reached a world-wide information threshold about the environment that set public responses in motion and caused corporate funds to be spent in dubious and destructive measures. The emergy analyses in this report suggest the responses were out of proportion to the size of the spill. Devastating as the oil was to the coast of Alaska and its people, the response was on a world scale, as if the spill had occurred in every television viewer's home state or district.

In centuries past, before there was a world-wide sharing of information, mechanisms of social psychology produced responses to disasters more or less in proportion to the number of people whose lives were affected. Journalists and politicians followed public behavior and opinion; behavior and opinion that was mostly oriented to the small scale of people's lives. Before the television era, with news arriving in muted form late or not at all, people at a distance were not drawn into the emotional responses of people directly affected by a disaster.

By 1991, with worldwide, instant sharing of information through television images, the impacts of disastrous phenomena are brought, as if they were local impacts, to millions of people far from the site of the disaster. In the Valdez example, the information was amplified by the number of television viewers so that the response was as if the spill was everywhere. In other words, the impacts of a moderate-scale disaster were amplified so vastly that people responded at a very large scale, too large a scale for the number of people directly affected. This public response resulted in a reaction by corporate and government leaders (accustomed to responding in proportion to the public outcry) out of proportion to the disaster. This mis-proportioned reaction was largely the result of the amplification of the Valdez disaster information by world television.

With the current deluge of information reaching people, repetition may elicit the social psychology of large-group response. The repetitive images of a developing crisis such as a spreading oil spill can amplify the information in the images such that disaster information and its emotional impact are shared and the enormous power of unified group response is released. In the Valdez disaster, people were already sensitized by years of bad environmental news. The Valdez disaster became a catalyst for group reaction to all environmental destruction.

The sharing of information increases the information's emergy and transformity and, therefore, the impact the information is capable of generating. Thus, transformity, as a general energy scaling factor, may be used to indicate the appropriate responses to environmental problems. These indicated appropriate responses might then be joined with the repetitive disaster images to produce actual public responses that are beneficial to both the impacted ecosystems and human society. In the Valdez oil spill, the appropriate response for people of Alaska was amplified into a world-wide response. It may be that social group response occurs in proportion to the number of people absorbing the information. The emergy of the information shared is proportional to the number of people sharing. The amount of information received depends on the amount of television transmission and the number of people watching the transmissions.

In the Valdez phenomenon, we were able to compare the emergy of the disaster with that of the shared information and the monetary responses. Our emergy evaluation showed the total response was much larger than the direct impact, but the amplification system may have been serving the evolving system of humanity by causing humanity to develop more global environmental responsibility. The government, legal, and corporate response of diverting billion dollar levels of emergy from their normal, productive processes, into the local disaster area without anything to accomplish, was nationally wasteful. Worst of all, by dumping in emergy without a useful task for it to perform, a secondary disaster was generated locally.

Energy cannot be released without doing work. In the absence of arrangements for useful work, dumping energy generates temporary systems of turbulent frenzy. The surge of money into the small area of the oil spill region had a similar effect, producing a secondary turbulence in the social structure of a pluralistic population that wrenched people from their previous roles and their relationships with the natural lands and waters.

The Valdez incident showed that human society has not yet learned how to put its responses on the appropriate scale for the phenomenon of interest. In fact, people in advertising, sports, politics, entertainment, and even conservation, work very hard to do the opposite. They work to make something of small scale cause a large-scale response for the benefit of their enterprise. Perhaps the Valdez example can be used as a symbol to show how to make appropriate responses. Once society recognizes that appropriate and inappropriate responses to disasters can be determined and (after the main classes of disaster are evaluated) guidelines for public policy can be set out to help prevent inappropriate, frenzied waste.

Eventually, as the global self-organization process proceeds in the relationship of society and resources, inappropriate responses may be displaced by responses with more common sense. Emergy analysis is a way to global common sense. In the Valdez example, the appropriate response after the frenzied information sharing generated a group demand for global action toward better environmental harmony and toward constraints on unfettered economic exploitation. Perhaps this action is already in progress and the opportunity is now available for global leadership by organizations like The Cousteau Society.

Net Emergy Analysis of Alaskan North Slope Oil

The area north of the Brooks Range along the coast of the arctic sea in the northern most part of Alaska is often referred to as the North Slope. Suggested to be one of the last great oil bearing areas in North America, to date, reserves of the main oil field at Prudhoe Bay have been estimated as 11 to 12 billion barrels (ADNR, 1990). In addition to the "proven reserves" the industry suggests that using what is termed enhanced recovery, an additional 11 billion barrels may be extracted from the north slope field. At current pumping rates (about 2 million barrels a day), north slope oil accounts for almost 25% of the energy needs of the U.S. economy.

Oil from the north slope is transported overland to the southern coast of Alaska through an 800 mile pipeline that terminates at the coastal town of Valdez, Alaska (Figure I.1). A large storage and transfer station is located at Valdez, where the oil is transferred to tankers for shipment to the "lower forty eight" states. Prior to construction in 1975, the pipeline and related facilities were estimated to cost $2.5 billion, yet by completion in 1978, the construction costs were over nine billion dollars. Useful life of the project was estimated at the time of completion as 30 years.

A systems diagram of the oil delivery system is shown in Figure III.12. Crude oil is extracted and shipped by pipeline to Valdez where it is loaded on tankers to be transported to the west coast of the U.S. The main external inputs to the delivery system are fuels, goods (steel) and services (human labor). State and Federal taxes are shown as emergy costs, and assumed to represent services consumed as part of the oil delivery system. Transportation costs are the costs of shipment by tanker to the west coast of the U.S. Environmental impacts are shown in two ways, direct stress on the ecological systems from production platforms, staging areas, pipeline roads etc. that results from clearing, and the direct impact of the oil spill. Social impacts of the pipeline construction and oil spill are also shown in the diagram.

Net Emergy Evaluation

Table III.15 and Figure III.13 summarize the emergy yield of crude oil for known reserves on the north slope and various costs associated with its extraction and delivery to the west coast of the United States. The evaluation assumes that the reserves and pipeline will last 30 years. The largest costs in emergy terms are services associated with production of the well fields, operation and maintenance, and transportation. Services used to construct the pipeline and terminal facilities amount to about 7% of total costs, while the emergy of steel used in the pipeline and terminal was only about 3% of the total costs. The services represented by State and Federal taxes are about 26% of total costs. The Exxon Valdez oil spill represented only about 2% of total costs. Direct environmental impacts are insignificant when compared to the other costs in Table III.15. The calculation of environmental impacts assumed impacted areas to be the areas that were directly influenced by roadways, pipelines, drilling platforms, and terminal facilities. While there was much discussion in the literature concerning potential secondary impacts, no estimates of the magnitude of secondary impacts were found.

The net emergy yield ratio for north slope oil (not including reserves in the Arctic National Wildlife Refuge) is about 13 to 1. Considering infrastructure requirements, adverse conditions, and distance to markets the yield ratio is relatively high. Not factored into the analysis are additional repairs to the pipeline in the coming years, or the effects of additional oil spills.

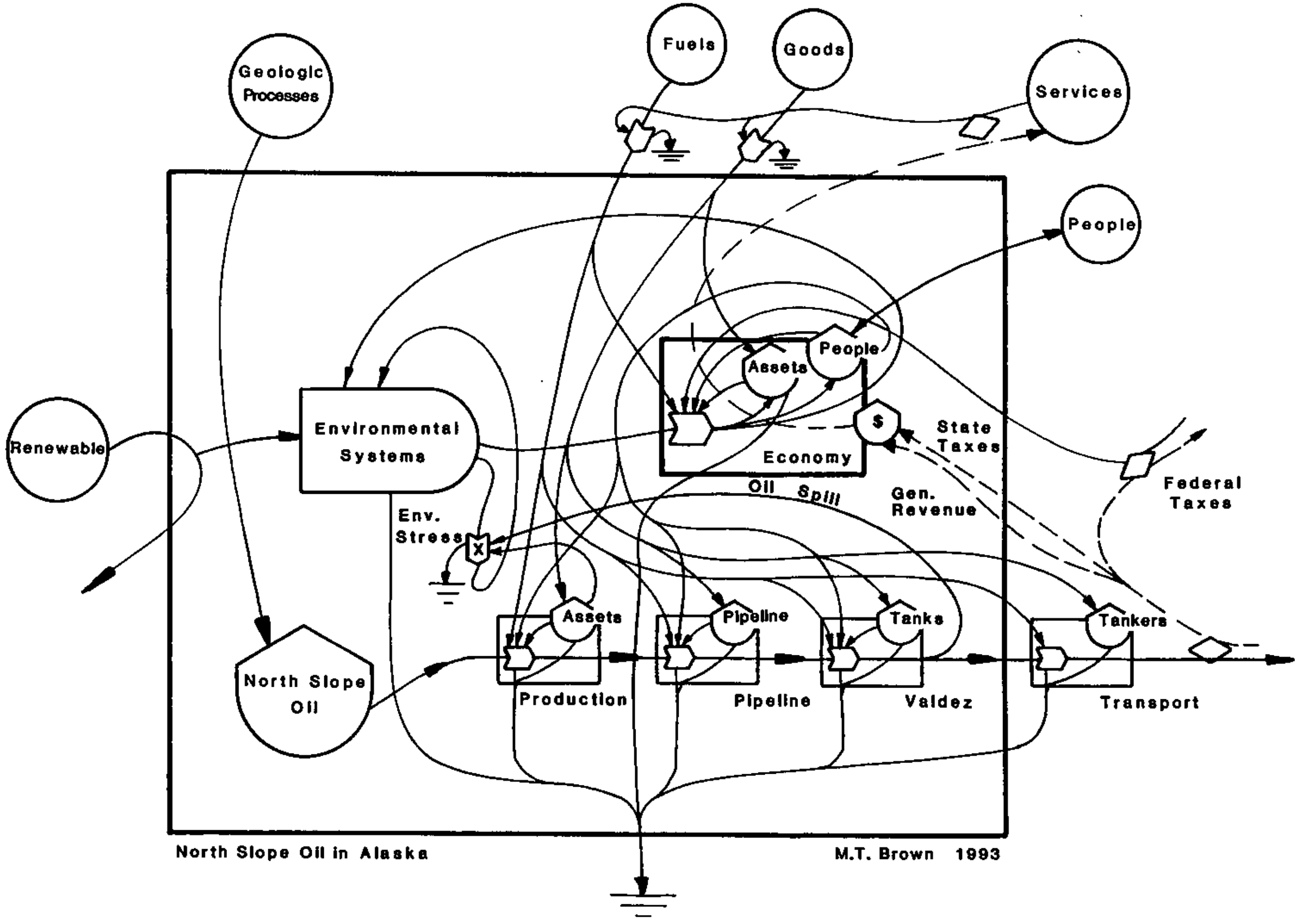
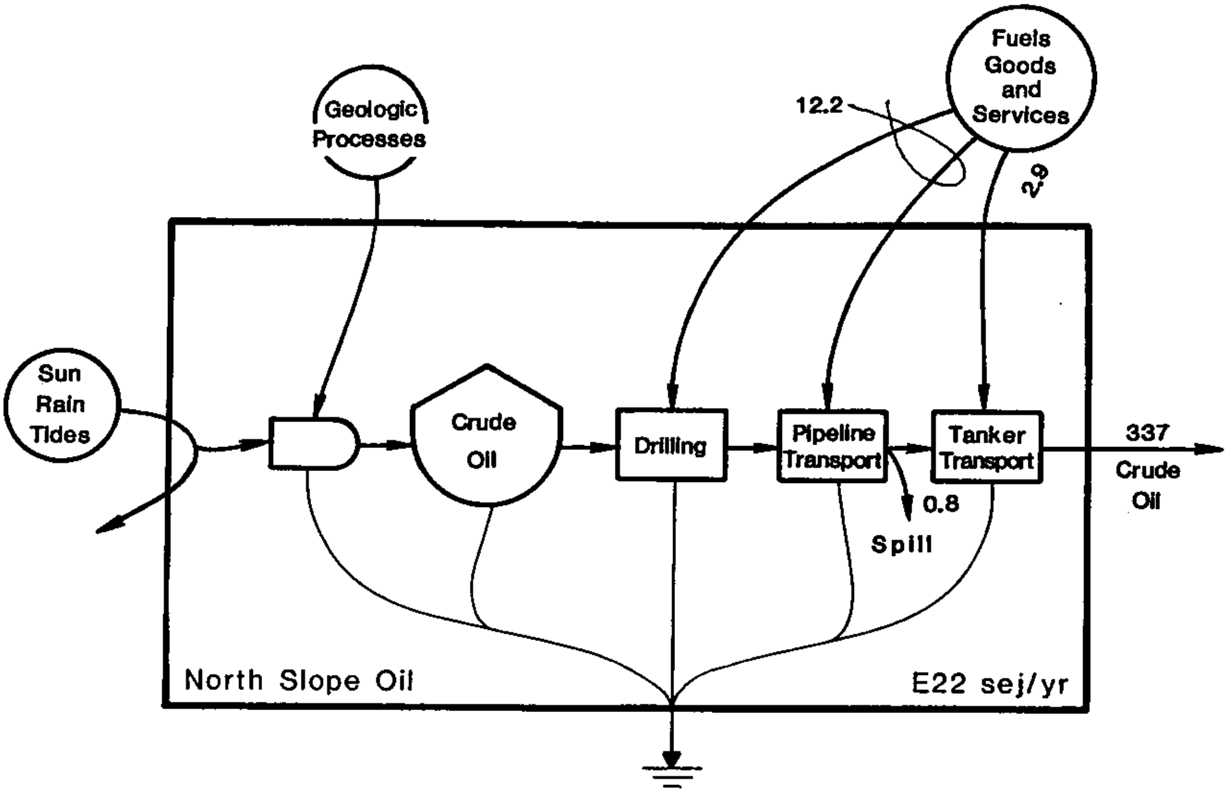


Figure III.12. Energy systems diagram of the economy of Alaska and oil delivery system. Oil is extracted from in the production process, shipped via pipeline, stored at valdez and finally shipped via tanker to the lower 48 states. Revenue to the State of Alaska from the sale of oil is divided into two categories: (1) general revenue in the form of purchases of goods and labor payments, and (2) state taxes.

