**A SURVEY OF APPLICATIONS
OF FUSION POWER TECHNOLOGY TO THE
CHEMICAL AND MATERIAL PROCESSING INDUSTRY**

by

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Summary and Conclusions

An initial survey of the application of controlled thermonuclear fusion power technology to the chemical and material processing industry has been made. The general principles concerning the forms of energy, the energy conversion efficiency terms, and the process design criteria, have been categorized, defined and evaluated. A survey of potential, conventional and advanced chemical processes are presented and capacity projections are made to the year 2000.

The principal conclusions of this survey are as follows:

1. The major forms of energy available in amounts of 30% or greater of the total power developed in a Controlled Thermonuclear Reactor (CTR) operating on a D-T fuel cycle are:

- (1) High temperature thermal energy
- (2) Electrical energy - high and low voltage
- (3) Neutron and gamma high energy radiation

2. The thermal and electrical forms of CTR energy can be applied to supply a significant fraction of the needs of a conventional heavy chemical and material processing industry. Processes which would require total CTR power capacities greater than 100,000 MW(t) include: (a) ammonia production, (b) cement production, (c) hydrogen production, (d) iron ore reduction, and (e) aluminum production. Total thermal and electrical power capacity for these applications can reach up to 2.1×10^6 MW(t) and 768,000 MW(e) respectively after the year 2000. As much as 60% of this capacity could be required for the production of hydrogen used primarily for chemical and petrochemical processing.

3. CTR thermal energy can be potentially applied to advanced processes which are not presently utilized. These are high temperature processes operating at 1500°C or higher and include such processes as acetylene production, nitrogen fixation, carbon dioxide decomposition and water decomposition.

4. CTR thermal and electrical energy can also find applications for alternative chemical processes which result in more environmentally acceptable systems because it either eliminates or reduces the requirement for fossil fuels and reduces the formation of noxious waste by-products.

5. The high energy neutron and gamma induced radiation in CTR blanket process streams can be potentially applied to

advanced processes, such as the decomposition of CO_2 to CO for liquid hydrocarbon fuel production, the synthesis of ozone for water treatment and the fixation of nitrogen for fertilizer production.

6. The minor forms of CTR energy, based on a D-T fuel cycle, available in amounts less than 10% of the total power developed in CTR reactors, include ultraviolet energy from the plasma, secondary high energy particle (p, α, β) energy and ionized particle energy from the blanket. These forms will be useful mainly as a by-product from either thermal or electrical CTR power generators. However, it is possible, with the more difficult D-D fuel cycle, to obtain higher UV conversion efficiencies for consideration as prime UV process reactors.

7. A comparative analysis of the energetics of several leading high volume chemical products using CTR energy indicates that hydrogen is best produced electrolytically, and ozone and carbon monoxide are best produced by radiolytic reactions.

8. One of the largest potential uses of CTR is the production of methanol as a synthetic liquid hydrocarbon fuel. Extraction of CO_2 from the atmosphere with radiolytic decomposition of CO_2 to CO combined with electrolytic hydrogen can produce an independent source of methanol supply which is environmentally highly acceptable. This system, which uses

only nuclear power, air and water would eliminate any terrestrial mining operation and its inherent hazards, minimizes pollution, and allows a high degree of freedom in plant siting. Plant capacities of 9000 MW(e) could produce ~ 200,000 bbl of methanol per day at costs roughly between \$2.00 and \$3.50/MMBTU in base loaded plants. Assuming the production of half the automotive fuel demand in the U.S., the total potential CTR capacity required can range to 2.6×10^6 MW(t) beyond the year 2000.

9. Further advanced systems include the direct electrochemical or radiolytic reduction of aqueous carbonate solutions to organic compounds and the synthesis of food-stuff from such reduced compounds as formaldehyde produced only with the use of CTR energy, air and water.

10. CTR reactors may be applicable to the development of multi-component chemical complexes which would optimize energy and raw material requirements, in conjunction with product markets while minimizing the overall environmental problems.

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I. Introduction

Controlled thermonuclear fusion research has in the past been mainly confined to developing the basic understanding of the underlying principles of high temperature plasmas. Much experimental evidence has supported this scientific research. In the last several years there has been a rapid achievement in the ability to magnetically confine plasmas. This has resulted in a projection of fusion power in a shorter time period than heretofore predicted. Scientific feasibility is presently predicted by 1980, a prototype by 1990 and a demonstration power reactor by the year 2000. Attention is thus being given to the engineering of controlled thermonuclear reactors (CTR). The application of fusion research is now emerging as a developing CTR technology.

Historically, the nuclear industry has been looked upon to supply the electrical power needs of the country. However, projections of the consumption of electrical energy even up to the end

of this century indicate that electrical energy will only be required to the extent of 25% of the total energy needs of the country. The larger consumption of energy will be in the form of thermal energy for industrial processing, domestic heating and transportation. The industrial processing sector alone is projected to consume over 30% of the energy requirements of the country by the year 2000.⁽¹⁾ It thus becomes important to examine the potential of fusion reactors to supply energy in all possible forms and to assess the effect of these energy forms on the economy. In a more specific sense it is the purpose of this report to examine and survey the use of fusion power technology in supplying various energy forms for the chemical and materials processing industry.

II. Fusion Energy Sources and Types

The initial fusion reactors will be fueled by deuterium and tritium. There are a number of possible fusion reactors based on the two basic D-T and D-D fuel cycles. These are listed in Table 1 together with the energy distribution in the products.

Because of the low thermal threshold and the high energy gain the D-T reaction is considered most feasible for first generation fusion reactors. It does however require the breeding of tritium or purchase from another source. The D-D reaction is attractive because it operates only on naturally occurring material.

The D-D reactions offer a number of options since T and ^3He produced in D-D fusion can each be used to fuse with D in turn. For purposes of assessing the value of fusion reactors for chemical purposes, the reference reactor will be based on D-T fusion assuming the availability of surplus T from other reactors. The assessment of combination D-D reactors is discussed later under the section on high energy radiation. The D-T reaction essentially produces 20% energy in the plasma in the form of charged particles. The charged particles in the plasma can transfer energy to process streams in the following forms:

1. Direct thermal energy can be transferred to heat process streams to high temperature.
2. Ultraviolet (UV) energy can be produced and transferred by seeding the plasma with suitable material.
3. Ionized particles in the plasma can be reacted directly with process streams.

The remaining 80% of the fusion energy is carried by the neutrons which can transfer energy in the following forms.

1. Capturing the neutrons in a moderating blanket material to convert them to high temperature thermal energy which is transferred to a process stream.
2. Absorbing the neutrons in a blanket material to convert them by inelastic and capture reactions to gamma radiation energy

which is subsequently absorbed by a process stream.

3. The neutrons can be captured in blanket materials to yield proton and alpha radiation energy which is absorbed in a process stream.

4. The neutrons themselves can be captured in the reactant process stream as a high energy radiation form.

III. Chemical Energy Conversion Efficiency and Capacity of CTR

1. Chemical Energy Conversion

Because of the relatively large power capacity for practical fusion reactors (500-20,000 MW(t)) the major impact on the chemical and material processing industries will be for endothermic or energy consuming chemical processes and for large tonnage basic chemical production. The basic energy requirement for conversion of reactants to a chemical product is as follows:

$$E = \frac{0.528\Delta H}{M} \quad (1)$$

when E = energy requirement in Kwh(t)/lb product

ΔH = endothermic heat of reaction in Kcal/mol.

M = molecular weight of the product

The power requirement for a given production rate of chemical product at 100% efficiency is given by:

$$P = 4.4 \times 10^{-2} \frac{\Delta HT}{M} \quad (2)$$

where P = power requirement in MW(t)

T = production rate in Tons/day of product

2. Efficiency Factors

The efficiency of conversion of input fusion energy to final output chemical product can be visualized by the following chain.

ϵ_f - is the fraction of primary energy from the fusion reaction available in a particular form, i.e., plasma, neutron, alpha.

ϵ_p - is the efficiency of conversion of the prime energy source to another physical energy source,

i.e., UV, electrical, thermal high energy radiation, gamma, proton or alpha.

ϵ_r - is the fraction of converted energy, absorbed in the chemical reactant.

ϵ_d - is the overall fraction of fusion energy deposited in the process stream available for chemical conversion.

$$\epsilon_d = \epsilon_f \epsilon_p \epsilon_r$$

ϵ_c - is the fraction of the energy absorbed in the reactant that is connected to chemical energy.

ϵ_o - is the overall energy conversion efficiency from fusion energy to chemical energy.

Thus the overall efficiency of a fusion reactor for chemical conversion is:

$$\epsilon_o = \epsilon_f \epsilon_p \epsilon_r \epsilon_c = \epsilon_d \epsilon_c \quad (3)$$

and the energy requirement from (1) above is:

$$E = \frac{0.528 \Delta H}{\epsilon_o M} \quad (4)$$

and the actual power requirement is:

$$P = \frac{4.4 \times 10^{-2} \Delta HT}{\epsilon_o M} \quad (5)$$

An evaluation and estimate of these factors are made in the following sections.

The intensities of energy available from a CTR range over a wide spectrum from a few electron volts to the million electron volt level. Table 2 lists, in order of intensity, the categories of energy available for chemical processing.

1. Thermal energy transferred to chemical reactants usually covers the range of a few eV to break chemical bonds. The basic conversion efficiency term is the enthalpy or heat of reaction ΔH .

2. The photolytic energy range extends from a few eV up to about 15 eV extending to the far ultraviolet. The efficiency term is the quantum yield, ϕ , the number of product molecules formed from the absorption of one quanta of energy in the reactant stream.

3. Electrolytic energy usually covers the range up to 10 eV and the conversion efficiency term is the current efficiency in terms of coulombs or amp-hrs. per gm equivalent of chemical product which is defined as the Faraday.

4. Electric discharge energy in arcs or gaseous discharges produces ionic species in a chemical reactant and conversion efficiency can be expressed in m/N values or molecules of product produced per ion-pair. A current efficiency can also be defined.

5. For high energy radiation (gamma, or particle radiation) the conversion efficiency term is the G-value or the number of

molecules of product formed per 100 eV deposited in the reactant stream. Another term is the chemical conversion per megarad deposited in the reactant.

The conversion efficiency terms are then used in expressions of energy yields shown in Table 2.

A survey evaluation of the above factors is made in the following sections.

IV. General Process Design Criteria

1. Thermal Energy

a. Direct heating

Direct heating of gases requires that the process gas also serve as the coolant for removal of thermal energy from the CTR. A special blanket design for this purpose is visualized. The blanket would consist of an array of modules which serve to absorb the energy of the neutrons, gamma radiation and other particles, convert the energy to heat, and transfer the heat to the reactant gas.

A module is shown in Figure 1. It consists of a stainless steel shell wound with stainless steel tubes for water-cooled protection of the shell. Inside the shell is a drilled graphite core which permits inlet gas to enter peripherally to the shell, undergo heatup, and exit through holes in the core.

Suitable headers to supply the modules and to direct the exit gases out would be required for the design. It is estimated that temperatures as high as 1500°C could be achieved in the process gas using this scheme. The temperature is mainly limited by material properties. Either direct chemical reaction could take place in the blanket, or high temperature process gas heating for subsequent use outside the CTR is envisioned using the direct heating method outlined here. In either case, the coolant gas employed must be compatible with the module materials employed.

The steam generated from the water-cooled module coils can be expanded in a conventional turbine to produce electricity for auxiliary plant use, or used directly as process steam in other parts of the chemical plant complex.

b. Indirect heating

Temperatures above 1500°C for process gas heating will be difficult to achieve in a CTR blanket because of materials compatibility problems. To overcome this limitation, an indirect heating cycle is outlined which employs He coolant from a conventional CTR to achieve process gas temperatures up to 2500°C . The process is outlined in Figure 2.

