RATIONALE FOR CONTINUING R&D IN INDIRECT COAL LIQUEFACTION

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Contract No: Sandia National Laboratories Contract AL-4159
Period of Performance: July 1994-October 1995

OBJECTIVE:

The objective of this analysis is to use the world energy demand/supply model developed at MITRE to examine future liquid fuels supply scenarios both for the world and for the United States. This analysis has determined the probable extent of future oil resource shortages and the likely time frame in which the shortages will occur. The role that coal liquefaction could play in helping to alleviate this liquid fuels shortfall is also examined. The importance of continuing R&D to improve process performance and reduce the costs of coal-derived transportation fuel is quantified in terms of reducing the time when coal liquids will become competitive with petroleum.

ACCOMPLISHMENTS AND CONCLUSIONS:

At the last World Energy Congress meeting in 1992[1], MITRE presented a world energy demand model that was used to estimate total commercial world energy demand to the year 2100. Several future world energy demand scenarios were developed. These scenarios assume that developing countries with low energy consumption per capita but high growth rates in per capita energy consumption, will mimic the rates of change of energy demand that countries ahead of them already experienced in their development progression. The analysis shows that there is an excellent correlation between average annual change in commercial energy (commercial energy is all traded energy but excluding traditional fuels like fuelwood, charcoal, bagasse etc.) use per capita and average energy consumption per capita. This correlation was used to calculate the per capita energy use for each country in the world for each year from the present to 2100. The total world energy demand was then calculated by multiplying these per capita energy consumptions by the population of each country projected to 2100.

This methodology resulted in the world energy demand estimates shown in Figure 1. The upper curve assumes no further efficiency improvements than the present, the lower curve assumes that future energy conversion and end-use efficiencies will continue to improve in the coming century. It is assumed that, after 33 years, existing equipment is replaced by new equipment saving 33 percent of the energy. This 33 year cycle continues for another two cycles of continuing efficiency improvements saving an additional 16.6 and 8.3 percent per cycle. These assumptions are consistent with historical improvements. The result of these cumulative efficiency improvements reduces the world commercial energy demand from 2,090 quads in the no-improvement upper curve case to about 1,050 quads, a three-fold increase over the present world energy demand.

Other analysts and organizations have estimated future world energy demand using various models, and the MITRE estimate is in good agreement with Holdren,[2] Greenpeace[3] and the U.S. Environmental Protection Agency (EPA).[4] The average of the EPA *Rapidly and Slowly Changing World Cases* gives a total world demand of 1,050 quads by the year 2100, in exact agreement with this analysis.

The hypothetical world energy demand scenario shown in Figure 1 estimates that, by 2100, demand may be three times the current demand. How can this demand be satisfied with known energy resources? To answer this, it is necessary to determine the world resource of oil and natural gas, and to make an assumption concerning the availability of nuclear power. Based on estimates from the United States Geological Survey (USGS)[5], the world ultimate resource of conventional oil is estimated to be the sum of the remaining reserve of 1103 billion barrels and the mean of the undiscovered resource of 583 billion barrels to give a total of 1.7 trillion barrels or about 10,000 quads. Because estimates for natural gas are less certain, two ultimate resource levels were assumed. These were: 10,000 quads[6] (10,000 trillion cubic feet TCF) and twice this resource (20,000 quads). Further, it was assumed that there would be no new starts for current technology nuclear plants after the year 2000. Figure 2 shows depletion curves for these resources. Any number of different depletion curves could be investigated, but the point illustrated is, that by 2100, oil and natural gas are essentially depleted. For the high gas assumption, there is still a gas resource remaining, although by 2100 even that is in rapid decline. Not shown in Figure 2 is a resource for coal. Coal availability worldwide is enormous with estimates ranging from 45,000 quads[7] for proved reserves in place, to 240,000 quads[8] for total resource in place. This represents between 500 and 2000 years supply of coal at current usage rates.

Having established the conventional fossil energy supply resource for the world and having estimated a hypothetical world energy demand scenario, these can be superimposed to produce a world energy demand/supply scenario of the type shown in Figure 3. In this scenario, it is assumed that the oil, gas, and present day nuclear follow the depletions shown in Figure 2, coal use remains constant at the present level, and hydroelectric potential triples between now and the year 2100. The area designated as *21st century* in Figure 3 represents the energy shortfall not satisfied by conventional fossil, present day nuclear, and hydroelectric. For this *constant coal use scenario,* this shortfall would have to be supplied by a combination of 21st century nuclear energy technologies and renewable or sustainable energy technologies.

