# Dual Fluid Reactor (DFR)*

## A New Concept For A Nuclear Power Reactor

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*Patent pending: http://www.google.com/patents/WO2013041085A2?cl=en

# Collaboration

## Institution & Personel

The Dual fluid Reactor was developed at the Institute For Solid-State Nuclear Physics in Berlin, Germany. http://festkoerper-kernphysik.de

- Dr. Konrad Czerski,
- Dr. Armin Huke,
- Dr. Ahmed Hussein,
- Dr. Götz Ruprecht,
- Dipl.-Ing. Stephan Gottlieb, and
- Daniel Weißbach
- Dario Gigliotti.
- + supporters and advisors

# World Wide Use of Nuclear Power

## Some General Facts

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- Nuclear power plants provided 12.9% of the world's electricity production in 2012.
- 13 countries relied on nuclear energy to supply at least 25% of their total electricity.

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## Current Reactors World Wide

| Country | Reactors | $MW_e$ | BkWh | % Of Total |
|---|---|---|---|---|
| Argentina | 2 | 935 | 5,903 | 4·7 |
| Armenia | 1 | 375 | 2,124 | 26·6 |
| Belgium | 7 | 5,927 | 38,464 | 51·0 |
| Brazil | 2 | 1,884 | 15,170 | 3·1 |
| Bulgaria | 2 | 1,906 | 14,861 | 31·6 |
| Canada | 20 | 14,135 | 89,060 | 15·3 |
| China | 17 | 12,860 | 92,652 | 2·0 |
| Czech RP | 6 | 3,804 | 28,603 | 35·3 |
| Finland | 4 | 2,752 | 22,063 | 32·6 |
| France | 58 | 63,130 | 407,438 | 74·8 |
| Germany | 9 | 12,068 | 94,098 | 16·1 |
| Hungary | 4 | 1,889 | 14,763 | 45·9 |
| India | 20 | 4,391 | 29,665 | 3·6 |
| Iran | 1 | 915 | 1,328 | 0·6 |
| Japan | 50 | 44,215 | 17,230 | 2·1 |
| Korea Rep. | 23 | 20,739 | 143,550 | 30·4 |
| Mexico | 2 | 1,530 | 8,412 | 4·7 |

continued..

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## Current Reactors World Wide

| Country | Reactors | $MW_e$ | BkWh | % Of Total |
|---|---|---|---|---|
| Netherlands | 1 | 482 | 3, 707 | 4·4 |
| Pakistan | 3 | 725 | 5, 271 | 5·3 |
| Romania | 2 | 1, 300 | 10, 564 | 19·4 |
| Russia | 33 | 23, 643 | 166, 293 | 17·8 |
| Slovakia | 4 | 1, 816 | 14, 411 | 53·8 |
| Slovenia | 1 | 688 | 5, 244 | 36·0 |
| South Africa | 2 | 1, 860 | 12, 398 | 5·1 |
| Spain | 8 | 7, 560 | 58, 701 | 20·5 |
| Sweden | 10 | 9, 395 | 61, 474 | 38·1 |
| Switzerland | 5 | 3, 278 | 24, 445 | 35·9 |
| Taiwan, China | 6 | 5, 028 | 38733 | 18·4 |
| Ukraine | 15 | 13, 107 | 84, 886 | 46·2 |
| U.K. | 18 | 9, 938 | 63, 964 | 18·1 |
| U.S. | 104 | 102, 136 | 770, 719 | 19·0 |
| Total | 440 | 374, 411 | 2, 346, 194 | *NA* |

# World Wide Use of Nuclear Power

## Reactors Under Construction World Wide

| Country | Reactors | Total $MW_e$ |
|---|---|---|
| Argentina | 1 | 692 |
| Brazil | 1 | 1,245 |
| China | 28 | 27,844 |
| China, Taiwan | 2 | 2,600 |
| Finland | 1 | 1,600 |
| France | 1 | 1,600 |
| India | 7 | 4,824 |
| Japan | 2 | 2,650 |
| Pakistan | 2 | 630 |
| Russia | 11 | 9,297 |
| Slovak Republic | 2 | 880 |
| S. Korea | 4 | 4,980 |
| Ukraine | 2 | 1,900 |
| United Arab Emirates | 2 | 2,690 |
| United States | 3 | 3,399 |
| Total | 69 | 66,831 |

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- Long life of the resource.
- Safe production and operation.