Two refractory pebble bed regenerative heaters are employed for the process. By use of a suitable valve arrangement, hot He coolant from the CTR blanket passes through the first

vessel to heat up the bed. The pebbles can be made of refractory carbides or oxides which are capable of standing temperatures to 2500°C. As the He is cooled in passing through the bed, it can be returned to the CTR blanket for further heating or passed through a turbine to generate power. When the bed has reached the desired temperature, the valves are switched to pass the He through the second bed. Process gas is then passed back through the first hot bed and heated to the temperature required. When the bed cools to the minimum temperature allowable, the procedure is again reversed. To prevent process gas from mixing with the He between cycles, a purge is required at every cycle change before He is admitted. This could be accomplished with a separate He stream to sweep out residual process gas between cycles. This stream would then be processed separately to remove the process gas and return a pure He stream.

The process gas would have some He mixed with it as a result of using the indirect heating cycle. This could also be recovered if necessary. Use of this cycle would require a highly optimized design to achieve efficient heat recovery, and to minimize He losses.

For processing at lower temperatures up to approximately 1000°C, the helium heat transfer media can be utilized in a heat exchanger, transferring thermal energy through the walls

of tubes made of a high Cr-Ni steel or titanium to the process stream. High and low pressure process steam can be produced in this type of double loop system.

The efficiency of converting to thermal energy and transferring to a process media can be relatively high from a CTR reactor. Essentially all the energy developed in the plasma and blanket degrades to thermal energy. The main losses are due to thermal losses through the outside walls of the reactor and piping to the surroundings and which could be as much as 25%. Thus for direct and indirect thermal transfer to a process media

$$\epsilon_d = \epsilon_f \epsilon_p \epsilon_r = 1.0 \times 1.0 \times 0.75 = 0.75.$$

These efficiency terms are summarized in Table 3.

c. CTR Plasma

High temperatures can be developed by directly diverting part of the plasma to contact a process stream. In this case the allowable pressures in the process stream must not exceed the pressure of the plasma to prevent plasma contamination and thus the process is restricted to low pressures (<1 atm). It is estimated that temperatures in the order of 3000°C can be obtained. For a D-T reaction only, 20% of the energy developed is available in the plasma. A fraction of

the energy in the plasma is in the form of charged particles which radiate away and is unavailable as thermal energy. The overall availability of thermal energy in the plasma to be transferred directly to a chemically reacting media is then about 10% of the total CTR energy.

$$\epsilon_d = \epsilon_f \epsilon_p \epsilon_r = 0.2 \times 0.50 \times 1.0 = 0.10$$

2. Electrical Energy

Electrical energy can be utilized for chemical processing in electrochemical devices. This technology is well known and need not be described in detail in this report. Electrochemical reduction is heavily practiced in the metallurgical industry such as for the production of aluminum and copper. In the heavy chemical industry, the electrolytic caustic and chlorine is a major factor. The high voltage use of electrical energy, although known for many years, has not reached the magnitude of the low voltage electrochemical cells. The reason for this is that the electric discharge (arc or spark) is not as efficient as the electrolytic devices. In any case, the technology for application of electric energy does not depend on the source of the electrical power.

However, there are major implications involved in CTR utilization. The major inference to be drawn is that fossil

fuel is not required for generation. Additionally, the higher capacity, compared to present-day fossil-fueled or nuclear fission plants, and the inherent low fuel cost should permit lower cost abundant fusion power. This would mean that power intensive processes which shift in technology as a function of power cost, such as phosphoric acid, would benefit economically from a CTR technology. A side-benefit of the electric process is that the waste products from the wet chemical process of phosphoric acid manufacture cause environmental problems of greater severity than those from the electric furnace.

Thus, electric power from CTR's can be utilized for the same low or high voltage applications presently employed, and may indeed offer economies for certain chemical processes which are highly sensitive to electrical power capacity and cost and which processes may also be more environmentally acceptable.

Essentially all the energy developed in a CTR can be transferred thermally to a coolant stream which is used in a power cycle, such as a Rankine cycle, to generate electrical power. Under normal power cycle conditions developing a high temperature stream up to $\sim 600^{\circ}\text{C}$, the thermal to electrical energy conversion efficiency is about 40%. Thus the overall electrical energy available to a process stream is:

$$\epsilon_d = \epsilon_f \epsilon_p \epsilon_r = 1.0 \times 0.40 \times 1.0 = 0.40$$

3. High Energy Radiation

a. Neutron Radiation Reactor

The largest source of high energy radiation available from CTR reactor is the 14.1 MeV neutrons emerging from the plasma. The ϵ_f as shown in Table 1 is 0.80. This energy can be deposited in process streams carried in blanket tubes surrounding the plasma cavity. Significant radiation chemical effects and transformations have been obtained in gases and liquids due to high energy neutral particle radiation. The interactions are similar in mechanism and efficiency to high energy gamma radiation. The mass absorption coefficients for absorbing and stopping neutrons are similar to gamma rays. In effect, neutrons will be scattered giving rise to gamma radiation so that a pure neutron field does not exist in reality. To a first approximation, the efficiency of deposition of neutron energy in the chemical reactant stream, ϵ_r , can be estimated from the ratio of mass of reactant to the sum of the masses of reactant and structure necessary to contain the reactant process stream.

As an example, it can be assumed that a blanket array of a process gas stream consisting of either water, oxygen or carbon dioxide is pressurized in 2" diameter metal tubes at pressures up to 100 to 200 atmospheres and temperatures to 500°C

surrounding the CTR plasma in a blanket array. The required mass of metal to contain the gas pressure will tend to absorb approximately 50% of the energy of the 14 MeV neutrons. Stainless steel, because of its lower allowable strength, will absorb a greater amount of neutron energy and titanium, because of its lower density, will absorb less neutron energy. The energy absorption efficiency ϵ_r for a neutron processing reactor is thus approximately 0.50.

For liquid process streams such as water, aqueous solutions or organic streams, the neutron absorption efficiency could approach 1.0 since the mass of containment structure would be small compared to the mass of process liquid handled.

A summary of the energy efficiency factors for a neutron reactor are as follows:

For gases (up to 200 atm and 500°C)

$$\epsilon_d = \epsilon_f \epsilon_p \epsilon_r = 0.8 \times 1.0 \times 0.5 = 0.4$$

For liquids (up to 200 atm and 500°C)

$$\epsilon_d = \epsilon_f \epsilon_p \epsilon_r = 0.8 \times 1.0 \times 1.0 = 0.8$$

A problem with a neutron CTR reactor is the activation of the reactant stream by absorption of neutrons. This is a problem with high atomic number elements. Many of the

more important industrial chemical products, however, consist of C, H, and O atoms and these have negligible neutron absorption cross sections. Thus the contamination of these products would be extremely low.

A sketch of a neutron chemical convector is shown in Figure 3.

b. Gamma Radiation Reactor

It would be valuable to convert the neutron energy emitted from the CTR plasma to high energy gamma radiation by absorption in suitable blanket materials. In this process inelastic scattering gammas and capture gammas may be obtained for each incident neutron. Table 4 indicates the amount of gamma energy obtainable from four fusion reactor schemes based on D-T and D-D fuel cycles. It is assumed that the neutron absorber and chemical reactant stream surrounds the plasma cavity in a blanket array. The estimates are based on a conservative conversion of 50% of the neutron energy converted to gammas by inelastic scattering, and obtaining 8 MeV prompt gammas from the neutron capture reactions. The second column indicates the data for the reference CTR design which is used as a base case in this study. It should be noted that due to secondary gamma emissions the total energy per fusion is greater in the D-T burner so the capacity of the various fusion reactors can vary. Neutron absorbers can be constructed of such materials as

aluminum and titanium.

It would be desirable from a chemical product purity point of view to convert all the neutron energy to gamma radiation. However, in an attempt to make this conversion, the same materials that absorb neutrons will also attenuate the gammas, so that it is not readily possible to obtain a pure gamma spectrum without neutrons. As previously mentioned, the neutron cross sections are in the same order of magnitude as the gamma cross sections for absorption and scattering, so that approximately the same efficiency factors will be obtained. In effect the reactant stream can be made to act as the scatterer and capture medium to yield the gamma energy, thus allowing utilization of this energy for chemical processing. The energy efficiency terms are as follows:

For gases:

$$\epsilon_d = (\epsilon_f \epsilon_p) \epsilon_r = (0.6) \times 0.5 = 0.3$$

For liquids:

$$\epsilon_d = (\epsilon_f \epsilon_p) \epsilon_r = (0.6) \times 1.0 = 0.6$$

c. Secondary Particle Radiation Reactors

This type of reactor takes the 14.1 Mev neutrons from the plasma and absorbs them in suitable materials to obtain, high energy protons, alphas and beta particles. This energy will usually be in the 2 Mev range. The efficiency of converting

neutrons to particle energy is probably in the range of 5%. The range of the heavier particles in chemical process streams are relatively short so that most of the energy can be readily absorbed within the reactant process media. The energy efficiency deposition factor is thus evaluated as follows:

$$\epsilon_d = \epsilon_f \epsilon_p \epsilon_r = 0.8 \times 0.05 \times 1.0 = 0.04$$

Therefore, only 4% of the total CTR reactor energy can be converted to particle energy. The process reactant stream can also become contaminated through nuclear activation by the high energy particles.

d. Ionized Particles from Plasma

The ionized particles in the plasma consisting of H, T and He ions with energies in the range of 10 Kev can be made to react with chemical reactants injected directly into the plasma in a diverter section of the CTR. Probably about 50% of ionization energy can be transferred to the process stream for producing chemical conversion. The overall energy deposition efficiency is then about 10%, evaluated as follows:

$$\epsilon_d = \epsilon_f \epsilon_p \epsilon_r = 0.2 \times 0.5 \times 1.0 = 0.1$$

Because of the relatively low energy deposition efficiency in the D-T fusion cycle, the secondary particle and ionized particle radiation reactors are essentially relegated to a secondary position. These systems can then only be considered as a by-product energy source.

4. Ultraviolet Energy

It has been suggested that significant amounts of photon energy can be extracted from an ultra-high temperature plasma by injection of elements of high atomic number directly into the plasma.⁽²²⁾ Ultraviolet and visible radiation can be produced by excitation of seed elements by a high temperature, low density hydrogen plasma. Thus substances such as aluminum can be injected into a plasma which excites the Al resonance lines and produces UV radiation in the wavelength range of 1800 and 1950 Å with efficiencies of energy conversion of as high as 86%. Other elements can yield photon energy at different wavelengths so that this system is potentially very versatile. The attenuation of the UV in the plasma is low because of the low pressure and high temperature. A UV transparent window is then provided to transmit the photon energy into the chemical system. Window materials such as quartz, (SiO_2) or sapphire (Al_2O_3) are needed for low attenuation. These materials are available; however, the cost is high and the strength of these materials is limited, so that low differential pressures will be required in the process streams. A plasma diverter section is necessary to divert a fraction of the plasma to a zone where the window material and process stream are protected from the high neutron flux. The diverter section causes another inefficiency

in the process of conversion of plasma energy to UV. The loss is estimated to be in the order of 30%.

One of the configurations of a reactor design is shown in Figure 3. This design is based on a Tokamak design reactor with diverter sections. (2) The UV transparent tubes are set around this section with the process stream flowing inside these tubes. An estimate of the efficiency factors for the UV system based on D-T cycle is as follows:

$$\begin{aligned}\epsilon_f &= 0.20 && \text{available from plasma} \\ \epsilon_p &= 0.50 && \text{plasma energy transferred to high Z elements,} \\ &&& \text{including losses in diverter.} \\ \epsilon_r &= 0.80 && \text{photon attenuation loss through window and} \\ &&& \text{process tubes} \\ \epsilon_d &= 0.20 \times 0.80 \times 0.50 = 0.08\end{aligned}$$

The overall energy deposition efficiency of 8% is relatively low primarily because of the fraction of total energy available in the plasma from the D-T cycle. However, for chemical conversion, the quantum yields are relatively high because of a close match of photon energy with chemical bond energy.