Figure 3 shows that before the year 2030, demand on world oil is such that supply cannot keep pace, and world oil supply starts to decline. This scenario is conservative by assuming that world oil use is essentially constant from the present to 2030. Recent data shows that world oil use is increasing. According to International Energy Agency (IEA)[9] estimates, worldwide consumption of petroleum increased by 1.1 million barrels per day to 68.2 MMBPD in 1994. IEA further estimates that total world demand will increase again by 1.1 MMBPD in 1995 to 69.3 MMBPD. The largest demand increase will occur in Asia (7.6 MMBPD). IEA further estimates that world oil demand will increase to 77 MMBPD by the year 2000, and 92.5 MMBPD by 2010. If oil use does in fact increase significantly worldwide instead of remaining essentially constant as depicted in Figure 3, then demand pressures will hasten the imbalance of oil supply and demand causing the decline to occur before the year 2030.

The U.S. currently produces about 17 quads annually of domestic crude oil and natural gas liquids (NGL) and this production is expected to continue its decline in the future. Figure 4 shows a resource depletion scenario for oil, natural gas, and power from current nuclear plants from the present to the year 2100. These depletion curves are based on the EIA[1] assumptions to the year 2010, and on MITRE energy model assumptions thereafter. The resource base used in this analysis is 136 billion barrels of conventional oil, 1300 TCF of natural gas and for NGL it is assumed that the present rate of production equal to 12 percent of natural gas production on a thermal basis is continued. It is assumed that nuclear energy from current technologies phase out over the time period shown. Justification for using these resource amounts comes from several sources. The Oil Resources Panel[10] in 1992 led by W.L. Fisher, estimated that the U.S. Oil Resource base was between 99 billion barrels (for existing technology at $20/bbl) to 204 billion barrels (for advanced technology at $27/bbl). These resources are the sum of proved reserves, reserve growth in existing fields, and undiscovered resources. The Oil and Gas Journal[11] in a recent article quoting the new U.S. Geological Survey estimates states that "land and state waters of the U.S. contain technically recoverable volumes of 112.6 billion bbl of oil and 1,073.8 tcf of conventional and unconventional gas". The DOE Office of Oil and Gas[12] uses 136 billion bbls as the U.S. resource base. This quantity of oil is made up of the following categories: proved reserves (23 billion barrels oil (BBO)), expected reserves with field development using existing technology (29 BBO), advanced recovery potentials (23 BBO), new reserves through existing exploration technology (37 BBO), new reserves with advanced exploration technology (16 BBO), and advanced recovery potential from discoveries (8 BBO). For natural gas, an average of several independent estimates has been used. These estimates are described in detail in a 1994 article in the Oil and Gas Journal[13].

Imports must be used to make up the shortfall in consumption and this analysis considers two import scenarios that may be applied to the U.S. energy situation from now till 2050. The first scenario assumes that the current U.S. consumption equal to 26 percent of total world petroleum consumption continues out to the year 2050. In this scenario, after about the year 2025, petroleum supply starts to decline because of worldwide supply inadequacies. The second scenario assumes that the quantity of oil that the U.S. can import is proportional to its GDP compared to the total world GDP. As the total world GDP increases due to increasing economic prosperity, so the U.S. percentage of total world GDP declines and thus the level of oil imports declines correspondingly. In this case, the decline is more rapid than the prior assumption of 26 percent of world oil consumption. The point is that the U.S. may not be able to keep on increasing its level of imports continuously without limit.

It is now necessary to turn to expected demand for energy in the U.S. in the future. Figure 5 shows two demand scenarios superimposed on the previously discussed supply scenarios. The higher demand scenario is taken from the EIA Annual Energy Outlook 1995[14] to the year 2010. The essentially constant demand scenario is from the MITRE energy model. If the EIA scenario is correct and U.S. imports are limited by GDP considerations, then a shortfall in required petroleum over domestic plus imports would occur before the year 2005. This shortfall would become significant by 2010. If the constant demand scenario is correct and imports are GDP limited, then a shortfall begins at 2015 and becomes significant (about 7 quads or 3.5 million barrels per day) in the year 2030. If imports are limited by 26 percent of total world consumption, the shortfall in 2030 would be about 1 million barrels per day. The probable situation may lie between these two scenarios, with a resulting shortfall in petroleum between 1 and 7 million BPD in 2030.

