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BENEFITS ANALYSIS FOR THE PRODUCTION

OF

FUELS AND CHEMICALS

USING

SOLAR THERMAL ENERGY

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AETA CORPORATION

ADVANCED ENERGY AND TECHNOLOGY ASSOCIATES, INC.

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EXECUTIVE SUMMARY

Numerous possibilities exist for using high temperature solar thermal energy in the production of various chemicals and fuels (Sun Fuels). Research and development activities have focused on the use of feedstocks such as coal and biomass to provide synthesis gas, hydrogen, and a variety of other end-products. Based on available information, there are at least twenty R&D processes actively being explored, with the hope of ultimate transition to the private sector.

The U. S. Department of Energy faces the problem of how to choose which of the various candidate processes deserve continued support. Specifically, the Solar Thermal Program sought to identify a single process for significant demonstration by 1985. AETA Corporation was asked to create a "black box," i.e., a rational analytical method, by which such a choice could be made.

To address the capital budgeting problem facing DOE, AETA developed a Decision Analysis technique geared to the analysis of Sun Fuels options. Conventional scoring methods were combined with multi-attribute utility analysis in a new approach called the Multi-Attribute Preference Scoring (MAPS) system. MAPS calls for the designation of major categories of attributes which describe critical elements of concern for the processes being examined. The six major categories, each of which has its own list of attributes, includes the following considerations: Process Demonstration; Full-Scale Process, Feedstock; End-Product Market; National/Social Considerations; and Economics.

In summary, MAPS calls for each attribute to be weighted on a simple scale for all of the candidate processes. Next, a weight is assigned to each attribute, thus creating a multiplier to be used with each individual value to derive a comparative weighting. Last, each of the categories of

attributes themselves are weighted, thus creating another multiplier, for use in developing an overall score. With sufficient information and industry input, each process can be ultimately compared using a single figure of merit.

After careful examination of available information, it was decided that only six of the candidate processes were adequately described to allow a complete MAPS analysis which would allow direct comparisons for illustrative purposes. These six processes include: synthesis gas (Lawrence Livermore Laboratory), synthesis gas (University of New Hampshire), synthesis gas (Princeton University), hydrogen (Westinghouse Electric Corporation), hydrogen (General Atomic Company), and ammonia (PFR Engineering Systems). The remaining fourteen processes, while fully characterized and critiqued, were subjected to only a partial MAPS assessment.

Of the top six processes, that of Lawrence Livermore Laboratory and Princeton ranked consistently lower than that of the University of New Hampshire, Westinghouse, General Atomic and PFR by AETA's evaluation team. However, the remaining four were sufficiently close in ranking that evaluation by others in the Sun Fuels community is appropriate. MAPS provides an analytical framework which can accommodate such input and a basis on which current and future R&D priorities can be assessed in a standard, broadly acceptable fashion.

1. INTRODUCTION

Nearly one-half of the oil and gas consumed in the United States is imported and liquid and gaseous fuels are critical for all sectors of the economy. As reserves are depleted, attention has focused on the creation of new fuels and associated products, often from widely available feedstocks such as coal and shale oil, as indicated in Figure 1-1. A key question for the country is how to find substitutes for conventionally available fuels and chemicals which can sustain a significant portion of our existing industrial and commercial infrastructure.

Most of the major processes used to produce gaseous and liquid fuels from coal or other carbon-rich feedstocks are endothermic, burning the feedstock itself to meet substantial thermal energy requirements. This often results in the mining, processing, transportation and use of even more fossil resources; consuming more energy, increasing the introduction of CO_2 into the atmosphere, and often creating ash and other by-product disposal difficulties. However, solar energy concepts have now been developed and demonstrated to the point where it is clear that the sun's energy can be tapped to provide the high temperatures required for the manufacture of a variety of fuels and chemicals, using central receiver and point-focusing technology.

In principle, the collection and concentration of solar energy to provide a high temperature heat source is quite simple. However, until the completion of the DOE Central Receiver Test Facility at Sandia National Laboratories in New Mexico and the Parabolic Dish Test Facility at Edwards Air Force Base in California, the demonstration of such solar concentration on a large scale has not been achieved. Now a 10 MW_E solar pilot plant for electric power generation has been constructed at Barstow, California, and larger installations throughout the country are under consideration. Conceptually, a wide spectrum of possibilities for using solar energy in the production of fuels and chemicals, dubbed "sun fuels," has been opened up for exploration since 1977. These are shown in Figure 1-2.

FIG. 1-1

FLOW CHART FOR THE PRODUCTION OF FUELS

Note: Process steps underlined are potential solar thermal F/C applications

*Transportation fuel or fuel reactant

**Some biological species can yield transportation fuels after only mechanical processing.

FIGURE 1-2

CONCEPTUAL SUN FUELS OPTIONS

Supports continued
R&D →

The direct utilization of high temperatures for fuel and chemical manufacture, rather than for the creation of steam to drive conventional processes, offers exciting possibilities for research and the development of new systems because fuels and chemicals: offer a convenient mechanism for storing solar energy; non-renewable resources are conserved; pollution is decreased; dependence on foreign sources is reduced; in some cases, the need for expensive oxygen plants is eliminated; and because the costs projected for solar energy are forecast to go down over time.

In addition to competition with conventional processes, two additional aspects of sun fuels are particularly exciting. First, a variety of renewable feedstocks may be appropriate for various processes. Thus, in conjunction with solar energy, more sustainable industries might be created. Second, the possibilities for replacing conventional energy sources with solar are not limited to mere substitution. Solar thermal systems which can efficiently produce high temperatures (e.g. above 1000°K) may be uniquely suited to the introduction of new processes of ultimate commercial value.

With support from the U. S. Department of Energy and other sources, a variety of specific sun fuels processes are being investigated in a preliminary fashion. Many of the investigations have yielded positive results thus far, and much of the overall analysis conducted to date suggests further exploration may be justified. However, most publications in the sun fuels area deal with concepts and potential of viable processes, rather than with experimental results. Hardly any of the work reported in the literature can be considered ready for testing at the pilot plant scale. Extensive research and development will be required before any of the reported processes can be considered appropriate for commercialization and the question now remains as to how to decide which experimental processes deserve further support.

Specifically, some twenty processes, as indicated in Figure 1-3, are candidates for continued funding of R&D activity. About half of these processes breakdown into two basic categories of end product: synthesis gas and hydrogen, with the remainder producing a wide spectrum of fuels and chemicals.

Are these lists
complete or are
there others?

FIGURE 1-3

CANDIDATE SUN FUELS R&D PROCESSES

1.1 SYNTHESIS GAS

- 1.11 Lawrence Livermore Laboratory
- 1.12 University of New Hampshire
- 1.13 Los Alamos Scientific Laboratory
- 1.14 Princeton University
- 1.15 CNRS/Odeillo (Lede)

2.2 HYDROGEN

- 2.21 Westinghouse
- 2.22 General Atomic
- 2.23 Los Alamos Scientific Laboratory
- 2.24 Institute of Gas Technology

3.3 OTHER PROCESSES/PRODUCTS

- 3.31 Wet Oxidation of Lignite, Jet Propulsion Laboratory
- 3.32 Oil Shale Retorting, Lawrence Livermore Laboratory
- 3.33 Calcium Carbide, Institute of Gas Technology
- 3.34 Furfural, Jet Propulsion Laboratory/Quaker Oats Company
- 3.35 CaCO_3 Decomposition, CNRS/Odeillo (Flamont)
- 3.36 Ammonia, PFR Engineering
- 3.37 $\text{CO}_2 - \text{CH}_4$ Reforming, Naval Research Laboratory
- 3.38 $\text{SO}_2 - \text{SO}_3$ Storage, Naval Research Laboratory
- 3.39 Ammonium Hydrogen Sulfate Storage, University of Houston
- 3.310 Diesel Fuel, Solar Energy Research Institute
- 3.311 Ore Processing

As in any program of research and development, decisions about solar thermal fuels and chemicals must be made at critical stages of activity in order to identify which avenues of R&D show the most promise and deserve the greatest attention. These decisions determine the efficiency and the ultimate success of R&D activities. This problem for DOE is identical to the problem a firm faces in allocating scarce capital resources to the most productive enterprises, and for this reason, can be referred to as a capital budgeting problem. The approaches to capital budgeting are numerous and the best choice(s) will depend on the particular application being made, as well as being a function of the quality of data available.

From a methodological point of view, there are numerous ways of analytically factoring the problem facing DOE. A variety of established methods have been examined by AETA Corporation in detail and the most applicable are briefly described in Section III. Each method has its advantages and disadvantages, and in different situations they all have their value. However, a unique approach sensitive to the relative paucity of data in the sun fuels area and the highly subjective nature of R&D assessment is necessary for justifying important funding decisions and AETA has designed such a method which incorporates the major features of two very powerful standard analytical approaches. This method combines the simplicity of conventional scoring techniques with the subtlety of multi-attribute utility theory. Thus, we have coined the title of "Multi-Attribute Preference Scoring System" (MAPS) for this hybrid and believe it will help the U.S. DOE decision-makers to chart proper courses of action in the years ahead.

no correct
finding? or
shared?
lights used before
during or after?

2. CURRENT SUN FUELS OPTIONS

The objectives of the DOE/SAN capital budgeting problems were specified by DOE Washington at the outset of this analysis. First, the decision must result in the selection of a single process demonstration experiment based on available data, to be performed at the Solar Thermal Test Facility in Albuquerque, New Mexico. In addition, there are three objectives of the process demonstration itself. These three are:

- o Significant demonstration by 1985
- o High visibility
- o Obvious end-product market

"Significant demonstration" by 1985 implies that the experiment will have been successful and will have provided by 1985 the necessary information and experience to allow technology development to proceed primarily with private sector support. "High Visibility" implies that the demonstration will have been sufficiently interesting and successful from both a technical and political perspective to merit considerable attention. The "obvious end-product market" objective specifies the need for a meaningful and significant technological development within the context of industrial production of fuels and chemicals. In other words, the fuel(s) or chemical(s) produced should have an important market and potential for an important impact in the chemicals/fuels industries. This decision is particularly difficult in that the choice is unitary; one experiment must be chosen from among many candidates. For obvious reasons, DOE/SAN wants its choice to be that which will yield the greatest level of benefits for the costs associated with it. Simply stated, DOE/SAN wants the "biggest bang for the buck" from its solar/fuels-chemicals process demonstration project.

Unfortunately, the problem facing DOE/SAN is complicated by the diverse nature of the projects being considered, as well as other considerations relevant to solar thermal energy. The problem must be analytically factored in a fashion which accommodates:

1. Disparate candidate processes using different feedstocks and

different technologies, and producing different products which are at various stages of development (concept, bench scale, or process development units).

2. Alternate commercial technologies which are available to produce the same product.
3. The combination of subsystem equipment and technology under development, e.g. solar receivers, gasifiers, chemical reactors.
4. The transient nature of solar energy and uncertain costs associated with high temperature solar thermal systems.
5. The lack of substantial qualitative hard data and economic analysis.

Alternative process demonstration projects are not subject to the same "return-on-investment" criteria that drive or motivate investments in commercial projects. Yet, the context of the analysis is complex in that it must still incorporate many considerations, including those relating to the potential for and value of ultimate commercialization. In addition, the outcomes of any particular choice are highly uncertain due to the long time-frame over which the benefits may accrue, the complexity of the analytical context, and the lack of good evaluative data for most, if not all, of the options.

These factors have a number of implications. The best method for choosing a process demonstration project will ultimately have to rely on minimal hard data and substantially on professional judgment. Such judgment must necessarily reflect subjective elements. In addition, each option will have many positive and negative features that have to be balanced and traded off for comparison with other projects. And finally, the method must be simple enough to allow continual re-testing and re-analysis for the purpose of evaluating changes that occur in time to improve data quality; yet it must also be complex enough to capture the subtleties of the trade-offs involved in making the final choice.

In any case, the basis for analysis of R&D priorities is a comprehensive review of all available information on research and experiments in the sun fuels area. Such a review was conducted, with information collected from journals, conference proceedings, and also through contact with individual research workers. For most processes, the data are based on laboratory scale experiments. In the case of "Steam Reforming of Methane", PFR Engineering has made only a conceptual study. Except for five processes, economic analysis giving capital investment estimate and operating cost for a commercial size plant has not been made.

We have summarized the results of this comprehensive survey in twenty brief outlines of the candidate processes. References for these summaries are found in the Appendix A Bibliography and referred to throughout the body of this Section.

2.1 SYNTHESIS GAS

2.1.1 SOLAR COAL GASIFICATION, Lawrence Livermore Laboratory

Gregg, et. al. (References No. 1 - 4) have conducted experiments at the White Sands Solar Facility on the gasification of bituminous coal using focused solar energy through a 20-cm diameter silicon-glass window and a gravity feed gasification reactor. The steam flows across the window kept the window free of deposits. In one of their tests, the solar flux was 18.2 KW with 4.242 mols/sec. steam. The product gas composition was 0.205 CO₂, 0.190 CO, 0.570 H₂, and 0.035 CH₄. In conventional gasifiers, the energy required for drying and pyrolysis of coal, to drive the endothermic reactions is supplied by burning part of the coal with oxygen.

Solar coal gasification does not use coal combustion to supply the required energy, so oxygen is not required and in addition, less coal is needed for a given amount of useful product. These two advantages for solar coal gasification have a major impact on the fundamental economics of the process. The product gases have more heating value than the starting coal. Thus, the solar energy ends up being chemically stored in the product gas.

Four types of reactors have been identified:

1. A packed-bed reactor,
2. A fluidized bed reactor at the tower top,
3. A fluidized bed reactor at the ground level with a closed loop heat transfer fluid.
4. An open heat exchange loop solar coal gasification reactor at the ground level with molten sodium carbonate.

A simple model of solar coal gasification has been developed and it is reported that their model fits with their experimental data and that a moving bed process results with an energy content 25% higher than the initial coal. This increase represents stored solar energy. An economic analysis of a commercial

size plant of capability 288.6 MMSCFD of pipe line gas has been presented. Total capital investment estimate is $\$1,904 \times 10^6$ (1978 \$). The annual operating cost figures are available.

Solar energy is focused directly on reacting coal with no intervening heat transfer stages and the plant operates only when the solar energy is available. There are no storage schemes considered. Economic analysis indicates that when coal cost exceed \$4 per million BTU, the solar coal gasification plant will be more economical than the conventional coal plant because solar coal gasification conserves 40% of coal. The process plant size suggested is 500 MW_t of solar energy. Biomass can be used as alternate feed.

2.12 A TWO-STAGE, FLUIDIZED-BED SOLAR HYBRID COAL GASIFICATION SYSTEM,
University of New Hampshire

A two-stage fluidized-bed hybrid coal gasification system has been designed at the University of New Hampshire to produce synthesis gas ($\text{CO} + \text{H}_2$); dubbed "sun gas" (References No. 5 - 12). By a dual heating technique, the system operates twenty-four hours a day.

Coal is devolatilized in the stage I reactor. The heat necessary to bring the coal to the devolatilization temperature of 823°K is supplied by the recirculating gas heated by the solar receiver/coal heater. The volatile products and the char obtained from the stage I reactor are fed along with steam and recirculating hot gas to the stage II reactor where the gasification of carbon with steam takes place at 1227°K . The necessary heat for the endothermic reaction:

is supplied by the recirculating gas entering the reactor at 1339°K and heated by the solar receiver/coal heater.

Since the volatile products are exposed to the high bed temperature in stage II reactor, tar and light oil are converted to CO , H_2CH_4 and other hydrocarbons that will not condense in the product gas line. Thus, the product gas is free of tar and other condensables.

This gasification reactor design utilizes the product gas as a heat exchange fluid to transfer heat from the solar tower to the reactor. Heat transfer efficiency is increased because of the direct contact between the fluid and the reactants. The advantage in this design is being able to position the coal-steam gasification reactor at the base of the tower and use a coal-fired reheat furnace to extend operation through the night and on cloudy days. However, the recycle ratio necessary to carry the heat into the reactor is very large.

The product gas stores substantial quantities of solar process energy. It is estimated that there is a savings of almost 10% of coal. The feedstock is abundantly available. The products are usable directly as fuel gases, as feedstocks for the production of hydrogen, methanol, liquid fuels by Fischer - Tropel synthesis, the oxo process, and methane.

An economic study of the University of New Hampshire solar hybrid unit using coal, lignite, or peat for the production of 250 MM SCF/day if SNG has been made and compared with the corresponding conventional plants. The cost estimates indicate that by 1995 the cost of SNG from the hybrid system will be cheaper by 5% to 6% than that from conventional systems. The total capital investment estimate is $\$2,028 \times 10^6$ (1980 \$). The annual operating figures are available. The process plant size recommended is 50 MM SCF/day. Bench scale experiments are in progress.

2.13 LASER SIMULATION OF SOLAR COAL GASIFICATION, Los Alamos Scientific Laboratory

Beattie and Sullivan have carried out gasification experiments with Western sub-bituminous coal having particle diameter of 0.45 to 0.33 mm and using a CO₂ laser to simulate concentrated sunlight in an entrained bed (Reference No. 13). Energy is absorbed directly by coal or char particles which are entrained in the reactant carrier gas - CO₂.

Their results showed that laser simulation of solar coal gasification works well, pyrolysis gas yield increase with flux and solar coal gasification appears to be technically feasible.

The intermittent and variable nature of solar energy places several important constraints on the design of solar coal gasifiers of the type suggested by Beattie. These are low inertia, high throughput devices operating as entrained gasifiers, and utilization of finely ground coal suspended directly in the resultant gas. Energy is absorbed directly in coal.

The results obtained using the output of a cw CO₂ laser to simulate concentrated sunlight are encouraging. However the laser results need to be compared to similar results obtained from irradiation of the coal with concentrated sunlight.

The above information is based on a laboratory scale experiment. Capital investment estimate for a commercial size plant, operating cost and economic feasibility studies have not been made. An economic size plant is not recommended and no date by which the process will become economically feasible is given.

2.14 BIOMASS FLASH PYROLYSIS, Princeton University

Initially, Antal of Princeton (References No. 14 - 18) studied the flash pyrolysis of powdered cellulose with steam in a tubular reactor made of quartz, with external electrical heating. In order to increase the absorptivity of the cellulose, it was colored grey by the addition of about 10% by weight of black charcoal; 0.1 to 2 gm. of cellulose was pyrolysed in each run. The amount of pyrolysis was about 50% of the total grey cellulose and almost nil with white cellulose. The product was a hydrocarbon rich synthesis gas containing commercially interesting amounts of ethylene, propylene, and methane.

Antal has concluded that the biomass gasification was a three step process: (1) pyrolysis at 300°C or more, (2) Cracking/reforming of the volatile matter at 600°C or more to form a hydrocarbon rich synthesis gas, (3) Char gasification with steam which played a less important role than steps (1) and (2). The first step was favored by high temperatures and rapid heating, producing combustible volatile matter at the expense of char formation. The second reaction was favored by low temperature and slow heating of the cellulose.

Since solar radiation can be used to achieve very rapid heating, Antal gasified cellulose and ground corn cob material in a windowed chemical reactor operating at the focus of the Odeillo 1 MW solar furnace. He obtained flux levels in excess of 1000 W/cm². However, impurities carried by the steam flew into the reactor, ultimately clouding the window. Some devitrification had occurred and char yield was low. Gas yields from the solar flash pyrolysis experiments were lower than had been anticipated from the results of earlier work since the Odeillo reactor did not provide for good control of the gas phase conditions.