Table III.15. Emergy analysis of North Slope oil (assuming a 30-year pipeline life).

Note	Item	Units		Transformity (sej/unit)	Emergy (1E+21 sej)	Emdollars (E9 $1988)
1	Total oil flow	6.4E+19	J	53000	3400	2100
	Costs					
2	Envir. production	8.0E+15	sej	1	0.00	0.0
3	Steel	4.6E+06	ton	1.8E+15	8.2	5.1
	Services					
4	Pipeline & Facilities	2.5E+09	$	6.9E+12	17	11
5	Production costs	4.7E+10	$	2.0E+12	94	598
6	O & M costs	3.9E+09	$	6.9E+12	27	17
7	Repairs	1.5E+09	$	2.0E+12	3.0	1.9
8	State taxes	2.3E+10	$	2.0E+12	45	28
9	Federal taxes	1.1E+10	$	2.0E+12	22	14
10	Transportation	4.2E+09	$	6.9E+12	29	18
11	Valdez oil spill				7.7	4.8
	Total Costs				250	160

Net Emergy Yield Ratio = (3400 / 250) = 13



Net Emergy of North Slope Oil=337/24.5=13.3/1

Figure III.13. Summary diagram of net emergy of north slope oil.

IV. SUMMARY AND CONCLUSIONS

Using techniques of emergy analysis, this study evaluated both economic and environmental impacts of the *Exxon Valdez* oil spill. The analysis quantified, on a common basis, the environmental components of the region that were impacted and the economic costs associated with clean up, lost fishery production, and social disruption. In addition, several oil spill prevention technologies were analyzed and related to the environmental losses they would prevent should they be implemented. Emergy benefit-cost ratios were calculated for proposed oil spill prevention technologies where the benefits were the damage that would not be incurred should the technology be implemented.

The spill, the ensuing cleanup, and the various alternatives that were proposed to prevent oil spills of its magnitude offered a unique opportunity to develop perspectives for the public policy arena that might shed some light on the complex questions surrounding environmental disasters and their prevention.

Natural Resource and Economic Losses of the *Exxon Valdez* Oil Spill

The costs of the *Exxon Valdez* oil spill can be grouped into two areas: 1.) natural resource losses (flora and fauna killed or impaired), 2.) direct economic losses (lost fishing revenue and the costs of cleanup). By far the greatest losses were associated with cleanup. Cleanup costs were between 56% and 80.6% of the total losses resulting from the spill. Losses resulting from death and impairment of flora and fauna amounted to between 4.6% and 33.9%. The unusually large spread in the estimates of natural resource losses was due to uncertainty concerning the actual losses in some compartments of the marine food chain, especially phytoplankton and zooplankton. Because of this uncertainty, we felt that it was better to report losses as a range rather than as an average between the two numbers. It is interesting to note that more fuel was consumed as part of the cleanup efforts than was spilled. While the environmental deterioration that may have resulted from the consumption of the fuels is probably less than oil spilled directly in the marine environment, none-the-less, there were some additional impacts associated with the use of this quantity of fuel.

An attempt was made to evaluate the social disruption that resulted from the spill and cleanup efforts by assuming that the normal productivity of the population in the spill region was disrupted for a period of two years. When analyzed in this manner, the social disruption was equal in magnitude to the fuels consumed in cleanup, and exceeded the natural resource damages in the lowest total loss estimate. A larger population was probably affected by the spill than just the population of the region; estimates of this disruption of normal activity were difficult to determine.

All told, the oil spill accounted for about 1% of the annual emergy budget of the State of Alaska, and between 87% and 130% of the annual emergy budget of the region from Prince William Sound to Kodiak Island. By far, the biggest impacts were experienced in Prince William Sound itself, where the spill represented between 330% to 490% of its total annual emergy budget. The spill had disastrous effects within these two smaller regions, judged by the relative proportion of their annual emergy budgets, yet probably had minor impact to the state's economy as a whole. In fact, when the consequences of spending $2.5 billion on the cleanup are considered at the scale of the State, the spill probably stimulated the economy.

Oil Spill Prevention Alternatives

There is no question that oil spills are costly, both in terms of their damages to natural resources and their economic costs. The total costs, when expressed in macro-economic dollars were between $3.3 and $4.8 billion. The majority of total losses associated with the *Exxon Valdez* oil spill were related to the economic costs of cleanup (about 90%). Thus, preventing oil spills before they happen would seem to make good economic and environmental sense. Yet, if the costs of prevention are greater than the losses incurred, the net overall effect is to reduce productivity and spend resources needlessly. In the wake of the

Exxon Valdez oil spill, there was a call for better protection, more stringent rules governing oil shipment, and modifications to tankers to reduce the likelihood of spills of its magnitude occurring again. To shed some light on the policy debate that ensued, we analyzed proposed oil spill prevention technologies and compared them to the damages that occurred in Alaska. In addition, we estimated what the damages would be if a spill of this magnitude were to occur in the lower 48 states and compared the costs of prevention to these damages.

Ten oil spill prevention alternatives studied by the National Research Council (1991) and by Keith et al.(1990) were analyzed to gain perspective on this most important public policy debate. The evaluation of prevention alternatives was conducted for two different scenarios: 1.) technologies applied to only the Alaskan tanker fleet;, and 2.) technologies applied to the U.S. tanker fleet. This second analysis was conducted assuming that the oil spill occurred in the lower 48 states and adjusted for increased economic and natural resource damages because of the greater densities of human populations and economic activity in the coastal zone and because of the larger area of highly productive coastal wetlands in the lower 48 states.

Results of the Emergy Analysis of Oil Spill Prevention Alternatives

The Alaskan Tanker Fleet: The emergy costs of five spill prevention alternatives when expressed in macroeconomic dollars varied from $281 million to $1.8 billion. On the face of it, it would seem that investments of this magnitude would provide a positive net yield. However, each of the alternatives will not completely stop oil spills, only decrease their magnitude. Keith et al. (1990) gave the expected volumes of oil that would be released with each of the five alternatives. Using the damage estimates from the *Exxon Valdez* spill and converting to damage per unit of oil spilled, benefit-cost ratios were calculated for each of the alternatives. Three of the five alternatives had net emergy benefit ratios greater than one:

- **4.4/1 to 6.4/1 - Group I System Modifications**
- **1.3/1 to 1.8/1 - Group II system Modifications**
- **1.4/1 to 2.0/1 - Group I and II System Modifications (combined)**

Group I system modifications, in general, consisted of alcohol and drug testing of crews, navigation training, two-person watch requirement, improved loading and unloading procedures, and improved spill response coordination. Group II system modifications included: vessel monitoring system, traffic separation lanes, designated anchorage areas, emergency response and pollution control vessels, and improved loading and unloading. Because of its high emergy costs, the two alternatives that included doubling hulling had net emergy benefit ratios less that one.

The U.S Tanker Fleet: The emergy costs of the 10 prevention alternatives for the U.S. tanker fleet measured in macroeconomic dollars varied from 288 million to 8.8 billion em$. As in the previous analysis, the net emergy benefit ratio was calculated using the damages that would not occur should the prevention alternative be implemented verses the costs of its implementation. Using the damage estimates from the *Exxon Valdez* spill and converting to damage per unit of oil spilled (but adjusting for increased damages that would result from a spill in the lower 48 states), benefit-cost ratios were calculated for each of the 10 alternatives. A range of net emergy ratios were calculated for each alternative's (minimum and maximum expected benefits). None of the 10 alternatives had minimum net emergy benefit ratios greater than one, while seven had maximum ratios greater than one. The majority of these had ratios less than 2/1; the exceptions, with best-case ratios greater than 2/1 were:

- **2.16/1 - Group I Modifications**
- **2.4/1 - Double Bottom**

The group I modifications consisted of the same modifications as for the Alaskan alternatives. Double bottom modifications studied by the National Research Council (1991) consisted of double hulling only the bottom portion of the hulls of the tanker fleet.

In all, the analysis of spill prevention alternatives suggested that:

1.) **Alternatives that consisted primarily of training, testing and improved response and technology for cleanup had the best chances of providing a net emergy benefit,**

2.) **Alternatives that consisted of redesign and modification of the tanker fleet had poor potential of providing a net emergy benefit, and**

3.) **Alternatives implemented on a regional scale with protection of particular high value resource areas as a target had the highest potential for providing net emergy benefits.**

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APPENDIX A

TRANSFORMITIES AND EMERGY-MONEY RATIOS USED IN THIS STUDY.

Table A.1. Transformities (T_i) and emergy-money ratios used in emergy calculations.

Designation	Name		units	Source
	Alaska Emergy-Money Ratio	2.3E+13	sej/$	state of Alaska analysis, this study
	Coal	40000	sej/J	Odum et al. (1987a)
	Crude Oil	53000	sej/J	Odum et al. (1987a)
	Earth cycle energy	29000	sej/J	Odum et al. (1987a)
	Fuel-generated electricity	160000	sej/J	Odum et al. (1987a)
	Fuelwood	35000	sej/J	Odum et al. (1987a)
	Gold	5000000	sej/g	Odum et al. (1987a)
	Human labor (high school education)	2.5E+07	sej/J	(Odum, 1988)
	Hydroelectricity	160000	sej/J	Odum et al. (1987a)
	Immigrating humans	9.4E+16	sej/person	estimated from Odum (1988)
	Mangrove biomass	15000	sej/J	Odum and Arding (1991)
	Natural gas	48000	sej/J	Odum et al. (1987a)
	Petroleum fuels	530000	sej/J	Odum et al. (1987a)
	Rain chemical energy	15000	sej/J	Odum et al. (1987a)
	Rain geopotential energy	8900	sej/J	Odum et al. (1987a)
	River water	41000	sej/J	Odum et al. (1987a)
	Seismic energy	7.3E+11	sej/J	Alexander (1978)
	Silver	750000	sej/g	estimated from Odum et al. (1987a)
	Salt marsh biomass	9000	sej/J	averaged for components from Hornbeck and Odum (In Review)
	Solar energy	1	sej/J	by emergy definition
	Tidal energy	24000	sej/J	Odum et al. (1987a)
	Timber	35000	sej/J	Odum et al. (1987a)
	Topsoil	63000	sej/J	Odum et al. (1987a)
	Wave energy	26000	sej/J	Odum et al. (1987a)
	Wind energy	620	sej/J	Odum et al. (1987a)
T_1	Primary Producers	1.1E+04	sej/J	Appendix C
T_{10}	Herring	1.1E+06	sej/J	Appendix C
T_2	Zooplankton	1.0E+05	sej/J	Appendix C
T_{212}	Fisheries	1.6E+06	sej/J	averaged for commercial species from Appendix C
T_{33}	Bald Eagles	2.5E+07	sej/J	Appendix C
T_{37}	Harbor Seals	6.1E+07	sej/J	Appendix C
T_{38}	Sea Otters	9.2E+07	sej/J	Appendix C (see text)
T_{39}	Killer Whales	1.7E+08	sej/J	Appendix C
T_{40}	Phytoplankton	1.1E+04	sej/J	from primary producers in Appendix C
T_{409}	Fisheries	1.6E+06	sej/J	averaged for commercial species from Appendix C
T_{41}	Intertidal Algae	1.1E+04	sej/J	from primary producers in Appendix C
T_{43}	Intertidal Herbivores	1.1E+05	sej/J	Appendix C
T_{44}	Intertidal Mieofauna	2.9E+05	sej/J	Appendix C
T_{45}	Intertidal Macrofauna	8.1E+05	sej/J	Appendix C
T_{46}	Murres	4.7E+07	sej/J	averaged for taxon transformities from Appendix C

Table A.1 continued.

Designation	Name		units	Source
T_{47}	Procellarids	2.3E+07	sej/J	averaged for taxon transformities from Appendix C
T_{AKNS}	crude oil	53000	sej/J	Odum et al. (1987a)
T_{fuel}	petroleum fuel	53000	sej/J	Odum et al. (1987a)
T_{oil}	crude oil	530000	sej/J	Odum et al. (1987a)
T_{steel}	steel	1.8E+09	sej/g	Huang and Odum (1991)
U.S. emergy-money ratio		1.6E+12	sej/$	Odum (1992)

APPENDIX B.

NOTES AND CALCULATIONS IN SUPPORT OF THE EMERGY ANALYSES OF THE STATE OF ALASKA AND PRINCE WILLIAM SOUND REGION

Table B.1. Conversion factors for storages and flows used in the state of Alaska and the Prince William Sound regional analyses.