The efficiency of conversion to UV from catalyzed D-D reactions or D-He³ reactions can be higher as evaluated in Table 5. Thus, up to 26% conversion can be obtained in the

D-D cycle and as much as 52% UV conversion efficiency can be obtained in the D-He³; however, the latter would require the purchase of He³ from a D-D cycle or from tritium decay.

UV processes are reviewed and evaluated in the next section on potential processes.

V. Survey of Potential Chemical Processes and Projections

Potential processes can be divided into two major categories. One is the use of conventional energy for processes presently in practice on a large scale or processes which would require little further development. In this category we are mainly concerned with the supply of thermal energy up to approximately 1500°C. This type of system includes process heat or steam for use in chemical process plants and the supply of electricity for such processes as electrochemical decomposition. The second category includes the applications of non-conventional energy, not readily available today, for use in processes which are not presently practiced on a large scale. Examples of these are high temperature thermal, high energy radiation and ultra-violet processes. These two categories are discussed in the following sections under (1) Conventional and Advanced Processes-Thermal and Electrical and (2) Advanced Processes - High Energy Radiation and UV.

1. Conventional and Advanced Processes - Thermal and Electrical

Table 6 presents a summary of high volume, energy intensive products with their production rates in the present time frame (3,4) and projected to the year 2000. (5) The unit energy requirement per ton of product is shown in Table 7, expressed both in terms of electrical and thermal energy. Fusion energy was calculated based on the projected year 2000 production. The energy projection assumes the entire production rate is met by CTR energy. Energy output is based on 75% heat recovery for thermal reactions, 40% conversion for electrical use, and a 0.8 plant factor. Obviously, the assumption that the entire production of these materials utilizes CTR energy is extremely optimistic, but it is also apparent that the potential demand in the chemical process sector to satisfy even a fraction of the total demand can still be very large.

Table 8 outlines the projected electrical demands for materials which can utilize electrical energy in their production. It should be noted that the equivalent thermal energy required to generate the electricity was included in Table 6. In some cases, such as H-Iron, ammonia, and methanol, it is assumed that the hydrogen required is generated by water

electrolysis. The hydrogen in these cases has not been included in the separate hydrogen category, which is slated to meet other needs such as coal gasification, petroleum refining, and general chemical applications.

Analysis of the information in Tables 6, 7 and 8 indicates the following significance for CTR application.

a. The thermal and electrical energy requirements to support a conventional heavy chemical processing industry projected to the year 2000 is quite substantial reaching up to 2.1×10^6 MW(t) and 768,000 MW(e).

b. Processes which would require total capacities greater than 100,000 MW(t) include (1) iron ore reduction, (2) aluminum reduction, (3) ammonia production, (4) cement production and (5) hydrogen production.

c. As much as 60% of the projected energy capacity could be required for the production of hydrogen primarily for chemical and petrochemical processing.

Table 9 list processes and products which are of interest for the potential application of fusion energy. A brief description of each follows, outlining present or past production methods, with an indication of the role fusion energy sources may play in their future production.

1.1 Thermal Processes

1. Wisconsin Process for Nitric Oxide⁽⁶⁾

This process employed a gas-heated pebble furnace for the thermal reaction of air to form nitric oxide (NO) at 2400°K followed by a rapid cooling in a regenerative pebble bed reactor. The yield was about 2% NO by volume at 1% thermal efficiency. The use of the indirect thermal reaction method with fusion energy appears directly applicable to this process.

2. Acetylene from Methane⁽⁷⁾

Acetylene production has not kept pace with the growth of the chemical industry because of increased reliance on petrochemical feedstocks for raw materials. Although acetylene was produced primarily from calcium carbide in the past, increasing power costs brought about a change to the use of hydrocarbons, typified by natural gas. The major process is the use of partial oxidation of methane:

Step (1) provides the heat to thermally crack methane to acetylene in step (2) at 1550°C. A rapid quench cooling stream stabilizes the product. It is apparent that a high-temperature gas stream from a CTR might be useful

as a heat source for reaction.⁽²⁾

3. Decomposition of CO_2 to CO and O_2

CO_2 is a waste product from many chemical processes which is normally vented to the atmosphere. It could serve as a carbon source by conversion to CO, which is useful as a component of synthesis gas in combination with hydrogen. CO can also be used to generate H_2 via the water gas reaction, or to synthesize methanol. An interesting, novel method of CO generation which is presently not utilized is the direct thermal decomposition of CO_2 . It can be calculated thermodynamically that at 2200°C a 7% yield of CO can be achieved. A major problem in this scheme is the separation of CO from O_2 .

4. Decomposition of Water⁽⁸⁾

Processes for the decomposition of water to produce hydrogen directly have been pursued for many years. Although the electrolysis of water is a well-known technology, it does not compete with hydrogen generation from natural gas, oil or coal in a near term fossil fuel economy. In the longer term, multi-step chemical cycles, in which the reactants are regenerated and the net result of which is the decomposition of water, are interesting since they require an external heat source to supply the reaction energies. Extensive work on these water splitting cycles have recently attracted much attention.⁽²⁰⁾

Should either the overall efficiency or the economics of these systems warrant commercial application, fusion reactors would be of interest for application to this technology.

5. Coal Gasification⁽⁹⁾

Coal gasification is a process in which steam reacts endothermically with carbon to produce a gas mixture which can be used for fuel. Actually, a complex series of reactions occurs in the reaction zone of the coal gasifier, which is a refractory-lined, water-cooled vessel. Steam and air are introduced at the bottom, coal at the top. The overall reaction is endothermic. The resultant gas is called low BTU gas, having a heating value of about 175 BTU per cu. ft. Although a waste heat boiler is utilized to raise steam from the hot exit gases, reducing their temperature from 950°F to 550°F, there is still a 40% steam deficit in the overall balance which could be supplied from a CTR. The ratio of additional steam required is about 0.32 lb. per lb. of coal consumed.

Coal gasification can also be considered in terms of producing synthesis gas (a mixture of CO and H₂) when oxygen is used instead of air in the gasifier. Synthesis gas is used for ammonia production or high BTU pipeline gas (1000 BTU per cu. ft.).

6. Shale Retorting⁽¹⁰⁾

The process of shale oil recovery has a

retorting enthalpy requirement of 300 BTU per lb. at 890°F.

The process envisioned, and presently under field test, employs a pre-heated ceramic pebble bed system for pyrolysis. The pyrolysis vapors are then condensed and fractionated. The indirect pebble-bed system previously described for employing CTR thermal energy appears directly applicable to the shale oil retorting process.

7. Lime⁽⁷⁾

Lime is produced from limestone directly by calcining to remove CO_2 . One ton of lime requires 5×10^6 BTU from coal or gas for the decomposition, which occurs above 900°C. The application of CTR thermal energy to this process is of obvious value.

8. Cement⁽¹¹⁾

Cement is obtained by calcining a mixture of clay and limestone or similar materials. There are many commercial variations, but the processes are similar despite some differences in the raw materials or their proportions. The reactions of dehydration and decarbonization which take place are both endothermic, although the clinker formation is exothermic. The net heat requirement has been estimated as about 900 BTU/lb., but the actual fuel used indicates a requirement about four times greater. The technology necessary to adapt the CTR as an energy source for this process would be similar to that required

for calcining lime.

9. Gypsum⁽⁷⁾

Calcium sulfate (gypsum) is manufactured by calcining gypsum rock to remove three-fourths of the water of crystallization. A calciner is used in a vertical configuration, and the process is completed when the mass reaches 160°C. The use of low-level heat from CTR steam or coolant to heat air for the calcining operation appears to be a direct technical adaptation.

10. Iron Ore Reduction

The direct reduction of iron ores has been extensively reviewed by Brown.⁽¹²⁾ He has defined direct reduction of iron oxides to iron as any process "which is carried out in equipment other than the blast furnace." The reducing agents generally used are carbon, carbon monoxide, hydrogen, or mixtures of these.

The H-Iron process has been widely publicized and extensively researched. It was the first commercial process to use a fluidized solids technique. The process operates at about 1000°F, 500 psia, and employs almost pure hydrogen as the reductant. The reduction takes place in three staged beds within the reducing vessel, employing 10 mesh ore moving downward countercurrent to a pre-heated hydrogen stream

at 1000°F. The reduced charge, of essentially the same size as the feed, is removed from the bottom of the vessel.

The hydrogen requirement is approximately 22,000 scf per ton of iron produced. Approximately one-third of the reaction heat required is supplied by the hydrogen reacting with the ore, and the additional energy to maintain the process is obtained from hydrogen preheating.

The energy for hydrogen preheating is obtainable by heat exchange with CTR coolant. The hydrogen required is available from electrolysis of water from CTR electric power, or through decomposition of CO₂ (radiolytic or thermal) in the CTR with subsequent water gas shifting, or by water-splitting cycles.

11. Ammonia⁽⁷⁾

Ammonia is mainly presently produced by reforming natural gas with steam to produce carbon monoxide and hydrogen,

Oil and coal are also used to produce synthesis gas where it is more economical to do so.

The carbon monoxide reacts further with additional steam to produce more hydrogen.

During the course of reaction (1), sufficient air is added to bring the nitrogen concentration to that required for the final synthesis of ammonia, which follows steps for the removal of carbon dioxide and residual carbon monoxide.

The necessary hydrogen may be generated by the processes previously described. The additional heat required for the steam reforming step is available by direct heating of the required air in the CTR blanket module array.

12. Titanium Dioxide⁽⁹⁾

Rutile titanium dioxide is made by chlorinating rutile ore, and oxidizing the resulting titanium chloride vapors to titanium oxide in a burner supplied with air.

The burner is the key to the process, providing for very rapid heating of the reacting gases to about 2400°F, the temperature at which rutile crystals form. The CTR may provide the thermal energy necessary for the oxidation step.

13. Sodium Silicate⁽⁷⁾

Sodium silicate is produced by the fusion of silica and sodium carbonate in a regenerative furnace at 2200-2600°F. Fuel gas (natural or producer gas) and air are

used to maintain the necessary temperature. The substitution of air heated in a CTR blanket module array may be considered for this purpose.

1.2 Electrical Processes

The application of potential low-cost power from any source is of obvious interest to the chemical industry. CTR technology offers this potential, and if it can be fulfilled, it is then also obvious that the chemical industry will utilize it. This is particularly true for products which can be produced by alternate methods, and the process choice is dictated by the power cost. A typical example is phosphoric acid, which is produced primarily by either the electric furnace method or the wet process; the choice is strongly affected by power cost.

A discussion of large power-consuming chemical processes is described in the following section, with appropriate implications about their role in an economy based on CTR technology.

1.2.1 Electrochemical

1. Hydrogen and Synthetic Fuels

The prospect of large blocks of off-peak, low cost power from CTR makes hydrogen attractive as a potential fuel or fuel component. It can be readily generated

by electrolysis of water. The theoretical power consumption is 14.9 kwh per lb. H_2 , ⁽⁸⁾ but practical cells are assumed to require about 22 kwh(e) per lb.

Hydrogen can be used directly in slightly modified internal combustion engines. For practical application in this area, a considerable problem is the fuel carrying capacity of a vehicle because of the low density of either the gas or liquid. The use of hydrides ⁽¹³⁾ is possible thus reducing high pressure gas storage but imposing a weight penalty.