The cellulose pyrolysis mechanism is as follows:

The first reaction is favored by high temperatures and rapid heating, producing combustible volatile matter (levoglucosan) at the expense of char formation. Production of levoglucosan ($C_6H_{10}O_5$, or the 'monomer' of cellulose), had been emphasized in Antal's work. Levoglucosan (and related compounds) have been described as potentially important industrial intermediate chemicals. Antal had observed that entrained flow, flash pyrolysis reactors were suited for the production of large yields of the reactive intermediate "levoglucosan" from cellulose.

Antal designed and fabricated a quartz reactor for use at the focus of the Georgia Tech ACTF 400 KW solar furnace. He carried out experiments at his facility using hardwood, ground corn cob material, and cellulose. Fifty percent pyrolysis was obtained since the residence times of the falling solid biomass material in the zone of intense radiant energy were insufficient to completely pyrolyze the material. The product gas had a higher heating value of 488 BTU/SCT and contained primarily CO , H_2 , CO_2 , CH_4 , and C_2H_4 . As in earlier research, the performance of the quartz reactor was affected by devitrification of the quartz nearest the focus of the solar furnace.

Bench scale research at Princeton had shown that concentrated radiant energy could be used to selectively produce high yields of liquid syrups from biomass. Antal claims that the liquid syrups are an exciting new chemical feedstock with more potential uses than petroleum.

2.15 CONTINUOUS FLASH PYROLYSIS OF BIOMASS IN A CYCLONE REACTOR, Jacques Lede, C.N.R.S. Odeillo, France.

There are several types of gas-solid reactors: fixed bed, fluidized bed, and transported bed, the latter of which are the more frequently utilized. In this study, centrifugal systems which are less studied are adapted. Among these, the most familiar cyclone reactor has been chosen by Lede (Reference No. 19) for study as a high temperature reactor for flash pyrolysis of biomass. Three main types of experiments have been carried out: residence time distribution studies, heat transfer studies, and continuous flash pyrolysis of sawdust.

Flash pyrolysis of sawdust in the 0.14 to 0.2 mm size range has been carried out in a cyclone reactor placed at the focus of an image furnace at 870°C. The reactor is fed by dry sawdust carried by argon. Liquid products such as tar are trapped in a dewar vessel and gaseous products escape at the top. Ashes are automatically separated under the influence of centrifugal force and collected at the bottom. It is claimed that there is excellent heat transfer among the carrier gas, the particles, and the wall and that the maximal absorption of radiation is from the hot wall. Thus the reactor can be heated by direct insolation. The heating rate is 2000°C/sec. Residence time is 0.43 sec. The temperature of the wall is 1050°C or 1922°F. The temperature of the exit gas and particles is 1598°F. The flow rate of sawdust is 0.0022g/sec. and that of argon is 0.039g/sec.

Gasification yields gaseous products to the extent of 58% of solid fed or 600 ml/g of sawdust (normal condition). From these preliminary experiments, it is claimed that flash pyrolysis of biomass in a cyclone reactor is a very efficient way to produce large quantities of gases containing a large amount of CO and H₂. The heat required for the reaction is provided by concentrated solar energy. All the biomass is then gasified instead of burning of one part of it as in most conventional gasifiers. In addition, the product gas has a higher form grade and contains less CO₂.

Further studies are in progress for scaling up the reactor for real conditions at solar facilities.

2.2 HYDROGEN

2.21 SOLAR THERMAL HYDROGEN PRODUCTION PROCESS, Westinghouse Electric Corporation

Westinghouse Electric Corporation has explored a sulfur cycle hydrogen generation process, consisting of two chemical reactions (References No. 20 & 21).

Hydrogen is generated electrolytically in an electrolysis cell which anodically oxidizes sulfurous acid to sulfuric acid (H_2SO_4), while simultaneously generating hydrogen (H_2) at the cathode.

Sulfuric acid formed in the electrolyzer is then vaporized using thermal energy from a high temperature heat source ($> 1600^\circ$).

The vaporized sulfuric acid ($\text{H}_2\text{O} + \text{SO}_3$) flows to an indirectly heated catalytic reduction reactor where sulfur dioxide (SO_2) and oxygen (O_2) are produced and the SO_2 is recycled to the electrolyzer.

Potentially attractive catalysts for the reduction of SO_3 to SO_2 via reaction (2) have been identified and tested. One per cent by weight of platinum on alumina spheres is found to give the best results when the space velocity was 5000 ft/hr. Both the liquid and vapor phases of H_2SO_4 are present in the vaporizer at elevated temperature and pressure (361°C , 55 psia and 425°C , 300 psia). Therefore, potential acid vaporizer structural material fabrication problems exist. Potential materials for compatibility with reduction reaction conditions in the temperature range of 480°C to 870°C have been screened. Polycrystal silicon, silicon carbide, and silicon nitride appear to have the best corrosion resistance.

General guidelines and ground rules have been formulated for conducting the process studies:

- o Solar portion of the process is to be limited to 350 - 400 MW_t.
- o Hydrogen production is to be in the range of 10 - 30 million SCFD.
- o Continuous (24 hour) plant operation using chemical energy storage is considered.
- o Flow sheet given shows two central receiver "power towers" - one for H₂SO₄ decomposition and one for electric power generation.

The solar receiver chosen was a downward facing cavity within a 360° collector field. The solar (field) flux is transferred directly into the vaporized H₂SO₄ through silicon carbide tubes (similar to the proposed Black and Veatch air receiver). Process conditions are specified and potential end-product processes compatible with the proposed 10 - 30 million SCFD of H₂ have been studied. The following five processes have been selected: ammonia, methanol, hydrogen peroxide, iron ore direct reduction, and coal liquefaction.

Flow sheets, mass flow rates, process flow sheets for the above five processes are given. Economic analysis of the proposed processes have been made.

Total capital estimate for a plant producing 190 tons of ammonia per day from 12.74×10^6 SCE/day of hydrogen is $\$235 \times 10^6$ (1978 \$). Capital estimates for methanol and hydrogen peroxide plants are also presented. The annual operating cost figures are available. The sulfur cycle hydrogen production plant costs represent a total plant investment of approximately \$5/SCFD.

A major issue identified was the capacity matching of the solar/hydrogen sub-system with end-product process requirements. The ammonia and methanol solar plant capacities are five or six times smaller than the new fossil fuel ammonia and methanol plants. Ammonia and methanol costs are about three times greater than current (1978) fossil-fuel production costs.

Further economic assessment has been made. A plot of ammonia costs versus design receiver capacity for each of the three design days is given. The "summer solstice" design day results in the lowest production costs for all receiver capacities. The optimized production cost of \$762 per ton is comparable to the 1978 estimates.

2.22 HYDROGEN PRODUCTION BY SULFUR-IODINE THERMOCHEMICAL WATER-SPLITTING,

General Atomic Company

Hydrogen production by the GA Sulfur-Iodine Process (References No. 24 - 26) consists of the following chemical reactions:

The HI_x represents the mixture of several polyiodides formed in the main solution reaction (Eq. 1). The H_2SO_4 and HI_x are separated by gravity, since the acid solutions are almost completely immiscible. The upper phase contains almost all of the H_2SO_4 , and the lower phase contains most of the HI_x .

Their bench scale model consists of three sub-units which can be operated separately or together and is capable of producing as much as 4 std. litres/minute ($6.7 \times 10^{-5} \text{ M}^3/\text{s}$ at standard conditions) of gaseous hydrogen. One sub-unit (main solution reaction) reacts liquid water, liquid iodine (I_2) and gaseous sulfur dioxide (SO_2) to form two separable liquid phases: 50 to 57 wt. % sulfuric acid (H_2SO_4) and a solution of iodine in hydriodic acid (HI_x) as represented in equation 1. The second sub-unit concentrates the H_2SO_4 phase to the azeotropic composition, then decomposes it at high temperature over a catalyst to form gaseous SO_2 and O_2 as given in equation 3. The third sub-unit separates the HI from water and I_2 by extractive distillation with phosphoric acid (H_3PO_4) and decomposes the HI in the liquid phase over a catalyst to form I_2 and product hydrogen as shown in equation 2.

Industrial experience in handling the corrosive fluids such as HI_x and sulfuric acid solutions specific to the GA sulfur-iodine process is limited. GA is testing various materials to identify materials that have demonstrated satisfactory compatibility with HI_x and sulfuric acid solutions. Thus, realistic material sections can be made for use in the conceptual design of a commercial process plant.

It is claimed that the results of the bench-scale experiments indicate that flow sheet conditions can be achieved. GA has proposed that high temperature solar thermal energy can be used to decompose H_2SO_4 during sunlit hours. The acid decomposition products are then heat exchanged with the incoming acid, the oxygen and water are removed, and the SO_2 is stored for use in the low temperature solution reaction. The low temperature solution reaction is conducted twenty-four hours per day, producing H_2SO_4 and HI . Solar energy is also used to heat a transport fluid such as a eutectic salt. During daylight, the salt charges a heat-storage reservoir, generates steam to drive compressors and pumps, and provides heat for concentration and cracking of the HI to yield the hydrogen product and iodine for recycle to the main reaction. At night, the heat-transport fluid continues to perform these functions, but by-passes the heat receiver and is heated by the heat-storage reservoir.

GA has evaluated several high temperature receivers. They recommend that the cavity design is the preferred concept from the standpoint of thermal efficiency. They are continuing their studies on fluidized bed receivers and others. They have selected a plant heat requirement of 400 MW_t with an estimated hydrogen output in the range of $4.64 \times 10^5 \text{ M}^3/\text{day}$ ($1.64 \times 10^7 \text{ ft}^3/\text{day}$).

2.23 HIGH TEMPERATURE THERMOCHEMICAL CYCLES FOR SOLAR HEAT SOURCES,
Los Alamos Scientific Laboratory.

Researchers at the Los Alamos Scientific Laboratory have defined some of the criteria required for high temperature thermochemical cycles to couple efficiently with solar heat sources for the production of hydrogen and have also examined potential cycles (References No. 27 - 28).

Ideal cycle is a two-step process in which a reactor (R) reduces water at a low temperature (T_1) to evolve hydrogen and form the compound RO (an oxide), followed by thermal decomposition of RO at high temperature (T_2) with evolution of O_2 .

$$\Delta G^\circ_T = \Delta H^\circ_{298} - T \Delta S^\circ_{298}$$

"Ideal" values for entropies and heats of formation of the compound RO are approximately defined as: $\Delta S^\circ_F = \frac{\Delta C^\circ_F (H_2O) \text{ at } T_1}{(T_2 - T_1)}$

$$\Delta H^\circ_F = \Delta S^\circ \times T_2$$

where $\Delta G^\circ_F (H_2O)$ is the free energy of formation of water at T_1 (the low temperature). At $T_1 + 400^\circ K$, $\Delta G^\circ_F (H_2O) = 223 KJ$. Since the entropies of formation of oxides are characteristically near 100 J/K, it is clear that very high temperatures will be required for two-step oxide cycles.

At L.A.S.L., a "pure" thermochemical cycle is under study that incorporates the decomposition of CdO.

Encouraging results have been achieved by using NH_4Cl as a catalyst for the reaction (3). Sufficient heat is available from the condensation of cadmium vapor to promote the carbonate decomposition. The cadmium oxide based cycles offer the potential for high efficiency, if:

1. Solar heat can be utilized efficiently for the oxide decomposition step.
2. The back reaction between cadmium vapor and oxygen is sufficiently slow.
3. The low temperature reactions to yield $\text{Cd}(\text{OH})_2$ or CdCO_3 can be conducted at practical rates and the resultant solid does not absorb or occlude too much water.

Another cycle being studied at L.A.S.L. involves the formation of bismuth oxysulfate. The overall cycle includes the following reactions.

Since reaction (8) requires only relatively dilute sulfuric acid, it is possible that less electrical energy will be required for the electrolysis step (7) than is required for the hybrid sulfuric acid process. However, bismuth is not an abundant element and is relatively expensive.

The following two reactions illustrate a concept for utilization of displacement reactions rather than direct decomposition reactions.

The heat requirement and reaction temperature are significantly lower than the corresponding direct decomposition reaction. It is reported that very encouraging reaction rates have been achieved for these reactions (10) and (11).

2.24 HIGH-TEMPERATURE SOLAR THERMOCHEMICAL HYDROGEN PROCESS, Institute of Gas Technology

The Institute of Gas Technology (IGT) hybrid cycle (References No. 29 - 31) consists of the following steps:

A relatively small electrical energy input is required to drive the first step. This cycle appears suitable for coupling with solar heat source since the latter is capable of supplying nearly isothermal heat.

The reaction (1) is an electrochemical step capable of operation at very low potentials at room temperature. A stirred mercury-cadmium anode and platinum cathode are used. The reaction (2) occurs at as low a temperature of 475°K. Experiments have confirmed that the decomposition of CdO occurs at 475°K. It has been shown experimentally at IGT that the decomposition of CdO takes place at 1500°K in a stream of inert gas flow at 101 kpa (1 atm.) pressure.

Solar thermal decomposition of CdO has been tested at White Sands solar furnace using a water-cooled 304 stainless steel solar receiver/reactor. To minimize the recombination of the exiting decomposition products, an argon sweep was used to dilute and carry away the gases and a water cooled heat exchanger used to condense out the metal vapors. The receiver/reactor performed well in decomposition experiments at 1290 - 1480°K and produced good deposits of Cd metal. The solar furnaces at Odeillo (France) and the White Sands Missile Range (New Mexico) provide the necessary high temperature for CdO decomposition.

CdO decomposition experiments have been carried out at White Sands using a reactor which consisted of type 304 stainless steel containment vessel. Cooling is by a water jacket around the portion of the reactor to be exposed to the solar

flux. The shell is protected by two concentric ceramic heat shields, the inner liner of high purity aluminium oxide and an outer liner of mullite, a form of aluminium silicate. Good deposits of cadmium metal are obtained at temperatures of 1575 to 1720°K with a metallic content of 84% Cd. Oxygen evolution rates have been measured with thermal conductivity detector. Mass and energy balances have been calculated. The hydrogen producing step has not yet been fully characterized.

2.3 OTHER PROCESSES/PRODUCTS

2.31 WET OXIDATION OF PEAT/LIGNITE, Jet Propulsion Laboratory

Wet air oxidation or wet pyrolysis is an oxidation process that is accomplished under water using air or oxygen. Peat has a low value as a fuel since it has high concentration of occluded and included water of up to 84%. Solar drying in the open field reduces its moisture content to only 50%. Other methods of dewatering peat require the expenditure of energy derived from the materials being dried.

The Jet Propulsion Laboratory concept (Reference No. 32) is to produce fuels and/or chemical intermediates from peat, lignite, and low bituminous coals without prior removal of the "as mined" water by carrying out a pyrolysis in a high temperature heat transfer fluid (HTF) such as Dowtherm (350°), syltherm (500°), etc. These high temperature heat transfer fluids (HTF) enhance heat and mass transfer, give high product yields and offer a means for rapid pyrolysis. In this process, the heat required to achieve pyrolysis is to be transferred from the solar collector by way of a HTF. The solar collector can also be used as the reactor by suspending the feed materials in the HTF for direct heat transfer.

The initial research program used a pyroprobe reactor with a gas chromatograph and the mass spectrograph for assessing the quality and quantity of the products obtained from the experiments. The feedstocks examined include peat with 84% moisture, lignites from North Dakota and Texas with 25% - 35% moisture and sub-bituminous coal from Wyoming with 18% moisture. Studies with the Pyroprobe consisted of the following: (1) rapid pyrolysis (in a helium atmosphere) with neat feed materials (as received) at various temperatures, various heating rates, various residence times, (2) pyrolysis of feed materials with inorganic catalysts at various temperatures, concentrations and heating rates, (3) pyrolysis of feed materials with HTF's at various temperatures, heating rates and with catalysts.

The data was examined by two methods: (1) amount of product divided by the total amount of gases or as a percent of the area under the curve, and (2) as a normalized value using the curve areas divided by the amount of material pyrolyzed. The volatile product analyses indicated that the volatile products were influenced by heating rate, heating interval, degree of wetness (water), pyrolysis maximum temperature, effect of catalysts and effect of the HTF. Major volatile products only were examined in this study. Products such as H_2 , H_2O , CO , CO_2 , N_2 , and O_2 were not measured.

Neat peat was found to produce a greater total amount of volatiles under all conditions than the other neat materials. This implies that the peat produced more of the compounds that were not measured in this study such as H_2 , CO , CO_2 , etc. The other neat materials produced more hydrocarbons. Major products from the peat-pyrolysis were methane, ethane, ethylene, methanol, acetaldehyde, acetone, and acetic acid. Coal and the lignites produced greater amounts of hydrocarbons, but little or no acetic acid.

The catalyst study indicated the effectiveness for lowering the reaction temperature. Calcium acetate was more effective at concentrations of 5% to 10% (wet, dry basis). Calcium oxalate was the most effective at concentrations of 1% and at $800^\circ C$.

The HTFs (dowtherm, therminol 66, and syltherm) lower the reaction temperature and the production of methanol, acetaldehyde and other products was increased over those of the neat feedstock materials. Since the temperatures used with the HTFs were substantially lower, the potential for solar coupling appears practical. The interfacing of solar supplied energy will be an economically efficient and environmentally acceptable method.

These preliminary experiments indicate that rapid heating and quenching of the products in a heat transfer fluid can be used to design a bench scale experimental equipment. Use of larger bench scale reactor will enable the examination of the effects of pressure on the system and on the quantities of H_2 , CO , CO_2 , H_2O , and HN_3 produced.

2.32 SOLAR RETORTING OF OIL SHALE, Lawrence Livermore Laboratory

In work at Lawrence Livermore Laboratory (References No. 33 - 34) the organic material in oil shale, namely Kerogen, decomposes by a two-step reaction. At a temperature of 650°C:

Kerogen -----) Bitumen -----) oil + gas + char

About 94% conversion of Kerogen occurs within 60 seconds. Shale contains about 20 to 30 gallons oil/ton. The oil yield and percent of organic matter (carbon) remaining in the spent shale are a function of heating rate. Since very high heating rates are achievable with concentrated solar energy, highest possible oil yield can be obtained with solar oil-shale retorting at 500°C.

The mineral matter, particularly the carbonates in oil shale, starts decomposing at 550°F. Because decomposition consumes energy, the solar oil-shale retorting is done by rapid heating to a temperature where Kerogen rapidly decomposes, but the carbonates do not. This results in the highest possible oil yield while minimizing the solar energy requirements.

In the proposed solar oil-shale retorting process, solar heat provides energy for all the endothermic processes: Kerogen pyrolysis, water release, and mineral carbonate decomposition, as well as the sensible heat losses that result primarily from the rejection of the hot spent shale. Assuming mass production of heliostats and the insolation over the oil-shale fields is 4/5 of that for Barstow, the cost of solar energy delivered at a point in space at the location of the shale fields is estimated to be about \$2.68/AJ.

During 1979, two solar oil-shale experiments were carried out at the White Sands Solar Furnace. In the first experiment, the solar heat was focused through a silicon-glass window fixed in an L-shaped retort, on a stationary bed of shale. About 30 kg of shale was loaded in the retort. In the second experiment, the shale was transported through the solar focus by a pneumatic mechanism built into the same retorting vessel used for the first experiment. Encouraging results were obtained. Oil yields in excess of 110% Fischer array was obtained. Many modifications to overcome the

problems faced in the experiment are suggested. Economic estimates indicate that the incremental cost of the solar energy (cost of the heliostat field only) will range from \$1 to \$3 per barrel, depending on the grade of the shale.

2.33 CALCIUM CARBIDE PRODUCTION IN A SOLAR FURNACE, Institute
Of Gas Technology

Calcium carbide is conventionally made from lime and coke at 2000°C in electrical resistance furnaces. Calcium carbide reacts with water to produce acetylene, which is used as a petrochemical intermediate. As the carbide is formed, equivalent amounts of CO are evolved at the same time, which can be used to produce hydrogen, methane, and in conjunction with acetylene, ethylene, and ethane. In fact, CO and acetylene constitute building blocks for many fuels and petrochemical products.

