Environmental Value Engineering (EVE) 
Environmental Life Cycle Assessment of 
Concrete and Asphalt Highway Pavement Systems

by Wilfred H. Roudebush

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ENVIRONMENTAL VALUE ENGINEERING (EVE)
ENVIRONMENTAL LIFE CYCLE ASSESSMENT
OF CONCRETE AND ASPHALT HIGHWAY PAVEMENT SYSTEMS

By

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asphalt, concrete, EMERGY, environmental life cycle assessment, pavement

ABSTRACT
An environmental life cycle assessment of concrete and asphalt highway systems was conducted using the Environmental Value Engineering methodology. The methodology compared environment, fuel energy, goods, and services input sources in terms of EMERGY for subsystems of both highway pavement system alternatives over a life cycle consisting of 10 phases: natural resource formation, natural resource exploration and extraction, material production, design, component production, construction, use, demolition, natural resource recycling, and disposal.

EMERGY input tables were prepared by calculating EMERGY inputs to subsystems of each pavement alternative during each of the environmental value engineering life cycle phases. Aggregated EMERGY input source data tables were compiled from EMERGY input table data.

Aggregated phase EMERGY input signatures were constructed for each pavement system alternative to compare inputs of environment, fuel energy, goods and services during the ten phase life cycle. A total phase EMERGY input signature and graphical simulation output of cumulative total input source EMERGY were constructed using aggregated EMERGY input source data tables to compare pavement system alternatives.

A comparison based on EMERGY input data presented in the report indicates that the concrete pavement system has approximately 47.6% less impact on the environment than the asphalt concrete pavement system. Further analysis of the data indicates potential EMERGY concentration reductions possible during the life cycle of both pavement system alternatives.

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ABSTRACT

An environmental life cycle assessment of concrete and asphalt highway systems was conducted using the Environmental Value Engineering methodology. The methodology compared environment, fuel energy, goods, and services input sources in terms of EMERGY for subsystems of both highway pavement system alternatives over a life cycle consisting of 10 phases: natural resource formation, natural resource exploration and extraction, material production, design, component production, construction, use, demolition, natural resource recycling, and disposal.

EMERGY input tables were prepared by calculating EMERGY inputs to subsystems of each pavement alternative during each of the environmental value engineering life cycle phases. Aggregated EMERGY input source data tables were compiled from EMERGY input table data.

Aggregated phase EMERGY input signatures were constructed for each pavement system alternative to compare inputs of environment, fuel energy, goods and services during the ten phase life cycle. A total phase EMERGY input signature and graphical simulation output of cumulative total input source EMERGY were constructed using aggregated EMERGY input source data tables to compare pavement system alternatives.
A comparison based on EMERGY input data presented in the report indicates that the concrete pavement system has approximately 47.6% less impact on the environment than the asphalt concrete pavement system. Further analysis of the data indicates potential EMERGY concentration reductions possible during the life cycle of both pavement system alternatives.
CHAPTER 1
INTRODUCTION

This environmental value engineering assessment compares the environmental impact of concrete and asphalt highway pavement alternatives. The comparison is conducted in terms of EMERGY inputs of environment, fuel energy, goods, and services (labor). EMERGY, spelled with an "M", is a scientific-based measure of wealth, that puts raw materials, commodities, goods, and services on a common basis, the energy of one type required to generate that item (Odum, 1991).

An environmental value engineering assessment compares multiple built environment alternatives over a life cycle consisting of 10 phases: natural resource formation, natural resource exploration and extraction, material production, design, component production, construction, use, demolition, natural resource recycling, and disposal. Because these phases successively accumulate the results of work, EMERGY tends to increase with each phase. This environmental value engineering assessment depicts EMERGY concentrations that occur during the life cycles of the concrete and asphalt concrete pavement system alternatives. The purpose of this assessment is to determine which pavement system alternative has the least environmental impact in terms of EMERGY.
Organization of the Assessment

Chapter 1 contains an introduction to the assessment, environmental value engineering concepts and definitions, and assessment description.

Chapter 2 presents the energy systems diagrams and language methods used in the assessment, aggregated environmental impact EMERGY input calculation and assessment methods.

The results of this assessment are presented in Chapter 3 in the form of EMERGY calculations, EMERGY input source data tables, aggregated and total phase EMERGY input signatures, and comparisons of the concrete and asphalt highway pavement system alternatives.

Chapter 4 presents a discussion of the assessment, recommendations for future research and applications, and closing remarks.

Concepts and Definitions

Built Environment Inputs

The term "built environment", as used in this assessment, includes all human-made objects (alternatives) on earth that consume environment (E), fuel energy (F), goods (G), and services (S) inputs. This is represented in the energy systems diagram of Figure 1-1 using energy systems language explained in CHAPTER 2 METHODS. Money circulates into the system to pay only for services (labor) rendered by human population. Money
is not paid to the environment, and money that is paid to people cannot be used to evaluate benefits or losses to the environment.

**Environmental Value Engineering**

An assessment system called environmental value engineering was developed to account for the environmental role of built environment alternatives. This evaluation system is based on Dr. Howard T. Odum's EMERGY analysis methodology. Dr. Odum is Graduate Research Professor and Director of the Center for Environmental Policy at the University of Florida.

Life cycle, was defined to include all phases that a built environment alternative goes through, from natural resource formation through final disposal. A built environment

![Energy systems diagram of pavement system alternative.](image)

Figure 1-1. Energy systems diagram of pavement system alternative.
alternative uses the earth's renewable and nonrenewable resources throughout its life cycle. Consumption of minerals and energy begins with the conception of a built environment alternative and continues beyond its use phase. For convenience, environmental value engineering has 10 built environment alternative life cycle phases (Figure 1-2).

Traditional evaluation uses money. Since money goes only to pay for human services, it is not suitable for environmental value engineering. Embodied energy could not be used either because it accounts only for fuel energy and does not include environmental, goods, or services input sources.

Since production and consumption processes, which take place during all phases of a built environment alternative's life cycle, use energy of differing quality or type, EMERGY was selected as the basic unit of quantification because it is energy of differing types into units of one type of energy. The name "EMERGY" was coined by David Scienceman in 1983 to distinguish it from other embodied energy concepts. Scienceman (1987) documented the nomenclature of energy and EMERGY. So as not to confuse EMERGY with energy, the word EMERGY is capitalized in this assessment. Solar emjoules (sej) are the units of solar EMERGY, used in environmental value engineering. According to Odum (1995), solar EMERGY is the solar energy required directly and indirectly to make a product or service (units: solar emjoules).

Environmental value engineering evaluates the
environmental contribution and impact of built environment alternatives in units of solar EMERGY over the life cycle. The sum of EMERGY contributions to each phase is added as an input to the next. EMERGY accumulates from one phase to the next. "EMERGY is not only a measure of what went into a product, it is a measure of the useful contributions which can be expected from that product as an economy self organizes for maximum production" (Odum, 1991, p. 91). An alternative is best which contributes most while drawing the least from the main economy.

<table>
<thead>
<tr>
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<th>PHASE D</th>
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Figure 1-2. Environmental value engineering phases of life cycle.
Environmental Value Engineering Phases of Life Cycle

The assessment period of environmental value engineering is subdivided into 10 phases through which built environment alternative materials, components, and systems proceed. This is a distinct difference between environmental value engineering and other assessment systems.

The 10 phases of environmental value engineering are based upon different production and consumption processes taking place within each phase. These production and consumption processes have distinct categorical environmental impact input requirements of environment (E), fuel energy (F), goods (G), and services (S). For example, the following are inputs accounted for during construction phase F:

E. Environment (renewable)
   E1. Atmosphere
   E2. Ecological production
   E3. Energy
       1. Sun
       2. Earth
   E4. Land
       1. Area
       2. Resources
   E5. Water
       1. Area
       2. Resources
   E6. Materials

F. Fuel energy (nonrenewable)
   F1. Equipment
   F2. Facilities
   F3. Materials

G. Goods
   G1. Equipment
   G2. Facilities
   G3. Materials
   G4. Tools

S. Services
   S1. Labor
   S2. Materials
A list of environmental impact EMERGY input sources for all 10 environmental value engineering phases is provided in Appendix A. Transportation of materials is included in all life cycle phases except natural resource formation phase A.

The production and consumption processes of the 10 phases of environmental value engineering are described in the following subsections. Phases A through C consist of the material transformity phases.

**Phase A: natural resource formation**

The natural resource formation phase involves the production and consumption of various environmental systems (ecosystems, geology systems, etc.). Natural resources utilized in built environment alternatives include minerals, which are formed by earth processes over millions of years, and biomass, resulting from living organism net production occurring over shorter periods of time.

**Phase B: natural resource exploration and extraction**

The natural resource exploration and extraction phase includes EMERGY of environment, fuel energy, goods, and services inputs occurring during natural resource exploration and extraction processes. Also, environmental impacts assignable to this phase include renewable environmental inputs in the form of land used during extraction and storage of extracted natural resources. Reclamation of land, after natural resource extraction, and transportation of natural resources for material production is included during this
phase. Transportation of pavement materials are included during construction phase F and use phase G. Environmental impact EMERGY related to natural resource exploration and extraction will probably increase in the future.

**Phase C: material production**

The material production phase includes EMERGY of environment, fuel energy, goods, and services inputs occurring during material production. Material production includes the conversion of natural resources into materials used in built environment alternative component production. Some materials are produced directly into standardized components. Examples of standardized components are structural steel, doors, windows, dimensional lumber, and roofing components. Many components of a built environment alternative are not produced until specific design information has been provided.

**Phase D: design**

The design phase includes EMERGY of environment, fuel energy, goods, and services inputs occurring during architectural and engineering design. The design phase includes five subphases. According to the American Institute of Architects (1987), these subphases are: 1) schematic design, 2) design development, 3) construction documents, 4) bidding and negotiations, and 5) construction administration.
Phase E: component production

The component production phase includes EMERGY of environment, fuel energy, goods, and services inputs occurring during component production. Some standard components are produced and stored, before use, while other components are obtained as needed. Component production is conducted by manufacturing facilities specializing in various built environment alternative components.

Production of components specifically designed for a built environment alternative proceed upon completion and acceptance of production documents during the construction administration subphase of design, which overlaps with the construction phase. Components produced at the job site are included in the construction phase instead of the component production phase. For example, concrete and asphalt concrete pavement systems are produced during construction phase F. Materials for systems such as this are included in material transformity phases A-C. Phase E includes the environmental impacts related to transportation of the various components to the built environment alternative site for construction.

Phase F: construction

During construction, materials, components, and subsystems are assembled into systems through the use of environment, fuel energy, goods, and services inputs into built environment alternative systems. Environment, fuel energy, goods, and services inputs used during this phase are
dependent upon such factors as type of construction, techniques of construction, time of construction, quality of materials, components and subsystems, and workmanship.

Construction related environmental impacts, such as construction wastes, are accounted for during this phase. This phase also includes work done during the guarantee and warranty periods of the construction contract, which commence at the beginning of the built environment alternative use phase.

Phase G: use

The use phase includes EMERGY of environment, fuel energy, goods, and services inputs occurring during use, operation, and maintenance up to time of built environment alternative demolition. Included are financing, maintenance, operation, alteration, repair, replacement, tax elements, insurance, and any other activities that require EMERGY inputs.

The use phase includes the period of time from substantial completion of construction to the demolition phase. Included are periods of nonuse or abandonment. The use phase is affected by quality of materials, decisions on utilization of recycled materials, components, and subsystems, and phase duration.

EMERGY inputs related to vehicular use of pavement system alternatives is not included in this assessment.
Phase H: demolition

The demolition phase includes EMERGY evaluation of environment, fuel energy, goods, and services inputs used to demolish and remove the materials, components, and systems. The EMERGY evaluation is sensitive to decisions on reuse and recycling of materials, components, and systems during this phase.

Currently, most built environment alternative materials, components, and systems are disposed of in the form of demolition debris during the demolition phase. Disposal of this demolition debris affects land use because one cubic yard of landfill is required for each 1000 to 1200 pounds of demolition debris (Roudebush, 1992). The EMERGY for disposals is accounted for in phase J (disposal phase). As land becomes less available for disposal of demolition debris, environmental policies related to the built environment will affect the selection of materials, components, and systems (Roudebush, 1991).

Phase I: natural resource recycling

The natural resource recycling phase includes the EMERGY of environment, fuel energy, goods, and services inputs used to recycle materials, components, and systems. EMERGY inputs can be reduced if recycling increases natural resource formation (Phase A), and decreases natural resource exploration and extraction (Phase B), material production (Phase C), and component production (Phase E) requirements of
future built environment alternatives.

Salvage of demolition debris for recycling reduces the EMERGY required for disposal and landfill land use. Thus there is an EMERGY credit for salvage of demolition debris. Resource recycling during any phase of environmental value engineering reduces total EMERGY required.

The natural resource recycling phase of a built environment alternative is similar to the nutrient feedback phase of natural systems. System designs that maximize empower (EMERGY flux) are also the systems that feed back to the larger system of which they are a part (Odum, 1988). Disposal of built environment alternative materials, components, and systems with stored EMERGY affects sustainable development that is discussed in Chapter 4 of this assessment.

Phase J: disposal

The disposal phase includes EMERGY of environment, fuel energy, goods, and services inputs occurring during the disposal of materials, components, and systems. Included in the evaluation are demolition debris placement, demolition debris compaction, demolition debris landfill containment, landfill closure, and landfill postclosure. According to Topp (1985), landfill closure and postclosure include groundwater monitoring, final cover, contour grading, surface water diversion, gas mitigation control, revegetation, security systems, and certification of closure. The EMERGY inputs of these activities must be included.
Land use for disposal of demolition debris will become more important in the future. The EMERGY of land will increase as intensity of land use increases with population growth. Cumulative EMERGY of lands and their stored demolition debris measures the environmental impact and loss of resource contribution (Roudebush, 1992).

Hierarchical Organization

Environmental value engineering synthesizes the total EMERGY of all systems of a built environment alternative during the 10 environmental value engineering life cycle phases. Each phase of a built environment alternative forms a portion of an EMERGY hierarchy for that alternative. It appears to be an example of an energy transformation hierarchy as defined in Odum (1991). The built environment alternative EMERGY hierarchy also may be represented by a series of stepwise transformations from materials, to components, to subsystems, to a whole alternative.

To account for total EMERGY input to highway pavement alternatives through all 10 life cycle phases of environmental value engineering, a hierarchical organization designation system was developed.

The EMERGY input designation system utilized in this assessment is based on divisions given in FP-92 Standard Specifications for Construction of Roads and Bridges on Federal Highway Projects (U. S. Department of Transportation, 1992). A list of these EMERGY input designation divisions and
subdivisions is provided in Appendix D.

Environmental value engineering incorporates the EMERGY input designation system to account for the EMERGY of environment, fuel energy, goods, and services inputs to be used through the environmental value engineering assessment of the concrete and asphalt highway pavement alternatives.

Description of Pavement System Alternatives

This section describes the concrete and asphalt concrete highway pavement system alternatives of this assessment. Assumptions for each pavement system alternative are listed in their respective sections.

Pavement dimensions for both pavement alternatives were 24 feet wide by 3280.8398 feet (one kilometer) long. Thicknesses for each pavement alternative are described in the following sections.

The use phase for each pavement alternative was 50 years. EMERGY inputs that occurred during the use phase of the concrete and asphalt concrete pavement alternatives for resurfacing, demolition, and removal are described in the following sections, respectively. EMERGY inputs related to vehicular use of pavement alternatives are not included in this assessment.

Concrete Pavement System

Components of the concrete pavement system alternative are given in Figure 1-3.
Figure 1-3. Concrete pavement system alternative.

Sequencing of components during the use phase are graphically given in Figure 1-4.

Figure 1-4. Concrete pavement system component sequencing.
Concrete pavement components and sequencing follows:

1. The original pavement consisted of 9 inches of concrete, with 1/2 inch diameter by 24 inch long tiebars spaced at 30 inches on-center along the pavement center line and 1 1/4 inch diameter by 18 inch long dowels spaced at 12 inches on-center at control joints spaced 15 feet on-center, over a 6 inch untreated aggregate base course.

2. A 1 inch asphalt bondbreaker and 9 inch concrete overlay were added at end of year 25.

3. The original concrete pavement, asphalt bondbreaker, and concrete overlay were demolished and removed at end of year 50. The untreated aggregate base course remained.

Assumptions related to the concrete pavement system alternative follow:

1. Pavement shoulders were the same for both pavement alternatives. EMERGY inputs are not included.

2. Demolition material for both pavement alternatives is totally recycled at the end of years 25 and 50. EMERGY inputs are not included.

3. EMERGY inputs of cement production were included in concrete material transformity.

Asphalt Concrete Pavement System

Components of the asphalt concrete pavement system alternative are given in Figure 1-5.
Figure 1-5. Asphalt concrete pavement system alternative.

Sequencing of components during the use phase are graphically given in Figure 1-6.

Figure 1-6. Asphalt concrete pavement system component sequencing.
Asphalt concrete pavement components and sequencing follows:

1. The original pavement consisted of 5 inches of asphalt concrete over a 14 inch untreated aggregate base course.
2. A 5 inch asphalt concrete overlay was added at end of year 14.
3. The original asphalt concrete pavement and overlay were demolished and removed at end of year 25.
4. A new 5 inch asphalt concrete pavement was constructed over the original 14 inch untreated aggregate base course at end of year 25.
5. A 5 inch asphalt concrete overlay was added at the end of year 39.
6. The asphalt concrete pavement and overlay were demolished and removed at end of year 50. The untreated aggregate base course remained.

Assumptions related to the asphalt concrete pavement system alternative follow:

1. Pavement shoulders were the same for both pavement alternatives. EMERGY inputs are not included.
2. Demolition material for both pavement alternatives is totally recycled at the end of years 25 and 50. EMERGY inputs are not included.
3. EMERGY inputs of asphalt cement production are included in asphalt concrete material transformity.
CHAPTER 2
METHODS

This chapter represents methods utilized to develop the environmental value engineering assessment system and its application to the environmental life cycle assessment of concrete and asphalt concrete highway pavement system alternatives.

Energy Systems Diagrams and Language

Energy systems diagrams (models) and language are used in this assessment to communicate the relationship of EMERGY to a built environment alternative's systems. Dr. Howard T. Odum has been developing the energy diagrams and language used in EMERGY analysis for more than three decades. This section of the assessment describes energy system diagrams and language. For a complete description of energy system diagrams and language development, see Odum (1971, 1983, 1991, and 1995) and Odum & Odum (1981).

Descriptions of energy systems diagram symbols and language are aggregated according to natural groupings and hierarchies (Appendix B). Energy systems diagrams are based on the fact that: 1) some energy flows on all pathways, 2) some energy is transformed through production, consumption and
storage processes, and 3) energy quality is increased through transformation of energy. This energy flow is measured in terms of its EMERGY content.

There is an EMERGY hierarchical organization to energy systems diagrams. Refer to the energy systems diagram of this assessment given in Figure 1-1. External to the energy system boundary are energy input sources, which are arranged from lowest quality in the lower left corner, then clockwise to the highest quality input source in the lower right corner. The bottom of the energy system diagram boundary is used only for the dispersion of potential energy into heat, which is indicated by a heat sink symbol. Within the energy system boundary are producers, consumers, and storages which ascend in energy quality (EMERGY content) from left toward the right. Relationships between these producers, consumers, and storages are indicated by energy circuits or pathways of energy flow.

The energy systems diagram and language were used to visually represent the influences and relationships of the various external EMERGY input sources to the concrete and asphalt concrete pavement system alternatives. Two levels of energy systems diagrams were constructed to represent these relationships. First, a detailed energy systems diagram (Figure 1-1) of a built environment pavement system alternative was drawn with its corresponding external EMERGY input sources. Second, an aggregated energy systems diagram of a pavement system alternative was drawn (Figure 2-1) to
indicate the relationship of EMERGY of all systems of a pavement system alternative through all 10 environmental value engineering life cycle phases.

**Aggregated EMERGY Input Diagram**

An aggregated EMERGY input diagram was drawn to represent the total source inputs of EMERGY from environment (E), fuel energy (F), goods (G), and services (S) for a pavement alternative over the 10 environmental value engineering life cycle phases. Figure 2-1 is an aggregated EMERGY input diagram indicating EMERGY inputs through these phases and pavement production output transformity for a pavement alternative.

![Figure 2-1. Aggregated EMERGY diagram.](image-url)
Components within the aggregated EMERGY input diagram boundary represent EMERGY accumulations that occur within each environmental value engineering life cycle phase. EMERGY pathways are indicated from the various external EMERGY input sources to the pavement alternative as it passes through the 10 environmental value engineering life cycle phases. The circulation of money is not indicated because environmental value engineering considers environmental impacts in terms of EMERGY and not money. Any external input sources involving money, such as services (labor), are converted to EMERGY using the appropriate input source transformity.

Environmental value engineering EMERGY calculations are conducted by use of EMERGY analysis input tables. Methods of EMERGY analysis table preparation are described in the following sections.

Environmental Value Engineering EMERGY Analysis Input Tables

An environmental value engineering EMERGY analysis input table is used to facilitate the calculation of EMERGY for the various sources of external input to a pavement system alternative through the 10 environmental value engineering life cycle phases.

Procedures for making an environmental value engineering EMERGY analysis input table are similar to those of an EMERGY analysis table as designed by Dr. Howard T. Odum, except for a few differences. One difference is that the external EMERGY input sources are consolidated into the four main categories
of environment, nonrenewable fuel energy, goods, and services (labor). Another difference between environmental value engineering and EMERGY analysis is that the environmental value engineering EMERGY analysis input table account for all subsystems of a built environment alternative through the 10 life cycle phases. Table 2-1 is an environmental value engineering EMERGY analysis input table.

Table 2-1. ENVIRONMENTAL VALUE ENGINEERING EMERGY ANALYSIS INPUT TABLE.

<table>
<thead>
<tr>
<th>Note</th>
<th>Item</th>
<th>Raw Units</th>
<th>Transformity</th>
<th>Solar EMERGY</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>ENVIRONMENT</td>
<td>g,J,$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E1</td>
<td>Atmosphere</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E2</td>
<td>Ecol. Prod.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E3</td>
<td>Energy</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E4</td>
<td>Land</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E5</td>
<td>Water</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E6</td>
<td>Materials</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>FUEL ENERGY</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F1</td>
<td>Equipment</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F2</td>
<td>Facilities</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F3</td>
<td>Materials</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G</td>
<td>GOODS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G1</td>
<td>Equipment</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G2</td>
<td>Facilities</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G3</td>
<td>Materials</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G4</td>
<td>Tools</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S</td>
<td>Services</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S1</td>
<td>Labor</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S2</td>
<td>Labor</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S3</td>
<td>Materials</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The procedures for making an environmental value engineering EMERGY analysis input table are:

1. Make an environmental value engineering EMERGY analysis input table for each pavement alternative system and each environmental value engineering phase with one line in the table for each environment, nonrenewable fuel energy, goods, and services EMERGY input source.

2. Number the lines to match calculation back-up sheets for data sources, references, calculations, or other details.

3. Put the input source in the item column.

4. In the second column of data put the raw data units for each item in grams, Joules, or U.S. dollars.

5. Put the appropriate solar transformity in the next column. Transformities (EMERGY conversions) for energies, resources, and commodities related to the built environment are given in Appendix C.

6. In the fourth column, multiply raw data units from column 2 by the solar transformity from column 3, thus obtaining solar EMERGY values in solar emjoules (SEJ).

7. Input the solar EMERGY values for each phase of each pavement alternative into the aggregated EMERGY input source data tables.
Solar transformities were obtained from EMERGY analysis research data that is based on the scientific methods of Dr. Howard T. Odum and his associates at the University of Florida, Gainesville, Florida.

**Assessment Methods**

Environmental value engineering was used to evaluate concrete and asphalt concrete highway pavement system alternatives. Pavement subsystems included USDOT divisions 301-Untreated Aggregate Courses, 401-Hot Asphalt Concrete Pavement, and 501-Portland Cement Concrete Pavement. The concrete pavement system alternative indicated in Figure 1-3 consists of USDOT divisions 301, division 401 for the asphalt concrete bondbreaker at the 9 inch overlay at the end of year 25, and division 501. The asphalt concrete pavement system alternative indicated in Figure 1-5 consists of USDOT divisions 301 and 401. Alternative A was the concrete pavement system alternative and alternative B was the asphalt concrete pavement system alternative.

Environmental value engineering EMERGY analysis tables were used to calculate the EMERGY inputs required by these two pavement system alternatives through all 10 environmental value engineering life cyclephases. The EMERGY data was then input into aggregated EMERGY input source data tables (Table 3-2 and Table 3-3 of results given in Chapter 3) for comparison purposes.
EMERGY Input Designation System

A key element of EMERGY calculations and data input organization is the EMERGY input designation system developed specifically for environmental value engineering. A description of the environmental value engineering EMERGY input designation system is provided in Figure 2-2. The EMERGY input designation system was developed to match the various aspects of the environmental value engineering assessment methodology. These aspects include environmental impact EMERGY input sources given in Appendix A, EMERGY analysis input tables, and corresponding calculation back-up sheets.

Figure 2-2. Description of environmental value engineering EMERGY input designation system.
**EMERGY Input Calculations**

EMERGY input calculation information applicable to the concrete and asphalt concrete pavement system alternatives was obtained from companies, individuals, and documents related to specific environmental value engineering life cycle phases. Specific pavement descriptions, dimensions, and use phase period duration were provided by the Portland Cement Association. EMERGY input calculation methods were applied to the assessment as follows:

1. Material mass quantity take-offs were conducted based on pavement descriptions and dimensions for initial environmental impact EMERGY of material transformity phases A-C for pavement alternatives A and B.