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Energy Content of Various Sources

| Source | Energy Density |
|---|---|
| Firewood (dry) | 16 MJ/kg |
| Brown coal (lignite) | 10 MJ/kg |
| Black coal (low quality) | 13-23 MJ/kg |
| Black coal (hard) | 24-30 MJ/kg |
| Natural Gas | 38 $MJ/m^3$ |
| Crude Oil | 45-46 MJ/kg |
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Energy Content of Wind and Solar

| Source | Natural Energy Flows Providing 1 kW of Available Power | |
|---|---|---|
| Wind | Turbine Wind speed 12.5 m/s | Turbine swept area 0.85 $m^2$ |
| | Wind speed 4 m/s | Turbine swept area 31.84 $m^2$ |
| Solar PV | Surface perpendicular to the sun's rays at noon with sun directly overhead | Surface area 1$m^2$ |
| | For an hourly average of 1kW taken over a day | Surface area 2.5 - 5 $m^2$ depending on location |

Source: http://www.mpoweruk.com/energy_resources.htm

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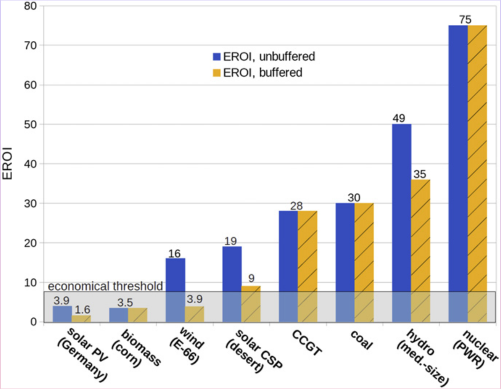


**Fig. 3.** EROIs of all energy techniques with economic "threshold". *Biomass*: Maize, 55 t/ha per year harvested (wet). *Wind*: Location is Northern Schleswig Holstein (2000 full-load hours). *Coal*: Transportation not included. *Nuclear*: Enrichment 83% centrifuge, 17% diffusion. *PV*: Roof installation. *Solar CSP*: Grid connection to Europe not included.

Source:
"Energy intensities, EROIs (energy returned on invested), and energy payback times of electricity generating power plants."
D. Weibach, G. Ruprecht, A. Huke, K. Czerski , S. Gottlieb, A. Hussein
Energy 52(2013)210-221.

# Nuclear Power

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Lifecycle Greenhouse Gas Emission Estimates for Electricity Generators

| Technology | Mean | Low | High |
| --- | --- | --- | --- |
| | g $CO_2$Eq./kWh$_e$ | | |
| Lignite | 1,054 | 790 | 1,372 |
| Coal | 888 | 756 | 1,310 |
| Oil | 733 | 547 | 935 |
| Natural Gas | 499 | 362 | 891 |
| Solar PV | 85 | 13 | 731 |
| Biomass | 45 | 10 | 101 |
| Nuclear | 29 | 2 | 130 |
| Hydroelectric | 26 | 2 | 237 |
| Wind | 26 | 6 | 124 |

Source: http://www.cameco.com/common/pdf/uranium_101/Cameco_-_Corporation_Report_on_GHG_Emissions_nov_2010.pdf

## Why Nuclear Power

"DeathPrint" of Various Energy Sources

| Energy Source | Mortality Rate (deaths/TkWhr) | Comments |
|---|---|---|
| Coal global average | 170,000 | 50% global electricity |
| Coal China | 280,000 | 75% China's electricity |
| Coal U.S. | 15,000 | 44% U.S. electricity |
| Oil | 36,000 | 36% of energy, 8% of electricity |
| Natural Gas | 4,000 | 20% global electricity |
| Biofuel/Biomass | 24,000 | 21% global energy |
| Solar (rooftop) | 440 | $<$ 1% global electricity |
| Wind | 150 | $\approx$ 1% global electricity |
| Hydro global average | 1,400 | 15% global electricity |
| Nuclear global average | 90 | 17% global electricity w/Chern&Fukush |