The feasibility of making calcium carbide from lime and coke using solar heat has been demonstrated in a series of experimental runs conducted at the Odeillo CNRS Laboratory by IGT (Reference No. 35). Using one gram samples placed in the focus of the 2 KW vertical beam furnace, as much as 30% to 40% of the lime-coke mixture was converted to carbide by rapid heating of the resultant mixture in an open, water cooled crucible. The solidified carbide melt was easily separated from the unreacted lime-coke mixture. Carbon monoxide which evolved could not be measured. There were losses caused by spouting of charge ingredients as gases evolved violently and by burning of carbon and calcium.

The major unknowns are the strength of the solar heat flux essential for the carbide forming reaction, and the configuration of the solar furnace required. A fluidized-bed technique holds promise for future development. Some additional work on both a horizontal and vertical beam furnace of the 2 KW power is indicated.

2.34 FURFURAL FROM BIOMASS, Quaker Oats Company/Jet Propulsion Laboratories

Furfural is produced from renewable agricultural sources such as corn-cobs, oat hulls, rice hulls, cottonseed hulls, bagasse, or any pentosan-containing substance, since pentosan polysaccharides are the precursors of furfural. The raw material is charged to a digester and treated with sulfuric acid. High pressure steam is introduced through the mass and after attaining operating temperature and pressure, furfural is steam distilled.

Pentosan -----) Pentoses -----) $C_5H_4O_2$

The steam distillate is condensed and the condensate is fed to a stripping column from which an enriched furfural - water distillate is withdrawn and condensed in a decanter where it separates into two layers. The furfural rich layer containing about 6% water is processed further to obtain the furfural. In general, the cellulose in the raw material undergoes only partial degradation and remains with the lignin and ash as by-product residue.

Furfural is a speciality solvent. It contributes low viscosity to resin formulations. It is used in the extractive distillation of entradiene and other C_4 hydrocarbons for the manufacture of synthetic rubber. It is also used in lube oil refining. It is suitable for use as motor transport fuel or diesel fuel replacement.

The Quaker Oats Company is producing on a commercial scale furfural using oat hulls as a raw material. Steam required for the process is to be obtained using solar energy as the fuel source. The thrust is to produce furfural using solar energy as the fuel source. The details of its economic feasibility are not available. However, the process is promising if solar heat is competitive (Reference No. 36).

2.35 DECARBONATION OF CaCO_3 , Gilles Flamant, Odeillo Font Romeu, France

A fluidized bed reactor and rotary kiln have been used to carry out an experimental study of the decarbonation of calcite (CaCO_3) by Flamant (Reference No. 37) using concentrated solar energy from parabolic shaped solar concentrators. The fluidized bed reactor has a transparent silicon wall height of 0.3 M, allowing concentrated solar flux to enter the reactor. There is a reflector surrounding the wall in order to decrease radiation losses. The gas flow rate across the bed, total pressure drop, and temperature inside the bed were continuously controlled. The available measured power was 1.4 ± 0.1 KW.

The rotary furnace is inclined at an angle of 5° to the horizontal axis of the concentrator. Its main features are: (a) a water cooled metallic frame which rotates inside a fixed shell (b) internal lining of refractory tubes at the wall (c) continuous feeding of the particles through a distributor along a vibrating pipe down to the back entrance of the tube.

Radiative properties of natural silicon sand, alumino-silicate, ilmenite calcium carbonate, etc. have been investigated. Decomposition of calcite is an endothermic reaction taking place at 900°C : $\text{CaCO}_3 = \text{CaO} + \text{CO}_2$ $\Delta H^\circ = 42.6$ kcal/mole. The variation of enthalpy is sufficiently large, the temperature of reaction is moderate, and the products are easy to separate. Furthermore, the thermal storage capacity per unit volume is large (~ 500 KWh M^{-3}).

The main results from both reactors indicate that the total or partial decomposition of calcite can be achieved with a thermal conversion efficiency of 10% to 40% directly comparable to other means for conversion of solar energy. Temperature level of the charge was $600 - 1300^\circ\text{C}$ for fluid reactor and $300 - 1500^\circ\text{C}$ for rotary kiln.

These experiments establish the feasibility of conversion of solar energy either thermally or thermo-chemically. The rotary kiln exhibits a large absorption coefficient while the main advantage with the fluid bed is the high transfer rate.

The authors have proposed a reactor where the advantage of both fluid bed and rotary kiln are combined. Such reactors could find applications for conversion of concentrated solar energy, e.g. heating of gas by means of fluid bed receiver, high temperature thermal storage with solid material, thermo-chemical storage involving gas-solid systems, preparative chemistry of carbonated materials thermal treatment of ores, drying and dehydration.

2.36 SOLAR CENTRAL RECEIVER REFORMER SYSTEM FOR AMMONIA PLANTS,

PFR Engineering Systems, Inc.

PFR has examined the concept and the feasibility of retrofitting an ammonia plant with a solar central receiver with special reference to the Valley Nitrogen Producers, El Centro Complex (Reference #38). At present, natural gas is consumed both as feed process and as fuel. It is burnt for providing heat required for the reforming process in the primary reformer where synthesis gas ($\text{CO} + \text{H}_2\text{O}$) is produced:

The above mixture is fed into a secondary reformer with air which provides the required nitrogen and oxygen used in a combustion process to provide the energy for further H_2 production. Carbon dioxide and water vapor are stripped off. Hydrogen and nitrogen react into an ammonia product by the following reaction:

The energy content of the feed for the above process is 147 MW_t , whereas the heat required for the process is 62 MW_t ; that for the steam is 64 MW_t and that for the boilers is 20 MW_t . It is proposed to use solar energy to provide the heat required for the process to the extent of 93,750 MW hrs per year and carry out the natural gas-steam reforming reaction in a solar receiver under similar conditions to a fossil fired reformer. The solar process conditions at the exit of the fossil and solar reformers are identical. Both streams join and flow to the secondary reformer. Downstream process system components are not affected by the introduction of solar energy resource.

The solar receiver tube panels are made of manaurite 36X alloy which contains 30% Ni and 25% Cr with a balance of iron and no cobalt. MDAC heliostats are used in the solar energy collector subsystem. The capital cost of the retrofit system is estimated as \$24 million. The discounted cash flow rate of return (DCF RR) approach has been used to analyze the profitability of this project. DCF RR is 21.3% with a payback period of 3.1 years.

The specific issues involved in this project are:

1. The concept must be demonstrated on a pilot-scale.
2. The retrofit system, by the nature of the variation in daily solar insolation, will operate under continual changes in flow rates and fuel firing. This is an inherently unsteady operation, safe and smooth operation during "cloud cover" and day to night switch. It is stated that this is not an insurmountable problem

In the economic analysis, the price of natural gas is taken as \$2.5 per MBtu and that of ammonia as \$180/ton. Ammonia is also manufactured from synthesis gas made from coal. The synthesis gas obtained from coal, with lignite or with biomass as feedstock is upgraded to substituted natural gas (SNG) as a transportable fuel. Since the natural gas resource is limited, the price of natural gas will increase faster than the price of abundant coal in the future. Plots of ammonia selling price vs. feedstock price are available. Based on the 1985 projected prices of coal and natural (\$26/ton of coal and \$3.5/10⁶ MW of gas), the cost to produce ammonia will be almost the same using either coal or natural gas. By 1990, the coal-based ammonia plants should be more economical, and by the year 2000, coal will have a significant advantage over all other fuels.

Due to the low probability that large new gas reserves will be discovered, the future prices of gas are expected to increase rapidly. Domestic

coal reserves are tremendous and the cost of coal will probably climb more slowly than the price of oil and gas. Thus, for economic energy policy reasons, coal will become the preferred feedstock and fuel for ammonia production within the next decade or so.

2.37 SOLCHEM CONCEPT: CO₂ - CH₄ REFORMING - METHANATION CYCLE,
Naval Research Laboratory.

A gas mix of CO₂ and CH₄ undergoes the reforming reaction at temperatures above about 700°C, producing CO and H₂. At temperatures below 600°C, CO and H₂ undergo the catalytically promoted methanation reaction, producing CO₂ and CH₄. The reforming reaction is accompanied by absorption of heat, ~ 260 KJ per mol of CH₄ destroyed. The same amount of heat is liberated during methanation.

This CO₂ - CH₄ reforming-methanation chemical cycle provides an attractive means of transporting solar energy to a central station in accord with the Solchem concept. In the Solchem energy system, (reference #39-40) a closed cycle chemical transport loop carries solar energy to a central energy storage area from which on-demand power is generated as needed.

A conceptual Solchem thermochemical receiver has been described. The receiver is of 25 KW capacity designed for a 7-M collector. The receiver consists of a hot cavity surrounded on its cylindrical wall by a spiral gas passage assembly, called the converter-heat exchanger. The bulk of the converter-heat exchanger is heat exchanger, whose dual function is to quickly cool the reformed gas and to heat the reformer feedstock from a near ambient input temperature to a reaction temperature near 750°C. Only the innermost wrap of the converter-heat exchanger forms the chemical converter and only this innermost wrap has a catalytically active surface.

Convergent sunlight is received into a cavity within which the trapping of energy occurs. This trapped energy is conducted through the cylindrical walls of the receiver onto surfaces interfacing with the reactive gas stream of the working fluid.

Nickel is used as a reforming catalyst. Tungsten-alumina, tungsten sulfide, molybdenum oxide (M_oO_3) are used as catalysts for methanation at 600°C.

$CO_2 - CH_4$ reforming-methanation system is suitable for small community power systems. The working fluid can be considered completely non-toxic as regards use in an open air environment. Delivery of heat at 500 - 600°C is achievable.

2.38 SOLCHEM CONCEPT: SO₃ DISSOCIATION - RECOMBINATION CYCLE,

Naval Research Laboratory

A working fluid SO₃ is first heated to about 750°C and then passes through solar heated catalytic reactor (Reference #41). SO₃ dissociates into SO₂ and O₂ at 800 - 1000°C range with the endothermic capture of 23 kcal of heat per mol of SO₃ reacted:

These product gases pass through heat exchangers and leave at 100 - 125°C. They are then transported to a central thermal storage or power utilization facility. Here, the components of the energy rich mixture of gas are catalytically recombined at 500 - 600°C to produce SO₃ and to release the chemical heat of reaction of 23 kcal per mol. SO₃ passes into circulation blowers back to the solar furnace. The result is a closed cycle circulation system whereby solar energy is converted to chemical energy in a form which can be transported and reconverted to high temperature (500°C) heat. This method of exploitation of solar energy is called Solchem by the NRL researchers. Other Solchem working fluids such as steam-methane and ammonia have been suggested. A mature Solchem includes storage tanks.

The use of SO₃ involve significant materials problems. Fused silica, aluminium rich alloys, such as kanthal A-1, stainless steel reactors have been tested in the SO₃ facility at the New Mexico State University, Las Cruces, New Mexico. Based on the results of this work, it is concluded that a 20 KW Solchem receiver could be assembled by stacking 10 helical receiver elements, each resembling the kanthal or the JPL stainless steel reactor, within a suitably insulated and manifolded canister. In this receiver the dissociation reaction can be catalyzed by platinum coated alumina spheres. With proper insulation and with proper cavity design, the receiver would probably convert 80% of the focused solar power entering the aperture. For long term operation, quartz coils are recommended.

2.39 AMMONIUM HYDROGEN SULFATE (AHS) CYCLE COGENERATION, University of Houston.

The AHS cycle examined by the University of Houston (Reference #42) is based on three chemical reactions: a two-step decomposition of ammonium hydrogen sulfate, and a recombination step:

The first two reactions absorb the solar energy. In the third reaction water, ammonia and sulfur trioxide react to give back ammonium hydrogen sulfate, releasing the energy. Approximately 280 MJ/kg more AHS is stored H_2O , SO_3 , NH_3 , all of which are liquids at approximately ambient conditions.

In order to make a maximum use of solar energy, it is essential that any solar power plant be based on simultaneous cogeneration of steam for power and heating. The details for a plant of 100 MW are given. Process engineering calculations have been made to determine how the cycle responded to a wide range of operating conditions. Solar energy usage and system efficiency are given. Preliminary cost estimates show that the capital required for (1) The solar energy collection subsystem is approximately \$105.7 million (2) The AHS cycle chemical storage subsystem is about \$44.2 million and (3) The power generation (both electrical plus steam) subsystem is about \$62.8 million for a total capital cost of approximately \$213 million. The operating cost is about \$67,900/day. The unit cost of electrical energy is 26.2 mils/KWH and steam cost is \$2.29/453.6 kg. or 1,000 pounds.

2.310 BIOMASS TO DIESEL FUEL, Solar Energy Research Institute

The thrust of SERI's project efforts has been to produce diesel fuel using gases obtained from an entrained-flow rapid pyrolysis of agricultural non-food materials such as wheat, straw and corn stalks (Reference #43).

The SERI entrained flow reactor is made of Vycor glass or stainless steel tube, with a 13 mm inside diameter and is electrically heated. Biomass is metered into a mixing chamber by a screw feeder where it is entrained by a flow of superheated steam. The reactor length is adjusted from 15 to 150 cm by adding or removing reactor sections. Pyrolysis gases and solid particles are separated by a cold water spray. The gases then pass through two tar traps and a flow meter where molecular weight and the mass flow rate are measured. The gas samples are analyzed with a gas chromatograph which yields data in hydrocarbons through C_5 . The flow rate of biomass particles was 500 to 1000 gm/hr. Runs of thirty minutes have been used.

The effects of reactor temperature, biomass residence time, and carrier gas flow rate on pyrolysis gas composition; percent of biomass pyrolyzed; and pyrolysis reactor energy requirements have been studied. Reactor temperatures have no influence on gas composition. Short residence time requires high reactor temperatures. It is suggested that practical reactors would be designed with much longer residence times to allow lower operating temperatures, perhaps 900°C or lower. Experiments have been conducted in a 30-cm reactor at temperatures from 1000°C to 1400°C and in a 90-cm reactor at temperatures from 700°C to 1200°C. The steam-to-biomass ratio was approximately 1:1. Particles had an average size of 240/M.

A few experiments were performed in the laboratory on catalytic synthesis (Fischer-Tropsch) of diesel fuel from simulated pyrolysis gas.

These experiments produced some liquid hydrocarbon product. The chromatogram of this liquid indicated that the primary components were saturated hydrocarbons in the C_6 - C_{14} range. The commercial diesel contains greater amounts of aromatics and unsaturates. Therefore the synthetic fuel should be a cleaner burning fuel due to its lower aromatic content.

2.311 ORE PROCESSING

S.R. Skaggs of Los Alamos Scientific Laboratory (References #44-45) has heated several 10 g samples of molybdenite ore containing 5 to 6% Mo as MoS_2 in one of the 2 KW solar furnaces at Odeillo, France. Excellent separation of MoO_3 from SiO_2 was achieved by the treatment of Molybdenite ore in an O_2 atmosphere in a solar furnace. Pure MoO_3 and SiO_2 products may be obtained. This experiment is an example of one that utilizes solar energy for process heat. It does not require a very high solar flux. The temperature is about 2550 - 2700°F.

Niobium and Zirconium follow the same path as Molybdenum, but the concentration of these elements is low and the data in enrichment are inconclusive. The oxidation of the MoS to MoO_3 is exothermic, and the kinetics appear to be rapid. MoO_3 separates in a solar furnace and the crystals of high purity (MoO_3) are obtained. These crystals can be used directly in steel making.

The Institute of Gas Technology has made a qualitative assessment of the potential to utilize solar energy for an energy intensive commercial process for elemental phosphorus from phosphate rock.

The CNRS in France produces several tons per year of a vanadium compound used in sensitizing photographic paper. The solar process is the most economical way to produce a product meeting the specifications and the product has a high value. Under circumstances such as these, solar processing is justified, although there is no significant impact on energy use in the country.

3. METHODOLOGICAL APPROACHES TO R&D DECISION-MAKING

3.1 GENERAL CONSIDERATIONS

Many formal methods for evaluating R & D projects and comparable activities have been developed and proposed. While a detailed search of the literature reveals literally dozens of different approaches, (see Appendix - Selective Bibliography on Decision Techniques) all the methods can be generally classified into three basic categories. These are "economic analysis," "operations research," and "decision analysis." Each of these basic categories is discussed below. In examining the various approaches, however, a number of features were identified which could describe the items of input and output of the methods. These are offered as an introduction to specific discussion.

3.11 Utility Measure - Does the method take into account some measure of the utility or value of success of a project? This measure may be profitability or some other measure of worth, i.e. a figure of merit.

3.12 Probability of Success - Does the method explicitly take into account an estimate of the probability of success of each individual project?

3.13 Orthogonality of Criteria - Are the criteria used by the method mutually exclusive (orthogonal) rather than being highly correlated or having a high degree of overlap?

3.14 Sensitivity - Has the sensitivity of the output to small changes in input been checked. A high degree of sensitivity to small variations in input is undesirable since the output then becomes unstable in the presence of minor perturbations in the input.

3.15 Time - Does the method take into account scheduling requirements, or provide scheduling information as an output?

3.16 Strategies - Does the method permit the user to take into account several possible scenarios?

3.17 System Cross Support - Does the method give a project for advancement of technology credit for support which it may provide to other system developments?

3.18. Technology Cross Support - Does the method give a project for advancement of technology credit for support which it may provide to the advancement of other technologies?

3.19 Display - Is the output amenable to presentation in some graphic form which gives the user a condensed picture of the evaluation of various projects?

3.20 Flagging - Does the method flag problem areas to bring them to the attention of responsible management?

3.21 Bias - Is the method susceptible to applications of evaluator biases that are hidden in the process, but affect output conclusions?

These features are important characteristics of the various methods of project selection. So, too, is ease of use. What are the data requirements? Are the data available? And at what level must the data be obtained? Is manual operation of the method possible or is a computer program necessary?

3.2 ECONOMIC ANALYSIS

Economic analysis is based on a detailed forecast of the profitability of each project proposed in terms of the investment required and the expected revenue resulting from it. This approach is probably the most common technique in practical use at the present time. The method for indicating the profitability of a proposal normally makes use of discounted cash flow, attempting to maximize a benefit/cost ratio or difference. The figure of merit so obtained determines the capacity of the project to service debt and contribute to subsequent investment by the borrower, or to determine the return to the investor. The estimate thus obtained for the "present worth" of a project may be multiplied by a subjective estimate of the probability of success of the project, to represent the risk involved. The "economic analysis" approach thus assures that the profit objective is the only objective to be considered in evaluating project proposals. It is critically dependent on the ability to make a realistic estimate of the anticipated amount of investment required by the project and the revenue expected as a result.

This method has the advantages that it appears objective, conservative, provides a figure of merit, is well understood, and is widely used. It does not, except subjectively, account for various levels of risk between projects and makes no attempt to accommodate uncertainties or intangibles. It is extremely sensitive to interest rate predictions, certainly a questionable matter in the current environment. It is the preferred method of the U. S. Army Corps of Engineers wherein benefit values may be allocated to non-economic criteria such as environmental or recreational considerations. However, in general, the basic limitation of this approach is that it cannot adequately take into account factors which are difficult to forecast in economic terms, eg. the need to explore a new technology, technology cross-support, macroimpacts, etc. Such national interests are extremely important in the selection of solar thermal R&D projects.

