A Compact Transportable Nuclear Power Reactor

Can be rapidly deployed to remote locations to support oil recovery, disaster relief and basic infrastructure

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Outline

- Motivation for Deployable Reactors
- Requirements (weight, fuel, safety)
- Two Designs based on fuel type, system weight and overall safety
- Applications
- Summary

Conventional Nuclear Power is…

BIG

BIG > 1000 MWe, **$7bn,** nuclear power plants dominate the headlines and the debate.

These projects, involve reactors that produce thousands of megawatts of electric power and require many billions of investment dollars.

Opponents question the safety of various designs.

- Disadvantage
  - High Capital Cost
  - > 48 to 96 Months License and Construction Time
  - 60 year plant life
- **Advantages**
  - **Cost effective (license, siting)**
  - **Economy of scale**
  - **Reliable base power**
  - **Nuclear is CLEAN POWER (No CO2)**

What are the Constraints on Realistic *Deployable* Nuclear Power Systems

- Based on Well Developed Nuclear Technology
  - Developing and certifying now nuclear fuels and coolant/power systems takes many years.
- Use Non-Weapons Grade Nuclear Fuel
  - Maximum enrichment of 20%.
- Safe and Easy to Operate
  - Complete containment of all radioactivity in fuel – no releases to environment.
- Able to be Rapidly Deployed to and Removed from Operating Sites
  - Minimal field construction required.
  - Deployable by existing ground and/or air transport systems.
  - Radiation exposure to operators, handlers, and transport personnel must be acceptable.
- Power Output Capability of at Least 10 MW(e) per Modular Unit
  - Larger power output capability desirable for certain applications.

Deployable Electric Energy Reactor (DEER)

DEER Reactor System

- Modular
- Rapidly Deployable to Remote Locations
- Quickly Removable if Required

Process Steam and Heat for Industry

Extraction of Oil from Oilands, Etc.

Micro-Grid System for Civilian Power

More Robust System for Critical Power Needs for Civil Sector

Disaster Relief

Provides Emergency Power to Areas Hit by Severe Storms, Tsunamis, Earthquakes, etc.

Electric Power and Heat for Remote Settlements

Provides Continuous Power and Heat for Remote Settlements in Alaska, Canada, Islands, Etc.

Power, Water, Etc. for Poor Nations

Provides Power, Water, Fuel & Fertilizer for Poor Populations in Africa, Etc.

Small Nuclear Power Systems Currently Under Development or Proposed

- “Small” is a flexible term depending on developer/proposer.
- Output of designs range from 10 MW(e) up to ~ 300 MW(e).

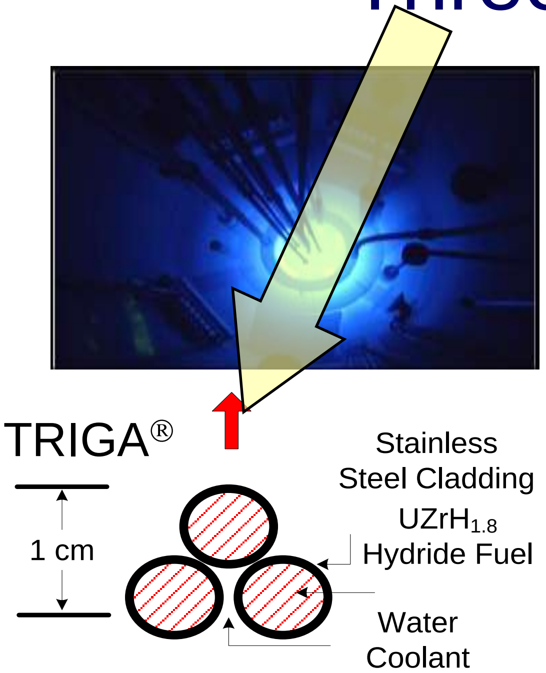
- Demands above 50 MW(e) could be met by multiple units.
- Development is being carried out world-wide.
- U.S. programs for small [~ 50 MW(e)] reactors are only proposals – not in development stage.