This shortfall in conventional petroleum could be supplied in part by utilizing non-conventional heavy oils and bitumens, extraction and use of immobile remaining oil, and by converting coal into liquid fuels. The heavy oil resource worldwide is estimated to be over 600 billion barrels, but very little of this is domestic. Most of this occurs in South America, the former Soviet Union, and Canada. In the U.S. the resource occurs in California and Alaska. The Alaskan resource may be difficult to recover since it is under the permafrost and the California resource is relatively small. Heavy oils are characterized by their low API gravity (<20API), high viscosity, high sulfur and nitrogen content, high asphaltene content, and very high metals content. These oils are so heavy that they must be mined or extracted using steam injection or other tertiary recovery methods. Refining of these heavy oils, that are predominantly residual material, when technically feasible, is expensive and requires sophisticated resid hydrocracking technologies. In contrast liquids from coal conversion technologies are easier to refine because they are either high quality diesel fuel (cetane of 75) and high quality low-aromatic gasoline such as are obtained from indirect liquefaction, or all-distillate, low sulfur and nitrogen liquids as obtained from direct liquefaction.

As mentioned above, this potential shortfall in petroleum in the 2005-2030 time frame, depending on the above assumed scenarios, could in part be made up by converting coal into high quality transportation fuels. If coal conversion technologies are to play a role in alleviating this potential world liquid fuel supply problem by or before the year 2030, then the technologies must be in a state of readiness for commercial deployment. From a technology standpoint, typical lead times for the introduction of new energy technologies can be in the order of 10 to 15 years even when the technologies are in a state of readiness for commercial deployment. For coal conversion technologies, considerable research and development still needs to be undertaken to achieve this state of technology readiness. In addition to preparing the technologies for deployment, continuing R&D can substantially reduce the cost of coal-derived fuels by improving process performance. Commercial deployment of technologies to produce fuels from coal should begin before the year 2015 in order for them to make a significant contribution to alleviating the liquid fuels shortfall in 2030.

Since the transportation sector would be the predominant user of petroleum, transportation fuels that meet the strict environmental regulations expected to be in force in the next century would be needed. These fuels can be made from domestic coal resources by both indirect and direct liquefaction technologies. Presently the cost of fuels from coal using these technologies is too high to compete with petroleum at $17-18/bbl. The cost of coal-derived fuels have been significantly reduced by R&D since the early 1980s, and continued R&D is likely to reduce the cost so that they are competitive with petroleum in the range of $25-$28 per barrel.

Technologies to convert coal to high quality liquid transportation fuels can be either indirect or direct. Indirect liquefaction uses gasification technology to produce a synthesis gas from coal, and this gas is cleaned and passed over catalysts to make either hydrocarbons or oxygenates. The important point to understand is that coal-derived liquids from indirect liquefaction are high quality, zero heteroatom, paraffinic gasoline and diesel components requiring minimal refining.

DOE contracted Bechtel[15] to develop a conceptual commercial designs of indirect coal liquefaction facilities to produce refined liquid transportation fuels from both Illinois and Wyoming coals. These designs were based on current technology that include Shell coal gasification and slurry-phase Fischer-Tropsch (SFT) technologies. The Shell technology has been demonstrated at a 200 TPD pilot facility in Texas, and a full-scale commercial facility has recently been completed in the Netherlands for production of electric power in an Integrated Coal Gasification Combined Cycle (IGCC) facility. The SFT technology is being developed by DOE and Air Products at the Laporte Alternative Fuels Development Unit (AFDU), by Exxon, and by SASOL in South Africa.

