
Reducing DoD Fossil-Fuel Dependence

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Table of contents

Table of contents	i
Executive summary	iii
World major oil trade movements and distribution of US oil imports	iv
I. Background and context	1
II. Briefings, discussions, and other input	2
III. Statement of the problem	3
IV. Global, domestic, and DoD fossil-fuel supply and demand	5
A. Global fossil energy perspectives	6
B. Domestic fossil energy perspectives	9
C. DoD fossil energy perspective	13
1. U.S. production and DoD consumption	13
2. DoD demand breakdown by service and fuel use	15
3. Regulatory factors affecting DoD fuel use, planning, and policies	29
4. Drivers to minimize DoD fuel use	31
V. Technology options for the reduction of DoD fossil fuel use	33
A. Modification of patterns of use of DoD platforms	33
B. Engine and drive-train technology options	35
1. Hybrid vehicles	35
2. All-electric vehicles	37
3. Fuel-cell vehicles	39
4. Advanced diesel engine vehicles	41
C. Lightweighting DoD platforms	43
1. Manned vehicles	43
2. Unmanned land vehicles	45
3. Unmanned aerial vehicles	49
D. Alternate fuels in place of crude oil-derived fuels	51
1. Fossil fuel fungibility: conversion of gaseous and solid forms of fossil fuel into liquid hydrocarbon fuels through the Fischer-Tropsch process	55
2. Biofuels	63
Ethanol derived from corn	63
Cellulosic ethanol	65
3. Well-To-Pump (WTP) and Well-To-Wheel (WTW) analyses	68

VI. Discussion and concluding remarks	75
A. International and national considerations	75
B. Considerations for the DoD	76
VII. Findings	79
A. Global, domestic, and DoD fossil-fuel supplies	79
B. DoD fuel costs	81
C. Decreasing DoD fuel use	83
D. Liquid fuels from coal or natural gas	85
E. Biofuels	87
VIII. Recommendations and path forward	89
Appendices	
Appendix I: Energy glossary	90
Appendix II: Air-to-air jet-fuel delivery costs	93

Executive summary

In light of an increasing U.S. dependence on foreign oil, as well as rising fuel costs for the U.S. and the DoD, and implications with regard to national security and national defense, the JASONs were charged in 2006 by the DDR&E with assessing pathways to reduce DoD's dependence on fossil fuels.

The study charge included the following tasks:

- A. Explore technology options to reduce the DoD dependence on fossil fuels and/or increase energy efficiency of our operating forces. This assessment will include an assessment of alternative fuels and energy sources at DoD-required energy densities, e.g., exotic alternate fuels, biomass/cellulosic biofuels, hydrogen, shale oil, oil sands, geothermal, etc., and an assessment of the potential of structural shaping, structural mechanical design, and novel materials application in enhancing the survivability of lightweight vehicles.
- B. Assess the viability of technologies to provide at least the performance required of current DoD platforms and effort to integrate the technology and achieve the desired level of performance. In particular, alternate fuels and energy sources are to be assessed in terms of multiple parameters, to include (but not limited to) stability, high & low temperature properties, water affinity, storage & handling.
- C. Assess blast and penetration resistance in lightweight vehicles.
- D. Analyze structures and materials designs that could be adapted for use on combat and utility vehicles, or other DoD platforms.
- E. In addition, JASON was asked to defer detailed analyses of USAF energy/fuel use.

Some key findings and recommendations are summarized below.

1. Based on proven reserves, estimated resources, and the rate of discovery of new resources, no extended world-wide shortage of fossil-fuel production is reasonably expected over, approximately, the next 25 years. While the possibility of short-term shortages of refined gasoline or diesel product exists, depending on domestic refining capacity relative to domestic petroleum demand, there is not a strong basis to anticipate sustained global shortages of crude oil in the next 25 year (or more) time frame. In addition, there is no basis to anticipate shortages in petroleum available to the DoD, especially considering that present DoD fuel consumption is less than 2% of the total U.S. domestic fuel consumption – a demand that can be met by only a few domestic supply sources, at present – even though likely decreases in domestic-oil production will make the future domestic-coverage margin smaller. *This finding is premised on the assumption of no major upheavals in the world, in general, and in the major oil-producing nations and regions, and oil-transportation corridors, in particular, over the next 25-year period.*
2. The 2006 DoD fossil-fuel budget is, approximately, 2.5-3% of the national-defense budget, the range dependent on what is chosen as the total national-defense budget.

Larger (percentage) fuel costs are borne by families and many businesses, for example, and fuel costs have only relatively recently become noticeable to the DoD.

3. At present, there is a large spread between oil-production cost and crude-oil prices. Many projections, however, including that of the U.S. Energy Information Agency, indicate that crude oil prices may well decrease to \$40-\$50/barrel within the next few years, as production and refining capacity increases to match demand.
4. DoD is not a sufficiently large customer to drive the domestic market for demand and consumption of fossil fuel alternatives, or to drive fuel and transportation technology developments, in general. Barring externalities, *e.g.*, subsidies, governmental and departmental directives, etc., non-fossil-derived fuels are not likely to play a significant role in the next 25 years.
5. DoD fuel consumption constraints and patterns of use do not align well with those of the commercial sector. Most commercial-sector fuel use, for example, is in ground transportation, with only 4% of domestic petroleum consumption used for aviation. In contrast, almost 60% of DoD fuel use is by the Air Force, with additional fuel used in DoD aviation if Naval aviation consumption is included. Options for refueling ships at sea are more limited (or nonexistent) compared to those for commercial vehicles in urban areas. Options for DoD use of electrical energy on ground vehicles are limited, since one can not expect to plug into the grid in hostile territory, for example, to refuel/recharge an electric vehicle. Furthermore, drive cycles for DoD ground vehicles differ significantly from EPA drive cycles that, as a consequence, provide poor standards for fuel consumption.
6. Even though fuel is only a relatively small fraction of the total DoD budget, there are several compelling reasons to minimize DoD fuel use:
 - a. Fuel costs represent a large fraction of the 40-50 year life-cycle costs of mobility aircraft and non-nuclear ships. Note that this is consistent with the life-cycle costs of commercial airliners.
 - b. Fuel use is characterized by large multipliers and co-factors: at the simplest level, it takes fuel to deliver fuel.
 - c. Fuel use imposes large logistical burdens, operational constraints and liabilities, and vulnerabilities: otherwise capable offensive forces can be countered by attacking more-vulnerable logistical-supply chains. Part of this is because of changes in military doctrine. In the past, we used to talk of the “front line”, because we used to talk of the line that was sweeping ahead, leaving relatively safe terrain behind. This is no longer true. The rear is now vulnerable, especially the fuel supply line.
 - d. There are anticipated, and some already imposed, environmental regulations and constraints.

Not least, because of the long life of many DoD systems,

- e. uncertainties about an unpredictable future make it advisable to decrease DoD fuel use to minimize exposure and vulnerability to potential unforeseen disruptions in world and domestic supply.

The JASONS conclude that the greatest leverage in reducing the DoD dependence on fossil fuel is through an optimization of patterns of use, e.g., planning and gaming, as well as the development of *in-situ* optimization tools of fuel use that would help planners and field officers choose between operational scenarios to minimize logistical support requirements by minimizing fuel consumption. Such tools for planning and for conducting operations could evolve and improve tactics, and enable significant reductions in fuel consumption, while improving military effectiveness at the same time.

The JASONS noted that little or no hard data are available on fuel consumption at the level of individual vehicles and vehicle types. Instrumenting an adequate fraction of vehicles with the equivalent of commercially available telemetry/logging vehicle-monitoring systems for fuel consumption, vehicle speed, acceleration, etc., e.g., equivalent to the GM “On-star” system, or the real-time fuel monitoring systems as in the Toyota Prius, Honda Accord, etc., would yield valuable database information and help establish realistic baselines against which vehicle mix and operational choices can be optimized with an eye towards fuel consumption.

Large fuel savings could potentially be achieved by considering and optimizing the unmanned platforms and systems to replace functionality of manned platforms and systems.

Other areas with high leverage, in order of importance, include:

1. Optimization of engine types for DoD missions and use patterns. Commercial hybrids are not optimized to DoD use patterns. Re-engine the M1A1 and M1A2 tanks, HMMWVs, B-52 bombers, etc. with modern engines designed and optimized for their pattern of use.
2. Lightweighting vehicles costs money but can return significant fuel savings and other benefits. The greatest potential weight savings are not in armor, but in design, structural materials, and components of the vehicle drive system, radiator, etc.

Alternative fossil-fuel derived fuels, e.g., Fisher-Tropsch liquid fuels from coal, etc., are more costly and less energy efficient than fuels produced by refining crude oil. If crude oil sources are, for some reason, not indicated, the next most-cost-effective method to achieve assured domestic fuels is Fisher-Tropsch on stranded natural gas, such as in Alaska, albeit with attendant Greenhouse Gas (GHG) emission burdens, unless carbon-sequestration measures are employed and prove efficacious and cost-effective. No scaleable biomass processes today can yield DoD-suitable fuels.

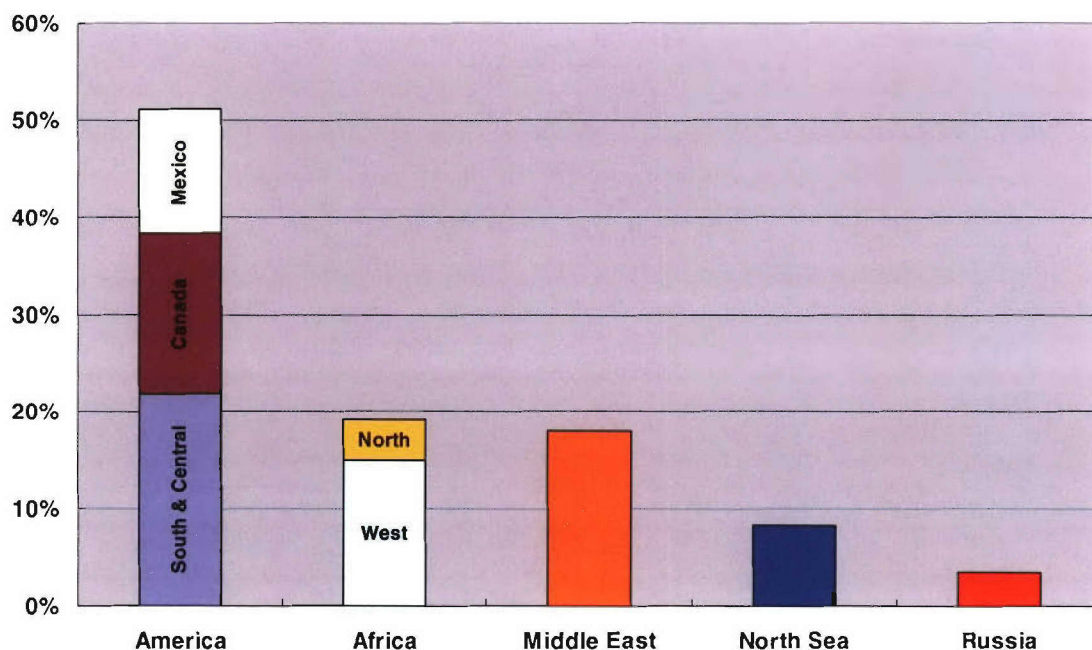
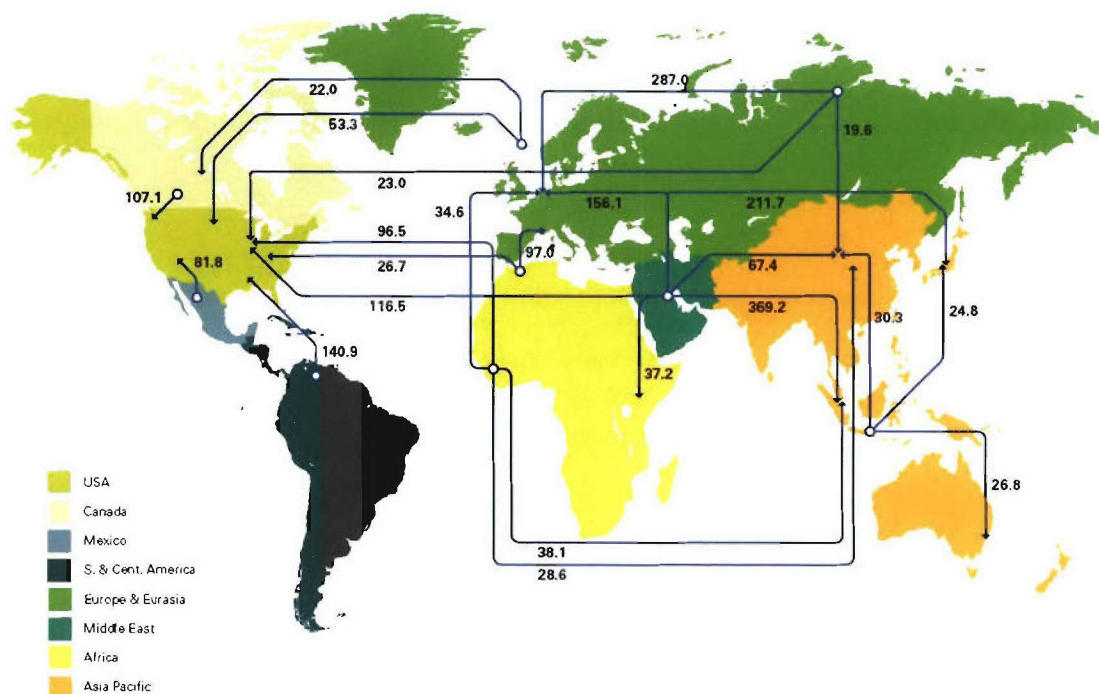
The key conclusions of the study are that, barring unforeseen circumstances, availability concerns are not a decision driver in the reduction of DoD fossil-fuel use at present. However, the need to improve logistics requirements and military capabilities, and, secondarily, the need to reduce fuel costs, as well as providing a prudent hedge against a foggy future, especially in the Middle East and South America, argue for a reduction in fuel use, in general.

We conclude by recommending that a more-in-depth analysis be undertaken that would consider future possibilities and scenarios that could invalidate these findings by altering the basic premise of no major upheavals in the next quarter-century, and the consequences to the DoD, indeed, to the nation, should such upheavals occur.

The figure below summarizes world-wide oil movements (crude + refined products) and is extracted from the *BP Statistical Review of World Energy* (June 2006, page 21). The bottom figure depicts the U.S. imports distribution.

Major trade movements

Trade flows worldwide (million tonnes)



U.S. oil import sources (based on the 2005 BP data in the figure above).

I. Background and context

In light of an increasing U.S. dependence on foreign oil, as well as rising fuel costs and implications with regard to national security and national defense, the JASONs were charged in 2006 by the DDR&E with assessing pathways that could enable a reduction of the DoD's dependence on fossil fuels.

The study charge included the following tasks:

- A. Explore technology options to reduce the DoD dependence on fossil fuels and/or increase energy efficiency of our operating forces. This assessment will include an assessment of alternative fuels and energy sources at DoD-required energy densities, e.g., exotic alternate fuels/biomass/cellulosic biofuels, hydrogen, shale oil, oil sands, geothermal, etc., and an assessment of the potential of structural shaping, structural mechanical design, and novel materials application in enhancing the survivability of lightweight vehicles.
- B. Assess the viability of technologies to provide at least the performance required of current DoD platforms and the effort required to integrate the technology and achieve the desired level of performance. In particular, alternate fuels and energy sources are to be assessed in terms of multiple parameters, to include (but not limited to) stability, high- and low-temperature properties, water affinity, storage and handling.
- C. Assess blast and penetration resistance in lightweight vehicles.
- D. Analyze structures and materials designs that could be adapted for use on combat and utility vehicles, or other DoD platforms.
- E. Defer detailed analyses of USAF energy/fuel use.

Part of the original study charge included a call for a study of energetic materials. That was addressed in a separate JASON 2006 study (Prentiss *et al.* JSR-06-130).

Prior studies on this general topic have been performed by the Defense Science Board (2001), by the Air Force Science Advisory Board (2005), and by other DoD advisory groups. These studies helped place the present study in context and provided an important input to the present study. Other studies for the DoD on this general topic are also in progress by the DSB and other groups at this time.

The JASON study focused more on Science and Technology aspects than on policy perspectives. In addition, the JASON study was performed within the context of the U.S. and global situation in 2006.

At present, U.S. crude oil imports provide 63% of domestic consumption and are slowly rising, public awareness or perception of climate change and global warming concerns attributable to fossil-fuel consumption are also rising, and there are tensions in the relationship between the U.S. and several countries with large proven oil reserves, both in the Middle East and South America (Venezuela, for example), as well as other regions of the world (cf. figures on page iv).

II. Briefings, discussions, and other input

This was a large study by JASON standards with many dimensions requiring attention, examination, and analysis. We are grateful to the following briefers for their presentations, follow-up materials and conversations, and general assistance and insights.

26Jun06:

Ed Schaffer [ARL / OSD APTI]: Energy and Power Technology Initiative Update
Marvin Wenberg [DESC, SC, USN]: DESC Overview
William Voorhees [NAVAIR]: Department of the Navy Future Fuels for Tactical Applications

27Jun06:

Charles Raffa [TARDEC]: Ground Vehicle Powertrains
Ghasan Kahlil [TARDEC]: Army Hybrid Electric Efforts
Anthony Nickens [ONR]: ONR Science and Technologies for Fuel Savings
James Webster [NAVSEA]: Propulsion Methods for Surface Combatants
Dieter Multhopp [AFRL]: Addressing Air Force Fuel Issues: Air Vehicle Efficiency
Chris Norden [AFRL]: Turbine Engine Technologies and Future Innovative Opportunities for Fuel Efficiency
Tim Edwards [AFRL]: Alternative Fuels

28Jun06:

Stan Horky [GM]: Current Development of Fuel-Cell Vehicles
Ann Karagozian [AFSAB]: Technology Options for Improved Air Vehicle Fuel Efficiency
Paul Scott [ISE]: Advanced Power-Trains and Hydrogen-Fueled Hybrid Electric Buses: Reporting on In-Service Experience and Fossil-Fuel Substitution.
Bill van Amburg [Weststart-CALSTART]: Medium and Heavy Hybrid Vehicles: Field Experience and Commercial Development
Scott Kochan [Ovonic Hydrogen]: Hydrogen ICES Vehicles

13Jul06:

Scott Schoenfeld [ARL]: Advances in Armor

17Jul06:

Tad Patzek [UC Berkeley]: The Real Biofuel Cycles
Michael Wang [ANL]: Well-to-Wheels Analysis of Vehicle/Fuel Systems

20Jul06: (VTC)

Robert Roche and Peter Melik [Army, AMSAA]: Fuel Consumption Modeling and Support Insights

In addition, we would like to acknowledge the assistance and reference material provided by Prof. David Pimentel [Cornell U.] on biofuels and agricultural-sustainability issues and to Dr. Steven Koonin [BP], for providing otherwise difficult to obtain cost and other data to our study, as acknowledged specifically below.

III. Statement of the problem

The JASON study was organized around the following series of questions:

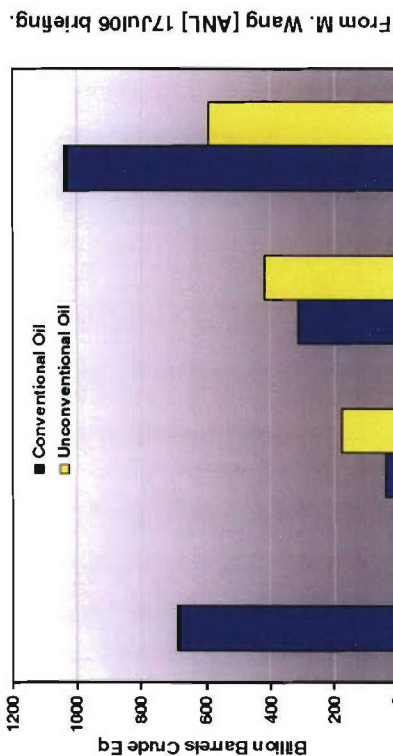
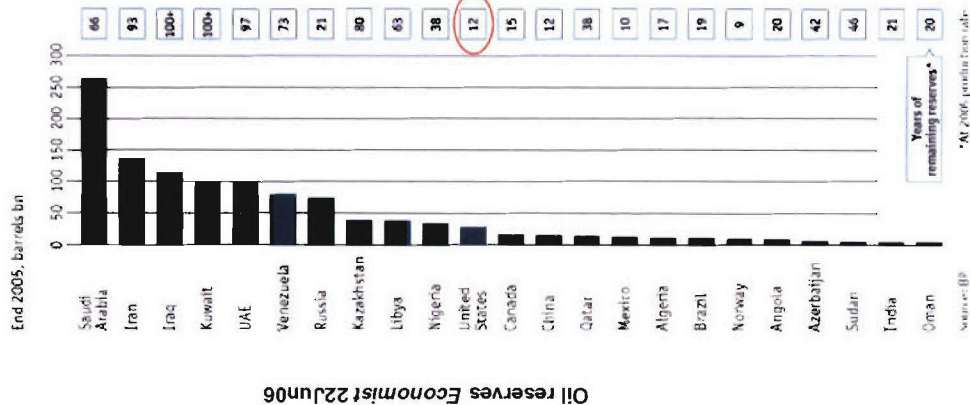
The first group of questions concerns the present:

1. Is there is a potential future shortage in (crude) oil supply to the DoD?
2. What are the national-security/national-defense implications of the global and domestic oil supply/demand picture?
3. Are present/anticipated DoD fuel costs a decision driver?
4. What are the logistical, operational, and tactical consequences of present DoD fuel-use patterns?
5. What are the main fuel-efficiency and conservation drivers?

The second series of questions relates to the future:

6. How could DoD fuel-use reductions be realized and what advantages (e.g., financial, operational, and tactical) would be realized if these reductions were to be achieved?
7. How could one beneficially change tactics, CONOPs, use patterns, etc., in response to a reduction in fossil fuel consumption?
8. What technology options are available to the DoD to facilitate reductions in (fossil-) fuel use?
9. Where should DoD invest for the greatest return on investment?

World proven resources — /



- 41 years remaining in present world proven resources, if used at 2005 production rate.
 - The world has traditionally maintained a 40-year reserve
 - Present U.S. reserves/production ratio of 12 years
- Most conventional proven oil resources are concentrated in the Middle East
- North America has relatively little conventional-oil but 30% of (world-wide) unconventional-oil resources

IV. Global, domestic, and DoD fossil-fuel supply and demand

A. Global fossil energy perspective

The present situation is assessed with respect to known, so-called “proven”, reserves and resources of fossil energy, globally. As indicated in the left figure on page 4, the world has approximately 41 years of proven reserves at this time, if the 2005 consumption rate is maintained. Less, of course, is assured if consumption increases. The inference, however, should not be drawn that the world will run out of oil in 40 years, or so. The world increased its oil reserves from somewhat beyond 30 years to over 40 years (reserves-to-production ratio), following the events in the early 1980s in the Middle East, in spite of substantial increases in total consumption.¹ Oil producers will not invest to secure reserves on a time scale longer than ~40 years. The net present value of such an investment would be small compared to the (cost of) capital required to explore and prove such additional reserves.

On the other hand, the data also indicate that present U.S. oil reserves, extracted at present production rates, will be depleted in the next 12 years. Whether this will be altered by new domestic discoveries during this period depends not only on whether they exist within the U.S., but also on whether the production cost differential between foreign oil sources and potential future U.S. resources warrants economic domestic production.

As indicated on the right, most conventional proven oil resources/reserves are concentrated in the Middle East. North America has relatively little of the world’s proven oil reserves and resources, but has 30% of the world’s unconventional oil resources, e.g., tar sands, shale, etc.

Oil available depends on the amount one is willing to pay to extract it from the ground and, ultimately, the amount remaining in the ground. Cumulative global crude oil production through the 20th century to the present accounts for approximately one trillion barrels ($Tbbl = 10^{12} \text{ bbl}$)² of oil.

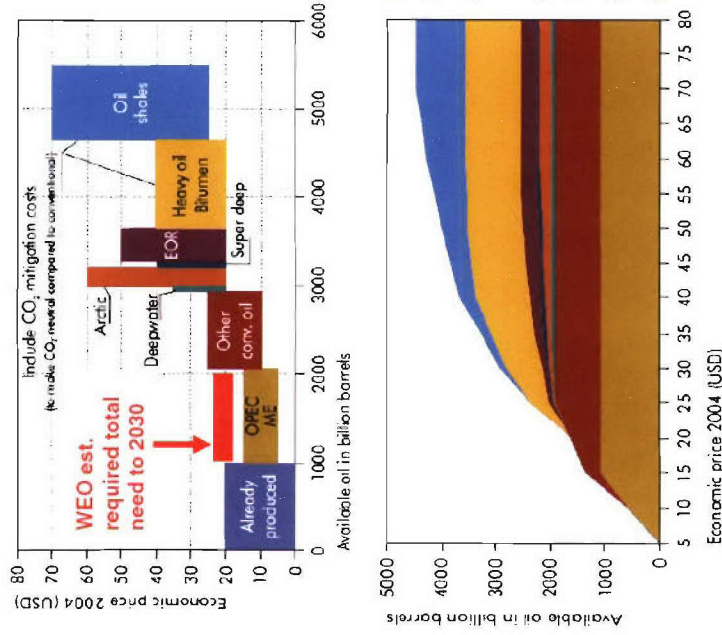
In the compilation depicted in the figures on page 6, the following assumptions are incorporated.

- All Middle East oil (proven and yet to be proved or discovered) is inexpensive to extract.
- Other proven reserves are below \$20/barrel by definition; a good portion of “reserve growth” and undiscovered oil will cost less than \$25/barrel, according to evolving technology.
- Deepwater will deliver 100 Bbbl at \$20-35/bbl.
- Arctic areas can deliver 200 Bbbl at \$20-60/bbl.
- Super-deep reservoirs will represent a small and relatively expensive oil contributor (they contain mostly gas).
- Enhanced Oil Recovery (EOR) can deliver 300 Bbbl above what is contained in the USGS reserve growth estimates, but some will remain quite expensive.

² The abbreviation ‘bbl’ stems from ‘blue barrel of oil’ that denotes the color of standard containers in the past that held 42 (U.S.) gallons.

¹ *BP Statistical Review of World Energy* (January 2006, page 10).

World proven resources — //



Source: IEA

Graphics [via S.E. Koonin, BP] plot same data two different ways.
WEO projection depiction by JASON.

- Approximately, 1000 billion barrels (Bbbl) of oil were (cumulatively) extracted through 2004
- World-wide fossil-fuel proven resources are a function of the economic price per barrel
 - Data used by oil companies to decide level of capital investment that potential future production warrants
 - Total proven resources estimated at ~5x of cumulative world production through 2004
- Projected world energy needs of (an additional) ~1000 Bbbl through 2030
 - Increasing new demand
 - 100 Mbbbl/day vs. 85 Mbbbl/day now
 - Can be met at a 2004 production cost of less than ~\$30 / barrel
- Est. U.S. fossil resources (oil, EOR, FT coal, shale, etc.) of ~2.0 Ttbbbl
 - Coal and gas not in the graphics

IEA World Energy Outlook 2004

- Non-conventional heavy oil has a large potential (some 1000 Bbbl between deposits in Canada, Venezuela and other countries) at \$20-40/bbl, including CO₂ and environmental-mitigation costs, e.g., carbon capture and storage (CCS) measures.
- Oil shales become economical at \$25/bbl and a significant portion of those resources can be exploited at less than \$70/bbl, including CO₂ and environmental-mitigation costs.