Item	Value	Units	Source
vertebrate dry wt. to live wt. biomass ratio			
	0.30	g-dry/g-live	Carter (1969)
uncured timber density			
	0.90	g/cm^3	estimated from F.A.O. (1980)
timber dry wt. to uncured wt. ratio			
	0.20	g-dry/g-uncured	estimated from F.A.O. (1980)
plant or invertebrate biomass to energy conversion			
	16700	J/g-dry wt.	estimated from Odum (1969)
vertebrate biomass to energy conversion			
	20900	J/g-dry wt.	estimated from Odum (1969)
coal mass to energy conversion			
	2.2E+13	J/Mg	Shonka (1979)
natural gas (wet) volume to energy conversion			
	3.8E+07	J/m^3	Shonka (1979)
crude oil volume to energy conversion			
	6.1E+09	J/bbl	Shonka (1979)
petroleum fuel volume to energy conversion			
	5.5E+6	J/bbl	Shonka (1979)

Notes to Table III.1. Emergy Analysis of the State of Alaska in 1985. All equations are from Odum et al. (1987) except equation B.5 which is from Odum and Arding (1991). Where necessary, flows were converted to energy using conversion factors given in Table D.1.

Note **Description & Source**

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1 **AK Solar Energy Inflow**

= ((AK Land Area) + (Continental Shelf Area of AK)) m^2 * (Solar Input) J/m^2-y * (1 - Albedo) (B.1)

Alaska Land Area = 1.49E+12 m^2 (Hartman and Johnson, 1978)
Solar Input = 3.13E+09 J/m^2-y (calculated from Lindsberg et al. (1965))
Albedo = 0.35 (estimated from Budyko (1974))

2 **AK Wind Energy Inflow** (estimated from Odum (1992))

3 **AK Rain Geopotential Energy Inflow**

= (Mean Elevation of AK) m * (Annual AK Precipitation Runoff) m^3/y * (Density of Fresh Water) kg/m^3 * (Gravitational Constant) m/s^2 (B.2)

Mean Elevation of AK = 1000 m (calculated from Hartman and Johnson (1978))
Annual AK Precipitation Runoff = 8.0E+11 m^3/y (calculated from Hartman and Johnson (1978))
Density of Fresh Water = 1.0E+06 kg/m^3
Gravitational Constant = 9.8 m/s^2

4 **AK Rain Chemical Energy Inflow**

= ((AK Land Area) m^2 * (1/Fraction of Rainfall Evapotranspirated) * (Mean Annual AK Rainfall Over Land) m/y + (AK Continental Shelf Area) m^2 * (Mean Annual AK Rainfall Over Continental Shelf) m^2/y) * ((Moles of Water) * Universal Gas Constant) * (Temperature)) kcal/^{o}K-g * ((Concentration of Sea water) * $\log_e$((Concentration of Sea Water)/(Concentration of Rain Water))) * (Density of Fresh Water) Kg/m^3 (B.3)

AK Land Area = 1.49E+12 m^2 (Hartman and Johnson, 1978)
Fraction of Rainfall Evapotranspirated = 0.5 (assumed)
Mean Annual AK Rainfall Over Land = 1.0 m/y (calculated from Hartman and Johnson (1978))
AK Continental Shelf Area = 1.68E+12 m^2 (Hartman and Johnson, 1978)
Mean Annual AK Rainfall Over Continental Shelf = 1.0 m/y (calculated from Hartman and Johnson (1978))
(Moles of Water) * (Universal Gas Constant) * (Temperature) = 3.12E-02 kcal/^{o}K-g
Concentration of Sea Water = 9.65E+05 ppm (assumed)
Concentration of Rain Water = 1.0E+06 (estimated from Odum et al. (1987a))
Density of Fresh Water = 1.0E+06 kg/m^3

5 **AK Tidal Energy Inflow**

= (Area of AK Continental Shelf) m^2 * 1/2 * (Annual Number of Tides in AK) #/y* (Mean AK Tidal Range)^2 m^2* (Fraction of Tide Absorbed in AK) * (Density of Ocean Water) kg/m^3* (Gravitational Constant) m/s^2* 1.0E-07 J/erg * 3.15+07 s/y * 100 cm/m (B.4)

Area of AK Continental Shelf = 1.68E+12 m^2 (Hartman and Johnson, 1978)
Annual Tides AK = 548 tides/y (estimated from Hartman and Johnson (1978))
Mean AK Tidal Range = 166 cm (calculated from Hartman and Johnson (1978))
Fraction of Tide Absorbed in AK = 0.13 (estimated from Odum et al. (1987a))
Density of Ocean Water = 1.025 kg/m^3
Gravitational Constant = 9.8 m/s^2

6 **AK wave energy inflow** (Odum, 1992)

Notes to Table III.1. Continued.

Note **Description & Source**

7 **AK earth cycle energy inflow**

= (Land Area of AK) m^2 * ((Fraction of AK Land Area that is Geologically Active) * (Heat Flow of Active Area) + (Fraction of AK Land Area that is Geologically Stable) * (Heat Flow of Stable Area)) (B.5)

Land Area of AK = 1.49E+12 m^2 (Hartman and Johnson, 1978)
Fraction of Land Area Geologically Active = 0.33 (estimated from Hartman and Johnson (1978))
Heat Flow of Active Area = 5.26E+06 J/m^2-y
Fraction of Land Area Geologically Stable = 0.66 (estimated from Hartman and Johnson (1978))

8 **AK Canadian River Water Inflow**

= (Annual Canadian River Water Inflow to AK) m^3/y * ((Moles of Water * Universal Gas Constant) * (Temperature)) kcal/^{o}K-g * ((Concentration of Sea water) * log$_e$((Concentration of Sea Water)/(Concentration of Canadian River Water))) * (Density of Fresh Water) Kg/m^3 (B.6)

Annual Canadian River Water Inflow to AK = 1.85E+11 m^3/y (Hartman and Johnson, 1978)
((Moles of Water) * (Universal Gas Constant) * (Temperature)) = 3.12E-02 kcal/^{o}K-g
Concentration of Sea Water = 9.65E+05 ppm (assumed)
Concentration of Canadian River Water = 1.0E+06 (estimated from Odum et al. (1987a))
Density of Fresh Water = 1.0E+06 kg/m^3

9 **1985 AK fuelwood use** (U.S.D.C, 1989)

10 **1985 AK hydroelectric generation** (U.S.D.C., 1989)

11 **1985 AK forest products use** (estimated from A.D.C.E.D. (1984))

12 **1985 AK fishery products consumption** (estimated from U.S.D.C (1988))

13 **1985 AK coal use** (U.S.D.C., 1989)

14 **1985 AK natural gas use** (U.S.D.C., 1989)

15 **1985 AK oil refined and used** (U.S.D.C., 1989)

16 **1985 AK electricity generation from fossil fuels** (calculated from U.S.D.C. (1989))

17 **1985 AK fuel imports** (calculated from U.S.D.C. (1988) & Smith (1990))

18 **1985 AK import of international service** (extrapolated from Smith (1990))

19 **1985 AK import of U.S. services** (Extrapolated from Federal Government & Tourism payments (U.S.D.C., 1989))

20 **1985 AK immigration** (averaged from U.S.D.C. (1989))

21 **1985 AK fishery products export to international systems** (Smith, 1990)

22 **1985 AK fishery products export to U.S.** (extrapolated from A.D.C.E.D. (1984) & Smith (1990))

23 **1985 AK forestry products exports** (Smith, 1990)

24 **1985 AK natural gas exports** (Smith, 1990)

Notes to Table III.1. Continued.

Note	**Description & Source**
25	**1985 AK oil exports** (Smith, 1990)
26	**1985 AK emergy of services embodied in exports to international systems** (extrapolated from Smith (1990))
27	**1985 AK emergy of services embodied in exports to U.S.** (extrapolated from Smith (1990))
28	**1985 AK silver exports** (U.S.D.I., 1988)
29	**1985 AK gold exports** (U.S.D.I., 1988)

Notes to Table III.2. Emergy values of major, long term storages (Q_i) of Alaska in 1985. Where necessary, storages were converted to energy using conversion factors given in Table D.1.

Storage	Description & Source
1	**Timber storage** (U.S.D.C., 1988)
2	**Coal storage** (Smith, 1990)
3	**Natural gas storage** (A.D.N.R., 1990)
4	**Crude oil storage** (A.D.N.R., 1990)
5	**Topsoil storage** = (AK Land Area) m^2 * (Average Humus Content of AK Soil) g/m^2 * (Energy Conversion Factor For Soil Humus) J/g (B.7) AK Land Area = 1.49E+12 m^2 (Hartman and Johnson, 1978) Average Humus Content of AK Soil = 3.6E+04 g/m^2 (estimated from Glazovskaya (1986)) Energy Conversion Factor For Soil Humus = 2.3E+04 J/g (Odum et al. , 1987a)
7	**Infrastructure, equipment & other capital assets storage** (U.S.D.C., 1988)

Notes to Table III.6. Emergy Analysis of the Prince William Sound Region of Alaska in 1988. Equations used to calculate flow estimates are from Odum et al. (1987). Where necessary, flows were converted to energy using conversion factors given in Table D.1.

Note	Description and Source
1	**PWS solar energy inflow**
	= (Area of PWS) m^2 * (Solar Input/m2) J/m^2-y * (1 - Albedo) (B.8) PWS Area = 9.14E+09 m^2 (Exxon Co. U.S.A., Unpublished Data) Solar Input = 3.13E+09 J/m^2-y (calculated from Lindsberg et al. (1965)) Albedo = 0.35 (estimated from Budyko (1974))
2	**PWS wind energy inflow**
	= (Area of PWS) m^2 * (Atmospheric Boundary Layer Height) m * (Density of Air) kg/m^3 * (Specific Heat of Air) kcal/kg-^{o}K * (Horizontal Temperature Gradient) ^{o}K/m * (PWS Wind Vector) m/s * 4186 J/kcal * 3.15E+07 s/y (B.9) PWS Area = 9.14E+09 m^2 (Exxon Co. U.S.A., Unpublished Data) Density of Air = 1.23 kg/m^3 Specific Heat of Air = 0.24 kcal/kg-^{o}K (Odum et al., 1987a) Horizontal Temperature Gradient = 3.0E-09 kcal/^{o}K-g (calculated from Royer (1982)) PWS Wind Vector = 8.0 m/s (Luick et al., 1987)
3	**PWS fresh water chemical potential energy inflow**
	= (Annual Fresh Water Input to PWS) m^3/y * ((Moles of Water * Universal Gas Constant) * (Temperature)) kcal/^{o}K-g * ((Concentration of PWS water) * log$_e$((Concentration of PWS Water)/(Concentration of Freshwater))) * (Density of Fresh Water) Kg/m^3 (B.10) Annual Fresh Water Input to PWS = 2.2E+10 m^3/y (estimated from Royer (1982; 1983)) ((Moles of Water) * (Universal Gas Constant) * (Temperature)) = 3.12E-02 kcal/^{o}K-g Concentration of PWS Water = 1.0E+06 ppm (estimated from Muench and Schmidt (1982)) Concentration of Fresh Water = 9.9E+05 (estimated from Odum et al. (1987a)) Density of Fresh Water = 1.0E+06 kg/m^3
4	**PWS tidal energy inflow**
	= (Area of PWS) m^2 * 1/2 * (Number of Tides per year in PWS) #/y* (Mean PWS Tidal Range)^2 m^2* (Fraction of Tide Absorbed in PWS) * (Density of Ocean Water) kg/m^3* (Gravitational Constant) m/s^2* 1.0E-07 J/erg * 3.15+07 s/y * 100 cm/m (B.11) PWS Area = 9.14E+09 m^2 (Exxon Co. U.S.A., Unpublished Data) Tides/y in PWS = 500 tides/y (estimated from Mickelson (1989) adjusting for semi-diurnal characteristics) Mean PWS Tidal Range = 232 cm (calculated from Hartman and Johnson (1978)) Fraction of Tide Absorbed in PWS = 0.13 (Estimated using 0.07 absorption for open waters and 0.50 for fjord waters) Density of Ocean Water = 1.025 kg/m^3 Gravitational Constant = 9.8 m/s^2

Notes to Table III.6. Continued

Note	Description and Source
5	**PWS wave energy inflow** = 1/8 * (Density of Water) kg/m^3 * (Gravitational Constant) m/s^2 * (Wave Height)^2 m^2 * ((Gravitational Constant) m/s^2 * (Depth Under Wave) m)$^{1/2}$ * (Length of Shoreline Exposed to Wave Action) * 1.0E-07 J/erg (B.12) Density of Ocean Water = 1.025 kg/m^3 Gravitational Constant = 9.8 m/s^2 Wave Height = 75 cm (estimated from Jahns et al.(1991)) Depth Under Wave = 300 cm (assumed) Length of Shoreline = 2.41E+06 m (estimated from Mickelson (1989))
6	**PWS seismic energy inflow** (calculated from Algermissen et al. (1969))
7	**1988 PWS fuel imports** (normalized for population from Alaskan fuel imports (Table III.1))
8	**1988 PWS service imports** (normalized for population from Alaskan service imports (Table III.1))
9	**1988 PWS fishery products export** (A.O.G., 1989)
10	**1988 PWS services embodied in exports** (estimated from A.O.G. (1989))

APPENDIX C.