2. Environmental value engineering EMERGY input tables were constructed for each environmental value engineering phase of applicable subsystems for pavement alternatives A and B.

3. Material raw unit quantities for phases A-C of both pavement alternatives A and B were entered into the EMERGY input tables provided in Appendix E.

4. Applicable transformities were added to the transformity column of EMERGY input tables.

5. EMERGY source inputs were categorized as environment (E), fuel energy (F), goods (G), and services (S).
6. Environmental value engineering EMERGY analysis tables were arranged in order by pavement alternative, life cycle phase, and pavement alternative system.

7. EMERGY calculation back-up sheets were constructed for each EMERGY source input of each environmental value engineering EMERGY analysis table for all phases.

8. Raw unit quantities of EMERGY source inputs E, F, G, and S were calculated on back-up sheets for inclusion on appropriate environmental value engineering EMERGY analysis input tables.

9. Solar EMERGY (solar emjoules) of EMERGY source inputs E, F, G, and S was calculated on each EMERGY analysis input table.

10. Solar input EMERGY source data was transferred to the aggregated EMERGY input source data Tables 3-2 and 3-3 for the concrete and asphalt concrete pavement system alternatives, respectively.

EMERGY source input quantities on the aggregated EMERGY input source data tables were used to construct aggregated phase EMERGY input signatures, a total phase EMERGY input signature, and a graphical simulation of cumulative total input source EMERGY. Results of the assessment of EMERGY inputs for the concrete and asphalt concrete pavement systems are presented in the following chapter.
This chapter presents the results obtained from an environmental value engineering assessment concrete and asphalt concrete pavement alternatives A and B, respectively. Application of methods described in the environmental value engineering analysis methods section of the previous chapter provides four basic types of results for both pavement alternatives: 1) the completed environmental value engineering EMERGY analysis tables with applicable EMERGY calculation back-up sheets; 2) aggregated phase EMERGY input signatures; 3) total phase EMERGY input signatures; and 4) graphical simulation output of cumulative total input source EMERGY of both pavement alternatives.

Environmental Value Engineering EMERGY Calculations

Pavement system environmental impact EMERGY quantities associated with input sources of environment, fuel energy, goods, and services are the result of calculations performed on the environmental value engineering EMERGY input tables and calculation back-up sheets provided in Appendix E.
Environmental Value Engineering EMERGY Analysis Tables

The environmental value engineering EMERGY analysis tables and calculation back-up sheets are arranged in order by pavement alternative, environmental value engineering phase, and pavement alternative system. An example of an environmental value engineering EMERGY analysis table is provided in Table 3-1. Figure 2-2 provides a description of the designation system used.

Information on the EMERGY analysis tables comes from three sources. First, the environmental impact EMERGY input source items are from the list given in Appendix A. Second, raw units are obtained from the EMERGY analysis table calculation back-up sheets, which are described in the following section. Third, transformities are obtained from the transformity list provided in Appendix C. Environmental value engineering EMERGY analysis tables and calculation back-up sheets are provided for each system of each alternative for all environmental value engineering life cycle phases, even though specific EMERGY inputs may not occur.

EMERGY Analysis Table Calculation Back-up Sheets

The EMERGY analysis table calculation back-up sheets serve two purposes. First, they contain the raw unit calculations for EMERGY input sources of environment, fuel energy, goods, and services associated with concrete and asphalt concrete pavement alternatives A and B, respectively.
TABLE 3-1. EXAMPLE ENVIRONMENTAL VALUE ENGINEERING EMERGY ANALYSIS TABLE.

TABLE AF501. Construction Phase EMERGY Input Table.

<table>
<thead>
<tr>
<th>Note</th>
<th>Item</th>
<th>Raw Units</th>
<th>Transformity</th>
<th>Solar EMERGY</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>g,J, $</td>
<td>sej/unit</td>
<td>sej</td>
</tr>
<tr>
<td>E</td>
<td>ENVIRONMENT</td>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>E1</td>
<td>Atmosphere</td>
<td>NA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E2</td>
<td>Ecol. Prod.</td>
<td>NA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E3</td>
<td>Energy</td>
<td>NA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E4</td>
<td>Land</td>
<td>NA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E5</td>
<td>Water</td>
<td>NA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>FUEL ENERGY</td>
<td></td>
<td></td>
<td>9.37E15</td>
</tr>
<tr>
<td>F1</td>
<td>Equipment</td>
<td>1.42E11 J</td>
<td>6.60E4</td>
<td>9.37E15</td>
</tr>
<tr>
<td>F2</td>
<td>Facilities</td>
<td>NA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G</td>
<td>GOODS</td>
<td></td>
<td></td>
<td>1.72E15</td>
</tr>
<tr>
<td>G1</td>
<td>Equipment</td>
<td>2.57E5 g</td>
<td>6.70E9</td>
<td>1.72E15</td>
</tr>
<tr>
<td>G2</td>
<td>Facilities</td>
<td>NA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G3</td>
<td>Materials</td>
<td>NA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G4</td>
<td>Tools</td>
<td>NA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S</td>
<td>SERVICES</td>
<td></td>
<td></td>
<td>3.60E16</td>
</tr>
<tr>
<td>S1</td>
<td>Labor</td>
<td>1.80E4 $</td>
<td>2.00E12</td>
<td>3.60E16</td>
</tr>
</tbody>
</table>
These units are utilized in the EMERGY analysis tables to calculate the environmental impact solar EMERGY related to each system of each alternative for all environmental value engineering life cycle phases. Second, the back-up sheets contain raw data source citations.

An example portion of an EMERGY analysis table calculation back-up sheet for concrete pavement alternative A designation AF501 is provided in Figure 3-1. Appendix E contains the EMERGY analysis input tables and corresponding calculation back-up sheets for concrete and asphalt concrete pavement alternatives A and B, respectively.

To compare phase EMERGY of pavement alternatives A and B, based on EMERGY inputs to all systems, detailed EMERGY inputs of individual systems were aggregated.

**Aggregated EMERGY Input Analysis**

The results of the aggregated EMERGY input analysis portion of environmental value engineering for the concrete and asphalt concrete pavement alternatives A and B, respectively, are represented first by aggregated EMERGY input source data tables and then by translation of this data into aggregated EMERGY input signatures.

The following two sections describe aggregated EMERGY input source data table nomenclature, sources of EMERGY input data, and aggregated EMERGY input signatures for concrete and asphalt concrete pavement alternatives A and B, respectively.
Concrete Highway Pavement System (Alternative A)
USDOT Pavement System 501 - Portland Cement Concrete Pavement

**TABLE AF501 EMERGY Input Calculations**
(Construction Phase F)

[Placement of original 9" concrete pavement]

E. Environment.
Not applicable. Use input = 0.

F. Fuel energy.
F1. Equipment.
F1.1: (1) Placer/Spreader, Concrete [GOMACO PS-68]
Fuel consumption = 8 gal/hr [Estimate]
Use = 10 hrs
(10 hrs use)(8 gal/hr) = 80 gal
((80 gal)/(42 gal/BBL))(6.28E9 J/BBL) = 1.20E10 J

F1.2: (2) Saw, Concrete [Magnum PS6585]
Fuel consumption = 3 gal/hr [Estimate]
Use 10 hrs
(10 hrs use)(3 gal/hr) = 30 gal
((30 gal)/(42 gal/BBL))(6.28E9 J/BBL) = 8.97E9 J

F1.3: (1) Slipform Paver, Concrete [GOMACO GP-4000]
Fuel consumption = 10 gal/hr [Estimate]
Use = 10 hrs
(10 hrs use)(10 gal/hr) = 100 gal
((100 gal)/(42 gal/BBL))(6.28E9 J/BBL) = 1.50E10 J

Figure 3-1. An example of an environmental value engineering EMERGY analysis table calculation back-up sheet.

**Aggregated EMERGY Input Source Data Tables**

An aggregated EMERGY input source data table represents the EMERGY of input sources for all systems of a pavement alternative during the 10 life cycle phases of environmental
value engineering. The aggregated EMERGY input source data tables for pavement alternatives A and B are given in Tables 3-2 and 3-3, respectively. Referring to Table 3-2, the EMERGY input sources of environment (E), fuel energy (F), goods (G), and services (S) are given in EMERGY input source data columns, and environmental value engineering life cycle phases are represented by rows along the left side. Phase EMERGY totals are given in the right column. EMERGY input source proportions of total phase EMERGY are given below each input source at applicable life cycle phases. Phase EMERGY proportions of total pavement system EMERGY are given below each total phase EMERGY at applicable life cycle phases. Total EMERGY for the pavement alternative is given in the lower right corner of each aggregated EMERGY input source data table.

EMERGY input source data for columns (E), (F), (G), and (S) of the data tables were obtained from EMERGY analysis input tables given in Appendix E.
### Table 3-2. Aggregated Emergy Input Source Data for Concrete Pavement System Alternative A.

<table>
<thead>
<tr>
<th>EVE PHASE</th>
<th>EMERGENCY INPUT SOURCE DATA (SEJ)</th>
<th>TOTAL PHASE EMERGY</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ENVIRON.</td>
<td>FUEL ENERGY</td>
</tr>
<tr>
<td></td>
<td>(E)</td>
<td>(F)</td>
</tr>
<tr>
<td>A-C TRANSFORMITY</td>
<td>5.33E18</td>
<td>3.15E17</td>
</tr>
<tr>
<td></td>
<td>0.8883</td>
<td>0.0525</td>
</tr>
<tr>
<td>D DESIGN</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>E COMP. PROD.</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>F CONSTRUCTION</td>
<td>2.63E13</td>
<td>1.59E16</td>
</tr>
<tr>
<td></td>
<td>0.0004</td>
<td>0.2646</td>
</tr>
<tr>
<td>G USE</td>
<td>3.99E18</td>
<td>3.42E17</td>
</tr>
<tr>
<td></td>
<td>0.8400</td>
<td>0.0720</td>
</tr>
<tr>
<td>H DEMOLITION</td>
<td>2.62E13</td>
<td>2.98E16</td>
</tr>
<tr>
<td></td>
<td>0.0003</td>
<td>0.3539</td>
</tr>
<tr>
<td>I RECYCLING</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>J DISPOSAL</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

TOTAL CONCRETE PAVEMENT SYSTEM EMERGY: 1.09E19

### Table 3-3. Aggregated Emergy Input Source Data for Asphalt Concrete Pavement System Alternative B.

<table>
<thead>
<tr>
<th>EVE PHASE</th>
<th>EMERGENCY INPUT SOURCE DATA (SEJ)</th>
<th>TOTAL PHASE EMERGY</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ENVIRON.</td>
<td>FUEL ENERGY</td>
</tr>
<tr>
<td></td>
<td>(E)</td>
<td>(F)</td>
</tr>
<tr>
<td>A-C TRANSFORMITY</td>
<td>6.40E18</td>
<td>8.49E17</td>
</tr>
<tr>
<td></td>
<td>0.7232</td>
<td>0.0959</td>
</tr>
<tr>
<td>D DESIGN</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>E COMP. PROD.</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>F CONSTRUCTION</td>
<td>8.67E13</td>
<td>2.34E16</td>
</tr>
<tr>
<td></td>
<td>0.0019</td>
<td>0.5189</td>
</tr>
<tr>
<td>G USE</td>
<td>6.69E18</td>
<td>1.84E16</td>
</tr>
<tr>
<td></td>
<td>0.5622</td>
<td>0.1546</td>
</tr>
<tr>
<td>H DEMOLITION</td>
<td>3.34E13</td>
<td>9.57E15</td>
</tr>
<tr>
<td></td>
<td>0.0019</td>
<td>0.5500</td>
</tr>
<tr>
<td>I RECYCLING</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>J DISPOSAL</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

TOTAL ASPHALT CONCRETE PAVEMENT SYSTEM EMERGY: 2.08E19
Table 3-2 represents the aggregated EMERGY input source data for concrete pavement alternative A. Comments on the main aspects of Table 3-2 follow:

1. Total phase EMERGY input ranking from highest to lowest are: First, material transformity phases A-C; second, use phase G; third, demolition phase H; and fourth, construction phase F.

2. No design phase D EMERGY input sources are included since they are equal for both pavement alternatives.

3. No component production phase E EMERGY input sources are included because component production for both pavement alternatives occurred during construction phase F.

4. No natural resource recycling phase I and disposal phase J EMERGY input sources are included because recycling and disposal inputs are assumed to be equal for both pavement alternatives at end of 50 year use phase.

5. Environment input source (E4) land is not included at construction phase F because land input is the same for both pavement alternatives.

Table 3-3 represents the aggregated EMERGY input source data for asphalt concrete pavement alternative B. Comments on the main aspects of Table 3-3 follow:

1. Total phase EMERGY input ranking from highest to
lowest are: First, use phase G; second, material transformity phases A-C; third, construction phase F; and fourth, demolition phase H.

2. No design phase D EMERGY input sources are included since they are equal for both pavement alternatives.

3. No component production phase E EMERGY input sources are included because component production occurred during construction phase F.

4. No natural resource recycling phase I and disposal phase J EMERGY input sources are included because recycling and disposal inputs are assumed to be equal for both pavement alternatives at end of 50 year use phase.

5. Environment input source (E4) land is not included at construction phase F because land input is the same for both pavement alternatives.

Refer to EMERGY analysis input table calculations in Appendix E.

**Aggregated Phase EMERGY Input Signatures**

An aggregated phase EMERGY input signature represents the total EMERGY of input sources during the life cycle of all systems of a pavement alternative. The aggregated phase EMERGY input signatures for concrete and asphalt concrete pavement alternatives A and B are given in Figures 3-2 and 3-3, respectively. Referring to these figures, the EMERGY input
sources of environment (E), fuel energy (F), goods (G), and services (S) for each environmental value engineering life cycle phase are given in columns and are labeled along the signature bottom.

Quantities of input source EMERGY are represented along the left side of the signature in units of $10^{13}$ solar emjoules (SEJ).

Environmental value engineering phase input source EMERGY quantities for columns (E), (F), (G), and (S) of Figures 3-2 and 3-3 were obtained from aggregated EMERGY input source data Tables 3-2 and 3-3, respectively.

![Figure 3-2. Concrete pavement aggregated phase EMERGY input signature.](image-url)
Figure 3-2 represents the aggregated phase EMERGY input signature for concrete pavement alternative A. Comments on the main aspects of Figure 3-2 follow:

1. No EMERGY input sources at the design, component production, natural resource recycling, and disposal phases, phases D, E, I, and J respectively, for reasons given in Table 3-2 comments.

2. Ranking of phase EMERGY inputs from highest to lowest follow:

<table>
<thead>
<tr>
<th>Rank</th>
<th>Phase</th>
<th>Input</th>
<th>Quantity (SEJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Material Transformity A-C</td>
<td>Environment</td>
<td>5.33E18</td>
</tr>
<tr>
<td>2</td>
<td>Use G</td>
<td>Environment</td>
<td>3.99E18</td>
</tr>
<tr>
<td>3</td>
<td>Use G</td>
<td>Fuel Energy</td>
<td>3.42E17</td>
</tr>
<tr>
<td>4</td>
<td>Material Transformity A-C</td>
<td>Fuel Energy</td>
<td>3.15E17</td>
</tr>
<tr>
<td>5</td>
<td>Use G</td>
<td>Services</td>
<td>2.93E17</td>
</tr>
<tr>
<td>6</td>
<td>Material Transformity A-C</td>
<td>Services</td>
<td>2.45E17</td>
</tr>
<tr>
<td>7</td>
<td>Use G</td>
<td>Goods</td>
<td>1.22E17</td>
</tr>
<tr>
<td>8</td>
<td>Material Transformity A-C</td>
<td>Goods</td>
<td>1.13E17</td>
</tr>
<tr>
<td>9</td>
<td>Demolition H</td>
<td>Services</td>
<td>4.40E16</td>
</tr>
<tr>
<td>10</td>
<td>Construction F</td>
<td>Services</td>
<td>4.16E16</td>
</tr>
<tr>
<td>11</td>
<td>Demolition H</td>
<td>Fuel Energy</td>
<td>2.98E16</td>
</tr>
<tr>
<td>12</td>
<td>Construction F</td>
<td>Fuel Energy</td>
<td>1.59E16</td>
</tr>
<tr>
<td>13</td>
<td>Demolition H</td>
<td>Goods</td>
<td>1.04E16</td>
</tr>
<tr>
<td>14</td>
<td>Construction F</td>
<td>Goods</td>
<td>2.60E15</td>
</tr>
<tr>
<td>15</td>
<td>Construction F</td>
<td>Environment</td>
<td>2.63E13</td>
</tr>
<tr>
<td>16</td>
<td>Demolition H</td>
<td>Environment</td>
<td>2.62E13</td>
</tr>
</tbody>
</table>

3. Highest total phase EMERGY occurred during material transformity phases A-C.

4. Second highest total phase EMERGY occurred during use phase G.

5. Third highest total phase EMERGY occurred during Demolition phase H.
6. Fourth highest total phase EMERGY occurred during construction phase F.

EMERGY quantities shown in Figure 3-2 are discussed in discussion Chapter 4.

Figure 3-3. Asphalt concrete pavement aggregated phase EMERGY input signature.

Figure 3-3 represents the aggregated phase EMERGY input signature for asphalt concrete pavement alternative B. Comments on the main aspects of Figure 3-3 follow:

1. No EMERGY input sources at the design, component production, natural resource recycling, and disposal phases, phases D, E, I, and J respectively, for reasons given in Table 3-3 comments.
2. Ranking of phase EMERGY inputs from highest to lowest follow:

<table>
<thead>
<tr>
<th>Rank</th>
<th>Phase</th>
<th>Input</th>
<th>Quantity (SEJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Use G</td>
<td>Environment</td>
<td>6.69E18</td>
</tr>
<tr>
<td>2.</td>
<td>Material Transformity A-C</td>
<td>Environment</td>
<td>6.40E18</td>
</tr>
<tr>
<td>3.</td>
<td>Use G</td>
<td>Fuel Energy</td>
<td>1.84E18</td>
</tr>
<tr>
<td>4.</td>
<td>Use G</td>
<td>Services</td>
<td>1.69E18</td>
</tr>
<tr>
<td>5.</td>
<td>Use G</td>
<td>Goods</td>
<td>1.68E18</td>
</tr>
<tr>
<td>7.</td>
<td>Material Transformity A-C</td>
<td>Goods</td>
<td>8.01E17</td>
</tr>
<tr>
<td>8.</td>
<td>Material Transformity A-C</td>
<td>Services</td>
<td>8.01E17</td>
</tr>
<tr>
<td>9.</td>
<td>Construction F</td>
<td>Fuel Energy</td>
<td>2.34E16</td>
</tr>
<tr>
<td>10.</td>
<td>Construction F</td>
<td>Services</td>
<td>1.82E16</td>
</tr>
<tr>
<td>12.</td>
<td>Demolition H</td>
<td>Services</td>
<td>6.54E15</td>
</tr>
<tr>
<td>15.</td>
<td>Construction F</td>
<td>Environment</td>
<td>8.67E13</td>
</tr>
<tr>
<td>16.</td>
<td>Demolition H</td>
<td>Environment</td>
<td>3.34E13</td>
</tr>
</tbody>
</table>

3. Highest total phase EMERGY occurred during use phase G.

4. Second highest total phase EMERGY occurred during material transformity phases A-C.

5. Third highest total phase EMERGY occurred during construction phase F.

6. Fourth highest total phase EMERGY occurred during demolition phase H.

EMERGY quantities shown in figure 3-3 are discussed in discussion Chapter 4.
Comparison of Pavement Alternatives

An environmental value engineering assessment includes the comparison of built environment alternatives. This section compares concrete and asphalt concrete pavement alternatives A and B, respectively, through use of a total phase EMERGY input signature and a graphical simulation output of cumulative total input source EMERGY.

A total phase EMERGY input signature was utilized to compare the total phase EMERGY of all systems of pavement alternatives A and B. The signature represents total phase EMERGY of input sources of environment (E), fuel energy (F), goods (G), and services (S) for each environmental value engineering life cycle phase of both pavement alternatives A and B.

To compare both pavement alternatives A and B over the 10 environmental value engineering life cycle phases, a graphical simulation output was produced to represent the cumulative total input source EMERGY of input sources of both pavement alternatives during the 10 phase environmental value engineering assessment period.

The following two sections describe the comparison of pavement alternatives using a total phase EMERGY input signature and a graphical simulation output of cumulative total input source EMERGY.
Total Phase EMERGY Input Signature

A total phase EMERGY input source signature was constructed to represent the total EMERGY of input sources of environment (E), fuel energy (F), goods (G), and services (S) for each environmental value engineering life cycle phase of concrete and asphalt concrete pavement alternatives A and B, respectively. Referring to this signature, given in Figure 3-4, the total input source EMERGY quantities for each environmental value engineering life cycle phase are indicated in columns designated for both alternatives A and B.

![Figure 3-4. Total phase EMERGY input signature.](image-url)
Total phase input source EMERGY quantities were obtained from the total phase EMERGY columns on aggregated EMERGY input source data Tables 3-2 and 3-3 for pavement alternatives A and B, respectively. The quantities represent total phase input source EMERGY of all systems within pavement alternatives A and B.

Quantities of input source EMERGY are represented along the left side of the signature in units of $10^{14}$ solar emjoules (SEJ). Each major quantity line represents an "order of magnitude" of 10 times.

Figure 3-4 represents the total phase EMERGY input signature for concrete and asphalt concrete pavement alternatives A and B, respectively. Comments on the main aspects of Figure 3-4 follow:

1. Ranking of total phase EMERGY inputs from highest to lowest follow:

<table>
<thead>
<tr>
<th>Rank</th>
<th>Pavement Alternative</th>
<th>Life Cycle Phase</th>
<th>Quantity (SEJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Asphalt Concrete</td>
<td>Use G</td>
<td>1.19E19</td>
</tr>
<tr>
<td>2.</td>
<td>Asphalt Concrete</td>
<td>Matl. Transf. A-C</td>
<td>8.85E18</td>
</tr>
<tr>
<td>3.</td>
<td>Concrete</td>
<td>Matl. Transf. A-C</td>
<td>6.00E18</td>
</tr>
<tr>
<td>4.</td>
<td>Concrete</td>
<td>Use G</td>
<td>4.75E18</td>
</tr>
<tr>
<td>5.</td>
<td>Concrete</td>
<td>Demolition H</td>
<td>8.42E16</td>
</tr>
<tr>
<td>6.</td>
<td>Concrete</td>
<td>Construction F</td>
<td>6.01E16</td>
</tr>
<tr>
<td>7.</td>
<td>Asphalt Concrete</td>
<td>Construction F</td>
<td>4.51E16</td>
</tr>
<tr>
<td>8.</td>
<td>Asphalt Concrete</td>
<td>Demolition H</td>
<td>1.74E16</td>
</tr>
</tbody>
</table>

2. No EMERGY input sources at the design, component production, natural resource recycling, and disposal phases, phases D, E, I, and J
respectively, for reasons given in Table 3-2 comments.

Refer to EMERGY analysis input calculations given in Appendix E.

Accounting for total phase EMERGY input quantities on a cumulative basis provides the means of comparing the concrete and asphalt concrete pavement alternatives A and B, respectively, over the environmental value engineering 10 phase life cycle assessment period. The following section describes the results of this comparison.

**Cumulative Total Input Source EMERGY**

Life cycle comparison of the environmental impact EMERGY of built environment alternatives is a key element of an environmental value engineering assessment. To assess the life cycle environmental impact EMERGY of pavement alternatives A and B, a graphical simulation output was produced to represent the cumulative total environmental impact EMERGY of input sources for both alternatives.

The graphical simulation output of cumulative total environmental impact EMERGY of input sources for pavement alternatives A and B is given in Figure 3-5. Referring to Figure 3-5, the cumulative total input source environmental impact EMERGY for both alternatives are indicated through the environmental value engineering 10 phase life cycle assessment period.
Quantities of input source environmental impact EMERGY, in units of $10^{19}$ solar emjoules (SEJ), are represented along the left side of the graphical simulation output. Environmental value engineering total phase input source EMERGY quantities for pavement alternatives A and B were obtained from the total phase EMERGY column of Tables 3-2 and 3-3, respectively.

![Figure 3-5. Cumulative total input source EMERGY.](image)

Figure 3-5 represents the graphical simulation output of the cumulative environmental impact EMERGY of concrete and asphalt concrete pavement alternatives A and B, respectively. Comments on the main aspects of Figure 3-5 follow:
1. Initial total input source EMERGY of pavement alternatives A and B begin at 0.

2. Slopes of cumulative total input source EMERGY of pavement alternatives do not reflect EMERGY intensity because environmental value engineering life cycle phases are not represented by actual phase period lengths.

3. EMERGY intensity of environmental value engineering life cycle phases is represented by quantity differences from beginning to end of individual phases.

4. Phase EMERGY intensities of pavement alternatives A and B correspond to total phase EMERGY represented in Figure 3-4.

5. The highest EMERGY intensity occurred during use phase G of asphalt concrete pavement alternative B.

6. Second highest total input source EMERGY occurred during material transformity phases A-C of asphalt concrete pavement alternative B.

7. Third highest total input source EMERGY occurred during material transformity phases A-C of concrete pavement alternative A.

8. Fourth highest total input source EMERGY occurred during use phase G of concrete pavement alternative A.
9. Highest total input source EMERGY at the end of material transformity phases A-C occurred at asphalt concrete pavement alternative B.

10. Highest total input source EMERGY at the end of the environmental value engineering 50 year assessment period occurs at asphalt concrete pavement system alternative B.