The Bechtel baseline design represents the current state of the technology and the costs associated with this baseline are in the order of $34 per barrel crude oil equivalent (COE) for a conceptual commercial plant processing about 28,000 tons per day of Illinois coal and producing about 72,000 BPSD of refined gasoline and diesel fuels. This baseline is a snapshot of the current state of the technology, but the technology is emerging and is therefore at an immature level of process development. Considerable R&D needs to be conducted to bring this promising technology to maturity. R&D is also needed to consolidate the current conceptual baseline technology. Proof-of-concept (POC) testing of system components is necessary to verify the performance assumed in the conceptual baseline design, especially in the areas of slurry Fischer-Tropsch synthesis and product refining. Also, component integration is needed to verify continuous operation of the complete system from coal to products.

The main areas where R&D can make the greatest contribution to reducing the costs of this technology are in improving the SFT system and in reducing the cost of synthesis gas production from coal. For the SFT system, more active catalysts, combined with improvements in the performance of the slurry reactor system, have the potential to significantly reduce the costs of fuels. The cost of synthesis gas production is a significant element in the total cost of production of fuels from coal using indirect liquefaction, therefore reducing the cost of this component will impact the cost of fuels. This can potentially be achieved by improving the air separation system. Ceramic membrane systems currently in the early stages of development by Amoco, ANL, and APCI, could significantly reduce both the costs and the energy required for oxygen production and hence will reduce synthesis production costs.

Table 1 shows the current elements of cost for the baseline indirect conceptual commercial plants, and the estimated reduction of costs that can be achieved by further R&D in the product refining, SFT, and synthesis gas production areas. It is estimated that costs of transportation fuels can be reduced from about $34 per barrel crude oil equivalent to $27 per barrel by about the year 2010 by continuing R&D in this area.

Figure 6 shows the estimated impact of this continued R&D on the time that the costs of fuels from indirect liquefaction will be competitive with the world oil price (WOP). This Figure shows the WOP estimate of the EIA[14] from the present to the year 2010. After 2010, the WOP is extrapolated linearly to the year 2035. With no further R&D other than that necessary to consolidate the present technology base, the COE cost of indirect liquids will remain at the Bechtel baseline cost of about $34 per barrel. The cost of indirect liquids would then only be competitive with the projected WOP in the year 2030, where the no R&D line and the WOP line intersect. With continuing R&D, and with the expected resulting cost reductions detailed in table 2, the cost of indirect liquids will be reduced to about $27 per barrel. Thus, transportation fuels from indirect liquefaction will be competitive with the WOP by about 2015 compared to 2030; 15 years earlier than if no further R&D was conducted.

This 15-year grace period, provided by the cost reductions as a result of further R&D, is very important if coal-derived fuels are to make a timely contribution to the potential shortfall in liquid fuels in the U.S. that was discussed earlier. If it is accepted from the earlier discussion that this liquid fuels shortfall will occur in the 2025-2030 time frame, and the magnitude of this shortfall is between 1 and 7 quads, then between 1 and 7 quads of fuels from coal should be available by 2030. This would be the case if the construction of commercial plants can be started by about 2012. This start date for construction would be feasible if coal-derived fuels were to be competitive with the WOP by the year 2015 as discussed earlier. On this construction schedule, about 15 indirect liquefaction plants could be in production by 2030, producing over 2 quads of transportation fuels from domestic resources of coal. However, if no further R&D were conducted and the cost of coal-derived fuels remained at about $34 per barrel, then commercial plant construction would not start until the year 2030, too late to make any timely contribution to the shortfall in fuel demand by 2030.

Indirect coal liquefaction technology is not necessarily limited to producing an all-liquid product slate. Plants that coproduce both transportation fuels and electric power have great potential. The synthesis gas from coal gasification after purification can be passed once-through the SFT reactors, and the unconverted tail gas can be sent to gas turbines for power production. This configuration eliminates the costly FT recycle section of the plant, and produces two valuable products, power and fuels. Depending on the location, additional coproducts such as hydrogen, alcohols, and chemicals can be produced with the power and fuels. Configurations can also be developed that would allow load following capabilities if needed. With power priced at break even cost, the resulting COE cost of liquid fuels is reduced by 25 percent compared to the baseline liquids-only plant using a once-through F-T configuration with coproduction of electric power.

Production of high quality transportation fuels from U.S. coal will be a domestic industry that will employ engineering and construction people, plant operators, coal miners, and indirect manpower. It has been estimated that the total number of jobs that would be created by the proposed one million barrel per day industry is approximately 330,000.