These estimates are illustrated on page 6. In the top figure, the vertical axis shows oil price at which the exploitation of various resource volumes becomes economical, taking into account the cost of capture and storage of CO₂ produced in the extraction of non-conventional oils. The horizontal axis shows cumulative resources. In contrast with classic cost curves, this presentation facilitates a link with the type of resources and therefore with the different technologies required. It also underlines that such projections are not an exact science and that only a range of costs can be projected. The bar labeled “WEO est. required total need to 2030” shows the cumulative oil demand expected between 2003 and 2030 according to the IEA World Energy Outlook (WEO) 2004. This provides a useful “scale” for levels of available oil.

The bottom figure depicts the same data in a different way. The horizontal axis represents oil-production cost and the vertical axis the corresponding cumulative economically exploitable resources. At the time of that assessment (2004), most companies based their investment decisions on a long-term cost of \$20-25/bbl. The graph suggests that accepting a long-term production cost of \$30-35/bbl, for example, would have a large impact on economically available future reserves.

If resources become economical at a given price, allowing for normal return on investment, this does not necessarily mean they will be exploited. Other factors, however, come into play:

- demand;
- competition from more appealing investments;
- regulations; tax, other incentives, and royalty frameworks;
- access to resources; and
- geopolitical factors.

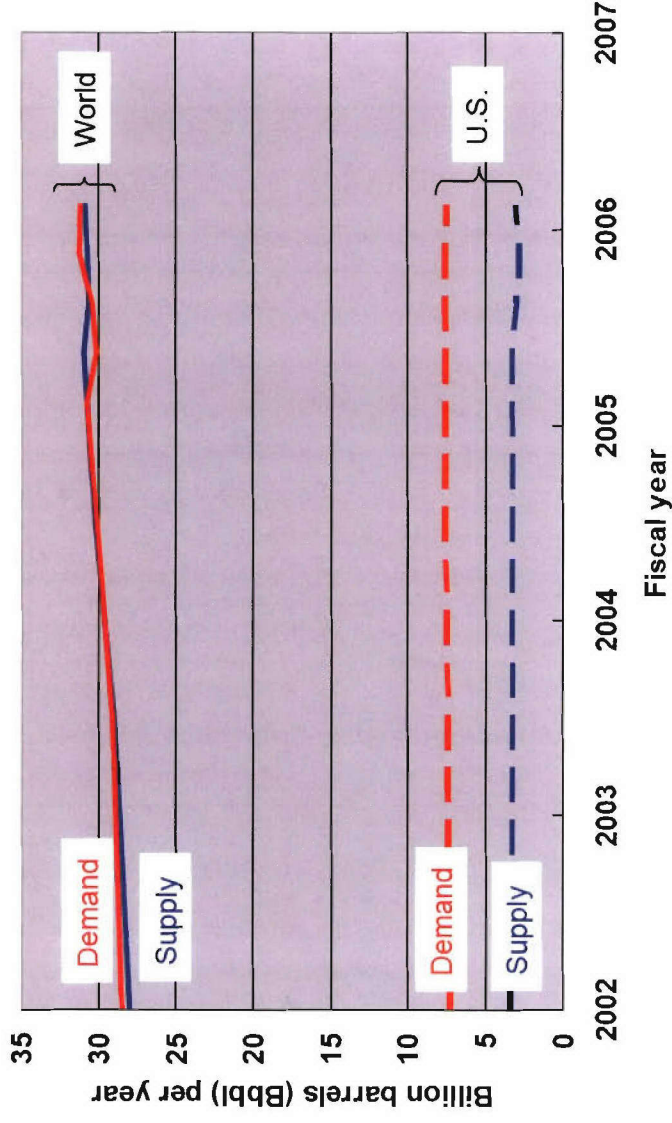
This means the price levels indicated are necessary but not (solely) sufficient to guarantee that a particular resource will contribute to world supplies. Also, these figures are based on long-term, sustained prices, not temporary peak-of-cycle prices, and they assume long-term costs for equipment and services. The latter costs also go through cycles and have increased considerably between 2003 and 2005.³

JASON agrees that, at least over the next 25 years and barring unforeseen circumstances, longer-term market mechanisms are likely to remove tightness in the supply and demand balance, enhancing the supply chain. Caveats stem from the increasing instability in the Middle East and the rise of national oil companies (NOCs) that presently dominate the world supply chain in recent years.⁴

³ The explanatory text on the data depicted in the figures on page 6 is based on IEA material relayed to the JASON study team by S. Koonin [BP].

⁴ The nationalization of Petróleos de Venezuela (PDVSA) under Hugo Chavez and the replacement of local and foreign professionals than ran it reportedly resulted in considerable damage to the high-maintenance Venezuelan oil fields, perhaps permanently removing as much as 0.4 Mbbl/day from the world production (*Economist*, 12Aug06).

World and U.S. supply and demand



- World supply/demand is increasing faster than U.S. demand
 - U.S. consumption is ~25% of world supply
- China is presently responsible for preponderant fraction of recent world demand increase
 - India is an important emerging consumer

Data from EIA Web site (30Jun06).

The world currently consumes 85 Mbbl (Mbbl = 10^6 bbl) of oil per day.⁵ The International Energy Agency (IEA) World Energy Outlook (WEO) projections, assuming a reasonable inflator for the future that rises to a world-wide demand of 100 Mbbl/day of oil averaged over the next 25 years, project a demand for the next 25 years of another ~1 Ttbl of oil. Hence, as much oil will be needed in the next 25-30 years as has been produced cumulatively to date over the last 150 years. Such growth can not be sustained indefinitely and projections beyond a 25-year span must be regarded as speculative.

The WEO data depicted on page 6 indicate that oil demand for the next 25 years can be met at a 2004 production cost under \$30/bbl. These data also indicate that a similar demand can be met for an additional 25 years, with the additional caveat that extrapolations to 50 years hence are of questionable value.

Noteworthy is that world-market crude-oil prices are currently much higher than crude oil production costs. This reflects a price premium commanded by a number of factors, including profit that can be sustained by the present supply-demand balance and the limited current supply marginal capacity relative to demand, geopolitical-risk considerations such as the present situation in the Middle East and Venezuela, and a number of other factors. For reference, according to the U.S. Energy Information Agency (EIA), a \$30/bbl production cost in a global commodity such as crude oil should, in the long term, should result in crude prices in the range of \$40-45/bbl.

⁵ World primary energy consumption increased by 2.7% in 2005. Coal was the world's fastest-growing fuel, increasing by 5% in 2005, with China accounting for 80% of global growth. *BP Statistical Review of World Energy* (January 2006).

Coal and natural gas resources are not included in this graph. Hence, the resource base for conversion of fossil energy into liquid fuels is potentially even larger than shown here. This will be discussed in greater detail below.

Estimated U.S. fossil resources, i.e., oil, enhanced oil recovery (EOR), coal, shale, natural gas (NG), etc., amount to about 2 Ttbl, i.e., approximately 260 years worth of resources at the present consumption rate of 7.5 Bbbl of oil per year. As noted later, however, the conversion of such resources to liquid fuels requires other resources, such as energy⁶ and considerable amounts of clean water, and the production of, in some cases, considerable green-house gas (GHG) emissions.

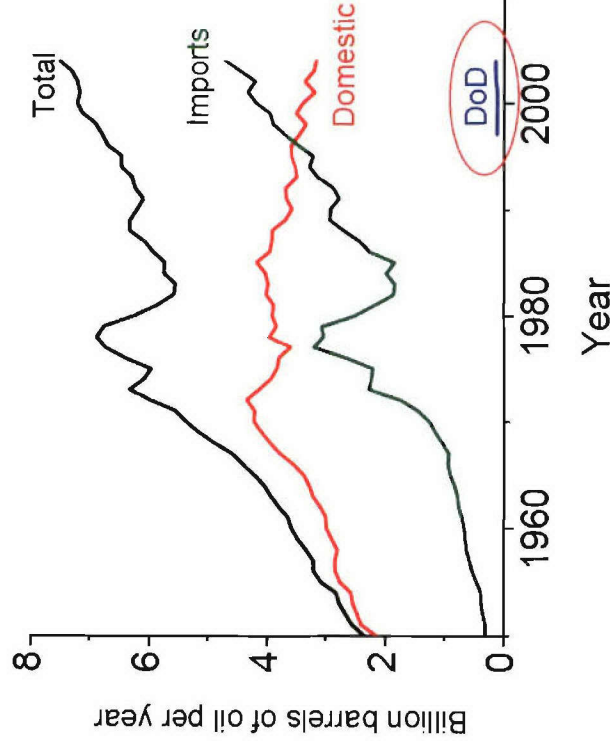
B. Domestic fossil energy perspective

As depicted in the figure on page 8, the U.S. consumes about one quarter of the world's oil production. One can see the effects of Hurricane Katrina as the small reduction in U.S. supply during the summer of 2005. The data were compiled by JASON corresponding to numbers published for annual totals prior to 2005, and quarterly thereafter by the EIA. The slight deviation between the world production and consumption lines in the graph occurs because a significant fraction of oil is in transit and storage at any one time. There are also seasonal adjustments.

⁶ Typically, conversion energy requirements are met by burning the feedstock, e.g., natural gas, or coal, albeit with an attendant decrease in energy efficiency relative to starting with crude oil as a source, for example, and an increased GHG production burden. Such issues will be assessed and discussed later.

Crude oil utilization — U.S., Government, and DoD

- Recent U.S. consumption and production curves
 - Presently, ~63% of consumption needs are met by (gross) imports
 - Similar ($\pm 10\%$) to EU and China
 - EU use increasing at $\frac{1}{2}$ US rate
 - China use increasing at 3.4%/yr
 - Much higher for Japan ($> 90\%$)
 - Recent U.S. consumption increases @ 0.5-1%/yr
- Present U.S. Government use
 - Represents 1.9% of U.S. total
 - Largest single user of energy/oil
 - DoD consumption
 - 93% of U.S. Government use
 - 1.8% of U.S. total



EIA 2004 Annual Energy Review
and 2005 DESC Fact Book

As already noted, present oil prices are significantly higher than the cost of production, primarily because demand is ahead of supply. This is exacerbated by instability in the parts of the world contributing to oil production. The market price of oil, defined by the futures market, builds into it a premium hedging against unanticipated reduction in production from such political instabilities and other factors. With oil demand close to supply, small reductions in supply, whether by accident, weather, embargo, or war, dramatically affect oil markets.

The spread between the price of crude and refined products in absolute terms is also rising for three reasons. Refining capacity is presently closer to demand. While U.S. refinery capacity and efficiency have increased in the last quarter century, no new U.S. refineries have been built in the last 30 years. Second, the increasing mix in high-sulfur Saudi oil increases refining costs if sulfur content is to be controlled. Finally, part of the spread is scaled by the price of oil itself.

At present, the U.S. uses 7.5 Bbbl/year of crude oil. Gross imports cover 63% of U.S. consumption. This is comparable ($\pm 10\%$) to the fraction of imported oil for Europe and China. In contrast, Japan imports 90% of its oil.⁷ U.S. consumption is

⁷ The significance of oil imports in national and regional economies, such as the E.U., is a strong function of the corresponding balance of payments. The E.U. as a whole, China, and Japan are net exporters (positive balance of payments) and, as a consequence, the main long-term concerns focus on availability of crude-oil supplies and transportation routes, and not on their economic consequences. This is not the case for the U.S., as discussed below. Also noteworthy is that China's balance of payments is actually negative with respect to the rest of the world, but

increasing at a rate of 0.5-1% per year, with recent increases closer to the lower bound. E.U. consumption is increasing at half the rate of increase of the U.S. consumption, while China's is increasing 6 times faster than the U.S. consumption.

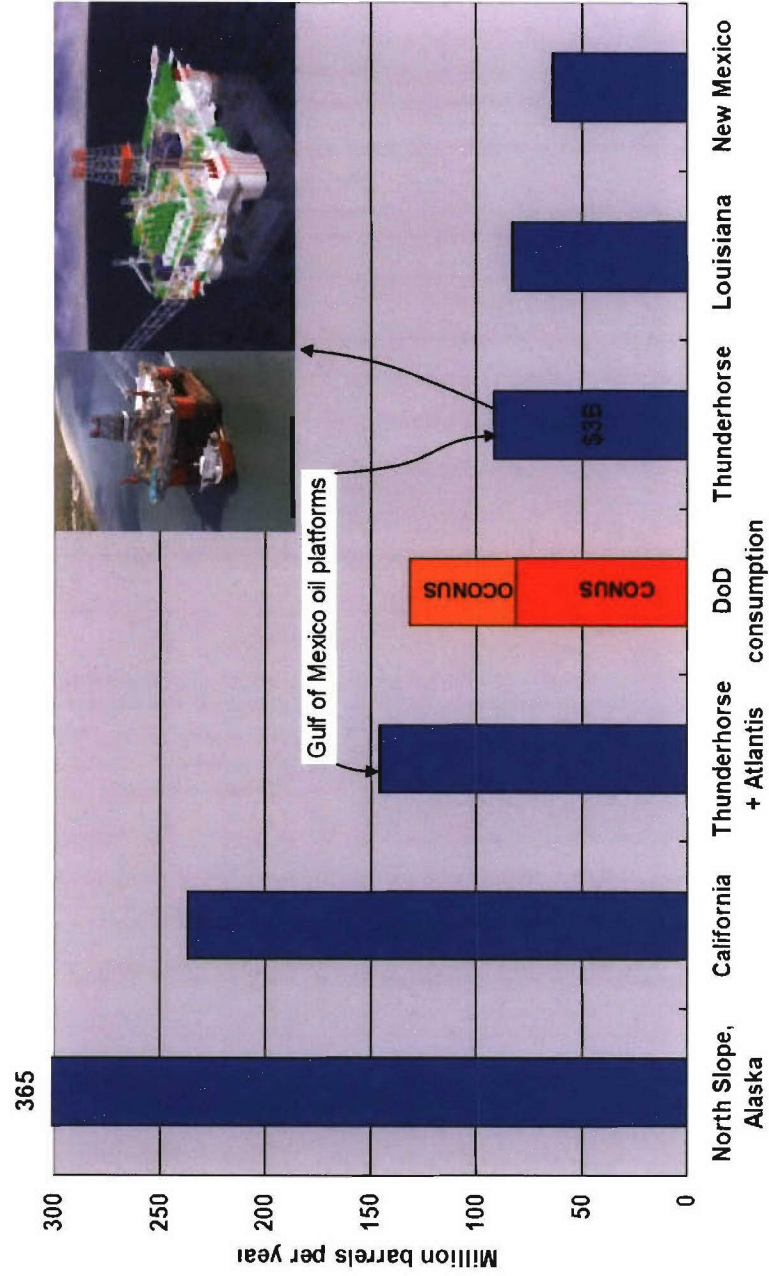
The peak in U.S. oil production, generally denoted as "peak U.S. oil", has often been interpreted to indicate that the amount of oil that can be extracted from U.S. soil is in irreversible decline. However, the particular peak is more directly related to the introduction at the time of inexpensive foreign oil ($<$ FY05\$ 4/bbl production costs), mostly from Saudi Arabia, into the world market. Recent economic drivers favor *reductions* of domestic production, with foreign sources of oil available at lower prices. Despite the ongoing depletion of the U.S. resource, domestic production is primarily driven by economics and perhaps secondarily by geological constraints.⁸ Conversely, rising oil (and other) imports, unbalanced by commensurate increases in exports, translate into a balance-of-payments issue for the U.S.

Noteworthy is the 2005 U.S. import source distribution (page iv), with the remainder of the American continent contributing 51.1%, Africa 19.1%, the Middle East 18%, and the balance from the North Sea and Russia.

positive overall, when the large and positive import-export balance with respect to the U.S. is included (FY2004 data).

⁸ That said, it is unlikely that future U.S. production will rise to values higher than the past peak before the 1980s.

Some U.S. production sites vs. DoD consumption



(2005) DoD consumption needs could be met by (2005) production capacity of a few U.S. production regions/sites

The graph on page 10 also indicates the dramatic reduction in domestic consumption in the early 1980s, in response to strong pricing signals (cf. figure on p. 61). The decline was in part because of conservation and in part because of the transition from oil-fired to coal-fired electric power plants.⁹ The data from the 1980s also demonstrate the ability to reduce oil consumption in response to sufficiently severe price signals on oil, even though a similar switch from consumption of oil in the power sector is no-longer available. Noteworthy is that the response to the economic impetus of the price hikes required about 5 years. Also noteworthy is that, at present, even in the face of high retail gasoline prices, U.S. oil consumption is at a record high. This indicates either that the capacity to reduce consumption was exhausted largely by de-emphasis of crude in the electric-power-production sector in the 1980's, that current prices are insufficiently high to spur significant conservation efforts, or that the time required to respond to the price change at this time is longer than has already transpired. However, production of high fuel-consumption vehicles (e.g., SUVs) is in decline, at present.

C. DoD fossil energy perspective

1. U.S. production and DoD consumption

The figures on pages 10 and 14 indicate that the U.S. Government consumes 1.9% of the oil consumed by the rest of the country. Furthermore, the DoD accounts for 93% of the

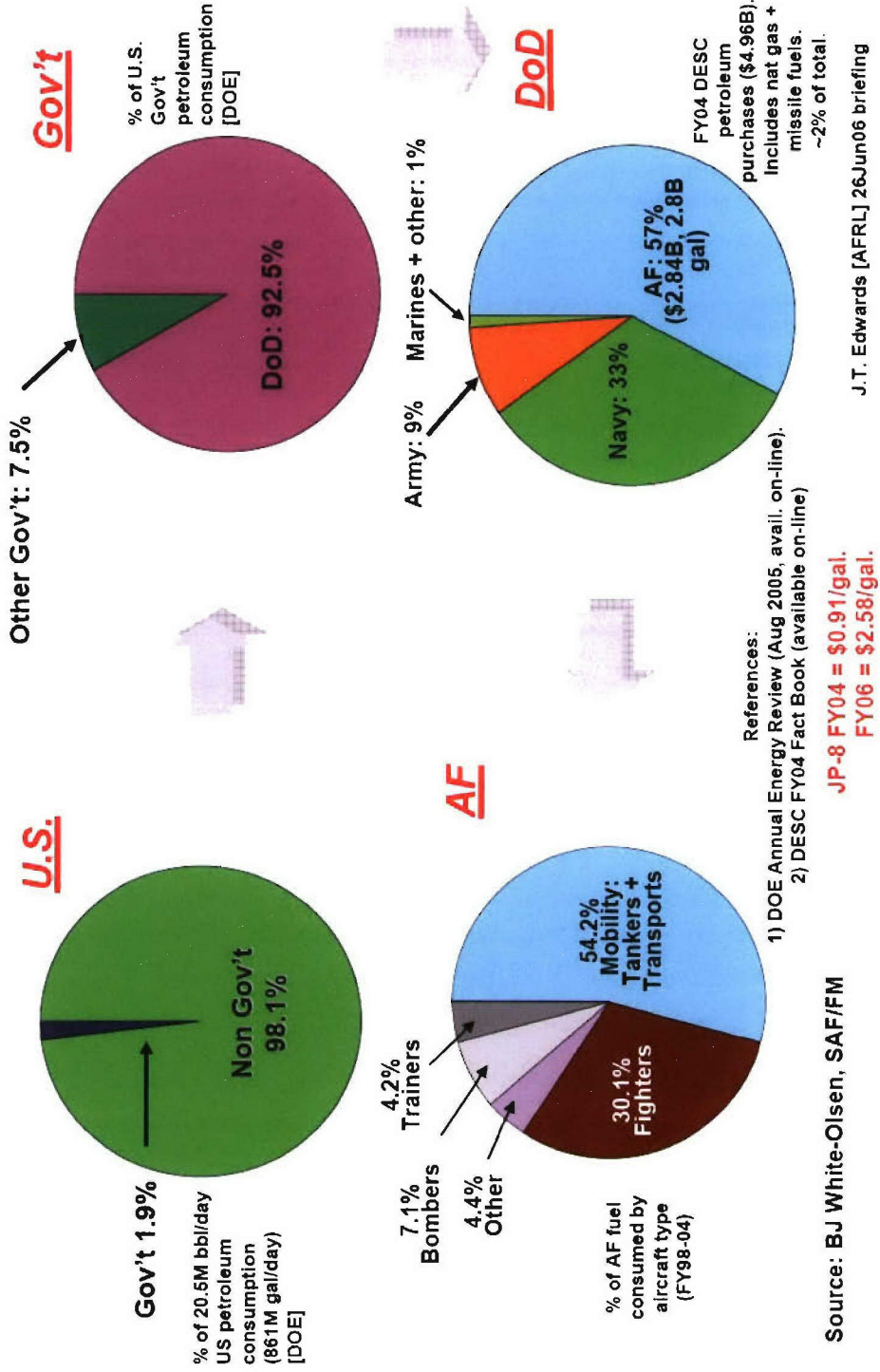
U.S. Government consumption. For reference, DoD consumed 0.36 Mbbl/day in FY05, or 133 Mbbl that year.

DoD fuel use both in the continental U.S. (CONUS) and abroad (out of CONUS, or, OCONUS), as reported by the Defense Energy Support Center (DESC), is a relatively small fraction of the total domestic current crude-oil *production* rate (cf. figure on p. 12). The annual DoD crude oil consumption can be covered by the total annual production of two Gulf of Mexico oil platforms (Thunderhorse and Atlantis), or by a small fraction of California and Alaska production, at present. Thunderhorse is a platform that cost ~\$3B, sized for a 0.25 Mbbl/day production, and which is presently producing, approximately, 90 Mbbl/year. If there were real supply issues for the DoD, the department could, in principle, purchase a Gulf oil platform for an assured supply for many years, at an amortized production cost of under \$30/bbl, as is done by the large commercial oil production firms at present, even though that is hardly advisable.

In this context, the total deep water Gulf of Mexico production is 1.5 Mbbl/day. Production from the North Slope of Alaska is, approximately, 1 Mbbl/day. Hence, total DoD needs could be provided from a portion of the production of just one of these regions of the U.S. Thus, even though 63% of US oil consumption is derived from imports, it does not follow that a domestic-supply shortage for DoD is inevitable. In fact, present-day DoD requirements are relatively modest when compared not only to the present national-consumption rate but also when compared with the present domestic-production rate.

⁹ This transition occurred with an attendant increase in green-house gas (GHG) emissions, per kWh of electrical power produced. At present, almost no oil-fired electric power plants are operated in the U.S.

US Gov't, DOD, AF fuel utilization — FY04



We note that these inferences assume relatively stable DoD mission requirements, e.g., missions no more demanding of fossil fuels than the current Iraqi conflict. JASON has not analyzed the consequences on fossil-fuel availability of a future, WWII-scale DoD mission. Presumably, such a conflict would require and induce considerable national sacrifice, including civilian restrictions on access to petroleum products, and is not considered as part of this study and report. Further, the analyses above also assume no major world-wide upheavals that could disrupt either supplies from, say, the Middle East or Venezuela, or main crude-oil or refined oil-product transportation corridors.¹⁰ Other than to note that such scenarios cannot be excluded at this time and to note the significant consequences on the DoD and the nation they would imply, they were not considered as part of the present JASON study.

Instability in the price of oil provides an important budgetary impact of fossil-fuel use on DoD. While present fuel costs represent a small part of the overall DoD budget, at current consumption rates, for every \$10/bbl rise in price, DoD requires an additional \$1.5B in its annual budget.

There are, in general, two ways to deal with this issue. One is to reduce DoD demand, which is discussed below. The second is to attempt to beat the commercial market price at any one time incurring some market risk by entering into long-term contracts, or hedging against future prices of crude oil on the world market.

¹⁰ The recent tensions and disagreements between Russia and the Ukraine over the Russian natural-gas pipeline over Ukraine had an immediate impact on the E.U.'s natural-gas supplies and outlook.

2. DoD demand breakdown by service and fuel use

The demand for petroleum in the DoD by service and by use is now assessed. As depicted on page 14, the U.S. government, at present, accounts for 1.9% of the total oil consumed by the country. DoD consumption represents 93% of the total U.S. government consumption. Within DoD, the U.S. Air Force is the largest consumer of petroleum products, its 75 Mbbl/year amounting to 57% of DoD consumption. Second is the Navy, with 33% of total DoD consumption, followed by the Army (9%) and the Marines (< 1%).

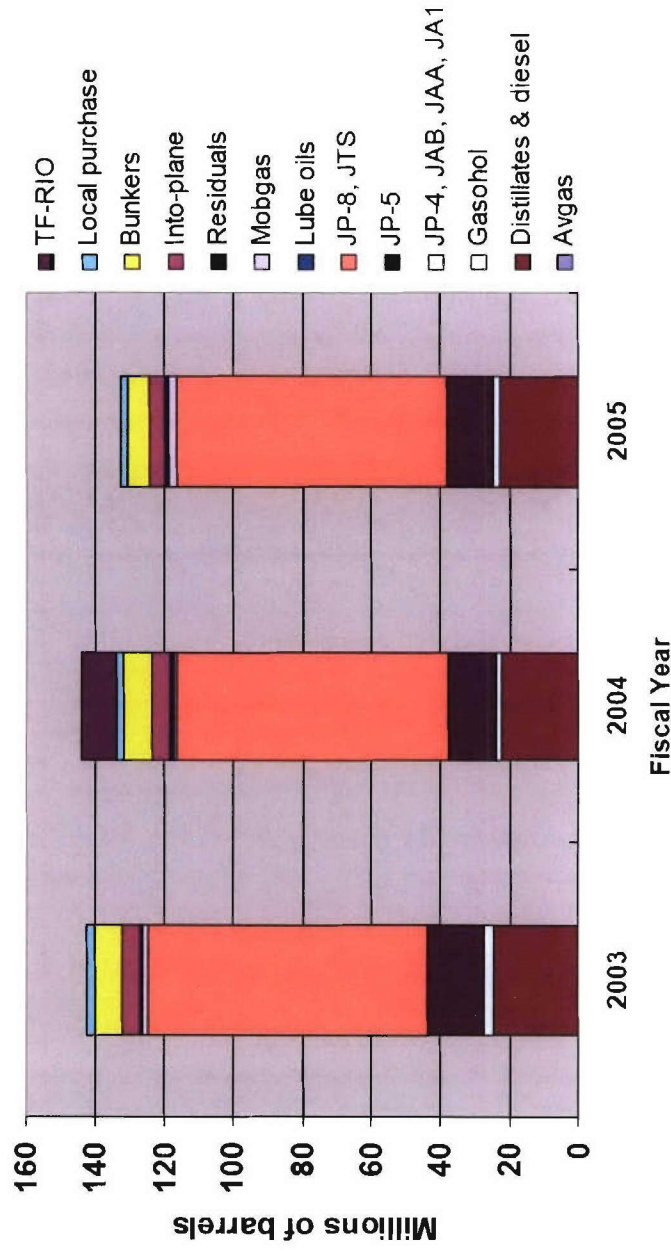
These figures are skewed by the fact that some part of the U.S. Air Force's use of jet fuel is consumed moving the Army and supplying the Navy. JASON was not able to obtain these numbers and we recommend that such accounting should be implemented to help provide the basis for a useful budgetary planning tool.