Another possibility is to use the generated hydrogen to produce methanol by reaction with carbon monoxide or carbon dioxide. The resultant liquid can be used in conventional vehicles (also slightly modified). Although methanol provides only half the BTU value compared to gasoline on a weight basis, its handling properties and ease of use make it a strong contender for automotive use. It should be noted that the projected production of methanol in Table 6 does not include any provision for methanol as a motor fuel. If, by the year 2000, 50% of the projected energy demand for transportation alone was met by methanol, the production required would increase by two orders of magnitude above the value given. Large quantities of power would be required to produce the necessary hydrogen, implying a concomitant

increase in CTR capacity. This is further discussed under the section on advanced processes.

2. Oxygen

Oxygen is presently produced by low-temperature air separation. The process requires about 300 kwh(e)/ton of oxygen for compression, thus the cost is strongly a function of power costs. If hydrogen from electrolysis becomes viable, large amounts of by-product oxygen will be available. In any case, a CTR economy producing power, hydrogen or both will benefit large users of oxygen.

3. Caustic-Chlorine⁽¹⁴⁾

Chlorine and caustic soda are produced from the electrolysis of brine; average energy consumption is about 2800 kwh(e) per ton of chlorine. A major problem in the industry is imbalance between supply and demand for the two products. Chlorine demand has been historically rising at a greater rate than caustic demand. In addition, caustic demand fluctuates more than does that for chlorine. For these reasons, other processes which do not produce caustic are of interest. Among these are the electrolysis of hydrochloric acid and the partial oxidation of hydrochloric acid. An added incentive for the greater use of such processes is the environmental problem of excess hydrochloric acid disposal. By-product

oxygen available from hydrogen electrolysis cells might strongly affect the process choice.

4. Metal Refining

Many metals are refined by electrochemical processes. Among these are aluminum, magnesium, and copper. Aluminum is a particularly large energy consumer, requiring 14,000 kwh(e) per ton for its production. Electric furnace steel production is also expanding; should H-iron production become feasible on a large scale, electric furnace expansion, and thus power requirements, would become enormous.

1.2.2 High Voltage Electrical

1. Phosphorus-Phosphoric Acid⁽⁷⁾

A primary method of phosphorous production is by electric furnace reduction of phosphate rock with coke to elemental phosphorus. Subsequent oxidation by air to phosphorous pentoxide followed by hydration yields phosphoric acid. The implication of CTR power for this method as opposed to the wet process, which produces phosphoric acid directly, has been discussed previously.

Some advantages of the furnace process are:

a. It produces phosphorus directly; this can be shipped to distribution areas cheaper than the acid.

The phosphorus is then easily converted to the acid for distribution.

b. The wet process has some serious environmental problems, among which are disposal of calcium sulfate waste, and fluorine dispersal into the air or streams.

2. Birkeland-Eyde, NO_2 ⁽¹⁵⁾

The first process for fixation of atmospheric nitrogen employed an air-current blown through an electric arc at 3000°C . Some nitrogen and oxygen in the air combined to form nitric oxide, and a rapid quench to 600°C caused further reaction with oxygen to produce nitrogen dioxide. This process is primarily of historic importance, although at one time it was in commercial use. Low cost CTR power may be of value on reexamining this process.

3. Acetylene via Arc Process ⁽⁷⁾

Several processes for acetylene manufacture employ hydrocarbon cracking in an electric arc. A high flux density keeps reaction time at a minimum. In the U.S., du Pont is the only company to have employed the arc process. The cracked gas is rapidly quenched in two steps with liquid propane and water. Power consumption is 5.6 kwh(e)/lb. of acetylene, and the acetylene yield is 100 lb. per 120 lb. methane and 40 lb. propane. This is about twice the power

consumption of the calcium carbide-acetylene route. Low cost CTR power may be a factor in its reconsideration.

4. Hydrogen Peroxide⁽⁷⁾

Hydrogen peroxide can be produced by electrolysis of ammonium bisulfate to produce ammonium persulfate. Outside the cell, the persulfate is hydrolyzed by steam to hydrogen peroxide and ammonium bisulfate, which is recycled. The electrical power requirement is 5700 kwh(e)/ton of hydrogen peroxide. The electrolysis method is being replaced by organic auto-oxidation processes which employ hydrogen and oxygen. Whichever method is eventually used, power will be required either directly for electrolysis of bisulfate or indirectly for oxygen and hydrogen production.

5. Ozone

Ozone is prepared commercially by the reaction of an oxygen-containing feed gas in an electric discharge. Another technique employs ultraviolet energy, but at present this method produces low volume and low concentration ozone.

Commercial ozone generators (ozonizers) generally consume 3.75-5.0 kwh(e) per lb. ozone generated from a pure oxygen feed. If air is the feed gas, power consumption is doubled.

Ozone is widely used in Europe for drinking water treatment, as opposed to chlorine which is used in the U.S. Chlorine is known to react with components of water, such as phenols and amines, to produce distasteful and toxic organic chlorides. Ozone, on the other hand, is an extremely powerful oxidant which can decompose many organic compounds. As a result, there has always been interest in using ozone to replace chlorine for water treatment. Ozone is further discussed in the following sections under advanced processes.

6. Multicomponent Chemical Complexes

An interesting speculation arises concerning the interplay between chemical processes and CTR. It may not be desirable to use a CTR to generate one specific chemical product, but it may be feasible to generate an entire range of products. This possibility arises through considerations of raw material sources, distance to market for finished materials, energy requirements and environmental problems. The situation may lead to the evolution of CTR "parks," where by-products from one process may become raw materials for another. As examples, by-product HCl from chlorinated hydrocarbon processes could be converted to chlorine by partial oxidation using oxygen from hydrogen electrolysis cells. Thus, the HCl

which is considered a pollutant from some processes becomes a valuable chlorine source. Another example is CO_2 from calcining operations, which is often vented. Combined with hydrogen, methanol can be produced for use as a fuel or organic intermediate.

2. Advanced Processes - High Energy Radiation and UV

2.1 High Energy Radiation Processes

There is much basic high energy radiation chemistry information available due to the extensive research performed in this field over the past 25 years. Much of this work has been supported by the AEC both from the point of view of the effects of photon and particle energy on the material properties of fission reactor materials and the possible use of fission products for chemical processing. The understanding of the interaction of high energy radiation with matter and the distribution and yield of products can now be of great value in fusion reactor materials technology and in chemical processing.

From an industrial application point of view, high energy radiation processes based on isotopic energy sources, i.e., Co^{60} , Cs^{137} and Sr^{90} have found only limited success, primarily because this energy is an expensive by-product of the fission process. Less than 1% of primary nuclear fission reaction can be transferred to a chemical process through the use

of isotopic power. As a result, the isotopic high energy sources are expensive and are relegated to small scale exothermic specialty chemical processes such as the production of ethyl bromide. Co^{60} gamma radiation has also gained success in biological processes such as in medical treatment, in the sterilization of medical supplies and in food pasteurization. Even in this respect high energy electron accelerators have been more successful in industrial processes such as the rapid curing of paint and plastic surface coatings.

A development effort has been conducted in the past⁽¹⁶⁾ on the utilization of fission fragment energy, whereby up to 85% of the fission energy could be utilized directly in high energy radiation chemical processes. This so called fission fragment chemonuclear reactor was developed up to pilot plant in-pile loop operations which held out special promise for such endothermic processes as (1) the fixation of nitrogen, (2) the decomposition of carbon dioxide to carbon monoxide and (3) the synthesis of ozone from oxygen. Several problems were manifest in the F.F. chemonuclear reactors. One was that very thin fuel elements ($<10 \mu$ in one dimension) were required to allow the heavy fission fragment particles produced from the fission of uranium to escape the element and deposit the energy in the reaction stream. Second, there was the possibility of

contaminating the product with highly active fission fragments. Another type of reactor, the neutron-gamma (α, γ) chemonuclear reactors which utilizes only the fast neutron energy and the prompt and capture gamma from the fission process, eliminated the fission fragment contamination problem. However, this type of reactor became uneconomical for endothermic reactions because the α, γ energy fraction of the total fission energy, deliverable to a process stream, is less than 10%.

The potential advent of CTR fusion reactors presents the possibility of depositing massive amounts of high energy neutron-gamma radiation in relatively large deliverable energy fractions. This type of reactor is a direct conversion of fusion energy to chemical energy. As shown in Table 3 in the previous section, with gaseous systems energy deposition efficiencies ϵ_d can be as high as 40% and with liquid systems as high as 80%. The main problems relate to minimizing neutron activation contamination of the product and maximizing gamma energy deposition.

The primary effect of high energy radiation causes ionization in materials. The subsequent electron-ion interaction causes chemical reaction. Gamma photons cause electron detachment and acceleration and the fast moving electrons cause ionization and chemical reaction. Neutrons lose energy

by elastic and inelastic collisions which accelerates protons causing electron displacements, ionization and chemical reaction. The chemical yields obtained from neutron energy transfer are more closely related to gamma energy yields than to the heavy fission fragment yields. The maximum radiation yields in terms of G-values and the heat of reaction as shown in Table 7 is determined as follows:

$$G_{\max} = \frac{2307}{\Delta H}$$

$G_{\max}$ is the maximum G-value for endothermic reactions; number of molecules of product formed per 100 ev of radiations energy absorbed in the chemical reactant.

The thermal efficiency for chemical conversion is obtained from the experimental G value as follows:

$$\epsilon_c = \frac{G_{\exp}}{G_{\max}} \times 100$$

A survey of some of the potential industrial endothermic chemical reactions for which experimental G-values can be found in the literature are listed in Table 10. ⁽³⁾

These reactions were selected because they lead to products having high potential market value, i.e., hydrogen, nitrogen dioxide, carbon monoxide, ozone, acetylene, hydrocarbon, etc. It is also noted that these chemical conversion processes deal with low cost readily available chemical raw materials which

are upgraded to higher value chemical products through the radiation chemical process.

Generally the G-values and the thermal efficiency for high energy radiation processes are all low, mainly because the Mev high energy radiation is much above the energy level of a few ev corresponding to the chemical bond. Thus radiation energy is non-discriminatory as far as chemical conversion is concerned and much of the energy becomes thermally degraded. However, radiation energy is not thermodynamically equilibrium limited so that, for example, dissociation reactions can take place much below the equilibrium temperature of the bulk materials.

The reactions given in Table 10 fall into several categories:

1. Higher efficiency reactions ($>15\%$); these include water decomposition for hydrogen production; CO_2 decomposition for CO synthesis and O_3 synthesis from O_2 . These processes may allow the use of the entire output of a reactor for chemical production requiring no support from another product component such as the production of power.

2. Intermediate efficiency (5-15%); these include hydrogen peroxide synthesis from water, ethylene formation from methane. These processes may require economic

assistance from a power producer in a multipurpose reactor system.

3. Low efficiency processes (<5%); these include valuable products such as nitrogen dioxide from air for fertilizer production, hydrazine from NH_3 as a fuel and acetylene from methane or benzene and formaldehyde from CO_2 and water.

Table 11 lists experimental G values for exothermic reactions yielding products of high commercial market value. Even though these reactions are exothermic, the G values for non-chain reactions are low and could be considered as candidates for α, γ CTR chemonuclear reactors.

In Table 12 the energy deposition efficiencies ϵ_d and the chemical conversion efficiency ϵ_c are combined to determine overall CTR to chemical conversion efficiency and the energy requirement E in kwh(t)/lb. of product is calculated. From this table, the synthesis of CO and the synthesis of O_3 appear to have low enough energy requirements to be considered for further evaluation in single or dual purpose reactors. The other reactions may be suitable as by-product or dual purpose process reactor systems. Within the limited scope of this study the H_2 , CO and O_3 are investigated further in this report.