3.3 OPERATIONS RESEARCH

The Operations Research approach is characterized by the use of linear or dynamic programming techniques to optimize the selection of projects. These techniques are used to maximize the total value of project proposals within the constraints of total budget and other resources available. The approach tends to be highly mathematically sophisticated and requires vast amounts of time as well as dependable data on projects, such as: costs, probabilities of success, discount rates, etc. Where possible, Operations Research satisfies many of the features enumerated in Section 3.1. For the purpose of exploring solar thermal R&D options however, it is far too demanding of undisputed data, and, even if the data were available, far too complex at this stage.

3.4 DECISION ANALYSIS

Decision Analysis is a body of formal techniques to aid a decision-maker in selecting a course of action in an uncertain environment. It is designed to help the individual make a choice from among a set of prespecified alternatives. Most importantly, it involves two distinctive features: an uncertainty analysis and a preference (value or utility) analysis.

Decisions may be characterised in two ways. First, is it a problem under certainty or uncertainty? When the consequences are certain, although the problem may be complex, there exists a range of mathematical programming techniques that can be employed. If it is under uncertainty, Decision Analysis assumes a well specified probability distribution over the possible consequences of any action.

Second, the decision may be a single or multi-attribute problem. In other words, the consequence of a decision can be described in terms of a single attribute (for instance, profit) or it may require several descriptions. In the latter case, the techniques of utility analysis are used to structure the necessary trade-offs.

The problem at hand is one of capital budgeting of limited R&D dollars to projects involving solar thermal fuels and chemical processes. The budgetor is a government body, and the objective is, ideally, to maximize society's utility. It is, to be sure, a multi-attribute problem that involves many non-quantifiable factors. Decision Analysis is more global than economic analysis or operations research in its consideration of such factors, and provides formal techniques for their assessment, thus, making some version most applicable to the problem at hand.

3.5 MULTI-ATTRIBUTE UTILITY (MAU) DECISION ANALYSIS

The general procedure of Decision Analysis involves five steps:

1. Pre-analysis - The problem is identified and viable action alternatives established.
2. Structural Analysis - The anatomy of the problem is structured into an orderly package via a decision tree. Decision modes (under the control of the decision-maker) and chance modes (not under full control) are determined.
3. Uncertainty Analysis - The decision-maker assigns probabilities to the branches emanating from the chance modes. The actual probabilities are developed using a variety of inputs. Actual data, modeling, expert testimony, and subjective judgments of the decision-maker.
4. Utility Analysis - At this stage utility values are assigned to consequences associated with the various paths through the decision tree. At this point there are two possibilities for resolving the trade-off issues. First, the decision-maker can informally weigh the trade-offs in his mind and assign utility values. Second, he may employ formal techniques of utility theory (utility functions, indifference curves, etc.) to reveal his value structure and use these to evaluate the contending alternatives.

5. Optimization Analysis - The decision-maker calculates his optimal strategy; i.e., the strategy that maximizes the expected utility. This strategy dictates what he should do at the start of the decision tree and what choices he should make at the various decision nodes along the way.

Among the advantages of the MAU method is that it provides a single figure of merit and leads to a clear choice among competing strategies. It offers a rational and quantifiable method for handling expert testimony, subjective judgments, and preferences. It is a prescriptive approach designed for normally intelligent people who want to think hard and systematically about a real problem. As such, it helps the decision-maker clarify in his own mind the course of action he should choose. This analysis recognizes that complex problems cannot be handled in purely objective ways and provides a formal, systematic method for handling subjective elements and attitudes. It allows for the use of multiple evaluation criteria and attempts to account for uncertainties in available information.

The disadvantages of MAU analysis are several. First, it is a new method and has not reached wide acceptance. Second, any attempt to reduce subjective judgments to formal analysis will, in and of itself, be subject to questions, especially in an area of intense budgetary competition. Third, and perhaps most important, this method is quite complex, requiring extensive analysis, repeated in depth interviewing, and, generally, complex computer code in the final analysis. Simple checks become quite difficult.

Although this method is not now well accepted and because it is complex and requires extensive interviewing and analysis, it is not directly applicable to the sun fuels problem. However, the method has important features which cannot be ignored and, a simpler scoring method, the Multi-Attribute Preference Scoring System (MAPS), is subac-

quently described. In this method, quantifiable attributes (e.g. cost/BTU, profitability, market potential) will be heavily weighted with respect to those that are qualitative (e.g. Nat/Social impacts). Attention will be given to describing all attributes as independent of one another as possible, reflecting the conceptual approach of MAU.

3.6 THE MULTI-ATTRIBUTE PREFERENCE SCORING SYSTEM

The Multi-Attribute Preference Scoring System (MAPS) provides analysts and decision-makers with a simple, yet powerful tool for analyzing complex capital budgeting problems. MAPS was developed by combining principles of Utility Theory with practical scoring procedures. The system is flexible and comprehensible, yet still captures the subtlety and complexity inherent in the real world decision making environment. MAPS is particularly valuable for capital budgeting decisions that must be based on relatively little hard data.

MAPS is premised on the identification of a discrete set of options available to the decision-maker. For the capital budgeting concept, these options correspond with specific investment opportunities that cannot be subdivided and that, for the most part, are mutually exclusive. Choosing among these options is based on the following general steps:

- o Establish Objectives - In this case, straightforward objectives have been provided by DOE.
- o Identify Attributes - These must be comprehensive, independent of one another, and phrased in a consistent fashion.
- o Weight Attributes - A judgmental exercise by professionals, using a simple "most important - important - least important" scheme.
- o Evaluate Options - Comparative evaluation process, scoring attributes of each process as "excellent, acceptable, or unacceptable."

- o Calculate Scores and Figures of Merit - Summation of option values for each attribute, weighted in accordance with attribute weights.
- o Perform Sensitivity Analyses - Exploration of changes in overall analysis, as a result of changes in weights and scores.

This process is depicted in Figure 3.61 on the following page. The feed-back loops indicated in the Figure relate to the sensitivity analysis and are extremely important elements of a MAPS analysis. The decision-maker should have a thorough understanding of what drives the results of the analysis in order to make reasoned judgments about handling uncertainty and subjective considerations.

A much fuller discussion of various considerations relating to MAPS is provided in the conceptual treatment of the approach, Appendix C to this report.

FIGURE 3.61

SCHEMATIC OF MAPS IN APPLICATION

3.7 | DECISION-MAKING RESPONSIBILITY

One particularly important feature of MAPS not referred to is that the elements comprising the ultimate decision matrix; i.e., data, judgment, importance, etc., are specifically identified and placed in distinct analytical subunits. To be more explicit, the technical elements of a decision, involving technical data and information, in depth knowledge of the specific decision options, etc., are carefully assigned to the evaluation/scoring position of the methodology. Evaluation of the options is clearly a function best performed by technical experts; it is also the only function in MAPS that can be performed solely on the basis of technical expertise.

The listing of attributes and the process used to assign weights on the basis of relative importance are more appropriately referred to as being on the managerial level. More specifically, attribute listing and weighting require value judgments about the context of a decision that are managerial in nature. What are the major considerations involved in this decision and how important are they? Such value judgments cannot be divorced from technical knowledge because they must establish a concept that is appropriate for the scoring/evaluation process. However, they are fundamentally managerial in nature and should be performed, if not by the decision-maker, then at least by the managers who must research the problem and implement the final decision.

In the application of MAPS, there is clearly a third layer of responsibility that can appropriately be called the policy level. The establishment of goals and objectives are clearly a policy level function. In addition, the analysis of categories of attributes and their relative importance is also at the policy level. These tasks are intimately connected with the very nature and outcome of the decision and thus should be the responsibility of the decision-maker. The initial determination of what the objectives are, and the ultimate tradeoffs, between categories of attributes in the final analysis are policy level tasks that transcend

both the technical and managerial elements of the decision; they are appropriately accomplished only through the first involvement of the decision-making strata of an agency or firm. Figure 3.71 depicts the very important correspondence between the layers of the MAPS methodology and the layers of the organization that must be efficiently incorporated into the decision-making process.

FIGURE 3.71

LEVELS OF RESPONSIBILITY IN MAPS

<u>INDIVIDUAL</u>	<u>LEVEL</u>	<u>EVENTS</u>	<u>FUNCTION</u>
Decision-Maker	Policy Level	Objectives, Categories	Tradeoffs Decisions
Program Manager	Managerial Level	Attributes	Listing & Weighting
Technical Experts	Technical Level	Options	Evaluation

4. THE MULTI-ATTRIBUTE PREFERENCE SCORING (MAPS) SYSTEM APPLIED TO SUN FUELS

Section 3 and Appendix C introduced the MAPS methodology in some detail. In this section it is conceptually applied to the general area of Sun Fuels and some examples are presented to demonstrate the application and to fine-tune the method.

4.1 CATEGORIES

Considering the complex nature of Sun Fuels R&D, the number of attributes must be quite large and very diverse to cover completely the considerations involved. Categories were established to allow for a simple specification and easier control of the attributes. These categories correspond with very dense and independent conceptual categories, and, therefore, will be quite easy to deal with. The six categories are:

- A. Process Demonstration Considerations
- B. Full-Scale Process Considerations
- C. Feedstock Considerations
- D. End-Product Market Considerations
- E. National/Social Considerations
- F. Economic Considerations

The above are largely self-explanatory. Process demonstration relates to the practical and immediate issues of conducting such an experiment with the technology at hand, while full-scale process refers to the potential costs, benefits, and problems of commercial-scale applications. End-product and feedstock considerations refer to the corresponding ends of the process to be selected for demonstration, i.e., the outputs and inputs, respectively. In particular, issues such as supply, logistics, and market structure are addressed in these two categories. Economics relates to the viability of a commercial-scale facility and

national/social considerations relate to issues of a general concern (e.g. environment) that are not specific to the process or its inputs and outputs.

4.2 DETAILS ON SPECIFIC ATTRIBUTES

A great deal of time was spent identifying, refining, and finalizing the list of attributes. Several iterations were run to weed out duplications, to expand the issues covered, and to provide phrasing for each attribute that was clear, concise, positive, and insured some measure of importance. The final result of the process is presented in Table 4-1. The categories and attributes have been identified by letter and number for identification purposes, not as an indication of any importance or ranking. The list is not perfect, and is clearly subject to interpretation in several areas due to the inability to express the concepts perfectly and due to the qualitative nature of some of these concepts. Each attribute is listed in sufficient detail to convey a fairly specific meaning, and to that extent, the list is self-explanatory. Some of the items do deserve additional explanation and such is provided below on a category by category basis.

However, prior to such discussion, Category F, Economic Considerations, deserves special comment because it is a key category for decision-making in the private sector. Optimally, some sort of economic feasibility assessment would be made for each candidate process on a standardized basis. In-so-far as the processes considered constitute R&D activities, key assumptions regarding capital costs, O&M, operational efficiency, etc., would be made. Unfortunately, the extreme variability in the stage of R&D yet achieved for each process creates a major problem for meaningful inclusion of economic criteria in our assessment.

Economic feasibility information is available for only four processes and cost projections for only three. Even for those candidates where projections are available, the figures remain only projections, based on

TABLE 4-1

LIST OF ATTRIBUTES FOR SUN FUELS

A. PROCESS DEMONSTRATION

1. Concept well known and demonstrated at bench scale
2. Demonstration is possible in sizable/ attractive module sizes
3. Demonstration unit provides data for further experiments
4. Demonstration is a reasonable technological step
5. Based on known component processes with which there is operating experience
6. Concept transferable to other sun fuels processes
7. Concept flexible to alternate solar thermal technology
8. Demonstration fits with future funding plans
9. Demonstration maximizes Federal expenditures on the solar portion
10. Demonstration expected to have high public appeal/political glamour

B. FULL SCALE PROCESS POTENTIAL

1. Commercial scale technically feasible
2. Readily available components
3. Low need for exotic materials
4. Effective use of variable isolation
5. Good opportunity for major retrofit or expansion of industry
6. Good probability of commercialization by private sector
7. By-product values
8. Export market potential for the technology

C. FEEDSTOCK

1. Relative abundance
2. Renewability
3. Location/transportability relative to isolation
4. Low cost relative to product value

D. END PRODUCT MARKET

1. Large market
2. Durable market
3. Good market infrastructure
4. Market proximity/transportability relative to isolation

E. NATIONAL/SOCIAL

1. Replaces or extends non-renewable resources
2. Improves national security
3. Positive environmental benefits
4. High value attributable to solar
5. Low demand for valuable land area

F. ECONOMICS

1. Capital cost is competitive with comparable non-solar processes
2. O&M costs are low
3. Long economic life cycle
4. Ultimate product(s) price competitive

differing assumptions. In short, at the present time, there is no meaningful way to factor in a very important category of information into a MAPS analysis of Sun Fuels because of severe data limitations. At such future point in time that this might change, however, economic considerations can easily be accommodated.

4.2.1 FEEDSTOCK

The attributes of the feedstock to be used in the solar processes are relative abundance (A-1), renewability (A-2), location and transportability (A-3), and cost relation to product value (A-4). A-1 and A-2 are fairly clear, while A-3 and A-4 are not. With respect to A-3, the location of the feedstock, relative to the possible processing sites in high insolation areas, is important only if the feedstock is costly to transport. Conversely, a feedstock that is easy and inexpensive to transport to high insolation areas need not be located in close proximity to those areas. Thus, location and transportability are a direct tradeoff and logically should be indicated in a single attribute. Attribute A-4 could more simply be referred to as "low cost," but it is clear that the importance of feedstock cost is in direct relationship to the cost relative to the value of the end product. A feedstock that is relatively non-costly could still be very expensive on a permanent basis, but the application would not necessarily be made any less attractive.

4.2.2 END-PRODUCT MARKET

The end-product market should be of sufficient size (B-1) and durability (B-2) (e.g. longevity) to warrant the investments in solar that full-scale development implies. The most attractive processes will be those that have a very large market (e.g. as an oil substitute) that is expected to be around for a long time. In addition, however, a successful commercialization process will be facilitated by a good market infrastructure (B-3) that can insure that the product can be transported, marketed, delivered,

and utilized efficiently. And finally, the markets should be sufficiently proximate to the high insolation areas where the product will be produced so that the costs of transporting the product are sufficiently lower (B-4). In other words, a direct tradeoff exists between the location of the market and the cost of transporting the product.

4.2.3 PROCESS DEMONSTRATION

The attributes in this category deal with the nature of the proposed process demonstration itself. Is the demonstration possible, is it risky, is it appropriate, etc.? These considerations are very important, and the category as a whole may be the most important, because the considerations represent the most immediate concerns; they must directly relate to the successful achievement of the stated objectives.

The attributes are fairly self-explanatory. Care should be taken to avoid confusing C-8 and C-9, however. The first refers to the applicability of the demonstration concept to other fuels/chemicals production technologies, and the second refers to the possibility of adapting the concept to other solar thermal technologies.

4.2.4 FULL-SCALE PROCESS POTENTIAL

The items in this category relate to the ultimate, long term viability of the concept being developed in the demonstration. In general, the concerns are: how likely is it that the technology will be commercialized; how successful such commercialization is likely to be; and how extensive and valuable the technology will be to the industries involved. Many of these concerns focus on the general requirements of the fuels and chemicals industries. For example, B-3 is listed because a good, commercial application of solar thermal fuels/chemicals production may fail if the economically optimum scale of the process is too small to be of interest to the large firms in the industry. In addition, B-8 is important because

another industry, with heavily depreciated plant, may be in a better position to make large investments than a more youthful industry.

D-5 and D-6 deserve special note. D-5 is related to the ability of the solar technology to use variable insolation and match it to the needs of the particular industry. A twenty-four hour a day processing operation may imply a need for tremendous thermal storage reserves, whereas a more intermittent batch production process could probably be matched quite well to the diurnal solar cycle. D-6, on the other hand, is important because if an otherwise attractive industrial activity is located only in low insolation areas, then the only way the solar technology would be attractive is if a totally new industry were to develop or the old industry were to relocate, an almost impossible feat.

4.2.5 NATIONAL/SOCIAL

In addition to the specific concerns and issues itemized in the other categories, there are several important attributes of a more general nature. Attribute E-1 refers to the fact that the technology of the end product should displace or extend non-renewable resources; the more non-renewable resources are saved/replaced, the more valuable is the technological development. Attribute E-2, national security, is important because the solar technology can lessen national strategic vulnerability and improve self-sufficiency. Conversely, it could worsen security by creating potential industrial bottlenecks, as might occur if a catalyst of strategic value were consumed in the production process. Positive environmental benefits (E-3) are also a plus for many solar applications as are positive macro-economic effects (E-5). Attribute E-4 refers to the relative value of the solar portion of the production process. The higher the value added

by solar, the greater the ultimate "payback" to the nation will be for investments in the technology. And finally, attribute E-6 is of concern because of demands for land that are likely to be spurred by larger scale solar developments. The degree to which the demand is for land of otherwise low value, the more attractive these developments will be.

4.2.6 ECONOMIC CONSIDERATIONS

The elements of Category F are all "bottom-line" issues which must be based on relatively hard data. Attribute F-1 indicates whether plant capital cost is in the same general ballpark as for processes which do not use solar thermal energy. Presumably, the solar thermal component generally increases capital costs, such that Attributes F-2, F-3, and F-4 indicate the process is commercially competitive. Although feedstock issues are separately treated in Category A, they bear directly on O&M costs. Significant expense is often incurred in the handling and storage of conventional fuels. The question is whether cost savings for conventional fuels and chemical processes are offset by O&M for the sun fuel process. If the economic life cycle, Attribute F-3, is sufficiently long, this may bear positively on corporate pricing policy for the ultimate end-product, Attribute F-4. The last attribute, of course, is the single most important determinate to any private investor. Can a sun fuel compete in the marketplace? Unless regulated otherwise by government, or other non-market criteria, this is the key to all potentially attractive processes.

4.3 ATTRIBUTE WEIGHTING

The attribute weighting process is in large part the application of value judgments as to the importance of one attribute over another. Weighting is done on a comparative basis within each category. In Section III and Appendix C, the issue of the numerical range for weighting is discussed. In order to specify an appropriate range, a preliminary trial using different ranges for a set of ten attributes in the process demonstration

category was held. Two engineers (#1 & 3 below) and two policy analysts (#2 & 4 below) rated the exercise. In addition to defining the range for weighting, it was hoped that some insight as to what problems we might encounter in the weighting process would be gained, as well as an opportunity to examine how consistent the weightings were likely to be among the various individuals. Ultimately, the establishment of weightings should be the result of a consensus process involving DOE and program participants which is designed to establish the relative importance of each attribute.

The initial weighting was done on a scale of 1 to 10, and it was quickly determined that the full order of magnitude range was unnecessary and overly discriminating. On the other hand, a 1 to 3 range was felt to be too restrictive. A 1 to 5 range was then used with the following results:

<u>Process Demonstration</u>	<u>Individual Professional Assessment</u>			
<u>ATTRIBUTE</u>	<u>#1</u>	<u>#2</u>	<u>#3</u>	<u>#4</u>
C1	3	3	5	5
C2	4	3	4	3
C3	2	4	3	1
C4	2	2	3	1
C5	4	4	5	5
C6	4	3	5	3
C7	3	3	5	3
C8	2	4	5	3
C9	2	2	3	2
C10	2	2	3	1

Note that #4 was the only individual using the full range and every numerical value. No. 4 also indicated that he had designed his weights to use the full range and that a smaller range would be preferable. In addition, the variations in weight between individuals in the example, are at best partly due to individuals using different parts of the range and not due to different perceptions of relative importance.

The exercise was run again for all twelve process demonstration attributes, using a range of 1 to 4, with the following results.