CALCULATION OF TRANSFORMITIES FOR THE PRINCE WILLIAM SOUND ECOSYSTEM

Methods

Two trophic web models of Prince William Sound were used to calculated the transformities for ecological damage in the *Exxon Valdez* oil spill. The first is an aggregated trophic web adapted from Parsons' (1987) trophic web model for Gulf of Alaska fjord regions (Figure C.1). The apex and demersal predator components were combined into a single apex predator component (component 6) and carbon flows were converted to energy flows using the conversion factor 42900 J/g-C calculated from a 39% carbon content for biomass (Curtis, 1983). Emergy values for the energy flows in the aggregated model were calculated by first assuming all energy entered the trophic web through primary producers. A transformity for primary producers was calculated by dividing the annual, emergy flux per square meter (determined in the Prince William Sound regional analysis) by Parson's (1987) estimate for annual primary production. Other transformities and emergy values were calculated using Parson's estimates for energy flows from component to component. Herbivore feces (flow from component 2 to component 3) was assumed to be a necessary byproduct of, rather than a flow of degraded material from, herbivore biomass production. As such, both herbivore feces and herbivore biomass must have higher transformities than if the flows were modeled as split flows. The flows of producer (component 1) biomass to herbivores (component 2) and the detrital pool (component 3) were modeled as a split flows.

An assumption inherent in the model is that the transformity of the flow of energy from a component is equal to the transformity of the storage within the component. The basis of this is the assumption that any differences between gross production and transfer to the next higher trophic level are necessary byproducts, inseparable from the process at steady state. The flows of producer detritus (component 1 to component 3) and herbivore feces were diagrammed as flowing through a dashed storage symbol to illustrate the combination of flows into a general detritus pool (component 3). They were assumed not to undergo transformations characteristic of actual storages (Odum, 1983). The herbivore (component 2), meiofauna (component 4) and macrofauna (component 5) components were aggregated into a single component, lower consumers (component 6, Figure C.2). The transformity of this aggregated component was used for all lower consumers in the detailed trophic web model to avoid problems in transposing the McRoy and Wyllie-Echeverria (1991) trophic groupings with those of Parson (1987).

The second trophic web model, a detailed Prince William Sound trophic web model (Figure C.2), is an adaptation of a series of trophic webs and trophic relationships reported by McRoy and Wyllie-Echeverria (1991). Energy flows were estimated by assuming a 10% Lindeman efficiency (Lindeman, 1942) of conversion from the sum of the flows to component *i*, to the non-heat flows from component *i*. The model includes only those flows that McRoy and Wyllie-Echeverria reported as comprising greater than 50% of a given species's carbon intake during some season of the year. These major flows were assumed to be of equal magnitude in the diet of the specific predator.

A method similar to Kercher and Shugart's (1975) method of effective trophic position was used in the detailed Prince William Sound trophic web model to calculate relative flows of energy because the actual animal populations were unknown. The energy input to a food web necessary to deliver 1 unit of energy input to a population of predators was calculated. In the method used, all energy flowing into the trophic web was assumed to flow though lower consumers (component 6) and the energy output from lower consumers required to generate 1 joule of net production from a specific predator component was calculated. Beginning with components that had no predators within the trophic hierarchy ($J_{i\text{-}0}$), to which 1 joule per year net productions were assigned, the production flows required from each *i-1* component were calculated using the 10% conversion efficiency. This flow-generating procedure was used until the entire web of flows from lower consumers through all predators was generated, whereupon any flows between the same two components were added.

Ulanowicz's (1986) NETWRK3, a matrix based computer program for calculating species' trophic positions, was used to compare the computed trophic levels to those calculated by DeGange and Sanger (1987) for Gulf of Alaska sea birds. This comparison was a test of the application of the McRoy and Wyllie-Echeverria data in the detailed Prince William Sound trophic web model under the assumption that no significant difference should be found if the application was successful.

Transformities were calculated for individual components of the detailed Prince William Sound trophic web model by converting the energy flows into each component to emergy, using the

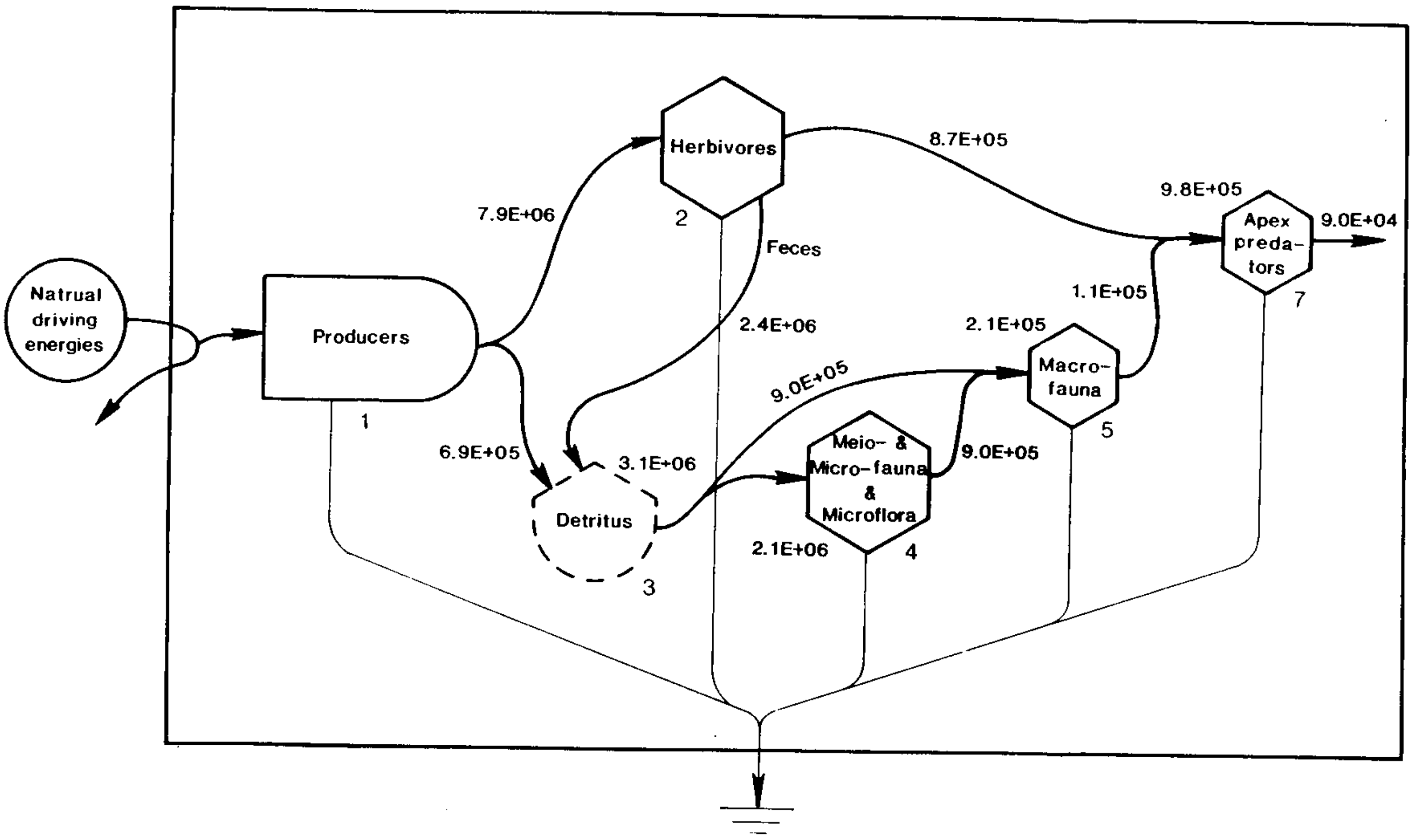

Figure C.1. The aggregated Prince William Sound trophic web model.

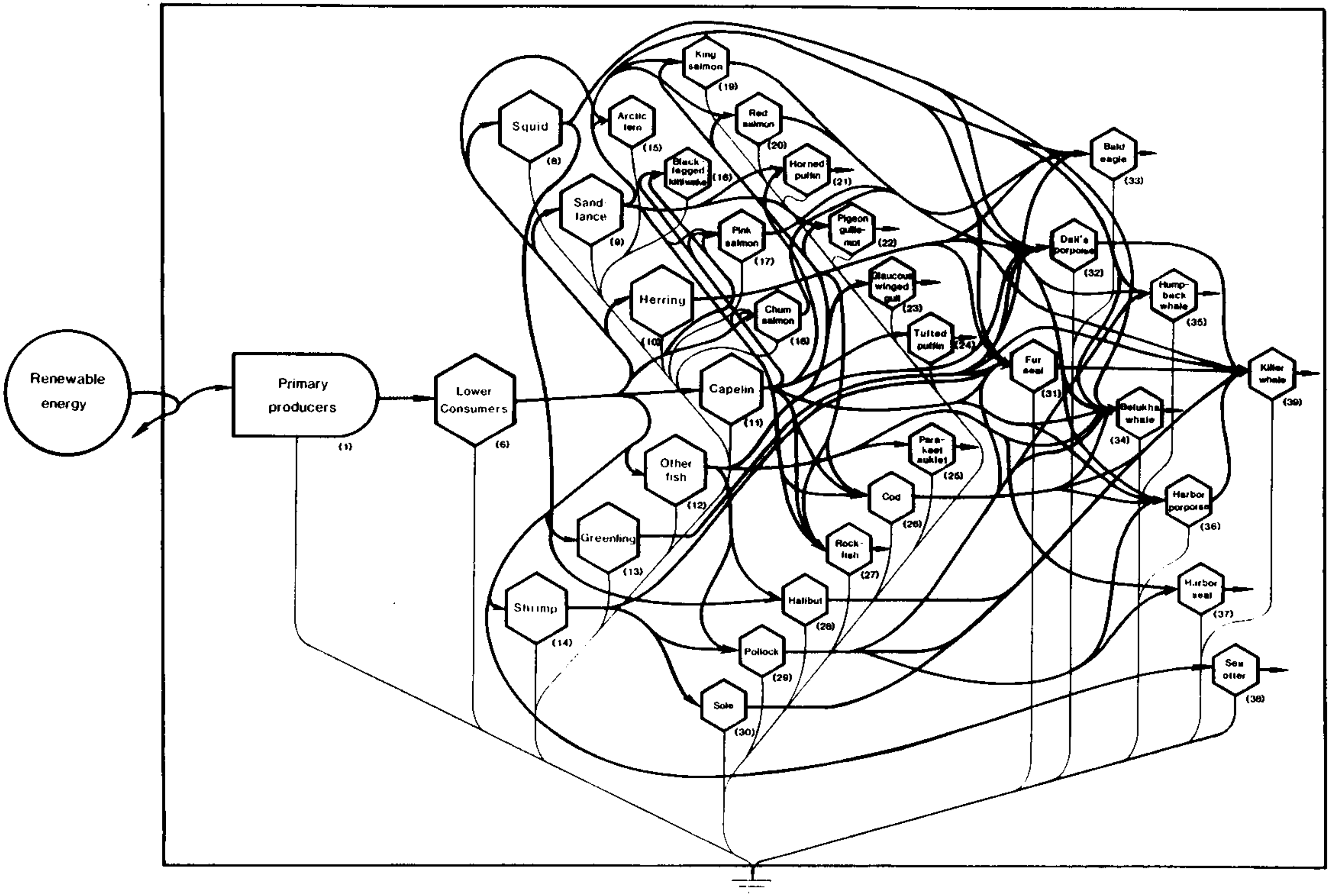

Figure C.2. The detailed Prince William Sound trophic web model.

transformities of the inflowing energies. Conversions were begun with components feeding solely on lower consumers (component 6) using the transformity for this component calculated in the aggregated trophic web model. Equation C.1 details the procedure,

$$T_j = (\mathrm{Sum} (J_{i-j} * T_i) / (\mathrm{Sum} (J_{j-(j+1)})) \qquad (C.1)$$

where,

T_i = the transformity of *i*
T_j = the transformity of *j*
J_{i-j} = the energy flow from *i* to *j*

such that the transformity of *j* equals the sum of the emergy flows to *j* divided by the sum of the energy flows from *j* to other model components. Flows of degraded energy in respiration losses from *j* are not summed into the flows from *j*.

Equation C.1 and the Lindeman efficiencies and energy flows from the detailed trophic web model were incorporated into a LOTUS 1-2-3 spreadsheet. This spreadsheet was used to perform a sensitivity analysis on the detailed trophic model in which the Lindeman efficiencies were varied from 5% to 30% for each component to determine their effects on the transformities. Except for the transformity for sea otters (component 38), transformities generated using a 10% efficiency were used in the natural resource damage, human system loss, state of Alaska and Prince William Sound regional analyses. The transformity used for sea otters was calculated using a daily food consumption of 30% of body weight (Kenyon, 1969) and an assumed annual net production to body weight of 0.10 g/g-y. This technique was only used for sea otters because the daily consumption data for many other species were lacking or much lower than 30%.

Results and Discussion

The aggregated Prince William Sound trophic web model is diagrammed in Figure C.1 and described in Table C.1. The solar transformities calculated using the aggregated trophic model are given in Table C.2. The transformity of the net production of lower consumers (component 6, Figure C.2) calculated from this model and used in the detailed trophic level model was 1.1E+05 sej/J. The detailed Prince William Sound trophic web model is diagrammed in Figure C.2, and described in Table C.3. The results of the transformity calculations from the detailed trophic web model for apex predators are given in Table C.4. The results of the procedure used to generate energy flows for the detailed model are given in Table C.5.