2.2 Ultraviolet Radiation Processes

A number of photochemical reactions have been studied in the past and a great deal of literature data is available. However, there have been comparatively few processes which have been practiced on a commercial scale. Primarily this has been the case, because equipment for producing this type of energy has been very limited in capacity and in operating performance and has been relatively expensive. As a result, for bulk commodity chemicals, alternate process routes have been more economical to practice and ultraviolet reactions have been relegated to specialty chemical production and laboratory processes. Ultraviolet processes which have been practiced on a limited scale include the synthesis of ozone in ozonation reactions, the halogenation of hydrocarbons such as hexachlorobenzene, and vitamin D production by UV irradiation of milk.

With the advent of the possibility of massive sources of UV radiation from CTR plasmas, a new situation presents itself. Many potential reactions can be considered based on literature data. A comprehensive study is outside the scope of this survey. However, several endothermic reactions producing potentially high volume basic chemical products can be evaluated in a preliminary manner. These are the synthesis of (1) hydrogen from water, (2) ozone from oxygen and (3) carbon

monoxide from CO_2 . The quantum yields for these reactions are listed in Table 13.⁽¹⁷⁾ Most of the experimental information available was obtained in the UV range from ~ 1300 to ~ 2000 Å. The energy conversion efficiencies have been calculated for each of the reactions mentioned. It is apparent that as a chemical energy converter, UV photolysis can be rather efficient running up to as high as 42% in the case of converting oxygen to ozone. However, because of the rather low overall energy deposition efficiency of $\sim 8\%$, the CTR thermal energy requirement to produce a unit of product becomes relatively high. In the next section a comparative analysis of these processes are further examined.

VI. Comparative Analysis of Specific Chemical Processes

For the purpose of assessing the various modes of energy utilization for chemical production, several processes are analyzed on a comparative basis in this section.

1. Hydrogen Generation

The production of hydrogen by decomposition of water is energetically analyzed in Table 14. Based on a single purpose system the least efficient system is the photolysis process which is about 1.2% efficient. The most efficient process is the electrolysis of water, which under good conditions is

about 34% efficient. The radiolytic and thermal processes run about 6 to 7.5% efficient. These efficiencies are based on the entire energy output from the CTR. Thus for the less efficient systems it becomes necessary to consider dual process systems so that the thermal energy not utilized in the primary process is converted to electrical power which then can be utilized to electrolytically decompose water. For hydrogen generation by the radiolytic and photolytic decomposition of water, it is assumed that the reaction temperature is high enough to extract power efficiently ($\sim 500^{\circ}\text{C}$). The overall efficiency for these dual systems is then given by the following expression:

$$\epsilon_t = \epsilon_{01} + \epsilon_{02} - \epsilon_{01} \epsilon_{02}$$

where ϵ_t = overall efficiency of dual process

ϵ_{01} = efficiency process 1 alone

ϵ_{02} = efficiency of process 2 alone

The overall efficiency for dual process systems for decomposition of water are evaluated in Table 14. It can be seen that the improvement in overall efficiency is limited. For example, the dual process of radiolysis of water with plasma energy and electrolytic decomposition of water with blanket energy yields only a 13% improvement in energy yield. (ϵ_0 = 34% for electrolytic and 38% for radiolytic plus electrolytic.)

It then becomes questionable as to the value of installing a separate process system for this relatively small incremental production capacity.

2. Ozone Synthesis

A potential large scale use for ozone is in the treatment of water supplies and disinfection of sewage. The electric discharge ozonizer synthesis of ozone has been practiced for a long period of time on a modest scale. The reason for its limited application has been mainly due to the limited capacity of equipment and the resulting high cost of the O_3 product. The chemical yields (ϵ_c) of the electric discharge process is compared with the yield by radiation and UV photolytic processes in Table 15. The radiation yield is almost twice as high as the electric discharge, and the photolytic yield is twice as high as the radiation yield. When taking into account the energy deposition efficiency (ϵ_d), the overall fusion energy to chemical energy conversion efficiency is less than 10%. Dual process systems must then be considered. However, since the ozone decomposes rapidly at temperatures above $100^\circ C$, lower temperature cooling streams are required to stabilize the O_3 . Therefore, the waste heat is not available for electrical energy production through an efficient power cycle.

A dual system is possible for a system which utilizes UV radiation from the plasma and neutron and gamma radiation from the blanket for converting oxygen to ozone. In this manner the overall efficiency can be increased significantly to 11.9% with a minimum energy requirement of 3.1 kwh(t)/lb. Thus with this dual system, the energy efficiency is increased 150% (2.5 times) over that of the electric discharge ozonizer process.

A flow sheet of the CTR radiation process is presented in Figure 5. The oxygen is separated from the atmosphere by liquefaction and the ozone can be recovered by a Freon absorption-stripping operation. The largest potential market for ozone is for treatment of sewage and for disinfection of drinking water. The ozonized oxygen stream from the CTR process may be used directly in a water treatment unit and the oxygen recycled to the CTR reactor.

Assuming 90% of the precipitation stream flow of water in the U.S. which is 368×10^{12} gallons/yr. is treated with 30 ppm of ozone for disinfection purposes, an annual production rate of 3.7×10^6 tons/yr. of ozone is needed. At the rate of 3.7 KW(t)/lb. O_3 which also includes power for oxygen production, the total CTR thermal power requirement amounts to 50,000 MW(t). The overall power requirement

is relatively small, compared to that for hydrogen or methanol. (See Table 19 later.) Because ozone production would be close to points of consumption, the size of an ozone CTR should be the smallest feasible (500 to 5000 MW(t)).

Since the capacity requirements are not large, single purpose O_3 reactors may not be justified. However, dual purpose reactors which produce primarily power and ozone as a by-product by the electric discharge process might be considered economical. They may be sited near sources of water supplies needing treatment as well as power load centers.

3. Methanol as a Synthetic Liquid Hydrocarbon Fuel

It has become increasingly apparent that the problem in providing an adequate energy source is the form in which fuel is required by the consumer. Thus in addition to the problem of availability of crude supplies of coal and oil, the conversion of these fuels to consumable liquids and gases becomes a critical item. Petroleum refining capacity, coal gasification and coal liquefaction become important factors in the energy supply chain. ⁽¹⁸⁾ A liquid hydrocarbon fuel being proposed as an automotive fuel and as a power plant fuel is methanol. ⁽¹⁹⁾ The reasons for methanol are:

(1) Methanol can be produced from coal, natural gas or oil by reforming and catalytic synthesis with relatively

well known technology.

(2) Methanol can be used as an automotive fuel with much less pollution than gasoline.

(3) Methanol has physical and chemical properties which allow convenient storage and transporting in conventional tankers. It is reported that foreign sources of methane and low boiling hydrocarbons are being considered for conversion to methanol, thus avoiding the problem of shipping these fuels in expensive and unavailable cryogenic tankers.

(4) Methanol can be blended with other liquid hydrocarbon fuels (gasoline) for extending supplies.

(5) Methanol can be used for powering fuel cells.

The main disadvantage to methanol as a fuel is its lower heating value at 9000 BTU/lb. compared to gasoline at 18,000 BTU/lb. Part of this disadvantage is said to be recovered by methanol's higher burning efficiency. Extensive large scale production runs are presently in progress to prove out methanol as a viable power plant fuel.

The use of nuclear energy and in particular CTR fusion energy for the synthesis and production of methanol presents an intriguing approach to the problem of providing a renewable supply of liquid hydrocarbon fuels. A very attractive possibility is to derive the raw materials only from air

and water. That is, the source of supply of carbon can be the carbon dioxide in the atmosphere and the hydrogen from water. As long as fossil fuel (coal, oil or gas) is available, it probably will be more economical to convert this carbon containing natural resource to liquid hydrocarbon fuels than by any CTR route using non-fossil fuel resources. CTR energy, as previously mentioned, can reduce fossil fuel requirements by the endothermic energy for coal reforming and hydrogenation processes. Limestone can also provide another source of carbon containing material which can be made available through thermal decomposition. However, an overriding problem with these condensed carbon sources is the restrictions imposed by environmental, ecological, political and social conditions. These restrictions could, in effect, render fossil fuels unavailable. If CO₂ can be derived from the atmosphere and converted to a liquid fuel, the following advantages would derive.

- (1) Eliminate the hazards of deep coal mining.
- (2) Eliminate the ecological problems of strip mining.
- (3) Eliminate the sulfur and trace element pollution problems due to burning fossil fuels.
- (4) A CO₂ balance can be kept in the atmosphere avoiding any possible greenhouse effect.
- (5) Plants will no longer be restricted to sites close to large deposits of fossil fuel.

An examination of the availability of CO_2 and the energy required to extract the CO_2 from the atmosphere can be made. There is a very large quantity of CO_2 in the atmosphere ($\sim 10^{13}$ tons). The concentration, however, is limited to 0.034 vol. %. It should be pointed out that this concentration is practically constant all over the world and mainly controlled by the CO_2 solubility in the vast oceans. Furthermore, there will be no depletion of CO_2 in the synthesis-combustion cycle. The methanol serves as an energy carrier only.

By analogy, the nuclear methanol-combustion cycle is similar to the photosynthetic-fuel cycle. The latter converts solar energy to cellulose (wood) by reaction of CO_2 and water, with the emission of oxygen. The cellulose is then oxidized back to CO_2 and water by combustion which releases thermal energy.

The Photosynthetic-Fuel Cycle

+ thermal energy

The Nuclear-Methanol Cycle

Whereas the photosynthetic cycle has a constant readily available energy source from the sun and the process operates with naturally occurring low concentrations of CO_2 in the atmosphere, in the synthetic nuclear-methanol cycle, the energy must be derived from man made nuclear energy and the methanol conversion process requires (for energy economy) much higher concentrations of CO_2 than occurs in the atmosphere naturally and must take place in the absence of oxygen.

The main question to be answered is how much energy is required to separate the CO_2 from the atmosphere and to recover a concentrated CO_2 stream. Thermodynamically, the minimum amount of energy required to perform the separation can be calculated from the ideal free energy of reversible processes:

$$\Delta F = 4.575 T \log \frac{P_2}{P_1}$$

where:

ΔF is the free energy of concentration in cal/gm mol

P_1 is the partial pressure of CO_2 in the atmosphere

(0.034% by vol = 3.4×10^{-4} atm)

P_2 is the desired partial presence of CO_2 in the concentrated stream (100% conc. = 1.00 atm)

T is the absolute temperature in $^{\circ}\text{K}$

thus:

$$F = 4.575 \times 298.2 \log \frac{1.000}{3.5 \times 10^{-4}}$$

$$= 4715 \text{ cal/gm mol}$$

$$= 113.0 \text{ kwh(t)/ton CO}_2$$

$$= 0.0565 \text{ kwh(t)/lb. CO}_2$$

Thus we have the minimum thermodynamic energy required to concentrate CO_2 from atmospheric conditions to 100% at 1 atm pressure. We now need a mechanism to perform this process. The separation can be performed either by (1) a low temperature refrigeration cycle similar to separation of oxygen by the well-known air liquefaction process, or (2) by solvent absorption-stripping recovery system, for example with a solvent such as water or methanol, or (3) by a solid adsorption-desorption process with such adsorbents as silica gel, or molecular sieves. As an example, let us examine the oxygen separation process to determine what kind of efficiencies can indeed be obtained in practice.