Within the Air Force, the largest share of fuel (54.2%) is consumed by tankers and transports. Fighters account for 30.1% of the fuel, bombers for 7.1%, and trainers for 4.2%. Modern computer-based systems can help decrease the latter further.

For reference, JP-8, the primary fuel used by the Air Force, cost \$0.91/gal in FY04 but rose to \$2.58/gal in FY06, i.e., a factor of over 2.8 in just two years.¹¹

¹¹ Commercial aviation has been faced with similar fuel price increases, as assessed and discussed below.

DoD fuel demand — DESC sales by category



- Mobility fuels represent preponderant fraction of DoD fuel use

— JP-5 is Navy shipboard jet fuel with a higher flash point temperature ($T_{\text{flash_JP5}} = 60^\circ\text{C} = 140^\circ\text{F}$, $T_{\text{flash_JP8}} = 38^\circ\text{C} = 100^\circ\text{F}$)

- Indicated DESC sales do not include natural gas

- Except for TF-RIO, continuous decrease in the FY03-05 period

DESC = Defense Energy Support Center

DESC FY05 Factbook. JP-5/-8 Flash data by J.T. Edwards [AFRL].

The Defense Energy Support Center (DESC) is responsible for the procurement, transportation, ownership, accountability, budgeting, quality assurance, and quality surveillance of all petroleum products used by the DoD. In FY05, DESC distributed 133 Mbbl oil.

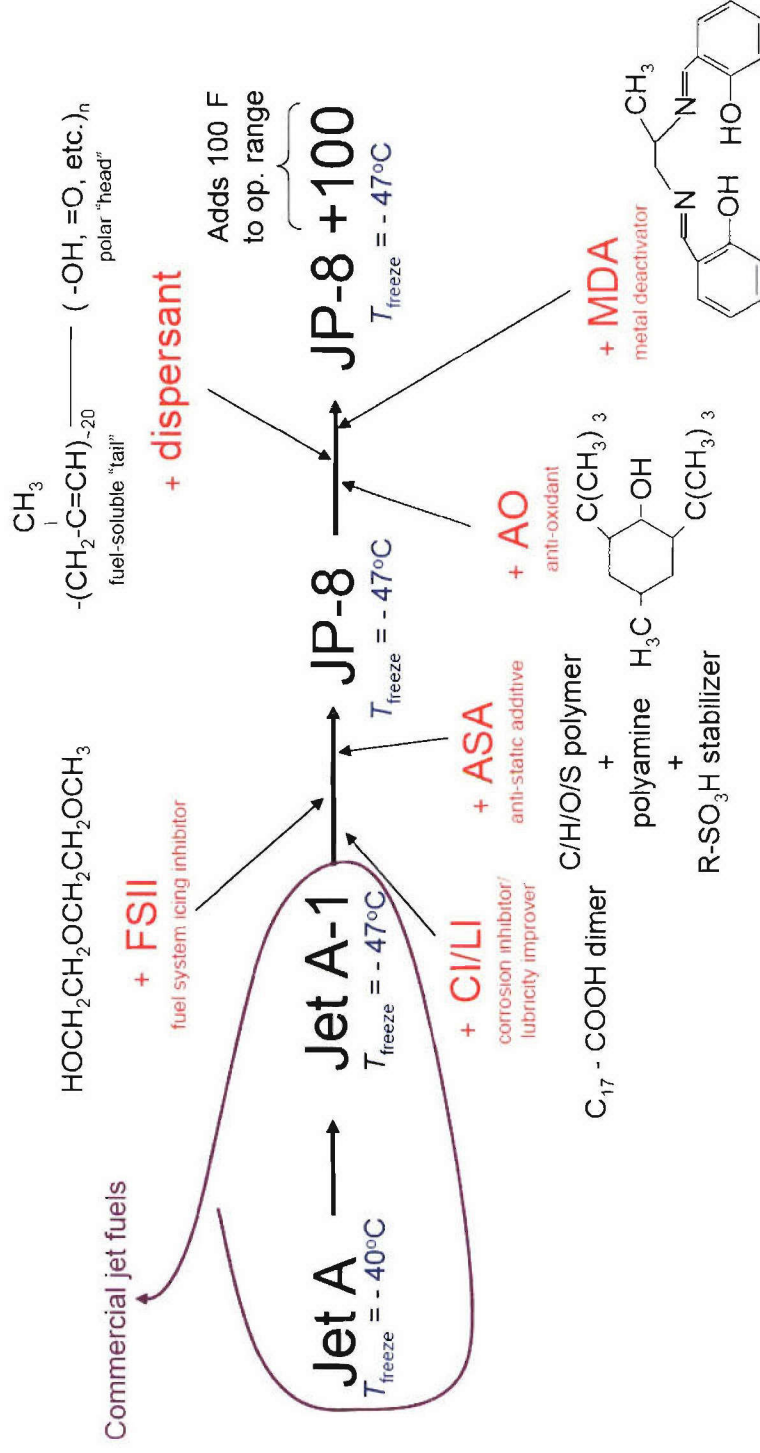
According to data provided by DESC and available on their Web site, mobility fuels represent the preponderant fraction of DoD fuel use. These mobility fuels are dominated by diesel fuel, and JP-5 and JP-8. The latter represents the largest single component, by category, of fuel supplied. JP-5 is a Navy shipboard jet fuel with a higher flash point temperature than JP-8. The flash temperature, T_{flash} , for JP-5 is +60°C (140°F), whereas T_{flash} for JP-8 is +38°C (100°F). Although JP-5 costs slightly more than JP-8, it is used on ships for safety reasons.

JASON notes that, excluding oil purchases/deliveries on behalf of TF-RIO,¹² DoD fuel consumption decreased continuously in the FY03-05 period.

Further decreases in fuel consumption by the U.S. Air Force, the largest consumer, are also anticipated, as the number of aircraft in the U.S. Air Force inventory decreases in the future, as discussed below.

¹² TF-RIO is the 2004 Task Force - Restore Iraqi Oil that provided oil to Iraq.

DoD jet fuels and additives



- DoD JP-8 and JP-8 + 100 can be derived from (commercial) Jet A-1 with additives
 - Small cost (~ \$0.05) per gallon

From J.T. Edwards [AFRL] 26Jun06 briefing

Jet A and Jet A-1, the dominant commercial aviation fuels, differ only by their respective freezing points, which are -40°C for Jet A and -47°C for Jet A-1, and in their flash points, as discussed above. While there are minor differences in and substantial overlap between world-wide commercial aviation fuel delivery specifications,¹³ most commercial aviation fuels today meet the Jet A-1 specification.

One can obtain JP-8 and JP-8 +100 from Jet A and Jet A-1 through the use of additives. Adding a fuel system icing inhibitor, a corrosion inhibitor/lubricity improver, and an anti-static additive to Jet A-1, yields the military JP-8. Further adding a dispersant, an anti-oxidant, and a metal deactivator to JP-8 yields JP-8 +100, which adds an additional 100°F to the operational range of JP-8. In total, these additives cost at present, approximately, \$0.05 per gallon of fuel.

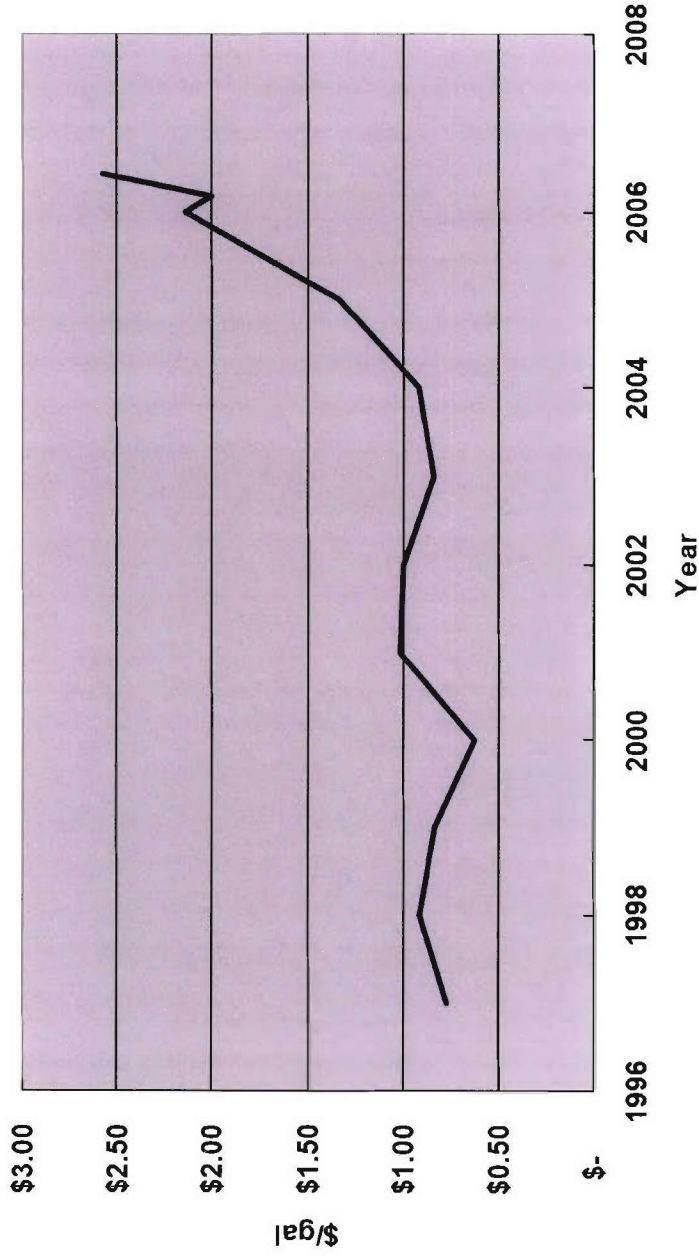
Oil refineries tend to realign their distribution of refined products every few days. If the DoD has an unusually large need for JP-8, DoD can induce the refineries to produce more JP-8 from their commercial aviation fuel stream at a nominal increased cost of, approximately, \$0.05/gal.

If DoD is operating in a part of the world where JP-8 is unavailable, it could produce JP-8 for its use by the addition of

the indicated additives to Jet A-1, which is generically available across much of the world, rather than transport it from CONUS. JASON is under the impression that this possibility has not been assessed and is not being exploited at this time.

¹³ By way of example, a question that arose in the investigation of the TWA-800 accident on 17 July 1996 is whether the (remaining) fuel in the aircraft's central tank was (somewhat) more volatile than usual because the aircraft had been fueled in Athens, Greece, for the return trip to New York, and not refueled in New York for the trip back, owing to the lighter load for the flight out. As a consequence, vapors in the central tank when the aircraft exploded were from fuel that had been obtained in Athens.

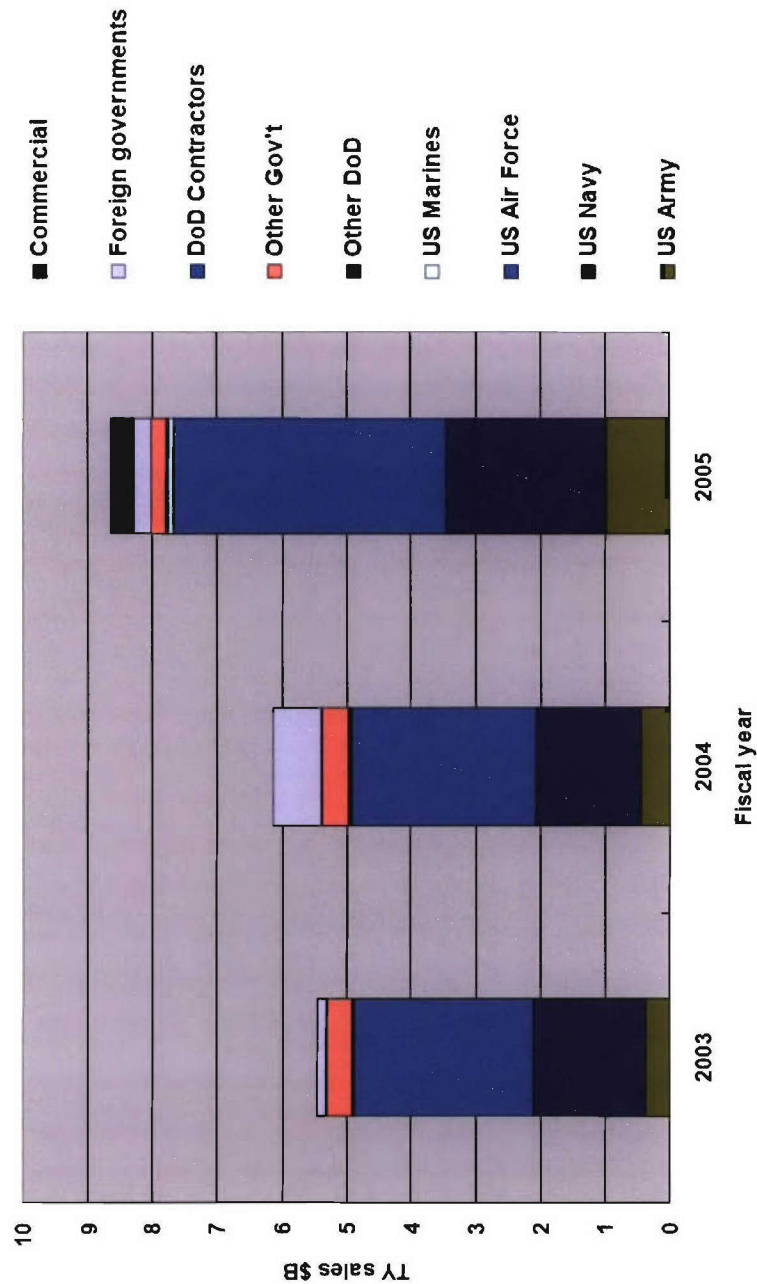
Jet fuel (JP-8) costs — 1997 to present



Cost increases of x2.8 since 2004 translate to > \$4B/yr extra for USAF.
Every \$10/barrel increase drives up USAF fuel costs by ~ \$0.6B/yr.

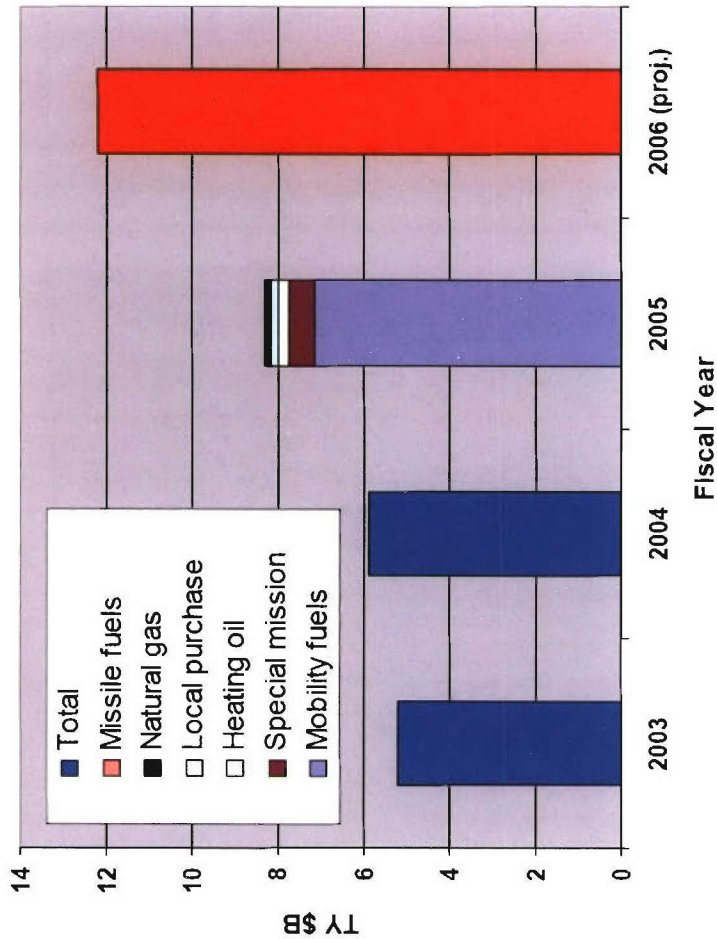
Data from J.T. Edwards [AFRL] 26Jun06 briefing

DoD fuel demand — DESC sales distribution



- Increasing cost, despite (slight) decreases in use
- Indicated DESC sales do not include natural gas

DoD fossil fuel demand — DESC sales



- Rapidly escalating DoD fossil fuel costs
- Mobility fuels represent preponderant fraction of DoD fuel use

As noted above, the cost of JP-8 has increased by a factor of 2.8 since 2004. This increase translates into a \$4B/yr additional cost for the U.S. Air Force. At present consumption rates, every \$10/bbl increase in price drives up U.S. Air Force fuel costs by ~ \$0.6B/yr.

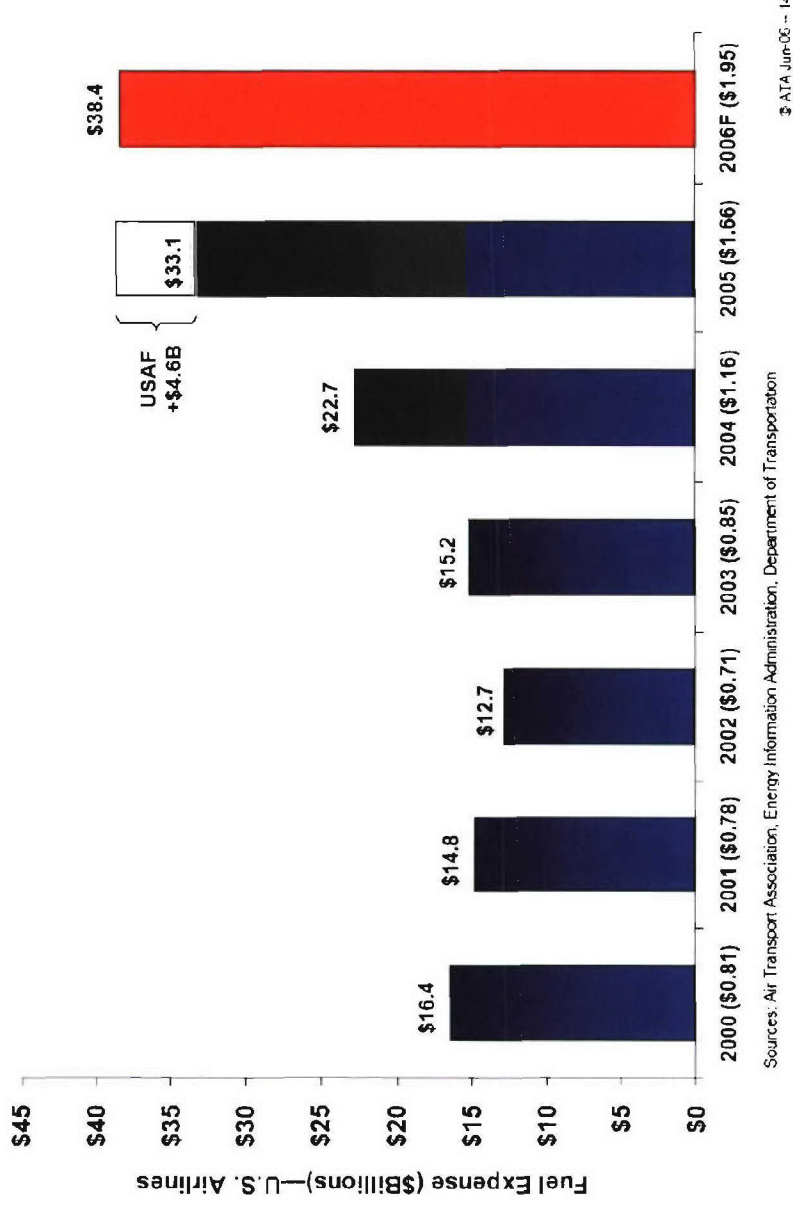
Shown on page 21 is the DESC sales distribution. As indicated, deliveries to foreign governments in 2004, as well as to foreign governments and commercial recipients (together) in 2005 are significant. JASON could not ascertain whether the TF-RIO deliveries (cf. page 16) were counted as 2004 deliveries to foreign governments, or whether the near-match of the total of foreign-government and commercial deliveries in 2005 with deliveries to foreign governments in 2004 is coincidental.

Noteworthy also in the figure on page 21 is the large increase in the cost of U.S. Air Force deliveries in 2005 over those in 2004.

As shown on page 22, despite some reduction in DoD fuel consumption, the price DoD paid for fuel has increased dramatically from FY04 (\$5.9B) to FY05 (\$8.3B). DoD fuel purchases in FY06 are expected to be higher than \$12B.

The figure on page 22 also indicates the large extent to which mobility fuels are responsible for the predominant fraction of DoD fuel consumption, as noted previously.

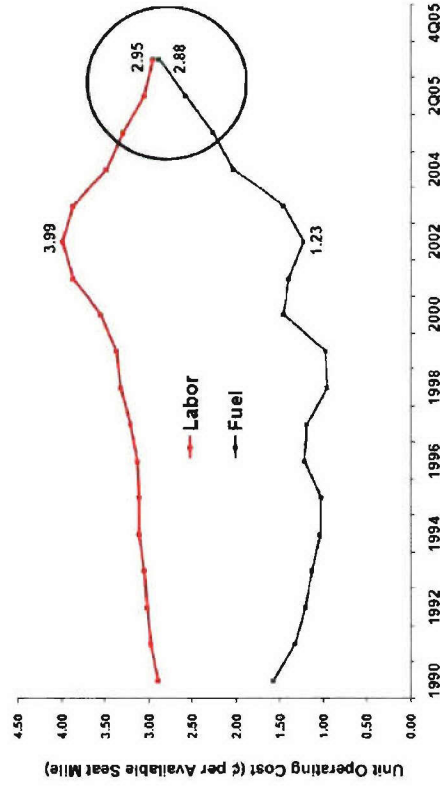
U.S. airlines — Jet fuel expenses



- U.S. airlines lost \$2.5B in FY05
 - FY05 oil at \$43/barrel would have allowed them to break even.
- USAF uses (somewhat) more fuel per year than largest U.S. airline
 - Not, however, a market driver, even in aviation fuels

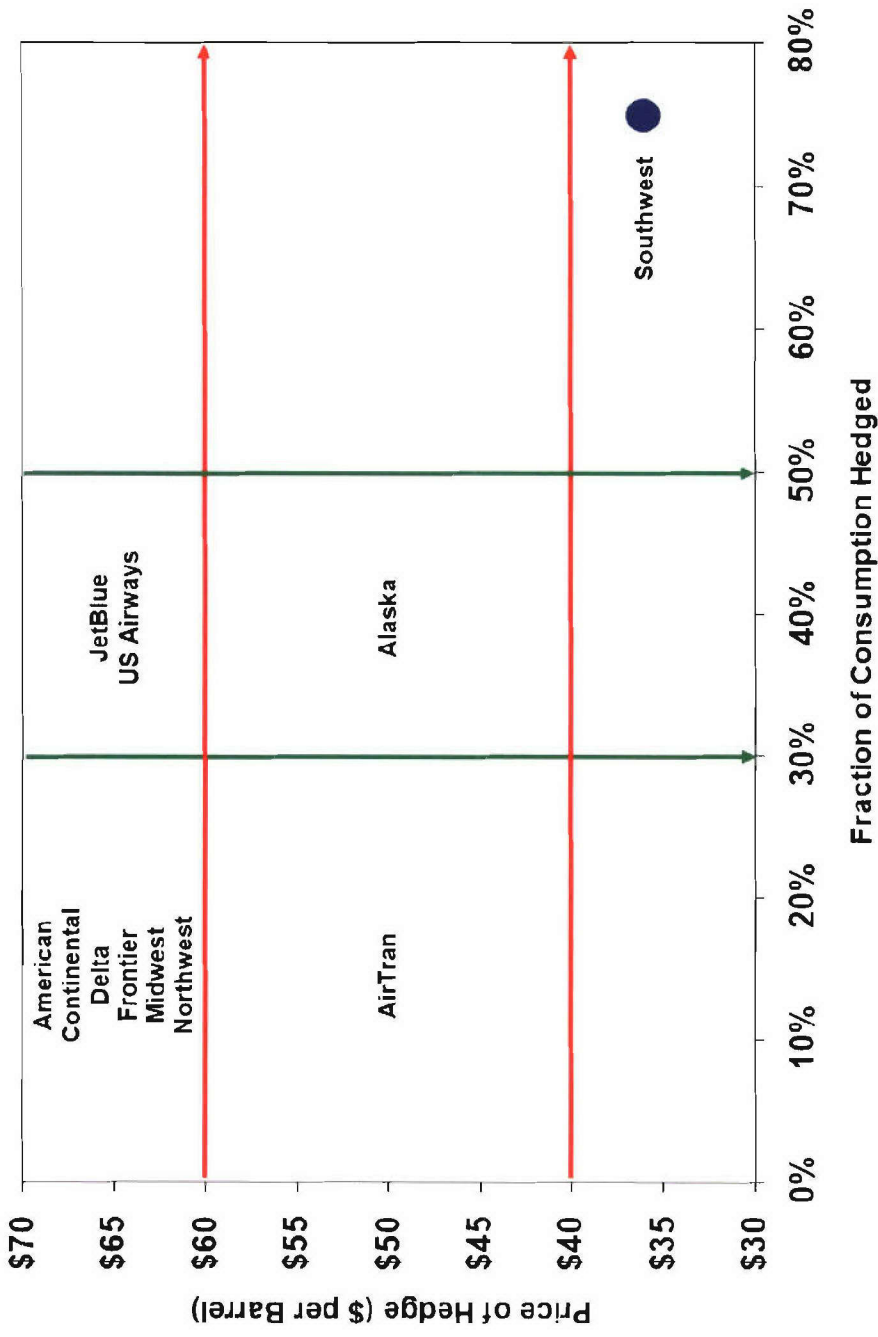
It is helpful to put the U.S. Air Force jet fuel consumption into the context of the domestic consumption of commercial aviation fuels. In terms of fuel, the Air Force with \$4.6B in fuel purchases in 2005, is a somewhat larger fuel consumer than, but close to, the largest commercial U.S. airline (American). As such, the DoD and the U.S. Air Force are not market drivers for aviation fuels, or any other petroleum product, for that matter.

Commercial aviation is expending considerable efforts to decrease its fuel use. At this time, commercial aviation fuel costs almost match labor costs, as indicated in the figure below that plots unit operating costs (¢ per available seat-mile) from 1990 through the fourth quarter of 2005. Note that the time units for 2005 are in quarters, vs. years for time prior to 2005, indicating the very rapid recent increase in fuel-cost burdens to U.S. commercial airlines.



© AITA Jan 06 15

U.S. airlines — Hedging



Sources: ATA research, Bear Stearns and carrier reports

* Weighted average for crude-equivalent prices; estimated in some cases

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In what can only be characterized as an aggressive but obviously correct call, Southwest Airlines, some time ago, hedged 75% of their fuel purchases at \$35/bbl in long-term contracts. In the commercial-aviation industry, which is characterized by very small profit margins and whose profits are a consequence of very high gross sales, lower fuel costs relative to competitors can produce large differences. Profits being the percentage-wise small difference of large numbers, small variations in unanticipated costs or even minor accounting errors translate into the difference between profit and (potentially large) losses. In the unregulated commercial aviation industry, competitors are limited in their ability to raise prices unilaterally, for fear of significant loss in market share. Partly as a result, Southwest Airlines is quite profitable, at present, certainly relative to the main body of the rest of the commercial airline industry.