Source: http://www.forbes.com/sites/jamesconca/2012/06/10/energys-deathprint-a-price-always-paid

## Why Nuclear Power

Life Expectancy of Fossil Fuels

| Fossil Fuel | Reserves | Consumption | Year | Life Time (years) | $CO_2$ Emissions (tonnes) |
|---|---|---|---|---|---|
| Natural Gas | $1{\cdot}90 \times 10^{14}$ m$^3$ | $3{\cdot}37 \times 10^{12}$ m$^3$ | 2011 | 56 | $1{\cdot}29 \times 10^{7}$ |
| Oil | $1{\cdot}47 \times 10^{12}$ bbl | $2{\cdot}87 \times 10^{10}$ bbl | 2011 | 51 | $1{\cdot}14 \times 10^{10}$ |
| Coal | $8{\cdot}60 \times 10^{11}$ ton | $6{\cdot}64 \times 10^{9}$ ton | 2008 | 129 | $1{\cdot}30 \times 10^{10}$ |

Source: US Energy Information Administration
http://www.eia.gov

# Nuclear Power

## Reactors Under Construction World Wide

| Reactor Type | Reactor Type Description | Number of Reactors | Total ($MW_e$) |
|---|---|---|---|
| BWR | Boiling Light-Water-Cooled and Moderated Reactor. | 4 | 5,250 |
| FBR | Fast Breeder Reactor. | 2 | 1,259 |
| HTGR | High-Temperature Gas-Cooled Reactor. | 1 | 200 |
| LWGR | Light-Water-Cooled, Graphite-Moderated Reactor. | 1 | 915 |
| PHWR | Pressurized Heavy-Water-Moderated and Cooled Reactor (CANDU) | 5 | 3,212 |
| PWR | Pressurized Light-Water-Moderated and Cooled Reactor. | 56 | 55,995 |
| Total | | 69 | 66,831 |

Sources: International Atomic Energy Agency PRIS database http://www.iaea.org/programmes/a2/index.html

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## Current Reactors

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  - Solid Fuel.

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  - Accumulated Pu opens the door for weapons proliferation.

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  - Requires active safety, very little passive safety features.

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  - Control through neutron absorbing rods

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  - Prolifiration resistant.

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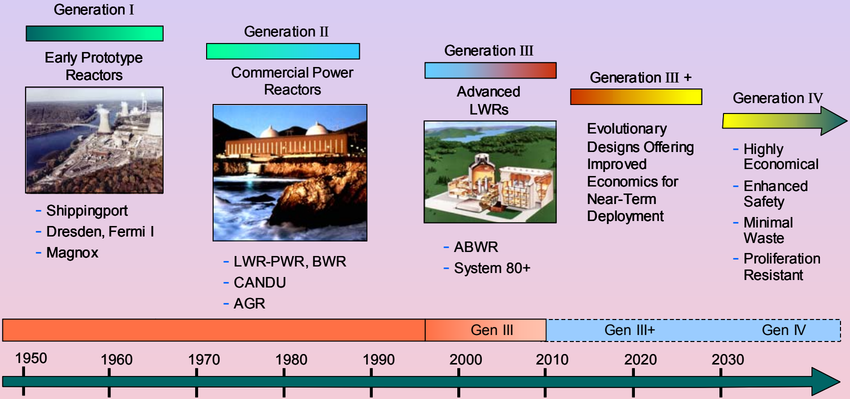


Source:
"A Technology Roadmap for Generation IV Nuclear Energy Systems"
U.S. DOE Nuclear Energy Research Advisory Committee and the Generation IV International Forum.

## Generation IV Reactors

Generation IV Reactor Systems

| System Description | Acronym |
|---|---|
| Gas-Cooled Fast Reactor System | GFR |
| Lead-Cooled Fast Reactor System | LFR |
| Molten Salt Reactor System | MSR |
| Sodium-Cooled Fast Reactor System | SFR |
| Supercritical-Water-Cooled Reactor System | SCWR |
| Very-High-Temperature Reactor System | VHTR |

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- Two version of the fuel/coolant were used,

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  - A frozen plug can provide passive safety (more on that later).