The minimum amount of energy required for oxygen separation is as follows:

$$\Delta F = 4.575 \times 298.2 \log \frac{1.000}{0.210}$$

$$= 924.7 \text{ cal/gm mol}$$

$$= 30.5 \text{ kwh/ton O}_2$$

$$= 0.015 \text{ kwh/lb. O}_2$$

It is known that the air liquefaction plant requires 300 kwh of electrical energy to produce 1 ton of oxygen. Thus the separation is 10% ($30.5/300 \times 100$) efficient based on the thermodynamic minimum value. By similar reasoning it should take about 10 times the amount of energy for CO_2 separation. Thus the energy requirement for CO_2 production from air should be 1130 kwh(e)/ton or 0.57 kwh(e)/lb. CO_2 . At present, one cannot a priori choose the most efficient method for CO_2 separation. It appears attractive to choose the water absorption-stripping process because of the readily available solvent and the well known chemical engineering unit operation of absorption-stripping. A compression refrigeration cycle may be just as attractive. This is a point to be thoroughly investigated for further evaluation and development. The humidity of the air may be a problem because of the relatively large amount of water which could separate in the process and must be handled. This water could be used as a source of supply of water for hydrogen production. The large cooling towers which provide cooling for the power cycle could act as a head end absorption tower for CO_2 recovery. The process may be less than 10% efficient, however, this will not make a significant difference, as will be seen below, because the predominant energy requirement involves the production of hydrogen.

Once the CO_2 is extracted from the atmosphere several process routes can be taken for methanol production. These are outlined in the following, and in Table 16.

(1) The CO_2 can be irradiated in a neutron-gamma process to CO and oxygen and the CO separated and reacted with water to form H_2 which is catalytically combined with CO to form methanol. A process flow sheet is shown in Figure 6, but without the electrical power generation and electrolytic cell line. This is a non-electrolytic process requiring 3 moles of CO per mole of methanol and due to the relatively low energy conversion efficiency, the thermal energy requirement is high, 27.8 kwh(t)/lb. CH_3OH . Out of this energy, approximately 5 kwh(t) is utilized to separate the CO_2 from the atmosphere.

(2) A dual process can be devised in which the CO_2 removed from the atmosphere is decomposed to CO and O_2 by α, γ irradiation and the hydrogen is produced by the electrolytic decomposition of water. The temperature of the CO_2 process stream is high enough to produce power. This gives the lowest energy requirement of 9.3 kwh(t)/lb. CH_3OH and only 1 mole CO is required per mol of methanol so that 2 kwh(t)/lb. CH_3OH is needed for CO_2 separation. A flow sheet of this process is shown in Figure 6.

(3) The third process is an all electrical process in which hydrogen is electrolytically generated and the CO_2 separated from air is catalytically reacted with the hydrogen to form methanol. The total energy requirement for this process is 10.5 kwh(t)/lb. methanol. A process flow sheet is presented in Figure 7.

It is noted in Table 6 that the dual radiolytic-electrolytic process yields the lowest energy requirement, but that it is only about 10% less than the all-electrolytic process. Additional analysis of the total production cost would be required to decide between the two systems. Another point is that the efficiency of converting CTR energy to energy in methanol as a combustible fuel is as high as 28%.

A further analysis of the electrolytic process is given in Table 17. The electrical energy required to separate CO_2 represents less than one fourth of the electrolytic requirement or 19% of the total energy. The production capacity in the range of CTR power levels of 1000 to 9000 MW(e) extends from 21,000 to 189,000 bbl/day which falls into the range of a modern day oil refinery.

For the purpose of establishing an order of magnitude value, a preliminary cost estimate for methanol production by the electrolytic hydrogen route and CO_2 from the atmosphere

is given in Table 18. The estimate is based on unit capital costs for CTR reactors varying from \$350 to \$225/KW(e) depending on capacity and the electrolytic cells at \$50 to \$25/KW(e). The methanol plant cost is mainly for the catalytic converters and heat exchangers ranging from \$2,500 to \$1,000/bbl methanol. The CO₂ separation plant is based on a rough estimate from large size (10,000 tons/day) oxygen separation plants which mainly involves extrapolation based on the handling capacity of huge volumes of air. Relatively large investments ranging from \$7,500 to \$3,000/bbl methanol are obtained for CO₂ separation and have a high degree of uncertainty attached to them. The total investment cost for these plants are huge, ranging up to \$3 billion for the 189,000 bbl/day plant. The largest part of the investment or about 2/3 is in the CTR reactor cost. Raw material cost is negligible in terms of D and T fuel and air. The methanol production cost range from 21.1 ¢/gallon down to 12.0 ¢/gallon and if a larger CTR based plant is available to provide off-peak power to a methanol plant at 1.5¢ kwh(e), methanol could be produced for as low as 7.5¢/gal. The cost in terms of thermal value range from \$3.50 to \$2.00/MM BTU and off-peak to \$1.25/MM BTU. Compared to gasoline at \$0.40/gallon (\$3.05/MM BTU) CTR methanol could be fairly reasonable. The conclusion is that the use of CTR for providing

an independent source of liquid fuels has an economically interesting potential.

Two other process possibilities exist for production of methanol.

(1) There is evidence in the literature that a K_2CO_3 solution can be electrolyzed to produce potassium formates and subsequently methanol. Figure 8 shows a general flow sheet of a possible process. There is not enough data in the literature to assess this process. However, from a processing point of view the process is simpler than the production of electrolytic H_2 and combination with CO_2 , since it eliminates the necessity for hydrogen generation and a catalytic converter. Experimental work needs to be undertaken for this system.

(2) There is some experimental evidence that formates and methanol form when an aqueous carbonate solution is irradiated by gamma. The aqueous solution is processed in an aluminum blanket as shown in Figure 9. The methanol is then produced directly. The advantages of such a system are that a condensed liquid system is a more efficient system, (see Table 3) and eliminates the difficult O_2 separation from the process stream as well as the power conversion equipment. The disadvantages relate to corrosion of aluminum in the presence of carbonate solutions and the neutron activation of salts and impurities in solution which could contaminate the product.

Neutron and gamma radiation experiments with aqueous carbonate solutions should be undertaken to determine yields and G values to better evaluate this process.

4. Fertilizer and Food Production

A considerable part of our increased agricultural production for food has been due to increased utilization of fertilizer on the farms. Fertilizer requirements mainly involve the fixation of nitrogen. The fixation of nitrogen can be accomplished with CTR energy directly through α, γ radiation reactors forming nitrogen oxides from air and indirectly through electrolytic decomposition of water, generating hydrogen, and combining with nitrogen to form ammonia. Ammonia and nitrogen dioxide are combined to form ammonium nitrate which is a desirable fertilizer.

The CTR Energy requirement for this system is
4.9 kwh(t)/lb N.

Another potentially large scale use of CTR may be in food and protein production. Through a series of reactions, CO_2

could be hydrogenated to methane, partially oxidized to formaldehyde and then condensed to formose sugars. (21)

The net reaction is similar to one that can be written for the photosynthesis of sugars. Research and development work is necessary to optimize the system for specific carbohydrate production.

5. CTR Capacity Projections

In Table 19, a summary of the capacity of CTR required in the year 2000 for the major products mentioned in the previous sections are made. The hydrogen capacity projection is for processing, mainly hydrogenation of fossil fuels and the reduction of iron ore. The ozone is for treatment of water mentioned earlier and the methanol is projected to supply 50% of the automotive transportation power. The conclusion is that hydrogen for chemical processing and methanol liquid fuel will require large multi-million megawatt CTR capacity, while ozone

being very important for the water treatment economy will be produced essentially as a by-product from the CTR power economy. The fixation of nitrogen could support several large plants around the country for supplying fertilizer.

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TABLE 1
ENERGY DISTRIBUTION FOR FUSION REACTIONS

Reaction	Total Energy Mev	ε _f - Distribution of Energy %		
		<u>Plasma</u>	<u>Neutron + prompt gamma</u>	<u>Alpha in blanket</u>
1. D-T Reaction				
D + T - ⁴ He (3.5 Mev) + x (14.1 Mev)	17.5	20%	80%	0
2. D-T Reaction with T breeding				
D + T - ⁴ He (3.5 Mev) + x (14.1 Mev)	22.3	16	63	21
x + ⁶ Li - T + α (4.7 Mev)				
3. D-D Reaction				
D + D $\begin{cases} \rightarrow \text{}^3\text{He} (0.82 \text{ Mev}) + x (2.45 \text{ Mev}) \\ \rightarrow \text{T} (1.01 \text{ Mev}) + p (3.02 \text{ Mev}) \end{cases}$	3.65	65	35	0
4. D- ³ He Reaction				
D + ³ He - ⁴ He (3.6 Mev) + p (14.7 Mev)	18.30	100	0	0

TABLE 2

ENERGY FOR CHEMICAL CONVERSION PROCESSES

Energy range, eV	Type of energy	Conversion efficiency term	Energy yield in various units		
			E, KWH/lb	G-value $\frac{\text{molecules}}{100 \text{ eV}}$	eV $\frac{\text{electron volts}}{\text{molecule}}$
0 to 5	Thermal	Heat of reaction = $\Delta H \frac{\text{Kcal}}{\text{g mol}}$	$\frac{0.528 \Delta H}{M}$	$\frac{2307}{\Delta H}$	$\frac{\Delta H}{23.07}$
1 to 15	Photolytic	Quantum yield = $\frac{\text{molecules}}{\text{quanta}}$	$\frac{1.51 \times 10^5}{\lambda M}$	$8.1 \times 10^{-3} \lambda \phi$	$\frac{12,400}{\lambda}$
0 to 10	Electrolytic	Faraday = $F \frac{26.8 \text{ amp-hr}}{\text{g. equivalent}}$	$\frac{12.16 n F e}{M}$	$\frac{100}{n F e}$	eV
10^3 to 10^5	Electric discharge	m/N -values = $(m/N) \frac{\text{molecules}}{\text{ion pair}}$	$\frac{405}{(m/N) M}$	$3 (m/N)$	$\frac{30}{(m/N)}$ for 30 eV per ion pair
		Current equiv $F = \frac{I t n}{26.8 M}$	$\frac{0.454 n I e t}{M}$	$\frac{2680}{n I e t}$	$\frac{n I e t}{26.8}$
10^5 to 10^7	High energy radiation	G value = $G \frac{\text{molecules}}{100 \text{ eV}}$	$\frac{1216}{G M}$	G	$\frac{100}{G}$
		C/R = % conversion/megarad	$\frac{1.26 \times 10^{-3} R}{C}$	$\frac{9.64 \times 10^3 C}{MR}$	$\frac{MR}{96.4 C}$

Notes: M = molecular weight; n = No. of equivalents per gm molecular wt.; e = potential drop, volts; λ = wavelength Å; I = current, amperes; t = time in hrs; R = radiation dose, megarads; C = conversion, %; m = molecules; N = ion pair.

