Nuclear Hydrogen Production

The View from General Atomics

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Hydrogen is Widely Seen as a Long-Term Replacement for Fossil Transportation Fuels

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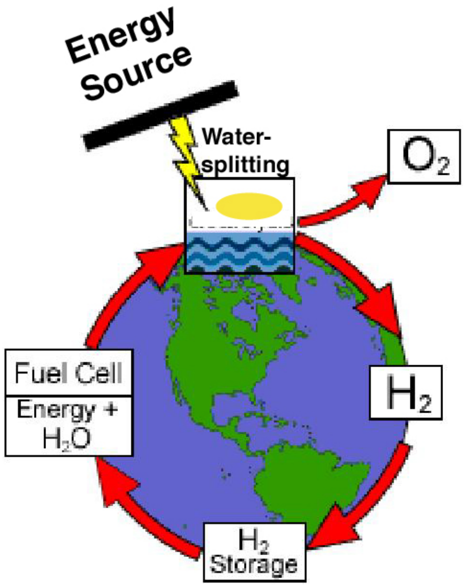
Nuclear Hydrogen

- **Reduced emissions and dependence on fossil fuel imports**
  - Low fuel-cycle CO_2 and tailpipe emissions
  - Enabling high-efficiency fuel cells
  - Widespread availability



- **Requires restructuring whole energy economy**
  - -Energy source – H_2 an energy carrier
    - -Greater than fossil energy replaced
    - -Environmental impact
  - -Infrastructure
    - -Distribution, storage, end use

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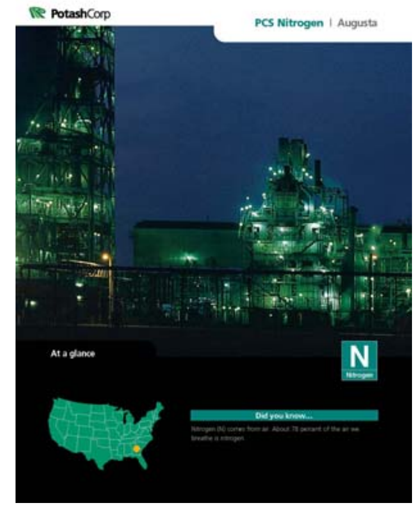
The Demand for Hydrogen Is Already Quite High

- **US now uses about 11 Mt H_2/y, largely in chemical and oil industries**

  ~50% to ammonia (fertilizers)
  ~37% to refineries for upgrading products
  ~8% to methanol production
  ~4% to chemicals, other
  ~1% space programs



PCS Nitrogen, GA
400 tons H/d

- **Most from Steam Methane Reformation (SMR) of natural gas**
  – Feedstock and heat source release ~115 Mt CO_2/yr

Future energy sources for hydrogen must be sustainable, non-fossil, non-greenhouse

Commercial Production for Hydrogen is Already at Scale

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Example: Air Products, Inc., operates 22 plants and 300 miles of H_2 pipelines, capable of moving 1900 t per day (most for refining gasoline)

Air Products, CA, H_2 plant

~200 tons/d <–> ~300 MW_H

. . . but the energy supply, natural gas, is both finite and carbon producing

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The Full Hydrogen Economy Will Need a Clean, Abundant Energy Source

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- **Fossil production makes no sense without sequestration**
  - Issues of geologic security of carbon – Gt's CO_2/yr.
  - Issues non-carbon pollution, mining impact, etc.
- **Renewables make sense, but only on the margin**
  - Quantity of energy required - TW's of power
  - Land and resource requirements
  - Diurnal & seasonal variations
  - Storage possible but, for base-load, large-scale storage likely expensive
- **Nuclear power seems the only answer today**
  - Nuclear is the natural option for supplying large, centralized users
  - Cost appears competitive with today's SMR
  - Both spent-fuel disposition and proliferation have technical solutions today, political will is required
  - For the longer term, fusion may be an option

Hydrogen for Transportation Raises Additional Questions, Issues and Options

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- **US would need 200 Mt/yr of H_2 for transportation**
- **Production at 50% efficiency requires 1.6 $TW_{primary}$**
  ≅ current primary energy for US electricity generation

- **How is the H_2 to be produced & distributed?**
  - Locally (made in home or station)?
  - Centrally (piped to home or station)?
- **How is it to be stored?**
  - As high-pressure gas? As a hydrocarbon?
  - Other?
- **How is it to be burned?**
  - In an IC engine? Hybrid? Fuel cell?