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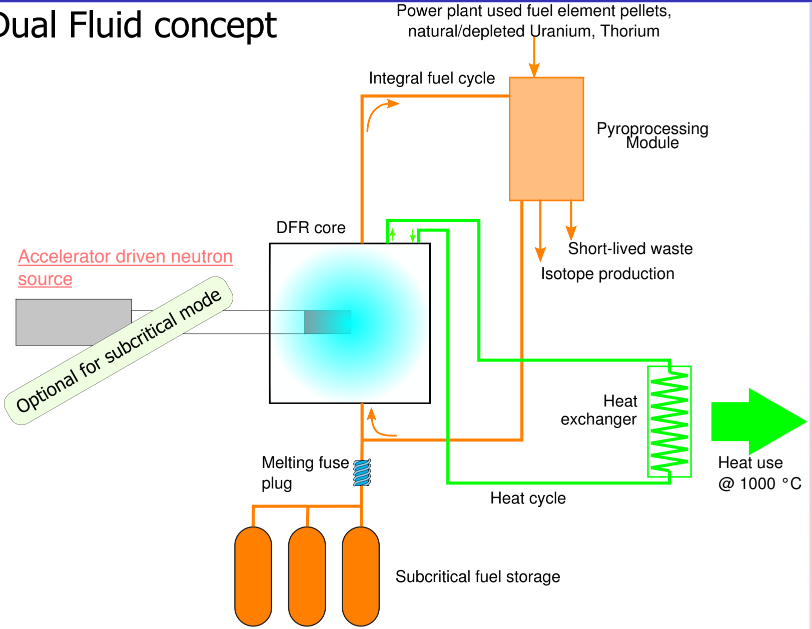

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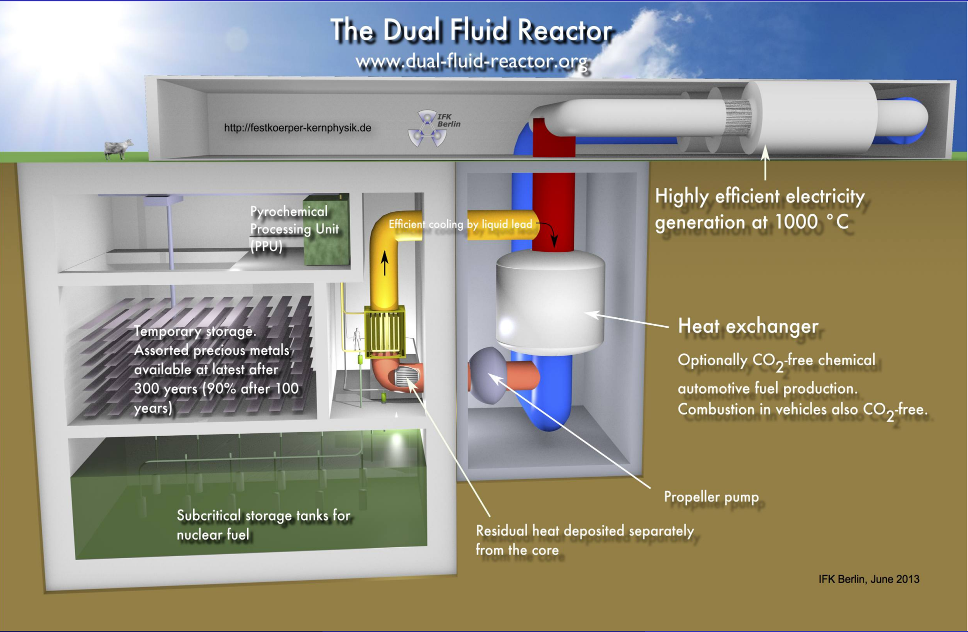

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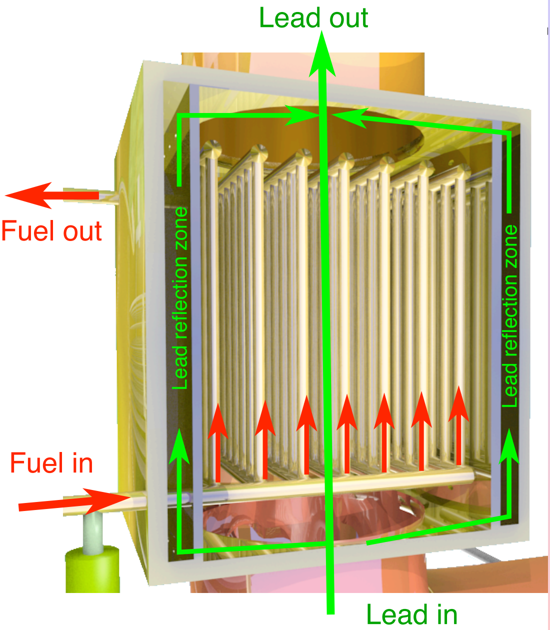