<u>Process Demonstration</u>	<u>Individual Professional Assessment</u>			
<u>ATTRIBUTE</u>	<u>#1</u>	<u>#2</u>	<u>#3</u>	<u>#4</u>
C1	3	3	4	4
C2	3	3	3	2
C3	3	4	3	3
C4	2	2	3	2
C5	4	2	3	4
C6	4	3	4	3
C7	3	3	4	3
C8	3	3	4	4
C9	1	2	2	2
C10	2	1	2	1
C11	2	1	2	1
C12	2	2	2	1

Note that only one individual (#3) did not use the full range and every numerical value. In addition, note that with the exception of Attribute C-5, the variance in weights between individuals is at most one. Attribute C-5 is "based on known component processes with which there is good operating experience," and discussion revealed that the difference was again a function of whether an individual tended to the high or the low of the range and was partly due to the individual's perceptions as to just how independent the attribute was, e.g. were the concerns involved partly incorporated in another attribute?

4.4 SCORING

The scoring process is a technical evaluation process in which each attribute is rated. As such, evaluation is properly the function of the technical specialist who knows and understands the technical details of the

options and is capable of assigning values of the basis of measurement, hard data, or judgment. Evaluation is accomplished by assigning a value to each option relative to each attribute that corresponds with the extent to which the option has that attribute. The values range from "0" to "1.0." A zero value indicates the option does not in any way satisfy the concern expressed by the attribute. A one value indicates that the concern is fully satisfied and the option is "perfect" with respect to that attribute.

Three values, 0, 0.5, and 1 are used for evaluation, corresponding in general to the concepts of "attribute not satisfied", "attribute partly satisfied", and "attribute completely satisfied." This practice will simplify the analysis, but is also consistent with the fact that many of the attributes are qualitative in nature, and thus cannot be assigned values with respect to an option that are any more discrete than the simple "no, partly, yes" system.

Once a simple weight has been determined for each process attribute, a decision must be made as to whether all of the attributes in any one category are of equal importance, or whether the attributes themselves should be weighted. Weighting of attributes allows a greater degree of distinction to be made by a technical evaluator, as opposed to distinctions among categories which reflect policy concerns more directly. In the Section 6 Matrix Assessment of Candidate Processes, top processes are scored in two ways: one where all attributes in all categories are considered to have equal value and the other in which our judgment as to the relative importance of each attribute, vis-a-vis one another (in their respective categories) is provided.

Before proceeding to the category ranking process, the raw scores, whether they reflect differently, weighted attributes or not, must be put on a common basis, so that there is consistency between categories. This is accomplished simply by dividing the scores by the number of attributes in that category. This operation does not affect the relative positions of the

options, but establishes a common base among categories. The end result is a score for each option that corresponds to the "average value per attribute" for each category.

4.5 CATEGORY RANKING

The results of the scoring process are a set of discrete scores for each candidate process that corresponds to the different categories. To determine which options are the most attractive in an overall sense, some means of assessing the relative importance of the categories can also be developed. Ultimately, the categories themselves can be weighted, and the scores summed to yield overall figures of merit for each option. However, analysis should begin with the examination of the category scores in the context of priority ranking of categories. In this sub-section, we will demonstrate by example how category ranking and analysis can be handled and what the results might be. Note that this analysis corresponds to policy level determinations, and is, therefore, legitimately in the realm of the decision-maker.

As an initial exploration, a preliminary set of values was assigned to the Princeton (P), Westinghouse (W), and PFR candidate processes and scores were calculated under the assumption that all attribute weights were equal. These values were summed and the scores then divided by the number of attributes in each category. The resulting adjusted scores are as follows:

<u>CATEGORY</u>	<u>P</u>	<u>W</u>	<u>PFR</u>
A	.67	.83	.67
B	.75	1.00	.38
C	.50	.88	1.00
D	.35	.45	.90
E	.38	.67	1.00

Initially, we can assume that all the categories are of equal importance. The scores above can then simply be summed yielding: P - 2.65, W - 3.83, and PFR - 3.95. Alternatively, one category may have much greater importance than all of the others. One could argue, in fact, that the Process Demonstration category in this example is the only one that has any real importance. On that basis, then, the PFR option would clearly be the most valuable. As a second alternative, one could put the categories in rank order and visually inspect the scores to see whether one of the options clearly stood out. The categories are listed above in the rank order of importance as determined in our discussions. A third alternative would be to look at the rank order and determine "how much more importance" each category has over the one below it. Thus, a set of numbers for category importance will be generated that can be used as weights in the calculation of overall figures of merit. The Table below shows the results of our examples in the form of weights for the different categories.

<u>CATEGORY</u>	<u>OPTION 1</u>	<u>OPTION 2</u>
A	1	5
B	1	4
C	1	3
D	1	3
E	1	1

When applied to the sample scores previously developed, the results are as follows:

<u>FIGURES OF MERIT</u>	<u>P</u>	<u>W</u>	<u>PFR</u>
Option 1: Equal Categories	2.7	3.8	4.0
Option 2: Weighted Categories	9.28	12.81	11.57

Thus, it can be seen that differences in category ranking can result in differences in the ultimate Figures of Merit calculated for each candidate

process. As with individual attribute weights, the Section 6 Matrix Assessment will also consider two options: equal category weights and differential category weights.

Overall, four basic assessed options for the processes exist:

1. Non-weighted attributes, non-weighted categories
2. Weighted attributes, non-weighted categories
3. Non-weighted attributes, weighted categories
4. Weighted attributes, weighted categories

It is this last option, of course, which offers the greatest degree of analytical distinction among the candidate processes.

5. EVALUATION CHARACTERISTICS OF CANDIDATE PROCESSES

In this Section, a summary of important characteristics of each process on which evaluation is based in the Matrix Assessment of Section 6 and Appendix D are provided. As has already been indicated, since the concept of producing fuels and chemicals using solar energy is relatively new, the processes are in various stages of development, ranging from those at a conceptual level to others having considerable experimental work to their credit. In addition, information on these processes is often hard to find, particularly in open literature. This makes the task of determining salient features of the processes very difficult. While every effort has been made to state the evaluation characteristics in an objective fashion, the difficult nature of such selective summary should be kept in mind when reading this Section.

5.1 SYNTHESIS GAS

5.11 SOLAR COAL GASIFICATION, Lawrence Livermore Laboratory

1. This process produces a transportation fuel SNG from non-renewable feedstock coal. It replaces non-renewable fuel coal in the production of chemicals. It extends the non-renewable fuel resource, and upgrades energy content.

2. Existing hardware can be used in part; however, operating experience of the quartz window is not available. To a large degree, it is based upon a known process. It is adaptable to solar heat sources. Modest temperatures of 1600°F are required. The materials problem has to be resolved. Many uncertainties have to be resolved before it can be scaled up using STTF work done to date.

3. There is a significant demand for SNG in the United States. Solar energy is available at locations where feedstock is available. It fits well into user's existing system. There is an abundant supply of feedstock.

Many problems connected with the material of the window, short-term transients, long-term transients, etc., have to be resolved before the process can be adapted to industrial production practices. It is not likely that this process will be picked up by private sector for commercialization.

4. Long-term economics relative to coal are favorable.

5. Feedstock is available in high insolation regions of U.S. Cost of transporting feedstock to high insolation regions of U.S. is not high. Existing pipe lines can be used to transport SNG produced.

6. It has been tested in STTF. It will probably be favorably perceived by the public. It reduces environmental pollution.

7. The solar coal gasification proposed is intermittent. It is subjected to cloud cover and diurnal effects. The temperature required is about 1500°F. The process plant size suggested will require 500 - MW_t solar energy. The process efficiency is the same as the conventional coal gasification plant. The reaction rates and residence time are comparable to the conventional plants. Materials problem has to be resolved. High solar flux available if used advantageously.

8. Technology developed for this experiment cannot be used for later experiments. Receiver/reactor contains a window.

5.12 TWO-STAGE, FLUIDIZED-BED SOLAR HYBRID COAL GASIFICATION SYSTEM,

University of New Hampshire

1. The process leads to a transportation fuel from non-renewable feedstocks and replaces non-renewable fuels in the production of synthesis gas. It extends the non-renewable fuels resource.

2. Existing hardware can be used in whole. This is a proven process. Operating experience is available except for the solar receiver. This is based upon known process to a large degree. The process is adaptable to solar heat source. Temperature required is 1950^oF. There are no materials problems. Experiments in the tower are yet to be conducted.

3. There is a significant demand for the product -- synthesis gas. Solar energy is available near the feedstock resource. Adequate feedstock resource is available. There is a probability of this process being adopted by the user.

This process is adaptable to industrial production practices and economics. Feedstock is abundantly available. There is good export market potential. Profitability versus size consideration has been assessed. It is estimated to be cost effective by 1995.

4. Long-term and near-term economics relative to coal are favorable. There is an economic potential relative to other alternate energy options.

5. Feedstock is available in high insolation regions of the U.S. Cost of transporting feedstock to high insolation regions of the U.S. has been estimated. The product gas can be transported via the existing pipeline to places beyond the area of high insolation. The cost also has been estimated.

6. The process can be tested in a significant module size. It will probably have a favorable impact on the public. This process leads to lower environmental impacts of the mining process. Atmospheric pollution is also abated since coal burning to drive reactions is eliminated.

7. This process is unique in that it operates for twenty-four hours a day. Temperature required for the process is 1750°F and for the recirculating gas is 1950°F. Solar system module size versus process plant size is reasonable. Process efficiency is comparable to that of the conventional processes. Reaction rates and residence time are comparable. Product gas is storable and transportable. Existing materials can be used. Solar flux requirements are normal. The process design is such that it can take care of transient and cyclic effects. The process maximizes fixed expenditures in solar research vis-a-vis non solar.

8. Technology developed for this experiment can potentially be used for later experiments. The process used a receiver/reactor consisting of opaque tubes or vessels. The product gas is readily usable in existing equipment.

5.13 LASER SIMULATION OF SOLAR COAL GASIFICATION, Los Alamos Scientific Laboratory

1. The process produces and leads to a transportation fuel from non-renewable feedstocks coal. It replaces and extends non-renewable fuel resource.

2. Existing hardware cannot be used. Operating experience is not available. It is based upon known process to a large extent and is adaptable to solar heat source. Modest temperature of 1700°F is needed, since the energy has to be absorbed directly by coal through a window. There are materials problems. The process has not been tested in a solar tower.

3. There may be a demand for this fuel gas in the U.S. The process will operate only during sunlit hours. There is adequate feedstock resource. The by-products are valuable.

4. Data on long-term and near-term economic potential relative to other alternate energy options are not available.

5. Feedstock is available in high insolation regions of the U.S. Cost of transporting feedstock to high insolation regions of the U.S. is reasonable. The product gas after conversion to methane can be transported at a reasonable cost to places beyond the area of high insolation.

6. Impact on the public may be favorable.

7. The process operates only during sunlit hours. Temperature is 1700°F. Solar system module size versus process plant size is not available. The data on process efficiency, reaction rates and residence time are not available. Product is storable, suitable material for the window or wall has to be obtained. There is enough solar flux. Transients and cyclic effects are not overcome.

8. Technology developed for this process can possibly be used for later experiments. The process uses a receiver containing a window.

5.14 BIOMASS FLASH PYROLYSIS, Princeton University

1. This process leads to a transportation fuel from renewable feedstocks such as wood, peat, and other biomass. It replaces non-renewable fuels in production of chemicals and extends non-renewable fuel resource. The process upgrades energy content and is more efficient.

2. Existing hardware can be used only in part. It is based on a new process and operating experience is not available. Though it can be adapted to solar heat source, materials problems have to be resolved. Some technological steps from STTF work have been done to date.

3. It is unclear as to what the demand for the product will be, as the syrup is an unknown material. It would appear that there is market potential for the syrup's constituent elements. The process can be operated only during sunlit hours. It will not fit into users existing system. Since there are alternate uses for the feedstock, it is possible that there will not be adequate feedstock resource. There is no immediate probability of being adapted by the user.

It is not likely that this process will be picked up by the private sector for commercialization.

4. Economic analysis is not available. Proposal for decentralized production and central refining needs critical study.

5. Feedstock is generally not available in high insolation regions of U.S. and cost of transporting feedstock to such regions will be prohibitive. The cost of transport of product beyond the area of high insolation will be acceptable. Existing modes of transport can be used.

6. It cannot be tested in a significant module size. It will probably have a favorable impact on the public. It will be environmentally acceptable.

7. It can be operated only during sunlit hours, and plant will remain idle for much of the day. Temperature required is about 1000°F. The process efficiency reaction rates and residence time are favorable. Solar flux levels of 1000 W/CM² are used to advantage. Material problems have to be resolved.

8. Technology developed for this experiment may not be used for later experiments. Receiver containing a window has been used for biomass flash pyrolysis.

5.15 CONTINUOUS FLASH PYROLYSIS OF BIOMASS IN A CYCLONE REACTOR, Jacques Lede, C.N.R.S., Odeillo, France

1. This process produces a transportable fuel CO and H₂ from renewable feedstock: sawdust. It replaces non-renewable fuels in the production of chemicals. It extends non-renewable fuel resource and is claimed as an efficient process.

2. Existing hardware can be used in part. This is a new process and operating experience is not available. However, it is based upon known process to a large degree. It is adaptable to solar heat source. The temperature required is 1950⁰F and hence there are material problems. No STTF work has been done to date.

3. There is a significant demand for the product gas; synthesis gas in the U. S. Adequate feedstock is available. It is not known that the process can be operated for 24 hours per day. It may fit into user's existing system. It is necessary to make further studies regarding profitability - versus - size considerations.

4. Economic viability studies of this process are not available. Hence, long-term and near-term economics, and economic potential relative to other alternate energy options are not known.

5. Feedstock is available in high insolation regions of the U. S. The product synthesis gas can be upgraded to SNG and transported to regions beyond area of high insolation at comparative cost.

6. The process can be tested in a significant module size. It may have favorable impact on general public. It is environmentally acceptable.

7. The process as envisaged now is intermittent. The temperature required is 1950°F. The process efficiency claimed is high. High reaction rates and very low residence time are reported. Solar flux requirement is high. Transient and cyclic effects are to be studied. There are material problems.

8. The technology developed for this experiment can potentially be used for later experiments. Receiver/reactor containing a window or direct insolation is recommended.

5.2 HYDROGEN

5.21 SOLAR THERMAL HYDROGEN PRODUCTION PROCESS, Westinghouse Electric Corporation.

1. This process produces a transportation fuel from renewable feedstock H_2O . It replaces non-renewable fuels in production of chemicals.

2. Existing hardware can be used only in part. Since this is a new process, operating experience is not available. It can be adapted to solar heat source. Temperature required is about $1600^{\circ}F$. The materials problem has to be resolved. Technology step from STTF work has not been done.

3. There is a significant demand for the product for chemical manufacture. Hybrid units will operate for 24 hours per day. It will fit into users existing system. There is adequate feedstock resource.

Its economics has to be studied critically. The materials making up the system are new in the industrial use and will be costly. The probability of being picked up by the private sector for commercialization is not high.

4. Further study is required to assess its economic viability.

5. Feedstock is available in the high insolation regions of the U. S. The product H_2 can be easily transported in the existing gas pipe lines at the same cost as natural gas.

6. It can be tested in a significant module size. It will have favorable impact on the public. It is environmentally accepted.

7. Hybrid units can operate continuously. The temperature required is about 1600°F . Solar system size of 350 - 400 MW_t is suggested for a plant size of 10 - 30 million SCFC, chemical energy storage is required. Materials problem has to be resolved.

8. Technology developed for this experiment can potentially be used for later experiments for chemical storage by solar energy. The receiver consisting of opaque tubes is suggested for the water splitting by sulfur cycle with catalysts.

5.22 HYDROGEN PRODUCTION BY SULFUR - IODINE THERMOCHEMICAL WATER SPLITTING,
General Atomic Company.

1. This process produces a transportation fuel, H_2 , from renewable feedstocks H_2O , recycled H_2SO_4 and I_2 . It replaces non-renewable fuels in the production of chemicals.

2. This process is adaptable to solar heat source and requires only modest temperatures ($1600^{\circ}F$). It is not based on known processes; operating experience is not available and existing hardware cannot be used. Materials problems have to be resolved.

3. There is a significant demand for fuel or chemicals in the United States. It can be operated twenty-four hours per day. It will fit easily into user's existing system. It has adequate feedstock resource.

4. Though the process is technically viable, it has no early possibilities for economic viability. Economic analysis is not available.

5. The feedstock is abundantly available in high insolation regions of the United States. There is no cost of transportation of feedstock. The cost of transport of product H_2 beyond area of high insolation is comparable to the transport of natural gas. No product can be transported through existing pipe lines.

6. It will probably have a favorable impact on the public. The process will probably be environmentally acceptable.

7. This process can be adapted to solar energy source. The temperature required is $1600^{\circ}F$. The plant size will match with the solar system module size. The process efficiency, reaction roles, residence time are favorable. Storage of immediate products, solar energy, etc., is possible.

The materials of construction have to be resolved in view of the corrosive nature of the sulfuric acid and SO_2 vapors.

8. The technology developed for this process can be used for other experiments such as storage of solar energy by $\text{SO}_3 - \text{SO}_2$ reaction. The reactors consist of opaque tubes fitted in a cavity receiver.

5.23 HIGH TEMPERATURE THERMOCHEMICAL CYCLES FOR SOLAR HEAT SOURCES, Los Alamos Scientific Laboratory.

1. This process produces a transportation fuel from renewable feedstock H_2O . It replaces non-renewable fuels in the production of chemicals.

2. Existing hardware can be used only in part. Since this is a new process, operating experience is not available. It can be adapted to solar heat source. Temperature required is about $2780^{\circ}F$. The materials problem has to be resolved. Technology step from STTF work has not been done.

3. There is a significant demand for the product for chemical manufacture. It is not known whether the cycles indicated here will operate as hybrid units. It will fit into users existing system. There is adequate feedstock resource. Enough experimental work has not been done to establish the successful working of these cycles. The materials making up the system are new in industrial use and may be expensive. It is premature to discuss the probability of the process being picked up by private sector.

4. Its economics relative to coal, oil, or gas have not been studied.

5. Feedstock is available in the high insolation regions of the U. S. The product H_2 can be easily transported in the existing gas pipelines at the same cost as natural gas.

6. It can be tested in a significant module size. It will have favorable impact on the public. It is environmentally accepted.

7. The temperature required is high $2780^{\circ}F$. Solar system requirement and plant size have not been indicated. Materials problem has to be resolved.

8. Technology developed for this experiment can potentially be used for later experiments for chemical storage of solar energy. The solar receiver required and other details are not indicated.

5.24 HIGH TEMPERATURE SOLAR THERMOCHEMICAL HYDROGEN PROCESS, Institute of Gas Technology.

1. This process produces a transporation fuel from renewable feedstock H_2O . It replaces non-renewable fuels in the production of chemicals.

2. Existing hardware can be used only in part. Since this is a new process, operating experience is not available. It can be adapted to solar heat source. Temperature required is about $2200^{\circ}F$. The materials problem has to be resolved. This process is a reasonable technology step from STTF work done.

3. There is a significant demand for the product for chemical manufacture. It is planned to operate as a hybrid unit. it will fit into users existing system. There is adequate feedstock resource. It is premature to discuss the probability of being picked up by private sector for commercialization.

4. Data on economics relative to coal, oil, or gas in the long run are not available and have to be studied, but appear favorable.

5. Feedstock is available in the high insolation regions of the U. S. The product H_2 can be easily transported in the existing gas pipe lines at the same cost as natural gas.

6. It can be tested in a significant module size. It will have favorable impact on the public. It is environmentally accepted.

7. The temperature required is high - $2200^{\circ}F$. Plant size has not been indicated. Materials problem has to be resolved.