As a system (and economic)issue, answers to such questions will determine the most practical production approach(es)

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Prevailing Infrastructure Will Have a Large Impact on Strategy for H-based Transportation

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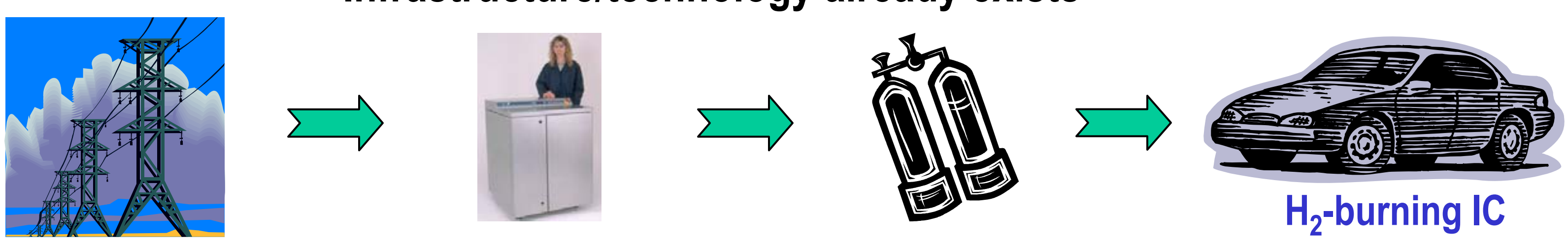
Energy infrastructure is currently based on petroleum and electricity. In the short term, this favors

- For the existing longer-haul fleet
  - Nuclear-H_2, using lowest-cost technique
  - H_2-enriched liquid hydrocarbons, e.g., methanol, synfuels
  - Distribution/storage using existing pipelines, gas tanks, etc.
  - Encouraging widespread IC-electric hybrid engines
- For shorter-haul, “early adopters”
  - H_2 in the home using electrolysis as primary source
  - Infrastructure/technology already exists



. . . enabling development of technologies needed for the H_2 vision

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Nuclear Hydrogen Could be Produced by a Variety of Means

- **Electric power**
  - Electrolysis; proven technology, matched to small unit size
  - Overall efficiency ~24% (LWR), ~36% (Hi-T reactors)
  - Distributed production using electricity infrastructure
- **Electricity & Heat**
  - Electro-thermal or electro-thermo-chemical
  - Developing technologies
  - Efficiencies to ~ 50%
- **High-temperature heat**
  - Thermo-chemical water-splitting
  - Avoids capital cost and efficiency loss of electricity production
  - Developing technology (35 yrs. old, never deployed)
  - Efficiencies to ~50%

. . . cost will determine the best approach(es)

Sulfur-Iodine Thermo-chemical Cycle Is Well Suited to Nuclear Production of H_2

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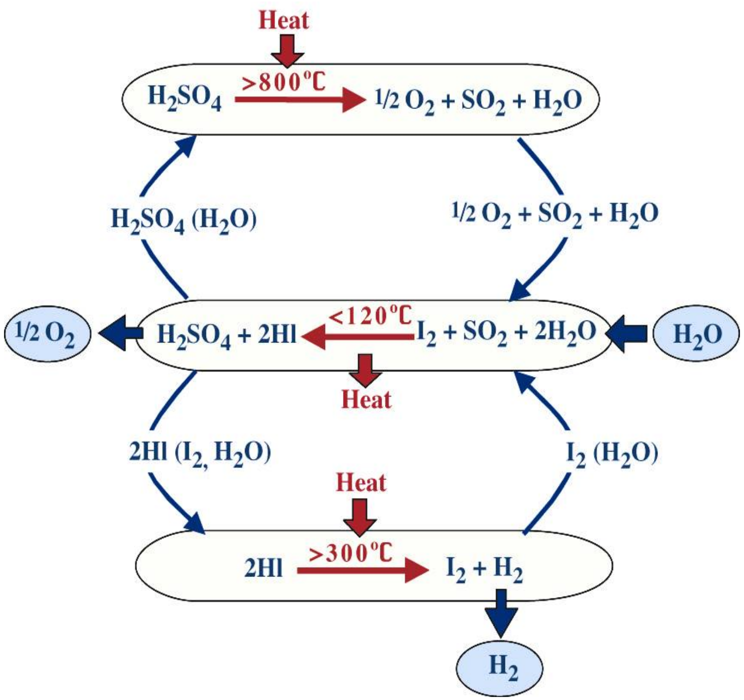
Nuclear Hydrogen