11. No increase in total input source EMERGY occurred during design phase D, component production phase E, natural resource recycling phase I, and disposal phase J of both pavement alternatives.

The following section discusses more complicated points developed in the environmental value engineering assessment of concrete and asphalt concrete pavement system alternatives A and B.
CHAPTER 4
DISCUSSION

Assessment Discussion

Discussion of concrete and asphalt concrete pavement system alternatives A and B is provided in an aggregated phase EMERGY input comparison.

Comparison of Aggregated Phase EMERGY Input

The aggregated EMERGY input signature given in Figure 3-4 provides a graphical representation of total phase input source EMERGY concentrations that occurred during environmental value engineering life cycle phases for all concrete and asphalt concrete pavement systems being assessed. The purpose of this section is to compare total aggregated phase EMERGY inputs of both pavement alternatives. Table 4-1 provides an aggregated phase EMERGY comparison based on data from Tables 3-2 and 3-3.

TABLE 4-1. COMPARISON OF AGGREGATED PHASE EMERGY INPUT.

<table>
<thead>
<tr>
<th>EVE Phase Comparison</th>
<th>Pavement Alternative</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-C Material transformity</td>
<td>A 32.2% less than B</td>
</tr>
<tr>
<td>D Design</td>
<td>Not applicable</td>
</tr>
<tr>
<td>E Component production</td>
<td>Not applicable</td>
</tr>
<tr>
<td>F Construction</td>
<td>A 33.3% more than B</td>
</tr>
<tr>
<td>G Use</td>
<td>A 60.1% less than B</td>
</tr>
<tr>
<td>H Demolition</td>
<td>A 383.9% more than B</td>
</tr>
<tr>
<td>I Natural resource recycling</td>
<td>Not applicable</td>
</tr>
<tr>
<td>J Disposal</td>
<td>Not applicable</td>
</tr>
<tr>
<td>Total pavement system EMERGY</td>
<td>A 47.6% less than B</td>
</tr>
</tbody>
</table>
Some general comments on data contained in Tables 3-2, 3-3, and 4-1 follow:

1. Construction phase F and demolition phase H, indicated in Table 4-1, only account for approximately one percent of the total pavement system EMERGY of both pavement alternatives.

2. If environment (E) inputs are excluded, the total asphalt concrete pavement system EMERGY is 388.0% higher than the concrete pavement system.

3. Environment (E) EMERGY inputs account for less than one percent of all inputs during construction phase F and demolition phase H.

4. Increased environment (E) inputs and reduced services (S) inputs during construction phase F and demolition phase H could reduce total EMERGY of both pavement alternatives.

5. The use of recycled materials during construction phase F and use phase G would reduce environment (E) inputs during material transformity phases (A-C) and use phase G.

Future Research and Applications

The systems approach and EMERGY basis of environmental value engineering provide a methodology to more accurately compare input requirements and related environmental impacts of built environment alternatives. Future research related to EMERGY input requirements and related environmental impacts
will adjust transformities, given in Appendix C, that relate to the built environment.

An objective of environmental value engineering is to accurately compare built environment alternatives by including as many input requirements and related environmental impacts as possible.

This analysis included specific subsystems of concrete and asphalt concrete pavement system alternatives. Certain subsystems and environmental value engineering life cycle phases were excluded because inputs were the same for both alternatives. To more accurately compare concrete and asphalt pavement system alternatives, variable inputs should be researched and included. Pavement lighting requirements and vehicle fuel consumption are two such variable inputs.

Inclusion of Pavement Lighting Inputs During Use Phase

The purpose of this assessment was to perform an environmental value engineering environmental life cycle assessment of concrete and asphalt concrete pavement system alternatives. The only subsystems included for the concrete and asphalt concrete pavement alternatives were USDOT pavement subsystem divisions 301, 401, and 501. To more accurately compare pavement system alternatives, all subsystems should be included that require inputs over the 50 year life cycle assessment period. Lighting, USDOT subsystem division 636, is one of these subsystems.

EMERGY inputs of environment, fuel energy, goods, and
services, that are required during the pavement life cycle, should be included for lighting subsystem requirements of both pavement system alternatives to more accurately compare pavement alternatives.

According to Richard E. Stark (1986), lighting requirements for concrete pavement are approximately 30% less than for asphalt pavement. Inclusion of EMERGY inputs for lighting requirements during the 50 year pavement life cycle would increase the difference in total system EMERGY between the pavement alternatives.

Inclusion of Vehicle Fuel Inputs During Use Phase

This assessment compared the EMERGY inputs of concrete and asphalt concrete pavement system alternatives. As stated previously, the only subsystems included in the pavement system alternatives were USDOT pavement subsystem divisions 301, 401, and 501. To more accurately compare pavement system alternatives, EMERGY inputs should be included for fuel consumption of vehicles using pavement alternatives during the 50 year pavement life cycle.

According to Dr. John P. Zaniewski, P.E. (1989), trucks consume approximately 20% less fuel on concrete pavements than on asphalt concrete pavements. Inclusion of EMERGY inputs for fuel energy requirements of vehicles using pavement alternatives during the 50 year pavement life cycle would increase the difference in total system EMERGY between the concrete and asphalt concrete pavement alternatives.
EMERGY Equivalences

Selection of built environment alternatives toward sustainable development should consider input differences between alternatives in terms of EMERGY equivalences. An EMERGY equivalence of the input difference is calculated by dividing the EMERGY of input difference, in terms of solar emjoules (SEJ), by various transformities given in Appendix C.

Assessment Conclusion

The purpose of this research project was to compare concrete and asphalt concrete pavement systems using the environmental life cycle assessment methodology called environmental value engineering. An assessment conclusion can be made based upon data presented in the results section of this report.

Based on EMERGY input data presented, the conclusion can be drawn that the concrete pavement system has approximately 47.6% less impact on the environment than the asphalt concrete pavement system.

Closing Remarks

Environmental value engineering provides a systems approach to environmental life cycle assessment. A systems approach must be used to accurately compare built environment alternatives because the input requirements are a complex web of interdependencies.
Sustainable development is dependent on the availability of EMERGY input from environment, fuel energy, goods, and services components. According to the World Commission on Environment and Development (1987, p. 43), "sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs."

Odum (1991, p. 93) states, "that greatest public wealth can be achieved by policies that bring in the most EMERGY and allocate it to uses that reinforce production, including environmental production processes on which the human production systems depend." Selection of built environment alternatives that minimize environmental impact EMERGY are possible through use of environmental value engineering.
APPENDIX A

ENVIRONMENTAL IMPACT EMERGY INPUT SOURCES
PHASE A. Natural Resource Formation
E. Environment (renewable)
   E1. Atmosphere
   E2. Ecological production
   E3. Energy
      (1) Sun
      (2) Earth
   E4. Land
      (1) Area
      (2) Resources
   E5. Water
      (1) Area
      (2) Resources

F. Fuel Energy (nonrenewable): none
G. Goods: none
S. Services (labor): none

PHASE B. Natural Resource Exploration and Extraction
E. Environment (renewable)
   E1. Atmosphere
   E2. Ecological production
   E3. Energy
      (1) Sun
      (2) Earth
   E4. Land
      (1) Area
      (2) Resources
   E5. Water
      (1) Area
      (2) Resources
   E6. Materials

F. Fuel Energy (nonrenewable)
   F1. Equipment
   F2. Facilities
   F3. Materials

G. Goods
   G1. Equipment
   G2. Facilities
   G3. Materials
   G4. Tools

S. Services
   S1. Labor
   S2. Materials

PHASE C. Material Production
E. Environment (renewable)
   E1. Atmosphere
   E2. Ecological production
   E3. Energy
      (1) Sun
      (2) Earth
   E4. Land
(1) Area
(2) Resources
E5. Water
(1) Area
(2) Resources
E6. Materials
F. Fuel Energy (nonrenewable)
F1. Equipment
F2. Facilities
F3. Materials
G. Goods
G1. Equipment
G2. Facilities
G3. Materials
G4. Tools
S. Services
S1. Labor
S2. Materials

PHASE D. Design (Architectural and Engineering)
E. Environment (renewable)
E1. Atmosphere
E2. Ecological production
E3. Energy
(1) Sun
(2) Earth
E4. Land
(1) Area
(2) Resources
E5. Water
(1) Area
(2) Resources
E6. Materials
F. Fuel Energy (nonrenewable)
F1. Equipment
F2. Facilities
F3. Materials
G. Goods
G1. Equipment
G2. Facilities
G3. Materials
G4. Tools
S. Services
S1. Labor
S2. Materials

PHASE E. Component Production
E. Environment (renewable)
E1. Atmosphere
E2. Ecological production
E3. Energy
(1) Sun
(2) Earth
E4. Land
   (1) Area
   (2) Resources
E5. Water
   (1) Area
   (2) Resources
E6. Materials
F. Fuel Energy (nonrenewable)
   F1. Equipment
   F2. Facilities
   F3. Materials
G. Goods
   G1. Equipment
   G2. Facilities
   G3. Materials
   G4. Tools
S. Services
   S1. Labor
   S2. Materials

PHASE F. Construction
E. Environment (renewable)
   E1. Atmosphere
   E2. Ecological production
   E3. Energy
      (1) Sun
      (2) Earth
   E4. Land
      (1) Area
      (2) Resources
   E5. Water
      (1) Area
      (2) Resources
   E6. Materials
F. Fuel Energy (nonrenewable)
   F1. Equipment
   F2. Facilities
   F3. Materials
G. Goods
   G1. Equipment
   G2. Facilities
   G3. Materials
   G4. Tools
S. Services
   S1. Labor
   S2. Materials

PHASE G. Use
E. Environment (renewable)
   E1. Atmosphere
   E2. Ecological production
E3. Energy
   (1) Sun
   (2) Earth
E4. Land
   (1) Area
   (2) Resources
E5. Water
   (1) Area
   (2) Resources
E6. Materials
F. Fuel Energy (nonrenewable)
   F1. Equipment
   F2. Facilities
   F3. Materials
G. Goods
   G1. Equipment
   G2. Facilities
   G3. Materials
   G4. Tools
S. Services
   S1. Labor
   S2. Materials

PHASE H. Demolition

E. Environment (renewable)
   E1. Atmosphere
   E2. Ecological production
   E3. Energy
      (1) Sun
      (2) Earth
   E4. Land
      (1) Area
      (2) Resources
   E5. Water
      (1) Area
      (2) Resources
   E6. Materials
F. Fuel Energy (nonrenewable)
   F1. Equipment
   F2. Facilities
   F3. Materials
G. Goods
   G1. Equipment
   G2. Facilities
   G3. Materials
   G4. Tools
S. Services
   S1. Labor
   S2. Materials

PHASE I. Natural Resource Recycling

E. Environment (renewable)
E1. Atmosphere
E2. Ecological production
E3. Energy
   (1) Sun
   (2) Earth
E4. Land
   (1) Area
   (2) Resources
E5. Water
   (1) Area
   (2) Resources
E6. Materials
F. Fuel Energy (nonrenewable)
   F1. Equipment
   F2. Facilities
   F3. Materials
G. Goods
   G1. Equipment
   G2. Facilities
   G3. Materials
   G4. Tools
S. Services
   S1. Labor
   S2. Materials

PHASE J. Disposal
E. Environment (renewable)
   E1. Atmosphere
   E2. Ecological production
   E3. Energy
      (1) Sun
      (2) Earth
   E4. Land
      (1) Area
      (2) Resources
   E5. Water
      (1) Area
      (2) Resources
   E6. Materials
F. Fuel Energy (nonrenewable)
   F1. Equipment
   F2. Facilities
   F3. Materials
G. Goods
   G1. Equipment
   G2. Facilities
   G3. Materials
   G4. Tools
S. Services
   S1. Labor
   S2. Materials
APPENDIX B

ENERGY SYSTEMS DIAGRAM SYMBOLS AND LANGUAGE
Energy circuit. A pathway whose flow is proportional to the quantity in the storage or source upstream.

Source. Outside source of energy delivering forces according to a program controlled from outside; a forcing function.

Tank. A compartment of energy storage within the system storing a quantity as the balance of inflows and outflows; a state variable.

Heat sink. Dispersion of potential energy into heat that accompanies all real transformation processes and storages; loss of potential energy from further use by the system.

Interaction. Interactive intersection of two pathways coupled to produce an outflow in proportion to a function of both; control action of one flow on another; limiting factor action; work gate.

Consumer. Unit that transforms energy quality, stores it, and feeds it back autocatalytically to improve inflow.

Producer. Unit that collects and transforms low-quality energy under control interactions of high-quality flows.

Box. Miscellaneous symbol to use for whatever subsystem, unit or function is labeled.

Transaction. A unit that indicates a sale of goods or services (solid line) in exchange for payment of money (dashed line). Price is shown as an external source.
Transformities (EMERGY conversions) for energies, resources, and commodities related to the built environment.

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>TRANSFORMITIES</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Refer to notes 1 and 2 unless noted otherwise)</td>
<td></td>
</tr>
<tr>
<td>Aluminum inguts (g)</td>
<td>1.60E10</td>
</tr>
<tr>
<td>Asphalt (J)</td>
<td>3.47E5</td>
</tr>
<tr>
<td>Asphalt concrete (g)</td>
<td>1.78E9 (Refer to note 3.)</td>
</tr>
<tr>
<td>Coal (J)</td>
<td>3.98E4</td>
</tr>
<tr>
<td>Concrete (g)</td>
<td>9.99E8 (Refer to note 4.)</td>
</tr>
<tr>
<td>Copper (g)</td>
<td>6.80E10</td>
</tr>
<tr>
<td>Electricity (J)</td>
<td>1.59E5</td>
</tr>
<tr>
<td>Glass (g)</td>
<td>8.40E8</td>
</tr>
<tr>
<td>Grain (J)</td>
<td>6.80E4</td>
</tr>
<tr>
<td>Iron (g)</td>
<td>1.80E9</td>
</tr>
<tr>
<td>Machinery (g)</td>
<td>6.70E9</td>
</tr>
<tr>
<td>Natural gas (J)</td>
<td>4.80E4</td>
</tr>
<tr>
<td>Nitrogen fertilizer (J)</td>
<td>1.69E6</td>
</tr>
<tr>
<td>Oil (J)</td>
<td>5.30E4</td>
</tr>
<tr>
<td>Paper (J)</td>
<td>2.15E5</td>
</tr>
<tr>
<td>Petroleum product (J)</td>
<td>6.60E4</td>
</tr>
<tr>
<td>Plastic (g)</td>
<td>3.80E8</td>
</tr>
<tr>
<td>Rubber (g)</td>
<td>4.30E9</td>
</tr>
<tr>
<td>Service, labor (US $)</td>
<td>2.00E12 (Refer to note 5.)</td>
</tr>
<tr>
<td>Steel (g)</td>
<td>1.80E9</td>
</tr>
<tr>
<td>Stone, mined (g)</td>
<td>1.00E9</td>
</tr>
<tr>
<td>Stone, natural state (g)</td>
<td>8.50E8</td>
</tr>
<tr>
<td>Topsoil (J)</td>
<td>6.30E4</td>
</tr>
<tr>
<td>Water, consumer (J)</td>
<td>6.66E5</td>
</tr>
<tr>
<td>Water, waste (J)</td>
<td>4.10E4</td>
</tr>
<tr>
<td>Wood (J)</td>
<td>3.49E4</td>
</tr>
<tr>
<td>Zinc Alloys (g)</td>
<td>6.80E10</td>
</tr>
</tbody>
</table>

Notes:
1. Transformity units are solar emjoules/Joule, solar emjoules/gram or solar emjoules/US $.
2. Source: Dr. Howard T. Odum, Department of Environmental Engineering Sciences, University of Florida, Gainesville, Florida.
3. Transformity calculations are given in Appendix G.
4. Transformity calculations are given in Appendix F.
5. Units in 1990 U. S. dollars.
APPENDIX D

USDOT PAVEMENT SYSTEM DIVISIONS
100 GENERAL REQUIREMENTS
101 TERMS, FORMAT, AND DEFINITIONS
102 BID, AWARD, AND EXECUTION OF CONTRACT
103 SCOPE OF WORK
104 CONTROL OF WORK
105 CONTROL OF MATERIAL
106 ACCEPTANCE OF WORK
107 LEGAL RELATIONS AND RESPONSIBILITY TO THE PUBLIC
108 PROSECUTION AND PROGRESS
109 MEASUREMENT AND PAYMENT

150 PROJECT REQUIREMENTS
151 MOBILIZATION
152 CONSTRUCTION SURVEY AND STAKING
153 CONTRACTOR QUALITY CONTROL
154 CONTRACTOR SAMPLING AND TESTING
155 SCHEDULES FOR CONSTRUCTION CONTRACTS
156 PUBLIC TRAFFIC
157 SOIL EROSION CONTROL

200 EARTHWORK
201 CLEARING AND GRUBBING
202 ADDITIONAL CLEARING AND GRUBBING
203 REMOVAL OF STRUCTURES AND OBSTRUCTIONS
204 EXCAVATION AND EMBANKMENT
205 ROCK BLASTING
206 WATERING
207 EARTHWORK GEOTEXTILES
208 STRUCTURE EXCAVATION AND BACKFILL FOR SELECTED MAJOR STRUCTURES
209 STRUCTURE EXCAVATION AND BACKFILL
210 DRAINAGE LAYER
211 ROADWAY OBLITERATION
212 LINEAR GRADING
213 SUBGRADE STABILIZATION

250 STRUCTURAL EMBANKMENTS
251 RIPRAP
252 SPECIAL ROCK EMBANKMENT
253 GABIONS
254 CRIB WALLS
255 MECHANICALLY STABILIZED EARTH WALLS
256 PERMANENT GROUND ANCHORS
257 ALTERNATE RETAINING WALLS

300 AGGREGATE COURSES
301 UNTREATED AGGREGATE COURSES
302 TREATED AGGREGATE COURSES
303 ROAD RECONDITIONING
304 AGGREGATE STABILIZATION
305 AGGREGATE-TOPSOIL COURSE
306 DUST PALLIATIVE
307 STOCKPILED AGGREGATES

400 ASPHALT PAVEMENTS AND SURFACE TREATMENTS
401 HOT ASPHALT CONCRETE PAVEMENT
402 MINOR ASPHALT CONCRETE PAVEMENT
403 HOT RECYCLED ASPHALT CONCRETE PAVEMENT
404 OPEN-GRADED ASPHALT TREATED FRICTION COURSE
405 HOT ASPHALT TREATED BASE COURSE
406 DENSE-GRADED EMULSIFIED ASPHALT PAVEMENT
407 OPEN-GRADED EMULSIFIED ASPHALT PAVEMENT
408 COLD RECYCLED ASPHALT BASE COURSE
409 ASPHALT SURFACE TREATMENT
410 SLURRY SEAL
411 ASPHALT PRIME COAT
412 ASPHALT TACK COAT
413 ASPHALT PAVEMENT MILLING
414 ASPHALT PAVEMENT CRACK AND JOINT SEALING
415 PAVING GEOTEXTILES

500 PORTLAND CEMENT CONCRETE PAVEMENT
501 PORTLAND CEMENT CONCRETE PAVEMENT
502 PORTLAND CEMENT CONCRETE PAVEMENT RESTORATION
503 PORTLAND CEMENT CONCRETE BASE COURSE

600 INCIDENTAL CONSTRUCTION
601 MINOR CONCRETE STRUCTURES
602 CULVERTS AND DRAINS
603 STRUCTURAL PLATE STRUCTURES
604 MANHOLES, INLETS, AND CATCH BASINS
605 UNDERDRAINS
606 CORRUGATED METAL SPILLWAYS
607 CLEANING, RECONDITIONING, AND REPAIRING EXISTING DRAINAGE STRUCTURES
608 PAVED WATERWAYS
609 CURB AND GUTTER
610 HORIZONTAL DRAINS
611 WATER SYSTEMS
612 SANITARY SEWER SYSTEMS
613 RESERVED
614 RESERVED
615 SIDEWALKS, DRIVE PADS, AND PAVED MEDIANS
616 SLOPE PAVING
617 GUARDRAIL
618 CONCRETE BARRIERS AND PRECAST GUARDWALLS
619 FENCES, GATES, AND CATTLE GUARDS
620 STONE MASONRY
621 MONUMENTS AND MARKERS
624 TOPSOIL
625 TURF ESTABLISHMENT
626 PLANTS, TREES, SHRUBS, VINES AND GROUNDCOVERS
627 SOD
628 SPRIGGING
629 MATTING
630 RESERVED
631 RESERVED
632 RESERVED
633 PERMANENT TRAFFIC CONTROL
634 PERMANENT PAVEMENT MARKINGS
635 TEMPORARY TRAFFIC CONTROL
636 SIGNAL, LIGHTING, AND ELECTRICAL SYSTEMS
637 FACILITIES AND SERVICES

APPENDIX E

EMERGY ANALYSIS INPUT TABLES AND CALCULATIONS
Concrete Highway Pavement System (Alternative A)
USDOT Pavement System 301 - Untreated Aggregate Courses

TABLE AC301. Material Transformity Phases A-C EMERGY Input Table.

<table>
<thead>
<tr>
<th>Note</th>
<th>Item</th>
<th>Raw Units</th>
<th>Transformity sej/unit</th>
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</table>
Concrete Highway Pavement System (Alternative A)
USDOT Pavement System 301 - Untreated Aggregate Courses

TABLE AC301 EMERGY Input Calculations
(Material Transformity Phases A-C)

[Original 6" crushed stone aggregate base course]

Materials
Stone (mined) transformity = 1.00E9 sej/g [Appendix C]
Stone (natural state) transformity = 8.50E8 sej/g [Append. C]
Stone weight (compacted) = 3180 lb/CY
[Granite or limestone with 2.7 specific gravity]

Stone quantity
Volume = \((6 \text{ in})/(12 \text{ in/ft})\)(24 ft width)
\(= 1458.2 \text{ CY/km}\)
Mass = \((1458.2 \text{ CY})(3180 \text{ lb/CY})(453.6 \text{ g/lb})\)
= 2.10E9 g

E. Environment.
Stone
Environment input transformity portion = 85 % [Est.]
\((1.00E9 \text{ sej/g})(0.85) = 8.50E8 \text{ sej/g}\)
\((2.10E9 \text{ g})(8.50E8 \text{ sej/g}) = 1.79E18 \text{ sej}\)

Total environment solar EMERGY input = 1.79E18 sej

F. Fuel energy.
Stone
Fuel energy input transformity portion = 5 % [Est.]
\((1.00E9 \text{ sej/g})(0.05) = 5.00E7 \text{ sej/g}\)
\((2.10E9 \text{ g})(5.00E7 \text{ sej/g}) = 1.05E17 \text{ sej}\)

Total fuel energy solar EMERGY input = 1.05E17 sej

G. Goods.
Stone
Goods input transformity portion = 5 % [Estimate]
\((1.00E9 \text{ sej/g})(0.05) = 5.00E7 \text{ sej/g}\)
\((2.10E9 \text{ g})(5.00E7 \text{ sej/g}) = 1.05E17 \text{ sej}\)

Total goods solar EMERGY input = 1.05E17 sej

S. Services.
Stone
Services input transformity portion = 5 % [Estimate]
\((1.00E9 \text{ sej/g})(0.05) = 5.00E7 \text{ sej/g}\)
\((2.10E9 \text{ g})(5.00E7 \text{ sej/g}) = 1.05E17 \text{ sej}\)

Total services solar EMERGY input = 1.05E17 sej
Concrete Highway Pavement System (Alternative A)  
USDOT Pavement System 501 - Portland Cement Concrete Pavement

TABLE AC501. Material Transformity Phases A-C EMERGY Input Table.