8. Technology developed for this experiment can potentially be used for later experiments for chemical storage of solar energy. A solar receiver containing a ceramic window has been used.

5.3 OTHER PROCESSES/PRODUCTS

5.3.1 WET OXIDATION OF PEAT/LIGRITE, Jet Propulsion Laboratory.

1. This process produces a transportation fuel, hydrocarbon gases, and chemicals intermediates from non-renewable feedstocks, including: peat, lignite, and sub-bituminous coal. It extends non-renewable fuels resource.

2. The existing hardware can be used in part. This is a new process and operating experience is not available. It can be adapted to solar heat source, but the process is intermittent. The temperature required is about 950°F.

3. There is a significant demand for the product, hydrocarbons and chemical intermediates. Solar energy is not available at the vicinity of major peat deposits. In the case of lignites and sub-bituminous coal available in Texas, New Mexico, and Colorado, the daily direct solar insolation is 5.0 to 6.5 KWH/M². There is adequate feedstock. The probability of being adopted by the user is high.

Though it is adaptable to industrial production practices, the cost effectiveness has still to be established. The investment required is not known to a degree of accuracy.

4. Economic viability has to be studied; economic analysis has not been conducted.

5. Feedstock is available in high insolation regions of the U. S. The cost of transport of the product beyond areas of high insolation is reasonable. Existing gas pipe lines can be used.

6. It can be tested in a significant module size. It will probably have favorable impact on the public. It will be environmentally accepted.

7. It can be adapted for continuous operation. The temperature required is about 950°F. Solar system module size versus process plant size has to be worked out. The process efficiency, reaction rates and residence time, etc. have to be evaluated. Storage requirements are necessary. Available solar flux can be used advantageously. Conventional materials can be used.

8. Either a receiver consisting of opaque tubes or a receiver containing a window can be used.

5.32 SOLAR RETORTING OF OIL SHALE, Lawrence Livermore Laboratory.

1. This process produces a transportation fuel, heavy oil from non-renewable feedstocks of oil-shale. It extends non-renewable fuels resource and it is more efficient than the conventional oil-shale retorting process.

2. The existing hardware can be used only in part. The operating experience is not available; this is a new process. It can be adapted to solar heat source, but the process is intermittent. The temperature required is about 1050°F. The materials problems have to be resolved.

3. There is a significant demand for the product - heavy oil. Solar energy is available at the vicinity of the oil-shale deposits in the Piceance Basin in Colorado where the daily direct solar insolation is 6.0 KWH/M². There is adequate feedstock resource. The cost effectiveness has still to be established. The investment required is not known to a great degree of accuracy. There is no export market potential. There is no immediate probability of being picked up by private sector for commercialization.

4. Economic viability has not been conducted.

5. The feedstock is available in Colorado, a high insolation area. The distance the oil shale has to be transported is minimum. Since the product is heavy oil, it can be transported with the help of existing facilities for petroleum products.

6. It can be tested in a significant module size. The process has negative environmental impacts and is likely not to be well received by the public.

7. The solar retorting of oil-shale is intermittent. The temperature required is about 1050° . The solar system module size vs. process plant size has to be studied. There is reasonable process efficiency. Storage requirements are not available. The window material has to be tested for long use. The solar flux is suitable and advantageous.

8. The technology developed for this process cannot potentially be used for other experiments. The reactor contains a window and solar heat is focused through it.

5.33 CALCIUM CARBIDE PRODUCTION IN A SOLAR FURNACE, Institute of Gas Technology.

1. This process leads to a transportable product from non-renewable feedstocks lime and coke and replaces non-renewable fuels in production of chemicals. It extends non-renewable fuel resource.

2. Existing hardware can be used in part. It is based upon known processes to a large degree, but its operating experience is minimum. It is adaptable to a solar heat source, but the temperature required is above 2000°C . Further work is required to establish the technological feasibility.

3. There will be a demand for this chemical only when the natural gas and petroleum resources become scarce. During the past two decades, however, ethylene has won the petrochemical market away from acetylene. Ethylene can be made at lower temperature ($800-1000^{\circ}\text{C}$) from hydrocarbons and is cheaper than acetylene. It does not fit well into user's existing system. There is adequate feedstock resource. At present there is no probability of being adopted by user. Recovery of by-product CO is being studied.

The feedstock is available and projected cost is competitive. Export market potential is not known. At the present there is no probability of being picked up by the private sector. There is no data available regarding profitability vs. size.

4. Long-term economics have to be studied. The near-term economics, relative to oil and gas, are unfavorable.

5. Feedstock is not available in high insolation regions of U. S. The cost of transporting feedstock to high insolation regions of the U. S. may be considerable. The product can be transported to areas beyond the

area of high insolation. The cost of transport of the product will be comparable with that of similar materials.

6. It can be tested in a significant module size. It will probably not have a favorable impact on the public. The process produces a by-product CO and leakage of CO in the open hearth will affect the environment.

7. It is adaptable to batch process. The temperature required is 2000°C - high solar system module size versus process plant size has to be studied. Process efficiency attained now is 40%. Residence time obtained now is 20 seconds. Short residence time and high heat flux favor carbide formation. The product (solid) can be easily moved. Material requirements are not exotic. Solar flux required is high. Transients and cyclic effects will increase the cost as they reduce the production rate.

8. Direct insolation reactor is used for this process.

5.34 FURFURAL FROM BIOMASS, Quaker Oats Company/Jet Propulsion Laboratories

1. This process produces a chemical from renewable feedstocks, biomass. It replaces non-renewable fuels in the production of chemicals. It extends non-renewable fuels resource.

2. Existing hardware can be used in part. Operating experience is available for the non-solar portion of the process. It is based on known processes to a large degree. It is adaptable to solar heat source. Minimum materials problems are anticipated. It is a reasonable technology step from STTF work done to date.

3. There is a significant demand for furfural in U. S. It fits well into user's existing system. The feedstock is available in abundance and the cost is only nominal. There will be export market for product if the price is competitive.

4. Far term economics and near term economics have to be studied.

5. Feedstock is available in high insolation regions of U. S. Cost of transporting feedstock to high insolation regions of U. S. will be considerable. The product can be transported just like other liquid fuels.

6. It can be tested in a significant module size. Its impact on the general public will probably be minimal. It is environmentally acceptable.

7. The process is intermittent. Product is storable. Material requirements are not exotic. Ordinary solar flux is sufficient. Transient and cyclic effects are not taken care of. It does not maximize fixed expenditures.

8. Receiver consisting of opaque tubes are used to produce steam required for the process.

5.35 DECARBONATION OF Ca CO₃, Gilles Flamant, Odeillo Fort Romeu, France.

1. This process produces a transportable bulk chemical and replaces non-renewable fuels in its production. It also extends non-renewable fuels resource.

2. Existing hardware can be used in part. Operating experience is available for the non-solar process. It is based upon known process to a large degree. It is adaptable to solar heat source. Temperature required is 1650^oF. Materials problems can be overcome.

3. There is a significant demand for this chemical in the U. S. There is adequate feedstock resource. There are no by-product values.

Raw material is cheap and available in plenty. There will be an export market for the process, but not for the product. It is premature to decide whether it will be picked up by private sector for commercialization.

4. Long term and near term economics relative to coal, oil, and gas are not known.

5. Feedstock is available in areas of high insolation. Transport of the raw material will be costly relative to its cost. Product value is low. Therefore, the cost of transport of the product will be relatively high.

6. It can be tested in significant module size. It may not have favorable impact on the public. It is environmentally acceptable.

7. The process is operated only during sunlit hours. Temperature required is 1650°F. Solar system vs. process plant size have not been worked out. Thermal efficiency reported is 40%. The product is storable. Material requirements can be met. The process is operable only during the day and will be affected by transients.

8. The technology developed for this experiment can potentially be used for later experiments. Receiver reactor consisting of opaque tubes are suggested.

5.36 SOLAR CENTRAL RECEIVER REFORMER SYSTEM FOR AMMONIA PLANTS,

PFR Engineering Systems, Inc.

1. The process produces a transportation fuel hydrogen from non-renewable feedstock natural gas. It replaces non-renewable fuels in production of the chemical ammonia. It extends non-renewable fuels resource.

2. Existing hardware can be used in whole. Operating experience is available. The process is based upon a known process to a large extent. It can be adapted to solar heat source. Reaction temperature is about 1450°F. Pressure is 24 atmosphere. Materials problems are minimal. No STTF work has been done to date.

3. There is a significant demand for H₂ and also for ammonia in U. S. Solar energy is available in the proposed site for retrofit. Twenty-four hours per day operation is possible. It fits well into user's existing system. In the long run there will not be adequate feedstock resource. It is not probable that this process will be adopted by the user in preference to other processes in the future.

It is adaptable to industrial production practices. Its economics is favorable now, but in ten years time it will not be economical because of the high price for natural gas. It is probable that feedstock natural gas may not be used at all. There is export market potential to a few countries having natural gas resources such as Mexico and Venezuela. It is not probable that the private sector will pick up the process for commercialization.

4. Long-term economics relative to coal is unfavorable to this process. Near-term economics relative to oil is competitive.

5. Feedstock is available in high insolation region of U. S., El Centro, California, with solar insolation ranging from 6.5 to 10.1 KWH/M². The cost of transport of feedstock to El Centro is small. The product is consumed for the production of ammonia and other fertilizers which are transported easily and cheaply to areas beyond the site of production.

6. It can be tested in a significant module size. It will probably have favorable impact on the public. It is environmentally acceptable.

7. The retrofit process is a hybrid and intermittent energy is available. Temperature required is about 1450°F. The solar system module size 150 MW_t versus process plant size is favorable. The process efficiency, reaction rates, and residence time are available for the conventional process and they have to be evaluated for the solar aided process. No storage requirement is necessary. Conventional materials can be used. Sufficient solar flux is available. Effects of short-term temperature transients (passive clouds) and long-term temperature transients (diurnal cycle) on reaction have to be evaluated.

8. The technology developed in this experiment can potentially be used for other experiments involving catalytic reactions in the gaseous phase. Receiver/reactor consisting of opaque tubes is used. Receiver cycle life is not known. Effects of diurnal cycle on solar receiver reactor, i.e., thermal stress, carbon deposition have to be evaluated. Matching of solar reactor to continuous process steps has to be studied.

5.37 SOLCHEM CONCEPT: CO₂-CH₄ REFORMING-METHANATION CYCLE,
Naval Research Laboratory.

1. This process produces an energy rich gaseous mixture which can be transported and reconverted to high temperature (500 - 600°C) heat. It extends non-renewable fuel resource. It is comparatively an efficient process.

2. The existing hardware can be used. This is a new process and operating experience is not available. It can be adapted to solar heat source. The process includes storage tanks. The temperature required is about (900°C) 1650°F.

3. The process can be carried out only in areas where solar energy is available. It includes storage tanks and energy will be available for 24 hours a day. It will fit well into users existing system. The cost-effectiveness has still to be established.

4. The long term and near term economics of the process have not been studied.

5. The process by itself has to be conducted in areas of high insolation. It can be used to provide high temperature heat for the production of electricity or chemicals.

6. It has not been tested in a solar facility. It can be tested in a significant module size. It will have favorable impact on members of Congress and general public. It is environmentally acceptable.

7. Transient effects and intermittent energy availability are overcome by storage of solar energy in a chemical form. Temperature required

is about 1650°F . Solar system module size versus process plant size given is 25 KW_e . The process efficiency, reaction rates, and residence time, etc., have to be evaluated.

8. The technology developed for this experiment can potentially be used for later experiments. Receivers consisting of opaque tubes or cavity receivers can be used.

5.38 SOLCHEM PROCESS: SO₃ DISSOCIATION-RECOMBINATION CYCLE, Naval Research Laboratory.

1. This process produces an energy rich gaseous mixture which can be transported and reconverted to high temperature (500°C) heat. It extends non-renewable fuel resource.

2. The existing hardware can be used in part. This is a new process. The operating experience for SO₃ dissociation is not available. It can be adapted to solar heat source. The process includes storage tanks. The temperature required is about (1000°C) 1800°F. Material problems are significant.

3. The process can be carried out only in areas where solar energy is available. It includes storage tanks and energy will be available for 24 hours a day. It will fit well into users existing system. The cost effectiveness has still to be established.

4. Long term and near term economics have not been studied.

5. The process by itself has to be conducted in areas of high insolation. It can be used to provide high temperature heat for the production of electricity and chemicals.

6. It has not been tested in a solar facility. It can be tested in a significant module size. It will probably have a favorable impact on general public. It is environmentally acceptable.

7. Transient effects and intermittent energy availability are overcome by storage of solar energy in a chemical form. Temperature required is about 1800°F. Solar system module size versus process plant size given

is 20 MW_e of peak power with 10 MW_e average power usage. The process efficiency, reaction rates and residence time, etc. have to be evaluated. Materials problems have to be resolved.

8. The technology developed for this experiment can potentially be used for later experiments. Receivers consisting of opaque tubes can be used.

5.39 AMMONIUM HYDROGEN SULFATE(AHS) CYCLE COGENERATION, University of Houston.

1. This process produces electric power and heat and replaces non-renewable fuels in the production of power. It also extends non-renewable fuel resource.

2. Existing hardware can be used in part. Operating experience is available in power production but not in the chemical storage of solar energy. It is based upon known processes to a considerable degree. It is adaptable to solar heat source. Temperature required is about 1800°F. Materials problems are not insurmountable. No STTF work has been done to date.

3. There is a significant demand for electric power and heat. The process can be operated only in locations where solar energy is available. It fits well into user's existing system. There is no need for feedstock. The chemicals are regenerated and used.

4. The process economics are favorable in the long-term.

5. Feedstock is available in regions of high insolation in U. S. The product can be transported to others; but with regard to heat, there is a limitation.

6. It can be tested in a significant module size. It will probably have a favorable impact on the general public. It is environmentally acceptable.

7. Intermittent solar energy availability is not a problem. Temperature required is 1800°F. Solar system module size is 100 MW_t. Process efficiency of about 30 to 40% is attainable. Storage require-

ments are met. Materials are no problem. Transient and cyclic effects of solar energy are taken care of.

8. Technology developed in this experiment can be used for later experiments. It uses receiver/reactor consisting of opaque tubes.

5.310 BIOMASS TO DIESEL FUEL, Solor Energy Research Institute.

1. The process produces a transporation fuel from renewable feedstocks, namely biomass. It extends non-renewable fuels resource and upgrades energy content.

2. Existing hardware can be used in whole. Operating experience for the non-solar portion is available. It is based upon known processes to a large degree. It is adaptable to solar heat source. Temperature required is 1300°F to 2200°F. The materials problems are expected to be minimum. No STTF work has been conducted to date.

3. There will be a significant demand for the diesel fuel. Solar energy will be available at the location where feedstock is available. The feedstock-wheat straw, cornstalks, grasses, tumbleweeds and damaged crops are abundantly available. Economic viability is not known. There is an export potential for the process to sunbelt regions. Profitability versus size consideration are not available.

4. Analysis of the economic potential relative to other alternate energy options is not available.

5. Feedstock is available in high insolation regions of U. S. The cost of transporting the product beyond area of high insolation is costly.

6. It can be tested in a significant module size. it will probably have a favorable impact on the general public. It is environmentally acceptable.

7. The process can be operated continuously. Temperature required is 1300°F to 2200°F. Solar system module size versus process plant - size is not known. Process efficiency is 93%. Reaction rates and residence

time are reasonable. The product diesel fuel can be stored. The existing materials may be used. Solar flux is available. The heat required is 4100 BTU/lb. Transient and cyclic effects are overcome.

8. No type of reactor is specified.

5.311 ORE PROCESSING

1. The process does not produce a fuel. However, it replaces non-renewable fuels in production of concentrated metal compounds and elements and thereby extends non-renewable fuel source.

2. Existing hardware can be used in part. Operating experience is available to some extent. The process is based on known processes to a large extent. It is adaptable to solar heat source. Temperatures required are 1700°F to 2700°F. Materials problems have to be resolved. In some cases, there may be reasonable technological steps from STTF work done to date.

3. There is a significant demand for the products in U.S. There is no perfect match between the availability of solar energy and the location of the raw materials. There is adequate feedstock resource. Adaptability to industrial production practices and economics require further study. There may not be export market potential. It is too early to say whether the private sector will pick up for commercialization.

4. Data regarding both long-term and near-term economics relative to the use of fossil fuels are not available.

5. Feedstock is not available in high insolation regions of U. S. The cost of transporting feedstock to high insolation regions of U. S. will be considerable except in the case of high value products such as vanadium compounds. The product is now transported long distances to areas of consumption. Hence the cost of transport of product beyond area of high insolation may not be a criterion.

6. The process can be tested in a significant module size. It may have high public relations appeal or favorable impact on the public. It will be environmentally acceptable.

7. In the case of high value products, batch process may not increase the cost. Intermittent energy availability will not be a drawback. Transient effects will affect the rate of production. Temperature required is 1700°F to 2700°F. These processes are in their infant stage and development data regarding process efficiency, reaction rates, residence time, storage requirements, etc are not available. Solar flux can be used advantageously. Materials problem requires resolution.

8. Technology developed in these processes can be used for later experiments. These are based mostly on direct insolation.

6. MATRIX ASSESSMENT OF CANDIDATE PROCESSES

During the last two years, a number of evaluation studies of various candidate processes have been undertaken, mostly using a standard qualitative engineering approach. The MAPS technique is the only one where a quantitative approach is adopted. However, in carefully considering the structure and applicability of MAPS, given the program goals established by DOE, it became clear that all of the processes could not be fairly and completely evaluated in a directly comparative fashion.

Critical review of the available literature pertaining to the process candidates indicates that there is a wide variation in the level of development of these processes. For example, per Section 5. - EVALUATION CHARACTERISTICS, processes 5.11, 5.12, 5.14, 5.21, 5.22, and 5.36 are well documented. On the other hand, process 5.37 is only at the conceptual stage. In some cases, such as 5.36, no experimental work has been done as yet. The process shows great promise. Processes 5.37, 5.38, and 5.39 do not produce any fuels and chemicals, but are used for the transportation of heat.

Because of the tremendous disparity among the candidates, we divided the list into two groups: those which could basically meet DOE goals based on information made available to us and those which do not. Specifically, sufficient information was provided on six processes to allow for assessment of their potential for desired demonstration qualities in the timeframe indicated:

- o Synthesis Gas, Lawrence Livermore Laboratory
- o Synthesis Gas, University of New Hampshire
- o Synthesis Gas, Princeton University
- o Hydrogen, Westinghouse Electric Corporation
- o Hydrogen, General Atomic Company
- o Ammonia, PFR Engineering Systems

Matrix assessments of these six processes are provided directly in this Section.

The MAPS technique was also applied to the remaining candidate processes as well, in order to provide the greatest level of standardized comparison possible. However, the analysis for this second group is provided in Appendix D, rather than in this Section, as the relative paucity of information made it inappropriate for direct comparison.

It is important to point out a critical consideration raised by this division of analysis. The separation of processes has been made because the available data is limited compared to the goals/objectives established by DOE. With different goals/objectives or with additional information, other divisions or no divisions might be appropriate. There are no limitations to the usefulness of the MAPS technique itself, the limitation lies with the amount of information and the purpose of evaluation.

The evaluation of the top six candidate processes which follows is based on assigning the values of 0, 0.5, and 1.0 to each attribute for five categories as previously indicated in Section 4. Table 6-1 contains the complete simple scoring for each attribute and Table 6-2 contains a summary of scores by category and candidate process.

The simple attribute scores are subsequently re-calculated using a weight for each attribute in Table 6-3. This represents a technical evaluation of which attributes are most important relative to one another. The summary of such weighted attributes for each candidate category is provided in Table 6-4.