Indirect coal liquefaction is an example of how coal can be cleanly converted from solid fuel to a clean synthesis gas, and this gas is transformed into clean, zero sulfur, ultra-low aromatic gasoline, diesel and oxygenated fuels. Byproducts of this process are elemental sulfur, ammonia, and a non-leachable slag. Although the process is essentially non-polluting, carbon dioxide is emitted during the transformation of coal to liquid hydrocarbon fuels. There is concern that anthropogenic carbon dioxide may be responsible, in part, for global climate change, and, if coal is to be used as a resource to produce liquid fuels, will the resulting carbon dioxide emissions be significantly increased in the U.S.? Figure 7 shows an energy mix that will result in no further increase in carbon dioxide emissions in the U.S. over the present. This shows that, because of the decrease in oil and gas, coal use can be increased substantially (by about 7 quads) after 2015 with no net increase in carbon dioxide emissions. If all of this additional coal were to be used for production of liquid fuels, then this would represent about 2 million barrels per day of coal-derived fuels.

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ACKNOWLEDGMENT:

This work, performed at the MITRE Corporation, was supported by Sandia National Laboratories under contract number DE-AC-04-94AL95000.

TABLE 1: ESTIMATED COST IMPACT OF CONTINUED R&D ON INDIRECT LIQUEFACTION

Elements of Cost $MM	Baseline 18,550tpd	Increased Plant 27,863 tpd	Improvements in Product Refining	Improvements in F-T Synthesis	Improvements in SynGas Production
Coal Handling	143	207	207	207	207
Gasification	703	1,018	1,018	1,018	1,018
Air Separation	322	466	468	468	323
Gas Cleaning/ByProduct Recovery	135	195	195	195	195
Fischer-Tropsch Synthesis	223	331	354	190	190
Synthesis Gas Recycle Loop	278	403	427	352	352
Product Refining	144	209	129	131	131
ISBL Field Cost	1,948	2,829	2,798	2,561	2,416
Power Generation	83	119	78	103	254
OSBL Field Cost	336	488	490	478	481
Total Field Cost	2,367	3,436	3,366	3,142	3,151
Total Plant Cost	2,950	4,283	4,195	3,916	3,927
Total Capital	3,181	4,620	4,529	4,228	4,231
Refined Product Cost	$/BBL	$/BBL	$/BBL	$/BBL	$/BBL
Capital	25.60	24.79	23.85	21.85	21.87
Coal	10.16	10.16	9.97	9.79	9.79
Catalyst	1.96	1.98	1.94	1.91	1.91
Other O&M	5.83	5.48	5.40	4.90	4.92
Power	1.24	1.24	2.01	1.28	-2.04
RSP	44.79	43.65	43.17	39.73	36.45
COE	35.49	34.35	33.87	30.43	27.15
Plant Output Barrels per year	15,796,097	23,691,630	24,133,433	24,592,583	24,590,739