- Invented in 1970's
  - Chemistry reactions demonstrated
  - Laboratory scale test in Japan successful
- Advantages
  - All fluid process, chemicals all recycled
  - H_2 produced at high pressure & (potential) 50% efficiency
- Challenges
  - High temperature, >800°C
  - Suitable materials
  - Next step: closed-loop demonstration under prototypical conditions



- S-I is on the scale of an oil refinery
  - Refineries like Chevron's El Segundo (~5 M gallons gas) inputs ~37,000 t/d of crude oil and 600 t/d H_2 from NG
  - S-I plant (2400 MW_t) inputs ~8000 t water per day and outputs 800 t/d of H_2 (725,000 gallons gasoline equivalent)

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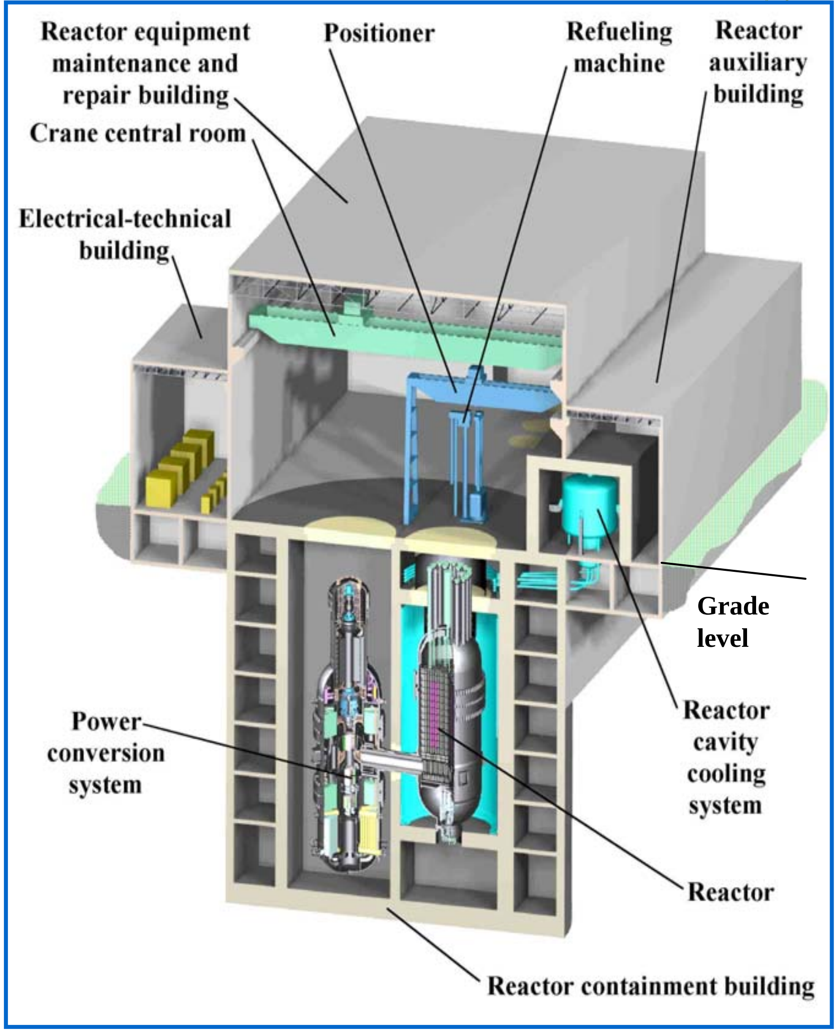
The GT-MHR is Well-Matched to the S-I Process