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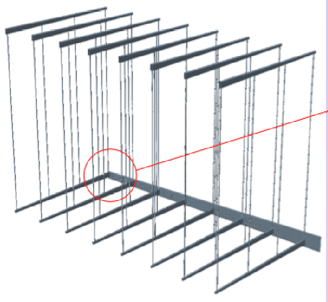

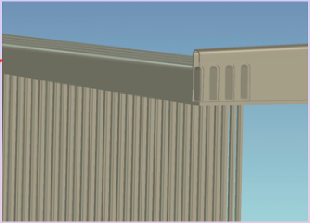

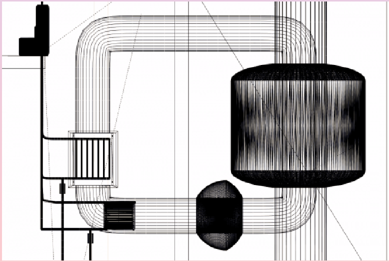

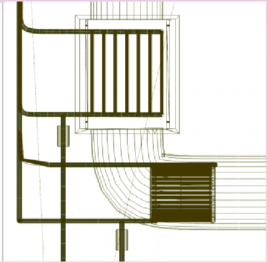

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- Th-U fuel cycle produces much less neutron yield than U-Pu cycle.

# Reactors: DFR and water-moderated

## DFR

- Consumes "waste"
- Consumes natural Uranium and natural Thorium
- Produces fuel for water-moderated reactors, if desired
- Produces $CO_2$-neutral chemical fuels
- Has a closed internal fuel cycle

vs.

## Water-moderated Reactor

- Produces "waste"
- Consumes U-235
- Can not produce chemical fuels
- Low power density, high costs
- Relies on fuel cycle infrastructure

Should not be an "either/or"

DFRs could be deployed on the site of water-moderated reactors, complementing their operation and closing their fuel cycle

# Economics of DFR

Energy input of the DFR

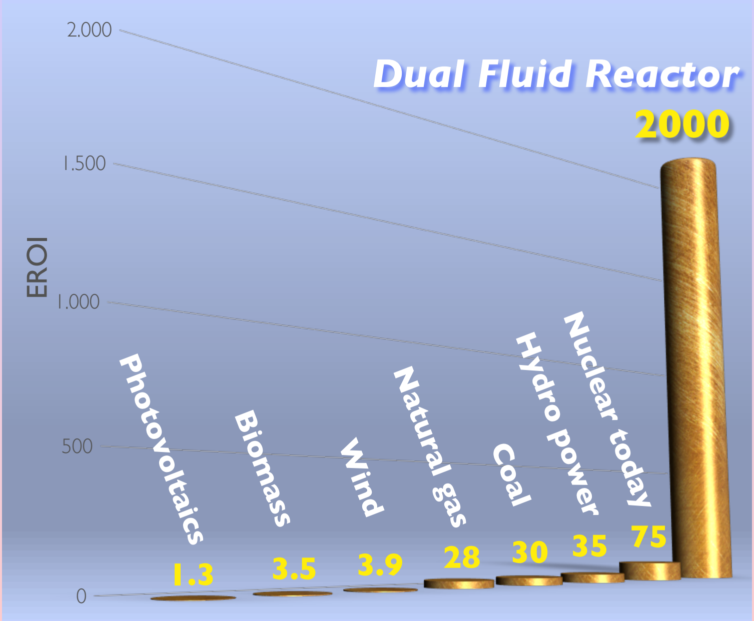
| Item | Units or Total (1000 kg) | Energy Inventory (TJ/1000 kg) | Total Inventory (TJ) |
|---|---|---|---|
| Concrete containment for reactor, fission products and turbine building | 21000 | 0·0014 | 30 |
| High performance refractory metals and ceramics (PPU and core) | 60 | 0·5 | 30 |
| High temperature isolation material for PPU and core | 100 | 0·1 | 10 |
| Initial load, isotopically purified 37Cl + fuel | $25 + 60$ | $2{\cdot}5/0.4$ | $50 + 25$ |
| Refractory metals and ceramics for the heat exchanger | 180 | 0·5 | 90 |
| Isolation and structural materials, heat exchanger | 300 | 0·1 | 30 |
| Unfabricated, low-alloyed metal for fission product encapsulation | 3000 | 0·033 | 100 |
| Structural materials (steel) for non-nuclear part | 1000 | 0·02 | 20 |
| Lead coolant | 1200 | 0·036 | 45 |