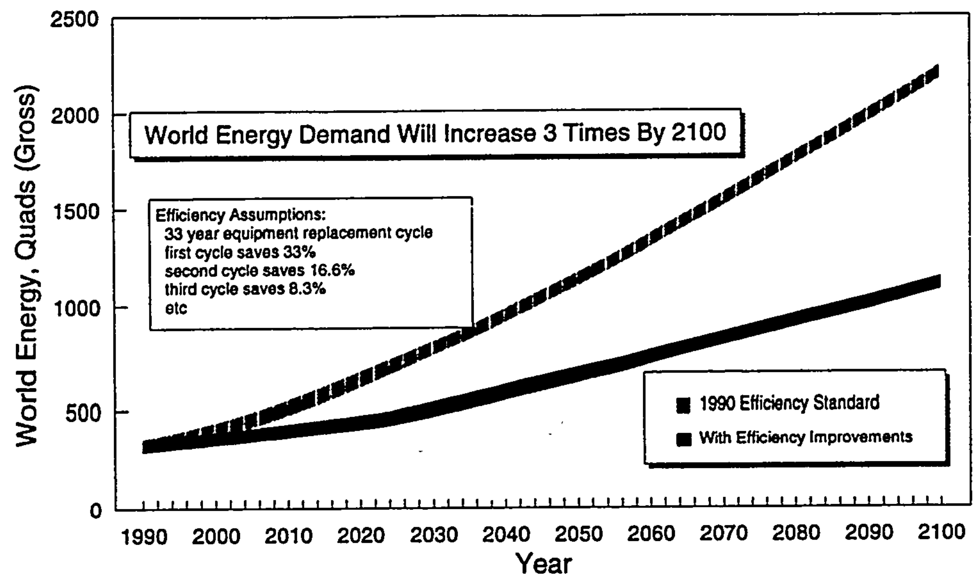

Figure 1: World Energy Demand Projections

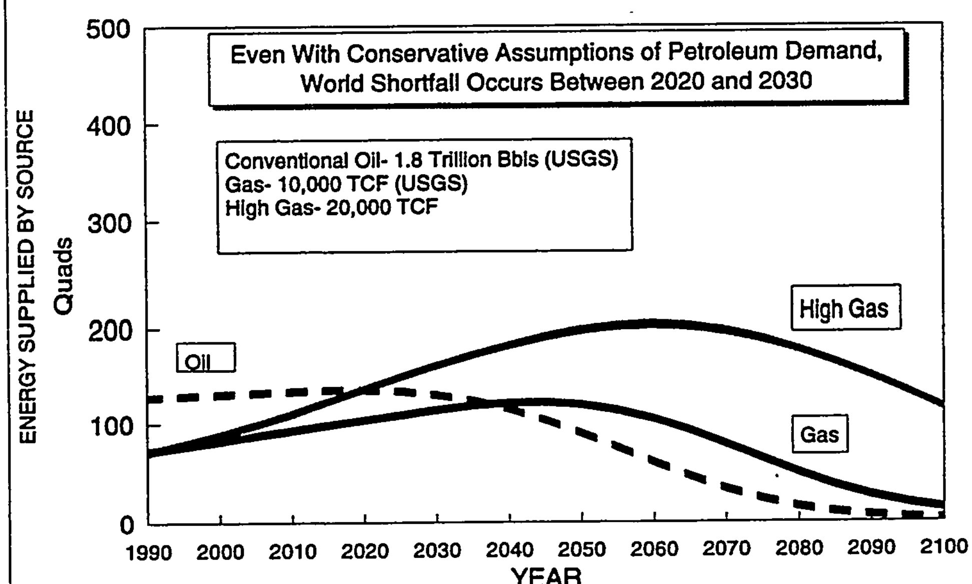

Figure 2: Depletion Curves for World Resources

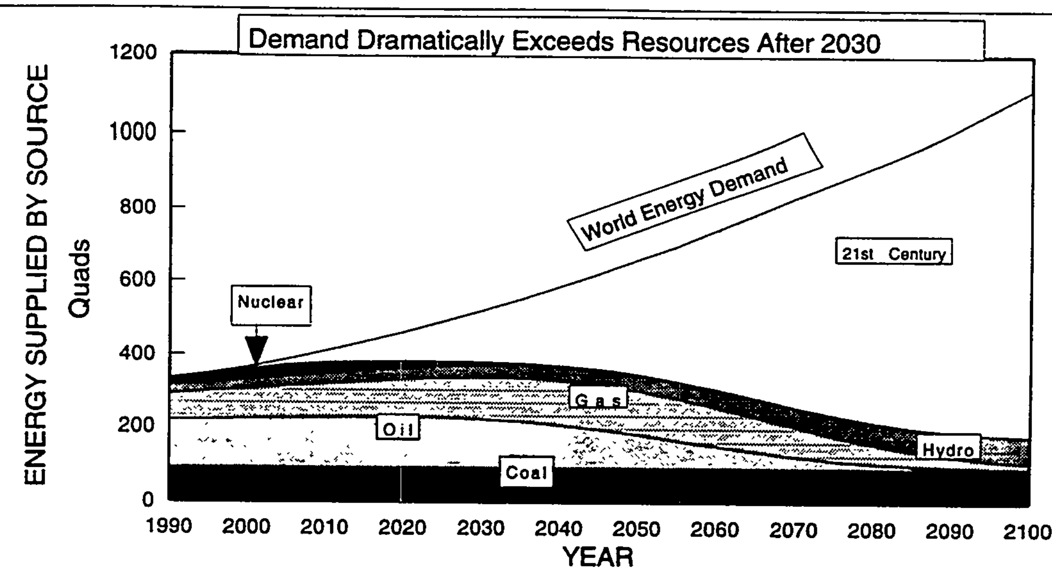