- **Inherent passive safety**
  - Inert He coolant
  - Low power density (~6 W/cc)
  - Refractory TRISO fuel (high-T, secure nuclear by-products & waste-form)
  - Graphite reactor core (high-T stability & slow thermal response)
- **High coolant T's, 850 - 950°C => 1000°C**
  - With gas turbine at 850°C, electricity at 48% efficiency
  - With S-I at 950°C, H_2 at 52% efficiency
  - High efficiency to reduced cost and waste
- **Proliferation & sabotage resistance**
- **Multiple fuel cycles**
  - U, Pu, Th, LWR spent fuel
  - Up to ~750,000 MW-d/t



Nuclear S-I Hydrogen Can Be Economic at Current Natural Gas Prices

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- SMR of NG
- SMR with carbon tax
- Nuclear S-I

Note: $1/kg = $7.44/MBtu

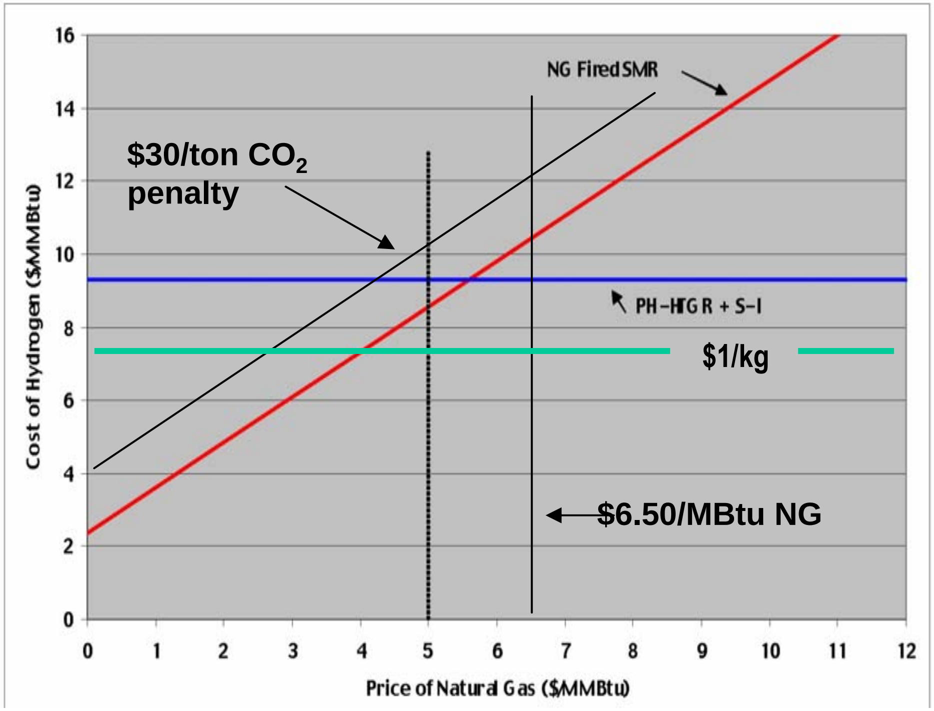

Figure courtesy of EPRI
$1000/kW$_e$, $20/ton O_2 credit, no CO_2 penalty
Regulated utility capital cost rates used, 12.6% CRF

.... and CO_2 Emission-Free

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DOE NGNP (Next Generation Nuclear Power) Plan is to Demonstrate Nuclear Production of H_2 at INL