continued..

# Economics of DFR

Energy input of the DFR

| Item | Units or Total (1000 kg) | Energy Inventory (TJ/1000 kg) | Total Inventory (TJ) |
|---|---|---|---|
| Turbines with generators | 3 | 40 | 120 |
| Mechanical engineering parts | | | 150 |
| Cooling tower (special concrete) | 20000 | 0·003 | 60 |
| Refueling, 1200 kg/a actinides over 50 years | $\approx 60$ | 0·4 | $\approx 25$ |
| 37Cl loss compensation | 2 | 2·5 | 5 |
| Maintenance, high-performance refractories+ isolation for 1 new core | $30 + 50$ | $0{\cdot}5/0.1$ | 20 |
| Maintenance, 50% of other reactor parts, refractories+ isolation | $90 + 175$ | $0{\cdot}5/0.1$ | 62·5 |
| Maintenance, 50% of mechanical engineering and turbines | | | 135 |
| Maintenance electricity, 2MW over 20 days/a and heating, 50*0.2 TJ | | | 182·5 |
| Sum | | | 1190 |
| Output over 50 years lifetime, $\approx$ 1500 MW net, $\approx$ 8300 full-load hours | | | $2,250,000$ |


2.000
1.500
1.000
500
0
EROI
Dual Fluid Reactor
2000
Photovoltaics
Biomass
Wind
Natural gas
Coal
Hydro power
Nuclear today
1.3
3.5
3.9
28
30
35
75

# Economics of DFR

## Estimated Construction Costs (Million US$)

| Item | 500 $MW_e$ DFR | 1500 $MW_e$ DFR |
|---|---|---|
| Concrete containment for reactor, earthquake-proof | 100 | 130 |
| Reactor with primary circuit, features including a facility for pyrochemistry | 250 | 300 |
| Secondary gas loop | 60 | 150 |
| Supercritical water turbine 500 MWe (3x), generator, transformer | 250 | 580 |
| Tertiary cooling system with cooling tower | 140 | 250 |
| Additional bunkers | 100 | 200 |
| Planning and building authority, contingency | 130 | 200 |
| Sum | 1000 | 1800 |
| Costs per installed power | 2 US$/W | 1.2 US$/W |

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- The above estimates use a more expensive external cooling system. A different choice could reduce the costs by 10%.

# Economics of DFR

## Operational Costs

Estimated Annual DFR Operating Costs (million US$)

| Item | 500 $MW_e$ | 1500 $MW_e$ |
|---|---|---|
| Operating personnel: 30 man-years<br>(3 shifts 10/12 man-years each 130,000 US$) | 4 | 5 |
| Operating supplies | 1.5 | 2.5 |
| Nuclear fuel: 500 kg<br>(330 US$ mining, 330 US$ transport,<br>650 US$ per kg waste management) | 0.5 | 1.5 |
| Maintenance, conventional section<br>(2.5% building costs per annum) | 9.5 | 25 |
| Maintenance, nuclear and pyrochemical section<br>(2% building costs per annum) | 5 | 7 |
| Reserve for dismantling<br>(25% of the building cost of 1000/1900 million US$) | 5 | 9 |
| Administration, safety | 2.5 | 4 |
| Sum | 26 | 54 |

# Economics of DFR

## Electricity Costs

Estimated Total Costs OF Electricity Produced With DFR In US¢/kWh

| Item | 500 $MW_e$ | 1500 $MW_e$ |
|---|---|---|
| Capital costs | 0.50 | 0.30 |
| Operating costs | 0.65 | 0.45 |
| Sum | 1.15 | 0.75 |
| DFR/PWR or Coal | 0.30 | 0.20 |

Note1: PWR ≡ Pressurized Water Reactor, most commonly used reactor.
Note2: Cost of electricity produced by Coal fired power stations are close to those produced by PWRs.

continued..