<table>
<thead>
<tr>
<th>Note</th>
<th>Item</th>
<th>Raw Units g,J, $</th>
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Concrete Highway Pavement System (Alternative A)  
USDOT Pavement System 501 - Portland Cement Concrete Pavement

**TABLE AC501 EMERGY Input Calculations**  
(Material Transformity Phases A-C)

[Original 9" concrete pavement]

**Materials**

- Concrete transformity = 9.99E8 sej/g  
- Petroleum product transformity = 6.60E4 sej/J  
- Steel transformity = 1.80E9 sej/g

**Concrete quantity**

- Volume = \((0.2286 \text{ m thick})(7.3152 \text{ m width})(1000 \text{ m})\)  
- Mass = \((1670.1870 \text{ m}^3)(2.3144E6 \text{ g/m}^3)\)  

**Petroleum product (Curing Compound) quantity**

- Rate of application = 0.06 gal/SY  
- Volume = 
  \[(7.3152 \text{ m})(1 \text{ km}) = 7,315.2 \text{ m}^2 = 78,742.734 \text{ ft}^2\]  
  \[(78,742.734 \text{ ft}^2)/(9 \text{ ft}^2/\text{SY}) = 8,749.19 \text{ SY}\]  
  \[(8,749.19 \text{ SY})(0.06 \text{ gal/SY})/(42 \text{ gal/BBL})(6.2839 \text{ J/BBL})\]  
  \[= 7.85E10 \text{ J}\]

**Petroleum product (Joint Sealant and filler) quantity**

- Joint width = \(1/4" = 0.00635 \text{ m}\)  
- Joint depth = \(3/4" = 0.01905 \text{ m}\)  
- Joint spacing = 15 ft = 4.572 m  
- Joint quantity = \((1000 \text{ m})/(4.572 \text{ m}) = 219 \text{ joints}\)  
- Joint volume = \(((219 \text{ joints})(7.3152 \text{ m}) + (1000 \text{ m})(0.01905 \text{ m depth})\)  
  \[= (0.00635 \text{ m width}) = 0.32 \text{ m}^3 \text{ joint sealant}\]  
  \[[((0.32 \text{ m}^3)(1000 \text{ l/m}^3))(0.264172 \text{ gal/l})]/(42 \text{ gal/BBL})(6.28E9 \text{ J/BBL})\]  
  \[= 1.26E10 \text{ J}\]

**Steel quantity**

- Dowels 1.25" Diameter x 18" length at 12'-0" on center  
- Dowel volume = \((1.27 \text{ in}^2)(18 \text{ in})(24/\text{joint})(218.5 \text{ joints})\)  
  \[= 69.3738 \text{ ft}^3 = 1.9645 \text{ m}^3\]  
- Dowel mass = \((6,441.8 \text{ g/m})(0.4572 \text{ m})(24/\text{joint})(218.5 \text{ joints}) = 1.545E7 \text{ g}\]

- Tiebars 0.5" Diameter x 24" length at 30" on center  
- Tiebar volume = \((0.20 \text{ in}^2)(24 \text{ in})(1312 \text{ tiebars})\)  
  \[= 3.6444 \text{ ft}^3 = 0.1032 \text{ m}^3\]  
- Tiebar mass = \((994.1 \text{ g/m})(0.6096 \text{ m})(1312 \text{ tiebars})\)  
  \[= 7.951E5 \text{ g}\]

**Total steel reinf. volume** = \((1.9645 \text{ m}^3) + (0.1032 \text{ m}^3)\)  
\[= 2.0677 \text{ m}^3\]

**Total steel reinf. mass** = \((1.545E7 \text{ g}) + (7.951E5 \text{ g})\)  
\[= 1.63E7 \text{ g}\]
E. Environment.

Concrete
Environment input transformity portion = 91.30 %
(9.99E8 sej/g)(0.9130) = 9.12E8 sej/g
(3.87E9 g)(9.12E8 sej/g) = 3.53E18 sej

Petroleum product (Curing Compound)
Environment input transformity portion = 25 %
(6.60E4 sej/J)(0.25) = 1.65E4 sej/J
(7.85E10 J)(1.65E4 sej/J) = 1.30E15 sej

Petroleum product (Joint Sealant)
Environment input transformity portion = 25 %
(6.60E4 sej/J)(0.25) = 1.65E4 sej/J
(1.26E10 J)(1.65E4 sej/J) = 2.08E14 sej

Steel (Reinforcement)
Environment input transformity portion = 37.3 %
(1.80E9 sej/g)(0.373) = 6.71E8 sej/g
(1.63E7 g)(6.71E8 sej/g) = 1.09E16 sej

Total environment solar EMERGY input = 3.54E18 sej

F. Fuel energy.

Concrete
Fuel energy input transformity portion = 5.04 %
(9.99E8 sej/g)(0.0504) = 5.04E7 sej/g
(3.87E9 g)(5.04E7 sej/g) = 1.95E17 sej

Petroleum product (Curing Compound)
Fuel energy input transformity portion = 25 %
(6.60E4 sej/J)(0.25) = 1.65E4 sej/J
(7.85E10 J)(1.65E4 sej/J) = 1.30E15 sej

Petroleum product (Joint Sealant)
Fuel energy input transformity portion = 25 %
(6.60E4 sej/J)(0.25) = 1.65E4 sej/J
(1.26E10 J)(1.65E4 sej/J) = 2.08E14 sej

Steel (Reinforcement)
Fuel energy input transformity portion = 46.5 %
(1.80E9 sej/g)(0.465) = 8.37E8 sej/g
(1.63E7 g)(8.37E8 sej/g) = 1.36E16 sej

Total fuel energy solar EMERGY input = 2.10E17 sej

G. Goods.

Concrete
Goods input transformity portion = 0.15 %
(9.99E8 sej/g)(0.0015) = 1.50E6 sej/g
(3.87E9 g)(1.50E6 sej/g) = 5.81E15 sej

Petroleum product (Curing Compound)
Goods input transformity portion = 25 %
(6.60E4 sej/J)(0.25) = 1.65E4 sej/J
(7.85E10 J)(1.65E4 sej/J) = 1.30E15 sej
Petroleum product (Joint Sealant)
Goods input transformity portion = 25 % [Estimate]
(6.60E4 sej/J)(0.25) = 1.65E4 sej/J
(1.26E10 J)(1.65E4 sej/J) = 2.08E14 sej
Steel
Goods input transformity portion = 3.5 %
(1.80E9 sej/g)(0.035) = 6.30E7 sej/g
(1.63E7 g)(6.30E7 sej/g) = 1.03E15 sej

Total goods solar EMERGY input = 8.35E15 sej

S. Services.
Concrete
Services input transformity portion = 3.48 %
(9.99E8 sej/g)(0.0348) = 3.48E7 sej/g
(3.87E9 g)(3.48E7 sej/g) = 1.35E17 sej
Petroleum product (Curing Compound)
Services input transformity portion = 25 % [Estimate]
(6.60E4 sej/J)(0.25) = 1.65E4 sej/J
(7.85E10 J)(1.65E4 sej/J) = 1.30E15 sej
Petroleum product (Joint Sealant)
Services input transformity portion = 25 % [Estimate]
(6.60E4 sej/J)(0.25) = 1.65E4 sej/J
(1.26E10 J)(1.65E4 sej/J) = 2.08E14 sej
Steel (Reinforcement)
Services input transformity portion = 12.7 %
(1.80E9 sej/g)(0.127) = 2.29E8 sej/g
(1.63E7 g)(2.29E8 sej/g) = 3.73E15 sej

Total services solar EMERGY input = 1.40E17 sej
Concrete Highway Pavement System (Alternative A)  
USDOT Pavement System 301 - Untreated Aggregate Courses

**TABLE AD301. Design Phase EMERGY Input Table.**

<table>
<thead>
<tr>
<th>Note</th>
<th>Item</th>
<th>Raw Units g,J,$</th>
<th>Transformity sej/unit</th>
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**AD301 EMERGY INPUT CALCULATION BACK-UP**

Design EMERGY inputs are zero because inputs are the same for the aggregate base course of both pavement alternatives.
Concrete Highway Pavement System (Alternative A)  
USDOT Pavement System 501 - Portland Cement Concrete Pavement

TABLE AD501. Design Phase EMERGY Input Table.

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<thead>
<tr>
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AD501 EMERGY INPUT CALCULATION BACK-UP

Design EMERGY inputs are zero because inputs are the same for both pavement alternatives.
Concrete Highway Pavement System (Alternative A)  
USDOT Pavement System 301 - Untreated Aggregate Courses

TABLE AE301. Component Production Phase EMERGY Input Table.

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<td>E2</td>
<td>Ecol. Prod.</td>
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<td>Land</td>
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<tr>
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<td>Labor</td>
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AE301 EMERGY INPUT CALCULATION BACK-UP

EMERGY inputs are zero because no components are produced for the aggregate base course of the concrete pavement alternative.
Concrete Highway Pavement System (Alternative A)
USDOT Pavement System 501 - Portland Cement Concrete Pavement

TABLE AE501. Component Production Phase EMERGY Input Table.

<table>
<thead>
<tr>
<th>Note</th>
<th>Item</th>
<th>Raw Units</th>
<th>Transformity</th>
<th>Solar EMERGY</th>
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<td>g,J,$</td>
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<td>Atmosphere</td>
<td>NA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E2</td>
<td>Ecol. Prod.</td>
<td>NA</td>
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<td>Energy</td>
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<td>E5</td>
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<td></td>
</tr>
<tr>
<td>F1</td>
<td>Equipment</td>
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<td>Facilities</td>
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<tr>
<td>S1</td>
<td>Labor</td>
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</table>

EMERGY inputs are zero because no components are produced for the concrete pavement alternative.
Concrete Highway Pavement System (Alternative A)  
USDOT Pavement System 301 - Untreated Aggregate Courses

TABLE AF301. Construction Phase EMERGY Input Table.

<table>
<thead>
<tr>
<th>Note</th>
<th>Item</th>
<th>Raw Units g, J, $</th>
<th>Transformity sej/unit</th>
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<td>Energy</td>
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<td>FUEL ENERGY</td>
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<td>Equipment</td>
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<td>Facilities</td>
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<td>Facilities</td>
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<td>S1</td>
<td>Labor</td>
<td>2.82E3 $</td>
<td>2.00E12</td>
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Aggregate base materials for the concrete pavement alternative are included in AC301.
Concrete Highway Pavement System (Alternative A)
USDOT Pavement System 301 - Untreated Aggregate Courses

TABLE AF301 EMERGY Input Calculations
(Construction Phase F)

[Placement of original 6" crushed stone aggregate base]

Stone weight (compacted) = 3180 lb/CY
[Granite or limestone with 2.7 specific gravity]

Stone quantity
Volume/km = ((6 in)/(12 in/ft))(24 ft width)
(3280.8398 ft/km)/(27 CF/CY)
= 1458.2 CY
Mass/km = ((1458.2 CY)(3180 lb/CY))/(2000 lb/T)
= 2318.5 T

Crushed stone aggregate base placement rate = 3500 T/day
Crushed stone aggregate base placement duration
= (2318.5 T)/(3500 T/day) = 0.66 days
Workday = 12 hrs
Base course placement duration = (0.66 days)(12 hrs) = 7.9 hrs

E. Environment.
E5. Water.
E5.1: (2) Water, Compactor
Water consumption = 1600 gal/day
Duration of water use = 0.66 days
(2)(1600 gal/day)(0.66 days)(3.7854 l/gal)
= 8.00E3 l
(8.00E3 l)(1000 g/l)(4.94 J/g) = 3.9537 J

F. Fuel energy.
F1. Equipment.
F1.1: (1) Bulldozer [Caterpillar D8N]
Fuel consumption = 9.0 gal/hr
Use = 7.9 hrs
(7.9 hrs use)(9.0 gal/hr) = 71.1 gal
((71.1 gal)/(42 gal/BBL))(6.28E9 J/BBL)
= 1.06E10 J

F1.2: (2) Compactor, Base [Caterpillar CS-433B]
Fuel consumption = 3.5 gal/hr [Estimate]
Use = 7.9 hrs
(2)(7.9 hrs use)(3.5 gal/hr) = 55.3 gal
((55.3 gal)/(42 gal/BBL))(6.28E9 J/BBL)
= 8.27E9 J
F1.3: (1) Grader [Caterpillar 140G]
Fuel consumption = 6.0 gal/hr
Use = 7.9 hrs
(7.9 hrs use)(6.0 gal/hr) = 47.4 gal
((47.4 gal)/(42 gal/BBL))(6.2839 J/BBL) = 7.09E9 J

F1.4: (1) Loader, Front-end [Caterpillar 930T]
Fuel consumption = 2.75 gal/hr
Use = 7.9 hrs
(7.9 hrs use)(2.75 gal/hr) = 21.7 gal
((21.7 gal)/(42 gal/BBL))(6.2839 J/BBL) = 3.25E9 J

F1.5: (8) Truck, Dump [Estimate]
Fuel consumption = 7.3 gal/hr
Use = 7.9 hrs
(8)(7.9 hrs use)(7.3 gal/hr) = 461.4 gal
((461.4 gal)/(42 gal/BBL))(6.2839 J/BBL) = 6.90E10 J

Total F1 equipment raw units = 9.82E10 J

G. Goods.
G1. Equipment.
G1.1: (1) Bulldozer [Caterpillar D8N]
Weight = 92,812 lb
Useful life = 18,000 hrs
Use = 7.9 hrs
((7.9 hrs use)/(18,000 hrs useful life))
(92,812 lb)(453.6 g/lb) = 1.85E4 g

G1.2: (2) Compactor, Base [Caterpillar CS-433B]
Weight = 13,865 lb
Useful life = 12,000 hrs
Use = 7.9 hrs
(2)((7.9 hrs)/(12,000 hrs useful life))
(13,865 lb)(453.6 g/lb) = 8.28E3 g

G1.3: (1) Grader [Caterpillar 140G]
Weight = 31,090 lb
Useful life = 15,000 hrs
Use = 7.9 hrs
((7.9 hrs use)/(15,000 hrs useful life))
(31,090 lb)(453.6 g/lb) = 7.43E3 g

G1.4: (1) Loader, Front-end [Caterpillar 930T]
Weight = 21,500 lb
Useful life = 10,000 hrs
Use = 7.9 hrs
((7.9 hrs use)/(10,000 hrs useful life))
(21,500 lb)(453.6 g/lb) = 7.70E3 g

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G1.5: (8) Truck, Dump
Weight = 25,000 lb
Useful life = 8,000 hrs [Estimate]
Use = 7.9 hrs
(8)((7.9 hrs use)/(8,000 hrs useful life))
(25,000 lb)(453.6 g/lb) = 8.96E4 g

Total G1 equipment raw units = 1.32E5 g

S. Services.

S1. Labor.
S1.1: (1) Bulldozer
Labor hours = 7.9 hrs
Labor salary/hour = $25.58
Labor = (7.9 hrs)($25.58/hr) = 2.02E2 $

S1.2: (2) Compactor, Base
Labor hours = 7.9 hrs
Labor salary/hour = $25.58
Labor = (2)(7.9 hrs)($25.58/hr) = 4.04E2 $

S1.3: (1) Grader
Labor hours = 7.9 hrs
Labor salary/hour = $25.58
Labor = (7.9 hrs)($25.58/hr) = 2.02E2 $

S1.4: (1) Loader, Front-end
Labor hours = 7.9 hrs
Labor salary/hour = $25.58
Labor = (7.9 hrs)($25.58/hr) = 2.02E2 $

S1.5: (8) Truck, Dump
Labor hours = 7.9 hrs
Labor salary/hour = $20.81
Labor = (8)(7.9 hrs)($20.81/hr) = 1.32E3 $

S1.6: (3) Labor, General
Labor hours = 7.9 hrs
Labor salary/hour = $20.65
Labor = (3)(7.9 hrs)($20.65/hr) = 4.89E2 $

Total S1 labor raw units = 2.82E3 $
Concrete Highway Pavement System (Alternative A)
USDOT Pavement System 501 - Portland Cement Concrete Pavement

TABLE AF501. Construction Phase EMERGY Input Table.

<table>
<thead>
<tr>
<th>Note</th>
<th>Item</th>
<th>Raw Units</th>
<th>Transformity</th>
<th>Solar EMERGY</th>
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<tr>
<td>E1</td>
<td>Atmosphere</td>
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</tr>
<tr>
<td>E2</td>
<td>Ecol. Prod.</td>
<td>NA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E3</td>
<td>Energy</td>
<td>NA</td>
<td></td>
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</tr>
<tr>
<td>E4</td>
<td>Land</td>
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<tr>
<td>E5</td>
<td>Water</td>
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</tr>
<tr>
<td>F</td>
<td>FUEL ENERGY</td>
<td></td>
<td>9.37E15</td>
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<tr>
<td>F1</td>
<td>Equipment</td>
<td>1.42E11, J</td>
<td>6.60E4</td>
<td>9.37E15</td>
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<td>F2</td>
<td>Facilities</td>
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<td></td>
<td></td>
<td>1.72E15</td>
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</table>

G   GOODS                   | 1.72E15 |
G1  Equipment              | 2.57E5, g| 6.70E9      | 1.72E15      |
G2  Facilities             | NA       |             |              |
G3  Materials              | NA       |             |              |
G4  Tools                  | NA       |             |              |
S   SERVICES               | 3.60E16  |
S1  Labor                  | 1.80E4, $| 2.00E12     | 3.60E16      |

Concrete pavement materials are included in AC401.
Concrete Highway Pavement System (Alternative A)
USDOT Pavement System 501 - Portland Cement Concrete Pavement

<table>
<thead>
<tr>
<th>TABLE AF501 EMERGY Input Calculations</th>
<th>(Construction Phase F)</th>
</tr>
</thead>
</table>

[Placement of original 9" concrete pavement]

E. Environment.
Not applicable. Use input = 0.

F. Fuel energy.

<table>
<thead>
<tr>
<th>F1. Equipment</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>F1.1: (1) Placer/Spreader, Concrete</td>
<td>[GOMACO PS-68]</td>
</tr>
<tr>
<td>Fuel consumption = 8 gal/hr</td>
<td>[Estimate]</td>
</tr>
<tr>
<td>Use = 10 hrs</td>
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<tr>
<td>(10 hrs use)(8 gal/hr) = 80 gal</td>
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</tr>
<tr>
<td>((80 gal)/(42 gal/BBL))(6.28E9 J/BBL)</td>
<td>= 1.20E10 J</td>
</tr>
</tbody>
</table>

| F1.2: (2) Saw, Concrete                  | [Magnum PS6585] |
| Fuel consumption = 3 gal/hr              | [Estimate]    |
| Use 10 hrs                               |              |
| (10 hrs use)(3 gal/hr) = 30 gal          |              |
| (2)((30 gal)/(42 gal/BBL))(6.28E9 J/BBL) | = 8.97E9 J   |

| F1.3: (1) Slipform Paver, Concrete       | [GOMACO GP-4000] |
| Fuel consumption = 10 gal/hr             | [Estimate]    |
| Use = 10 hrs                             |              |
| (10 hrs use)(10 gal/hr) = 100 gal        |              |
| ((100 gal)/(42 gal/BBL))(6.28E9 J/BBL)   | = 1.50E10 J  |

| F1.4: (1) Texturing/Curing Mach., Conc.  | [GOMACO T/C-600] |
| Fuel consumption = 2 gal/hr              | [Estimate]    |
| Use = 10 hrs                             |              |
| (10 hrs use)(2 gal/hr) = 20 gal          |              |
| ((20 gal)/(42 gal/BBL))(6.28E9 J/BBL)    | = 2.99E9 J   |

| F1.5: (8) Truck, Dump (Concrete to Conc. Placer/Spreader) |  |
| Fuel consumption = 8 gal/hr               | [Estimate]    |
| Use = 10 hrs                             |              |
| (8)(10 hrs use)(8 gal/hr) = 640 gal      |              |
| ((640 gal)/(42 gal/BBL))(6.28E9 J/BBL)   | = 9.57E10 J  |
F1.6: (1) Truck, Water Tanker (Saw and Seal)
Fuel consumption = 5 gal/hr [Estimate]
Use = 10 hrs
(10 hrs use)(5 gal/hr) = 50 gal
((50 gal)/(42 gal/BBL))(6.28E9 J/BBL) = 7.48E9 J

Total F1 equipment raw units = 1.42E11 J

G. Goods.
G1. Equipment.
G1.1: (1) Placer/Spreader, Concrete [Gomaco PS-68]
Weight = 145,000 lb [Gomaco]
Useful life = 10,000 hrs [Estimate]
Use = 10 hrs
((10 hrs use)/(10,000 hrs useful life))
(145,000 lb)(453.6 g/lb) = 6.58E4g

G1.2: (2) Saw, Concrete [Magnum PS6585]
Weight = 1,450 lb [Magnum]
Useful life = 7,500 hrs [Estimate]
Use = 10 hrs
(2)((10 hrs use)/(7,500 hrs useful life))
(1,450 lb)(453.6 g/lb) = 1.75E3g

G1.3: (1) Slipform Paver, Concrete [GOMACO GP-4000]
Weight = 115,000 lb [GOMACO]
Useful life = 10,000 hrs [Estimate]
Use = 10 hrs
((10 hrs use)/(10,000 hrs useful life))
(115,000 lb)(453.6 g/lb) = 5.22E4g

G1.4: (1) Texturing/Curing Machine [GOMACO T/C-600]
Weight = 12,500 lb [GOMACO]
Useful life = 7,500 hrs [Estimate]
Use = 10 hrs
((10 hrs use)/(7,500 hrs useful life))
(12,500 lb)(453.6 g/lb) = 7.56E3g

G1.5: (8) Truck, Dump (Concrete to Conc. Placer/Spreader)
Weight = 25,000 lb
Useful life = 8,000 hrs [Estimate]
Use = 10 hrs
(8)((10 hrs use)/(8,000 hrs useful life))
(25,000 lb)(453.6 g/lb) = 1.13E5g
GI.6: (1) Truck, Water Tanker (Saw and Seal)
Weight = 30,000 lb
Useful life = 8,000 hrs [Estimate]
Use = 10 hrs
\[\frac{(10 \text{ hrs use})}{(8,000 \text{ hrs useful life})}\]
\[(30,000 \text{ lb})(453.6 \text{ g/lb}) = 1.70E4 \text{ g}\]

Total GI equipment raw units = 2.57E5 g

S. Services.

S1. Labor.
S1.1: Placer/Spreader and Slipform Paver
Labor hours = 514 hrs
Labor salary/hour = $20.97
Labor = (514 hrs)($20.97/hr) = 1.08E4 $

S1.2: Saw and Seal
Labor hours = 200 hrs
Labor salary/hour = $20.97
Labor = (200 hrs)($20.97/hr) = 4.19E3 $

S1.3: Trucking
Labor hours = 141 hrs
Labor salary/hour = $20.97
Labor = (141 hrs)($20.97/hr) = 2.96E3 $

Total S1 labor raw units = 1.80E4 $

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Concrete Highway Pavement System (Alternative A)  
USDOT Pavement System 301 - Untreated Aggregate Courses  

**TABLE AG301. Use Phase EMERGY Input Table.**

<table>
<thead>
<tr>
<th>Note</th>
<th>Item</th>
<th>Raw Units g,J,$</th>
<th>Transformity sej/unit</th>
<th>Solar EMERGY sej</th>
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<td>E</td>
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<tr>
<td>E1</td>
<td>Atmosphere</td>
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<tr>
<td>E2</td>
<td>Ecol. Prod.</td>
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<tr>
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<td>Energy</td>
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<td></td>
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<tr>
<td>E4</td>
<td>Land</td>
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No inputs are required to the aggregate base course for the concrete pavement alternative during the use phase.
Concrete Highway Pavement System (Alternative A)
USDOT Pavement System 401 - Hot Asphalt Concrete Pavement

TABLE AG401. Use Phase EMERGY Input Table.