Species transformities that were calculated using the detailed model were very sensitive to the Lindeman efficiencies used in the trophic web. The sensitivity was magnified at the higher trophic levels. The lower apex predators (sandlance (component 9), herring (component 10), and capelin (component 11)) at the third trophic level, changed by almost an order of magnitude when the Lindeman efficiencies for all apex predator model components were varied from 5.0% to 30%. The trophic level 4.9, killer whale (component 39) transformity changed almost three orders of magnitude with this variation of Lindeman efficiency. Other higher trophic level species such as belukha whale (component 34), humpback whale (component 35), harbor porpoise (component 36), and harbor seal (component 37) responded similarly to these changes in Lindeman efficiency. Trophic levels calculated from the detailed model are given in Table 3.4 along with those reported by DeGange and Sanger (1987) for sea birds. For the sea birds, the two sets of trophic level results were not significantly different (paired t-test, p=0.37).

The transformities calculated from the Prince William Sound trophic models (Tables C.2 and C.4) are within the ranges of those calculated by other researchers. Odum and Arding (1991) reported transformities for Gulf of Mexico and Ecuadorean shrimp pond pandalid shrimp as 3.77E+05 sej/J and 1.3E+07 to 1.89E+07 sej/J respectfully. The detailed trophic web model was used to calculate a 3.7E+05 to 2.2E+06 sej/J transformity for pandalid shrimp (Table C.4). Odum et al. (1987b) reported 9.37E+03 sej/J dispersed algae, 1.41E+05 sej/J zooplankton, and 7.97E+06 sej/J upper consumer transformities for the Gulf of Mexico. Odum (1986) calculated 1.0E+04 sej/J vegetation consumed by herbivores, 2.5E+05 sej/J herbivores consumed by carnivores, 6.3E+07 sej/J migrating fish, and 7.0E+06 sej/J prey consumed by top carnivore transformities for the aquatic system of Silver Springs, Florida. The aggregated trophic

Table C.1. Designations for the aggregated Prince William Sound trophic web model (Figure C.1).

Component Designation		Species Name, Trophic Group or other component name
1	primary producers	
	phytoplankton:	diatoms, dinoflagellates, microflagellates & others
	intertidal producers:	Algae spp.
2	herbivores	filter feeders
3	detritus	
4	meio- & micro-fauna, & microflora	bacteria, nematodes, & others
5	macrofauna	deposit feeders
6 (Figure C.2)	lower consumers	components 2, 4, & 5 this table
7	apex predators	(see Figure C.2)

Table C.2. The solar transformities calculated using the aggregated Prince William Sound trophic web model (Figure C.1).

Component	Description	Solar Transformity sej/J
1	primary producers	1.1E+04
2	herbivores	1.0E+05
4	meiofauna, microfauna and microflora	2.9E+05
5	macrofauna	8.1E+05
6 (Figure C.2)	lower consumers (2, 4, & 5 this table)	1.1E+05
7	apex predators	1.0E+06
J_{2-3}	herbivore feces	3.6E+04

Table C.3. Designations for the detailed Prince William Sound trophic web model (Figure C.2).

Component Designation		Species Name, Trophic Group or other component name
1	primary producers	phytoplankton & intertidal producers
6	lower consumers	planktonic, intertidal & benthic invertebrates
8	squid	Cephalopoda
9	sandlance	*Ammodytes hexapterus*
10	pacific herring	*Clupea pallassii*
11	capelin	*Mallotus villosus*
12	other fish	juvenile fish, euchalon and others
13	greenling	Hexagrammidae
14	pandalid shrimp	*Pandalus* spp.
15	arctic tern	*Sterna paradisaea*
16	black-legged kittiwake	*Rissa tridactyla*
17	pink salmon	*Oncorhynchus gorbuscha*
18	chum salmon	*O. keta*
19	king salmon	*O. tshawytscha*
20	red salmon	*O. nerka*
21	horned puffin	*Fratercula corniculata*
22	pigeon guillemot	*Cepphus columba*
23	glaucous-winged gull	*Larus glaucescens*
24	tufted puffin	*Lunda cirrhata*
25	parakeet auklet	*Cyclorrhynchus psittacula*
26	cod	*Gadus macrocephalus*
27	rockfish	*Sebastes* spp.
28	pacific halibut	*Hippoglossus stenolepis*
29	walleyed pollock	*Theragra chalcogramma*
30	sole	Pleuronectidae
31	northern fur seal	*Callorhinus visinus*
32	dall's porpoise	*Phocoenoides dalli*
33	bald eagle	*Haliaeetus leucocephalus*
34	belukha whale	*Delphinopterus leucas*
35	humpback whale	*Megaptera novaeangliae*
36	harbor porpoise	*Phocoena phocoena*
37	harbor seal	*Phoca vitulina richardsi*
38	sea otter	*Enhydra lutris*
39	killer whale	*Orcinus orca*

Table C.4. The solar transformities of the detailed Prince William Sound trophic model (Figure C.2) calculated from Table C.5 and equation C.1 assuming 30%, 10%, and 5% Lindeman efficiencies.

		Solar Transformities (sej/J) calculated at:		
Component		30% Efficiency	10% Efficiency	5% Efficiency
8	squid	3.7E+05	1.1E+06	2.2E+06
9	sandlance	3.7E+05	1.1E+06	2.2E+06
10	herring	3.7E+05	1.1E+06	2.2E+06
11	capelin	3.7E+05	1.1E+06	2.2E+06
12	other fish	3.7E+05	1.1E+06	2.2E+06
13	greenling	3.7E+05	1.1E+06	2.2E+06
14	shrimp	3.7E+05	1.1E+06	2.2E+06
15	arctic tern	9.4E+05	7.7E+06	3.0E+07
16	black-legged kittiwake	7.9E+05	6.1E+06	2.3E+07
17	pink salmon	7.1E+05	5.1E+06	1.9E+07
18	chum salmon	7.1E+05	5.1E+06	1.9E+07
19	king salmon	1.2E+06	1.1E+07	4.4E+07
20	red salmon	1.2E+06	1.1E+07	4.4E+07
21	horned puffin	1.2E+06	1.1E+07	4.4E+07
22	pigeon guillemot	1.2E+06	1.1E+07	4.4E+07
23	glaucous-winged gull	1.2E+06	1.1E+07	4.4E+07
24	tufted puffin	1.2E+06	1.1E+07	4.4E+07
25	parakeet auklet	1.2E+06	1.1E+07	4.4E+07
26	cod	1.2E+06	1.1E+07	4.4E+07
27	rockfish	1.2E+06	1.1E+07	4.4E+07
28	halibut	1.2E+06	1.1E+07	4.4E+07
29	pollock	1.2E+06	1.1E+07	4.4E+07
30	sole	1.2E+06	1.1E+07	4.4E+07
31	fur seal	1.7E+06	2.8E+07	1.8E+08
32	dall's porpoise	1.6E+06	2.3E+07	1.4E+08
33	bald eagle	1.6E+06	2.5E+07	1.6E+08
34	belukha whale	1.9E+06	3.6E+07	2.5E+08
35	humpback whale	1.8E+06	3.1E+07	2.1E+08
36	harbor porpoise	2.4E+06	5.1E+07	3.8E+08
37	harbor seal	2.6E+06	6.1E+07	4.6E+08
38	sea otter	3.7E+05	1.1E+06	2.2E+06
39	killer whale	4.4E+06	1.7E+08	2.0E+09

Table C.5. Flows of the detailed Prince William Sound trophic web model generated from the relationships reported by McRoy and Wyllie-Echeverria (1991). These flows were used in the program NETWRK3 (Ulanowicz, 1986) to calculate trophic levels. Flows with no terminus within the model are designated $J_{i\text{-}0}$, while flows which are imports to the model are designated $J_{0\text{-}i}$.

Flow $J_{i\text{-}j}$	Energy J/y	Flow $J_{i\text{-}j}$	Energy J/y	Flow $J_{i\text{-}j}$	Energy J/y
$J_{0\text{-}1}$	365170	$J_{14\text{-}35}$	2.00	$J_{6\text{-}15}$	3.33
$J_{1\text{-}6}$	36517	$J_{15\text{-}0}$	1.00	$J_{6\text{-}16}$	5.00
$J_{10\text{-}23}$	5.00	$J_{16\text{-}0}$	1.00	$J_{6\text{-}17}$	7.45
$J_{10\text{-}26}$	15.3	$J_{17\text{-}32}$	0.463	$J_{6\text{-}18}$	7.45
$J_{10\text{-}27}$	2.50	$J_{17\text{-}33}$	0.500	$J_{6\text{-}38}$	10.0
$J_{10\text{-}31}$	1.85	$J_{17\text{-}39}$	0.278	$J_{6\text{-}8}$	68.0
$J_{10\text{-}32}$	1.85	$J_{18\text{-}32}$	0.463	$J_{6\text{-}9}$	574.6
$J_{10\text{-}33}$	2.00	$J_{18\text{-}33}$	0.500	$J_{8\text{-}28}$	3.70
$J_{10\text{-}34}$	1.25	$J_{18\text{-}39}$	0.278	$J_{8\text{-}32}$	1.85
$J_{10\text{-}35}$	2.00	$J_{19\text{-}32}$	0.463	$J_{8\text{-}34}$	1.25
$J_{10\text{-}36}$	2.22	$J_{19\text{-}33}$	0.500	$J_{9\text{-}15}$	3.33
$J_{11\text{-}15}$	3.33	$J_{19\text{-}39}$	0.278	$J_{9\text{-}17}$	2.48
$J_{11\text{-}16}$	5.00	$J_{20\text{-}32}$	0.463	$J_{9\text{-}18}$	2.48
$J_{11\text{-}17}$	2.48	$J_{20\text{-}33}$	0.500	$J_{9\text{-}19}$	6.21
$J_{11\text{-}18}$	2.48	$J_{20\text{-}39}$	0.278	$J_{9\text{-}20}$	6.21
$J_{11\text{-}21}$	5.00	$J_{21\text{-}0}$	1.00	$J_{9\text{-}21}$	5.00
$J_{11\text{-}24}$	10.0	$J_{22\text{-}0}$	1.00	$J_{9\text{-}22}$	5.00
$J_{11\text{-}26}$	15.3	$J_{23\text{-}0}$	1.00	$J_{9\text{-}26}$	15.3
$J_{11\text{-}27}$	2.50	$J_{24\text{-}0}$	1.00	$J_{9\text{-}27}$	2.50
$J_{11\text{-}31}$	1.85	$J_{25\text{-}0}$	1.00	$J_{9\text{-}31}$	1.85
$J_{11\text{-}32}$	1.85	$J_{26\text{-}34}$	1.25	$J_{9\text{-}32}$	1.85
$J_{11\text{-}33}$	2.00	$J_{26\text{-}36}$	2.22	$J_{9\text{-}33}$	2.00
$J_{11\text{-}34}$	1.25	$J_{26\text{-}39}$	1.11	$J_{9\text{-}34}$	1.25
$J_{11\text{-}35}$	2.00	$J_{27\text{-}0}$	1.00	$J_{9\text{-}35}$	2.00
$J_{11\text{-}36}$	2.22	$J_{28\text{-}39}$	1.11		
$J_{12\text{-}19}$	6.21	$J_{29\text{-}31}$	1.85		
$J_{12\text{-}20}$	6.21	$J_{29\text{-}34}$	1.25		
$J_{12\text{-}22}$	5.00	$J_{29\text{-}35}$	2.00		
$J_{12\text{-}23}$	5.00	$J_{29\text{-}36}$	2.22		
$J_{12\text{-}25}$	10.0	$J_{29\text{-}37}$	5.00		
$J_{12\text{-}27}$	2.50	$J_{29\text{-}39}$	1.11		
$J_{12\text{-}28}$	3.70	$J_{30\text{-}39}$	1.11		
$J_{12\text{-}29}$	67.2	$J_{31\text{-}39}$	1.11		
$J_{12\text{-}32}$	1.85	$J_{32\text{-}39}$	1.11		
$J_{12\text{-}34}$	1.25	$J_{33\text{-}0}$	1.00		
$J_{12\text{-}36}$	2.22	$J_{34\text{-}0}$	1.00		
$J_{12\text{-}37}$	5.00	$J_{35\text{-}0}$	1.00		
$J_{13\text{-}31}$	1.85	$J_{36\text{-}39}$	1.11		
$J_{13\text{-}33}$	2.00	$J_{37\text{-}0}$	1.00		
$J_{13\text{-}39}$	1.11	$J_{38\text{-}0}$	1.00		
$J_{14\text{-}28}$	3.70	$J_{39\text{-}0}$	1.00		
$J_{14\text{-}29}$	67.2	$J_{6\text{-}10}$	339.7		
$J_{14\text{-}30}$	11.1	$J_{6\text{-}11}$	572.6		
$J_{14\text{-}31}$	1.85	$J_{6\text{-}12}$	1161		
$J_{14\text{-}34}$	1.25	$J_{6\text{-}13}$	49.6		
		$J_{6\text{-}14}$	871		

web model was used to estimate transformities of 1.1E+04 sej/J for primary produces, 1.0E+05 sej/J for zooplankton, and 1.0E+06 sej/J for apex predators. The detailed trophic web model was used to estimate transformities of 3.7E+05 to 2.0E+09 sej/J for upper consumers (Table C.4). Odum's (1987a) calculation of a 1.2E+07 sej/J transformity for a South Pacific whale is similar to the transformities of 3.1E+07 sej/J for humpbacked whales, and 3.6E+07 sej/J for belukha whales calculated with the detailed model using a 10% Lindeman efficiency (Table C.4).