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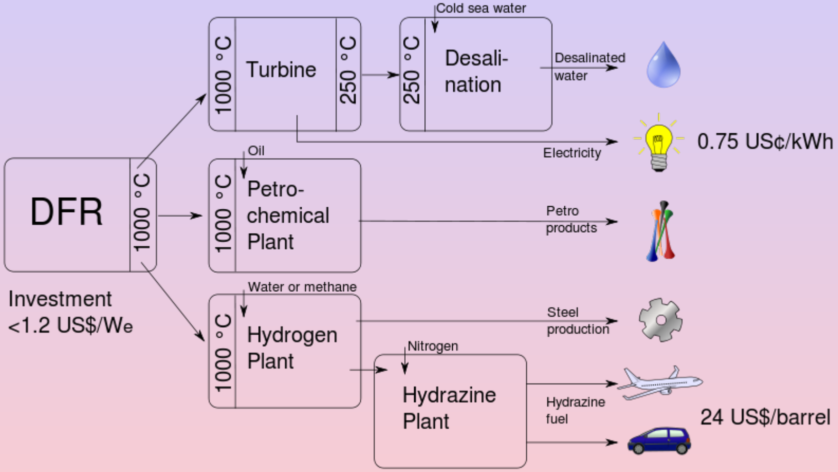

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- This cheap Hydrogen makes the production of Nitrogen and Silicon based synthetic automotive fuels economically viable.

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- All these fuels are “organic fuels”, based on carbon and hydrogen. As a result, they all produce Carbon Dioxide as they burn.

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- It can be used in automotive combustion engines with proper additives, resulting in Water Vapour and Nitrogen as waste.

continued..

# Economics

## Synthetic Automotive Fuels

- There are other synthesized fuels that are not based on Carbon. Examples are Hydrazine and Silane
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- Hydrazine has been used as rocket fuel in NASA's space program.
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- Similarly, Silane burns to Water Vapour and Silicon Nitride, an inert compound.

continued..

# Economics

## Synthetic Automotive Fuels

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continued..

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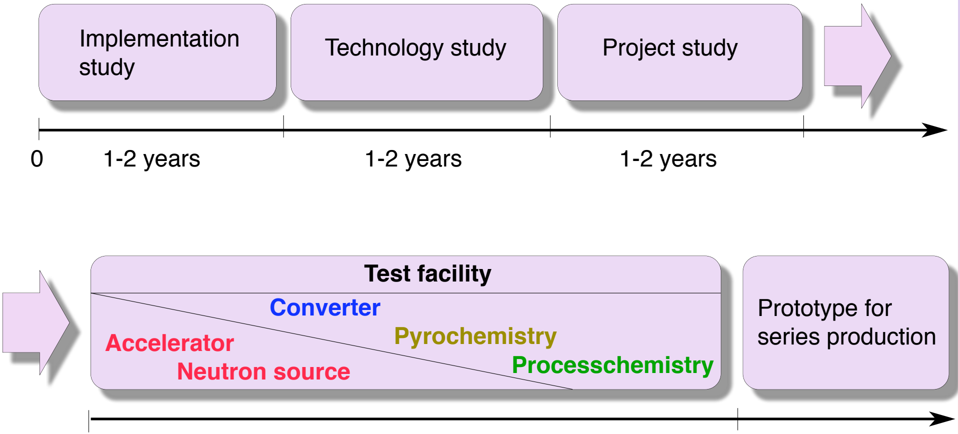
- The hazardous properties and toxicity of these fuels are similar to Gasoline.

continued..

# Overall Plan

## Estimated timeline



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  - 1.5 scientists for experimental work on material testing and pyroprocessing component testing @ $\approx$ \$1.2 million, includes salaries and benefits, equipment and laboratory space rental.

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- TRIUMF????