<table>
<thead>
<tr>
<th>Note</th>
<th>Item</th>
<th>Raw Units</th>
<th>Transformity</th>
<th>Solar EMERGY</th>
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Concrete Highway Pavement System (Alternative A)
USDOT Pavement System 401 - Hot Asphalt Concrete Pavement

TABLE AG401 EMERGY Input Calculations
(Use Phase G)

[1" asphalt bond breaker at year 25]

Material transformity
Asphalt concrete transformity = 1.78E9 sej/g [Appendix C]
Machinery (Equipment) transformity = 6.70E9 sej/g [Append. C]
Petroleum product (Fuel energy) transformity = 6.60E4 sej/J [Appendix C]
Water (Consumer) transformity = 6.66E5 sej/J [Appendix C]

Asphalt concrete pavement quantity
Asphalt pavement weight = 4000 lb/CY
Volume = (((1 in)/(12 in/ft))(24 ft)(3280.8398 ft/km))
/(27 CF/CY) = 243.03 CY/km
Mass = (243.03 CY)(4000 lb/CY)(453.6 g/lb) = 4.41E8 g
Asphalt concrete pavement placement workday = 13 hours

E. Environment.
E5. Water.

E5.1: (2) Water, Asphalt Roller
Water consumption = 1600 gal/day/roller
Duration of water use = (3280.8398 ft/km)/(5280 ft/day) = 0.621 day
(2)(1600 gal/day)(0.621 day)(3.7854 l/gal)
= 7.52E3 l
(7.52E3 l)(1000 g/l)(4.94 J/g) = 3.72E7 J

Asphalt concrete
Environment input transformity portion = 56.43 %
(1.78E9 sej/g)(0.5643) = 1.01E9 sej/g
(4.41E8 g)(1.01E9 sej/g) = 4.45E17 sej

F. Fuel energy.
F1. Equipment.

F1.1: (1) Paver, Asphalt [Barber-Greene BG-240B]
Fuel consumption = 7.5 gal/hr
Use = (0.621 day)(13 hr/day) = 8.1 hrs
(1)((8.1 hrs)(7.5 gal/hr)/(42 gal/BBL))
(6.28E9 J/BBL) = 9.08E9 J

F1.2: (1) Roller, Asphalt (3 Wheel)
Asphalt pavement rate = 1 mi/day
Fuel consumption = 20 gal/mi of pavement
Use = (3280.8398 ft/km)/(5280 ft/mi) = 0.621 mi
(1)((20 gal/mi)(0.621 mi))/(42 gal/BBL)
(6.28E9 J/BBL) = 1.86E9 J
F1.3: (1) Roller, Asphalt (Tandem)
Asphalt pavement rate = 1 mi/day
Fuel consumption = 20 gal/mi of pavement
Use = (3280.8398 ft/km)/(5280 ft/mi) = 0.621 mi
(1) ((20 gal/mi)(0.621 mi))/(42 gal/BBL)
(6.28E9 J/BBL) = 1.86E9 J

F1.4: (8) Truck, Dump (Asphalt from plant to pavement)
Fuel consumption = 5 mpg [Estimate]
Truck capacity = 16 T
Asphalt pavement mass = (243.03 CY)(2.0 T/CY) = 486.06 T
Use = 24 mi/truckload roundtrip [Estimate]
Truckloads = ((486.06 T)/(16 T/truckload))/ (8 trucks) = 4 truckloads/truck
(8)((4 truckloads)(24 mi/truckload)/(5 mpg)/(42 gal/BBL))(6.28E9 J/BBL) = 2.30E10 J

Total F1 equipment raw units = 3.58E10 J

Asphalt concrete
Fuel energy input transformity portion = 15.35%
(1.78E9 sej/g)(0.1535) = 2.73E8 sej/g
(4.41E8 g)(2.73E8 sej/g) = 1.20E17 sej

G. Goods.
G1. Equipment.
G1.1: (1) Paver, Asphalt [Barber-Greene BG-240B]
Weight = 33,460 lb
Useful life = 10,000 hrs [Estimate]
Use = (0.621 day)(13 hr/day) = 8.1 hrs
(1)((8.1 hrs)/(10,000 hrs useful life))
(33,460 lb)(453.6 g/lb) = 1.23E4 g

G1.2: (1) Roller, Asphalt (3 Wheel)
Weight = 28,000 lb
Useful life = 5 years at 196 work days/yr [Estimate]
Use = 0.621 day
(1)((0.621 day)/(5 years)(196 work days/yr))
(28,000 lb)(453.6 g/lb) = 8.05E3 g

G1.3: (1) Roller, Asphalt (Tandem)
Weight = 20,000 lb
Useful life = 5 years at 196 work days/yr [Estimate]
Use = 0.621 day
(1)((0.621 day)/(5 years)(196 work days/yr))
(20,000 lb)(453.6 g/lb) = 5.75E3 g

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G1.4: (8) Truck, Dump [Asphalt from plant to pavement]
Weight = 25,000 lb [Estimate]
Useful life = 250,000 mi [Estimate]
Truckloads = ((486.06 T)/(16 T/truckload))/
(8 trucks) = 4 truckloads/truck
Use = 24 mi/truckload roundtrip [Estimate]
(8)((4 truckloads/truck)(24 mi/truckload)/
(250,000 mi useful life))(25,000 lb)
(453.6 g/lb) = 3.48E4 g

Total G1 equipment raw units = 6.09E4 g

  Asphalt concrete
  Goods input transformity portion = 14.11 %
  (1.78E9 sej/g)(0.1411) = 2.51E8 sej/g
  (4.41E8 g)(2.51E8 sej/g) = 1.11E17 sej

S. Services.
  S1. Labor.
  Pavement rate = 1 mi/13 hr workday
  Pavement duration = ((3280.8398 ft/km)/(5280 ft/mi))
  (13 hr workday/mi) = 8.1 hr/km
  Crew: [Salaries RE: AH401/AH501]
    (3) Equipment operators @ $25.58/hr = $76.74
    (3) Laborers @ $20.65/hr = $61.95
    (8) Truck drivers @ $20.81/hr = $166.48
  Total labor cost/hr = $305.17
  ($305.17/hr)(8.1 hours) = 2.47E3 $

  Asphalt concrete
  Services input transformity portion = 14.11 %
  (1.78E9 sej/g)(0.1411) = 2.51E8 sej/g
  (4.41E8 g)(2.51E8 sej/g) = 1.11E17 sej
Concrete Highway Pavement System (Alternative A)  
USDOT Pavement System 501 - Portland Cement Concrete Pavement

**TABLE AG501. Use Phase EMERGY Input Table.**

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<tr>
<th>Note</th>
<th>Item</th>
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<th>Transformity sej/unit</th>
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</table>
Concrete Highway Pavement System (Alternative A)
USDOT Pavement System 501 - Portland Cement Concrete Pavement

**TABLE AG501 EMERGY Input Calculations**
(Use Phase G)

[9" concrete overlay at year 25]

**Material transformity**

Concrete transformity = 9.99E8 sej/g [Appendix C]
Petroleum product transformity = 6.60E4 sej/J [Appendix C]
Steel transformity = 1.80E9 sej/g [Appendix C]

**Concrete quantity**

\[
\text{Volume} = (0.2286 \text{ m thick})(7.3152 \text{ m width})(1000 \text{ m}) - (2.0677 \text{ m}^3\text{ steel reinf. volume}) = 1670.1870 \text{ m}^3
\]

\[
\text{Mass} = (1670.1870 \text{ m}^3)(2.3144E6 \text{ g/m}^3) = 3.87E9 \text{ g}
\]

**Petroleum product (Curing Compound) quantity**

Rate of application = 0.06 gal/SY
\[
(7.3152 \text{ m})(1 \text{ km}) = 7,315.2 \text{ m}^2 = 78,742.734 \text{ ft}^2
\]
\[
(78,742.734 \text{ ft}^2)/(9 \text{ ft}^2/\text{SY}) = 8,749.19 \text{ SY}
\]
\[
((8,749.19 \text{ SY})(0.06 \text{ gal/} \text{SY})/(42 \text{ gal/BBL}))(6.28E9 \text{ J/BBL}) = 7.85E10 \text{ J}
\]

**Petroleum product (Joint Sealant and Filler) quantity**

Joint width = 1/4" = 0.00635 m
Joint depth = 3/4" = 0.01905 m
Joint spacing = 15 ft = 4.572 m
Joint quantity = (1000 m)/(4.572 m) = 219 joints
\[
((219 \text{ joints})(7.3152 \text{ m}) + (1000 \text{ m})(0.01905 \text{ m depth}) (0.00635 \text{ m width}) = 0.32 \text{ m}^3\text{ joint sealant}
\]
\[
((0.32 \text{ m}^3)(1000 \text{ l/m}^3)(0.264172 \text{ gal/l}))/\text{42 gal/BBL}) (6.28E9 \text{ J/BBL}) = 1.26E10 \text{ J}
\]

**Steel quantity**

Dowels 1.25" Diameter x 18" length at 12'-0" on center
\[
\text{Dowel volume} = (1.27 \text{ in}^2)(18 \text{ in})(24/\text{joint})(218.5 \text{ joints}) = 69.3738 \text{ ft}^3 = 1.9645 \text{ m}^3
\]

\[
\text{Dowel mass} = (6,441.8 \text{ g/m})(0.4572 \text{ m})(24/\text{joint}) (218.5 \text{ joints}) = 1.545E7 \text{ g}
\]

Tiebars 0.5" Diameter x 24" length at 30" on center
\[
\text{Tiebar volume} = (0.20 \text{ in}^2)(24 \text{ in})(1312 \text{ tiebars}) = 3.6444 \text{ ft}^3 = 0.1032 \text{ m}^3
\]
\[
\text{Tiebar mass} = (994.1 \text{ g/m})(0.6096 \text{ m})(1312 \text{ tiebars}) = 7.951E5 \text{ g}
\]

Total steel reinf. volume = (1.9645 \text{ m}^3) + (0.1032 \text{ m}^3) = 2.0677 \text{ m}^3

Total steel reinf. mass = (1.545E7 \text{ g}) + (7.951E5 \text{ g}) = 1.63E7 \text{ g}
E. Environment


Concrete

Environment input transformity portion = 91.30 %
(9.99E8 sej/g)(0.9130) = 9.12E8 sej/g
(3.87E9 g)(9.12E8 sej/g) = 3.53E18 sej

Petroleum product (Curing Compound at year 25)

Environment input transformity portion = 25 %

(6.60E4 sej/J)(0.25) = 1.65E4 sej/J
(7.85E10 J)(1.65E4 sej/J) = 1.30E15 sej

Petroleum product (Joint Sealant and Filler at year 12)

Environment input transformity portion = 25 %

(6.60E4 sej/J)(0.25) = 1.65E4 sej/J
(1.26E10 J)(1.65E4 sej/J) = 2.08E14 sej

Petroleum product (Joint Sealant and Filler at year 25)

Environment input transformity portion = 25 %

(6.60E4 sej/J)(0.25) = 1.65E4 sej/J
(1.26E10 J)(1.65E4 sej/J) = 2.08E14 sej

Petroleum product (Joint Sealant and Filler at year 37)

Environment input transformity portion = 25 %

(6.60E4 sej/J)(0.25) = 1.65E4 sej/J
(1.26E10 J)(1.65E4 sej/J) = 2.08E14 sej

Steel (Reinforcement)

Environment input transformity portion = 37.3 %
(1.80E9 sej/g)(0.373) = 6.71E8 sej/g
(1.63E7 g)(6.71E8 sej/g) = 1.09E16 sej

Total E6 materials solar EMERGY input = 3.54E18 sej

F. Fuel energy.

F1. Equipment.

F1.1: (1) Placer/Spreader, Concrete

[GOMACO PS-68]

Fuel consumption = 8 gal/hr [Estimate]
Use = 10 hrs
(1)(10 hrs use)(8 gal/hr)/(42 gal/BBL)
(6.28E9 J/BBL) = 1.20E10 J

F1.2: (2) Saw, Concrete

[Magnum PS6585]

Fuel consumption = 3 gal/hr [Estimate]
Use = 10 hrs
(2)(10 hrs use)(3 gal/hr)/(42 gal/BBL)
(6.28E9 J/BBL) = 8.97E9 J

F1.3: (1) Slipform Paver, Concrete

[GOMACO GP-4000]

Fuel consumption = 10 gal/hr [Estimate]
Use = 10 hrs
(1)(10 hrs use)(10 gal/hr)/(42 gal/BBL)
(6.28E9 J/BBL) = 1.50E10 J
F1.4: (1) Texturing/Curing Mach., Conc. [GOMACO T/C-600]
Fuel consumption = 2 gal/hr [Estimate]
Use = 10 hrs
(1) ((10 hrs use)(2 gal/hr)/(42 gal/BBL))
(6.28E9 J/BBL) = 2.99E9 J

F1.5: (8) Truck, Dump (Concrete to Conc. Placer/Spreader)
Fuel consumption = 8 gal/hr [Estimate]
Use = 10 hrs
(8) ((10 hrs use)(8 gal/hr)/(42 gal/BBL))
(6.28E9 J/BBL) = 9.57E10 J

F1.6: (1) Truck, Water Tanker (Saw and seal)
Fuel consumption = 5 gal/hr [Estimate]
Use = 10 hrs
(1) ((10 hrs use)(5 gal/hr)/(42 gal/BBL))
(6.28E9 J/BBL) = 7.48E9 J

Total F1 equipment raw units = 1.42E11 J

Concrete
Fuel energy input transformity portion = 5.04 %
(9.99E8 sej/g)(0.0504) = 5.04E7 sej/g
(3.87E9 g)(5.04E7 sej/g) = 1.95E17 sej

Petroleum product (Curing Compound at year 25)
Fuel energy input transformity portion = 25 % [Estimate]
(6.60E4 sej/J)(0.25) = 1.65E4 sej/J
(7.85E10 J)(1.65E4 sej/J) = 1.30E15 sej

Petroleum Product (Joint Sealant and Filler at year 12)
Fuel energy input transformity portion = 25 % [Estimate]
(6.60E4 sej/J)(0.25) = 1.65E4 sej/J
(1.26E10 J)(1.65E4 sej/J) = 2.08E14 sej

Petroleum Product (Joint Sealant and Filler at year 25)
Fuel energy input transformity portion = 25 % [Estimate]
(6.60E4 sej/J)(0.25) = 1.65E4 sej/J
(1.26E10 J)(1.65E4 sej/J) = 2.08E14 sej

Petroleum Product (Joint Sealant and Filler at year 37)
Fuel energy input transformity portion = 25 % [Estimate]
(6.60E4 sej/J)(0.25) = 1.65E4 sej/J
(1.26E10 J)(1.65E4 sej/J) = 2.08E14 sej

Steel (Reinforcement)
Fuel energy input transformity portion = 46.5 %
(1.80E9 sej/g)(0.465) = 8.37E8 sej/g
(1.63E7 g)(8.37E8 sej/g) = 1.36E16 sej

Total F3 materials solar EMERGY input = 2.11E17 sej
G. Goods.
  G1. Equipment.

G1.1: (1) Placer/Spreader, Concrete [Gomaco PS-68]
Weight = 145,000 lb [Gomaco]
Useful life = 10,000 hrs [Estimate]
Use = 10 hrs
(1)((10 hrs use)/(10,000 hrs useful life))
(145,000 lb)(453.6 g/lb) = 6.58E4 g

G1.2: (2) Saw, Concrete [Magnum PS6585]
Weight = 1,450 lb [Magnum]
Useful life = 7,500 hrs [Estimate]
Use = 10 hrs
(2)((10 hrs use)/(7,500 hrs useful life))
(1,450 lb)(453.6 g/lb) = 1.75E3 g

G1.3: (1) Slipform Paver, Concrete [GOMACO GP-4000]
Weight = 115,000 lb [GOMACO]
Useful life = 10,000 hrs [Estimate]
Use = 10 hrs
(1)((10 hrs use)/(10,000 hrs useful life))
(115,000 lb)(453.6 g/lb) = 5.22E4 g

G1.4: (1) Texturing/Curing Machine [GOMACO T/C-600]
Weight = 12,500 lb [GOMACO]
Useful life = 7,500 hrs [Estimate]
Use = 10 hrs
(1)((10 hrs use)/(7,500 hrs useful life))
(12,500 lb)(453.6 g/lb) = 7.56E3 g

G1.5: (8) Truck, Dump (Concrete to Conc. Placer/Spreader)
Weight = 25,000 lb
Useful life = 8,000 hrs [Estimate]
Use = 10 hrs
(8)((10 hrs use)/(8,000 hrs useful life))
(25,000 lb)(453.6 g/lb) = 1.13E5 g

G1.6: (1) Truck, Water Tanker (Saw and Seal)
Weight = 30,000 lb
Useful life = 8,000 hrs [Estimate]
Use = 10 hrs
(1)((10 hrs use)/(8,000 hrs useful life))
(30,000 lb)(453.6 g/lb) = 1.70E4 g

Total G1 equipment raw units = 2.57E5 g

Concrete
Goods input transformity portion = 0.15 %
(9.99E8 sej/g)(0.0015) = 1.50E6 sej/g
(3.87E9 g)(1.50E6 sej/g) = 5.81E15 sej
Petroleum product (Curing Compound at year 25)
Goods input transformity portion = 25 % [Estimate]
\[(6.60E4 \text{ sej/J})(0.25) = 1.65E4 \text{ sej/J} \]
\[(7.85E10 \text{ J})(1.65E4 \text{ sej/J}) = 1.30E15 \text{ sej} \]

Petroleum product (Joint Sealant and Filler at year 12)
Goods input transformity portion = 25 % [Estimate]
\[(6.60E4 \text{ sej/J})(0.25) = 1.65E4 \text{ sej/J} \]
\[(1.26E10 \text{ J})(1.65E4 \text{ sej/J}) = 2.08E14 \text{ sej} \]

Petroleum product (Joint Sealant and Filler at year 25)
Goods input transformity portion = 25 % [Estimate]
\[(6.60E4 \text{ sej/J})(0.25) = 1.65E4 \text{ sej/J} \]
\[(1.26E10 \text{ J})(1.65E4 \text{ sej/J}) = 2.08E14 \text{ sej} \]

Petroleum product (Joint Sealant and Filler at year 37)
Goods input transformity portion = 25 % [Estimate]
\[(6.60E4 \text{ sej/J})(0.25) = 1.65E4 \text{ sej/J} \]
\[(1.26E10 \text{ J})(1.65E4 \text{ sej/J}) = 2.08E14 \text{ sej} \]

Steel (Reinforcement)
Goods input transformity portion = 3.5 %
\[(1.80E9 \text{ sej/g})(0.035) = 6.30E7 \text{ sej/g} \]
\[(1.63E7 \text{ g})(6.30E7 \text{ sej/g}) = 1.03E15 \text{ sej} \]

Total G3 materials solar EMERGY input = 8.76E15 sej

S. Services.
S1. Labor.
S1.1: Placer/Spreader and Slipform Paver
Labor hours = 514 hrs
Labor salary/hour = $20.97
Labor = (514 hrs)($20.97/hr) = 1.08E4 $

S1.2: Saw and Seal
Labor hours = 200 hrs
Labor salary/hour = $20.97
Labor = (200 hrs)($20.97/hr) = 4.19E3 $

S1.3: Trucking
Labor hours = 141 hrs
Labor salary/hour = $20.97
Labor = (141 hrs)($20.97/hr) = 2.96E3 $

Total S1 labor raw units = 1.80E4 $

Concrete
Services input transformity portion = 3.48 %
\[(9.99E8 \text{ sej/g})(0.0348) = 3.48E7 \text{ sej/g} \]
\[(3.87E9 \text{ g})(3.48E7 \text{ sej/g}) = 1.35E17 \text{ sej} \]

Petroleum product (Curing Compound at year 25)
Services input transformity portion = 25 % [Est.]
\[(6.60E4 \text{ sej/J})(0.25) = 1.65E4 \text{ sej/J} \]
\[(7.85E10 \text{ J})(1.65E4 \text{ sej/J}) = 1.30E15 \text{ sej} \]
Petroleum product (Joint Sealant and Filler at year 12)
Services input transformity portion = 25 % [Est.]
(6.60E4 sej/J)(0.25) = 1.65E4 sej/J
(1.26E10 J)(1.65E4 sej/J) = 2.08E14 sej

Petroleum product (Joint Sealant and Filler at year 25)
Services input transformity portion = 25 % [Est.]
(6.60E4 sej/J)(0.25) = 1.65E4 sej/J
(1.26E10 J)(1.65E4 sej/J) = 2.08E14 sej

Petroleum product (Joint Sealant and Filler at year 37)
Services input transformity portion = 25 % [Est.]
(6.60E4 sej/J)(0.25) = 1.65E4 sej/J
(1.26E10 J)(1.65E4 sej/J) = 2.08E14 sej

Steel (Reinforcement)
Services input transformity portion = 12.7 %
(1.80E9 sej/g)(0.127) = 2.29E8 sej/g
(1.63E7 g)(2.29E8 sej/g) = 3.73E15 sej

Total S2 materials solar EMERGY input = 1.41E17 sej
Concrete Highway Pavement System (Alternative A)
USDOT Pavement System 301 - Untreated Aggregate Courses

TABLE AH301. Demolition Phase EMERGY Input Table.

<table>
<thead>
<tr>
<th>Note</th>
<th>Item</th>
<th>Raw Units</th>
<th>Transformity</th>
<th>Solar EMERGY</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ENVIRONMENT</td>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>E1</td>
<td>Atmosphere</td>
<td>NA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E2</td>
<td>Ecol. Prod.</td>
<td>NA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E3</td>
<td>Energy</td>
<td>NA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E4</td>
<td>Land</td>
<td>NA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E5</td>
<td>Water</td>
<td>NA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F1</td>
<td>Equipment</td>
<td>NA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F2</td>
<td>Facilities</td>
<td>NA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G1</td>
<td>Equipment</td>
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<td></td>
</tr>
<tr>
<td>G2</td>
<td>Facilities</td>
<td>NA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G3</td>
<td>Materials</td>
<td>NA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G4</td>
<td>Tools</td>
<td>NA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S1</td>
<td>Labor</td>
<td>NA</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**TABLE AH301 EMERGY Input Calculations**

All EMERGY inputs equal zero because concrete pavement alternative assumes no demolition of the aggregate base course at the end of the use phase.
Concrete Highway Pavement System (Alternative A)
USDOT Pavement System 401 - Hot Asphalt Concrete Pavement
USDOT Pavement System 501 - Portland Cement Concrete Pavement

TABLE AH401/AH501. Demolition Phase EMERGY Input Table.

<table>
<thead>
<tr>
<th>Note</th>
<th>Item</th>
<th>Raw Units g,J,$</th>
<th>Transformity sej/unit</th>
<th>Solar EMERGY sej</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>ENVIRONMENT</td>
<td></td>
<td></td>
<td>2.62E13</td>
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<tr>
<td>E1</td>
<td>Atmosphere</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>E2</td>
<td>Ecol. Prod.</td>
<td>NA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E3</td>
<td>Energy</td>
<td>NA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E4</td>
<td>Land</td>
<td>NA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E5</td>
<td>Water</td>
<td>3.94E7 J</td>
<td>6.66E5</td>
<td>2.62E13</td>
</tr>
<tr>
<td>F</td>
<td>FUEL ENERGY</td>
<td></td>
<td></td>
<td>2.98E16</td>
</tr>
<tr>
<td>F1</td>
<td>Equipment</td>
<td>4.51E11 J</td>
<td>6.60E4</td>
<td>2.98E16</td>
</tr>
<tr>
<td>F2</td>
<td>Facilities</td>
<td>NA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G</td>
<td>GOODS</td>
<td></td>
<td></td>
<td>1.04E16</td>
</tr>
<tr>
<td>G1</td>
<td>Equipment</td>
<td>1.55E6 g</td>
<td>6.70E9</td>
<td>1.04E16</td>
</tr>
<tr>
<td>G2</td>
<td>Facilities</td>
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<td></td>
</tr>
<tr>
<td>G3</td>
<td>Materials</td>
<td>NA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G4</td>
<td>Tools</td>
<td>NA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S</td>
<td>SERVICES</td>
<td></td>
<td></td>
<td>4.40E16</td>
</tr>
<tr>
<td>S1</td>
<td>Labor</td>
<td>2.20E4 $</td>
<td>2.00E12</td>
<td>4.40E16</td>
</tr>
</tbody>
</table>
Concrete Highway Pavement System (Alternative A)
USDOT Pavement System 401 - Hot Asphalt Concrete Pavement
USDOT Pavement System 501 - Portland Cement Concrete Pavement

TABLES AH401 and AH501 EMERGY Input Calculations
(Demolition Phase H)

[Demolition of original 9" concrete pavement, 1" asphalt bondbreaker, and 9" concrete overlay at year 50]

E. Environment.
E5. Water.

E5.1: (1) Saw, Concrete [Vermeer CC135]
Water consumption at concrete saw
= 40 gal/hr
Use = 55 hrs
(1)(55 hrs)(40 gal/hr)(8 lb/gal)
(453.6 g/lb)(4.94 J/g) = 3.94E7 J

F. Fuel energy.
F1. Equipment.
F1.1: (1) Bulldozer [John Deere 750]
Fuel consumption = 5 gal/hr
Use = 112 hrs
(1)((112 hrs use)(5 gal/hr)/(42 gal/BBL))
(6.28E9 J/BBL) = 8.37E10 J

F1.2: (1) Excavator [Caterpillar 235C]
Fuel consumption = 7 gal/hr
Use = 112 hrs
(1)((112 hrs use)(7 gal/hr)/(42 gal/BBL))
(6.28E9 J/BBL) = 1.17E11 J

F1.3: (1) Saw, Concrete [Vermeer CC135]
Fuel consumption = 5 gal/hr
Use = 55 hrs
(1)((55 hrs use)(5 gal/hr)/(42 gal/BBL))
(6.28E9 J/BBL) = 4.11E10 J

F1.4: (5) Truck, Dump
Fuel consumption = 2.5 gal/hr
Use = 112 hrs
(5)((112 hrs use)(2.5 gal/hr)/(42 gal/BBL))
(6.28E9 J/BBL) = 2.09E11 J

Total F1 equipment raw units = 4.51E11 J

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### G. Goods.

#### G1. Equipment.

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
<th>Weight</th>
<th>Useful Life</th>
<th>Use</th>
<th>Equivalent Units</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>G1.1:</strong></td>
<td>Bulldozer [John Deere 750]</td>
<td>29,300 lb</td>
<td>8,000 hrs</td>
<td>112 hrs</td>
<td>$1.86E5 g</td>
</tr>
<tr>
<td><strong>G1.2:</strong></td>
<td>Excavator [Caterpillar 235C]</td>
<td>92,820 lb</td>
<td>8,000 hrs</td>
<td>112 hrs</td>
<td>$5.89E5 g</td>
</tr>
<tr>
<td><strong>G1.3:</strong></td>
<td>Saw, Concrete [Vermeer CC135]</td>
<td>21,170 lb</td>
<td>4,500 hrs</td>
<td>55 hrs</td>
<td>$1.17E5 g</td>
</tr>
<tr>
<td><strong>G1.4:</strong></td>
<td>Truck, Dump</td>
<td>32,500 lb</td>
<td>12,500 hrs</td>
<td>112 hrs</td>
<td>$6.60E5 g</td>
</tr>
</tbody>
</table>

Total G1 goods raw units = $1.55E6 g

### S. Services.

#### S1. Labor.

<table>
<thead>
<tr>
<th>Crew</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operators</td>
<td>$25.58/hr</td>
</tr>
<tr>
<td>Laborers</td>
<td>$20.65/hr</td>
</tr>
<tr>
<td>Truck drivers</td>
<td>$20.81/hr</td>
</tr>
</tbody>
</table>

Total labor cost/hr = $196.51

($196.51/hr) (112 hours) = 2.20E4 $

Total S1 labor raw units = 2.20E4 $
Concrete Highway Pavement System (Alternative A)
USDOT Pavement System 301 - Untreated Aggregate Courses
USDOT Pavement System 401 - Hot Asphalt Concrete Pavement
USDOT Pavement System 501 - Portland Cement Concrete Pavement

TABLE AI301/AI401/AI501. Natural Resource Recycling Phase
EMERGY Input Table.

<table>
<thead>
<tr>
<th>Note</th>
<th>Item</th>
<th>Raw Units g,J,$</th>
<th>Transformity sej/unit</th>
<th>Solar EMERGY sej</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>ENVIRONMENT</td>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>E1</td>
<td>Atmosphere</td>
<td>NA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E2</td>
<td>Ecol. Prod.</td>
<td>NA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E3</td>
<td>Energy</td>
<td>NA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E4</td>
<td>Land</td>
<td>NA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E5</td>
<td>Water</td>
<td>NA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>FUEL ENERGY</td>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>F1</td>
<td>Equipment</td>
<td>NA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F2</td>
<td>Facilities</td>
<td>NA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G</td>
<td>GOODS</td>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>G1</td>
<td>Equipment</td>
<td>NA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G2</td>
<td>Facilities</td>
<td>NA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G3</td>
<td>Materials</td>
<td>NA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G4</td>
<td>Tools</td>
<td>NA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S</td>
<td>SERVICES</td>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>S1</td>
<td>Labor</td>
<td>NA</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

TABLES AI301, AI401, and AI501 EMERGY Input Calculations
All EMERGY inputs equal zero because recycling inputs are assumed to be the same for the concrete and asphalt pavement alternatives.
Concrete Highway Pavement System (Alternative A)
USDOT Pavement System 301 - Untreated Aggregate Courses
USDOT Pavement System 401 - Hot Asphalt Concrete Pavement
USDOT Pavement System 501 - Portland Cement Concrete Pavement

TABLE AJ301/AJ401/AJ501. Disposal Phase EMERGY Input Table.