This method illustrates one approach to ensuring stability of fuel pricing: entering into long-term contracts as a hedge against significant future price increases and thus allowing for budgetary planning for a period of years into the future. The potential downside, of course, is the higher costs in the event of future decreases in crude-oil prices. Such effects can be mitigated by hedging for only a fraction of future anticipated oil needs, as the airlines listed on page 26 have done.

DoD fossil fuels — Regulatory environment

Ground tactical vehicles (e.g., HEMMT, PLS, HMMWV) fielded in the U.S. must meet the 15ppm sulfur regulation JP-8 does not meet this requirement

Ground combat vehicles (e.g., Abrams, Bradley, Stryker) are exempt EPAct 2005 Sec. 369

Congress declares that it is the policy of the U.S. that —

- (1) U.S. **oil shale, tar sands,** and other unconventional fuels are strategically important domestic resources that should be developed to reduce the growing dependence of the U.S. on politically and economically unstable sources of foreign oil imports
- (2) The development of oil shale, tar sands, and other strategic unconventional fuels, for research and commercial development, should be conducted in an environmentally sound manner, using practices that minimize impacts and
- (3) Development of those strategic unconventional fuels should occur, with an emphasis on sustainability, to benefit the U.S. while taking into account affected States and communities

EPAAct 2005 Sec. 239a

Procurement of fuel derived from coal, oil shale and tar sands

- (a) Use of Fuel to Meet DoD Needs — The SecDef **shall develop a strategy to use fuel produced, in whole or in part, from coal, oil shale, and tar sands** (referred to in this section as a “covered” fuel) that are extracted by either mining or in-situ methods and refined or otherwise processed in the U.S. in order to assist in meeting the fuel requirements of the DoD **when the Secretary determines that it is in the national interest**
- (b) Authority to Procure — The SecDef may enter into 1 or more contract or other agreements (that meet the requirements of this section) to procure a covered fuel to meet 1 or more fuel requirement of the DoD
- (c) Clean Fuel Requirements — A covered fuel may be procured under subsection (b) only if the covered fuel meets such standards for clean fuel produced from domestic sources as the SecDef shall establish for purposes of this section in consultation with the DoE

- (d) Multi-year Contract Authority — Subject to applicable provisions of law, any contract or other agreement for procurements of covered fuel under subsection (b) may be for 1 or more years at the election of the SecDef
- (e) Fuel Source Analysis — In order to facilitate the procurement by the DoD of covered fuel under subsection (b), the SecDef may carry out a comprehensive assessment of current and potential location in the U.S. for the supply of covered fuel to the Department

Coal-to-Liquid Fuel Development Plan (Title X - General Provisions: - Page 790)

The SecEnergy, in coordination with the SecDef, **shall prepare and submit** to the SASC, Senate Energy and Natural Resources Committee, and Senate Appropriations Committee (SAC), and to the HASC, House Energy and Commerce Committee, House Science Committee, and House Appropriations Committee (HAC), **a development plan for the coal-to-liquid fuel program.** The development plan shall be prepared taking into consideration:

- (1) technology needs and developmental barriers;
- (2) economic and national security effects;
- (3) environmental standards and carbon capture and storage opportunities;
- (4) financial incentives;
- (5) timelines and milestones;
- (6) diverse regions having coal reserves that would be suitable for liquefaction plants;
- (7) coal-to-liquid fuel testing to meet civilian and military engine standards and markets; and
- (8) any roles other federal agencies, state governments, and international entities could play in developing a coal-to-liquid fuel industry, not later than 90 days after the date of enactment of this Act.

The SecDef, in coordination with the SecEnergy, shall prepare and submit to the SASC, Senate Energy and Natural Resources Committee, and SAC, and to the HASC, House Energy and Commerce Committee, House Science Committee, and HAC, a report on the potential use of the fuels by DoD, not later than 90 days after the date of enactment of this Act.

++ ..

3. Regulatory factors affecting DoD fuel use, planning, and policies

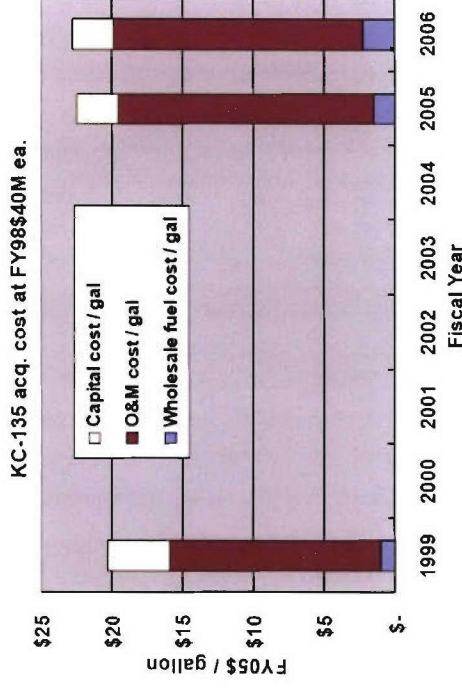
DoD lives in a complex and changing regulatory environment. Additionally, most of the DoD fuel is consumed in the continental U.S. Congress has mandated that most of this fuel must meet the 15 ppm sulfur regulation in the future. JP-8 does not meet this specification. Note that exceptions are provided for ground combat vehicles, e.g., Bradley, Abrams, and Stryker vehicles.

A myriad of other regulations and directives are mandated by Congress. For instance, as the slide indicates, DoD has been directed to develop a strategy to use fuel produced, in whole or in part, from coal, oil shale, and tar sands and to develop a plan for coal-to-liquid fuel production and consumption. The trade-offs between obtaining liquid fuel from coal relative to biomass, natural gas, municipal solid waste, or other sources are discussed in some depth and in response to the study charge, in a later section of this report.

DoD must live within these Congressional, typically unfunded, mandates and other directives. To the extent that it has influence over them, DoD should attempt to ensure that the most cost-effective means are encouraged and implemented in each case in obtaining the fuel it needs to support its missions effectively.

Logistics, supply costs, and other considerations

- Delivering fuel is costly in \$s, infrastructure, and lives
- Fuel delivery costs
 - Large multipliers
 - It takes (a lot of) fuel to deliver fuel
 - Difficult to quantify
 - Air-to-Air: \$20-25/gal
 - Some of this is fixed (not scaled by gallons) by prepositioned tankers around the globe
 - Assumes 40-year life for KC-135s
 - Army theater: \$100-600/gal
 - Large cost range depends on "front line" to "back line" separation in distance, terrain, defense, etc.
- ★ Infrastructure costs
 - A large fraction of infrastructure costs and vulnerabilities scale with fuel volume that must be delivered
- ★ Cost in lives
 - Changes in military doctrine
 - Present logistic supply designed at a time when "behind the front lines" denoted more-or-less safe terrain



- JASON estimated cost/gal delivered in the air
 - In 2005, 6.5% (165 Mgal) of USAF use
 - Gallons delivered also include non-USAF gallons
 - O&M costs dominate
 - 1999 O&M costs back-calculated to match DSB2001 estimate
 - JASON estimate adds acquisition cost/gal

AF air-to-air data from L. Klapper [AF Cost Analysis Agency].

4. *Drivers to minimize DoD fuel use*

Barring unforeseen upheavals and if price is important but not a decision driver, why should the DoD reduce fuel use? As discussed below, there are *compelling* reasons for the DoD to reduce fuel consumption, for which the drivers are: potential future uncertainties over the next 25 years and beyond, logistics, supply costs, and other related considerations. In particular, delivery of fuel is costly not only in terms of fuel-acquisition dollars, but also in infrastructure and lives.

Fuel delivery costs are accompanied by large multipliers. As can be appreciated via variants of the rocket or Breguet equations, it can require a lot of fuel to deliver fuel. Fuel delivered is the payload of the fuel-delivery vehicle. Unfortunately, little quantitative information is available on the multipliers that pervade the logistics chain for representative scenarios of missions. To wit, how much fuel must be delivered at the rear to supply a gallon of fuel to the front?

As part of this study, JASON attempted to analyze what it costs to deliver fuel air-to-air. Details of the analysis are provided in Appendix II. The estimated FY05 cost is \$20-25/gal. This includes the cost of the fuel, which represents the smallest fraction, the cost of operations and maintenance (O&M), and the acquisition cost of the KC-135 tanker aircraft (FY98-\$40M, each, acquisition cost, amortized over a 40 year lifetime of the aircraft, adjusted for inflation to FY05 dollars) and in terms of gallons delivered in air-to-air refueling.

This analysis demonstrates that the cost of fuel is not the decision driver; rather, the primary cost is O&M. For reference, in 2005, only 6.5% (3.9 Mbbl) of U.S. Air Force fuel

was delivered in the air. The JASON estimate is also in accord with the 2001 DSB estimate, even though capital costs for the tanker fleet were not considered in that analysis.¹⁴

JASON was advised that the cost of delivering Army fuel to the front line can be in the range of \$100-600/gal. The large cost range depends on “front line” to “back line” separation in distance, terrain, defense and other logistics requirements, etc.

A large fraction of infrastructure costs and vulnerabilities scale with the fuel volume that must be delivered. One must also consider the cost in lives of delivering fuel due to recent changes in military doctrine. The present logistic supply chain was designed at a time when “behind the front lines” denoted more-or-less safe terrain. This is no longer true. Further, fuel-supply vehicles are not armored and, as a consequence, present a vulnerable target and a costly liability in terms of lives and treasure for U.S. forces.

We conclude that the greatest driver for reducing fuel use lies not in the reduction of the direct cost of the fuel itself, but in the reduction of the attendant indirect costs of logistics to supply the fuel, the cost of the fuel required to deliver the fuel needed, as well as the enhancements in tactics that would accompany increased vehicular range, if fuel consumption were to be decreased on a given type of vehicle.

¹⁴ Defense Science Board Task Force on Improving Fuel Efficiency of Weapons Platforms (January 2001) *More capable warfighting through reduced fuel burden.*

Army combat/tactical vehicles — Hybrid vehicles

- Advantages
 - Use of stored energy (e.g., in batteries) to augment peak power demands
 - Decreases installed ICE plant peak-power requirements
 - Allows ICE to operate (mostly) within peak-efficiency regime
 - Decreases peak-power fuel consumption
 - Electric generator and storage system can augment electric-power demands when vehicle is stopped
 - Exploits efficient/capable generator for other needs (e.g., EMA).
 - If no other demands (e.g., sustained hotel power), stopped vehicle can turn engine off completely, eliminating idling fuel costs
- Disadvantages
 - Small, or no, fuel savings if average power is close to (> 30% of) peak power
 - Strongly dependent on use patterns
 - Higher mpg for Toyota PRIUS for city vs. highway driving
 - Scott Kochan [Ovonic Hydrogen]
 - But, ... Your Mileage May Vary
 - Higher (capital) cost and power-plant complexity that is difficult to amortize over vehicle life
 - Average HMMV use is ~2000 mpy
 - Higher hybrid power-plant costs cannot be justified by fuel savings
- Recent inline-6 diesel engine*
 - Greater fuel savings for Army combat vehicle pattern of use
 - Low fuel consumption at idle and when providing hotel power
 - Obviates advantages of hybridization

* C. Raffa [TARDEC] 27Jun06 JASON briefing.

V. Technology options for the reduction of DoD fossil fuel use

Given that most of DoD fossil fuel use is related to mobility and given the compelling rationale for reducing fossil fuel use, various vehicle technology options are now evaluated that would enable fuel-use reductions. Technology options evaluated include hybrid diesel-electric vehicles, all-electric vehicles, fuel-cell vehicles, structural-weight reduction and light-armored vehicles, comparisons between manned and unmanned vehicles, and vehicle mix.

In a subsequent section, other generic approaches are examined, i.e., replacing DoD fuel consumption from 100% of fuels derived from crude oil to include fuels derived from a diversity of sources, including material contributions from alternate fuels such as gas-to-liquids, coal-to-liquids, biofuels, and/or other supply-side fuel technologies.

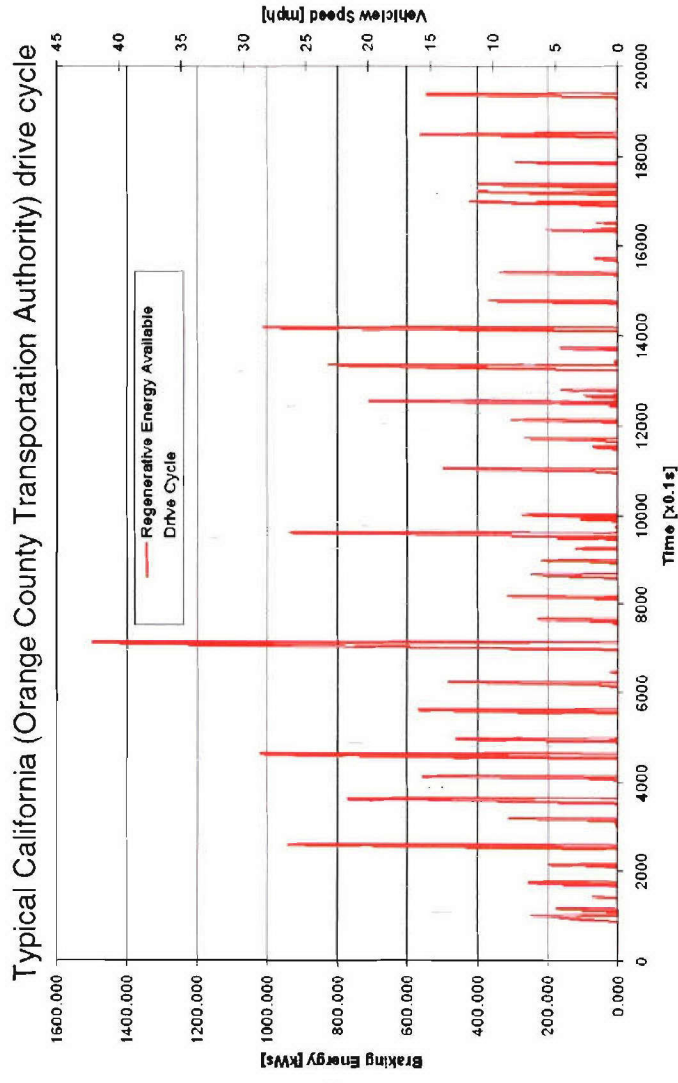
A. Modification of patterns of use of DoD platforms

Overall fuel consumption is strongly dependent on the patterns of use of vehicles, which include vehicle mix, the total number of engine-hours per day, mobility vs. idling/hotel-power consumption when stopped, etc. Apparently, the Army does not have sufficient data on this subject to facilitate a quantitative evaluation of the various options. We therefore strongly recommend, as a critical first step to achieving improved fuel efficiency, that the Army install relatively inexpensive, commercially available, systems similar to the GM “On-Star” vehicle monitoring system, or equivalent, to

track fuel use. This will allow the Army to develop a database that will enable planning, projection, and operational optimization, as well as providing a baseline against which future vehicles can be compared and assessed. Fuel consumption rate, per unit power produced, is a strong function of the power levels required for each vehicle and engine, which depend on the pattern of use. If the use pattern is not understood, reliable optimization of engine selection and efficiency is not possible.

Despite the lack of quantitative data on actual Army vehicle operation, it is possible to draw some qualitative and semi-quantitative inferences regarding the relative merits of technology options to achieve fuel consumption reduction in Army vehicles. These various options broadly involve new engine design options and/or structural lightweighting. Such choices are discussed and evaluated below in the context of their suitability for DoD missions and goals.

Hybrid vehicles — *Use pattern*



- Greatest fuel savings by hybrid vehicles, for example, for
 - City buses: stop-n-go traffic
 - Utility-service vehicles: long idling periods
 - Postal delivery vehicles
- Most DoD use patterns involve long “stop” periods and smaller continuous “go”

Graphic from P.B. Scott [ISE Corp.] 28Jun06 JASON briefing

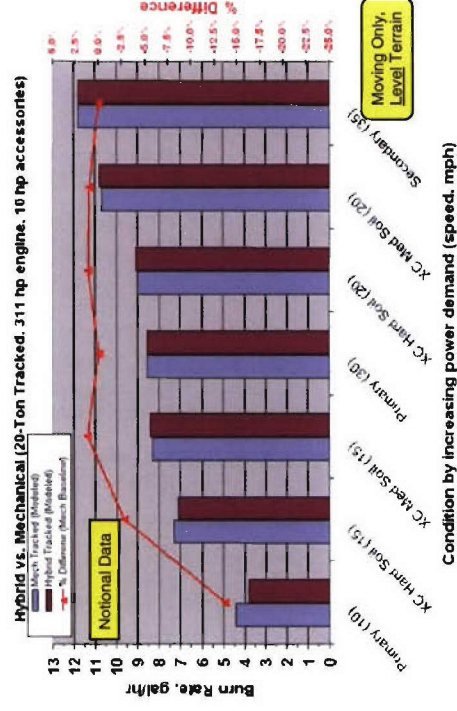
B. Engine and drive-train technology options

1. Hybrid vehicles

Hybrid vehicles have the capacity to do work using both an internal combustion engine (ICE) and an electrical motor, in series, or in parallel. The ICE drives an electric generator, storing energy in batteries. The energy stored is used to augment the ICE output to meet peak-power demands. This combination results in a decrease in the installed ICE plant peak-power requirements, which is what scales engine size (displacement) and, ultimately, fuel consumption. Additionally, hybridization of the engine with the electrical motor portion of the power plant allows the ICE to operate (mostly) within its peak-efficiency regime. The electric generator and storage system can augment electric-power demands when the vehicle is stopped. The efficient and capable generator can also be used for other vehicle needs, e.g., in providing hotel and other (electrical-) power requirements.

Hybrid vehicles are attracting much attention in the commercial transportation sector due to their increased fuel economy relative to conventional ICE vehicles. The efficiency of hybrid vehicles is, however, strongly dependent on their use patterns. Recovery of energy by regenerative braking makes these vehicles especially good in stop-and-go driving on low-friction surfaces. Thus, the greatest fuel savings for hybrid vehicles are incurred for city buses, utility-service vehicles, especially if power demands when stopped are modest and can be (mostly) provided by stored electrical energy in batteries, and postal-delivery vehicles. As an example of this, the Toyota Prius can obtain (slightly) better mileage in city driving than

under highway driving conditions. Under highway driving conditions, the advantage of regenerative braking energy recovery is minimal, and fuel economy is actually adversely affected by having to carry the extra weight associated with the (unused under these conditions) batteries, generator, and more complicated/heavy drive train for the required horsepower.

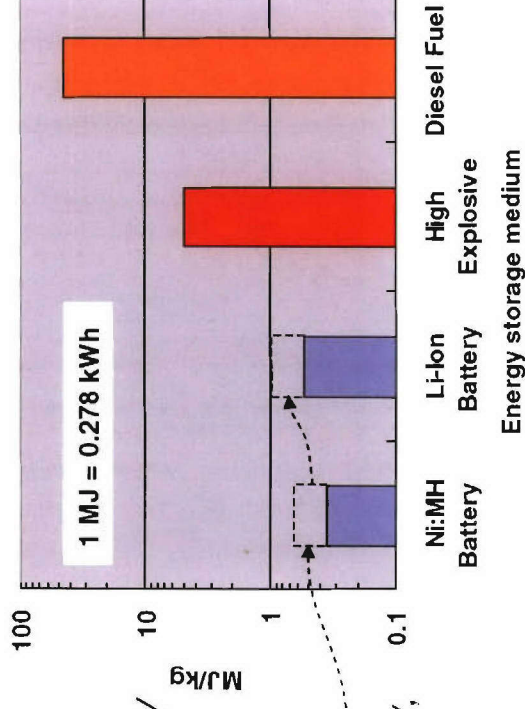


This is confirmed by the results of the analysis depicted in the figure above that compares hybrid vs. conventionally powered, 20-ton tracked vehicles, modeled as operating over a variety of terrains.¹⁵ In general, hybrid vehicles offer little or no fuel savings if the average power delivered by the engine is close to (i.e., within approximately 30% of) the peak power load of a typical driving cycle.

¹⁵ Robert M. Roche [Army Materiel Systems Analysis Activity - AMSAA] Fuel Consumption Modeling Support and Insights. JASON 20 July 2006 (VTC) briefing.

Army — All-electric vehicles

- Advantages
 - Efficient conversion of stored electrical energy to mechanical power (~85-90%)
 - All-electric power is well-suited to vehicles with high electrical demands.
 - Enable quiet/stealthy operation
 - Acoustic noise emissions
 - IR emissions
 - No combustion exhaust/odors, or other GHG emissions
- Disadvantages
 - Cost : battery life-cycle, +
 - Charging is slow and requires diesel generator or wall-plug electricity
 - Energy storage per unit mass/volume is too small for most uses
 - ~ 1% of diesel fuel (by volume)
 - ~ 2% of diesel-fuel equivalent (x2 ← improved efficiency)
 - Electrical energy out is, approximately, 85% of energy in
 - Small range, unless aggressively lightweighted



In off-road environments, conditions for when hybrids can offer improved performance are even more discouraging. Such conditions more-closely reflect DoD vehicle use than the EPA drive cycle for commercial vehicle use, for example, or the bus drive cycle depicted above. Hence, the pattern of use for the Army does not lend itself to rendering hybrid-vehicle designs advantageous for fuel-use-reduction purposes.

Another possible advantage of hybrid vehicles involves the capability for silent watch. If no other demands are placed on the system (*i.e.*, sustained hotel power), the stopped vehicle can turn the engine off completely, eliminating idling fuel costs. The engine would then be turned on only when the batteries need to be replenished.

Army combat vehicles spend as much as 80% of the time stopped, *i.e.*, providing hotel power, only. Hence, a silent watch capability seems attractive. However, for the future combat system, hotel power requirements are specified to be 25-32 kW (the additional 7 kW for air conditioning where needed). To meet this requirement for even 1-2 hours would require a very large suite of batteries, which are heavy per unit of stored energy. A typical Li battery pack would, for example, provide 0.2 kW-hr/kg. Supplying 25 kW for 2 hours is 50 kW-hr would require an additional 200 kg of extra battery weight just to meet hotel-power requirements. This extra weight would come at the expense of payload, fuel carried, and fuel economy while driving the vehicle.

The disadvantages of the increased weight of the hybrid extend further. Heavier vehicles are more difficult to deploy by airlift. Additionally, if the overall weight of the hybrid relative to that

of a conventional platform is increased, the payload of the hybrid vehicle is necessarily reduced. Considering that a large fraction, if not the majority, of tactical ground vehicles are used for carrying supplies in theater, a more appropriate metric for fuel efficiency should be payload-miles (ton-miles) per gallon instead of vehicle-miles per gallon. By this metric, hybrid vehicles offer even fewer advantages in terms of potential fuel savings.

Additionally, hybrid vehicles have higher capital costs and increased power-plant complexity (and maintenance). These costs are difficult to amortize over vehicle life even in the case of an average commercial-vehicle 10,000 mile per year range. In the case of the military, JASON was informed that the typical HMMWV travels only ~2000 miles per year. Such low mileage makes it especially difficult to justify the higher cost of the hybrid system powerplant on the basis of fuel cost savings (if any) alone.

As discussed below, JASON found that modern diesel engines offer a considerable advantage over hybrid vehicles for most DoD combat, and perhaps tactical, vehicle patterns of use.

2. *All-electric vehicles*

All-electric vehicles provide efficient conversion (~85-90%) of stored electrical energy to mechanical power. An all-electric power train is well-suited to vehicles with high electrical demands. In principle, such vehicle designs enable quiet/stealthy operation, with a reduction in acoustic noise emissions, IR emissions, (detectable) combustion exhaust/odors, and other greenhouse gas (GHG) emissions.

Fuel-cell vehicles

- Advantages
 - Direct fuel-to-electricity conversion
 - Demonstrated high benchtop efficiency
 - Fuel-cell: > 50%, ICE typical: 15-25%
 - No vehicle GHG emissions for H₂ FCs
 - GHGs from reformed H₂ and other fuels
- Disadvantages
 - Low power density (including thermal-management systems)
 - Scale poorly to high power
 - Poisoned by impurities: S, CO, etc.
 - For current H₂ fuel cells, prohibitive catalyst costs
 - Possibly (projected at scale), \$100K-\$1M for 100 kW power plant
 - Very expensive membrane costs with no long-term durability
 - For direct diesel use, high-T ceramics prohibitively expensive; long start-up times; coking, scale poorly to high power
 - For reformers, low efficiency at moderate power and energy density



Graphic from P.B. Scott [ISE Corp.] 28Jun06 JASON briefing

All-electric vehicles, however, have very expensive battery life-cycle costs. Charging is slow and requires either a diesel generator or access to wall-plug electricity. This by itself seems to preclude their widespread use in military tactical operations. Moreover, these vehicles have a small range unless aggressively light-weighted.

Energy storage (per unit mass or volume) of even the best available Li batteries is too small for most military vehicular uses. The energy storage density of the best batteries is, approximately, 1% that of diesel fuel (by volume), i.e., 2% of diesel-fuel equivalent (because electric vehicles are ~2x more efficient than a diesel ICE). Electric vehicles (like gas or diesel-based hybrids) might be suited for specialized civilian-type uses (local-mail delivery, base patrols, etc.) on DoD bases in CONUS, and could provide fuel savings in that capacity, but are not indicated for use in general military applications in theater.

3. *Fuel-Cell vehicles*

Fuel cell vehicles provide direct conversion of fuel to electricity. They have demonstrated high bench-top efficiency (> 50%) relative to the typical ICE powerplants (15-25%). Hydrogen fuel cells have no (vehicle) GHG emissions, though their upstream GHG emissions can be large, as well as their emissions from in-vehicle-produced reformed hydrogen.

Fuel cells are low power density systems, if the required thermal-management systems are included. Fuel cells generally scale poorly to high power densities on a mass basis. Low-

temperature fuel cells are poisoned by fuel impurities such as sulfur and carbon monoxide and, as a consequence, require highly purified fuel. Additionally, even if the fuel feedstock were suitably purified, introduction of these contaminants into the air intake of a fuel cell vehicle rapidly poisons the catalyst and immobilizes the vehicle.

Current H₂-based fuel cells have prohibitive catalyst costs, of order \$100K-\$1M, for 100 kW power plants, typical of busses, heavy-duty cars, or trucks, for example. Additionally, such fuel cells have very expensive membrane costs with no long-term (i.e., 1-year) durability and/or warranty.

Another drawback of H₂-fuel-cell based vehicles is the logistics train that would be required to supply the gas-phase fuel, H₂, to theater. Canisters to contain H₂ gas are large and heavy; an obvious flammability and, under some conditions, an explosion and detonation liability would exist throughout the logistics train. On-board H₂ storage also requires much larger mass (weight) or volume than liquid fuels. This drawback would deleteriously impact vehicle range, military performance, and supply-chain logistics of such a system.