TABLE 3

**SUMMARY OF CTR ENERGY FORMS FOR
CHEMICAL AND MATERIAL PROCESSING**

General Process Conditions and Available Efficiency Factors

<u>Energy Form</u>	<u>Intensity</u>	<u>Pressure</u>	<u>Available efficiency factors from D-T cycle</u>			
			ϵ_f	ϵ_p	ϵ_r	$\epsilon_d = (\epsilon_f \epsilon_p \epsilon_r)$
1. Thermal						
a. Direct blanket coolant	1500°C	30 atm	1.0	1.0	0.75	0.75
b. Indirect blanket coolant	2500°C	30 atm	1.0	1.0	0.75	0.75
c. Direct CTR Plasma	>3000°C	low	0.2	0.5	1.0	0.1
2. Electrical						
a. Low voltage - electrochemical	to 10V	-	1.0	0.4	1.0	0.4
b. High voltage - arc & discharge	to 50. kV	-	1.0	0.4	1.0	0.4
3. High Energy Radiation						
a. Neutrons	≤ 14.1 Mev	200 atm				
		gas	0.8	1.0	0.5	0.4
		liquid	0.8	1.0	1.0	0.8
b. Gamma - direct & indirect	≤ 10 Mev	200 atm				
		gas		0.6	0.5	0.3
		liquid		0.6	1.0	0.6
c. Secondary particles - p, α, β	2 Mev	100 atm	0.8	0.05	1.0	0.04
d. Ionized particles from plasma	10 Kev	100 atm	0.2	0.5	1.0	0.1
4. UV from plasma						
	5-20 ev	1-10 atm	0.2	0.5	0.8	0.08

TABLE 4

GAMMA ENERGY CONVERSION EFFICIENCIES OBTAINABLE FROM FUSION REACTOR CYCLES

	1. D-T Reactor with Breeding of Tritium	2. D-T Burner Tritium Surplus from other Reactors	3. Catalyzed D-D Reactor	4. D-D Reactor with Conversion of ^3He to T by Neutron Capture
Neutron Energy-MEV	14.1	14.1	14.1 2.5	28.2 2.5
Gamma Energy from Neutrons-MEV				
a) Inelastic Gammas*	7	7	8.3	15.3
b) Capture Gammas**	<u>-</u>	<u>8</u>	<u>16</u>	<u>16</u>
Total	7	15	24.3	31.3
Total Energy Released, MEV	22.3/D-T Fusion	25.6/D-T Fusion	59.2/2D-D Fusion	59.2/2D-D Fusion
Gamma Radiation Fraction % of Total Energy	7/22.3 31.5%	15/25.6 58.6%	24.3/59.2 41.0%	31.3/59.2 53.0%

* Assumes conservatively 50% conversion to gamma radiation

** Assumes conservative average of 8 MEV prompt gamma radiation

TABLE 5

UV ENERGY CONVERSION EFFICIENCIES OBTAINABLE
FROM FUSION REACTOR CYCLES

<u>Efficiency term</u>	<u>D-T Reactor</u>	<u>D-D Catalyzed Reactor</u>	<u>D-He³ Reactor</u>
ϵ_f = fraction of plasma energy/fusion	0.2	0.65	1.00
ϵ_p = fraction converted to UV - seed and diverter	0.5	0.51	0.65
ϵ_r = fraction absorbed in process stream	0.8	0.80	0.80
ϵ_d = available UV energy = $\epsilon_f \epsilon_p \epsilon_r$	0.08	0.26	0.52

TABLE 6

PROJECTION OF THERMAL ENERGY REQUIREMENTS FROM CTR
FOR CONVENTIONAL HEAVY CHEMICAL INDUSTRY
IN THE YEAR 2000

<u>CHEMICAL</u>	<u>PRODUCTION, 10⁶ TONS</u>		⁽¹⁾ <u>FUSION ENERGY</u>
	<u>PRESENT</u>	<u>2000</u>	<u>CONSUMPTION, MW(t), 2000</u>
Cement	80	320	120,000
H-Iron	85	130-174	182,000-244,000
Chlorine	10.3	26-44	50,000-85,000
Oxygen	16	39-75	6,000-11,700
Ammonia (Anh.)	16.2	28-51	80,000-150,000
Hydrogen	5.2	19-104	242,000-1,296,000
TiO ₂	0.8	1.8-3.9	--
Phosphoric Acid	6.8	24	35,000
Acetylene	0.5	0.5	2,000
Sodium Silicate	0.7	2.8	600
Lime	19.7	80	18,000
NaOH	10.6	31	See Chlorine
Gypsum	8.6	21-31	500-1,700
Methanol	3.5	14	33,000
Aluminum	5.0	22-44	<u>110,000-220,000</u>
TOTAL			1.3-2.1 x 10⁶ MW(t)

¹ Taken at 75% Thermal Efficiency for Thermal Reactions, 40% Electrical Energy Conversion Efficiency, 0.8 Plant Factor

TABLE 7

UNIT ENERGY REQUIREMENTSPRESENTLY PRACTICED CONVENTIONAL PROCESSES

<u>Chemical</u>	<u>Process</u>	<u>Energy Consumed</u>	
		<u>BTU/Ton</u>	<u>kwh(e)/Ton</u>
Cement	Calcining	7×10^6	
H-Iron	Ore Reduction	13.7×10^6	
Chlorine	Electrolysis	22×10^6	+ 2.8×10^3
Oxygen	Air Separation		400
Ammonia	Nat. Gas Reforming	34×10^6	
Hydrogen	Electrolysis		44×10^3
Phosphoric Acid	Electric Furnace		4×10^3
Acetylene	Nat. Gas-Oxidation	190×10^6	+ 1.5×10^3
Sodium Silicate	Furnace	5×10^6	
Lime	Calcining	5×10^6	
NaOH	Electrolysis		See Chlorine
Gypsum	Calcining	0.4×10^6	
Methanol	Nat. Gas Reforming	18×10^6	
Aluminum	Electrochemical Reduction		14×10^3

TABLE 8

PROJECTION OF ELECTRICAL ENERGY REQUIREMENTS FROM CTR
FOR THE CONVENTIONAL HEAVY CHEMICAL INDUSTRY
IN THE YEAR 2000

<u>Chemical</u>	<u>MW(e), 2000</u>
H-Iron	45,000 - 61,000
Chlorine	10,000 - 17,000
Oxygen	2,400 - 4,700
Ammonia	28,000 - 51,000
Hydrogen	97,000 - 518,000
Phosphoric Acid	14,000
Acetylene	800
Sodium Hydroxide	See Chlorine
Methanol	13,000
Aluminum	<u>44,000 - 88,000</u>
Total	254,200 - 767,500

TABLE 9

POTENTIAL THERMAL AND ELECTRICAL PROCESSES FOR APPLICATION
OF FUSION ENERGY

Thermal Reactions

1. Wisconsin Process for nitric oxide
2. Acetylene from Methane
3. Decomposition of CO_2 to CO and O_2
4. Decomposition of Water
5. Coal Gasification
6. Shale Retorting
7. Lime
8. Cement
9. Gypsum
10. Iron Ore Reduction
11. Ammonia
12. Titanium Dioxide
13. Sodium Silicate

Electrical Processes

Electrochemical

1. Hydrogen and Synthetic Fuels
2. Oxygen
3. Caustic-Chlorine
4. Metal Refining - Al, Mg, Cu

High Voltage Electrical

1. Phosphorus and Phosphoric Acid
2. Birkland-Eyde, NO_2
3. Acetylene via Arc Process
4. Hydrogen Peroxide
5. Ozone

TABLE 10

HIGH ENERGY RADIATION REACTIONS

EXPERIMENTAL G VALUES AND THERMAL EFFICIENCIES FOR ENDOTHERMIC REACTIONS

Reaction	Product	Heat of reaction at 25°C ΔH kcal/mole	G _{max} molecules 100 eV	G _{exp} molecules 100 eV	^ε _C Thermal efficiency %	Type of radiation
$\text{H}_2\text{O}(l) = \text{H}_2(g) + \frac{1}{2}\text{O}_2(g)$	Hydrogen	+68.3	33.8	1.7	5.0	F.F.
$\text{H}_2\text{O}(g) = \text{H}_2(g) + \frac{1}{2}\text{O}_2(g)$	Hydrogen	+57.9	39.9	6.0	15.0	α
$2\text{H}_2\text{O}(l) = \text{H}_2\text{O}_2(l) + \text{H}_2(g)$	Hydrogen peroxide	+91.4	25.2	1.7	6.6	F.F.
$\frac{1}{2}\text{N}_2(g) + \text{O}_2(g) = \text{NO}_2(g)$	Nitrogen dioxide	+8.1	284	5 7.4	1.8 2.6	n, v F.F.
$\text{N}_2(g) + \frac{1}{2}\text{O}_2(g) = \text{N}_2\text{O}(g)$	Nitrous oxide	+19.6	116	3.0	2.5	n, v
$\text{CO}_2(g) = \text{CO}(g) + \frac{1}{2}\text{O}_2(g)$ NO ₂ inhibited	Carbon monoxide	+67.6	34.1	10.0	29.4	α and F.F.
$2\text{NH}_3(l) = \text{N}_2\text{H}_4(l) + \text{H}_2(g)$	Hydrazine	+48.0	48.1	0.13 1.9	0.3 4.0	γ F.F.
$\frac{3}{2}\text{O}_2(g) = \text{O}_3(g)$	Ozone	+34.0	68.1	15	22.0	β
$2\text{CH}_3\text{OH}(l) = (\text{CH}_2\text{OH})_2(l) + \text{H}_2(g)$	Ethylene glycol	+3.6	640	3	0.5	F.F.
$2\text{CH}_4(g) = \text{C}_2\text{H}_4(g) + 2\text{H}_2(g)$	Ethylene	+48.3	47.3	3	6.3	β
$2\text{CH}_4(g) = \text{C}_2\text{H}_2(g) + 3\text{H}_2(g)$	Acetylene	+90.0	25.6	0.5	2.0	β
$\frac{1}{2}\text{C}_6\text{H}_6(l) = \text{C}_2\text{H}_2(g)$	Acetylene	+49.0	47.0	0.42	2.0	β
$\text{CO}_2(g) + \text{H}_2\text{O}(l) = \text{CH}_2\text{O}(l) + \frac{1}{2}\text{O}_2(g)$	Formaldehyde	+134.7	19.2	0.85	4.4	γ
$\text{CO}_2(g) + \text{H}_2\text{O}(l) = \text{CH}_2\text{O}_2(l) + \frac{1}{2}\text{O}_2(g)$	Formic acid	+64.6	35.7	0.25	0.7	γ

Subscripts (l) and (g) refer to liquid and gaseous state.

TABLE 11

HIGH ENERGY RADIATION REACTIONS

EXPERIMENTAL G VALUES AND THERMAL EFFICIENCIES FOR EXOTHERMIC REACTIONS

Reaction	Product	Heat of reaction at 25°C ΔH kcal/mole	G_{exp}	Type of radiation
$\frac{1}{2}N_2(g) + 3H_2(g) = NH_3(g)$	Ammonia	-11.0	1	α
$2N_2O(g) = \frac{1}{2}N_2(g) + NO_2(g)$	Nitrogen dioxide	-47.3	5	F.F.
$C_6H_6(l) + \frac{1}{2}O_2(g) = C_6H_5OH(l)$	Phenol	-1.9	1,000	γ
$nC_2H_4(g) = (C_2H_4)_n(s)$	Polyethylene	-22.0	136,000*	γ
$C_6H_6(l) + 3Cl_2(g) = C_6H_6Cl_6(l)$	Hexachlorobenzene	-	85,000	γ
$C_2H_4(g) + HBr(l) = C_2H_5Br(l)$	Ethyl bromide	-24.2	39,000	γ
$nC_2H_2(g) = (C_2H_2)_n(s)$	Polyacetylene	-	75*	α
$3CO(g) = C_3O_2(s) + \frac{1}{2}O_2(g)$	Carbon suboxide	-	2	α
$H_2(g) + O_2(g) = H_2O_2(l)$	Hydrogen peroxide	-45.2	-	-

* G_{exp} values for these reactions are in terms of number of reactant molecules removed due to reaction per 100 eV deposited.

Subscripts (l), (g) and (s) refer to liquid, gaseous, and solid state.