<table>
<thead>
<tr>
<th>Note</th>
<th>Item</th>
<th>Raw Units</th>
<th>Transformity</th>
<th>Solar EMERGY</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>g,J,$</td>
<td>sej/unit</td>
<td>sej</td>
</tr>
<tr>
<td>E</td>
<td>ENVIRONMENT</td>
<td>NA</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>E1</td>
<td>Atmosphere</td>
<td>NA</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>E2</td>
<td>Ecol. Prod.</td>
<td>NA</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>E3</td>
<td>Energy</td>
<td>NA</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>E4</td>
<td>Land</td>
<td>NA</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>E5</td>
<td>Water</td>
<td>NA</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>FUEL ENERGY</td>
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<td>0</td>
<td></td>
</tr>
<tr>
<td>F1</td>
<td>Equipment</td>
<td>NA</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>F2</td>
<td>Facilities</td>
<td>NA</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>G</td>
<td>GOODS</td>
<td>NA</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>G1</td>
<td>Equipment</td>
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</tr>
<tr>
<td>G2</td>
<td>Facilities</td>
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</tr>
<tr>
<td>G3</td>
<td>Materials</td>
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<td>0</td>
<td></td>
</tr>
<tr>
<td>G4</td>
<td>Tools</td>
<td>NA</td>
<td>0</td>
<td></td>
</tr>
<tr>
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<td></td>
</tr>
<tr>
<td>S1</td>
<td>Labor</td>
<td>NA</td>
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</tr>
</tbody>
</table>

TABLES AJ301, AJ401, and AJ501 EMERGY Input Calculations

All EMERGY inputs equal zero because no disposal is assumed for the concrete and asphalt pavement alternatives.
TABLE BC301. Material Transformity Phases A-C EMERGY Input Table.

<table>
<thead>
<tr>
<th>Note</th>
<th>Item</th>
<th>Raw Units</th>
<th>Transformity sej/unit</th>
<th>Solar EMERGY sej</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>ENVIRONMENT</td>
<td>[RE: CALCULATION BACK-UP]</td>
<td>4.17E18</td>
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</tr>
<tr>
<td>E1</td>
<td>Atmosphere</td>
<td>NA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E2</td>
<td>Ecol. Prod.</td>
<td>NA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E3</td>
<td>Energy</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>E4</td>
<td>Land</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>E5</td>
<td>Water</td>
<td>NA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>FUEL ENERGY</td>
<td>[RE: CALCULATION BACK-UP]</td>
<td>2.46E17</td>
<td></td>
</tr>
<tr>
<td>F1</td>
<td>Equipment</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>F2</td>
<td>Facilities</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>G</td>
<td>GOODS</td>
<td>[RE: CALCULATION BACK-UP]</td>
<td>2.46E17</td>
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</tr>
<tr>
<td>G1</td>
<td>Equipment</td>
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</tr>
<tr>
<td>G2</td>
<td>Facilities</td>
<td>NA</td>
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</tr>
<tr>
<td>G3</td>
<td>Materials</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>G4</td>
<td>Tools</td>
<td>NA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S</td>
<td>SERVICES</td>
<td>[RE: CALCULATION BACK-UP]</td>
<td>2.46E17</td>
<td></td>
</tr>
<tr>
<td>S1</td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>
Asphalt Highway Pavement System (Alternative B)
USDOT Pavement System 301 - Untreated Aggregate Courses

**TABLE BC301 EMERGY Input Calculations**
(Material Transformity Phases A-C)

[Original 14" crushed stone aggregate base course]

<table>
<thead>
<tr>
<th>Materials</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Stone (mined) transformity</td>
<td>$1.00E9 \text{ sej/g}$</td>
</tr>
<tr>
<td>Stone (natural state) transformity</td>
<td>$8.50E8 \text{ sej/g}$</td>
</tr>
<tr>
<td>Stone weight (compacted)</td>
<td>$3180 \text{ lb/CY}$</td>
</tr>
<tr>
<td>[Granite or limestone with 2.7 specific gravity]</td>
<td></td>
</tr>
</tbody>
</table>

**Stone quantity**
- **Volume** = $((14 \text{ in})/(12 \text{ in/ft}))(24 \text{ ft width})$
  - $(3280.8398 \text{ ft/km})/(27 \text{ CF/CY})$
  - $= 3402.4 \text{ CY/km}$
- **Mass** = $(3402.4 \text{ CY})(3180 \text{ lb/CY}(453.6 \text{ g/lb})$
  - $= 4.91E9 \text{ g}$

**E. Environment.**
- **Environment input transformity portion** = $85 \%$
  - $(1.00E9 \text{ sej/g})(0.85) = 8.50E8 \text{ sej/g}$
  - $(4.91E9 \text{ g})(8.50E8 \text{ sej/g}) = 4.17E18 \text{ sej}$

**Total environment solar EMERGY input** = $4.17E18 \text{ sej}$

**F. Fuel energy.**
- **Fuel energy input transformity portion** = $5 \%$ [Est.]
  - $(1.00E9 \text{ sej/g})(0.05) = 5.00E7 \text{ sej/g}$
  - $(4.91E9 \text{ g})(5.00E7 \text{ sej/g}) = 2.46E17 \text{ sej}$

**Total fuel energy solar EMERGY input** = $2.46E17 \text{ sej}$

**G. Goods.**
- **Goods input transformity portion** = $5 \%$ [Estimate]
  - $(1.00E9 \text{ sej/g})(0.05) = 5.00E7 \text{ sej/g}$
  - $(4.91E9 \text{ g})(5.00E7 \text{ sej/g}) = 2.46E17 \text{ sej}$

**Total goods solar EMERGY input** = $2.46E17 \text{ sej}$

**S. Services.**
- **Services input transformity portion** = $5 \%$ [Estimate]
  - $(1.00E9 \text{ sej/g})(0.05) = 5.00E7 \text{ sej/g}$
  - $(4.91E9 \text{ g})(5.00E7 \text{ sej/g}) = 2.46E17 \text{ sej}$

**Total services solar EMERGY input** = $2.46E17 \text{ sej}$
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Asphalt Highway Pavement System (Alternative B)  
USDOT Pavement System 401 - Hot Asphalt Concrete Pavement

**TABLE BC401 EMERGY Input Calculations**  
(Material Transformity Phases A-C)

[Original 5" asphalt concrete pavement]

**Material transformity**  
Asphalt concrete transformity = 1.78E9 sej/g  
Asphalt concrete pavement quantity  
Asphalt concrete pavement weight = 4000 lb/CY  
Volume = ((5 in)/(12 in/ft))(24 ft)(3280.8398 ft/km)  
/ (27 CF/CY) = 1215.13 CY/km  
Mass = (1215.13 CY)(4000 lb/CY)(453.6 g/lb)  
= 2.21E9 g

**E. Environment.**  
Asphalt concrete  
Environment input transformity portion = 56.43 %  
(1.78E9 sej/g)(0.5643) = 1.01E9 sej/g  
(2.21E9 g)(1.01E9 sej/g) = 2.23E18 sej

Total environment solar EMERGY units = 2.23E18 sej

**F. Fuel energy.**  
Asphalt concrete  
Fuel energy input transformity portion = 15.35 %  
(1.78E9 sej/g)(0.1535) = 2.73E8 sej/g  
(2.21E9 g)(2.73E8 sej/g) = 6.03E17 sej

Total fuel energy solar EMERGY units = 6.03E17 sej

**G. Goods.**  
Asphalt concrete  
Goods input transformity portion = 14.11 %  
(1.78E9 sej/g)(0.1411) = 2.51E8 sej/g  
(2.21E9 g)(2.51E8 sej/g) = 5.55E17 sej

Total goods solar EMERGY units = 5.55E17 sej

**S. Services.**  
Asphalt concrete  
Services input transformity portion = 14.11 %  
(1.78E9 sej/g)(0.1411) = 2.51E8 sej/g  
(2.21E9 g)(2.51E8 sej/g) = 5.55E17 sej

Total services solar EMERGY units = 5.55E17 sej
### Table BD301. Design Phase EMERGY Input Table.

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### BD301 EMERGY INPUT CALCULATION BACK-UP

Design EMERGY inputs are zero because inputs are the same for the aggregate base course of both pavement alternatives.
Asphalt Highway Pavement System (Alternative B)
USDOT Pavement System 401 - Hot Asphalt Concrete Pavement

TABLE BD401. Design Phase EMERGY Input Table.

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**TABLE BD401 EMERGY Input Calculations**

Design EMERGY inputs are zero because inputs are the same for both pavement alternatives.
Asphalt Highway Pavement System (Alternative B)
USDOT Pavement System 301 - Untreated Aggregate Courses

TABLE BE301. Component Production Phase EMERGY Input Table.

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<th>Note</th>
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**TABLE BE301 EMERGY Input Calculations**

EMERGY inputs are zero because no components are produced for the aggregate base course of the asphalt pavement alternative.
Asphalt Highway Pavement System (Alternative B)
USDOT Pavement System 401 - Hot Asphalt Concrete Pavement

TABLE BE401. Component Production Phase EMERGY Input Table.

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<th>Note</th>
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TABLE BE401 EMERGY Input Calculations

EMERGY inputs are zero because no components are produced for the asphalt pavement alternative.

113
Crushed stone base material is included in BC301.

114
Asphalt Highway Pavement System (Alternative B)
USDOT Pavement System 301 - Untreated Aggregate Courses

**TABLE BF301 EMERGY Input Calculations**

[Placement of original 14" crushed stone aggregate base]

Stone weight (compacted) = 3180 lb/CY

![Granite or limestone with 2.7 specific gravity]

Stone quantity

\[
\text{Volume/km} = \left(\frac{14 \text{ in}}{12 \text{ in/ft}}\right) (24 \text{ ft width}) \\
\left(\frac{3280.8398 \text{ ft/km}}{27 \text{ CF/CY}}\right) = 3402.4 \text{ CY} \\
\text{Mass/km} = \left(\frac{3402.4 \text{ CY}}{3180 \text{ lb/CY}}\right)/2000 \text{ lb/T} \\
= 5409.8 \text{ T}
\]

Crushed stone aggregate base placement rate = 3500 T/day

Crushed stone aggregate base placement duration = (5409.8 T)/(3500 T/day) = 1.55 days

Workday = 12 hrs

Base course placement duration = (1.55 days) (12 hrs/day) = 18.6 hrs

E. Environment.

E5. Water.

E5.1: (2) Water, Compactor

Water consumption = 1600 gal/day

Duration of water use = 1.55 days

(2) (1600 gal/day) (1.55 days) (3.7854 l/gal)

= 1.88E4 l

(1.88E4 l) (1000 g/l) (4.94 J/g) = 9.29E7 J

F. Fuel energy.

F1. Equipment.

F1.1: (1) Bulldozer [Caterpillar D8N]

Fuel consumption = 9.0 gal/hr

Use = 18.6 hrs

(18.6 hrs use) (9.0 gal/hr) = 167.4 gal

(167.4 gal) / (42 gal/BBL) (6.28E9 J/BBL)

= 2.50E10 J

F1.2: (2) Compactor, Base [Caterpillar CS-433B]

Fuel consumption = 3.5 gal/hr [Estimate]

Use = 18.6 hrs

(2) (18.6 hrs) (3.5 gal/hr) / (42 gal/BBL)

(6.28E9 J/BBL) = 1.95E10 J

F1.3: (1) Grader [Caterpillar 140G]

Fuel consumption = 6.0 gal/hr

Use = 18.6 hrs

(18.6 hrs use) (6.0 gal/hr) = 111.6 gal

(111.6 gal) / (42 gal/BBL) (6.28E9 J/BBL)

= 1.67E10 J

115
F1.4: (1) Loader, Front-end [Caterpillar 930T]
Fuel consumption = 2.75 gal/hr
Use = 18.6 hrs
(18.6 hrs use)(2.75 gal/hr) = 51.2 gal
((51.2 gal)/(42 gal/BBL))(6.28E9 J/BBL)
= 7.66E9 J

F1.5: (8) Truck, Dump
Fuel consumption = 7.3 gal/hr [Estimate]
Use = 18.6 hrs
(8)(18.6 hrs use)(7.3 gal/hr) = 1086.2 gal
((1086.2 gal)/(42 gal/BBL))(6.28E9 J/BBL)
= 1.62E11 J

Total F1 equipment raw units = 2.31E11 J

G. Goods.
   G1. Equipment.
   G1.1: (1) Bulldozer [Caterpillar D8N]
Weight = 92,812 lb
Useful life = 18,000 hrs
Use = 18.6 hrs
((18.6 hrs use)/(18,000 hrs useful life))
(92,812 lb)(453.6 g/lb) = 4.35E4 g

G1.2: (2) Compactor, Base [Caterpillar CS-433B]
Weight = 13,865 lb
Useful life = 12,000 hrs
Use = 18.6 hrs
(2)((18.6 hrs)/(12,000 hrs useful life))
(13,865 lb)(453.6 g/lb) = 1.95E4 g

G1.3: (1) Grader [Caterpillar 140G]
Weight = 31,090 lb
Useful life = 15,000 hrs
Use = 18.6 hrs
((18.6 hrs use)/(15,000 hrs useful life))
(31,090 lb)(453.6 g/lb) = 1.75E4 g

G1.4: (1) Loader, Front-end [Caterpillar 930T]
Weight = 21,500 lb
Useful life = 10,000 hrs
Use = 18.6 hrs
((18.6 hrs use)/(10,000 hrs useful life))
(21,500 lb)(453.6 g/lb) = 1.81E4 g
G1.5: (8) Truck, Dump
Weight = 25,000 lb
Useful life = 8,000 hrs
Use = 18.6 hrs
(8)((18.6 hrs use)/(8,000 hrs useful life))
(25,000 lb)(453.6 g/lb) = 2.11E5 g

Total G1 equipment raw units = 3.10E5 g

S. Services.

S1. Labor.
S1.1: (1) Bulldozer
Labor hours = 18.6 hrs
Labor salary/hour = $25.58
Labor = (18.6 hrs)($25.58/hr) = 4.76E2 $

S1.2: (2) Compactor, Base
Labor hours = 18.6 hrs
Labor salary/hour = $25.58
Labor = (2)(18.6 hrs)($25.58/hr) = 9.52E2 $

S1.3: (1) Grader
Labor hours = 18.6 hrs
Labor salary/hour = $25.58
Labor = (18.6 hrs)($25.58/hr) = 4.76E2 $

S1.4: (1) Loader, Front-end
Labor hours = 18.6 hrs
Labor salary/hour = $25.58
Labor = (18.6 hrs)($25.58/hr) = 4.76E2 $

S1.5: (8) Truck, Dump
Labor hours = 18.6 hrs
Labor salary/hour = $20.81
Labor = (8)(18.6 hrs)($20.81/hr) = 3.10E3 $

S1.6: (3) Labor, General
Labor hours = 18.6 hrs
Labor salary/hour = $20.65
Labor = (3)(18.6 hrs)($20.65/hr) = 1.15E3 $

Total S1 labor raw units = 6.63E3 $
Asphalt Highway Pavement System (Alternative B)  
USDOT Pavement System 401 - Hot Asphalt Concrete Pavement

**TABLE BF401. Construction Phase EMERGY Input Table.**

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<td>6.66E5</td>
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<tr>
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<td>6.60E4</td>
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<td>G</td>
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<td>2.00E12</td>
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Asphalt concrete pavement materials are included in BC401.
Asphalt Highway Pavement System (Alternative B)
USDOT Pavement System 401 - Hot Asphalt Concrete Pavement

TABLE BF401 EMERGY Input Calculations
(Construction Phase F)

[Placement of original 5" asphalt pavement]

Machinery transformity = 6.70E9 sej/g
Petroleum product (Fuel energy) transformity = 6.60E4 sej/J
Water transformity = 6.66E5 sej/J

Asphalt concrete pavement quantity

Asphalt concrete pavement weight = 2.0 T/CY
Volume = (((5 in)/(12 in/ft))(24 ft)(3280.8398 ft/km))
/(27 CF/CY) = 1215.13 CY/km
Mass = (1215.13 CY)(2.0 T/CY) = 2430.26 T

Asphalt concrete pavement placement workday = 13 hours
Pavement production rate = 5,280 ft/day
Pavement construction duration = (3280.8398 ft/km)/(5280 ft/day)
= 0.621 day/km

E. Environment.

E5. Water

E5.1: (2) Roller, Asphalt
Water consumption = 1600 gal/day/roller
Duration of water use = (3280.8398 ft/km)/(5280 ft/day) = 0.621 day
(2)(1600 gal/day)(0.621 day)(3.7854 l/gal)
= 7.52E3 l
(7.52E3 l)(1000 g/l)(4.94 J/g) = 3.72E7 J

Total E5 water raw units = 3.72E7 J

F. Fuel energy.

F1. Equipment.

F1.1: (1) Paver, Asphalt [Barber-Greene BG-265B]
Fuel consumption = 7.5 gal/hr
Use = (0.621 day)(13 hr/day) = 8.1 hrs
(1)((8.1 hrs)(7.5 gal/hr)/(42 gal/BBL))
(6.28E9 J/BBL) = 9.08E9 J

F1.2: (1) Roller, Asphalt (3 Wheel)
Asphalt pavement rate = 1 mi/day
Fuel consumption = 20 gal/mi of pavement
Use = (3280.8398 ft/km)/(5280 ft/mi) = 0.621 mi
(1)((20 gal/mi)(0.621 mi)/(42 gal/BBL))
(6.28E9 J/BBL) = 1.86E9 J
F1.3: (1) Roller, Asphalt (Tandem)
Asphalt pavement rate = 1 mi/day
Fuel consumption = 20 gal/mi of pavement
Use = $(3280.8398 \text{ ft/km})/(5280 \text{ ft/mi}) = 0.621 \text{ mi/mi}$
(1) $(20 \text{ gal/mi})(0.621 \text{ mi})/(42 \text{ gal/BBL})$
$(6.28E9 \text{ J/BBL}) = 1.86E9 \text{ J}$

F1.4: (8) Truck, Dump (Asphalt from plant to pavement)
Fuel consumption = 5 mpg [Estimate]
Truck capacity = 16 T
Asphalt pavement mass = $(1215.13 \text{ CY})(2.0 \text{ T/CY})$
$= 2430.26 \text{ T}$
Use = $24 \text{ mi/truckload roundtrip} [\text{Estimate}]$
Truckloads = $((2430.26 \text{ T})/(16 \text{ T/truckload})/\ (8 \text{ trucks}) = 19 \text{ truckloads/truck}$
(8) $(19 \text{ truckloads})(24 \text{ mi/truckload})/ \ (5 \text{ mpg})/(42 \text{ gal/BBL}) (6.28E9 \text{ J/BBL}) = 1.09E11 \text{ J}$

Total F1 equipment raw units = $1.22E11 \text{ J}$

G. Goods.

G1. Equipment.

G1.1: (1) Paver, Asphalt [Barber-Greene BG-265B]
Weight = 40,575 lb
Useful life = 10,000 hrs [Estimate]
Use = $(0.621 \text{ day})(13 \text{ hr/day}) = 8.1 \text{ hrs}$
(1) $(8.1 \text{ hrs})/(10,000 \text{ hrs useful life})$
$(40,575 \text{ lb})(453.6 \text{ g/lb}) = 1.49E4 \text{ g}$

G1.2: (1) Roller, Asphalt (3 Wheel)
Weight = 28,000 lb
Useful life = 5 years at 196 work days/yr [Estimate]
Use = $0.621 \text{ day}$
(1) $(0.621 \text{ day})/(5 \text{ years})(196 \text{ work days/yr})$
$(28,000 \text{ lb})(453.6 \text{ g/lb}) = 8.05E3 \text{ g}$

G1.3: (1) Roller, Asphalt (Tandem)
Weight = 20,000 lb
Useful life = 5 years at 196 work days/yr [Estimate]
Use = $0.621 \text{ day}$
(1) $(0.621 \text{ day})/(5 \text{ years})(196 \text{ work days/yr})$
$(20,000 \text{ lb})(453.6 \text{ g/lb}) = 5.75E3 \text{ g}$
G1.4: (8) Truck, Dump [Asphalt from plant to pavement]
Weight = 25,000 lb [Estimate]
Useful life = 250,000 mi [Estimate]
Truckloads = ((2430.26 T)/(16 T/truckload))/(8 trucks) = 19 truckloads/truck
Use = 24 mi/truckload roundtrip [Estimate]
(8)((19 truckloads/truck)(24 mi/truckload)/(250,000 mi useful life))(25,000 lb)
(453.6 g/lb) = 1.66E5g

Total G1 equipment raw units = 1.95E5 g

S. Services.

S1. Labor.
Pavement rate = 1 mi/13 hr workday
Pavement duration = ((3280.8398 ft/km)/(5280 ft/mi))
(13 hr workday/mi) = 8.1 hr/km
Crew: [Salaries RE: AH401/AH501]
(3) Equipment operators @ $25.58/hr = $ 76.74
(3) Laborers @ $20.65/hr = $ 61.95
(8) Truck drivers @ $20.81/hr = $166.48

Total labor cost/hr = $305.17

($305.17/hr)(8.1 hours) = 2.47E3 $

Total S1 labor raw units = 2.47E3 $
No inputs are required to the aggregate base course for the asphalt pavement alternative during the use phase.
Asphalt Highway Pavement System (Alternative B)
USDOT Pavement System 401 - Hot Asphalt Concrete Pavement

TABLE BG401. Use Phase EMERGY Input Table.

<table>
<thead>
<tr>
<th>Note</th>
<th>Item</th>
<th>Raw Units</th>
<th>Transformity</th>
<th>Solar EMERGY</th>
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</tbody>
</table>
Asphalt Highway Pavement System (Alternative B)
USDOT Pavement System 401 - Hot Asphalt Concrete Pavement

**TABLE BG401 EMERGY Input Calculations**
(Use Phase G)

[5" asphalt overlay at year 14, demolition of original 5" asphalt pavement and 5" asphalt overlay at year 25, new 5" asphalt pavement at year 25, and 5" asphalt overlay at year 39]

Material transformity
Asphalt concrete transformity = 1.78E9 sej/g [Appendix C]
Machinery (Equipment) transformity = 6.70 sej/g [Appendix C]
Petroleum product (Fuel energy) transformity
= 6.60E4 sej/J [Appendix C]
Water (Consumer) transformity= 6.66E5 sej/J [Appendix C]

Asphalt concrete pavement quantity
Asphalt pavement weight = 4000 lb/CY
Volume = (((5 in)/(12 in/ft))(24 ft)(3280.8398 ft/km))
/(27 CF/CY) = 1215.13 CY/km
Mass = (1215.13 CY)(4000 lb/CY)(453.6 g/lb)
= 2.21E9 g

E. Environment.

[5" Asphalt overlay at year 14]

E5. Water
E5.1: (2) Roller, Asphalt
Water consumption = 1600 gal/day/roller
Duration of water use = (3280.8398 ft/km)/(5280 ft/day) = 0.621 day/km
(2)(1600 gal/day)(0.621 day)(3.7854 l/gal)
= 7.52E3 l
(7.52E3 l)(1000 g/l)(4.94 J/g) = 3.72E7 J

Asphalt concrete
Environment input transformity portion = 56.43 %
(1.78E9 sej/g)(0.5643) = 1.01E9 sej/g
(2.21E9 g)(1.01E9 sej/g) = 2.23E18 sej
[Demolition of 5" asphalt pavement and 5" asphalt overlay at year 25]

E5. Water

E5.1: (1) Cold planer
[ Caterpillar PR-450C]
Water consumption = 200 gal/hr
Demolition rate = 175 T/hr
Use = (1215.13 CY) (2.0 T/CY)/(175 T/hr)
= 14 hrs
(1)(14 hrs)(200 gal/hr)(8 lb/gal)
(453.6 g/lb)(4.94 J/g) = 5.02E7 J

E5. Water

E5.1: (2) Roller, Asphalt
Water consumption = 1600 gal/day/roller
Duration of water use = (3280.8398 ft/km)/(5280 ft/day) = 0.621 day
(2)(1600 gal/day)(0.621 day)(3.7854 l/gal)
= 7.52E3 l
(7.52E3 l)(1000 g/l)(4.94 J/g) = 3.72E7 J


Asphalt concrete
Environment input transformity portion = 56.43 %
(1.78E9 sej/g)(0.5643) = 1.01E9 sej/g
(2.21E9 g)(1.01E9 sej/g) = 2.23E18 sej

[New 5" asphalt pavement at year 25]

E5. Water

E5.1: (2) Roller, Asphalt
Water consumption = 1600 gal/day/roller
Duration of water use = (3280.8398 ft/km)/(5280 ft/day) = 0.621 day
(2)(1600 gal/day)(0.621 day)(3.7854 l/gal)
= 7.52E3 l
(7.52E3 l)(1000 g/l)(4.94 J/g) = 3.72E7 J


Asphalt concrete
Environment input transformity portion = 56.43 %
(1.78E9 sej/g)(0.5643) = 1.01E9 sej/g
(2.21E9 g)(1.01E9 sej/g) = 2.23E18 sej

[5" Asphalt overlay at year 39]

E5. Water

E5.1: (2) Roller, Asphalt
Water consumption = 1600 gal/day/roller
Duration of water use = (3280.8398 ft/km)/(5280 ft/day) = 0.621 day
(2)(1600 gal/day)(0.621 day)(3.7854 l/gal)
= 7.52E3 l
(7.52E3 l)(1000 g/l)(4.94 J/g) = 3.72E7 J


Asphalt concrete
Environment input transformity portion = 56.43 %
(1.78E9 sej/g)(0.5643) = 1.01E9 sej/g
(2.21E9 g)(1.01E9 sej/g) = 2.23E18 sej

Total E5 water raw units = 1.62E8 J
Total E6 materials solar EMERGY units = 6.69E18 sej
F. Fuel energy.