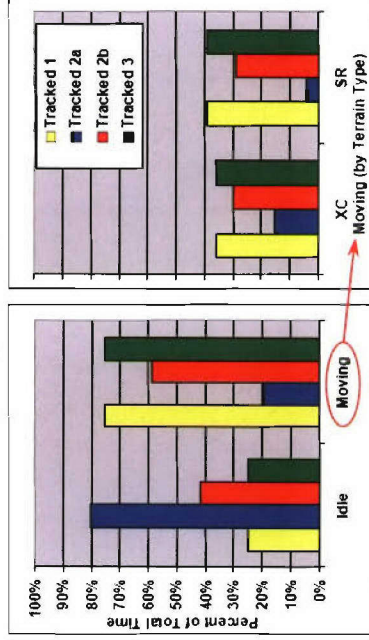
For direct diesel use in a fuel cell, high-temperature ceramics are also prohibitively expensive, have long start-up times, suffer coking, and scale poorly to high power. Fuel cells used in conjunction with reformers exhibit low efficiency at moderate power and energy density.

Patterns of use — Wheeled and tracked vehicles

Wheeled (tactical) vehicles

LEVEL Condition	HMMWV M998 Baseline				M998 w/Armor no AC				M998 w/Armor w/AC			
	Burn Rate, gal/hr	Moving Economy, mpg	Consumed, gallons	Burn Rate, gal/hr	Moving Economy, mpg	Consumed, gallons	Burn Rate, gal/hr	Moving Economy, mpg	Burn Rate, gal/hr	Moving Economy, mpg	Consumed, gallons	Burn Rate, gal/hr
Total Mission	1.4	6.8	32.6	1.4	6.4	33.5	1.9	5.3	1.9	5.3	46.0	
Primary Rds	3.3	10.6	1.9	3.4	10.3	1.9	4.2	8.4	4.2	8.4	2.4	
Secondary Rds	3.4	8.8	5.7	3.4	8.8	5.7	4.2	7.2	4.2	7.2	7.0	
Trails	4.8	5.2	3.9	5.7	4.4	4.6	6.5	3.8	6.5	3.8	5.2	
Cross-Country	3.2	3.1	3.2	3.4	3.0	3.4	4.2	2.4	4.2	2.4	4.2	
Idling	0.9		18.0	0.9		18.0	1.4		1.4		27.2	

Tracked (combat) vehicles



- Estimated 50-80% of time spent idling
 - Hotel power is too large to be supplied by batteries
 - Recent in-line 6-cylinder diesel engine, will have much lower fuel consumption at idle and low power
 - Such redesigns would not be characterized by increased fuel economy on an EPA drive cycle, but could significantly decrease DoD land vehicle fuel consumption
- No DoD telemetry system (e.g., "On-Star") to monitor fuel consumption and use patterns of individual vehicles

Data from R. Roche [Army Material Systems Analysis] 20Jul06 briefing

4. *Advanced diesel engine vehicles*

The commercial sector is focused on optimizing engines to excel on the EPA drive cycle and testing protocols. In that testing, which involves a dynamometer, there is no electrical load on the vehicle due to the air conditioner, for example, no aerodynamic (wind) resistance, and no road friction.¹⁶ Nor does the pattern of use in an EPA drive cycle (city stop-and-go or highway driving) reflect the pattern of use of DoD vehicles. In particular, DoD combat vehicles spend a significant amount of time stopped and providing hotel power. They also go off-road and go through mud, etc. Hence, engines that do not yield high scores in the EPA drive cycle and test conditions could yield very different results for military use and, in particular, significant improvements in DoD land-vehicle fuel economy if they are well-matched to DoD patterns of use.

Specifically, recent advances in diesel engines offer a greater return in fuel savings for Army patterns of use, and obviate most, if not all, of the potential advantages that might possibly be gained by hybridization. In particular, the new inline-6 diesel engines are very attractive in this regard. They are also much more fuel efficient than prior diesel engines. These engines are designed to have very good efficiency at idle and when providing hotel power.¹⁷ They thus appear to be preferable to hybridization as a method of improving fuel

¹⁶ The variance between peoples' actual miles-per-gallon experience and expectations based on show-room EPA sticker mileage data ("*Your mileage may vary.*") are not difficult to understand.

¹⁷ Charles Raffa [TARDEC] 27Jun06 JASON briefing and accompanying material.

efficiency for Army vehicles, reducing fossil-fuel consumption, improving vehicle range, decreasing the thermal-management burden, and thereby improving military capability. Additionally, they are capable of a fairly rapid transition into the existing military fuel infrastructure and perhaps pose less of a perturbation on logistics and O&M.

Noteworthy is that increases in engine efficiency, i.e., a reduction in fuel consumption for a given (mechanical) horsepower output is accompanied by decreases in the thermal management burden. This is a very important consideration in that armored vehicles are not only severely volume-limited, but are forced to reject unwanted heat through places on the vehicle of higher vulnerability to enemy fire; the more heat that must be rejected the more vulnerable the armored vehicle is, other factors held constant.

Estimates from tests in the late 70s for the fuel consumption of the turbine-powered Abrams vs. the diesel-powered M60 tanks were roughly 2:1, but field data from the REFORGER exercises in Germany showed the turbine tanks had about 4:1 rather than the previously estimated 2:1 fuel consumption. The difference was attributed to time at idle, estimated to be as much as 83% of total operating time. What little data exist indicate that, at idle, the ratio of fuel consumption between the two tanks is more than 4:1 (at 10 kW electrical output, 10.6 gal/hr normal idle vs. 2.3 gal/hr). At the Abrams "tactical idle" setting with the engine at 1200-1250 rpm instead of the 890-900 rpm of normal idle and with the transmission in neutral, installed fuel consumption is about 17 gal/hr.¹⁸

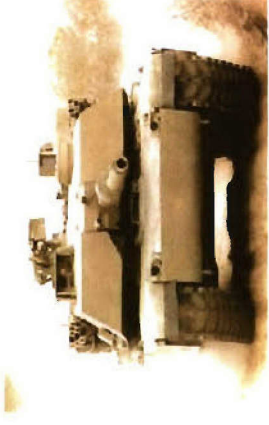
¹⁸ Charles Raffa [TARDEC] 31Jul06 pvt. comm. (cf. also figure on p. 35).

Army — Weight reduction and light-armor vehicles

- Overall fuel consumption is strongly dependent on
 - Pattern of use
 - Fraction of engine-hours per day
 - Mobility vs. hotel-power consumption
 - Fuel consumption rate per unit power produced
 - Engine efficiency
- Mobility fuel
 - Consumption of heavy vehicle in motion at moderate speeds is dominated by friction losses to ground



- (Nearly) proportional to weight and distance, i.e., per ton-mile



- Armor is ~20% of total weight for armored vehicles
 - Progress in armor capabilities could decrease armor weight by ~ x2, for a given protection level.
 - Changes in threat levels and engagement scenarios drive towards increased protection for the same weight, rather than decreased armor weight
- Potential savings in ton-miles likely possible by reduction in
 - Required payload through improvements in patterns of use
 - Vehicle structural weight — modern materials and construction methods
 - ★ Currently, up-armor is at the expense of payload

Relative to the turbine engines currently used in the Abrams tank, modern diesels offer improved efficiency, especially at idle, dramatic improvements in fuel consumption (3-4x, depending on the pattern of use), decreases in maintenance costs, and an increase in (autonomous) range (~2x, or more).¹⁹

For these reasons, the M1-Abrams tank should be re-engined with diesel engines as soon as possible. These vehicles are likely to remain in the inventory for some time – perhaps through 2020, or more – and should be upgraded. This proposal has been argued for some time and the reasons are more compelling today than they were in the past.

C. Lightweighting DoD platforms

Another method to increase fuel efficiency will now be discussed: reduction of vehicle weight while maintaining military performance. There are two approaches: lightweight manned vehicles, and replace manned vehicles by unmanned vehicles. The former maintains similar missions and personnel demands and requirements to the ones in place now, the latter changes those demands and requirements significantly. Each option is discussed separately.

1. *Manned vehicles*

The fuel consumption of a heavy vehicle in motion at moderate speeds is dominated by friction losses to ground, as opposed to aerodynamics. For this reason, fuel consumption is nearly

proportional to the product of weight and distance (i.e., ton-mile). Thus, if the weight of a vehicle is reduced by 2x, the fuel consumption is reduced by approximately 2x. The net effect of this increased efficiency multiplies significantly back through the supply chain.

Army vehicle weight can be partitioned into armor, structure, fuel, and payload. For military vehicles used in combat, armor weight naturally attracts attention as a weight–reduction candidate. However, at present, armor is ~20% of total weight of most armored vehicles, so the potential overall benefits are not large. Progress in armor capabilities could decrease armor weight by a factor of two, for a given protection level. However, changes in threat levels and engagement scenarios drive the design space towards increased protection for the same weight, rather than decreased armor weight. JASON encourages further improved-armor capabilities, but favors increased protection over reductions in total armor weight.

Potential savings in weight are likely possible by reduction of the remaining 80% of vehicle weight. This can be done by reducing vehicle structural weight by the use of modern materials and construction methods, such as carbon reinforced polymer and the reduction in fuel weight/volume for a given range that the reduction in weight will enable. Additionally, one may be able to reduce the required payload through improvements in patterns of use.

It is worth noting that, as currently practiced in Iraq, up-armor is done at the expense of payload. This is not a good trade for overall fuel consumption purposes, but of course is necessary in the current theater environment to counter the threat to personnel in these vehicles.

¹⁹ One (minor) drawback may be in acceleration in that turbine-engine rpm can increase/decrease faster than with a diesel.

Land manned/unmanned vehicles

- Fuel savings per mile traveled on land are scaled by weight
 - Aerodynamic drag *unimportant for most DoD land vehicles/use*
 - *Fuel use*
 - (nearly) proportional to ton-miles driven, times power-plant efficiency,
 - plus consumption idling and for hotel-power production when stopped
- Specialized unmanned vehicles can obviate (most) armor and can have much smaller hotel power needs
 - *Very different TRL for guided vs. autonomous vehicles*
 - *(Much lighter) guided unmanned vehicles driving ahead of other vehicles in a column could help clear IEDs*
- Large fuel-use savings by reengining M1 tank with (modern) diesel engines
 - *At least x2 increase in range and approximately x3-4 decrease in fuel use per day*
 - Tanks spend most of their time at near-idling power levels, providing hotel power
 - *Large fuel-savings multiplier via reduction in logistics-train requirements*
 - It takes fuel to move fuel

2. *Unmanned land vehicles*

Fuel consumption per mile traveled on land is scaled by weight (aerodynamic drag is not important for most DoD land vehicles). Fuel use is then (nearly) proportional to the ton-miles driven, multiplied by the power-plant efficiency, and including the fuel consumption idling and the need for hotel-power production when stopped.

Specialized unmanned vehicles can obviate (most) armor – they could be treated as expendable – and could require much lower hotel power. Both guided and autonomous land vehicles are, however, at a very different technical readiness level than unmanned air vehicles, for example, discussed below. For land vehicles, the leap to totally autonomous vehicles may not be warranted, considering the technical difficulties and development costs, considering the potential benefits from the use of guided (remote-controlled) vehicles that can relay data from their own sensors, including cameras, creating a virtual panel for a (remote) controller who may be either distant, or in a following vehicle, depending on application. For example, much lighter guided unmanned vehicles driving ahead of other vehicles in a column could help serve either as decoys for, or to help clear improvised explosive devices (IEDs).

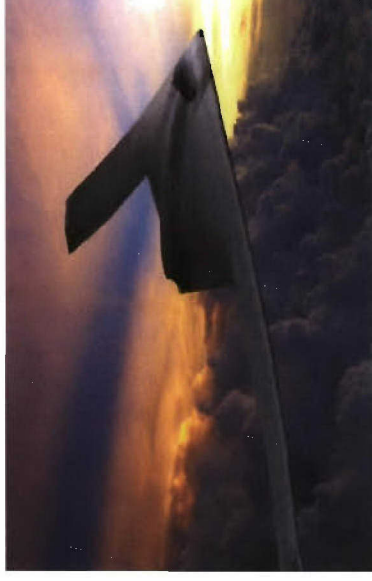
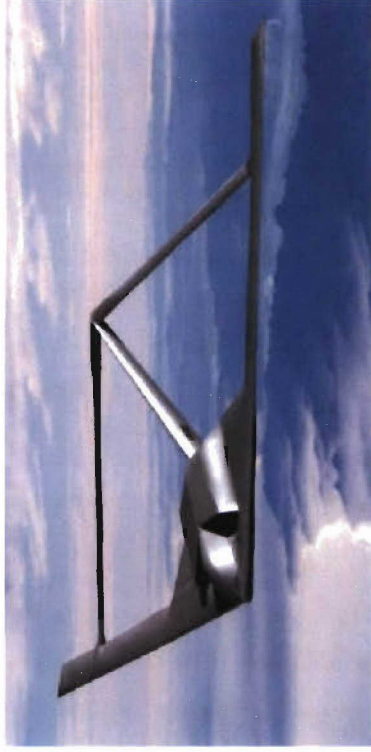
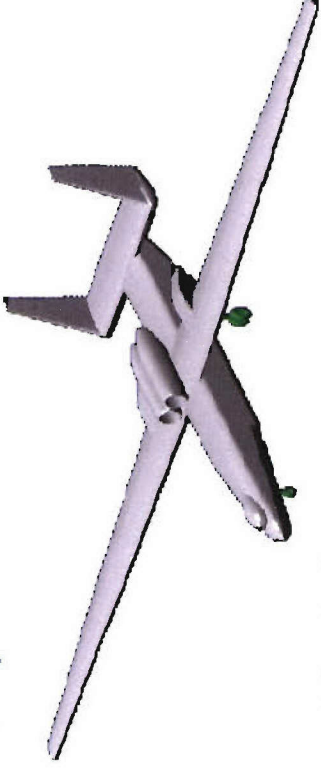
Air manned/unmanned vehicles — *Radical redesigns*

- Fuel-use per mile of travel scaled by Drag-to-Lift ratio
- Among DoD unmanned vehicles, UAVs are most mature
- Relegating traditional piloted-A/C functions to UAVs can result in large fuel-use reductions
 - *Can obviate air-to-air refueling altogether*
- Very large potential fuel savings from UAVs, especially if optimized to exploit niche regimes in altitude-speed-size corridors

AFRL case study — *SensorCraft* for persistent ISR

High-altitude, long-endurance ISR platform

- High vehicle L/D
- Possibly high M^2C_L
- Low drag over large range of C_L
- Light weight
- High aspect ratio, possibly swept or joined wing, with large conformal structural arrays



From D. Multhopp [AFRL] 27Jun06 JASON briefing

SensorCraft — Fuel savings vs. current systems

- One unmanned system replaces functions of 3 manned systems
 - JSTARS, AWACS, Rivet Joint
- No in-flight refueling required
 - Saves 200 klb of fuel per aircraft sortie
- Single SensorCraft 30hr loiter sortie
 - Equals 3 current ISR 10 hr loiter missions
 - Equals capability of 9 ISR sorties and 9 tanker sorties
- Total fuel savings of ~ 97% , i.e., a factor of 30
- ★ JASON note:
 - Larger savings yet because of large fuel-delivery multipliers

3. Unmanned aerial vehicles

Among the DoD unmanned vehicles, UAVs represent the most mature technology, benefiting from decades of development of autopilot systems in manned aircraft. The transfer of traditional piloted-aircraft functions to UAVs could enable the realization of very high fuel-use reductions. This is especially true if air-to-air refueling can be obviated completely.

In a major development program, on-going since 2000 and now focused on a major flight test in 2010, the Air Force Research Laboratory (AFRL) has been working on a design for a high-altitude, long-endurance, autonomous ISR platform dubbed SensorCraft. One such unmanned system could replace and integrate the functionality of 3 manned systems: JSTARS, AWACS, and Rivet Joint. Its long endurance would obviate in-flight refueling, saving 200 klb of fuel (28,560 gallons) per aircraft sortie. A single SensorCraft with a 30 hr loiter sortie would replace 3 current ISR 10 hr loiter missions, which would require 9 ISR sorties and 9 tanker sorties. The resulting fuel savings is approximately 97%, i.e., a fuel-saving factor of 30. If operational or other considerations indicate that the three functions that can be integrated in this UAV should not be collocated, three such craft would more than restore the previous functionality with a still-significant fuel-use reduction factor of 10, rather than the factor of 30 for a single craft.

As the AFRL slides imply, UAVs can be sized and configured to accommodate conformal array antennas for SAR, for example. Assuming an antenna size of $20 \times 0.5 \text{ m}^2$, for example, SAR performance, with the central frequency of the Lynx SAR of about 17 GHz (Ku band), the forward-looking real-aperture azimuth resolution would be,

$$\Delta x_{\text{real}} = \frac{\lambda R}{D} = 0.7 (R/\text{km}) \text{ m},$$

Where D is the (real) aperture, λ is the radar wavelength, and R the range. A transverse aperture of $D_{\perp} = 20 \text{ m}$ is then pertinent to forward-looking resolution and an along-path aperture of $D_{\parallel} = 0.5 \text{ m}$ for side-looking resolution. The implied range resolution is 1 m in the strip-map mode and 0.1 m in the spot-light mode. In ground-moving target indicator (GMTI) mode, the minimum detectable velocity (MDV) is,

$$\Delta u = \frac{\lambda U}{D},$$

at UAV speeds of $U = 100\text{--}200 \text{ m/s}$, i.e., $\Delta u_{\perp} = 0.15 \text{ m/s}$ in forward-looking mode ($D = D_{\perp}$) and $\Delta u_{\parallel} = 3\text{--}5 \text{ m/s}$ in sideward mode ($D = D_{\parallel}$).

As part of this study, JASON explored the design possibilities offered by the altitude-speed-size corridor, with an eye to maximizing endurance (unrefueled flight time) for UAVs in the 1000 kg-class payload regime. Preliminary calculations suggest that it should be possible to do considerably better ($> 2\times$) than the target 30 hr endurance target indicated for SensorCraft. The potential for persistent ISR as well as for other uses need not be emphasized here.

Considering the multipliers of delivering fuel to the air tankers, the savings would be larger yet because of the fuel-delivery multipliers. As is the case generically, fuel savings propagated through the entire supply chain should be an important part of the system cost analysis in the planning, logistics, and DoD acquisition process.

Alternative energy/fuels — Sources

- Non-carbon energy sources: Nuclear, solar, wind, geothermal, tides
 - Useful in production of electricity
 - Best used as such
 - Production of liquid fuels would convert high-value (high-thermodynamic-availability) energy into low-value energy
 - Would incur additional cost penalties and a x3 loss to convert to work
- Fossil
 - Oil
 - Coal
 - Gas
- Biofuels
 - Ethanol
 - Biodiesel
 - Bio-FT diesel

D. Alternate fuels in place of crude oil-derived fuels

Another tool to reducing the DoD dependence on fossil fuels is to substitute some portion of crude-oil-derived fuels with fuels derived from other sources. In this context, an alternative fuel is defined to be any fuel that is not directly derived from crude oil. Hence, liquid hydrocarbon fuels derived from coal or natural gas would be classified as alternative fuels, even though they are in fact derived from fossil sources.

Possible primary energy sources for production of alternative fuels also include non-carbon energy sources such as nuclear, solar, wind, geothermal, and tidal-energy sources. These sources, however, are best used in the production of electricity, which is high thermodynamic availability energy. Using such sources to produce liquid fuels converts high-value (high-thermodynamic-availability) energy into low-value energy. In addition to conversion losses to obtain fuel, an additional factor of, approximately, 3 reduction in its ultimate energy value, e.g., towards the production of mechanical work, is then incurred in the conversion of the (low-value) fuel to (high-value) work. As a rule, high-availability/-value energy is best used as such, rather than being converted to low-value energy to then be converted back, at considerable loss, to high-value energy and work.

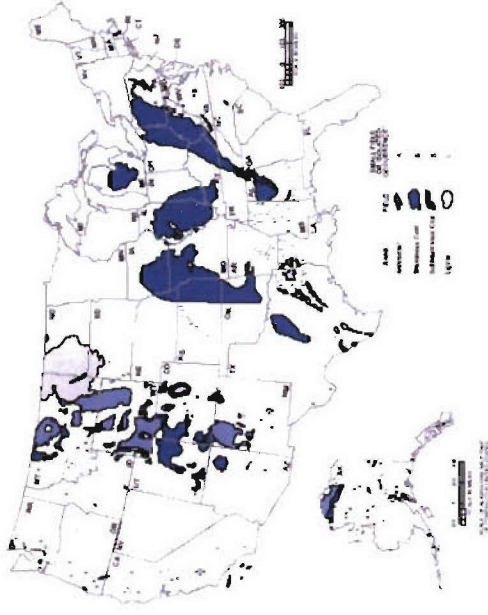
Further, there is currently no straightforward or economical method to convert these electrical energy sources into fuels, other than H₂ (through electrolysis), and H₂ is not well-suited for use by the DoD for a variety of technical and infrastructure-based reasons (vide infra). A breakthrough in this area would be a method to directly convert, for example, sunlight efficiently and cost-effectively into liquid fuels without going

through electricity as an intermediate step. Absent such breakthroughs, such alternative energy sources will not be considered further in this report, at least in the context of potential DoD fuel-supply sources.

Below, alternative fossil-derived fuels are considered, including those from enhanced oil recovery (EOR), coal and gas, as well as biofuels, including ethanol, biodiesel, and bio-Fischer-Tropsch (FT) diesel.

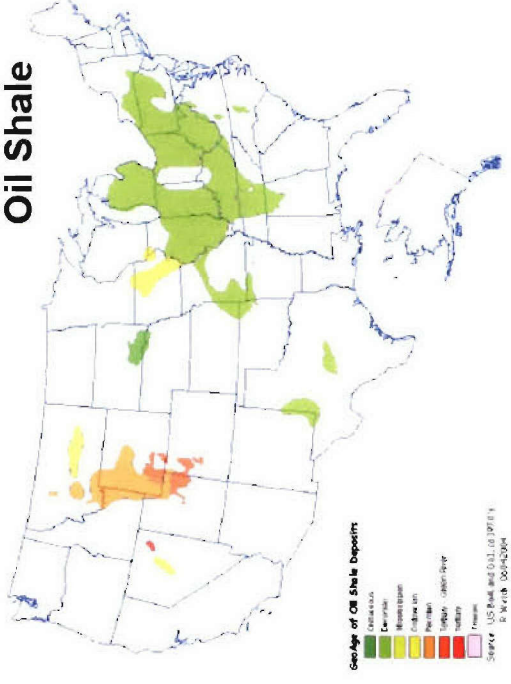
U.S. fossil energy resources

Coal

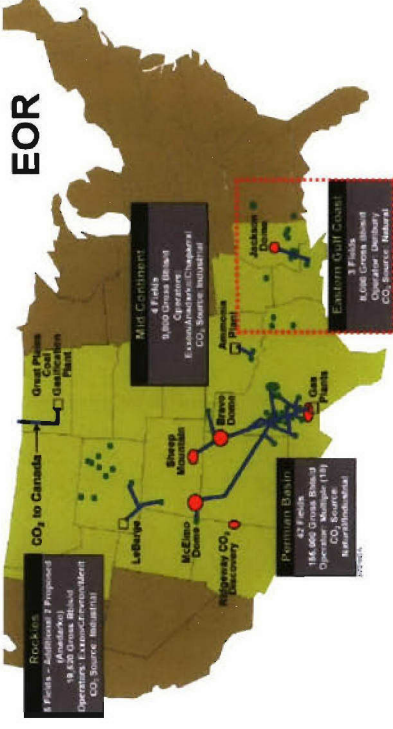


Sources: United States Geological Survey, Coalfields of the United States, 1960-1961; Texas Bureau of Economic Geology, Lignite Resources in Texas, 1960; Louisiana Geological Survey, Near Surface Lignite in Louisiana, 1971; Colorado Geological Survey, Coal Resources and Development Map, 1971; and Mississippi Bureau of Geology, 1982.

Oil Shale



EOR



Domestic Resources

- 1 trillion barrels (shale)
- 800 billion barrels of FT (coal)
- 0.15 billion barrels (pet coke)
- 22.7 billion barrels oil reserves
- 32+ billion barrels of oil (EOR)
- **Total of 1.9 trillion barrels**

Graphic from T.K. Barna et al. [OSD] presentation

As noted earlier, even though the U.S. has only 2% of the world's conventional oil reserves, it has approximately 30% of the world's unconventional fossil resources, including ~1 Tbbl (trillion barrels of oil equivalent = 1000 boe) of shale oil, 800 boe of FT coal, 0.15 boe of petroleum-derived coke, and greater than 32 boe of oil from enhanced oil recovery (EOR). In total, the U.S. has estimated resources equaling 1.9 Tboe.

At a U.S. consumption rate of 7.5 Bbbl/yr, this can yield a ~260 year supply from these sources alone. The FT process that converts one form of fossil energy into another, e.g., via coal-to-liquid (CTL) or gas-to-liquid (GTL) processes would yield an assured domestic supply of liquid hydrocarbon fuels for the DoD for many decades into the future, albeit accompanied with large environmental burdens, as discussed below, unless carbon sequestration and other measures are adopted with attendant increases in cost.

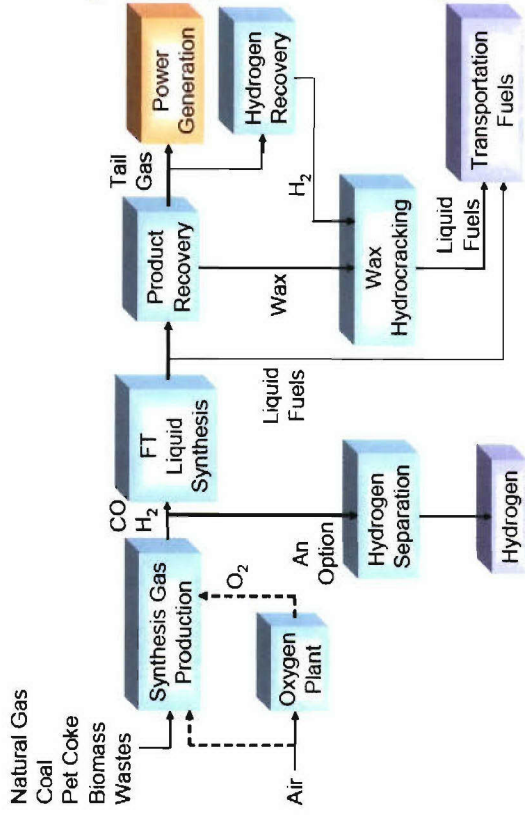
In addition to production costs, carbon sequestration, basically, capturing CO₂ from the combustion of fossil fuels and burying it under ground to keep it from contributing to greenhouse-gas emissions in the atmosphere, also entails environmental unknowns. For example, a pilot experiment in Houston, Texas, found that, the CO₂ dropped the pH of the formation's brine from a near-neutral 6.5 to 3.0, about as acidic as vinegar. That change in turn dissolved many minerals, releasing metals such as iron and manganese. Organic matter entered solution as well, and relatively large amounts of carbonate minerals dissolved. These naturally occurring chemicals seal pores and fractures in the rock that, if opened, could release CO₂ as well as fouled brine into overlying aquifers that supply drinking and irrigation water. Perhaps more troubling, is that the acid mix

could attack carbonate in the cement seals plugging abandoned oil or gas wells, 2.5 million of which pepper the United States. The lesson is that whatever we do [with CO₂], there are environmental implications that we have to deal with.²⁰

It is important to establish scientifically whether in fact, at scale, if carbon sequestration can be relied upon to keep CO₂ from leaking to the atmosphere for the indefinite future – if not, the problem is only delayed – or if other, secondary, side effects prove to be serious.