The detailed trophic web model was generated using Lindeman efficiencies because no quantitative description of the Prince William Sound trophic web energetics is available. The similarity of the NETWRK3 calculated trophic levels to those reported by DeGange and Sanger (Table C.6) lend support to the detailed trophic web model adaptation of McRoy and Wyllie-Echeverria's data. However, the wide variety of Lindeman efficiencies reported for marine systems and the sensitivity of the model to Lindeman efficiencies suggests the actual trophic energy flows could yield transformities significantly different than those calculated at a 10% efficiency. Slobodkin (1960) reported 5% to 15% and Kozlovsky (1968) reported consistent 10% ecological efficiencies from reviews of five ecosystem studies. Parsons (1987) suggested a 5% efficiency for baleen whales feeding at lower trophic levels. Kemp et al. (1975) described a trophic web with ecological efficiencies of 5% to 30% for the northeastern Gulf of Mexico. Pace et al. (1984) modeled continental shelf ecological efficiencies of 36% to 73% for bacteria, 16% to 46% for zooplankton, 9% to 29% for meiobenthos, 1% to 16% for macrobenthos, and 9% to 27% for fishes. They concluded assigning a constant 10% efficiency across trophic levels was unrealistic. Lasker (1988) used a 10% efficiency to analyze potential marine fisheries production citing the lack of data on secondary production, transfer efficiencies of energy through trophic levels, and feedback mechanisms in food chains.

Tennenbaum (1988) calculated slightly lower transformities than Odum et al. (1987b) for the same Gulf of Mexico system using a matrix-based method of generating feedbacks. Burns et al. (1991), modelling feedbacks in a similar fashion, found higher efficiencies which, given the data in Table C.4, might also indicate lower transformities. Yet, because of the variability in reported efficiencies, there are few data to suggest the use of an efficiency other than 10% for the detailed trophic web model (Table C.4).

Table C.6. Trophic levels calculated from the detailed Prince William Sound trophic model (Table C.3) using NETWRK3 (Ulanowicz, 1986) compared to those given by DeGange and Sanger (1987).

Component	Species	NETWRK3 Trophic Level	DeGange & Sanger Trophic Level
8	squid	3	
9	sandlance	3	
10	pacific herring	3	
11	capelin	3	
12	other fish	3	
13	greenling	3	
14	pandalid shrimp	3	
15	arctic tern	3.67	3.5
16	black-legged kittiwake	3.5	4.1
17	pink salmon	3.4	
18	chum salmon	3.4	
19	king salmon	4.0	
20	red salmon	4.0	
21	horned puffin	4.0	4.0
22	pigeon guillemot	4.0	4.1
23	glaucous-winged gull	4.0	4.0
24	tufted puffin	4.0	4.1
25	parakeet auklet	4.0	
26	cod	4.0	
27	rockfish	4.0	
28	pacific halibut	4.0	
29	walleyed pollock	4.0	
30	sole	4.0	
31	northern fur seal	4.07	
32	dall's porpoise	4.11	
33	bald eagle	4.12	
34	belukha whale	4.29	
35	humpback whale	4.33	
36	harbor porpoise	4.4	
37	harbor seal	4.5	
38	sea otter	3.0	
39	killer whale	4.92	

APPENDIX D.

NOTES AND CALCULATIONS IN SUPPORT OF THE EMERGY ANALYSIS OF THE *EXXON VALDEZ* OIL SPILL

Table D.1. Mass-energy conversion factors (GJ_i) used in the natural resource damage and economic system loss analyses.

Designation		Conversion	Source
GJ_{37}	harbor seal	25800	J/g-dry wt. National Research Council (1971)
GJ_{39}	killer whale	25800	J/g-dry wt. estimated from National Research Council (1971)
GJI	invertebrates	16700	J/g-dry wt. estimated from Odum (1969)
GJP	primary producer	16700	J/g-dry wt. estimated from Odum (1969)
GJV	vertebrates	20900	J/g-dry wt. estimated from Odum (1969)

Table D.2. Designations for the *Exxon Valdez* oil spill natural resource and economic loss analyses (Table III.9)

Component Designation	Species Name, Trophic Group or other component name
2 zooplankton	copepods, amphipods, euphasiids, larvae & others
10 Prince William Sound fisheries catch	
33 bald eagle	*Haliaeetus leucocephalus*
37 harbor seal	*Phoca vitulina richardsi*
38 sea otter	*Enhydra lutris*
39 killer whale	*Orcinus orca*
40 phytoplankton	diatoms, dinoflagellates, microflagellates & others
41 intertidal primary producers	Algae spp.
43 intertidal herbivores	filter feeders
44 intertidal meiofauna, microfauna and microflora	
45 intertidal macrofauna	deposit feeders
46 murres	Alcidae
46a first-year murres	Alcidae
47 procellarids	Procellariidae
AKNS	decreased pipeline flow in 1989
fuel	fuel used in cleaning operations
oil	*Exxon Valdez* cargo lost
services	human services embodied in cleaning operations
vessel	vessel deterioration during cleaning operations

Table D.3. Biomass and energy estimates of the natural resource damage associated with the *Exxon Valdez* oil spill (Table III.9. Emergy losses (L_i, LPP_i, and M_i) of the *Exxon Valdez* oil spill.). Biomass estimates were converted to energy using the conversion factors in Table D.1.

	Estimate				Description
	g-dry weight		joules		
	mantissa	exponent	mantissa	exponent	
LPP_{40}	0.0-3.7	15	0-3.7	15	lost phytoplankton production
LPP_{41}	1.3-7.5	14	1.4-7.5	15	lost intertidal primary production
M_{2}	3.2-95	10	0.53-16	15	zooplankton mortality
M_{33}	3.9	6	8.0	10	bald eagle mortality
M_{37}	4.2	6	6.0	11	harbor seal mortality
M_{38}	2.5-4.0	7	5.3-8.4	11	sea otter mortality
M_{39}	2.0	7	0-5.3	11	killer whale mortality
M_{40}	0.0-1.7	12	0-2.9	16	phytoplankton mortality
M_{41}	3.1-9.0	11	5.2-15	15	intertidal producer mortality
M_{43}	1.6-3.2	9	2.7-5.3	13	intertidal herbivore mortality
M_{44}	0.0-1.4	10	0-2.3	14	intertidal meiofauna mortality
M_{45}	0.0-7.8	9	1-1.3	14	intertidal macrofauna mortality
M_{46}	6.7-7.6	7	1.5-1.7	12	murre mortality
M_{46a}	6.3	6	1.4	11	murre chick mortality
M_{47}	7.6-8.5	6	1.6-1.8	11	procellarid mortality

Notes to Table IIID.3. Biomass and energy estimates of the natural resource damage associated with the *Exxon Valdez* oil spill.

Loss **Description & Source**

LPP_{40} **Lost Phytoplankton Primary Production**

= (Annual Phytoplankton Net Primary Production) g-dry wt./m^2-y * (Fraction of Phytoplankton Photosynthesis Reduced Due to Oil Exposure) * (Area Of the Valdez Spill) m^2 * (Time the Slick Blocked Light & Prevented Phytoplankton Production) y (D.1)

Annual Phytoplankton Net Primary Production = 512 g-dry wt./m^2-y (Parsons, 1987)

Fraction of Phtyoplankton Photosynthesis Reduced Due to Oil Exposure = 0-0.50 (estimated from Trudel (1978))

Area Of the Valdez Oil Slick = 6.7E+09 m^2 (largest extent of contiguous slick (A.D.N.R., 1989)

Time the Slick Blocked Light & Prevented Phytoplankton Production = 0.13 y (estimated from A.O.G. (1989))

LPP_{41} **Lost Intertidal Primary Production**

= (Sum of Annual Intertidal Algae Standing Stock Biomass Deficits Until Recovery From the Valdez Spill) g-dry wt. * (Intertidal Net Primary Production per Gram per Year) g-dry wt./g-dry wt.- y (D.2)

Sum of Annual Intertidal Algae Standing Stock Biomass Deficits Until Recovery From the Valdez Spill g-dry wt. = 7.6E+10 - 4.5E+11 g-dry wt. (integrated over 5 to 10 years assuming a linear recovery)

Intertidal Net Primary Production per Gram per Year = 0.10 g-dry wt./g-dry wt.-y (estimated from Parsons (1987))

M_2 **Zooplankton Mortality**

= (Pre-spill Zooplankton Standing Stock) g-dry wt./m^2 * (Zooplankton Fractional Mortality) * Area of the Valdez Spill) m^2 (D.3)

Pre-spill Zooplankton Standing Stock = 417 g-dry wt./m^2 (Parsons, 1987)

Zooplankton Fractional Mortality = 0.01-0.30 (estimated from Johansson et al. (1980))

Area of the Valdez Spill = 6.7E+09 m2 (largest extent of contiguous slick (A.D.N.R., 1989))

M_{33} **Bald Eagle Mortality**

= (Bald Eagle Individual Mortality) animals * (Bald Eagle Live Body Weight) g-live wt. * (Ratio of Dry Weight to Live Weight for Bald Eagle) g-dry wt./g-live wt. (D.4)

Bald Eagle Individual Mortality = 1440 animals (calculated from Bottini and Nicholl (1991))

Bald Eagle Live Body Weight = 4.65E+03 g-live wt. (estimated from Daum (1984))

Ratio of Dry Weight to Live Weight for Bald Eagle = 0.60 g-dry wt./g-live wt. (estimated from N.R.C. (1971))

M_{37} **Harbor Seal Mortality**

= (Harbor Seal Individual Mortality) animals * (Harbor Seal Live Body Weight) g-live wt. * (Ratio of Dry Weight to Live Weight for Harbor Seal) g-dry wt./g-live wt. (D.5)

Harbor Seal Individual Mortality = 1440 animals (Bottini and Nicholl (1991))

Harbor Seal Live Body Weight = 8.1E+04 g-live wt. (from A.D.F.G. (1986))

Ratio of Dry Weight to Live Weight for Harbor Seal = 0.26 g-dry wt./g-live wt. (estimated from N.R.C. (1971))

Notes to Table IIID.3. Continued

Loss **Description & Source**

M_{38} **Sea Otter Mortality**

= (Sea Otter Individual Mortality) animals * (Sea Otter Live Body Weight) g-live wt. * (Ratio of Dry Weight to Live Weight for Sea Otters) g-dry wt./g-live wt. (D.6)

Sea Otter Individual Mortality = 3500-5500 animals (Bottini and Nicholl (1991))
Sea Otter Live Body Weight =2.4E+04 g-live wt. (estimated from Kenyon (1969))
Ratio of Dry Weight to Live Weight for Sea Otters = 0.30 g-dry wt./g-live wt. (estimated from Carter (1969))

M_{39} **Killer Whale Mortality**

= (Killer Whale Individual Mortality) animals * (Killer Whale Live Body Weight) g-live wt. * (Ratio of Dry Weight to Live Weight for Killer Whale) g-dry wt./g-live wt. (D.7)

Killer Whale Individual Mortality = 0-13 animals (Bottini and Nicholl (1991))
Killer Whale Live Body Weight = 6.0E+06 g-live wt. (estimated from Dalheim (1981))
Ratio of Dry Weight to Live Weight for Killer Whale = 0.26 g-dry wt./g-live wt. (estimated from N.R.C. (1971))

M_{40} **Phytoplankton Mortality**

= (Pre-spill Phytoplankton Standing Stock) g-dry wt./m^2 * (Phytoplankton Fractional Mortality) * (Area of the Valdez Spill) m^2 (D.8)

Pre-spill Phytoplankton Standing Stock = 5122 g-dry wt./m^2 (Parsons, 1987
Phytoplankton Fractional Mortality = 0.0-0.05 (estimated from N.R.C. (1985))
Area of the Valdez Spill = 6.7E+09 m^2 (largest extent of contiguous slick (A.D.N.R., 1989))

M_{41} **Intertidal Producer Mortality**

= (Pre-spill Intertidal Producer Standing Stock) g-dry wt./m^2 * (Intertidal Producer Fractional Mortality) * (Area of the Valdez Spill) m^2 (D.9)

Pre-spill Intertidal Producer Standing Stock = 25600 g-dry wt./m^2 (Parsons, 1987)
Intertidal Producer Fractional Mortality = 0.34-1.0 (estimated from Houghton et al. (1991))
Area of the Valdez Spill = 6.7E+09 m^2 (largest extent of contiguous slick (A.D.N.R., 1989))

M_{43} **Intertidal Herbivore Mortality**

= (Pre-spill Intertidal Herbivore Standing Stock) g-dry wt./m^2 * (Intertidal Herbivore Fractional Mortality) * (Area of the Valdez Spill) m^2 (D.10)

Pre-spill Intertidal Herbivore Standing Stock = 92.2 g-dry wt./m^2 (Parsons, 1987)
Intertidal Herbivore Fractional Mortality = 0.48-1.0 (estimated from Houghton et al. (1991))
Area of the Valdez Spill = 6.7E+09 m^2 (largest extent of contiguous slick (A.D.N.R., 1989))

M_{44} **Intertidal Meiofauna Mortality**

= (Pre-spill Intertidal Meiofauna) g-dry wt./m^2 * (Intertidal Meiofauna Fractional Mortality) * (Area of the Valdez Spill) m^2 (D.11)

Pre-spill Intertidal Meiofauna Standing Stock =402 g-dry wt./m^2 (Parsons, 1987)
Intertidal Meiofauna Fractional Mortality = 0.0-1.0 (estimated from Houghton et al. (1991)).
Area of the Valdez Spill = 6.7E+09 m^2 (largest extent of contiguous slick (A.D.N.R., 1989))

Notes Table IIID.3. Continued

Loss **Description & Source**

M_{45} **Intertidal Macrofauna Mortality**

= (Pre-spill Intertidal Macrofauna Standing Stock) g-dry wt./m^2 * (Intertidal Macrofauna Fractional Mortality) * (Area of the Valdez Spill) m^2 (D.12)

Pre-spill Intertidal Macrofauna Standing Stock = 223 g-dry wt./m^2 (Parsons, 1987)

Intertidal Macrofauna Fractional Mortality = 0.0-1.0 (estimated from Houghton et al. (1991)).