As an additional level of distinction among categories, in order that the number of attributes in each not become the basis on which one candidate process scores higher in total than another, Table provides the average weighted score for each process in each category.

Last, Tables 6-6 and 6-7 add the additional dimension of category weight, with unweighted average attribute scores and weighted average attribute scores respectively.

The results of different scoring approaches using MAPS results in some clear distinctions, and as importantly, leave certain distinctions unclear. What becomes evident from the following Tables is that the Lawrence Livermore Laboratory Synthetic Gas Process and the Princeton University Synthetic Gas Process are consistently ranked lower than the remaining four candidates, regardless of what level of the MAPS technique is used. Thus, the top four candidates remaining are: University of New Hampshire, Westinghouse, General Atomic, and PFR.

However, the lack of sufficient data and input and the need for policy level distinctions to be made become clear in attempting to rank order the remaining candidates. The following summaries illustrate the range of choices which arise:

A. SIMPLE SCORE RANKING

1.	PFR	26.0
2.	U. N. H.	25.0
3.	General Atomic	24.0
4.	Westinghouse	23.0

B. WEIGHTED SCORE RANKING

1.	U. N. H.	44.5
2/3	General Atomic/PFR	44.0/44.0
4.	Westinghouse	42.5

C. AVERAGE WEIGHTED SCORE RANKING

1. General Atomic	7.99
2. Westinghouse	7.87
3. U. N. H.	7.51
4. PFR	7.26

D. WEIGHTED CATEGORIES/UNWEIGHTED AVERAGE SCORES

1. PFR	12.89
2. U. N. H.	12.55
3. General Atomic	12.53
4. Westinghouse	11.89

E. WEIGHTED CATEGORIES/WEIGHTED AVERAGE SCORES

1. General Atomic	24.13
2. U. N. H.	23.26
3. Westinghouse	23.25
4. PFR	22.59

On almost every level of evaluation, the top four candidate processes are ranked so closely that meaningful distinctions cannot but be called arbitrary or based on subjective decisions of the evaluators. Thus, an evaluation reflecting many different viewpoints, which we subsequently recommend or unilateral decisions made by appropriate program managers at DOE Washington and/or San Francisco is necessary. At this time, AETA would not be prepared to choose unilaterally any specific one of the top four candidate processes to the exclusion of the remaining three. We believe that the numerical tradeoffs which we have selected as judgmental do not necessarily represent the current program direction of the DOE nor the needs of the experimenters and industrial decision makers.

TABLE 6-1
SIMPLE ATTRIBUTE SCORES
TOP SIX CANDIDATES

A. PROCESS * DEMONSTRATION	LLL	UNH	PRINCETON	WESTINGHOUSE	GA	PFR
1.1	0.5	1.0	0.5	0.5	0.5	0.5
1.2	1.0	1.0	0.5	1.0	1.0	1.0
1.3	1.0	1.0	0.0	1.0	1.0	1.0
1.4	0.5	1.0	0.5	1.0	1.0	1.0
1.5	0.5	1.0	0.5	0.5	0.5	1.0
1.6	0.5	0.5	0.5	0.0	0.5	1.0
1.7	0.0	1.0	0.0	0.0	0.5	1.0
1.8	0.5	1.0	0.5	1.0	1.0	1.0
1.9	0.5	0.5	0.5	0.5	0.5	1.0
1.10	<u>0.5</u>	<u>1.0</u>	<u>0.0</u>	<u>1.0</u>	<u>1.0</u>	<u>1.0</u>
SUB TOTALS	5.5	9.0	3.5	6.5	7.5	9.5
B. FULL SCALE PROCESS						
2.1	0.0	0.5	0.0	1.0	1.0	1.0
2.2	0.0	0.5	0.0	0.5	0.5	1.0
2.3	0.0	1.0	0.0	0.5	0.5	1.0
2.4	0.0	1.0	0.0	1.0	1.0	1.0
2.5	0.0	1.0	0.0	0.0	0.0	1.0
2.6	0.0	0.5	0.0	0.0	0.5	0.5
2.7	0.0	0.0	0.0	0.0	0.0	0.0
2.8	<u>0.0</u>	<u>0.5</u>	<u>0.0</u>	<u>1.0</u>	<u>1.0</u>	<u>0.5</u>
SUB TOTALS	0.0	5.0	0.0	4.0	4.5	6.0

*Reference should be made to Table 4-1, "List of Attributes for Sun Fuels," Categories A-E, for names of specific attributes.

TABLE 6-1 SIMPLE ATTRIBUTE SCORES - TOP SIX CANDIDATES Continued

C.	<u>FEEDSTOCK</u>	<u>LLL</u>	<u>UNH</u>	<u>PRINCETON</u>	<u>WESTINGHOUSE</u>	<u>GA</u>	<u>PFR</u>
	3.1	1.0	1.0	0.5	1.0	1.0	0.0
	3.2	0.0	0.0	0.5	1.0	1.0	0.0
	3.3	1.0	1.0	0.0	1.0	1.0	1.0
	3.4	<u>0.5</u>	<u>0.5</u>	<u>0.5</u>	<u>1.0</u>	<u>1.0</u>	<u>0.5</u>
	SUB TOTAL	2.5	2.5	1.5	4.0	4.0	1.5
D.	<u>END-PRODUCT</u>						
	4.1	1.0	1.0	0.0	1.0	1.0	1.0
	4.2	1.0	1.0	0.0	1.0	1.0	1.0
	4.3	1.0	1.0	0.0	0.5	0.5	1.0
	4.4	<u>0.5</u>	<u>0.5</u>	<u>0.0</u>	<u>1.0</u>	<u>1.0</u>	<u>1.0</u>
	SUB TOTAL	3.5	3.5	0.0	3.5	3.5	4.0
E.	<u>NAT/SOCIAL</u>						
	5.1	1.0	1.0	0.5	1.0	1.0	1.0
	5.2	1.0	1.0	0.5	1.0	1.0	1.0
	5.3	1.0	1.0	0.5	1.0	0.5	1.0
	5.4	1.0	1.0	1.0	1.0	1.0	1.0
	5.5	<u>1.0</u>	<u>1.0</u>	<u>1.0</u>	<u>1.0</u>	<u>1.0</u>	<u>1.0</u>
	SUB TOTAL	5.0	5.0	3.5	5.0	4.5	5.0

TABLE 6-2

SUMMARY OF SIMPLE ATTRIBUTE SCORES

TOP SIX CANDIDATES

<u>CATEGORY</u>	<u>LLL</u>	<u>UNH</u>	<u>PRINCETON</u>	<u>WESTINGHOUSE</u>	<u>GA</u>	<u>PFR</u>
A. PROCESS DEMONSTRATION	5.5	9.0	3.5	6.5	7.5	9.5
B. FULL SCALE	0.0	5.0	0.0	4.0	4.5	6.0
C. FEEDSTOCK	2.5	2.5	1.5	4.0	4.0	1.5
D. PRODUCT	3.5	3.5	0.0	3.5	3.5	4.0
E. NATIONAL/ SOCIAL	<u>5.0</u>	<u>5.0</u>	<u>3.5</u>	<u>5.0</u>	<u>4.5</u>	<u>5.0</u>
TOTALS	16.5	25.0	8.5	23.0	24.0	26.0

TABLE 6-3
WEIGHTED ATTRIBUTE SCORES
TOP SIX CANDIDATES

<u>A. PROCESS *</u> <u>DEMONSTRATION</u>	<u>ATTRIBUTE</u> <u>WEIGHT</u>	<u>LLL</u>	<u>UNH</u>	<u>PRINCETON</u>	<u>WH</u>	<u>GA</u>	<u>PFR</u>
1.1	3	1.5	3.0	1.5	1.5	1.5	1.5
1.2	1	1.0	1.0	0.5	1.0	1.0	1.0
1.3	2	2.0	2.0	0.0	2.0	2.0	2.0
1.4	1	0.5	1.0	0.5	1.0	1.0	1.0
1.5	3	1.5	3.0	1.5	1.5	1.5	3.0
1.6	1	0.5	0.5	0.5	0.0	0.5	1.0
1.7	1	0.0	1.0	0.0	0.0	0.5	1.0
1.8	1	0.5	1.0	0.5	1.0	1.0	1.0
1.9	1	0.5	0.5	0.5	0.5	0.5	1.0
1.10	1	<u>0.5</u>	<u>1.0</u>	<u>0.0</u>	<u>1.0</u>	<u>1.0</u>	<u>1.0</u>
TOTALS		8.5	14.0	5.5	9.5	10.5	13.5
 <u>B. FULL SCALE</u>							
2.1	3	0.0	1.5	0.0	3.0	3.0	3.0
2.2	2	0.0	1.0	0.0	1.0	1.0	2.0
2.3	1	0.0	1.0	0.0	0.5	0.5	1.0
2.4	2	0.0	2.0	0.0	2.0	2.0	2.0
2.5	1	0.0	2.0	0.0	0.0	0.0	1.0
2.6	2	0.0	1.0	0.0	0.0	1.0	1.0
2.7	1	0.0	0.0	0.0	0.0	0.0	0.0
2.8	1	<u>0.0</u>	<u>0.5</u>	<u>0.0</u>	<u>1.0</u>	<u>1.0</u>	<u>0.5</u>
TOTALS		0.0	9.0	0.0	7.5	8.5	10.5

*Reference should be made to Table 4-1, "List of Attributes for Sun Fuels," Categories A-E, for names of specific attributes.

TABLE 6.3 WEIGHTED ATTRIBUTE SCORES - TOP SIX CANDIDATES Continued

C.	<u>FEEDSTOCK</u>	<u>ATTRIBUTE WEIGHT</u>	<u>LLL</u>	<u>UNH</u>	<u>PRINCETON</u>	<u>WH</u>	<u>GA</u>	<u>PFR</u>
	3.1	3	3.0	3.0	1.5	3.0	3.0	0.0
	3.2	2	0.0	0.0	1.0	2.0	2.0	0.0
	3.3	2	2.0	2.0	0.0	2.0	2.0	2.0
	3.4	2	<u>1.0</u>	<u>1.0</u>	<u>1.0</u>	<u>2.0</u>	<u>2.0</u>	<u>1.0</u>
	TOTALS		6.0	6.0	3.5	9.0	9.0	3.0
D.	<u>PRODUCT</u>							
	4.1	3.	3.0	3.0	0.0	3.0	3.0	3.0
	4.2	2	2.0	2.0	0.0	2.0	2.0	2.0
	4.3	1	1.0	1.0	0.0	0.5	0.5	1.0
	4.4	3	<u>1.5</u>	<u>1.5</u>	<u>0.0</u>	<u>3.0</u>	<u>3.0</u>	<u>3.0</u>
	TOTALS		7.5	7.5	0.0	8.5	8.5	9.0
E.	<u>NATIONAL/ SOCIAL</u>							
	5.1	3	3.0	3.0	1.5	3.0	3.0	3.0
	5.2	1	1.0	1.0	0.5	1.0	1.0	1.0
	5.3	1	1.0	1.0	0.5	1.0	0.5	1.0
	5.4	2	2.0	2.0	2.0	2.0	2.0	2.0
	5.5	1	<u>1.0</u>	<u>1.0</u>	<u>1.0</u>	<u>1.0</u>	<u>1.0</u>	<u>1.0</u>
	TOTALS		8.0	8.0	6.5	8.0	7.5	8.0

TABLE 6-4
SUMMARY OF WEIGHTED ATTRIBUTE SCORES
TOP SIX CANDIDATES

<u>CATEGORY</u>	<u>LLL</u>	<u>UNH</u>	<u>PRINCETON</u>	<u>WESTINGHOUSE</u>	<u>GA</u>	<u>PFR</u>
A. PROCESS DEMONSTRATION	8.5	14.0	5.5	9.5	10.5	13.5
B. FULL SCALE	0.0	9.0	0.0	7.5	8.5	10.5
C. FEEDSTOCK	6.0	6.0	3.5	9.0	9.0	3.0
D. PRODUCT	7.5	7.5	0.0	8.5	8.5	9.0
E. NATIONAL/ SOCIAL	<u>8.0</u>	<u>8.0</u>	<u>6.5</u>	<u>8.0</u>	<u>7.5</u>	<u>8.0</u>
TOTALS	30.0	44.5	15.5	42.5	44.0	44.0

TABLE 6-5
AVERAGE WEIGHTED ATTRIBUTE SCORES
TOP SIX CANDIDATES

<u>CATEGORY</u>	<u>LLL</u>	<u>UNH</u>	<u>PRINCETON</u>	<u>WESTINGHOUSE</u>	<u>GA</u>	<u>PFR</u>
A. PROCESS	.85	1.4	.55	.95	1.05	1.35
B. FULL SCALE	0.0	1.13	0.0	0.94	1.06	1.31
C. FEEDSTOCK	1.5	1.5	0.88	2.25	2.25	0.75
D. PRODUCT	1.88	1.88	0.0	2.13	2.13	2.25
E. NATIONAL/ SOCIAL	<u>1.6</u>	<u>1.6</u>	<u>1.3</u>	<u>1.6</u>	<u>1.5</u>	<u>1.6</u>
TOTALS	5.83	7.51	2.73	7.87	7.99	7.26

TABLE 6-6
SUMMARY OF WEIGHTED CATEGORY
AND
UNWEIGHTED ATTRIBUTE SCORES
TOP SIX CANDIDATES

<u>CATEGORY</u>	<u>CATEGORY WEIGHT</u>	<u>LLL</u>	<u>UNH</u>	<u>PRINCETON</u>	<u>WH</u>	<u>GA</u>	<u>PFR</u>
A. PROCESS	5	2.75	4.5	1.75	3.25	3.75	4.75
B. FULL SCALE	4	0.0	2.52	0.0	2.0	2.24	3.0
C. FEEDSTOCK	3	1.89	1.89	1.14	3.0	3.0	1.14
D. PRODUCT	3	2.64	2.64	0.0	2.64	2.64	3.0
E. NATIONAL/ SOCIAL	1	<u>1.0</u>	<u>1.0</u>	<u>0.7</u>	<u>1.0</u>	<u>0.9</u>	<u>1.0</u>
TOTALS		8.28	12.55	3.59	11.89	12.53	12.89

TABLE 6-7
SUMMARY OF WEIGHTED CATEGORY
AND
AVERAGE WEIGHTED ATTRIBUTE SCORES
TOP SIX CANDIDATES

<u>CATEGORY</u>	<u>CATEGORY WEIGHT</u>	<u>LLL</u>	<u>UNH</u>	<u>PRINCETON</u>	<u>WH</u>	<u>GA</u>	<u>PFR</u>
A. PROCESS	5	4.25	7.0	2.75	4.75	5.25	6.75
B. FULL SCALE	4	0.0	4.52	0.0	3.76	4.24	5.24
C. FEEDSTOCK	3	4.5	4.5	2.64	6.75	6.75	2.25
D. PRODUCT	3	5.64	5.64	0.0	6.39	6.39	6.75
E. NATIONAL/ SOCIAL	1	<u>1.6</u>	<u>1.6</u>	<u>1.3</u>	<u>1.6</u>	<u>1.5</u>	<u>1.6</u>
TOTALS		15.99	23.26	6.69	23.25	24.13	22.59

7. CONCLUSIONS AND RECOMMENDATIONS

In summary fashion we would conclude and recommend the following based on the work conducted over the past year:

7.1 CONCLUSIONS

7.11 A SOUND ANALYTICAL METHOD HAS BEEN CREATED (MAPS):

The Multi-Attribute Preference Scoring (MAPS) System represents a relatively simple and efficient method to assess and rank diverse and differentially developed candidate Sun Fuels processes for testing at the Central Receiver Test Facility (CRTF) at Albuquerque. MAPS permits the input of expert technical judgments, as well as non-technical consideration in such areas as end product market, national and social policy, and feedstock considerations. While the method can accommodate gaps in information which is either not available or is not provided, it cannot easily overcome evaluator biases, except through adequate input from diverse sources. Thus, a larger group of evaluators are essential ($\approx 15-20$) to pinpoint optimal choices.

7.12 INSUFFICIENT AVAILABLE INFORMATION REMAINS A PROBLEM IN ASSESSING SUN FUELS OPTIONS:

AETA Corporation, from the inception of the project, had difficulty in obtaining technical reports and relevant data about many of the twenty candidate processes which were ultimately examined in detail. Of these twenty, sufficient information to allow a meaningful demonstration of the MAPS technique was only provided on six. In no case was sufficient information on comparative economics available to allow for direct comparisons. It is not entirely clear whether more information would have changed our evaluation in any substantive fashion, but it is appropriate to note potential concern for program purposes.

7.13 FOUR PROCESSES REMAIN TOP CANDIDATES, BUT OUTSIDE EVALUATION
IS NECESSARY AND APPROPRIATE:

Sufficient information was made available for a preliminary and illustrative application of MAPS which included Lawrence Livermore Laboratory (syn gas), Princeton (syn gas), University of New Hampshire (syn gas), Westinghouse Electric (hydrogen), General Atomic (hydrogen), and PRF Engineering (ammonia). Of these six, the Lawrence Livermore and Princeton processes ranked sufficiently below the remaining four on a number of evaluation bases, to consider them in a lower category of order. However, UNH, Westinghouse, General Atomic, and PFR all ranked sufficiently close to suggest they all be considered for testing at the CRTF. This finding, however, must be considered only preliminary because of the limited input data already noted and because the process evaluators were perforce chosen from a small group of professionals from AETA Corporation and the University of New Hampshire. Thus, inadvertent bias must be considered.

7.14 MAPS OFFERS A USEFUL ANALYTICAL TOOL FOR OTHER R&D PROBLEMS:

The MAPS can be applied to a wide variety of problems where selection is complicated by limited hard data and a need for value judgments in both technical and non-technical areas. It should be very useful for future DOE R&D decision-making in an era of tight budgetary constraints and intense competition for research dollars.

7.2 RECOMMENDATIONS

7.21 INPUT FROM SUN FUELS PROGRAM PARTICIPANTS SHOULD BE FACTORED INTO
MAJOR PLANNING DECISIONS:

Structured evaluation of the twenty candidate sun fuels processes should incorporate input from researchers on the processes themselves, and other program participants, as well as DOE SAN FRAN and Washington

program managers. Such input is the only way to insure an adequate articulation of all relevant hard data and balance among subjective judgments concerning different process attributes. Because of changing Federal goals and objectives in the energy area, MAPS priorities might well be substantially changed from those outlined in this report.

Specifically, a workshop/meeting should be organized to expose those involved in the Sun Fuels field to the comprehensive evaluations which have been conducted on various processes. The MAPS technique should be introduced as an analytical framework which, after discussion and debate, can be accepted as a standardized evaluative approach for candidate R&D activity. Some sort of consensus on or statistically meaningful treatment of various priorities should be sought.

7.22 MAPS SHOULD BE COMPUTERIZED

Because manual manipulation of attribute and category weights is a time-consuming process, the MAPS technique should be computerized on a simple desk-top machine. This will allow for quick and efficient analysis of changing weights and sensitivity thereof, as it bears on ultimate figures of merit and ranking of candidates.

7.23 PUBLICATION ON SUN FUELS PROCESSES SHOULD BE ENCOURAGED:

The lack of information on sun fuels in the general literature is a major inhibition to autonomous development of interest by potential researchers in this area. Given DOE's mandate to assist in the "transition of technology to the private sector," the publication of journal articles and presentations at professional meetings, beyond DOE-sponsored functions, should be strongly encouraged.

7.24 MAPS SHOULD BE USED FOR ASSESSING NEW R&D PROPOSALS:

Not only should MAPS be used in making decisions about current candidates

for R&D support, but for new processes and activities which are proposed. Standard evaluation will allow comparison of the potential of new activity against work which has already been supported, as well as against other proposals.