²⁰ Y.K. Kharaka *et al.* (2006) Gas-water-rock interactions in Frio Formation following CO₂ injection: Implications for the storage of greenhouse gases in sedimentary basins. *Geology* 34:577-80.

Fischer-Tropsch (FT) technology



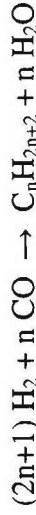
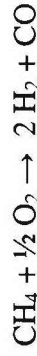
- FT process is capital-intensive
 - Approximately, x4 compared from crude oil [S.E. Koonin, BP numbers]
- FT fuel energy requirements
 - Less of the feedstock (e.g., coal) energy content (MJ/kg) ends up in the fuel compared to crude oil
 - Integrated design of Coal-To-Liquid (CTL) plants would improve plant efficiency
- Increased WTW GHG burden per ton-mile
 - More feedstock carbon released as GHGs to produce FT fuels than from crude oil
 - Potentially mitigated by carbon-sequestration methods, albeit at an increase in cost and some uncertainty on future and secondary consequences
 - A 50% CTL energy efficiency leads to x2 more CO₂ emissions than from petroleum diesel (M. Wang, ANL, 17 Jul06 briefing).
- Ignoring pass-through water, a CTL plant would require 8 gallons of water per gallon of FT diesel produced

Graphic from J.T. Edwards [AFRL] 26Jun06 briefing.

1. *Fossil fuel fungibility: conversion of gaseous and solid forms of fossil fuel into liquid hydrocarbon fuels through the Fischer-Tropsch process*

Over suitable catalysts, heating any carbonaceous material in the presence of water will produce synthesis gas (syngas): CO and H₂. Through use of appropriate Fischer-Tropsch (FT) catalysts, the syngas can then be converted into liquid hydrocarbon fuels. The FT process was used for large-scale production of liquid fuels from coal by the Germans and Japanese during World War II.

In the gas-to-liquid (GTL) process, one burns methane (CH₄) with air to (partially) produce hydrogen (H₂) and carbon monoxide (CO), and then the higher hydrocarbons, i.e.,



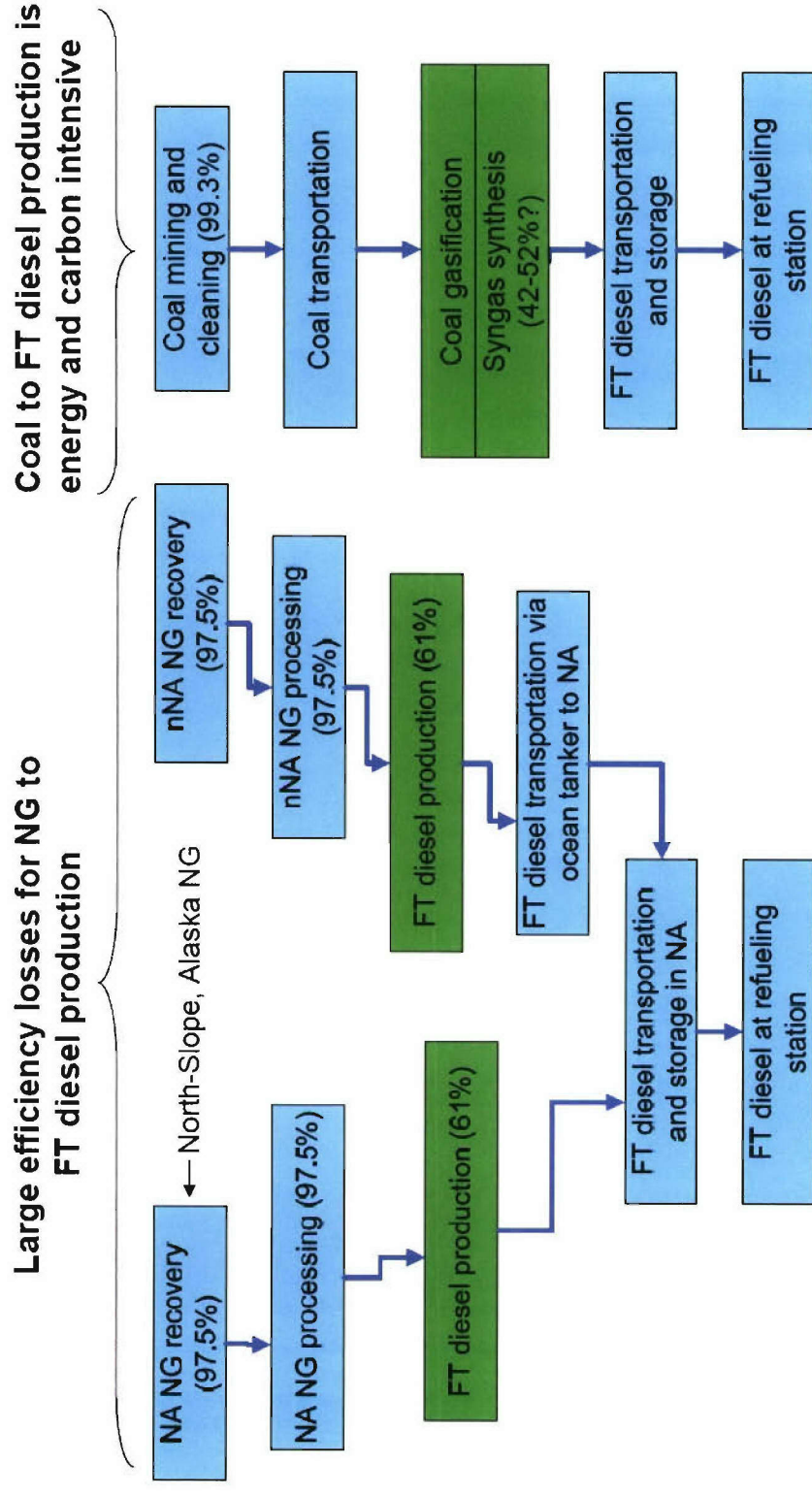
The first reaction is very endothermic and requires energy input. In addition, more H₂ is needed than is formed along with CO in the first reaction for the second reaction to proceed. Further, part of the methane in the first reaction is oxidized all the way to CO₂, i.e., not all makes CO, decreasing efficiency further. The ratio of H₂ to CO is further adjusted by running the water-gas shift reaction, $\text{CO} + \text{H}_2\text{O} \rightarrow \text{CO}_2 + \text{H}_2$, involved in the chemistry of catalytic converters. These consume energy, which ultimately comes from the fossil or other energy feedstock, one way or the other. For CTL, starting from coal, which is essentially all carbon, H₂ must come from water and O₂, and that requires more coal energy input (burned to make CO₂ output) to form H₂ in the first place so as to make the hydrocarbon fuel in the second place.

All DoD mobility fuel stocks can be made by FT processes. In some cases, the lack of aromatics in the FT process requires introduction of additives to restore the exact diesel fuel specifications of JP-8, for example, but this can be done for relatively little cost by paying a refinery to blend the needed additives into the FT fuel. Another option is to mix the FT fuel 50:50 with conventional JP-8 diesel fuel, so as to produce a mixture that generally meets the JP-8 fuel specifications for lubricity, volatility, and other performance-related properties. There should thus be no need to requalify all DoD engines on FT fuel, since it can be made to be nominally identical to JP-8 fuel with relatively low-cost blending processes.

The FT process is capital-intensive, with capital costs approximately four times higher than those required to produce an equivalent quantity of fuels by refining crude oil. The largest coal-to-liquid production plant is presently located in South Africa (SASOL), producing up to 200 kbbbl of liquid fuel per day. Originally built to counter earlier fuel-embargo policies against that country, at present it also produces FT aviation fuel that it mixes (50:50) with crude-oil-derived aviation fuel, as discussed above. It has installed no carbon sequestration measures, however, and at present, it reportedly represents the largest single CO₂ emission source in the African continent and, perhaps, the world. At present, Royal Dutch Shell and SASOL are developing 10 CTL plants in China.

In the figure on page 54, ‘WTW’ is an abbreviation for ‘Well-To-Wheels’ analysis that will be discussed below.

GTL & CTL — FT energy recovery example



From M. Wang [ANL] 17Jul06 briefing.

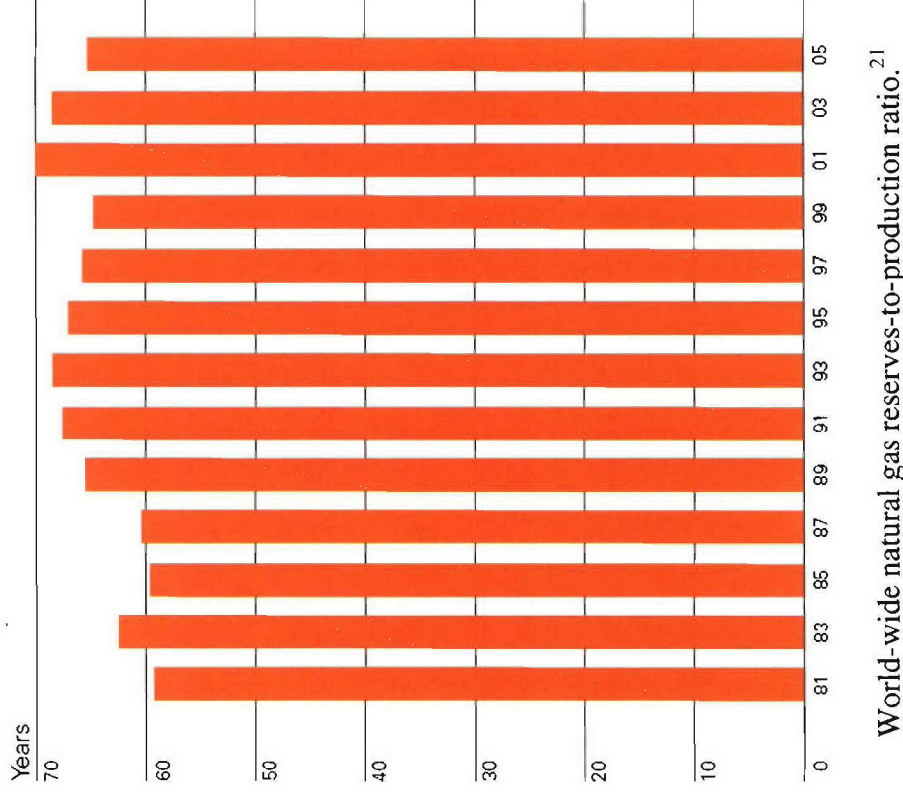
Less of the energy content (MJ/kg) of the feedstock (e.g., coal, natural gas) ends up in FT-derived fuels compared to crude oil processing and refining. Ignoring pass-through water, a CTL plant would require 8 gallons of water per gallon of FT diesel produced (cf. page 54).

Additionally, in the FT process, more feedstock carbon is released as GHGs than would be released to produce the same amount of fuel from crude oil. These processes therefore have an increased well-to-wheel (WTW) GHG burden per ton-mile.

GTL-FT is more efficient (and less costly) than CTL-FT, as alluded to above and as indicated in the figure on page 56. The 50% CTL energy efficiency leads to two times more CO₂ emissions than from petroleum-derived diesel fuel, for the same ultimate mechanical power delivered to the vehicle wheel. While it is possible to mitigate the GHGs by carbon-sequestration measures, such measures come at an increase in cost (+ 25-40%) and with some uncertainty on future and secondary consequences, as discussed above.

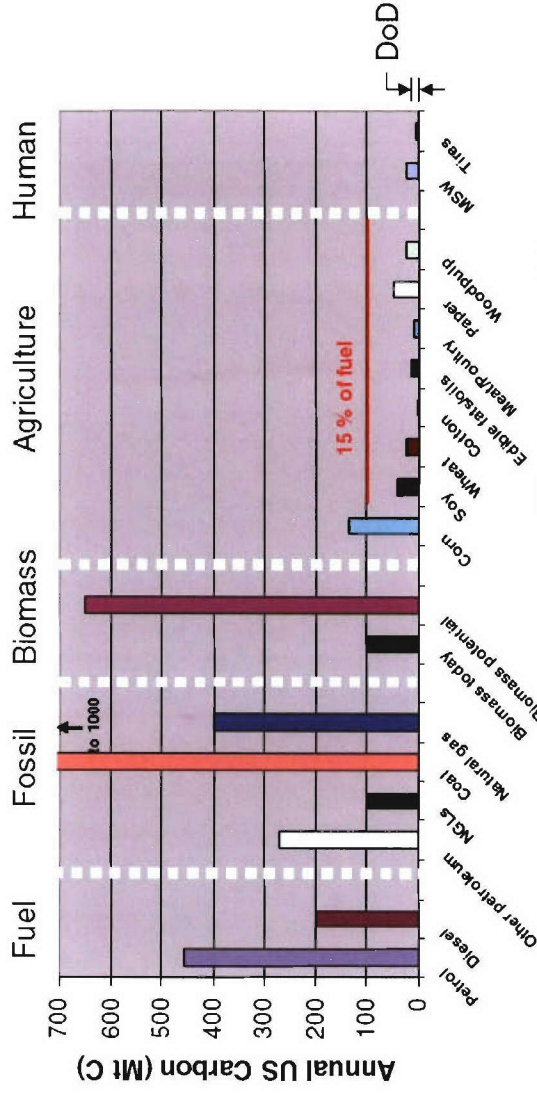
Finally, as noted on page 54, an FT plant is (very) capital-intensive, approximately 4 times that of an equivalent plant (oil refinery) that produces fuel starting with crude oil feedstock. Absent externalities and other considerations, the cost of capital alone suffices to discourage such plants.

In a manner that parallels recent crude-oil reserves vs. production patterns, world natural-gas reserves/production ratios have been sustained at around 60 years, or more, as indicated in the graphic on this page, despite increases in consumption over the same period.



²¹ BP Statistical Review of World Energy (January 2006, page 26).

Biofuels — Annual US carbon production



NGLs

Natural Gas Liquids (propane, butane, etc.)

Biomass

Energy feedstock

~0.5 ton-C per ton dry biomass

Biomass today

Corn, wood, waste, etc.

Corn component also included in the "Corn" (total) bar under "Agriculture"

Biomass potential

DOE-USDA est. of ~1.3 Gt dry biomass

Agriculture = 73%, forest = 27%

No independent JASON assessment of sustainability

Agriculture

For animal feed, food, and energy

Human MSW = Municipal Solid Waste

Graphic from S.E. Koonin [BP]. Biomass data based on DOE-USDA 2005 study.

The resource base of the various carbon sources is now evaluated to assess whether there would be sufficient domestic production capability to at least meet anticipated DoD fuel supply needs. The graphic on page 58 shows the annual US consumption and production of fuels, potential fuel sources, and biomass, referenced to carbon mass. The data on the left-most side of the graph indicate carbon domestically consumed in the form of fossil fuels, including gasoline ('petrol') and diesel fuels, other petroleum products, natural gas liquids (propane, butane, etc.), coal and natural gas. In total, these domestically consumed fuels amount to 2.4 Gt-C (billion metric tons of carbon) each year.

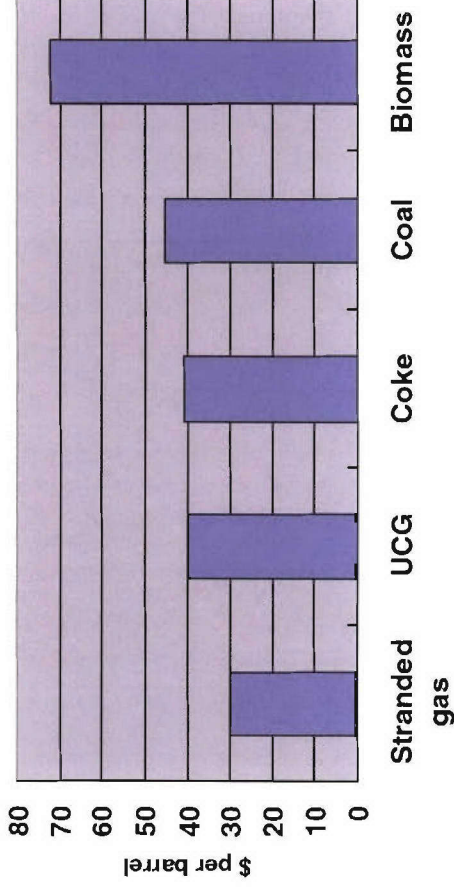
The graphic also shows the biomass carbon-equivalent currently used domestically for energy. Most of that biomass is waste products used to make electricity. However, the total also includes the 14% of the corn crop that is currently used to make ethanol, as discussed below. The biomass potential represents the 1.3 Gt (total, $\times \frac{1}{2}$ for carbon) of dry biomass that the DOE-USDA estimates can be sustainably produced for energy consumption in the U.S. This estimate assumes that 73% of the biomass will come from agriculture and that 27% will come from forest products. JASON did not have the opportunity to assess the assertion of sustainability in the DOE-USDA study of such large amounts of domestically produced biomass.

Finally, for reference, the right-most side of the chart depicts the equivalent carbon content of current domestic agricultural production. Clearly, these values are relatively modest in

comparison to the amount of biomass that would have to be produced to displace a reasonable quantity of current domestically consumed liquid fuel derived from crude oil.

Of some significance is the indication of the equivalent carbon-mass requirements that the DoD fossil-fuel needs correspond to (far right). If economically permissible, they could, in principle, be covered by exploiting the national municipal solid-waste (MSW) stream alone.

Alternative fuel conversion costs — FT diesel



- FT diesel costs more than crude-based JP-8
- High capital costs
 - Assured demand could motivate industry to develop
 - But, DoD alone is not a large-enough client
- Cheapest source is from stranded gas
 - E.g., Alaska North Slope gas
- Could possibly provide hedge on crude-oil prices

S.E. Koonin [BP] cost numbers

Having established the feasibility of converting non-liquid forms of fossil energy into liquid hydrocarbon fuels through the FT process and having established that there is, in principle at least, an ample supply of such carbon from a variety of domestic resources, the relative costs of producing liquid fuel from the various different forms of carbon available in the U.S. are now assessed.

Production costs of FT diesel depend on the choice of feedstock. Differential costs reflect differences in handling the feedstock in the facility (solid vs. gas, etc.) as well as energy costs needed to produce the high temperatures from gaseous (natural gas) vs. porous material (biomass), vs. solids (coal). Production costs vary from \$30/bbl for stranded gas (GTL),²² to \$70+/bbl for biomass. CTL (\$45/bbl) is 50% more expensive than GTL (\$30/bbl). In all cases, it costs more to produce diesel by any FT process than it does to make JP-8 from crude oil.

The most-cost-effective source of FT diesel is via conversion of stranded gas, e.g., on the north slope of Alaska. As also noted above, in addition to high production costs, FT processes have high capital costs that deter investment in the face of uncertain future crude-oil prices, i.e., in the event of a fall in prices. That large swings are part of the historical record is

²² A 'stranded gas' reserve is a natural gas field that has been discovered, but remains unusable for either physical or economic reasons. Gas that is found within oil wells is conventionally regarded as associated gas [or stranded gas] and has historically been flared. It is also sometimes recirculated back into oil wells to maintain extraction pressure, or converted into electricity using gas-powered engines.
[http://en.wikipedia.org/wiki/Stranded_gas_reserve, 6 August 2006]

amply documented in the figure below that depicts the price of crude oil, since 1861, in FY05 dollars. It illustrates the considerable risk that would be incurred by assuming that the current high prices in the vicinity of \$75/bbl will be sustained. It also illustrates that they were exceeded around 1980 (Iranian revolution).²³

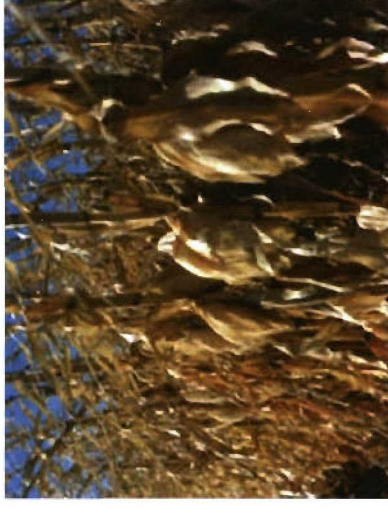


As with any investments and barring externalities, investments in biofuels, FT processes, etc., need to compete with current returns from drilling for crude oil.

²³ *BP Statistical Review of World Energy* (January 2006, p. 16).

Biofuels — Corn ethanol

- Main presence, at this time, is ethanol
 - Primarily used as an oxygenate in automotive fuel
 - Replacement for MTBE (toxic)
 - Lower (2/3) volumetric energy content compared to gasoline, or diesel
 - Highly flammable (high vapor pressure)
 - Unacceptable penalty from a DoD logistics point of view
 - Derived from grains: corn, wheat, soybeans. Presently mostly from
 - US: Corn
 - Brazil: Sugar cane (needs tropical climate)
 - Corn is converted to ethanol in either a dry or wet milling process.
 - Dry milling: liquefied corn starch produced by heating corn meal with water and enzymes. A second enzyme converts the liquefied starch to sugars that are fermented by yeast into ethanol and carbon dioxide.
 - Wet milling (preferred): separate fiber, germ (oil), and protein from starch before fermentation to ethanol.
 - Of solar energy incident per unit area farmed, 0.1% ends in corn
 - Only 0.03-0.05% of ~220 W/m² insolation in liq. fuel
- ★ No significant net energy benefit
 - Within ±20% of “energy breakeven”
 - Actual depends on assumed production cycle, and energy and other inputs to the process
- Presently, ethanol provides < 2% of the U.S. transportation pool, and requires 14% of U.S. corn production.



2. Biofuels

For comparison, the production of liquid fuels from non-fossil energy sources will now be discussed. Biomass is the most oft-cited route for such purposes because, in principle, biomass-derived fuels could be widely available. Additionally, biofuels could be, at least to some extent, sustainable and renewable. Of concern, therefore, is not only the relative cost of the biofuel with respect to the cost of crude-oil-based fuels, or FT-derived fuels, but the suitability of bio-derived fuels for the DoD mission and whether the production of such fuels stems from a renewable process, e.g., the fraction of sunlight energy stored in the final fuel product, as well as the result of a full account of all other energy and other inputs required to produce the biofuel.

Ethanol derived from corn

The main presence in the domestic biofuels market at this time is ethanol derived from corn. In the U.S., ethanol is primarily used as an oxygenate in automotive fuel, replacing the additive MTBE (methyl tertiary-butyl ether). Presently, 14% of U.S. corn production is used to provide the ethanol that comprises 2% of U.S. transportation fuel.

The volumetric energy content of ethanol (C_2H_5OH) is $2/3$ that of gasoline or diesel fuels (1.5 gallons of ethanol store the same energy as 1 gallon of gasoline). This is because one carbon in ethanol is already partly oxidized and therefore is less of a contributor to the heat of combustion to form CO_2 than the fully reduced form of carbon in liquid hydrocarbon fuels.

Corn is converted to ethanol in either a dry or wet milling process. In dry milling, liquefied corn starch is produced by heating corn meal with water and enzymes. A second enzyme converts the liquefied starch to sugars that are fermented by yeast, producing ethanol and carbon dioxide. In the (preferred) wet milling process, the fiber, germ (oil), and protein are separated from the starch before fermentation to ethanol.

In Brazil, ethanol is derived from sugar cane. Ethanol can also be produced from wheat and soybeans.

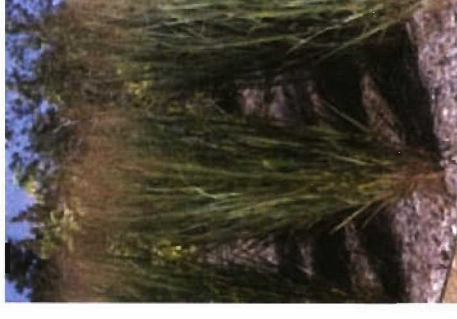
Of the solar energy incident per unit area farmed, approximately, 0.22 kW/m^2 yearly and day-night averaged at representative mid-latitudes, only 0.1% ends up in corn. After the final process, only 0.03-0.05% of the initial insolation energy is contained in liquid fuel.²⁴ Another factor of three is then lost during conversion of the fuel into useful work in an internal combustion engine.

The low solar-energy conversion efficiency, coupled with the energy-intensive process to produce corn ethanol, results in an overall process that yields *no significant net energy benefit from corn-derived ethanol*, as it is within $\pm 20\%$ of “energy breakeven”. As implemented in the U.S. at present, much of the energy used to make corn-based ethanol is produced by burning coal to provide heat to the process.

²⁴ Another factor of 3, or so, is then lost in converting the (low-value) energy in the fuel to work (high-value energy), i.e., an overall conversion efficiency of incident sunlight energy to high-value energy (e.g., mechanical work) of 0.01%. In contrast, solar cells have an efficiency in the range of 15-22% and produce high-value energy (electricity), albeit at too high a cost in terms of \$/installed-kW to be competitive for most applications.

Biofuels — Cellulosic ethanol

- Cellulosic ethanol
 - Net energy conversion potentially x3 higher for corn
 - A proper thermodynamic-cycle analysis (mass conservation and sustainability) will reduce this figure (for corn)
 - Could be produced from wide variety of cellulosic biomass feedstocks
 - Agricultural plant wastes (corn stover, cereal straws, sugarcane bagasse),
 - Wastes from forest products (sawdust, paper pulp, +)
 - Crops grown for fuel production (miscanthus, switchgrass).
 - Cellulosic biomass is composed of cellulose, hemicellulose, and lignin, with smaller amounts of proteins, lipids (fats, waxes, and oils) and ash.
 - Roughly, 2/3 of dry mass of cellulosic materials are present as cellulose and hemicellulose. Lignin makes up most of the remaining dry mass.
- Challenges
 - Must compete economically with growing food
 - Presently, (unsubsidized) farming for food is more profitable than (unsubsidized) farming for energy (UK studies)
 - Develop cost-effective processes to convert cellulosic biomass to liquid fuels
 - Compete with fossil-fuel-based liquid fuels
 - ★ Establish that sustainable agriculture cycles can provide sufficient feedstock



Switchgrass

Cellulosic ethanol

The net energy conversion efficiency in a process in which cellulosic biomass is converted into liquid fuel is potentially at least three times higher than the 0.03-0.05% value characteristic of ethanol from corn. However, a proper (thermodynamic-) cycle analysis that accounts for conservation of mass and what fraction of the energy is sustainable will reduce this figure. The low conversion efficiency combined with the relatively low power/energy density of the yearly averaged insolation require very large areas to provide significant (net) energy resources from such a process.

The requisite cellulosic biomass could be produced from a wide variety of feedstocks, including agricultural plant wastes (corn stover, cereal straws, sugarcane bagasse), wastes from forest products (sawdust, paper pulp, etc.), and crops grown specifically for fuel production (miscanthus, switchgrass). As discussed above, the 2005 DOE-USGA *Billion Ton View* estimated that the U.S. could sustainably produce 1.3 Gt of dry biomass annually, of which approximately half is carbon by mass.