Area of the Valdez Spill = 6.7E+09 m^2 (largest extent of contiguous slick (A.D.N.R., 1989))

M_{46} **Murre Mortality**

= (Murre Individual Mortality) animals * (Murre Live Body Weight) g-live wt. * (Ratio of Dry Weight to Live Weight for Murre) g-dry wt./g-live wt. (D.13)

Murre Individual Mortality = 2.1E+05 -2.4E+05 animals (calculated from Piatt et al. (1990))

Murre Live Body Weight = 1060 g-live wt. (averaged from individual species given by DeGange and Sanger (1987))

Ratio of Dry Weight to Live Weight for Murre = 0.30 g-dry wt./g-live wt. (estimated from Carter (1969))

M_{46a} **Murre Chick Mortality**

= (Murre Chick Individual Mortality) animals * (Murre Chick Live Body Weight) g-live wt. * (Ratio of Dry Weight to Live Weight for Murre Chick) g-dry wt./g-live wt. (D.14)

Murre Chick Individual Mortality = 2.15E+05 animals (Bottini and Nicholl (1991))

Murre Chick Live Body Weight = 100 g-live wt. (estimated from Freethy (1987))

Ratio of Dry Weight to Live Weight for Murre Chicks = 0.30 g-dry wt./g-live wt. (estimated from Carter (1969))

M_{47} **Procellarid Mortality**

= (Procellarid Individual Mortality) animals * (Procellarid Live Body Weight) g-live wt. * (Ratio of Dry Weight to Live Weight for Procellarid) g-dry wt./g-live wt. (D.15)

Procellarid Individual Mortality = 4.2E+04-4.7E+04 animals (calculated from Piatt et al. (1990))

Procellarid Live Body Weight = 300 g-live wt. (averaged from species given by DeGange and Sanger (1987))

Ratio of Dry Weight to Live Weight for Procellarid = 0.60 g-dry wt./g-live wt. (estimated from N.R.C. (1971))

Notes to economic losses in Table III.9 Emergy losses (L_i, LPP_i, and M_i) of the *Exxon Valdez* oil spill.

Loss **Description & Source**

L_{10} **Lost Prince William Sound Fishery Harvest in 1989 as a Result of the Valdez Spill**

= ((Lost Fishery Catch) + (Lost Roe Harvest)) g-live wt. * (Ratio of Live Weight to Dry Weight for Fish) g-dry wt./g-live wt. (D.15)

Lost Fishery Catch = 7.5E+09 g-live wt. (from Baker et al. (1991))

Lost Roe Harvest = 1.7E+09 g-live wt. (from Royce et al. (1991))

Ratio of Live Weight to Dry Weight for Fish & Roe = 0.26 g-dry wt./g-live wt. (estimated from N.R.C. (1971))

L_{AKNS} **Decreased Trans-Alaskan Pipeline Flow in 1989 Following Valdez Grounding**

= 1.3E+07 bbl (N.R.T., 1989)

L_{fuel} **Fuel Used in Valdez Spill Cleanup**

= 1.0E+06 bbl (1.5 times Harrison's[a] fuel use for Exxon 1989-1991 vessel operations in the Gulf of Alaska)

L_{oil} ***Exxon Valdez* Crude Oil Cargo Lost In Grounding**

= 2.58E+05 bbl (Harrison, 1991)

L_{vessel} **Vessel Deterioration During Valdez Cleaning Operations** [b]

= (Vessels in 1989 Cleanup Related Operations) vessels + (Average Size of Vessels) Mg/vessel + (Fraction of Vessel Life Spent in Cleanup Operations) (D.16)

Vessels in 1989 Cleanup Related Operations = 850 vessels (Carpenter et al., 1991)

Average Size of Vessels = 150 Mg/vessel (estimated from A.O.S.C. (1990))

Fraction of Vessel Life Spent in Cleanup Operations = 0.050 (assumed)

L_{people} **Social Disruption Resulting From the Valdez Spill and Cleanup**

(Brown and Owen, Unpublished Data)[c]

= (Number of people affected) * (Time) (D.17)

number of people = 8,000 people (fraction of population in region affected (estimted from A.D.C.E.D (1984); Michelson (1989), and Impact Assesment, Inc. (1990))

time = 2 years (estimated from Impact Assesment, Inc. (1990))

$L_{services}$ **Human Services Embodied In Valdez Cleaning Operations**

= (Cost of Alaska State Government Cleanup Related Operations) \$ + (Cost of Exxon Cleanup Related Operations) \$ + (Cost of Federal Government Cleanup Related Operations) \$(D.18)

Cost of Alaska Operations = 4.0E+07 \$ (A.O.G. (1991), excluding research and legal costs)

Cost of Exxon Operations = 2.5E+09 \$ (Holloway (1991), excluding legal costs)

Cost of Federal Operations = 1.54E+08 \$ (Holloway (1991), excluding research and legal costs)

L_{10} **Lost Prince William Sound Fishery Harvest in 1989 as a Result of the Valdez Spill**

= ((Lost Fishery Catch) + (Lost Roe Harvest)) g-live wt. * (Ratio of Live Weight to Dry Weight for Fish) g-dry wt./g-live wt. (D.19)

Lost Fishery Catch = 7.5E+09 g-live wt. (from Baker et al. (1991))

Lost Roe Harvest = 1.7E+09 g-live wt. (from Royce et al. (1991))

Ratio of Live Weight to Dry Weight for Fish & Roe = 0.26 g-dry wt./g-live wt. (estimated from N.R.C. (1971))

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[a] Data given by O.R. Harrison, Exxon Co., U.S.A., during presentation of Harrison (1991), San Diego, CA., 5 March 1991.

[b] Not included in Table III.9 as the calculated value was too small to be significant in the analysis.

[c] M.T. Brown and P. Owen. University of Florida, Center for Wetlands and Water Resources.

APPENDIX E

NOTES AND CALCULATIONS IN SUPPORT OF THE EMERGY ANALYSIS OF OIL SPILL PREVENTION ALTERNATIVES

Table E.1. Designations for the oil spill prevention analyses.

Alternative Designation	Oil Spill Prevention Alternative
United States Tanker Fleet:	
1	Group I System Modifications: mandatory crew drug and alcohol testing; emergency and high-risk navigation area training; port restrictions/port closure system; two person watch standing requirement; improved loading/unloading procedures; local spill cleanup/prevention involvement; spill response equipment coordination (Keith et al., 1990)
2	Group II System Modifications: vessel monitoring system, traffic separation lanes, designated anchorage areas, emergency response/pollution control vessels, improved loading/unloading design (Keith et al., 1990)
3	Groups I and II System Modifications: (Keith et al., 1990)
4	double hull with hydrostatic vacuum tanker design (National Research Council, 1991)
5	double side with hydrostatic vacuum tanker design (National Research Council, 1991)
6	MARPOL vessel with hydrostatic vacuum tanker design. MARPOL refers to a ship designed according to the International Maritime Organization's 1978 Protocol on reducing marine pollution (National Research Council, 1991)
7	intermediate oil-tight deck with double sides tanker design (National Research Council, 1991)
8	double-hull tanker design (National Research Council, 1991)
9	small-tank tanker design (National Research Council, 1991)
10	double-bottom tanker design (National Research Council, 1991)
Alaskan Tanker Fleet:	
11	Group I System Modifications: mandatory crew drug and alcohol testing; emergency and high-risk navigation area training; port restrictions/port closure system; two-person watch standing requirement; improved loading/unloading procedures; local spill cleanup/prevention involvement; spill response equipment coordination (Keith et al., 1990)
12	Group II System Modifications: vessel monitoring system, traffic separation lanes, designated anchorage areas, emergency response/pollution control vessels, improved loading/unloading design (Keith et al., 1990)
13	double-hull tanker design (Group III System Modifications (Keith et al., 1990)
14	Groups I and II System Modifications: (Keith et al., 1990)
15	Groups I, II, and III System Modifications: (Keith et al., 1990)

Table E.2. The equations used in the oil spill prevention alternatives analyses to calculate net emergy benefits for each alternative *i*.

Emergy Required to Implement Alternative *i* = (Monetary Cost of Implementing & Operating *i*) \$ * Emergy-Money Ratio sej/\$ + (Steel Required to Implement and Operate *i*) g * Transformity of Steel) sej/g (E.1)

Emergy Benefit in Natural Resources or Natural Resource Damage Prevented by Implementing *i* = (Oil Spillage Prevented By Alternative *i*) Mg oil * (Natural Resource Loss From the Valdez Spill) sej / (Oil Spillage In the Valdez Spill) Mg oil (E.2)

Emergy Benefit in Economic System Losses Prevented by Implementing *i* = (Oil Spillage Prevented by *i*) Mg oil * (Economic System Loss in the Valdez Spill) sej / (Oil Spillage in the Valdez Spill) Mg oil (E.3)

Preliminary Net Emergy Benefit to Society of Implementing *i* = (Emergy Benefit in Economic System Losses of Implementing i) sej + (Emergy Benefit in Natural Resource of Implementing *i*) sej - (Emergy Required to Implement *i*) sej (E.4)

Ratio of Net Emergy Benefit of Implementing *i* = (Emergy Benefit in Natural Resources of *i*) + (Emergy Benefit in Economic System Losses of *i*) sej / (Emergy Required to Implement *i*) sej (E.5)

Table E.3. Data used in calculation of U.S. tanker fleet oil spill prevention alternative net emergy benefits in Table III.10

Term	Estimate	Units	Description & Source
Alternative *i*'s Implementation And Annual Operating Cost Plus Amortized Over 20 Years			
i_{max}		\$/y	maximum estimate for *i*
i_{min}		\$/y	minimum estimate for *i*
1_{max}	1.24E+08	\$/y	calculated from Keith et al.(1990)
1_{min}	2.86E+06	\$/y	calculated from Keith et al.(1990)
2_{max}	4.91E+08	\$/y	calculated from Keith et al.(1990)
2_{min}	1.99E+06	\$/y	calculated from Keith et al.(1990)
3_{max}	6.15E+08	\$/y	calculated from Keith et al.(1990)
3_{min}	2.28E+07	\$/y	calculated from Keith et al.(1990)
4	2.10E+09	\$/y	(National Research Council, 1991)
5	8.70E+08	\$/y	(National Research Council, 1991)
6	1.10E+09	\$/y	(National Research Council, 1991)
7	8.70E+08	\$/y	(National Research Council, 1991)
8	7.10E+08	\$/y	(National Research Council, 1991)
9	4.30E+08	\$/y	(National Research Council, 1991)
10	4.60E+08	\$/y	(National Research Council, 1991)
Oil Spillage Prevented Annually by Alternative *i*			
i_{max}		Mg/y	maximum estimate for *i*
i_{min}		Mg/y	minimum estimate for *i*
1	950	Mg/y	calculated from Keith et al.(1990)
2	2800	Mg/y	calculated from Keith et al.(1990)
3	3300	Mg/y	calculated from Keith et al.(1990)
4_{max}	5100	Mg/y	National Research Council (1991)
4_{min}	3500	Mg/y	National Research Council (1991)
5_{max}	5000	Mg/y	National Research Council (1991)
5_{min}	3500	Mg/y	National Research Council (1991)
6_{max}	4900	Mg/y	National Research Council (1991)
6_{min}	3400	Mg/y	National Research Council (1991)
7_{max}	4900	Mg/y	National Research Council (1991)
7_{min}	3600	Mg/y	National Research Council (1991)
8_{max}	4800	Mg/y	National Research Council (1991)
8_{min}	3000	Mg/y	National Research Council (1991)
9_{max}	2500	Mg/y	National Research Council (1991)
9_{min}	1900	Mg/y	National Research Council (1991)
10_{max}	4100	Mg/y	National Research Council (1991)
10_{min}	2400	Mg/y	National Research Council (1991)
Emergy Of Materials Invested In Implementing *i*			
i_{max}		g/y	steel used in implementing alternative for 1500 different tankers/y of average world fleet size docking in U.S. (National Research Council, 1991) amortized over 20 years
i_{min}		g/y	steel used in implementing alternative for 257 U.S. flag tankers of average world fleet size (National Research Council, 1991) amortized over 20 years

Table E.3. Continued.