- None of the current “small” proposed or under development systems are transportable.
- All operate at a fixed site and require extensive field construction.

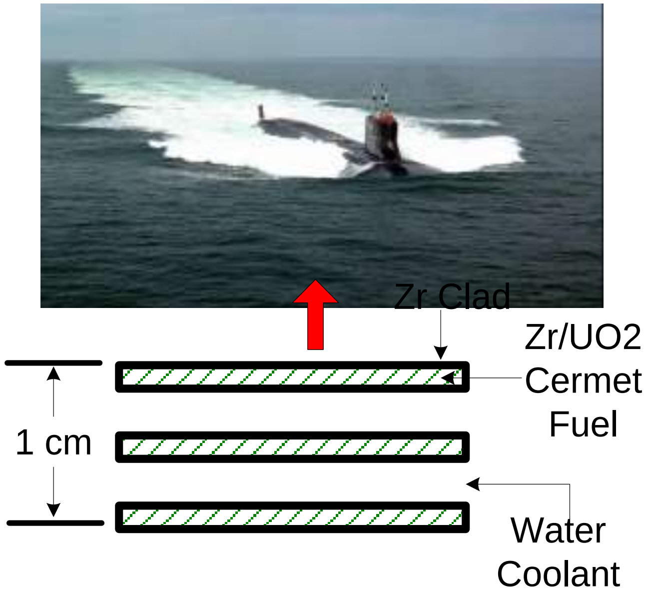
List of "Small" [≤ 50 MW(e)] Nuclear Power Systems Currently Under Development or Proposed

	Reactor	Type	Power Level	Country	Status	Siting
1.	CAREM	PWR	27 MW(e)	Argentina	Under Development	Ground
2.	KLT – 40S	PWR	35 MW(e)	Russia	Developed	Barge
3.	ABV – GM	BWR	18 MW(e)	Russia	Under Development	Ground or Barge
4.	MRX	PWR	30 MW(e)	Japan	Under Development	Ground or Ship
5.	RS – MHR	HTGR	10 – 25 MW(e)	U.S. (GA)	Proposed	Ground
6.	4S	LMR	10 – 50 MW(e)	Japan & U.S. (Westinghouse)	Under Development	Ground
7.	SSTAR	LMR	10 – 50 MW(e)	Japan & U.S. (Argonne)	Under Development	Ground
8.	ENHS	LMR	50 MW(e)	U.S. (U. of Cal)	Proposed	Ground
9	NuScale	PWR	45MW(e)	U.S.	Proposed	Ground
9.	Hyperion	U-Hydride Fuel-Coolant Not Specified	10 MW(e)	U.S.	Proposed	Ground

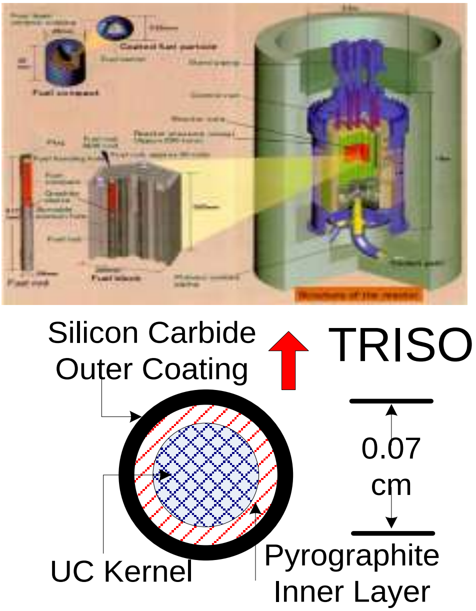
Three Nuclear Fuel Options



- Used in dozens of research reactors around the world for decades.
- Extremely safe – automatically shuts down when control rods are pulled out.
- $UZrH_{1.8}$ hydride fuel can withstand high temperatures.
- Zero release of fission products.