Cellulosic biomass is composed of cellulose, hemicellulose, and lignin, with smaller amounts of proteins, lipids (fats, waxes, and oils) and ash. Roughly, 2/3 of the dry mass of cellulosic materials is composed of cellulose and hemicellulose, while lignin makes up most of the remaining dry mass. Cellulose and hemicellulose can be converted into ethanol, while lignin can not. Lignin can be burned to produce electricity, or could be converted to fuel through the FT process.

The cellulosic-biomass community must develop cost-effective processes to convert cellulosic biomass to liquid fuels if they are to compete in the marketplace with fossil-fuel based liquid fuels. At present, a viable process does not exist.

Cellulosic biomass must also compete economically with growing food on the same parcel of land. Presently, (unsubsidized) farming for food is more profitable than (unsubsidized) farming for energy.

Fuel from Biomass — A more-complete process

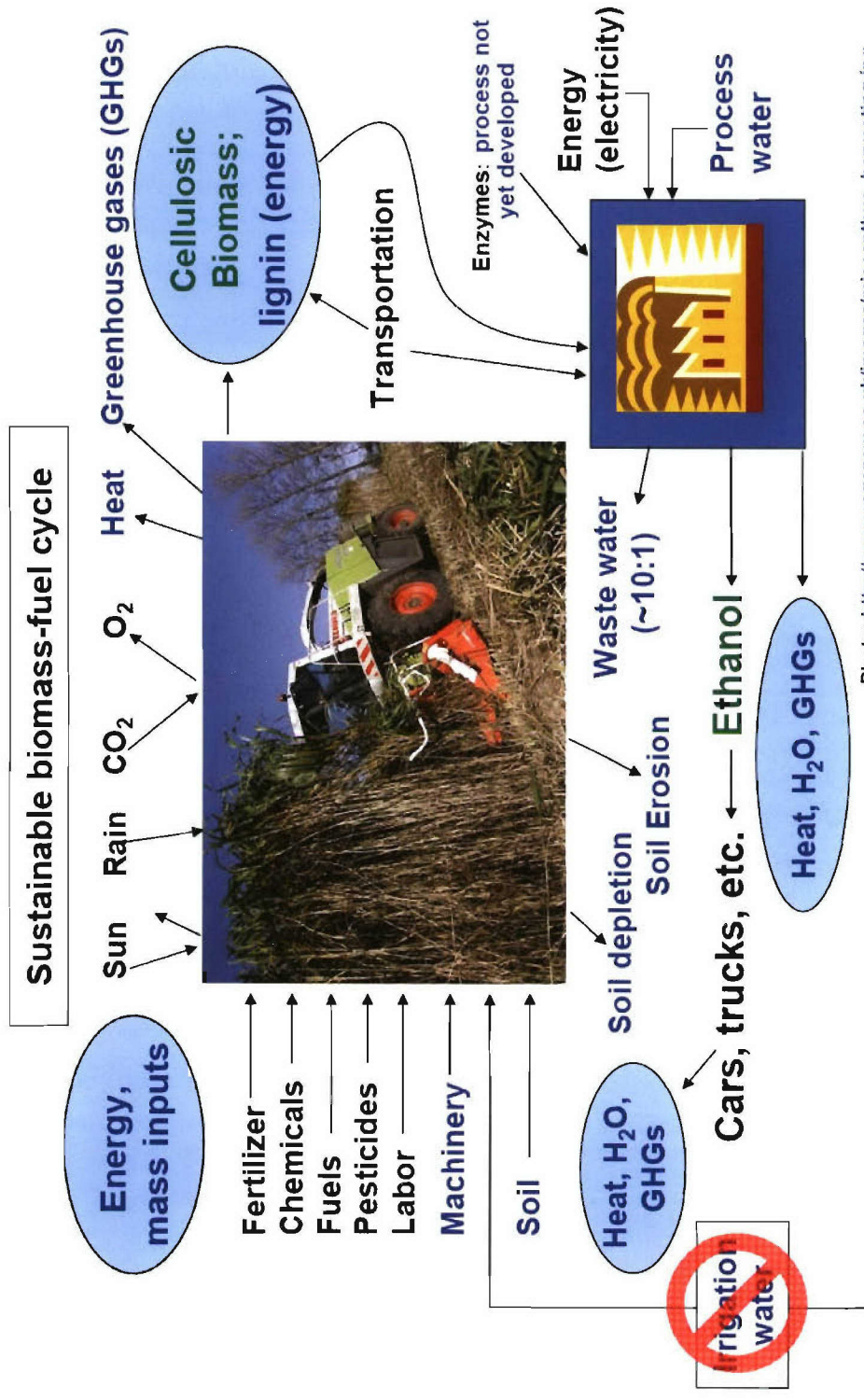


Photo: http://www.regensw.co.uk/images/miscanthus_harvesting.jpg

It must also be demonstrated that sufficient cellulosic biomass feedstock can be harvested with *sustainable* agricultural cycles. Sustainability requires that a full thermodynamic cycle for the process be considered, including the mass, particular inorganic, organic, and biomass species, as well as energy required to remediate any “damage” to crop land from growing and harvesting the energy crop over many years (in order to maintain production indefinitely). Top soil is generated on century time scales. Monitoring for damage/depletion from even careful agricultural practices on such a time scale is a challenge.

The sustainable biomass fuel cycle should include all of the inputs and outputs of the process. Inputs to the cycle would need to include fertilizer and the energy and feedstock to produce it, chemicals, fuels, pesticides, labor, machinery, soil, sun, rain, CO₂ uptake, and any water. Outputs should include heat, GHGs, and waste water.

An important aspect of a complete cycle is water. Using water, other than reliance on rainwater, to grow energy crops is commonly acknowledged to incur a large penalty because of the required energy (and cost) to deliver the water (energy is required to deliver it, or pump it up from the ground: a 100 m rise is not atypical), and because long term irrigation implies a build-up of salinity (soil salification).²⁵

²⁵ See articles in (1994) *Agr. Water Management*, vol. 25, “Management of Irrigation Water and its Ecological Impact,” Commission II: Symposia of the *Transactions of the 15th World Congress of Soil Science* (Acapulco, Mexico, 1994), vol. 3a; Pimentel *et al.* (1995) Environmental and economic costs of soil erosion and conservation benefits. *Science* 276:1117-23; T. Patzek & D. Pimentel (2005) “Thermodynamics of

Even where there is plenty of rain to grow the candidate feedstock, ethanol generation from biomass requires a great deal of process water. Assuming an enzymatic process that reaches 10-15% ethyl alcohol, there will be about 6-10 gallons of waste water for every gallon of fuel-quality alcohol. The dregs will have to be removed from the water (and perhaps returned to the land), if the water is to be re-used and that part of the cycle closed. This also incurs transportation costs. The only alternative to bearing the energy cost of this water transportation and cleanup is pollution of waterways or the ocean.

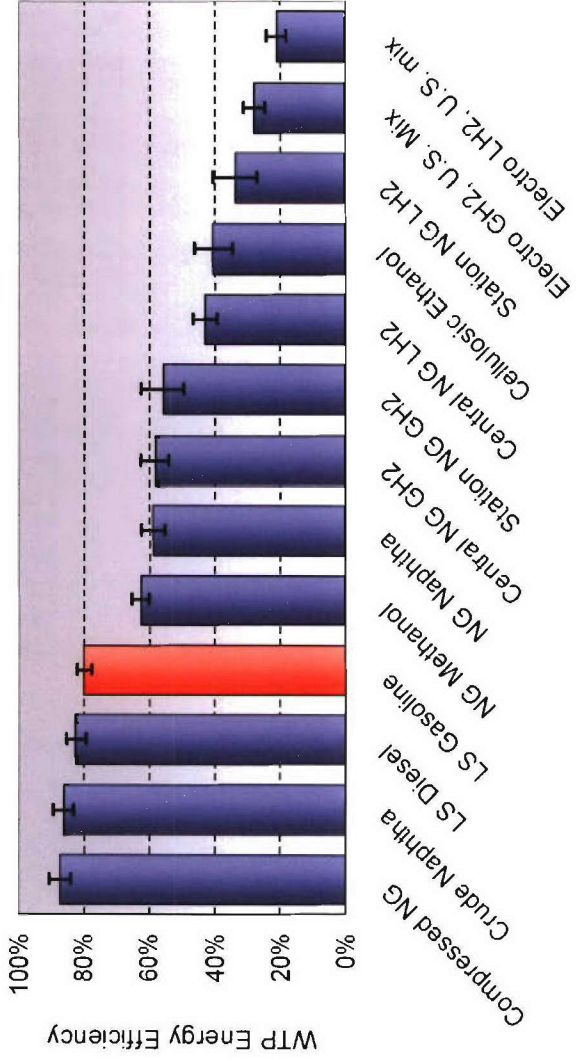
Finally, no cellulosic conversion technology exists today on a commercial scale and an evaluation of its efficacy, relative costs, sustainability, or its potential to meet DoD fuel-supply needs cannot be made at this time.

Energy Production from Biomass,” *Critical Reviews in Plant Sciences*, 24:327-64; and Pimentel (2006) Soil erosion: A food and environmental threat. *Env. Dev. & Sustainability* 8:116-137.

Well-To-Pump (WTP) energy efficiency

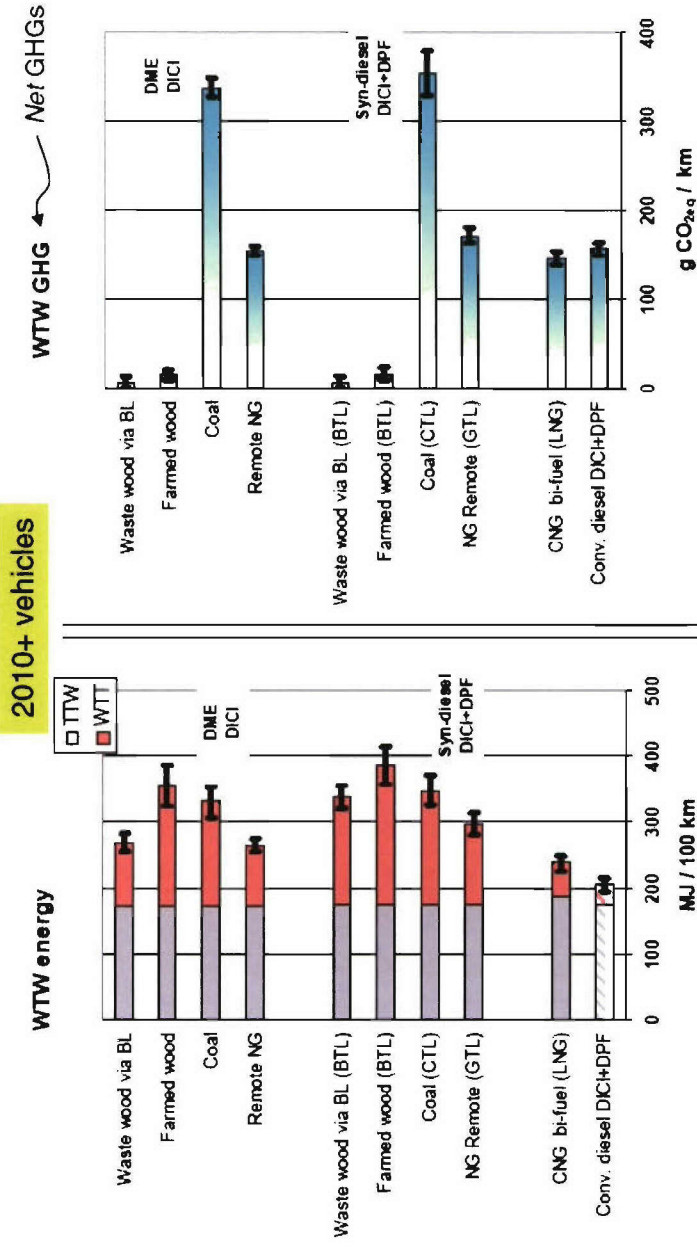


Graphics above from G.J. Rusek [GM-GAPC] WTP Energy Analysis Study (21Mar01).



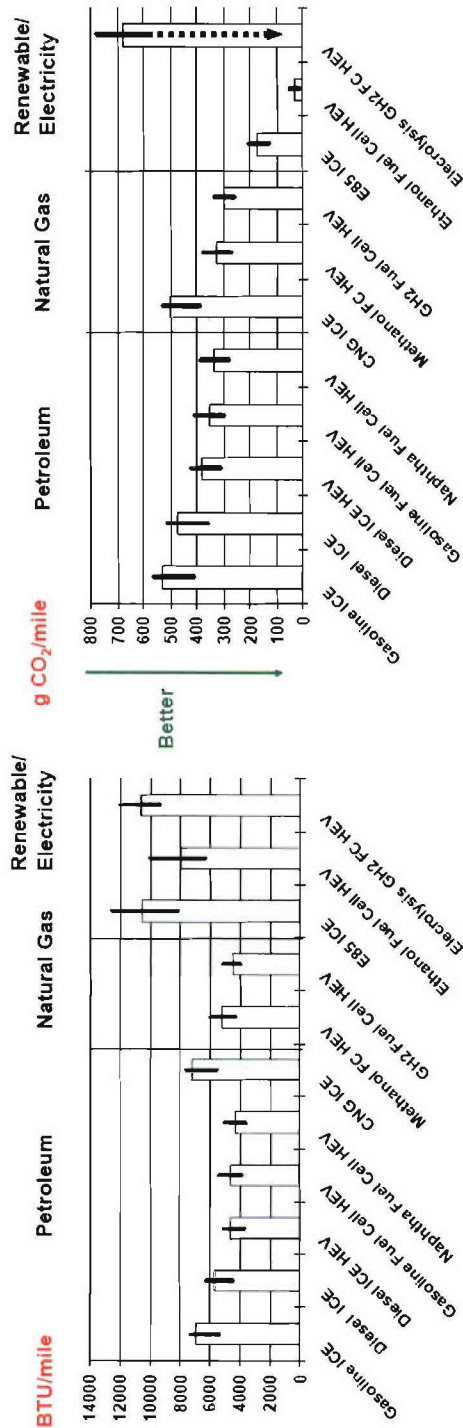
From M. Wang [ANL] 17Jul06 briefing.

WTW synfuels — New European Driving Cycle



- FT diesel (FTD) requires more energy than diesel from crude oil
- WTT GHG from NG and conventional diesel about the same
- GHGs from FTD about x2 of conventional diesel
- Remote NG (CNG or LNG) has lower energy consumption and lower GHG than via GTL or DME

Well-To-Wheel (WTW) fuel comparisons



- Diesel ICE best
 - DoD use patterns will not result in the level of commercial HEV fuel savings
- Fuel-cell efficiencies predicated on future technology developments
 - No FC vehicles in production at present
- GHG emissions are a consideration that will affect (commercial) future fuel production
 - DoD is already subject to some emission regulations (Army tactical vehicles)
 - DoD is not a large-enough player by itself and GHGs could be added to DoD fuel-use externalities thereby

G.J. Ruselewski [GM-GAPC] WTW Energy Analysis Study (21Mar01).

3. *Well-To-Pump (WTP) and Well-To-Wheel (WTW) analyses*

A proper analysis requires the evaluation of the energy required to not only produce, but also to store, distribute, and ultimately utilize various fuels of potential interest to the DoD. Without such an analysis, a focus on only fuel production will not adequately capture the true supply constraints and needs, nor the suitability of the fuel for DoD use. In such an analysis, it is useful to account for the entire energy stream from the well, i.e., the energy source, to the wheel, i.e., the (fuel) energy consumption by the end user. This is known as the Well-To-Wheel (WTW) process. This process is often subdivided into two separate components, one from the well to the pump (WTP), and the second from the pump to the wheel (PTW).

The WTP energy efficiency for diesel and gasoline is of order 85%, while the WTP efficiency of cellulosic ethanol is estimated to be closer to 40% (cf. page 68).²⁶ Hence, to supply a certain needed energy to DoD platforms would require almost twice as many joules in ethanol production as in diesel or gasoline production from crude oil.

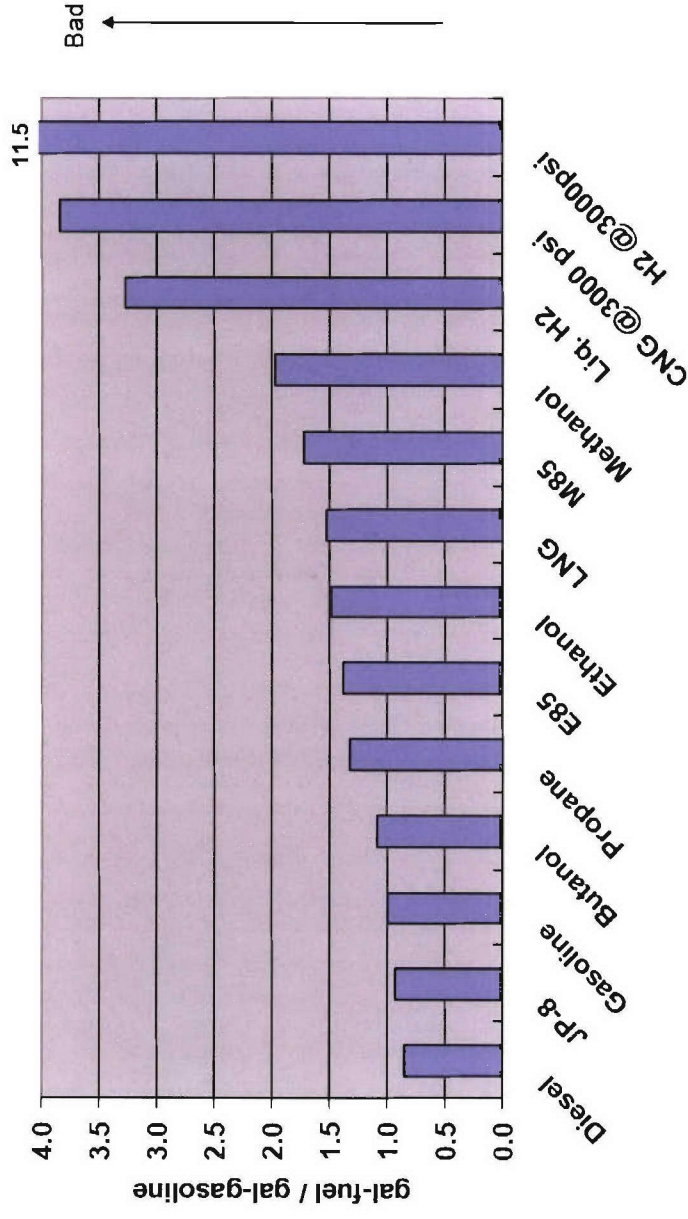
The PTW efficiency is primarily a function of engine type. It is typically of order 30%, which is a measure of the fraction of the energy of the fuel that can be converted to useful work.

Combining these two components into the analysis of an overall energy process produces the full WTW analysis.

It is useful to perform two separate WTW analyses, one based on the net energy delivery/input and the other based on the net GHGs emitted for the full fuel production to consumption process. The left-most WTW graphic on page 69 depicts the total energy required to move 100 km. Conventional diesel and gasoline fuels are superior on this energy basis, while wood products are the worst. However, on a GHG basis, biomass can be a very low GHG source, when measured WTW, while most all fossil fuels are less favorable. Coal is by far the most offensive GHG emitter. From this perspective, gas (GTL) is a much better source of fuel than coal (CTL).

²⁶ 'LS Diesel' and 'LS Gasoline' denote 'Low-Sulfur' diesel/gasoline, as produced in Europe. Removal of sulfur from transportation fuels is required to prevent poisoning of catalytic converters in the exhaust-gas stream. At present, U.S. diesel does not meet the low-sulfur requirement and diesel-powered cars in the U.S., at present, cannot avail themselves of the same emissions burden reduction technology.

Alternative fuels — Volume per unit energy content



- Gallon of alternative fuel matching energy content of gallon of gasoline
 - Difficult to match diesel/JP-8/gasoline in terms of energy content per gallon
- Butanol (C_4H_9OH) comes close (90% of gasoline)
 - Ethanol has 50% less energy per gallon than gasoline

Overall-process (WTW) energy and GHG emissions provide useful criteria, but not the only considerations for assessing the suitability of various fuels for DoD use. An especially important operational constraint for the DoD is energy density, i.e., the energy content per unit volume, or its reciprocal, the fuel volume required for a given energy content. Energy per unit volume in essence determines vehicle range for a given fuel-tank capacity, and can dictate (limit or enhance) military tactics of mobile platforms.

In this regard, it is useful to consider the fuel volume required for a given energy content in terms of the ratio of the fuel volume for a given energy content, relative to that of gasoline. The graphic on page 72 illustrates that diesel, gasoline, and JP-8 are very similar, with butanol (C_4H_9OH) possessing 90% of the energy density of gasoline.

Ethanol, however, has a 50% lower volumetric energy density than gasoline. With 50% less energy density than gasoline, DoD operations will require 50% more fueling sorties by tanker trucks, implying a 50% greater danger for those responsible for that endeavor. To keep the same range per fill-up by combat vehicles, fuel tanks would have to be increased in size by 50%. Furthermore, ethanol has a lower flash point and, therefore, more prone to explosion than is gasoline. Hence, even if it were comparable on a WTW energy or GHG emissions basis, ethanol would still be unsuitable for use on DoD missions on a performance basis.

On this performance basis, liquid hydrocarbon fuels emerge as the preferred energy source for mobility on DoD tactical and combat vehicles, both air and land-based. Since these fuels are most cheaply made from fossil energy of one type or another,

and since, barring unforeseen upheavals, the fossil-fuel feedstock supplies appear adequate for sometime into the future, the best method for reduction of a DoD fuel consumption is to reduce demand, as described above, through a variety of methods including patterns of use, lightweighting vehicles, re-engining tanks and B-52 bombers, and replacing manned platforms with unmanned ones. In aggregate, these approaches can yield considerable fuel savings while at the same time enhancing performance of DoD platforms and opening up new mission capabilities for DoD forces.

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VI. Discussion and concluding remarks

The preceding data and analysis provide a basis for assessing problems and issues associated with U.S. and DoD fossil-fuel use, the short- and intermediate-term prospects, as well as guidance for a path forward that would reduce the DoD's fossil-fuel dependence.

A. International and national considerations

The two figures on page iv, following the executive summary, depict the movement of crude oil and oil products across boundaries of the major production and consumption areas in the world. They also depict the present dependence of the U.S. on its major foreign suppliers.

Oil imports account for a large fraction of the U.S. current account balance. The *Economist* (20 April 2006) notes that,

“Plenty of Americans blame unfair competition from Asia, and especially China, for their country's gigantic current-account deficit. Yet the group of countries with the world's biggest current-account surpluses is no longer emerging Asia, but exporters of oil. As the price of their chief resource has climbed—this week it hit a new nominal record price of more than \$70 a barrel—these economies have enjoyed a huge windfall. From an American point of view, *the rise in oil prices has explained half of the widening of the current-account deficit since 2003, a bigger share than that accounted for by China.* [italics ours] ...

America gains little, in terms of its current-account balance, even from the imports that oil exporters do buy. It now accounts for only 8% of OPEC countries' total imports; the European Union has 32%. So even if the exporters spent all their extra revenue,

America's current-account deficit would increase as oil prices rise. This partly explains why in recent years the EU's trade balance with the oil exporters has barely changed even as America's deficit has grown sharply.”

It is significant that the preponderant fraction (51.1%) of crude oil and refined oil products imported into the U.S. derives from the (remainder) of the American continent (South and Central America, Mexico, and Canada). West and North Africa come second with a total of 19.1% of U.S. oil imports, and the Middle East, while it is the world's major oil supplier to be sure, it is third in importance as a U.S. supplier, accounting for 18% of U.S. oil imports. These data indicate that under the assumption that U.S. and non-Middle-Eastern production could be held (approximately) constant, it would suffice to decrease U.S. fossil-fuel consumption by 12%, at present, for the U.S. to be in a position to wean itself free from Middle East oil, in the short term, should the need arise. As discussed earlier, however, the world fungibility of oil through the world oil supply markets would respond to this decrease by adjusting the supply-demand balance.

Such a goal might be achieved without deleterious effects to the U.S. economy by any of a number of means in combination. This would produce, at least temporarily, a world-wide excess production capacity and a decrease in oil prices, improving both the national economy and the national defense posture.

Regarding oil prices, it's worth noting that they are not at historically high levels when adjusted for inflation. As the chart on page 61 indicates, prices around the 1980 time period peaked at \$36/bbl in then-year money, corresponding to

FY05\$ 85/bbl. The rapid *decrease* in pricing following that peak and the data depicted in the figures on page 6 can only induce a conservative stance in the oil industry, discouraging investments that require that the present high prices must be sustained to be justified.

Finally, adding to the general caveat of a foggy future, vis-à-vis instability in the Middle East, consequences on world production from inefficiencies and damage from the rise of (most) national oil companies,^{4,27} and the consequences of poor governance and hostility towards the U.S. in many of the world's oil-producing nations, strongly argue for conservation.

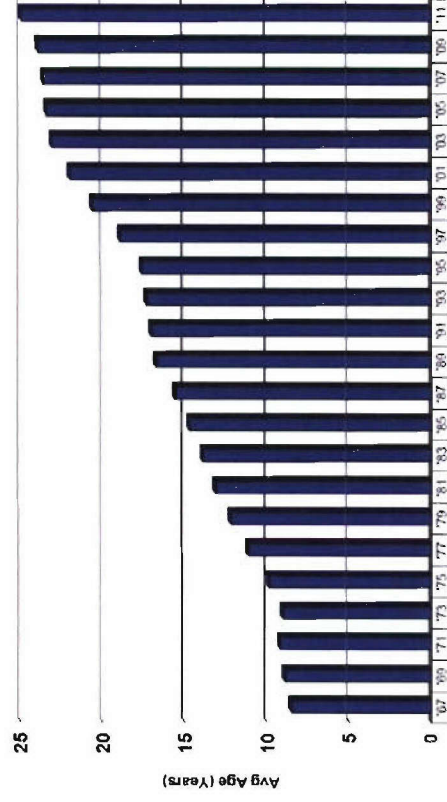
B. Considerations for the DoD

This study finds that the greatest leverage on DoD fossil-fuel use is exerted by patterns of DoD fossil-fuel use. Recent and present doctrine, tactics, and practices evolved during a time when fuel costs represented an insignificant fraction of the U.S. national-defense budget, with fuel costs entirely dominated by the associated O&M logistical supply chain costs and not by those of the fuel itself. While O&M costs continue to dominate, actual fuel costs have recently risen rapidly, attaining a significant recent visibility. At present, fuel budgets are in competition with other DoD non-fixed costs, such as research, development, and engineering (RD&E), and other discretionary funding, of which they are a much larger part.²⁸

²⁷ Indonesia, an important oil producer with significant (proven) reserves, recently became a net oil importer. [*Economist*, 12Aug06]

²⁸ Al Shaffer [ODDRE] 24Jul06 private communication.

Within the DoD, the largest fuel consumer is the Air Force (cf. pages 14 and 21). Continuous efforts and monitoring by the Air Force and other services have resulted in decreases in fuel use over the last few years,²⁹ despite the prosecution of the war in Iraq. This can only be applauded. As the data and analysis above indicate, however, considerably greater benefits can be expected from a more-aggressive stance as regards fuel use across all DoD services.