TABLE 12
RADIATION PROCESSES
OVERALL EFFICIENCY AND ENERGY REQUIREMENT
FOR SELECTED PROCESSES

<u>Reaction</u>	<u>Product</u>	<u>ΔH Kcal/mol</u>	<u>ϵ_d Energy Deposit. Eff.</u>	<u>ϵ_c Chemical Conv. Eff.</u>	<u>ϵ_o Overall Eff.</u>	<u>E Kwh(t)/lb</u>
$\text{CO}_2(\text{g}) = \text{CO}(\text{g}) + 1/2 \text{O}_2(\text{g})$	Carbon Monoxide	67.6	0.4	0.294	0.12	10.6
$\text{H}_2\text{O}(\text{g}) = \text{H}_2(\text{g}) + 1/2 \text{O}_2(\text{g})$	Hydrogen	57.9	0.4	0.15	0.06	252.0
$\text{H}_2\text{O}(\text{l}) = \text{H}_2(\text{g}) + 1/2 \text{O}_2(\text{g})$	Hydrogen	68.3	0.8	0.05	0.04	450.0
$2\text{H}_2\text{O}(\text{l}) = \text{H}_2\text{O}_2(\text{l}) + \text{H}_2(\text{g})$	Hydrogen Peroxide	91.4	0.8	0.068	0.054	29.3
$3/2 \text{O}_2(\text{g}) = \text{O}_3(\text{g})$	Ozone	34.0	0.4	0.22	0.088	4.2
$2\text{CH}_4(\text{g}) = \text{C}_2\text{H}_4(\text{g}) + 2\text{H}_2(\text{g})$	Ethylene	48.3	0.4	0.063	0.029	31.4
$2\text{CH}_4(\text{g}) = \text{C}_2\text{H}_2(\text{g}) + 3\text{H}_2(\text{g})$	Acetylene	90.0	0.4	0.020	0.080	22.9
$\text{CO}_2(\text{g}) + \text{H}_2\text{O}(\text{l}) = \text{CH}_2\text{O}(\text{l}) + \text{O}_2(\text{g})$	Formal- dehyde	134.7	0.8	0.044	0.035	68.0
$1/2 \text{N}_2(\text{g}) + \text{O}_2(\text{g}) = \text{NO}_2(\text{g})$	Nitrogen Dioxide	8.1	0.4	0.026	0.010	9.3

TABLE 13

PHOTOCHEMICAL REACTIONS
EXPERIMENTAL QUANTUM YIELDS AND ENERGY REQUIREMENT
FOR ENDOTHERMIC REACTIONS

Reaction	Product	ΔH Kcal/ mole	Quantum Yield ϕ	Wavelength λ , Å	ϵ_c	ϵ_d	ϵ_o	E Kwh(t) lb
$H_2O(g) = H_2(g) + 1/2 O_2(g)$	Hydrogen	57.9	0.4	1849Å	0.15	0.08	0.012	1260.0
$3/2 O_2(g) = O_3(g)$	Ozone	34.0	2.0	1751-2050	0.42	0.08	0.034	11.0
$CO_2 = CO + 1/2 O_2$	Carbon Monoxide	67.6	1.0	1295-1470	0.31	0.08	0.025	51.0
	Amino acids							

TABLE 14

COMPARISON OF HYDROGEN GENERATION BY ALTERNATE CTR PROCESSES

<u>Process</u>	<u>ϵ_f</u>	<u>ϵ_p</u>	<u>ϵ_r</u>	<u>ϵ_d</u>	<u>ϵ_c</u>	<u>ϵ_o</u>	<u>ϵ_t</u>	<u>E $\frac{\text{Kwh (t)}}{\text{lb}}$</u>
Electrolysis liquid	1.0	0.4	1.0	0.4	0.85	0.34		45
Radiolysis gas	0.8	1.0	0.5	0.4	0.15	0.06		252
Photolysis gas	0.2	0.8	0.5	0.08	0.15	0.012		1260
Thermal dissociation	1.0	1.0	0.75	0.75	0.10	0.075		202
Dual Process Radiolysis + Electrolysis							0.38	39.7
Dual Process Photolysis + Electrolysis							0.35	43.2
Dual Process Thermal + Electrolysis							0.39	38.8

TABLE 15

COMPARISON OF OZONE SYNTHESIS BY ALTERNATE CTR PROCESSES

<u>Process</u>	<u>ϵ_f</u>	<u>ϵ_p</u>	<u>ϵ_r</u>	<u>ϵ_d</u>	<u>ϵ_c</u>	<u>ϵ_o</u>	<u>ϵ_t</u>	<u>E $\frac{\text{Kwh}(t)}{\text{lb}}$</u>
Electric Discharge	1.0	0.4	1.0	0.4	0.12	0.048		7.8
Radiolysis	0.8	1.0	0.5	0.4	0.22	0.088		4.2
Photolysis	0.2	0.8	0.5	0.08	0.42	0.034		11.0
Dual Process Photolysis and Radiolysis							0.119	3.1

TABLE 16

METHANOL SYNTHESIS UTILIZING CTR ENERGY

CTR Process	ϵ_o overall energy conversion efficiency	E KWh(t) lb CH ₃ OH	% Efficiency of conversion of CTR energy to methanol used as a fuel
1. α, γ Radiation Process		27.9	9.4%
(1) CO ₂ extraction from air			
(2) 3 CO ₂ = 3CO + 3/2 O ₂ (radiation)	0.12		
(3) 2 CO + 2H ₂ O = 2CO ₂ + 2H ₂ (shift)			
(4) CO + 2H ₂ = CH ₃ OH (catalytic)			
2. α, γ Radiation Process and Electrolysis		9.3	28.4%
(1) CO ₂ extraction from air			
(2) 2H ₂ O = 2H ₂ + O ₂ (electrolysis)	0.34		
(3) CO ₂ = CO + 1/2 O ₂ (radiolysis)	0.12		
(4) CO + 2H ₂ = CH ₃ OH (catalytic)			
3. Electrolytic Process		10.5	25.1%
(1) CO ₂ extraction from air			
(2) 3H ₂ O = 3H ₂ + 1/2 O ₂ (electrolysis)	0.34		
(3) CO ₂ + 3H ₂ = CH ₃ OH + H ₂ O (catalysis)			

TABLE 17

ELECTRICAL ENERGY REQUIREMENT
FOR PRODUCTION OF LIQUID HYDROCARBON FUEL
(METHANOL) FROM AIR, WATER AND NUCLEAR FUSION (CTR) POWER

Reactions

CO₂ separation from atmosphere 0.034% CO₂ - 100% CO₂ (atm. press.)

$$\Delta F = 4715 \text{ cal/mol}$$

Electrolysis $3\text{H}_2\text{O} = 3\text{H}_2 + 3/2 \text{O}_2$

$$\Delta F = 170,100 \text{ cal/3 mol H}_2$$

Catalysis $\text{CO}_2 + 3\text{H}_2 = \text{CH}_3\text{OH} + \text{H}_2\text{O}$

$$\Delta H \text{ exothermic} = 10,000 \text{ cal/mol}$$

<u>Electrical Energy Requirement</u>	<u>Kwh(e)/lb CH₃OH</u>	<u>% of Total Energy</u>
Electrolytic H ₂ (85% eff. cells)	3.31	81
Separation of atmospheric CO ₂ (10% eff.)	<u>0.78</u>	<u>19</u>
Total Electrical Energy	4.09	100
	27.8 Kwh(e)/gal.	

PRODUCTION CAPACITY

<u>Nuclear Reactor Power</u> <u>MW(e)</u>	<u>Methanol Production Capacity</u> <u>bbl/day</u>
1000	21,000
3000	63,000
9000	189,000

TABLE 18

PRELIMINARY COST ESTIMATE FOR PRODUCTION OF LIQUID HYDROCARBON FUEL (METHANOL)
FROM AIR, WATER AND NUCLEAR FUSION (CTR) POWER

Electrical Energy Requirement = 4.09 KWh(e)/lb = 27.8 KWh(e)/gal CH₃OH

Capacity		Capital Investment						
MW(e)	bbl/day methanol	Power plant \$/KWh(e)	Electro- lyzers \$/KWh(e)	Power plant & electrolyzers total (\$ 10 ⁶)	CO ₂ separation \$/bbl	Methanol synthesis \$/bbl	CO ₂ methanol plant-total (\$10 ⁶)	Total capital investment (\$ 10 ⁶)
1000	21,000	\$350	\$50	\$400	7,500	2,500	200	600
3000	63,000	285	35	960	5,000	1,500	470	1,430
9000	189,000	225	25	2,250	3,000	1,000	700	3,000
9000 ⁽³⁾	189,000				3,000	1,000	750	

Capacity		Production Cost					
MW(e)	bbl/day methanol	Electrical energy cost mills/KWh(e) ⁽¹⁾	Raw materials	Operating & Maint.	Amortiz.	Total	Thermal value \$/MMBTU
1000	21,000	5	0.0¢ ⁽²⁾	0.5¢	20.6¢	21.1¢	\$3.50
3000	63,000	4	0.0	0.5	16.5	17.0	2.85
9000	189,000	3	0.0	0.5	12.5	12.0	2.00
9000	189,000	1.5 ⁽³⁾	0.0	3.3 ⁽³⁾	4.2 ⁽³⁾	7.5	1.25

Notes:

- 1) Nominal cost of power from CTR power plant
- 2) D-T fuel cost/gal CH₃OH = 0.02¢/gal; air is free
- 3) Off-peak power from larger base load CTR - Power taken on oper. cost and amortization taken only on methanol plant.
- 4) Amortization based on 90% plant operating factor and 10% straight line depreciation.
- 5) Gasoline at \$.040/gal = \$3.05/MMBTU

TABLE 19

PROJECTED CTR POWER CAPACITY FOR PRODUCTION OF
HYDROGEN, OZONE, METHANOL AND
FIXED NITROGEN FERTILIZER
IN THE YEAR 2000

<u>Process and Product</u>	<u>Production capacity tons/year</u>	<u>Unit energy required KWh(t)/lb</u>	<u>CTR fusion power capacity requirement MW(t)</u>
Electrolytic Hydrogen	104×10^6	45	1.3×10^6
Photolytic-Radiolytic Ozone	3.7×10^6	3.7 ⁽¹⁾	0.05×10^6
Electrolytic-Radiolytic Methanol	1.0×10^9	9.3 ⁽²⁾	2.6×10^6
Electrolytic-Radiolytic Fixed Nitrogen ⁽³⁾	41×10^6	4.9	0.2×10^6

1) Includes energy for separation and supply of O_2 from air

2) Includes energy for separation and supply of CO_2 from air

3) Nitrogen fixed as, NH_3 , NO_2 and NH_4NO_3 and reported in terms of tons/year of N

Figure 1

**THERMAL PROCESS
REVERSING HEAT EXCHANGER CYCLE FOR INDIRECT HEATING**

Figure 2

**NEUTRON-GAMMA
RADIATION PROCESS CTR**

Figure 3

UV PROCESS CTR

Figure 4

OZONE PRODUCTION BY GAMMA RADIATION

FROM A

CONTROLLED THERMONUCLEAR FUSION REACTOR (CTR)

REACTIONS

FUSION REACTION IN PLASMA

n, γ NUCLEAR REACTIONS IN BLANKET

GAMMA RADIATION REACTION IN BLANKET

Figure 5

LIQUID METHANOL FUEL PRODUCTION
FROM AIR, WATER AND A
CONTROLLED THERMONUCLEAR FUSION REACTOR (CTR)

REACTIONS

FUSION REACTION IN PLASMA

n, γ NUCLEAR REACTIONS IN BLANKET

GAMMA RADIATION REACTION IN BLANKET

CATALYTIC REACTION

ELECTROLYTIC REACTION

Figure 6

REACTIONS

$0.034\% CO_2 \rightarrow 100\% CO_2$ (CONC. FROM AIR)

$3 H_2O = 3 H_2 + \frac{3}{2} O_2$

$CO_2 + 3 H_2 = CH_3OH + H_2O$

PRODUCTION OF SYNTHETIC HYDROCARBON FUEL (METHANOL)
FROM FUSION ENERGY (CTR), AIR AND WATER

Figure 7

SYNTHETIC LIQUID HYDROCARBON FUEL FROM ELECTRICITY, AIR AND WATER

Figure 8

DIRECT CONVERSION OF FUSION ENERGY
FOR
PRODUCTION OF LIQUID METHANOL FUEL

Figure 9