Term	Estimate	Units	Description & Source
4_{max}	1.1E+12	g/y	assuming 200% MARPOL lightweight
4_{min}	1.9E+11	g/y	assuming 200% MARPOL lightweight
5_{max}	5.3E+11	g/y	assuming 150% MARPOL lightweight
5_{min}	9.3E+10	g/y	assuming 150% MARPOL lightweight
6_{max}	0	g/y	assuming 100% MARPOL lightweight
6_{min}	0	g/y	assuming 100% MARPOL lightweight
7_{max}	2.6E+11	g/y	assuming 125% MARPOL lightweight
7_{min}	4.6E+10	g/y	assuming 125% MARPOL lightweight
8_{max}	1.1E+12	g/y	assuming 200% MARPOL lightweight
8_{min}	1.9E+11	g/y	assuming 200% MARPOL lightweight
9_{max}	5.3E+11	g/y	assuming 150% MARPOL lightweight
9_{min}	9.3E+10	g/y	assuming 150% MARPOL lightweight
10_{max}	2.6E+11	g/y	assuming 125% MARPOL lightweight
10_{min}	4.6E+10	g/y	assuming 125% MARPOL lightweight
Oil Spilled by the *Exxon Valdez*			
	34,400	Mg	Harrison (1991)

Notes to Table III.10. The emergy investments in implementation, natural resource damage prevented, and net emergy benefits for 10 spill prevention alternatives for the U.S. tanker fleet. Adjustments are added to the estimates for loss per metric ton of oil spilled in the Valdez incident. The sum of the two estimates is multiplied by oil spillage prevention estimates to generate the values in Table III.10.

Column B Adjustment: Ecological Damage Adjustment

= (Valdez Ecological Damage/Mg oil spilled) sej /Mg + (Salt Marsh Damage/Mg oil spilled) sej /Mg + (Mangrove Damage/Mg oil spilled) sej/Mg (E.6)

Valdez Damage = 7.6E+15 - 7.3E+16 sej/Mg (Table III.9)

Salt Marsh Damage = (ha oiled/Mg oil spilled) ha/Mg * ((Biomass/ ha) J/ha) + ((Recovery Time) y * (net production/ha) J/ha-y * (percent of production lost during recovery))) * (Salt Marsh Biomass Transformity) sej/J (E.7)

ha oiled/Mg oil spilled = 0.58 - 2.0 ha/Mg (Brown, 1989; Fischel et al., 1989)
Biomass/ha = 6.0E+10 J/ha (Turner, 1976)
Recovery Time = 4 y (estimated from Hampson and Moul (1978) and Burns and Teal (1979)
Percent of production lost during recovery = 50% (assumed)
Salt Marsh Biomass Transformity = 9000 sej/J (estimated from Hornbeck and Odum (In Review))

Mangrove Damage = (ha oiled/Mg oil spilled) ha/Mg * ((Biomass/ ha) J/ha) + ((Recovery Time) y * (net production/ha) J/ha-y * (percent of net production lost during recovery))) * (Mangrove Biomass Transformity) sej/J (E.8)

ha oiled/Mg oil spilled = 3.2E+02 - 5.9E+02 ha/Mg (estimated from Ballou and Lewis (1989) and Teas et al. (1989))
Biomass/ha = 7.0E+10 J/ha (calculated from Lugo et al. (1976))
Mangrove net primary production = 2.0E+11 J/ha-y (calculated from Brown and Lugo, 1982)
Recovery Time = 20 y
Percent of production lost during recovery = 50% (assumed)
Mangrove Biomass Transformity = 15000 sej/J (Odum and Arding, 1991)

Column C Adjustment: Economic Damage Adjustment

= (Valdez Economic Damage/Mg oil spilled) sej/Mg + (Florida case study Coastal Tourism loss/Mg oil spilled) sej/Mg (E.9)

Valdez Economic Damage = 1.4E+17 sej (Table III-B-1)

Florida case study Coastal Tourism loss/Mg oil spilled) = (((FL beach tourism employment) person-y * (J/person-y) * (% of y devoted to labor) * (high school educational level Transformity) sej/J) + (Annual FL beach tourism receipts) $/y) * (U.S. Emergy Money Ratio))* (% of tourism loss in Cadiz spill) * (length of tourism loss) y / (Florida Coastline Length) km) * (Valdez coastline oiling / Mg oil spilled) km/Mg (E.10)

FL beach tourism employment = 1.79E+05 person-y (Bell and Leesworthy, 1986)
J/person-y = 3.8E+09 (Odum, 1988)
% of y devoted to labor = 66% (assumed)
high school educational level Transformity = 2.5E+07 sej/J (Odum, 1988)
Annual FL beach tourism receipts = 4.6E+09 $/y (Bell and Leesworthy, 1986)
% of tourism loss in *Amoco Cadiz* oil spill = 17% (Bonnieux and Rainelli, 1978)
length of tourism loss = 1 - 4 y (Assumed)
Florida Beach Coastline Length = 1400 km (estimated from Bell and Leesworthy (1986)
Valdez coastline oiling / Mg oil spilled = 38 km/Mg (estimated from *Exxon Valdez* spill (A.D.N.R., Unpublished Data)

Table E.4. Data used in calculation of Alaskan tanker fleet oil spill prevention alternative net emergy benefits in Table III.11

Term	Estimate	Units	Description & Source
Alternative *i*'s Implementation And Annual Operating Cost Plus Amortized Over 15 Years			
i_{max}		$/y	maximum estimate for *i*
i_{min}		$/y	minimum estimate for *i*
11_{max}	1.9E+06	$/y	Keith et al.(1990)
11_{min}	1.9E+06	$/y	Keith et al.(1990)
12_{max}	2.0E+07	$/y	Keith et al.(1990)
12_{min}	2.0E+07	$/y	Keith et al.(1990)
13_{max}	5.6E+08	$/y	Keith et al.(1990)
13_{min}	2.8E+08	$/y	Keith et al.(1990)
14_{max}	3.9E+06	$/y	Keith et al.(1990)
14_{min}	3.9E+06	$/y	Keith et al.(1990)
15_{max}	5.6E+08	$/y	Keith et al.(1990)
15_{min}	2.8E+08	$/y	Keith et al.(1990)
Oil Spillage Prevented Annually by Alternative *i*			
i_{max}		Mg/y	maximum estimate for *i*
i_{min}		Mg/y	minimum estimate for *i*
11	1400	Mg/y	Keith et al.(1990)
12	4000	Mg/y	Keith et al.(1990)
13_{max}	2.9E+04	Mg/y	estimated from Keith et al.(1990)
13_{min}	5400	Mg/y	Keith et al.(1990)
14	4800	Mg/y	Keith et al.(1990)
15_{max}	3.3E+04	Mg/y	estimated from Keith et al.(1990)
15_{min}	7500	Mg/y	Keith et al.(1990)
Emergy Of Materials Invested In Implementing *i*			
i_{max}		Mg/y	steel used in double hulling 1/2 the 93 vessel fleet licensed for AK (A.O.S.C., 1990) amortized over 20 years
i_{min}		Mg/y	steel used in double hulling the 93 vessel fleet licensed for AK (A.O.S.C., 1990) amortized over 20 years
13_{max}	6.9E+05	Mg/y	assuming 200% MARPOL lightweight
13_{min}	3.5E+05	Mg/y	assuming 200% MARPOL lightweight
15_{max}	6.9E+05	Mg/y	assuming 200% MARPOL lightweight
15_{min}	3.5E+05	Mg/y	assuming 200% MARPOL lightweight
Oil Spilled by the *Exxon Valdez*			
	34,400	Mg	Harrison (1991)

APPENDIX F

NOTES AND CALCULATIONS IN SUPPORT OF THE EMERGY ANALYSIS OF INFORMATION FRENZY AND THE VALDEZ OIL SPILL DISASTER

Notes to Table III.12. Emergy analysis of the U.S. television industry.

Note:

1 TV transmission using figures collected by Morton (1991) in an emergy analysis of television transmission and image of the United States,

2 10.4 E17 J/y * 2.0E+04 sej. H = 20.3E+22 sej/y

3 3.6 E10 $* .05 * 1.6E+12 sej/$ = 0.28 E22 sej/y

4 3.87 E5 people * 2500 kcal/d/person * 4186 J/kcal* 365 d/y * 150E+06 sej/J = 22, 1E+22 sej/y

5 TV reception using figures collected by Morton (1991)

6 0.15 kwh/hr*7.1 h/day*365 d/y*3.6E+06 J/kwh*160 E6 sets*2E+05 sej/J = 4.48E+22 sej/y

7 (TV sets 4.65E+10 $/y and cable 1.28E+10 $./y)*1.6E+12 sej/$ = 9.5E+22 sej/y; $287 each set

8 1.749+E11 people watching * (7 hr/24 hr) *900E+22 sej/y

9 845E+22 sej/y for 1983 increased by 1.0E+19 J/y fuel use using 5.4E+04 sej/J.

10 4.5E22+ 9.5E+22 = 11.5E+22 sej/y/1.62E+08 TV sets = 7.1E+14 sej/set/y

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Notes to Table III.13. Emergy aspects of the *Exxon Valdez* oil spill based on one hour television transmission and 0.5 hour reception per person.

Note:

1 Oils spill evaluation 4.0E+20 sej in oil loss

2 Averaged from Woithe (1992)

3 Assume the emergy value of the information transmitted as that required to create the image, and the emergy of the actual damage

4 TV copying and transmission from Table III.12: 42.7E+22 sej/8760 hrs/y =0.49 sej/hr

5 Reception in U.S.A. from Table III.12, 14.0E+22 sej/hr;
7hr/day * 365 days = 2555 hours per person watching TV
(14.0E+22 sej/hr)/(2555 hrs)= 0.55E+20 sej/hr watching

6 Emergy added for people watching one half-hour each:
Emergy per person per hour from total annual emergy of U.S.
365 * 24 = 8760 hours per year
(900E+22 sej/USA/y)(0.5/8760 hr/y)= 5.1E+20 sej

7 Total of items 4-7

8 2.5 billion dollar expenditure by Exxon and 0.1 billion by Federal Government; half spent in Alaska and half in mainland USA (0.5 * 2.6E+09 $/y * 8.6E+12 sej/$) + (.5 * 2.6E+09 $/y * 1.6E+12 $/y) = 1.32E+22;

9 Eight-day interruption of oil shipments: 0.47.7E+22 sej

Notes to Table III.14. Emergy analysis of human disturbance from the *Exxon Valdez* oil spill.

Note:

1. In 1989 the unemployment rate in the Valdez-Cordova area dropped to 5.5%, about 1% less than in 1988, half thought to be due to the spill. (Alaska Oil Spill Reporter, 1989). The population in the Valdez-Cordova area in 1988 was about 6,210. (Alaska Dept. of Labor, 1990) (6,210)(.065)-(6,210)(.055)=62/2=31.

2. Since drug abuse costs $60 billion per year in the USA in lost productivity (The White House, Sept. 1989) and the population of the USA in 1988 was 246E+06 (US Statistical Abstract, 1990), loss of productivity averaged $243.90. The spill area population was 27,500 in 1988 (Alaska Dept. of Labor, 1990). It was estimated that the number of DUI's (driving under the influence of alcohol or drugs) increased by 600% (Townsend and Heneman, 1989)(6)($243.9)(27,500) = $4.0E+07

3. Population changes

   (Alaska Dept. of Labor, 1990) (State of Alaska, 1991)

	July 1, 1988	1990 census	change
Spill area	27,592	27,537	-0.2%
Alaska state	531,000	550,043	+3.8%

   The spill area population change is a difference from the state average change which is 3.8%. (.038)*(27592 people) = 1045 people

4. Alaska Governor Steve Cowper approved $1.3 million in state assistance to communities impacted by the *Exxon Valdez* oil spill. (Alaska Information Service, 1989)

5. The earned income in the spill area in 1989 was estimated at $280 million and in 1989 at $410 million. (Keeble, 1991)

APPENDIX G

NOTES AND CALCULATIONS IN SUPPORT OF THE NET EMERGY ANALYSIS OF ALASKAN NORTH SLOPE OIL

Notes to Table III.15. Emergy analysis of North Slope oil.

Note:

1 Total Oil Flow = 10.4E+09 bbl (Resource Development Council, Feb. 1991)
Energy = (10.4E+09 bbl) * (6.12 E9 J/bbl)
= 6.3648E+19 J

2 Environmental Production Lost in area of terminals and pipeline (30 yrs)
Area = 1.27E+04 ha (estimated)
Production = 2.1E+10 sej/ha/yr
Energy = (area) * (production) * (30 years)
= 8.0E+15 sej

3 Steel used in pipeline and supports
Pipe = 3.3E+06 tons (estimated)
Supports = 0.35E+06 tons (estimated)
Terminal = 0.96E+06 tons (estimated)
Total 4610000 tons

4 Cost of pipeline and facilities (1971 dollars)
$2,500,000,000.0 (Cicchetti, 1972)

5 Oil field production costs (1990 dollars)
$4.7E+10 (Resource Development Council, 4/1991)

6 Operation and Maintenance costs (1971 dollars)
($0.13E+09/yr) = $3,900,000,000.0 (Cicchetti, 1972)

7 Repair costs (1990 dollars)
$1,500,000,000.0 (Alaska Information Service, 2/1991)

8 State taxes (1988 dollars)
Taxes = $2.17/bbl (Alaska Information Service, 3/1989)
Oil flow = 10.4E+09 bbl
Total taxes = $2.3E+10

9 Federal taxes (1988 dollars)
Taxes = $1.06/bbl (Alaska Information Service, 3/1989)
Oil flow = 10.4E+09 bbl
Total taxes = $1.1E+10

10 Transportation Costs
$0.35/bbl (1971 dollars) (Cicchetti, 1972)
$0/56/bbl (1975 dollars) (U.S. Congress, 1975)
Total costs = ($0.40/bbl)(10.4E+09 bbl)
= $4,160,000,000.0

11 Losses associated with Exxon Valdez oil spill (Table III.9)
Env. damage = 2.61E+21
Economic costs = 4.31E+21
Misc costs & losses = 7.78E+20
Total = 7.70E+21 sej