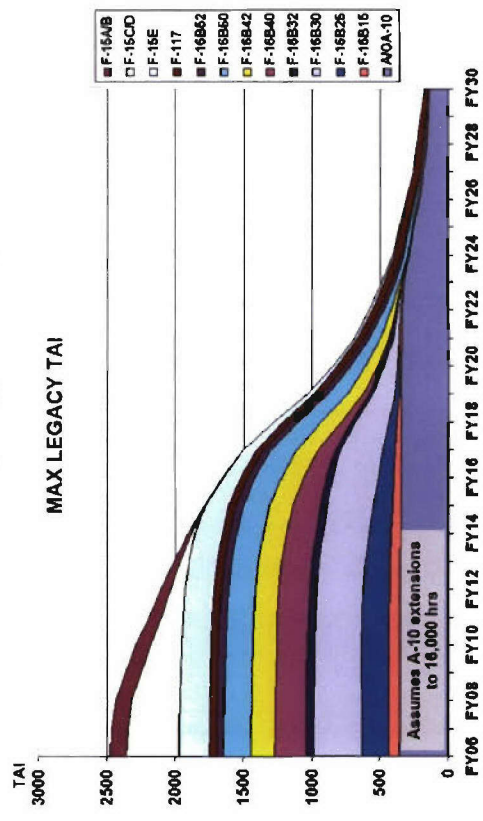


Average age of U.S. Air Force aircraft.³⁰

Some, perhaps significant, future reductions in fuel use will occur of their own accord, as in the U.S. Air Force, for example, where the aircraft inventory is expected to decline, as the figure on page 76 suggests, despite an aging U.S. Air Force

²⁹ P.E. Mike Aimone [Asst. Dep. Chief of Staff, Logistics, Installations & Mission Support] 5Jun06 presentation: *The Air Force Energy Strategy for the 21st Century*.

fleet (cf. figure above).³⁰ While new aircraft will be placed in service during the next decade, it is unlikely they will replace the number that will retire (cf. figure below).^{30,31}



In conclusion, while there may be no single silver bullet to reduce the dependence of the DoD on fossil-fuels, many steps, in the aggregate, many of which have been discussed and addressed by analysis on the subject in the past, should be undertaken.

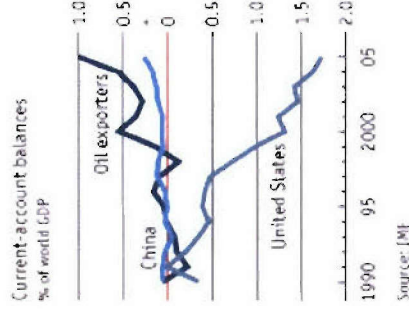
³⁰ Brig. Gen. "Andy" Dichter [Dep. Dir., AF Operational Capability Requirements (AF/XOR)] 20 October 2005 presentation: Force Multipliers for the Joint Battlespace: Issues, Challenges and Opportunities.

³¹ The retirement of the F-117 was recently announced, despite the projection depicted in the figure on this page that it would remain in service for some time.

As with sailing racing, one can win (big) by not losing in lots of little ways.

Findings — /

- Oil is a worldwide-fungible commodity
 - Long-term (25-, or 50-year) outlook is necessitated by life of DoD weapon systems
 - Barring unforeseen, major, world-wide upheavals, no DoD fossil-fuel supply shortages are expected in the next 25 years
 - As much is projected to be needed in the next 25 years as total already produced to date
 - Significant changes in oil production-consumption rates are expected within 50 years
 - Present oil prices
 - are high relative to production costs
 - compound production costs with other factors
 - Future oil prices are difficult to predict, especially in \$-denominated terms
- At present, the American and African continents supply 51.1% and 19.1%, respectively, with the Middle East supplying 18% of U.S. imports (12% of present U.S. consumption).
- Increasing U.S. imports relative to domestic supply
 - Have no direct national-defense implications, other than financial
 - Have clear balance-of-payments and national-economy consequences, and significant indirect national-security implications thereby
- Rise in oil prices = 1/2 of U.S. current-account deficit since 2003 and a bigger share than that accounted for by China (*Economist* 20Apr06)



Graphic from *Economist* 20Apr06

VII. Findings

In this section we summarize the key findings of the JASON study, broken down into key categories:

A. Global, domestic, and DoD fossil-fuel supplies

Oil is a worldwide-fungible commodity. Consistent with global proven reserves, no DoD fossil-fuel supply shortages are expected in the next 25 years. Although as much oil is projected to be needed in the next 25 years as the total already produced to date, world proven reserves are capable of accommodating this demand at less than \$30/bbl production cost.

JASON emphasizes that this finding is premised on the assumption of no major world-wide upheavals, or political and other changes in the primary oil and natural-gas production regions of the world that supply the U.S., notably, the Middle East, Venezuela, and Russia, or other events and developments that may compromise the security of major fossil-fuel feedstock routes and transportation corridors (cf. figure on page iv of this report). Such upheavals have occurred in the past producing major changes in the world-wide availability and pricing of fossil-fuel resources, as documented for the period around 1980 in the graphics on pages 10 and 61, following the Iranian revolution and its consequences on the Middle East and the world.

Present oil prices on the spot market are high relative to production costs. Production costs are compounded with other factors to yield these high market prices, the difference reflects the market's confidence in assured future supplies, imbalances

between supply and demand, and, not least, the profits that the market is willing to bear. On the other side of the fulcrum, however, JASON notes that while short-term response options to oil price increases are limited, longer-term options are not inconsiderable, as every dollar increase in world market prices invite additional fossil-fuel sources to join the world mix, as well as non-fossil energy sources to become economical. The oil-producing nations are quite conscious of this balance. Saudi Arabia, in particular, has used its reserve production capacity for the last few decades to dampen both rapid increases and decreases in oil prices.

Future oil prices are difficult to predict, especially in dollar-dominated terms, the latter hedge as a consequence of the significant U.S. current-account imbalance depicted in the inset graphic on page 78.

At present, the working assumption of the energy industry, as documented in EIA assessments, is that the market price of oil will return to a \$40-45/bbl range in the next five years, as increased production facilities come on line, accommodating increases in demand.

Thus, increasing U.S. imports relative to domestic supply have no direct national-defense implications, other than financial. They do, however, impose clear balance-of-payments and national-economy consequences, and significant indirect national-security implications thereby. Strong defense is and has historically always been predicated on a strong economy.

Findings — //

- DoD fuel costs have become visible only relatively recently
- Present DoD fuel costs represent a 2.5-3% fraction of the national-defense budget
 - Larger fuel/energy % costs faced by most businesses and families
 - While fuel cost is not a primary decision driver, at present, its uncertainty compounds planning/budgeting, and it may become a significant issue in the future
- Largest fraction (~62%) of DoD fuel use is expended in CONUS
 - Continuous progress by DoD in recent years to decrease energy/fuel use
- ★ However, fuel represents a significant fraction of life-cycle costs, at present, for

– USAF mobility carriers	~ 40%	Potentially serious problem if there are significant future fuel cost increases
– Commercial airliners	~ 40%	
– Conventionally fueled Navy ships	~ 30%	

(not discussed in this presentation)
- DoD fuel use is subject to complex interrelated governmental and congressional regulations, foreign/domestic policies, and directives
 - These inject externalities that complicate bookkeeping and DoD fuel-use optimization

The study notes that a reduction of 12% in U.S. oil consumption, at present, would relax the world-wide tight supply-demand situation, at least for a while, and allow the U.S. the option of foregoing *all* oil imports from the Middle East and avoidance of the dependencies and vulnerabilities imposed by this sensitive import stream, should the need arise.

B. DoD fuel costs

DoD fuel costs have become visible only relatively recently. Even at present, they represent only 2.5-3% of the national-defense budget, the spread depending on what is chosen as the denominator for total national-defense costs. While uncertainties and the recent large increase in fuel costs present DoD budget planners with formidable challenges, representing a (much-larger) fraction of non-fixed (“discretionary”) spending, JASON must conclude that fuel costs, *per se*, while not negligible, cannot be regarded as a primary decision driver, at present.

The largest fraction (~ 62%) of DoD fuel use is expended in CONUS. Continuous progress has been made by DoD in recent years to decrease energy and fuel use. However, because weapons systems have very long life-cycles, fuel represents a significant fraction of life-cycle costs for U.S. Air Force mobility carriers (~40%) and conventionally fueled Navy ships (~30%). JASON also notes that expected reductions in the U.S. Air Force tactical inventory (number and type of aircraft on active duty), as discussed on pages 76 and 77, will, perforce, decrease future consumption of aviation fuel, which represents the largest single DoD fuel-use component.

DoD fuel use is subject to complex interrelated governmental and congressional regulations, as well as foreign and domestic policies and directives. These inject externalities that complicate bookkeeping and often hamper proper DoD fuel-use optimization.

JASON finds compelling reasons for the DoD to minimize fuel use, both overall and in individual vehicles and carriers. Fuel, even if it is currently a relatively small portion of the overall budget is accompanied by large multipliers – it takes fuel to deliver fuel – and is accompanied by high costs in both infrastructure (O&M) and, in the battlefield, in lives.

Price uncertainties compound budget planning, and fuel costs may rise to represent a more-significant factor for the DoD in the future, even though current projections may indicate otherwise. More importantly, the impacts of delivering fuel are evident in dictating tactics, operations costs, maintenance costs, and military capabilities.

Findings — III

- Lightweighting costs money but saves fuel and adds capability
- Hybrid vehicles
 - Fuel-consumption benefits mostly for intermittent/stop-n-go use patterns
 - Little/no fuel consumption benefit if power expended is close to power average
 - Little/no/negative fuel consumption benefit for vehicles with high hotel-power requirements
- All-electric vehicles
 - No significant foreseeable DoD role
 - Possible applications limited to vehicles that are
 - short-range
 - light-weight
 - low-friction terrain
 - special-purpose (robotic?)
- Fuel-cell vehicles
 - Very costly
 - Not mature
 - Not anticipated to play a role in DoD tactical or combat vehicles in the foreseeable future
- Unmanned vehicles
 - Air
 - High fuel savings, relative to manned A/C
 - Especially if designed to exploit optimal size-speed-altitude corridor
 - Land
 - Future special-use robotic vehicles can play an important role by saving lives and fuel
 - Navy
 - Important potential ISR roles for UAVs discussed previously (JSR-01-225)

C. Decreasing DoD fuel use

Hybrid vehicles are optimized for intermittent/stop and go use patterns with fuel-consumption benefits that are anticipated in that driving environment. Hybrid vehicles offer little or no fuel-economy benefits if the average power expended is close to the peak-power capability of the powerplant. Hence, hybrids offer much more fuel consumption savings in the commercial sector than in the typical DoD (Army) pattern of vehicle use.

JASON finds no significant foreseeable DoD role for all-electric vehicles. These vehicles have possible applications in the limit of short-range, low-friction terrain, if the vehicles are very light weight, and for special-purpose missions such as robotic vehicles. Most of these applications are outside (current) DoD patterns of use.

Similarly, JASON sees no significant DoD use for fuel-cell vehicles on any reasonable time horizon. These vehicles are very costly and the technology is not mature. We also do not see a good mechanism by which the fuel to power them could be supplied to theater. As such, JASON does not anticipate that they will play a role in DoD tactical or combat vehicles in the foreseeable future.

JASON believes that there can be revolutionary changes in the use of unmanned vehicles, especially aircraft, if the design space is explored to optimize fuel efficiency and endurance. Such vehicles would improve fuel efficiency and add new capabilities, potentially obviating air-to-air refueling in many instances.

Future special-use robotic vehicles can play an important role by saving lives and fuel. This is true for air, sea, and for land (cf. JSR-01-225).

In general, light-weighting costs money, but can in return save fuel and will enhance military capability.

Finally, modern diesel engines offer large increases in fuel consumption relative to turbines or older diesel engines that are very inefficient, especially at idle, or near-idle conditions.

Findings — IV

- DoD is not a large-enough customer to drive the market and future developments in alternative fuels
 - *Less than 2% of US consumption*
- Liquid fuels from stranded natural gas provide the economically and environmentally most-favorable alternative to fuels from crude oil
 - *Underground coal gasification (including carbon sequestration) provides the next-best alternative, economically*
- Ethanol's low energy density and high flammability, relative to diesel/JP-8, render it unsuitable as a DoD fuel
 - *Significant added logistical and packaging burden from x1.5 volume penalty for same energy, especially considering the multipliers*
 - *Safety*

D. Liquid fuels from coal or natural gas

DoD is not a large enough customer to drive the fuel market or to drive future developments in alternative fuels. Accounting for less than 2% of U.S. fuel consumption, DoD is likely to depend on the world-wide and commercial sectors for its supplies and alternative fuels are a world-wide issue.

Liquid fuels from stranded natural gas provide the economically and environmentally most-favorable alternative to fuels from crude oil. Underground coal gasification (UCG) provides the next-best alternative from an economic perspective, but is only acceptable from an environmental perspective if GHG emissions (mostly CO₂) from the fuel production process are sequestered.

Findings — V

- Present fuel-from-biomass processes do not compete with fossil fuels
 - *Inadequate (potential) production to substitute for fossil-fuel-derived transportation fuels*
 - *Little, if any, net energy benefit*
 - *Not economically competitive (without subsidies)*
 - *Significant environmental burden (GHGs, soil depletion/erosion, waste water, etc.)*
- Externalities (subsidies, governmental directives, etc.) could mandate biomass-derived-fuel use
- Fuel processes based on cellulosic ethanol, butanol, etc.
 - *Per previous, cellulosic ethanol would still not address DoD needs*
 - *Non-ethanol biofuels cannot be quantitatively assessed (economics, environment, etc.) at present (do not exist)*
 - *Must demonstrate sustainability (soil depletion/erosion, waste water, etc.)*
 - *Must demonstrate that they are preferred environmentally (WTW analysis) to provide a credible alternative*

E. Biofuels

Presently, liquid fuel from biomass processes do not compete economically with production of fuel from crude oil.

Biofuels provide little, if any, net energy benefit, especially if the complete process is taken into account, and are not economically competitive (without subsidies) with other uses of agricultural land, e.g., growing food.

Current biomass-to-fuel methods of production present a significant environmental burden (GHGs, soil depletion and erosion, waste water, etc.).

Fuel processes based on cellulosic ethanol, butanol, etc. could eventually provide a significant fraction of the fuel demands of the U.S., if they are proven economically viable and if associated environmental burdens are acceptable. Such processes do not exist at present, however, and neither they, nor other non-ethanol biofuels and biofuels processes can be assessed, either in terms of their economics or environmental ramifications, at this time.

The biofuels community must demonstrate sustainability with respect to soil depletion/erosion, waste water, and other related considerations, and they must demonstrate that such methods are also preferred environmentally, i.e., through a Well-To-Wheels analysis, if it is to be argued that they can provide a sensible alternative to fossil-derived fuels.

Ethanol's low energy density, high flammability, and transportation difficulties, relative to diesel and JP-8, for example, render it unsuitable as a DoD fuel. The primary

considerations that enter this finding are logistics, energy density (high volume per unit energy content), and safety.

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VIII. Recommendations and path forward

1. Consider buffers against future crude-oil and fuel price increases:
 - a. inventory timing, e.g., seasonal buying choices,
 - b. investing in long-term contracts, and
 - c. diversifying sources and supplies.
2. Make long-term planning for future fuel sources, production, and use. Be aware of present and anticipated environmental (GHG, etc.) regulations.
3. Optimize exploitation of commercial aviation fuels. Consider distributed and OCONUS local production of military fuels (JP-5, JP-8, JP-8 +100) from commercial aviation fuels.
4. Review and minimize CONUS fuel use; most DoD fuel is used in CONUS.
 - a. Increase reliance on simulator training programs
 - b. Devise fuel-use optimization tools for gaming, planning, and *in-situ* field use with an eye to fuel consumption (vehicle mix, tactics, operational choices) and logistical requirements.
 - c. Optimize vehicles to DoD patterns of use.
5. Track the pattern of use for vehicles and fuels.
 - a. Track fuel use and different vehicle patterns of use (idling vs. in-motion engine use time fractions) across the DoD to develop a database for use in optimizing fuel efficiency, and designing/selecting future vehicles.
 - b. Optimize platforms, powerplants, with respect to DoD-relevant patterns of use, in each case. Include fuel in vehicle/platform life-cycle costs as a (strong) factor in the optimization.
6. Develop the necessary accounting and tracking tools to determine fuel delivery and logistics burdens and multipliers, so that it is possible to know what has been saved throughout the logistics chain when a gallon of fuel consumption is reduced at any point in the fuel demand chain.
7. Determine fuel delivery/use logistics burdens and multipliers.
 - a. Gallons required per gallon delivered.
 - b. Cost per gallon delivered to the field, in the air, at sea, etc.
8. Reengine the M1 tank, the B-52 bomber, etc., to exploit modern engine technology and engines designed for the purpose, in each case.
9. Lightweight armored and tactical vehicles, leveraging modern design, structural, and materials developments. Exploit new armor technologies for increased effectiveness for the same mass. We recommend that DoD resist down-armoring. Weight reductions are more likely achievable without loss in functionality in other parts of the vehicle.
10. Manned vs. unmanned vehicles: Reexamine and extend UAV, UUV, and robotic land vehicle uses. Consider new designs that can only be realized in unmanned vehicles and platforms.

Appendix I: Energy glossary

AAFC	Agriculture and Agri-Food Canada
AAV	Amphibious Assault Vehicle
ARMS	Agricultural Resources Management Survey
bagasse	(sometimes spelled bagass): biomass remaining after crushing sugarcane stalks to extract their juice. A sugar factory produces nearly 30% of bagasse out of its total crushing that is often used as a primary fuel source for sugar mills. When burned in quantity, it produces sufficient heat energy to supply all the needs of a typical sugar mill, with energy to spare. A secondary use for this waste product is in cogeneration to provide both heat energy, used in the mill, and electricity, which is typically sold to the grid. [Wikipedia, 13Aug06]
barrel	(of oil) = 42 (U.S.) gallons = 1 bbl ("blue barrel" of oil).
BL	Black Liquor. By-product of paper pulping that contains the lignin part of the wood, commonly used as an internal fuel source to power the paper mills. Through gasification, one can generate syngas and syngas
boe	barrel of oil equivalent = 5.8 MBTU = 6.12 MJ
BTL	Biomass-To-Liquid (fuel)
BTU	British Thermal Unit = (heat) energy needed to raise the temperature of one pound (lbm) of water by one °F = 1.055056 kJ
BTU/ft ³	= 37.258946 kJ/m ³
BTU/gal	= 0.278716 kJ/liter
BTU/lbm	= 2.326 kJ/kg
CAA	Clean Air Act Amendments
CCGT	Combined-cycle gas turbine: refers to a power plant that utilizes both the Brayton (gas-turbine) cycle and the Rankine (steam) cycle. The exhaust from the gas turbine is used to generate the energy for the Rankine cycle.
CCS	Carbon capture and storage, aka, carbon sequestration
CGF	Corn gluten feed (21 percent protein)
CGM	Corn gluten meal (60 percent protein)
CHP	Combined heat and power: the simultaneous and high-efficiency production of heat and electrical power in a single process.
CO	Carbon monoxide. Constituent, along with H ₂ , of the first step(s) of the Fischer-Tropsch process
CO ₂	Carbon dioxide: a gas produced by many organic processes, including human respiration and the decay or combustion of animal and vegetable matter. Greenhouse gas with strong absorption bands at the thermal-emission spectrum.
CTL	Coal to Liquid (fuel), as via the Fisher-Tropsch process.
DB	Dry basis, i.e., w/o water, for starch content in grains
DDGS	Distiller's dried grains with solubles

DICI	Direct Injection Compression Ignition (engine)
DME	Dimethyl ether. Surrogate for diesel.
DOE	Department of Energy. The federal agency that oversees the production and distribution of electricity and other forms of energy.
DPF	Diesel Particulate Filter (emissions mitigation). Decreases diesel-engine power output if installed.
E85	A fuel mixture of 85% ethanol and 15% gasoline
EIA	Energy Information Administration: the statistical and data-gathering arm of the Department of Energy.
EOR	Enhanced oil recovery
EPA	U.S. Environmental Protection Agency: the agency that oversees and regulates the impact of, among other things, the production of energy on the environment of the United States.
ERRATA	Energy Regulatory Reform and Tax Act: a plan to deregulate the production and distribution of electricity, to update environmental laws regarding energy production, and to alter the existing tax structures.
Ethanol	$\text{C}_2\text{H}_5\text{OH}$: Next-lightest alcohol, after methanol.
FC	Fuel Cell
FCRS	Farm Costs and Returns Survey
GHG	Greenhouse gas.
REET	Greenhouse gases, regulated emissions, and energy use in transportation
GTL	Gas To Liquid (conversion)
GW	Gigawatt = 10^9 Watts.
GWh	Gigawatt-hour: the amount of energy available from one gigawatt in one hour.
HFCS	High-fructose corn syrup
HHV	High-heat value
HICE	Hydrogen internal combustion engine
ICE	Internal combustion engine
IEA	International Energy Agency: a twenty-six member union of national governments with the goal of securing global power supplies.
IED	Improvised explosive device
IPP	Independent power producers: companies that generate electrical power and provide it wholesale to the power market. IPPs own and operate their stations as non-utilities and do not own the transmission lines.
Joule	The (kinetic) energy acquired by a mass of one kilogram moving at a speed of one meter per second
kJ	kilojoule = 10^3 Joules
kW, KW	kilowatt = 10^3 Watts = 1.341 HP
kWh, KWh	= energy available from one kilowatt in one hour = 3.6 MJ
LHV	Low-heat value

LNG	Liquified Natural Gas
LPG	Liquefied petroleum gas
M85	a fuel mixture of 85% methanol and 15% gasoline
Methane	CH ₄ : Main constituent of natural gas. Also, important greenhouse gas.
Methanol	CH ₃ OH: Lightest alcohol. Toxic, causing nerve and eye damage.
MJ	Megajoule = 10 ⁶ Joules = 0.2778 kWh
MTBE	Methyl tertiary-butyl ether. Fuel oxygenate additive. Being phased out (toxic) in favor of ethanol.
MW	Megawatt = 10 ⁶ Watts = 1 MJ/s
MWh	Megawatt hour: energy available from one megawatt in one hour.
NASS	National Agricultural Statistics Service
NEDC	New European Driving Cycle (standard)
NEV	Net energy value
NOX, NO _x	Nitrogen oxide(s): assorted oxides of nitrogen, generally considered pollutants, that are commonly produced by combustion reactions.
PISI	Port Injection Spark Ignition (engine)
PM ₁₀	Particulate matter in the atmosphere that is between 2.5 and 10 µm in size.
PTW	Pump-To-Wheels (analysis)
PURPA	Public Utility Regulatory Policy Act: act of Congress targeting the reduction of American dependence on foreign oil through the encouragement of the development of alternative energy sources and the diversification of the power industry.
Quad	Quadrillion BTU = 10 ¹⁵ BTU = 1.055 EJ (exajoule)= 172 Mbbl-eq
RFG	Reformulated gasoline
S	Sulfur
SAGD	Steam Assisted Gravity Drainage
stover	(corn): the leaves and stalks of corn (maize), sorghum or soybean plants left in a field after harvest. It can be directly grazed by cattle or dried for use as fodder (forage). It is similar to straw, the residue left after any cereal grain or grass has been harvested at maturity for its seed. [<i>Wikipedia</i> , 13Aug06]
TW	Terawatt = 10 ¹² Watts
UAV	Unmanned/Unpiloted Air Vehicle
UCG	Underground coal gasification
USDA	U.S. Department of Agriculture
UUV	Unmanned Underwater Vehicle
Watt	= one Joule per second.
WEO	World energy outlook: a projection analysis made by the IEA
WTP	Well-To-Pump (analysis)
WTW	Well-To-Wheels (analysis)

Appendix II: Air-to-air jet-fuel delivery costs

As part of this study, an estimate was made of the cost per gallon delivered in mid-air using one of the 530 KC-135s or one of the 59 KC-10s in the U.S. Air Force tanker fleet. The resulting estimates are depicted in the figure on page 30.

An earlier study [DSB2001] reported that, “the fully burdened cost per gallon delivered in midair” was \$17.50/gal in FY1999 (then-year dollars). This cost is shown in the figure on page 30, brought forward to FY2005 dollars. The present study’s estimates of FY05\$22/gal and FY06\$23/gal are consistent with the previous (DSB2001) estimate reported for FY99.

The present study considered the per-gallon cost breakdown for the mid-air refueling enterprise into infrastructure capital costs; operations and maintenance (O&M); and the DESC wholesale cost of fuel carried by the tankers. Costs to fuel and fly the tankers themselves are captured in the O&M costs for the tankers. The wholesale fuel costs cover only the cost of the fuel delivered to tanker customers in mid-air.

To normalize the per-gallon estimates, the total volume of AVFUEL (JP-8, F-76 and Jet-A) delivered to tanker customers was used in the denominator: 207 million gallons in FY05 and 213 million gallons in FY06 estimated based on figures through May of 2006.

These include fuel delivered mid-air via tanker to non-USAF customers (~ 20% of tanker deliveries). Excluding non-USAF mid-air deliveries, the fraction of USAF fuel consumption delivered to USAF aircraft in midair was about 6.3%. This is similar to the percentage previously reported [DSB2001].

The wholesale price per gallon of AVFUEL was obtained from the DESC Fact Book for 2005 and 2006, while the 1999 figure was taken from the earlier study [DSB2001]. If the DESC price changed during the fiscal year, then the time-weighted average of the various per-gallon prices was calculated and used for that year.

Because the acquisition history of the tanker fleet was not available for this study, the annual cost of midair fuel delivery infrastructure (i.e., the KC-135 tanker fleet) was based on a reported \$40M (FY1998 dollars) unit cost, amortized over a 40 year aircraft life, brought forward to current-year dollars. A fleet of 516 KC-135s was used for this calculation as an equivalent to the actual current fleet, based on reported capabilities of KC-135Rs versus KC-135Es versus KC10s.

O&M costs were obtained for FY05 from the USAF directly [L. Klapper, AFCAA, pvte. Comm.], and were reported as \$3.7B for the operation of 112 KC135Es, 418 KC135Rs, and 59 KC10s. Based on separate cost figures also provided by the USAF, the variable cost per gallon delivered by aircraft was calculated and summed over the fleet to get the component of O&M costs that scale with the amount of fuel delivered. This was ~30% of total O&M costs. Using these figures the 2006 O&M per-gallon costs were estimated by scaling the variable costs by the estimated volume delivered in midair in 2006, keeping the fixed O&M costs the same as 2005. These calculations were done in FY05 dollars.

The results of this cost analysis, shown in the figure on page 30, illustrate how infrastructure, and operations (O&M, here) multiply the cost of fuel delivered to a front-end user. A numerical estimate of the fuel-multiplier in this case can be estimated by

assuming, conservatively, that 20% of the O&M costs result from mobility fuel to fly the tankers themselves. This assumption yields the estimate that tankers burned 482 million gallons (20% of \$O&M / [\$ /gal at wholesale]) of fuel to deliver 207 million gallons of fuel in FY2005. This yields a fuel-delivery multiplier of 3.3 . This multiplier leads to corresponding overhead and logistics costs, in both dollars and tactical/operational terms.

At least 37% of the \$20-\$25 /gal cost, i.e., ~\$8.45/gal, is estimated to scale with fuel consumption, illustrating the potential benefit of improved fuel efficiency.

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