Figure 3: World Energy Mix for Nominal Oil and Gas With Constant Coal Use

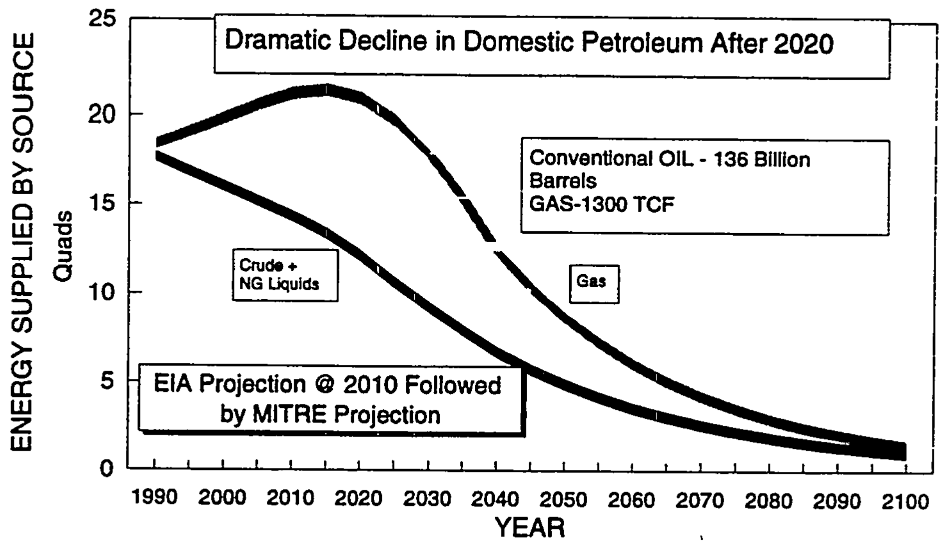

Figure 4: Depletion Curves for U S Domestic Oil and Gas

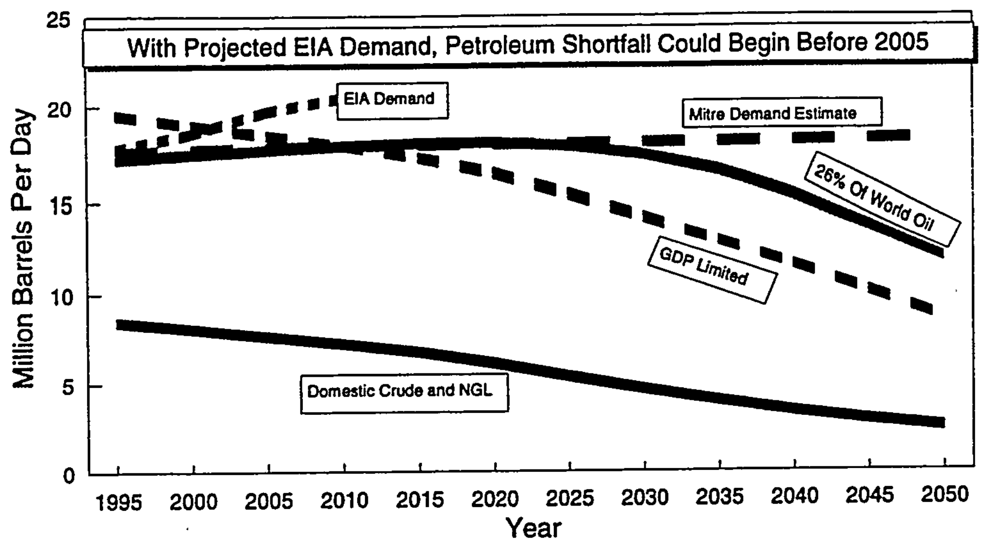