[5" Asphalt overlay at year 14]

F1. Equipment.

F1.1: (1) Paver, Asphalt [Barber-Greene BG-240B]
Fuel consumption = 7.5 gal/hr
Use = (0.621 day)(13 hr/day) = 8.1 hrs
(1)((8.1 hrs)(7.5 gal/hr)/(42 gal/BBL))
(6.28E9 J/BBL) = 9.08E9 J

F1.2: (1) Roller, Asphalt (3 Wheel)
Asphalt pavement rate = 1 mi/day
Fuel consumption = 20 gal/mi of pavement
Use = (3280.8398 ft/km)/(5280 ft/mi)
    = 0.621 mi
(1)((20 gal/mi)(0.621 mi))/(42 gal/BBL)
(6.28E9 J/BBL) = 1.86E9 J

F1.3: (1) Roller, Asphalt (Tandem)
Asphalt pavement rate = 1 mi/day
Fuel consumption = 20 gal/mi
Use = (3280.8398 ft/km)/(5280 ft/mi)
    = 0.621 mi
(1)((20 gal/mi)(0.621 mi))/(42 gal/BBL)
(6.28E9 J/BBL) = 1.86E9 J

F1.4: (8) Truck, Dump (Asphalt from plant to pavement)
Fuel consumption = 5 mpg [Estimate]
Truck capacity = 16 T
Use = 24 mi/truckload roundtrip [Estimate]
Truckloads = ((2430.26 T)/(16 T/truckload))/
(8 trucks) = 19 truckloads/truck
(8)((19 truckloads)(24 mi/truckload))/
(5 mpg)/(42 gal/BBL))(6.28E9 J/BBL)
= 1.09E11 J


Asphalt concrete
Fuel energy input transformity portion = 15.35 %
(1.78E9 sej/g)(0.1535) = 2.73E8 sej/g
(2.21E9 g)(2.73E8 sej/g) = 6.03E17 sej
Demolition of 5" asphalt pavement and 5" asphalt overlay at year 25]

F1.1: (1) Cold planer [Caterpillar PR-450C]
Fuel consumption = 17 gal/hr
Demolition rate = 175 T/hr
Use = (1215.13 CY)(2.0 T/CY)/(175 T/hr)
= 14 hrs
(17 gal/hr)(14 hrs use)/(42 gal/BBL))
(6.28E9 J/BBL) = 3.56E10 J

F1.2: (8) Truck, Dump (3 axle)
Truck capacity = 17 T
Fuel consumption = 6.5 gal/hr
Cold planer demolition rate = 175 T/hr
Truck quantity
= (60 min/hr)/(8 min/truckload cycle)
= 8 truckloads/hr
Use = (1215.13 CY)(2.0 T/CY)/(175 T/hr)
= 14 hrs
(14 hrs use)(6.5 gal/hr)/(42 gal/BBL))
(6.28E9 J/BBL) = 1.09E11 J

[New 5" asphalt pavement at year 25]

F1. Equipment.
F1.1: (1) Paver, Asphalt [Barber-Greene BG-265B]
Fuel consumption = 7.5 gal/hr
Use = (0.621 day)(13 hr/day) = 8.1 hrs
(1)(8.1 hrs)(7.5 gal/hr)/(42 gal/BBL))
(6.28E9 J/BBL) = 9.08E9 J

F1.2: (1) Roller, Asphalt (3 Wheel)
Asphalt pavement rate = 1 mi/day
Fuel consumption = 20 gal/mi
Use = (3280.8398 ft/km)/(5280 ft/mi)
= 0.621 mi
(20 gal/mi)(0.621 mi)/(42 gal/BBL)
(6.28E9 J/BBL) = 1.86E9 J

F1.3: (1) Roller, Asphalt (Tandem)
Asphalt pavement rate = 1 mi/day
Fuel consumption = 20 gal/mi
Use = (3280.8398 ft/km)/(5280 ft/mi)
= 0.621 mi
(20 gal/mi)(0.621 mi)/(42 gal/BBL)
(6.28E9 J/BBL) = 1.86E9 J
F1.4: (8) Truck, Dump (Asphalt from plant to pavement)
Fuel consumption = 5 mpg [Estimate]
Truck capacity = 16 T
Use = 24 mi/truckload roundtrip [Estimate]
Truckloads = ((2430.26 T)/(16 T/truckload))/
(8 trucks) = 19 truckloads/truck
(8)((19 truckloads)(24 mi/truckload)/
(5 mpg)/(42 gal/BBL)) (6.28E9 J/BBL)
= 1.09E11 J

Asphalt concrete
Fuel energy input transformity portion = 15.35 %
(1.78E9 sej/g)(0.1535) = 2.73E8 sej/g
(2.21E9 g)(2.73E8 sej/g) = 6.03E17 sej

[5" Asphalt overlay at year 39]

F1. Equipment.
F1.1: (1) Paver, Asphalt [Barber-Greene BG-240B]
Fuel consumption = 7.5 gal/hr
Use = (0.621 day)(13 hr/day) = 8.1 hrs
(1)((8.1 hrs)(7.5 gal/hr)/(42 gal/BBL))
(6.28E9 J/BBL) = 9.08E9 J

F1.2: (1) Roller, Asphalt (3 Wheel)
Asphalt pavement rate = 1 mi/day
Fuel consumption = 20 gal/mi
Use = (3280.8398 ft/km)/(5280 ft/mi)
= 0.621 mi
(1)((20 gal/mi)(0.621 mi))/(42 gal/BBL)
(6.28E9 J/BBL) = 1.86E9 J

F1.3: (1) Roller, Asphalt (Tandem)
Asphalt pavement rate = 1 mi/day
Fuel consumption = 20 gal/mi
Use = (3280.8398 ft/km)/(5280 ft/mi)
= 0.621 mi
(1)((20 gal/mi)(0.621 mi))/(42 gal/BBL)
(6.28E9 J/BBL) = 1.86E9 J

F1.4: (8) Truck, Dump (Asphalt from plant to pavement)
Fuel consumption = 5 mpg [Estimate]
Truck capacity = 16 T
Use = 24 mi/truckload roundtrip [Estimate]
Truckloads = ((2430.26 T)/(16 T/truckload))/
(8 trucks) = 19 truckloads/truck
(8)((19 truckloads)(24 mi/truckload)/
(5 mpg)/(42 gal/BBL)) (6.28E9 J/BBL)
= 1.09E11 J
Asphalt concrete
Fuel energy input transformity portion = 15.35 %
\[(1.78E9 \text{ sej/g})(0.1535) = 2.73E8 \text{ sej/g}\]
\[(2.21E9 \text{ g})(2.73E8 \text{ sej/g}) = 6.03E17 \text{ sej}\]

Total F1 equipment raw units = 5.10E11 J
Total F3 materials solar EMERGY units = 1.81E18 sej

G. Goods.

[5" Asphalt overlay at year 14]

G1. Equipment.
G1.1: (1) Paver, Asphalt [Barber-Greene BG-240B]
Weight = 33,460 lb
Useful life = 10,000 hrs [Estimate]
Use = (0.621 day)(13 hr/day) = 8.1 hrs
\[(1)((8.1 \text{ hrs})/(10,000 \text{ hrs useful life}))\]
\[(33,460 \text{ lb})(453.6 \text{ g/lb}) = 1.23E4 \text{ g}\]

G1.2: (1) Roller, Asphalt (3 Wheel)
Weight = 28,000 lb
Useful life = 5 years at 196 work days/yr [Estimate]
Use = 0.621 day
\[(1)((0.621 \text{ day})/(5 \text{ years})(196 \text{ work days/yr}))\]
\[(28,000 \text{ lb})(453.6 \text{ g/lb}) = 8.05E3 \text{ g}\]

G1.3: (1) Roller, Asphalt (Tandem)
Weight = 20,000 lb
Useful life = (5 yrs.)(196 workdays/yr) [Est.]
Use = 0.621 day
\[(1)((0.621 \text{ day})/(5 \text{ years})(196 \text{ workdays/yr}))\]
\[(20,000 \text{ lb})(453.6 \text{ g/lb}) = 5.75E3 \text{ g}\]

G1.4: (8) Truck, Dump [Asphalt from plant to pavement]
Weight = 25,000 lb [Estimate]
Useful life = 250,000 mi [Estimate]
Use = (19 truckloads/truck)(24 mi/truckload)
\[= 456 \text{ mi/truck}\]
\[(8)((456 \text{ mi})/(250,000 \text{ mi useful life}))\]
\[(25,000 \text{ lb})(453.6 \text{ g/lb}) = 1.66E5 \text{ g}\]

Asphalt concrete
Goods input transformity portion = 14.11 %
\[(1.78E9 \text{ sej/g})(0.1411) = 2.51E8 \text{ sej/g}\]
\[(2.21E9 \text{ g})(2.51E8 \text{ sej/g}) = 5.55E17 \text{ sej}\]
[Demolition of 5" asphalt pavement and 5" asphalt overlay at year 25]

G1.1: (1) Cold planer  [Caterpillar PR-450C]
Weight = 52,400 lb
Useful life = 9000 hrs  [Estimate]
Demolition rate = 175 T/hr
Use = (1215.13 CY) (2.0 T/CY) / (175 T/hr) = 14 hrs
(1)(14 hrs use) / (9000 hrs useful life)
(52,400 lb) (453.6 g/lb) = 3.70E4 g

G1.2: (8) Truck, Dump
Weight = 24,000 lb
Useful life = 250,000 mi
Use = (1215.13 CY) (2.0 T/CY) / (17 T/truckload)
(24 mi roundtrip/truckload) / (8 trucks)
= 429 mi/truck
(8)(429 mi) / (250,000 mi useful life)
(24,000 lb) (453.6 g/lb) = 1.50E5 g

[New 5" asphalt pavement at year 25]
G1. Equipment.
G1.1: (1) Paver, Asphalt  [Barber-Greene BG-265B]
Weight = 40,575 lb
Useful life = 10,000 hrs  [Estimate]
Use = (0.621 day)(13 hr/day) = 8.1 hrs
(1)(8.1 hrs) / (10,000 hrs useful life)
(40,575 lb) (453.6 g/lb) = 1.49E4 g

G1.2: (1) Roller, Asphalt (3 Wheel)
Weight = 28,000 lb
Useful life = 5 years at 196 work days/yr  [Estimate]
Use = 0.621 day
(1)(0.621 day) / (5 years)(196 work days/yr)
(28,000 lb) (453.6 g/lb) = 8.05E3 g

G1.3: (1) Roller, Asphalt (Tandem)
Weight = 20,000 lb
Useful life = 5 years at 196 work days/yr  [Estimate]
Use = 0.621 day
(1)(0.621 day) / (5 years)(196 work days/yr)
(20,000 lb) (453.6 g/lb) = 5.75E3 g
G1.4: (8) Truck, Dump [Asphalt from plant to pavement]
Weight = 25,000 lb [Estimate]
Useful life = 250,000 mi [Estimate]
Use = (19 truckloads/truck)(24 mi/truckload)
   = 456 mi/truck
(8)((456 mi)/(250,000 mi useful life))
(25,000 lb)(453.6 g/lb) = 1.66E5 g

Asphalt concrete
Goods input transformity portion = 14.11 %
(1.78E9 sej/g)(0.1411) = 2.51E8 sej/g.
(2.21E9 g)(2.51E8 sej/g) = 5.55E17 sej

[5" Asphalt overlay at year 39]

G1. Equipment.
G1.1: (1) Paver, Asphalt [Barber-Greene BG-240B]
Weight = 33,460 lb
Useful life = 10,000 hrs [Estimate]
Use = (0.621 day)(13 hr/day) = 8.1 hrs
(1)((8.1 hrs)/(10,000 hrs useful life))
(33,460 lb)(453.6 g/lb) = 1.23E4 g

G1.2: (1) Roller, Asphalt (3 Wheel)
Weight = 28,000 lb
Useful life = 5 years at 196 work days/yr [Estimate]
Use = 0.621 day
(1)((0.621 day)/(5 years)(196 work days/yr))
(28,000 lb)(453.6 g/lb) = 8.05E3 g

G1.3: (1) Roller, Asphalt (Tandem)
Weight = 20,000 lb
Useful life = 5 years at 196 work days/yr [Estimate]
Use = 0.621 day
(1)((0.621 day)/(5 years)(196 work days/yr))
(20,000 lb)(453.6 g/lb) = 5.75E3 g

G1.4: (8) Truck, Dump [Asphalt from plant to pavement]
Weight = 25,000 lb [Estimate]
Useful life = 250,000 mi [Estimate]
Use = (19 truckloads/truck)(24 mi/truckload)
   = 456 mi/truck
(8)((456 mi)/(250,000 mi useful life))
(25,000 lb)(453.6 g/lb) = 1.66E5 g
Asphalt concrete
Goods input transformity portion = 14.11 %
\( (1.78 \times 10^8 \text{ sej/g})(0.1411) = 2.51 \times 10^8 \text{ sej/g} \)
\( (2.21 \times 10^9 \text{ g})(2.51 \times 10^8 \text{ sej/g}) = 5.55 \times 10^9 \text{ sej} \)

Total G1 equipment raw units = 7.66E5 g
Total G3 materials solar EMERGY units = 1.67E18 sej

S. Services.

[5" Asphalt overlay at year 14]

S1. Labor.
Pavement rate = 1 mi/13 hr workday
Pavement duration = \( ((3280.8398 \text{ ft/km})/(5280 \text{ ft/mi})) \)
\( (13 \text{ hr workday/mi}) = 8.1 \text{ hr/km} \)

Crew: [Salaries RE: AH401/AH501]
(3) Equipment operators @ $25.58/hr = $ 76.74
(3) Laborers @ $20.65/hr = $ 61.95
(8) Truck drivers @ $20.81/hr = $166.48

Total labor cost/hr = $305.17

\( ($305.17/hr)(8.1 \text{ hours}) = 2.47E3 \text{ $} \)

Asphalt concrete
Services input transformity portion = 14.11 %
\( (1.78 \times 10^8 \text{ sej/g})(0.1411) = 2.51 \times 10^8 \text{ sej/g} \)
\( (2.21 \times 10^9 \text{ g})(2.51 \times 10^8 \text{ sej/g}) = 5.55 \times 10^9 \text{ sej} \)

[Demolition of 5" asphalt pavement and 5" asphalt overlay at year 25]

S1. Labor.
Demolition rate = 175 T/hr
Demolition duration = \( (1215.13 \text{ CY})(2.0 \text{ T/CY})/(175 \text{ T/hr}) \)
= 14 hrs

Crew: [Salaries RE: AH401/AH501]
(1) Cold planer operator @ $25.58/hr = $ 25.58
(2) Laborers @ $20.65/hr = $ 41.30
(8) Truck drivers @ $20.81/hr = $166.48

Total labor cost/hr = $233.36

\( ($233.36/hr)(14 \text{ hours}) = 3.27E3 \text{ $} \)
[New 5" asphalt pavement at year 25]

S1. Labor.
  Pavement rate = 1 mi/13 hr workday
  Pavement duration = \((3280.8398 \text{ ft/km})/(5280 \text{ ft/mi})\)
  \(= 8.1 \text{ hr/km}\)
  Crew: [Salaries RE: AH401/AH501]
    (3) Equipment operators @ $25.58/hr = $ 76.74
    (3) Laborers @ $20.65/hr = $ 61.95
    (8) Truck drivers @ $20.81/hr = $166.48
  Total labor cost/hr = $305.17
  \((305.17/hr)\)(8.1 hours) = 2.47E3 $

  Asphalt concrete
  Services input transformity portion = 14.11 %
  \((1.78E9 \text{ sej/g})(0.1411) = 2.51E8 \text{ sej/g}\)
  \((2.21E9 \text{ g})(2.51E8 \text{ sej/g}) = 5.55E17 \text{ sej}\)

[5" Asphalt overlay at year 39]

S1. Labor.
  Pavement rate = 1 mi/13 hr workday
  Pavement duration = \((3280.8398 \text{ ft/km})/(5280 \text{ ft/mi})\)
  \(= 8.1 \text{ hr/km}\)
  Crew: [Salaries RE: AH401/AH501]
    (3) Equipment operators @ $25.58/hr = $ 76.74
    (3) Laborers @ $20.65/hr = $ 61.95
    (8) Truck drivers @ $20.81/hr = $166.48
  Total labor cost/hr = $305.17
  \((305.17/hr)\)(8.1 hours) = 2.47E3 $

  Asphalt concrete
  Services input transformity portion = 14.11 %
  \((1.78E9 \text{ sej/g})(0.1411) = 2.51E8 \text{ sej/g}\)
  \((2.21E9 \text{ g})(2.51E8 \text{ sej/g}) = 5.55E17 \text{ sej}\)

Total S1 labor raw units = 1.07E4 $

Total S2 materials solar EMERGY units = 1.67E18 sej
Asphalt Highway Pavement System (Alternative B)  
USDOT Pavement System 301 - Untreated Aggregate Courses

**TABLE BH301. Demolition Phase EMERGY Input Table.**

<table>
<thead>
<tr>
<th>Note</th>
<th>Item</th>
<th>Raw Units</th>
<th>Transformity</th>
<th>Solar EMERGY</th>
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**TABLE BH301 EMERGY Input Calculations**

All EMERGY inputs equal zero because asphalt pavement alternative assumes no demolition of the aggregate base course at the end of the use phase.
TABLE BH401. Demolition Phase EMERGY Input Table.

<table>
<thead>
<tr>
<th>Note</th>
<th>Item</th>
<th>Raw Units</th>
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<td>Ecol. Prod.</td>
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<tr>
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<td>Energy</td>
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<td>Land</td>
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Asphalt Highway Pavement System (Alternative B)  
USDOT Pavement System 401 - Hot Asphalt Concrete Pavement

**TABLE BH401 EMERGY Input Calculations**  
(Demolition Phase H)

[Demolition of 5" asphalt concrete pavement (constructed in year 25) and 5" asphalt concrete overlay (constructed in year 39) at year 50]

E. Environment.  
E5. Water.  
E5.1: (1) Cold planer  
[Caterpillar PR-450C]  
Water consumption = 200 gal/hr  
Demolition rate = 175 T/hr  
Use = (1215.13 CY)(2.0 T/CY)/(175 T/hr)  
= 14 hrs  
(1)(14 hrs)(200 gal/hr)(8 lb/gal)  
(453.6 g/lb)(4.94 J/g) = 5.02E7 J  

Total E5 water raw units = 5.02E7 J

F. Fuel energy.  
F1. Equipment.  
F1.1: (1) Cold planer  
[Caterpillar PR-450C]  
Fuel consumption = 17 gal/hr  
Demolition rate = 175 T/hr  
Use = (1215.13 CY)(2.0 T/CY)/(175 T/hr)  
= 14 hrs  
(1)(17 gal/hr)(14 hrs use)/(42 gal/BBL))  
(6.28E9 J/BBL) = 3.56E10 J  

F1.2: (8) Truck, Dump (3 axle)  
Truck capacity = 17 T  
Fuel consumption = 6.5 gal/hr  
Cold planer demolition rate = 175 T/hr  
Truck quantity  
= (60 min/hr)/(8 min/truckload cycle)  
= 8 truckloads/hr  
Use = (1215.13 CY)(2.0 T/CY)/(175 T/hr)  
= 14 hrs  
(8)((14 hrs use)(6.5 gal/hr)/(42 gal/BBL))  
(6.28E9 J/BBL) = 1.09E11 J  

Total F1 equipment raw units = 1.45E11 J
G. Goods.

G1. Equipment.

G1.1: (1) Cold planer [Caterpillar PR-450C]

- Weight = 52,400 lb
- Useful life = 9000 hrs
- Demolition rate = 175 T/hr
- Use = (1215.13 CY)(2.0 T/CY)/(175 T/hr) = 14 hrs
- (1)(14 hrs use)/(9000 hrs useful life))

\[ \text{Use} = \frac{(14 \text{ hrs use})}{9000 \text{ hrs useful life}} \]

\[ \text{Weight} = 52,400 \text{ lb} \times \frac{453.6 \text{ g/lb}}{} = 3.70E4 \text{ g} \]

G1.2: (8) Truck, Dump

- Weight = 24,000 lb
- Useful life = 250,000 mi
- Use = (1215.13 CY)(2.0 T/CY)/(17 T/truckload)

\[ \text{Use} = \frac{(1215.13 \text{ CY})(2.0 \text{ T/CY})}{17 \text{ T/truckload}} \]

- (24 mi roundtrip/truckload)/(8 trucks) = 429 mi/truck

\[ \text{Use} = \frac{24 \text{ mi roundtrip}}{8 \text{ trucks}} = 3.0 \text{ mi/truck} \]

\[ \frac{429 \text{ mi}}{250,000 \text{ mi useful life}} = 1.50E5 \text{ g} \]

Total G1 goods raw units = 1.87E5 g

S. Services.

S1. Labor.

- Demolition rate = 175 T/hr
- Demolition duration = (1215.13 CY)(2.0 T/CY)/(175 T/hr) = 14 hrs

\[ \text{Demolition duration} = \frac{1215.13 \text{ CY}(2.0 \text{ T/CY})}{175 \text{ T/hr}} \]

Crew:

- (1) Cold planer operator @ $25.58/hr = $ 25.58
- (2) Laborers @ $20.65/hr = $ 41.30
- (8) Truck drivers @ $20.81/hr = $166.48

Total labor cost/hr = $233.36

\[ \text{($233.36/hr)(14 \text{ hours}) = 3.27E3 \text{ $}} \]

Total S1 labor raw units = 3.27E3 $
Asphalt Highway Pavement System (Alternative B)
USDOT Pavement System 301 - Untreated Aggregate Courses
USDOT Pavement System 401 - Hot Asphalt Concrete Pavement

TABLE BI301/BI401. Natural Resource Recycling Phase
EMERGY Input Table.

<table>
<thead>
<tr>
<th>Note</th>
<th>Item</th>
<th>Raw Units</th>
<th>Transformity sej/unit</th>
<th>Solar EMERGY sej</th>
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<td>Atmosphere</td>
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<td>E2</td>
<td>Ecol. Prod.</td>
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<td>Energy</td>
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<tr>
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<td>Water</td>
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</table>

TABLES BI301 and BI401 EMERGY Input Calculations

All EMERGY inputs equal zero because recycling inputs are assumed to be the same for the concrete and asphalt pavement alternatives.
Asphalt Highway Pavement System (Alternative B)
USDOT Pavement System 301 - Untreated Aggregate Courses
USDOT Pavement System 401 - Hot Asphalt Concrete Pavement

TABLE BJ301/BJ401. Disposal Phase EMERGY Input Table.