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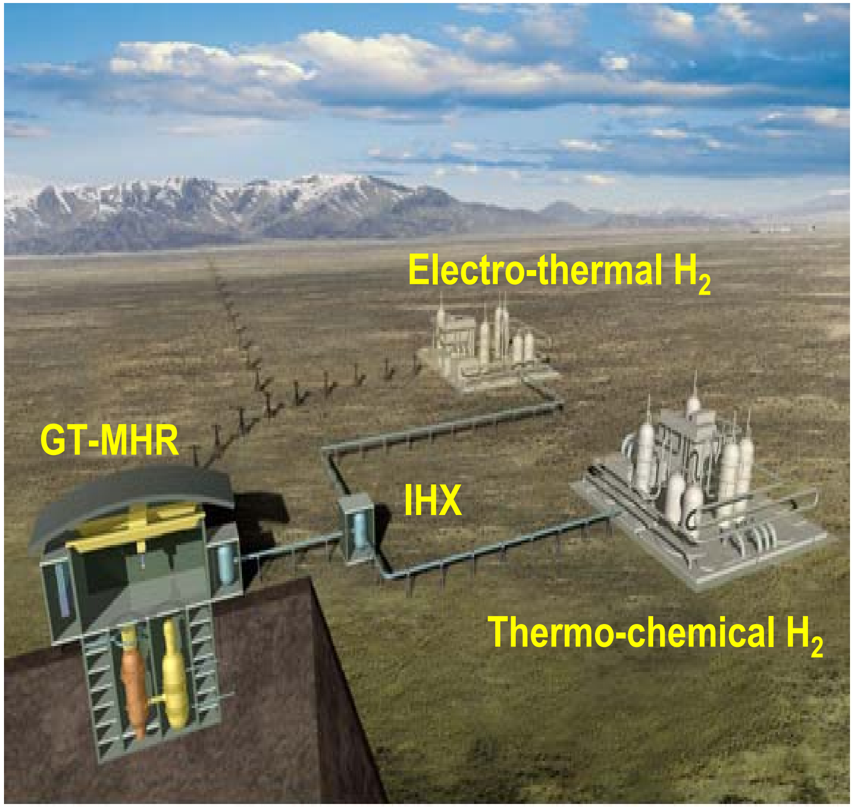

The time scale to commercialization necessitates governmental support

- **Hydrogen production to 60 MW_t**
  - **Allow smooth transition between 100% electricity and 90% electricity/10% hydrogen**
  - **Up to 20 t H_2 per day**
- **Safe reactor/hydrogen interface**
- **Hydrogen purity**
  - **Tritium release below NRC and EPA limits**
  - **Radioactivity < 10CFR20 limits**
  - **Meet fuel-cell standards**
- **Provide basis for commercialization**

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Summary and Conclusions

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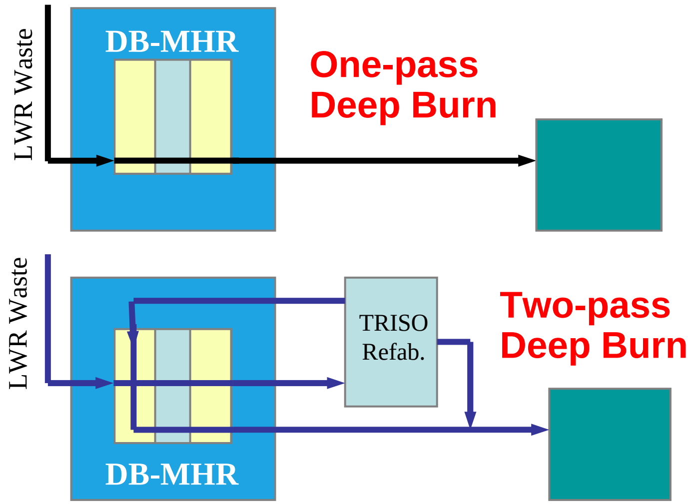
- The H_2 economy will require significant new sources of power.
  - 1.6 TW for transportation alone
- Nuclear power appears to be the only energy source available to reap the environmental advantages of hydrogen-based fuels. However, the time scale and state of development of nuclear H_2 necessitates government lead through demonstration.
- Progress towards a full hydrogen economy will be made *via* a series of technologically manageable, cost competitive steps that exploit prevailing infrastructure.
  - Take an evolutionary approach to a revolutionary goal
- Within this approach, centralized nuclear power can play important near-term roles for both chemical and transportation uses of hydrogen.