Figure 5: U S Oil Supply And Demand Scenarios

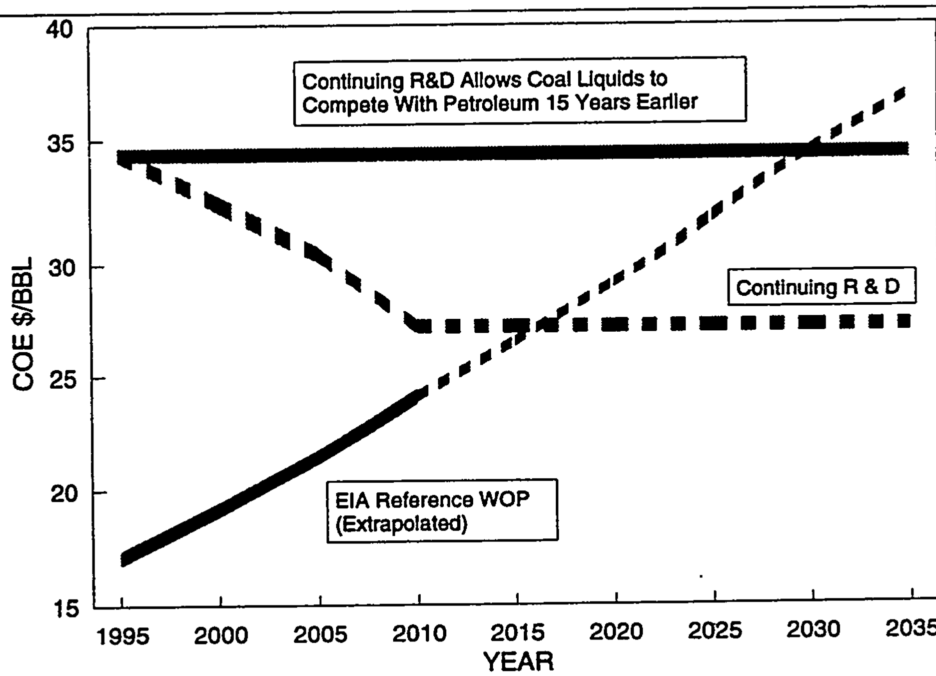

Figure 6: Cost Impact of R&D in Indirect Liquefaction

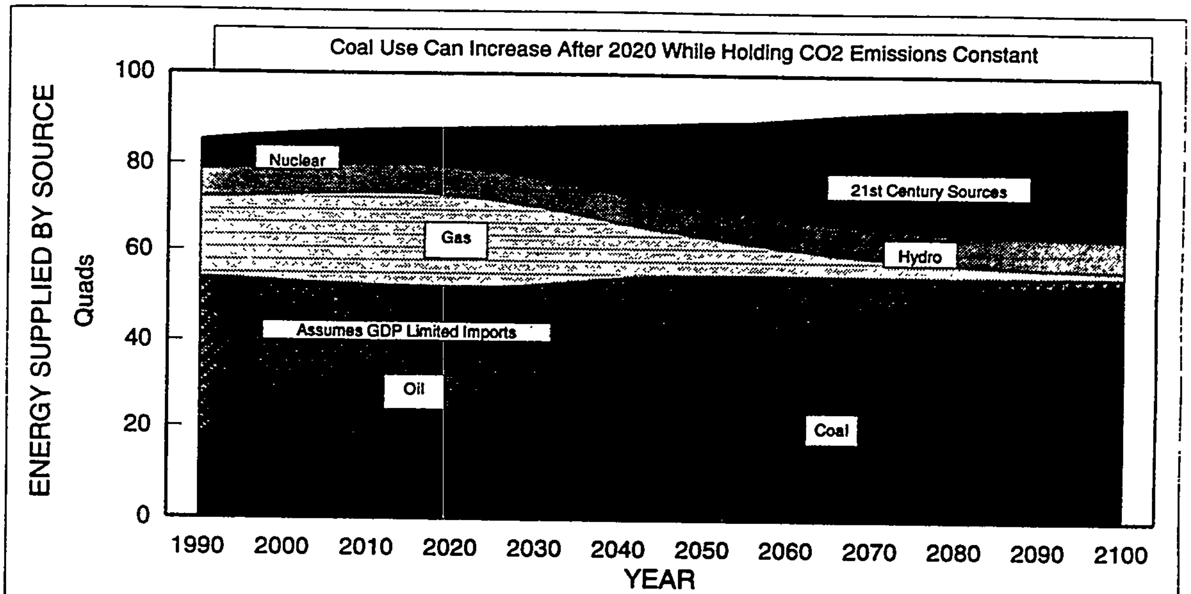

Figure 7: U S Energy Mix For Constant Carbon Dioxide Emissions