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<thead>
<tr>
<th>Note</th>
<th>Item</th>
<th>Raw Units</th>
<th>Transformity</th>
<th>Solar EMERGY</th>
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TABLES BJ301 and BJ401 EMERGY Input Calculations
All EMERGY inputs equal zero because no disposal is assumed for the concrete and asphalt pavement alternatives.
APPENDIX F

CONCRETE TRANSFORMITY CALCULATIONS
Concrete Transformity (Summary Sheet)

Concrete Inputs:
(E) = Environment    (G) = Goods
(F) = Fuel energy     (S) = Services (labor)

(E,F,G,S) Cement:
Cement Inputs:
(E) Environment = 8.50E8 sej/g
(F) Fuel Energy = 2.81E8 sej/g
(G) Goods = 6.31E6 sej/g
(S) Services = 1.27E7 sej/g

1.15E9 sej/g of cement

((1.15E9 sej/g) (564 lb/CY) (453.6 g/lb))/
(1,769,494 g/CY)
= 1.66E8 sej/g

(E) Water:
((4.94 J/g) (6.66E5 sej/J) (237 lb/CY)
(453.6 g/lb))/ (1,769,494 g/CY)
= 2.00E5 sej/g

(E) Aggregate:
Aggregate weight = 3100 lb/CY

((1.00E9 sej/g) (3100 lb/CY) (453.6 g/lb))/
(1,769,494 g/CY)
= 7.95E8 sej/g

(F,G,S) Aggregate transport from quarry to concrete batch plant:
Transport Inputs:
(F) Fuel Energy = 2.04E6 sej/g
(G) Goods = 3.14E5 sej/g
(S) Services = 2.39E6 sej/g

= 4.74E6 sej/g of aggregate

(F) Fuel energy at concrete batch plant:
= 3.55E6 sej/g

(G) Goods at concrete batch plant:
= 3.80E5 sej/g

(S) Services (labor) at concrete batch plant:
= 2.86E7 sej/g

Concrete Transformity = 9.99E8 sej/g of concrete

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Concrete Transformity (Calculations)

General data:

Concrete weight/CY = (3,901 lb/CY)(453.6 g/lb) = 1,769,494 g

Concrete components/CY of concrete:
  Cement:
    (564 lb)/((3.15 Sp.Gr.)(62.4 lb/CF))
    = 2.87 CF
  Water:
    Water/cement ratio = 0.42
    ((0.42)(564 lb))/((1.00 Sp.Gr.)(62.4 lb/CF))
    = 3.80 CF
  Air:
    Air content = 6%
    (0.06)(27 CF) = 1.62 CF
  Aggregates:
    X = weight
    (X)/((Sp.Gr.)(62.4 lb/CF)) = (27 CF - 8.29 CF)
    With Sp.Gr. = 2.67 then X = 3,117.24 lb
    With Sp.Gr. = 2.62 then X = 3,058.86 lb
    Assume Sp.Gr. = 2.66
    Assume 3,100 lb of aggregates per CY of concrete
Environmental input to cement:

Environmental input of limestone to cement = 8.50E8 sej/g

Fuel energy input at cement plant:


Cement production (1992) = 58,810,841 T

C = coal and coke
NG = natural gas
PP = petroleum products
E = electricity

<table>
<thead>
<tr>
<th>Fuel type</th>
<th>BTUs (E9)</th>
<th>Joules</th>
<th>Transformity (sej/J)</th>
<th>EMERGY (sej)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(C) Coal</td>
<td>146,274.72</td>
<td>1.54E17</td>
<td>39,800</td>
<td>6.14E21</td>
</tr>
<tr>
<td>(PP) Gasoline</td>
<td>154.97</td>
<td>1.64E14</td>
<td>66,000</td>
<td>1.08E19</td>
</tr>
<tr>
<td>(PP) LPG</td>
<td>25.11</td>
<td>2.65E13</td>
<td>66,000</td>
<td>1.75E18</td>
</tr>
<tr>
<td>(PP) Middle Distillates</td>
<td>2,176.30</td>
<td>2.30E15</td>
<td>66,000</td>
<td>1.52E20</td>
</tr>
<tr>
<td>(NG) Natural Gas</td>
<td>30,316.50</td>
<td>3.20E16</td>
<td>48,000</td>
<td>1.54E21</td>
</tr>
<tr>
<td>(C) Petro. Coke</td>
<td>34,056.51</td>
<td>3.59E16</td>
<td>39,800</td>
<td>1.43E21</td>
</tr>
<tr>
<td>(PP) Residual Oil</td>
<td>640.97</td>
<td>6.76E14</td>
<td>66,000</td>
<td>4.46E19</td>
</tr>
<tr>
<td>(PP) Wastes</td>
<td>20,068.87</td>
<td>2.12E16</td>
<td>66,000</td>
<td>1.40E21</td>
</tr>
<tr>
<td>(E) Electricity</td>
<td>25,569.19</td>
<td>2.70E16</td>
<td>159,000</td>
<td>4.29E21</td>
</tr>
</tbody>
</table>

Total fuel energy EMERGY for 58,810,841 T of cement = 1.50E22 sej

Total fuel energy EMERGY per gram of cement:

\[
(\frac{1.50E22 \text{ sej}}{((58,810,841 \text{ T})(2,000 \text{ lb/T})(453.6 \text{ g/lb})}) = 2.81E8 \text{ sej/g}
\]
Goods inputs at cement plant:

Machinery transformity = 6.70E9 sej/g of cement plant


Number of cement plants = 83
Total cement production = 58,810,841 T

Cement plant weight = 40,000,000 lb [Estimate]
Cement plant useful life = 30 years [Estimate]
Average annual cement production per cement plant
= (58,810,841 T)/(83 cement plants)
= 708,564.4 T/yr

Cement plant (goods) usage per year:
= ((40,000,000 lb)(453.5 g/lb))/(30 year useful life)
= 6.05E8 g/yr

Cement plant (goods): 
= ((6.05E8 g/yr)(6.70E9 sej/g))/
= ((708,564.4 T/yr)(2000 lb/T)(453.6 g/lb))
= 6.31E6 sej g of cement

Services inputs at cement plant:


Cement production = 58,810,841 T
Labor for 58,810,841 T of cement = 22,610,134 hours

Services transformity = 2.0E12 sej/U.S. $
Average salary = $15.00/hr [Estimate]

= ((22610,134 hrs)($15.00/hr)(2.0E12 sej/$))/
= ((58,810,841 T)(2,000 lb/T)(453.6 g/lb))
= 1.27E7 sej/g of cement
Aggregate transport from quarry to concrete batch plant:

General data:

Haul distance from quarry to concrete batch plant
= 15 mi roundtrip [Estimate]

(F) Fuel energy:

(1) Truck, Dump
Petroleum product transformity = 6.60E4 sej/J
Fuel consumption = 5 mpg [Estimate]
Truck capacity per load = 16 T

\[
\frac{(15 \text{ mi roundtrip})}{(5 \text{ mpg})} = 3 \text{ gal/roundtrip}
\]

\[
\frac{\left(\frac{3 \text{ gal}}{42 \text{ gal/BBL}}\right)\left(6.2839 \text{ sej/BBL}\right)}{\left(6.60E4 \text{ sej/J}\right)\left(16 \text{ T}\right)\left(2,000 \text{ lb/T}\right)\left(453.6 \text{ g/lb}\right)}
= 2.04E6 \text{ sej/g of aggregate}
\]

(G) Goods:

(1) Truck, Dump
Weight = 25,000 lb [Estimate]
Useful life = 250,000 mi [Estimate]

\[
\frac{\left(1\left(\frac{15 \text{ mi roundtrip}}{250,000 \text{ mi useful life}}\right)\right)}{\left(25,000 \text{ lb}\right)\left(453.6 \text{ g/lb}\right)\left(6.70E9 \text{ sej/g}\right)}
= 3.14E5 \text{ sej/g}
\]

(S) Services:

Average truck driver salary = $20.81 [Estimate]
Services transformity = 2.00E12 sej/U.S. $

Roundtrip time:
Quarry to batch plant = 20 minutes
Unload at batch plant = 5 minutes
Batch plant to quarry = 20 minutes
Load at batch plant = 5 minutes

Total roundtrip time = 50 minutes

\[
\frac{(50/60 \text{ hr})\left(\frac{$20.81}{\text{hr}}\right)\left(2.00E12 \text{ sej/$}\right)}{\left(16 \text{ T}\right)\left(2,000 \text{ lb/T}\right)\left(453.6 \text{ g/lb}\right)}
= 2.39E6 \text{ sej/g of aggregate}
\]

Total inputs for aggregate hauling = 4.74E6 sej/g of concrete
Fuel energy input at concrete batch plant:

General data:

Electricity transformity = 1.59E5 sej/J
Natural gas transformity = 4.80E4 sej/J
Concrete batch plant output (annual) = 28,385.00 CY [Estimate]

Electricity input = 113,520.00 KWH
Natural gas input = 1,015.20 MCF

Fuel energy (F) for concrete batch plant:

Electricity:

\[
\frac{(113,520.00 \text{ KWH})(3.60E6 \text{ J/KWH})(1.59E5 \text{ sej/J})}{(28,385.00 \text{ CY})(1,769,494 \text{ g/CY})} = 1.29E6 \text{ sej/g of concrete}
\]

Natural gas:

\[
\frac{(1,015.20 \text{ MCF})(1.10E9 \text{ J/MCF})(4.80E4 \text{ sej/J})}{(28,385.00 \text{ CY})(1,769,494 \text{ g/CY})} = 1.07E6 \text{ sej/g of concrete}
\]

Fuel energy (F) for (2) front-end loaders at concrete batch plant:

Fuel consumption = 4 gal/hr [Caterpillar]
Use = 10 hrs [Estimate]

\[
\frac{(2)(10 \text{ hrs use})(4 \text{ gal/hr})}{(42 \text{ gal/BBL})} = 1.20E10 \text{ J}
\]

\[
\frac{(1.20E10 \text{ J})(6.60E4 \text{ sej/J})}{(3.87E9 \text{ g})} = 2.05E5 \text{ sej/g of concrete}
\]

Fuel energy (F) for (1) tanker truck to haul cement to concrete batch plant:

Fuel consumption = 6.5 mi/gal [Estimate]
Haul distance (roundtrip) = 100 mi [Estimate]
Use = (25 loads)(100 mi/load) = 2,500 mi [Estimate]
Concrete weight/km of concrete pavement (minus steel tiebars and dowels) = 3.87E9 g

[Re: EMERGY analysis input table AC501 in Appendix E]

\[
\frac{((2,500 \text{ mi})/(6.5 \text{ mi/gal})}{(42 \text{ gal/BBL})} = 5.75E10 \text{ J}
\]

\[
\frac{(5.75E10 \text{ J})(6.60E4 \text{ sej/J})}{(3.87E9 \text{ g})} = 9.81E5 \text{ sej/g of concrete}
\]

Total fuel energy at concrete batch plant = 3.55E6 sej/g of concrete
Goods inputs at concrete batch plant:

Machinery transformity = 6.70E9 sej/g of concrete batch plant

Concrete mass/km of concrete pavement (minus steel tiebars and dowels) = 3.87E9 g
[Re: EMERGY analysis input table AC501 in Appendix E]

(1) Batch Plant, Concrete
Weight = 163,000 lb [Estimate]
Useful life = 15,000 hrs [Estimate]
Use = 10 hrs

\[
\frac{(10 \text{ hrs})}{(15,000 \text{ hr useful life})} \times \frac{163,000 \text{ lb}}{453.6 \text{ g/lb}} = 4.93E4 \text{ g}
\]

\[
\frac{(4.93E4 \text{ g}) \times (6.70E9 \text{ sej/g})}{(3.87E9 \text{ g})} = 8.54E4 \text{ sej/g of concrete}
\]

(2) Loader, Front-end
Weight = 21,500 lb [Caterpillar]
Useful life = 15,000 hrs [Estimate]
Use = 10 hrs

\[
\frac{(10 \text{ hrs use})}{(15,000 \text{ hr useful life})} \times \frac{21,500 \text{ lb}}{453.6 \text{ g/lb}} = 1.30E4 \text{ g}
\]

\[
\frac{(1.30E4 \text{ g}) \times (6.70E9 \text{ sej/g})}{(3.87E9 \text{ g})} = 2.25E4 \text{ sej/g of concrete}
\]

(1) Truck, Tanker
Weight = 34,500 lb [Estimate]
Useful life 250,000 mi [Estimate]
Haul distance (roundtrip) = 100 mi [Estimate]
Use = (25 loads) (100 mi/load) = 2,500 mi

\[
\frac{(2,500 \text{ mi})}{250,000 \text{ mi}} \times \frac{34,500 \text{ lb}}{453.6 \text{ g/lb}} = 1.57E5 \text{ g}
\]

\[
\frac{(1.57E5 \text{ g}) \times (6.70E9 \text{ sej/g})}{(3.87E9 \text{ g})} = 2.72E5 \text{ sej/g of concrete}
\]

Total Goods at concrete batch plant = 3.80E5 sej/g of concrete
Services inputs related to concrete batch plant:

General data:

Concrete production = 28,385 CY [Estimate]
   = $777,808.26
1994/1995 salaries converted to 1992 at Consumer Price Index (CPI) of 4% increase per year = $719,127.46

1992 salary/CY = $719,127.46/28,385 CY
   = $25.33/CY

Concrete weight = (3901 lb/CY)(453.6 g/lb)
   = 1,769,494 g/CY

((25.33/CY)(2.0E12 sej/$))/(1,769,494 g/CY)
   = 2.86E7 sej/g of concrete
APPENDIX G

ASPHALT CONCRETE TRANSFORMITY CALCULATIONS
## Asphalt Concrete Transformity (Summary Sheet)

### Asphalt Concrete Inputs:

<table>
<thead>
<tr>
<th>Total inputs per gram of asphalt concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asphalt cement</td>
</tr>
<tr>
<td>Aggregates</td>
</tr>
</tbody>
</table>

### Aggregate transport from quarry to asphalt concrete batch plant:

#### Transport Inputs:

| (F) Fuel Energy | 2.04E6 sej/g |
| (G) Goods       | 3.14E5 sej/g |
| (S) Services    | 2.39E6 sej/g |

| Total transport energy per gram of asphalt concrete | 4.74E6 sej/g |

### Asphalt cement plant:

| (G) Goods | 3.79E5 sej/g |
| (S) Services | 7.62E5 sej/g |

### Asphalt concrete plant:

2.36E7 sej/g

### Loader, Wheel (Asphalt concrete plant):

3.49E5 sej/g

### Truck, Tanker (Asphalt cement to asphalt concrete plant):

6.89E5 sej/g

### Asphalt Concrete Transformity = 1.78E9 sej/g of asphalt concrete
Asphalt Concrete Transformity (Calculations)

Asphalt Cement:

Asphalt concrete weight = 4,000 lb/CY  
Asphalt cement = 6% of asphalt concrete weight  
Asphalt cement = 8.5 lb/gal  
[Asphalt Construction Handbook, Barber-Greene, 1992]

Asphalt transformity = 3.47E5 sej/J  
((6.28E9 J/BBL)(3.47E5 sej/J)(0.06))/  
((42 gal/BBL)(8.5 lb/gal)(453.6 g/lb))  
= 8.07E8 sej/g of asphalt concrete

Aggregates:

Aggregate (stone, mined) transformity = 1.00E9 sej/g  
Asphalt concrete mass = 4,000 lb/CY  
Asphalt cement = 6% of asphalt concrete mass  
Aggregates = 94% of asphalt concrete mass

Inputs:
(E) = Environment  
(F) = Fuel energy  
(G) = Goods  
(S) = Services (labor)

(E) Environment input: 85%  
((4,000 lb/CY)(453.6 g/lb)(0.94)(0.85)(1.00E9 sej/g))/  
((4,000 lb/CY)(453.6 g/lb))  
= 7.99E8 sej/g of asphalt concrete

(F) Fuel energy input: 5%  
(0.94)(0.05)(1.00E9 sej/g)  
= 4.70E7 sej/g  
[Estimate]

(G) Goods input: 5%  
(0.94)(0.05)(1.00E9 sej/g)  
= 4.70E7 sej/g  
[Estimate]

(S) Services input: 5%  
(0.94)(0.05)(1.00E9 sej/g)  
= 4.70E7 sej/g  
[Estimate]

Total inputs for aggregates = 9.40E8 sej/g of asphalt concrete
Aggregate transport from quarry to asphalt concrete plant:

General data:

Haul distance from quarry to asphalt concrete plant
= 15 mi roundtrip [Estimate]

(F) Fuel energy:
(1) Truck, Dump
Petroleum product transformity = 6.60E4 sej/J
Fuel consumption = 5 mpg [Estimate]
Truck capacity per load = 16 T

(15 mi roundtrip)/(5 mpg) = 3 gal/roundtrip

[((3 gal)/(42 gal/BBL))((6.28E9 sej/BBL)
(6.60E4 sej/J))]/((16 T)(2,000 lb/T)(453.6 g/lb))
= 2.04E6 sej/g of aggregate

(G) Goods:
(1) Truck, Dump
Weight = 25,000 lb [Estimate]
Useful life = 250,000 mi [Estimate]

[((1)(15 mi roundtrip)/(250,000 mi useful life))
(25,000 lb)(453.6 g/lb)(6.70E9 sej/g)]/
((16 T)(2,000 lb/T)(453.6 g/lb))
= 3.14E5 sej/g

(S) Services:
Average truck driver salary = $20.81 [Estimate]
Services transformity = 2.00E12 sej/U.S. $
Roundtrip time:
Quarry to batch plant = 20 minutes
Unload at batch plant = 5 minutes
Batch plant to quarry = 20 minutes
Load at batch plant = 5 minutes

Total roundtrip time = 50 minutes

[((50/60 hr)($20.81/hr)(2.00E12 sej/$))/
((16 T)(2,000 lb/T)(453.6 g/lb))
= 2.39E6 sej/g of aggregate

Total inputs for aggregate hauling = 4.74E6 sej/g of asphalt concrete
Asphalt cement plant:
Inputs:
(G) = Goods
(S) = Services (labor)

(G) Goods input:
Asphalt cement plant goods input
= 6.31E6 sej/g of asphalt concrete
[Estimate input/unit of asphalt cement similar to concrete cement plant]
Asphalt cement = 6% of asphalt concrete mass

(6.31E6 sej/g)(0.06)
= 3.79E5 sej/g of asphalt concrete

(S) Services input:
Asphalt cement plant services input
= 1.27E7 sej/g of asphalt concrete
[Estimate input/unit of asphalt cement similar to concrete cement plant]
Asphalt cement = 6% of asphalt concrete mass

(1.27E7 sej/g)(0.06)
= 7.62E5 sej/g of asphalt concrete

Asphalt concrete plant:
General data:

Asphalt concrete pavement
Asphalt concrete pavement mass = 2.0 T/CY
Volume = (5 in)(12 in/ft)(24 ft)(3,280.8398 ft/km))
/(27 CF/CY) = 1,215.13 CY/km
Mass = (1,215.13 CY)(2.0 T/CY) = 2,430.26 T
Machinery transformity = 6.70E9 sej/g
Petroleum product transformity = 6.60E4 sej/J
Services transformity = 2.00E12 sej/U.S $

Inputs:
(F) = Fuel energy
(G) = Goods
(S) = Services (labor)

(F) Fuel energy input:
Asphalt concrete plant (Drum type)
Fuel consumption to heat aggregate/mix = 2.0 gal/T
[Estimate]
Fuel consumption to heat A/C = 5.0 gal/hr
[Estimate]
Fuel consumption to generate electricity
= 30.0 gal/hr [Estimate]
Asphalt concrete pavement mass = 2,430.26 T
Asphalt concrete plant production rate = 300 T/hr [Estimate]

Asphalt concrete production duration
= (2,430.26 T)/(300 T/HR) = 8.1 hrs
[((1)(2.0 gal/T)(2,430.26 T) + (5 gal/hr)(8.1 hrs)
+ (30 gal/hr)(8.1 hrs))/(42 gal/BBL)](6.28E9 J/BBL)
= 7.69E11 J
((1)(7.69E11 J)(6.60E4 sej/J))/
((2,430.26 T)(2,000 lb/T)(453.6 g/lb))
= 2.30E7 sej/g of asphalt concrete

(G) Goods input:
Asphalt concrete plant (Drum type)
Asphalt concrete plant production rate = 300 T/hr
Weight = 420,000 lb [Estimate]
Useful life = 15,000 hrs [Estimate]
((1)(420,000 lb)(453.6 g/lb)(6.70E9 sej/g))/
((15,000 hrs useful life)(300 T/hr)
(2,000 lb/T)(453.6 g/lb))
= 3.13E5 sej/g of asphalt concrete

(S) Services input:
(2) Laborers at $20.65/hr [Estimate]
((2)(8.1 hrs)($20.65/hr)(2.0E12 sej/$))/
((2,430.26 T)(2,000 lb/T)(453.6 g/lb))
= 3.04E5 sej/g of asphalt concrete

Total asphalt concrete plant inputs = 2.36E7 sej/g of asphalt concrete

Loader, Wheel (Asphalt Concrete Plant):

General data:
Asphalt concrete pavement
Asphalt concrete pavement mass = 2.0 T/CY
Volume = ((5 in)(12 in/ft)(24 ft)(3,280.8398 ft/km))
/(27 CF/CY) = 1,215.13 CY/km
Mass = (1,215.13 CY)(2.0 T/CY) = 2,430.26 T
Machinery transformity = 6.70E9 sej/g
Petroleum product transformity = 6.60E4 sej/J
Services transformity = 2.00E12 sej/U.S $
Asphalt Concrete Plant
Asphalt concrete plant production rate = 300 T/hr
Asphalt concrete production duration
= (2,430.26 T)/(300 T/hr) = 8.1 hrs

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Inputs:
(F) = Fuel energy
(G) = Goods
(S) = Services (labor)

(F) Fuel energy input:
Fuel consumption = 4 gal/hr

\[\frac{(1)(8.1 \text{ hrs use}) (4 \text{ gal/hr})}{(42 \text{ gal/BBL})} \times \frac{(6.28E9 \text{ J/BBL})}{(4.85E9 \text{ J})} = (1)(4.85E9 \text{ J}) \times \frac{(6.60E4 \text{ sej/J})}{((2,430.26 \text{ T})(2,000 \text{ lb/T})(453.6 \text{ g/lb}))} \]

= 1.45E5 sej/g of asphalt concrete

(G) Goods input:
Weight = 21,500 lb
Useful life = 15,000

\[\frac{(1)(21,500 \text{ lb})(453.6 \text{ g/lb})}{(15,000 \text{ hrs useful life})(300 \text{ T/hr})(453.6 \text{ g/lb})} \times \frac{(6.70E9 \text{ sej/g})}{(2,000 \text{ lb/T})(453.6 \text{ g/lb})} \]

= 1.60E4 sej/g of asphalt concrete

(S) Services input:
(1) Equipment operator at $25.58/hr

\[\frac{(1)(8.1 \text{ hrs})}{(2,430.26 \text{ T})(2,000 \text{ lb/T})(453.6 \text{ g/lb})} \times \frac{(2.0312 \text{ sej/$})}{(2.430.26 \text{ T})(2,000 \text{ lb/T})(453.6 \text{ g/lb})} \]

= 1.88E5 sej/g of asphalt concrete

Total wheel loader inputs = 3.49E5 sej/g of asphalt concrete

Truck, Tanker (Asphalt cement to asphalt concrete plant):

General data:

Asphalt concrete pavement
Asphalt concrete pavement mass = 2.0 T/CY
Volume = ((5 in)(12 in/ft)(24 ft)(3,280.8398 ft/km))
\/(27 CF/CY) = 1,215.13 CY/km
Mass = (1,215.13 CY)(2.0 T/CY) = 2,430.26 T

Asphalt Concrete Plant
Asphalt concrete plant production rate = 300 T/hr
Asphalt concrete production duration
\[= \frac{(2,430.26 \text{ T})}{(300 \text{ T/hr})} = 8.1 \text{ hrs} \]
Machinery transformity = 6.70E9 sej/g
Petroleum product transformity = 6.60E4 sej/J
Services transformity = 2.00E12 sej/$
Asphalt cement = 8.5 lb/gal [Asphalt Construction Handbook, Barber-Greene, 1992]
Inputs:
(F) = Fuel energy
(G) = Goods
(S) = Services (labor)

(F) Fuel energy input:
Fuel consumption = 6.5 gal/hr [Estimate]
Truck, Tanker capacity = 6,300 gal [Fruehauf]
Haul distance 100 mi roundtrip [Estimate]
Asphalt cement = 6% of asphalt concrete pavement mass
Use = (((1,215.13 CY)(4,000 lb/CY)(0.06)/(8.5 lb/gal))/((6,300 gal/truckload))
= 6 truckloads
= 1.38E10 J
= (1)(1.38E10 J)(6.60E4 sej/J))/
= (2,430.26 T)(2,000 lb/T)(453.6 g/lb))
= 4.13E5 sej/g of asphalt concrete

(G) Goods input:
Weight = 29,600 lb [Fruehauf]
Useful life = 200,000 mi [Estimate]
Truck, Tanker capacity = 6,300 gal [Fruehauf]
Haul distance 100 mi roundtrip [Estimate]
Asphalt cement = 6% of asphalt concrete pavement mass
Use = (((1,215.13 CY)(4,000 lb/CY)(0.06)/(8.5 lb/gal))/((6,300 gal/truckload))
= 6 truckloads
= 200,000 mi useful life)) (29,600 lb)(453.6 g/lb)
= 4.03E4 g
= (1)(4.03E4 g)(6.70E9 sej/g))/
= (2,430.26 T)(2,000 lb/T)(453.6 g/lb)
= 1.23E5 sej/g of asphalt concrete

(S) Services input:
(1) Truck driver at $20.81/hr [Estimate]
= (1)(8.1 hrs)($20.81/hr)(2.0E12 sej/$))/
= (2,430.26 T)(2,000 lb/T)(453.6 g/lb))
= 1.53E5 sej/g of asphalt concrete

Total tanker truck inputs = 6.89E5 sej/g of asphalt concrete
APPENDIX H

GLOSSARY
Available energy. Energy with the potential to do work (Odum, 1991).

Built environment. All human-made objects (alternatives) on earth that consume environment, fuel energy, goods, and services inputs.

Embodied energy. Coal equivalent BTUs of fuels used directly and indirectly and assigned to particular materials or products in proportion to their costs using input-output methods of Hannon et al. (1978) and Herendeen (1973).

EMERGY. All the available energy that was used in the work of making a product expressed in units of one type of energy (Odum, 1991).

EMERGY analysis. Calculation and comparison of EMERGY inputs and outputs of a system.

EMERGY signature. A graphical representation of empower.

Emjoule. The unit of EMERGY which has the dimensions of the energy previously used (grams-centimeter squared per second squared) (Odum, 1991).

Empower. Flux of EMERGY production and use.

Energy. A property of all systems which can be turned into heat and measured in heat units (Calories, BTUs or Joules) (Odum, 1991).

Energy hierarchy. The convergence and transformation of energy from many small units into smaller amounts of higher-level types of energy (often in units of larger size) with greater ability to interact with and control smaller units (Odum, 1991).

Energy systems language. A general systems language for representing units and connections for processing materials, energy, and information of any system; diagrammatic representation of systems with a set of symbols (Appendix B) that have precise mathematical and energetic meanings (Odum, 1991).

Maximum empower principle. An explanation of the structure and function observed in self-organizing systems (energy transformations, hierarchical patterns, feedback (recycle) controls, amplifier actions, etc.). Systems prevail that draw in more available energy and use it more efficiently than alternatives.
Solar emjoule (sej). The solar joules previously required through direct and indirect transformations to produce all the inputs for a service or product.

Solar transformity. The equivalent solar energy that would be required to generate (create) a unit of an object or resource efficiently and rapidly (Odum, 1991).

Sustainable use. Resource use that can be continued by society in the long run because the use level and system design allow resources to be renewed by natural or man-aided processes (Odum, 1991).

Transformity. The EMERGY of one type required to make a unit of energy of another type (Odum, 1991).

Wealth. Usable products and services however produced (Odum, 1991)
REFERENCES


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