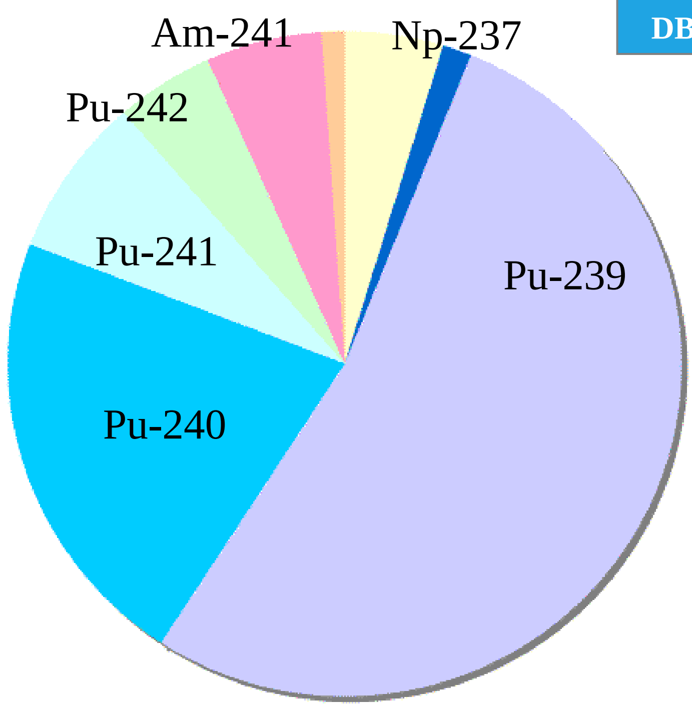
Backup

Substantial Destruction of Transuranics Achieved in Deep-Burn MRSs

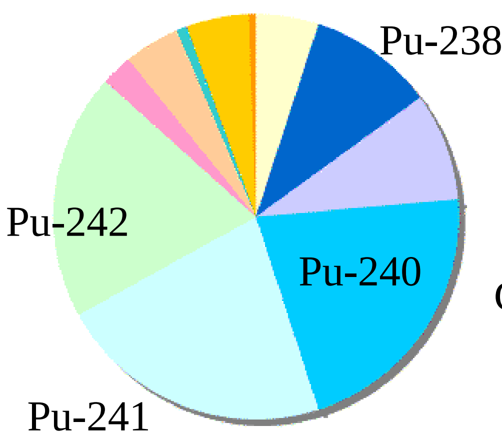


	from LWRs	DB-MHR 1P	DB-MHR 2
Np-237	4.81%	1.98%	0.17%
Pu-238	1.39%	3.94%	3.89%
Pu-239	53.00%	3.46%	0.64%
Pu-240	21.50%	8.46%	0.40%
Pu-241	7.79%	8.66%	0.44%
Pu-242	4.72%	7.92%	4.43%
Pu-243	0.00%	0.00%	0.00%
Pu-244	0.00%	0.00%	0.00%
Am-241	5.67%	0.97%	0.03%
Am-242	0.02%	0.01%	0.00%
Am-243	1.04%	1.74%	1.37%
Cm-242	0.00%	0.32%	0.06%
Cm-243	0.00%	0.01%	0.01%
Cm-244	0.00%	1.98%	6.13%
Cm-245	0.00%	0.20%	0.53%
Cm-246	0.00%	0.02%	0.35%
Cm-247	0.00%	0.00%	0.01%
Cm-248	0.00%	0.00%	0.00%
	100.00%	39.70%	18.50%

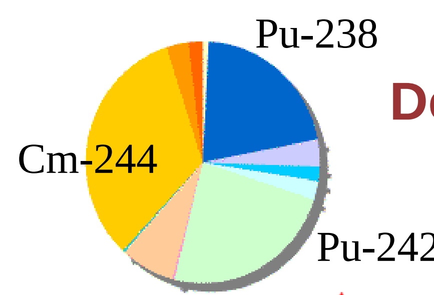
LWR spent fuel actinides



Deep Burn 1 Pass



Deep Burn 2 Pass



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