8. APPENDICES

APPENDIX A

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APPENDIX B

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APPENDIX C
Conceptual Treatment of Maps

C-1 OBJECTIVES

The goals of the decision making process must be clearly defined for the analysis to be successful, as they will, to a great extent, determine how MAPS is implemented. In general, the objectives will fall into two categories. The first category deals with what the results of the analysis should be, i.e. defining the problem. In many cases this definition and the corresponding objectives of the analysis may be trivial, but in others, poor specification of the problem can lead to a hopelessly misdirected analysis. One of the most difficult elements in any application of decisions theory is problem definition, and in some cases it requires artful and imaginative application of judgment to yield a problem definition that is both tractable and meaningful.

The second category of objectives related to the outcomes and results of the decision to be made. What is it that this decision is supposed to accomplish? What is the premise of the capital budgeting problem, and what is it that the firm (i.e. the decision-maker) hopes to accomplish? Again, defining these objectives may be very simple, where the sole criteria of a successful solution to the capital budgeting problem is profit maximization. Difficulties will arise, however, when other concerns are involved. In some cases, there may be secondary objectives to profit maximization, such as opening up a new market or implementing new technology. But in areas such as research and demonstration, objectives other than profit maximization take on an increasingly important role.

C-2 IDENTIFICATION OF ATTRIBUTES

Given a set of objectives, the analyst must define the attributes with which the decision making options can be evaluated. The attributes should, to the extent possible, be complete. In other words, the list of attributes should be exhaustive and cover every significant feature of the possible

outcomes of the decision. To give an example, suppose you were trying to decide whether to walk or drive to a point one mile away. Some of the more important considerations would be: how long will it take; will I get wet; how much money might be saved; what is the risk and cost of an accident; etc. These considerations define the features of the outcomes of the decisions which are important. They are attributes, and if properly developed, the list of attributes will exhaust all of the considerations that are involved in the decision.

These considerations, in the form of attributes, can be specified in a wide variety of ways. In addition to being comprehensive, the attributes specified should be independent of each other. That is, no one consideration should be included twice. For the example above, "inches of rainfall" and "percent of clothes getting wet" could both be used as measurable attributes, but they both essentially relate to the concern of becoming wet. Thus, using them both would amount to a double counting of a single consideration. Independence of attributes is a very important criteria and one which can be very difficult to satisfy. Independence is a second example of how judgment and imagination are important to the success of the analysis.

Completeness and independence are the most important analytical criteria concerning the identification of attributes. In addition, there are some practical concerns that can affect the analysis in more subtle ways. First, the attribute list should not be unduly long and should not be too specific. To use an ancient euphemism, one must not "lose sight of the forest for the trees." Psychologically, a long list of attributes is boring. An individual scoring or weighting the attributes will probably lose concentration and will tend not to be consistent with too long a list. In addition, a too specific set of attributes will unnecessarily prolong the analysis and will be distracting. The specificity of the attributes should be consistent with the accuracy of the measurements that are possible, and the sensitivity of the entire methodology to changes in those measurements. On the other hand, the attribute list must be sufficiently specific to capture the important but subtle aspects of the decision, and to yield an

analysis that is capable of distinguishing slightly more attractive options from slightly less attractive options.

In addition, attributes should be phrased in a consistent fashion. Positive phrasing is preferable due to the psychological benefits and to the simplicity of being consistent. Scrupulously neutral phrasing may be preferable on purely analytical grounds, but will be impossible to achieve except in those cases where virtually all of the attributes are measurable in quantitative terms.

In some cases where a problem is sufficiently complex and where a large number of attributes is needed, it is advisable to group attributes in categories. The categories should have a rational basis, and the best categories are those that distinguish fundamentally different types of concerns. The use of categories adds one additional layer of complexity in the analyses, but in many cases can be a real asset.

C-3 WEIGHTING ATTRIBUTES

The weighting of attributes is intended to correspond with the assigning of importance to the considerations represented by each attribute. Weighting is required because attributes generally will not have the same importance. In particular, attribute weights are very much a function of the objectives previously defined, and the relative importance of one attribute over another may change another differing objective. If the sole objective is profit maximization, then clearly those attributes most directly related to financial performance and return on investment will be the most important, and should receive the greatest weight. In addition, some attributes will relate to the risk involved in choosing one option versus another. If the decision-maker is highly risk averse, then these attributes should be heavily weighted.

It should be stressed that weighting is largely a judgmental exercise and, therefore, is most appropriately done at the management level of a firm. Technical experts alone cannot fully define the value framework for a capital budgeting decision, although they may be the only ones to fully comprehend

the technical characteristics of the options. MAPS is designed in such a way that the preponderance of value judgments, generally the prerogative of the decision-makers and managers, is made by assigning weights to attributes. The preponderance of technical judgements, generally the prerogative of technical experts, is contained in the option evaluation process discussed below.

With respect to the specific numbers utilized for weighting, positive integers, beginning with one, are consistent with the concept of weighting. The range can vary considerably, depending on the level of detail required and the range of importance for the attributes. Too wide a range should be avoided as it complicates the process and implies the existence of very fine distinctions that probably do not exist. Too narrow a range, on the other hand, can eliminate distinctions that do exist and can make the sensitivity analysis meaningless. As a rule of thumb, a range with one order of magnitude (1-10) should be more than sufficient for any application of MAPS. If the relative importance of attributes varies more than that, then some attributes should probably be redefined. In addition, a range of 1-3 is probably the narrowest range desirable, and it could correspond to a simple "most important - important - least important" conceptual scheme for assigning weights.

C-4 EVALUATION OF OPTIONS

Evaluating the available options with respect to the attributes, as mentioned above, is largely a technical function and involves technical measurement and judgment. Specifically, numerical values are assigned to each option relative to each attribute. Figure C-A depicts the scoring matrix that results from this process.

FIGURE C-A
Scoring Matrix

<u>Attribute #</u>	<u>Weight</u>	<u>Options</u>			
		<u>A</u>	<u>B</u>	<u>C</u>	<u>D</u>
1	2	X	X	X	X
2	2	X	X	X	X
3	1	X	X	X	X
4	3	X	X	X	X

The numerical basis for the option evaluation process should be a scale of 0 to 1. The scale is not particularly important for MAPS applications where the evaluation process is limited to simply a scoring procedure. However, in a highly quantitative context, a more sophisticated approach can be used. In particular, the values for options with respect to the most important attributes can be analyzed using techniques from Utility Theory. For example, expected quantitative measure for a attribute can be mapped through a utility function to yield a "utility score," a number between zero and one, that corresponds to the value to the decision-maker of that option with respect to that attribute.

In most simple applications, the 0 to 1 scale is useful because it can apply to both quantitative and qualitative values. Quantitative values are simply normalized or subdivided on the basis of the range of possible numerical values, and qualitative values are assigned on a basis such as:

- 1 = excellent
- 0.5 = acceptable
- 0.0 = unacceptable

In addition, the 0 to 1 scale, by specifying a fixed and constant range, matches analytically with the weighting process for attributes. For example, all attributes have some importance (e.g. 1 is the minimum), but some options may have no value with respect to that attribute (e.g. a value of 0). Also, the highest numerical value for an option is 1, and thus in the final figure of merit, the effective score for that option with respect to that attribute is the full numerical weight (i.e. importance) for that attribute.

C-5 FIGURE OF MERIT

The figure of merit is simply the total score for an option. It is calculated by summing the option values for each attribute weighted in accordance with the attribute weight. The numbers themselves will have no meaning except in a relative sense. The highest numbers will correspond with the most attractive options, the lowest numbers with the least attractive.

When attributes are grouped by categories, as in Figure 2, the calculation of figures of merit is slightly more complicated. Initially, total scores for options by category are calculated as above, by summing the weighted values for each option. Then the scores in each category are divided by the number of attributes in the category to yield a normalized set of scores for all categories. The normalized scores correspond in a sense to the "average score per attribute" for each option in each category. Thus, the scores are comparable from category to category. The next step, as shown in Figure 2, is to rank or weight the categories and perform sensitivity analyses on the categories. In some cases, weighting of categories may not be needed if the results can be determined through visual inspections and comparisons of the scores by category. This may be particularly true if one category is clearly the most important.

In cases where visual inspection is insufficient, then the categories would be assigned weights, and the weighted category scores summed to yield an overall figure of merit for each category. Sensitivity analysis on the category weighting will indicate where the important tradeoffs are and will further determine the certainty of the solution.

C-6 SENSITIVITY ANALYSIS

Sensitivity analysis is an extremely important part of MAPS. Both the weighting of attributes and the scoring of options have an element of uncertainty: the more complex and qualitative the context, the greater the uncertainty. In order to understand how this uncertainty can change the results of the analyses, the sensitivity of the results to changes in

weights and scores must be examined. Sensitivity of the results to changes in all inputs, except in a small number of cases, need not be analyzed. As a rule of thumb, only the most important of attributes and the scores with the least variance need be analyzed carefully. These elements are the ones most likely to change the results.

Sensitivity analysis should be done first by altering the inputs one at a time to see which have the greatest impact on the final results. Most often, the rank order of the decision options will not change, but the numerical figure of merit will. Once the sensitive variables have been identified, then a more thorough analysis of best case and worst case events can be examined. If the rank order of options does not change, the analyses need not go any further. If the rank order changes dramatically, then a more detailed, step-by-step iteration should be performed; the decision-maker should be apprised of the sensitive points in the analysis so that he can make appropriate judgments.

Ideally, the probability of each different rank ordering of options would be calculated, based on the probability of the necessary changes in inputs being valid. These probabilities and the magnitude of the variances in figures of merit would yield a picture of what choice has the greatest "expected value." In most cases, such a thorough analysis will be completely unnecessary. So long as the decision-maker knows where the uncertainty lies and how it is likely to affect the results, he can evaluate the necessary tradeoffs and the risks and make the appropriate decision.

C-7 SUMMARY

The material above outlines in detail the MAPS system and consideration involved in implementing it. As the discussions pointed out, MAPS is extremely flexible and can be applied to a wide variety of capital budgeting problems. The only significant constraint is that MAPS requires decision options that are discrete, and is not designed for those cases where options exist in a continuous range. Of particular note is the fact that MAPS can be implemented in its most rudimentary form for fairly simple problems, or

in an extremely sophisticated form for the most complex of problems. Thus, it has one of the most valuable characteristics of an effective decision-making tool: the cost and the time required to implement MAPS can be tailored to match exactly the magnitude of the capital budgeting problem. For small problems, MAPS is a simple, inexpensive and easily used tool. For big problems, MAPS is a highly sophisticated and very sensitive tool. In addition, it can incorporate qualitative data in a systematic way.

APPENDIX D

MATRIX ASSESSMENT OF NON-COMPETITIVE PROCESSES

TABLE D-1

SIMPLE ATTRIBUTE SCORES
BALANCE OF CANDIDATE PROCESSES

CATEGORY	LASL - SYN GAS	LEDE LRNS - SYN GAS	LASL - HYDROGEN	IGT - HYDROGEN	JPL - WET OXIDATION LIGNITE	LLL - OIL SHALE RETORTING	IGT - CALCIUM CARBIDE	QUAKER OATS/JPL FURFURAL	FLAMANT - CaCO ₃ DECOMPOSITION	NRL - CO ₂ -CH ₄ REFORMING	NRL - SO ₂ -SO ₃ STORAGE	UNIVERSITY OF HOUSTON AHS	SERI - DIESEL FUEL	LASL - ORE PROCESSING
A. <u>PROCESS. DEMONSTRATION*</u>														
1.1	0.5	0.5	0.5	0.5	0.5	0.5	0.5	1.0	1.0	0.0	1.0	0.5	0.5	0.5
1.2	0.0	0.5	0.5	0.5	1.0	1.0	1.0	1.0	1.0	0.0	0.5	1.0	1.0	1.0
1.3	0.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.0	1.0	1.0	1.0	1.0
1.4	0.5	0.5	0.5	0.5	1.0	0.5	0.5	1.0	0.5	0.0	1.0	1.0	0.5	1.0
1.5	0.5	0.5	0.5	0.5	1.0	0.5	0.5	1.0	0.5	0.0	0.5	0.5	0.5	0.5
1.6	0.5	0.5	0.0	0.0	0.5	0.5	0.5	0.5	1.0	1.0	1.0	1.0	0.5	1.0
1.7	0.0	0.5	0.0	0.0	0.5	0.0	0.0	0.0	0.0	1.0	1.0	0.0	0.0	0.5
1.8	0.5	0.5	1.0	1.0	1.0	0.5	1.0	0.5	0.5	0.5	1.0	1.0	1.0	1.0
1.9	0.5	0.5	0.5	0.5	1.0	0.5	0.5	0.5	0.5	0.5	1.0	1.0	1.0	1.0
1.10	<u>0.5</u>	<u>0.5</u>	<u>1.0</u>	<u>1.0</u>	<u>1.0</u>	<u>0.5</u>	<u>0.5</u>	<u>0.0</u>	<u>0.5</u>	<u>1.0</u>	<u>1.0</u>	<u>1.0</u>	<u>1.0</u>	<u>0.5</u>
SUB TOTAL	3.5	5.5	5.5	5.5	8.5	5.5	6.0	6.5	6.5	4.0	9.0	8.0	7.0	8.0

*Reference should be made to Table 4-1, "List of Attributes for Sun Fuels," Categories A-E, for names of specific attributes.

TABLE D-1 - SIMPLE ATTRIBUTE SCORES - BALANCE OF CANDIDATE PROCESSES Continued

B. FULL SCALE PROCESS

2.1	0.0	0.0	0.0	0.0	0.5	0.0	0.5	1.0	0.0	0.5	0.5	0.5	0.0	0.5
2.2	0.0	0.0	0.0	0.0	0.5	0.0	0.5	1.0	0.0	0.5	0.5	0.5	1.0	0.0
2.3	0.0	0.0	0.0	0.0	1.0	0.0	0.5	1.0	0.0	0.5	0.5	1.0	1.0	0.0
2.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.0	1.0	0.0	1.0
2.5	0.0	0.0	0.5	0.5	0.0	0.0	0.0	0.5	0.0	0.5	0.5	0.0	0.0	0.0
2.6	0.0	0.0	0.5	0.5	0.5	0.0	0.5	0.5	0.0	0.5	0.5	0.5	0.0	0.5
2.7	0.0	0.0	0.0	0.0	0.5	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2.8	<u>0.0</u>	<u>0.0</u>	<u>0.5</u>	<u>0.5</u>	<u>0.5</u>	<u>0.0</u>	<u>0.5</u>	<u>0.5</u>	<u>0.0</u>	<u>0.5</u>	<u>0.5</u>	<u>0.5</u>	<u>0.0</u>	<u>0.0</u>
SUB TOTAL	0.0	0.0	1.5	1.5	3.5	0.0	3.0	4.5	0.0	4.0	4.0	4.0	2.0	2.0

C. FEEDSTOCK

3.1	1.0	0.5	1.0	1.0	1.0	1.0	0.5	1.0	1.0	NA	NA	NA	1.0	0.5
3.2	0.0	0.5	1.0	1.0	0.0	0.0	0.0	1.0	0.0	NA	NA	NA	1.0	0.0
3.3	1.0	0.5	1.0	1.0	1.0	1.0	1.0	0.5	1.0	NA	NA	NA	0.5	0.5
3.4	<u>0.5</u>	<u>1.0</u>	<u>1.0</u>	<u>1.0</u>	<u>0.5</u>	<u>0.5</u>	<u>0.5</u>	<u>1.0</u>	<u>1.0</u>	<u>NA</u>	<u>NA</u>	<u>NA</u>	<u>1.0</u>	<u>1.0</u>
SUB TOTAL	2.5	2.5	4.0	4.0	2.5	2.5	2.0	3.5	3.0	NA	NA	NA	3.5	2.0

TABLE D-1 - SIMPLE ATTRIBUTE SCORES - BALANCE OF CANDIDATE PROCESSES Continued

D. END PRODUCT

4.1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	NA	NA	NA	1.0	1.0
4.2	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	NA	NA	NA	1.0	1.0
4.3	1.0	1.0	0.5	0.5	0.5	1.0	0.5	0.5	0.5	0.5	NA	NA	NA	1.0	1.0
4.4	<u>0.5</u>	<u>0.5</u>	<u>1.0</u>	<u>0.5</u>	<u>0.5</u>	<u>1.0</u>	<u>1.0</u>	<u>0.5</u>	<u>1.0</u>	<u>1.0</u>	<u>NA</u>	<u>NA</u>	<u>NA</u>	<u>1.0</u>	<u>0.5</u>
SUB TOTAL	3.5	3.5	3.5	3.0	3.0	4.0	3.5	3.0	3.5	3.5	NA	NA	NA	4.0	3.5

E. NATIONAL/SOCIAL

5.1	1.0	0.5	1.0	1.0	1.0	1.0	1.0	0.5	1.0	1.0	1.0	1.0	1.0	1.0	0.0
5.2	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.5	1.0	1.0	1.0	1.0	1.0	0.0
5.3	1.0	0.5	1.0	1.0	1.0	0.0	1.0	0.5	1.0	1.0	1.0	1.0	1.0	1.0	1.0
5.4	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
5.5	<u>1.0</u>	<u>1.0</u>	<u>1.0</u>	<u>1.0</u>	<u>1.0</u>	<u>1.0</u>	<u>1.0</u>	<u>1.0</u>	<u>1.0</u>	<u>1.0</u>	<u>1.0</u>	<u>1.0</u>	<u>1.0</u>	<u>1.0</u>	<u>1.0</u>
SUB TOTAL	5.0	4.0	5.0	5.0	5.0	4.0	5.0	4.0	4.5	5.0	5.0	5.0	5.0	5.0	3.0

TABLE D-2

SUMMARY OF SIMPLE ATTRIBUTE SCORES

BALANCE OF CANDIDATE PROCESSES

CATEGORY	LASL - SYN GAS	LEDE LRNS - SYN GAS	LASL - HYDROGEN	IGT - HYDROGEN	JPL - WET OXIDATION LIGNITE	LLL - OIL SHALE RETORTING	IGT - CALCIUM CARBIDE	QUAKER OATS/JPL FURFURAL	FLAMANT - CaCO ₃ DECOMPOSITION	NRL - CO ₂ -CH ₄ REFORMING	NRL - SO ₂ -SO ₃ STORAGE	UNIVERSITY OF HOUSTON AHS	SERI - DIESEL FUEL	LASL - ORE PROCESSING
A. PROCESS DEMONSTRATION	3.5	5.5	5.5	5.5	8.5	5.5	6.0	6.5	6.5	4.0	9.0	8.0	7.0	8.0
B. FULL SCALE PROCESS	0.0	0.0	1.5	1.5	3.5	0.0	3.0	4.5	0.0	4.0	4.0	4.0	2.0	2.0
C. FEEDSTOCK	2.5	2.5	4.0	4.0	2.5	2.5	2.0	3.5	3.0	NA	NA	NA	3.5	2.0
D. END PRODUCT	3.5	3.5	3.5	3.0	3.0	4.0	3.5	3.0	3.5	NA	NA	NA	4.0	3.5
E. NATIONAL/SOCIAL	<u>5.0</u>	<u>4.0</u>	<u>5.0</u>	<u>5.0</u>	<u>5.0</u>	<u>4.0</u>	<u>5.0</u>	<u>4.0</u>	<u>4.5</u>	<u>5.0</u>	<u>5.0</u>	<u>5.0</u>	<u>5.0</u>	<u>3.0</u>
TOTALS	14.5	15.5	19.5	19.0	22.5	16.0	19.5	21.5	17.5	NA	NA	NA	21.5	18.5