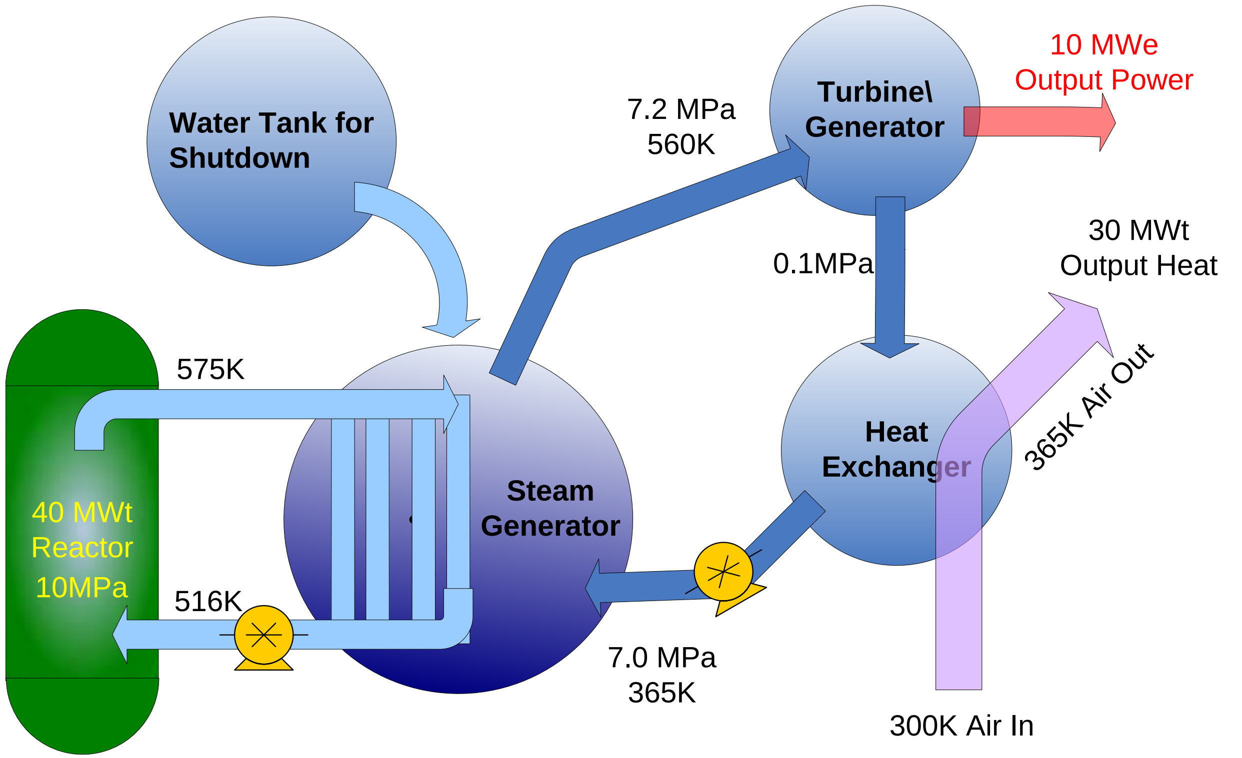
- Used in 100's of reactors operating around the world for decades.
- UO2 particles dispersed in Zr metal matrix.
- Fuel is very tough and rugged.
- Operates to high burnings with Zero release of fission products.



- Used in high temperature graphite reactors for decades.
- TRISO particles imbedded in graphite blocks or potable.
- Normally helium cooled. In DEER, TRISO. Particles would be water cooled.
- Operates to high temperature with Zero release of fission products.

TRIGA® Fuel Selected for Baseline DEER System

- TRIGA® Reactors Operate at Many Locations Worldwide
- Have operated safely for decades and 1000s of reactor years
- Perceived as Safe, Reliable and Simple to Operate
- Automatic, Safe Shutdown from Large Reactivity Insertions

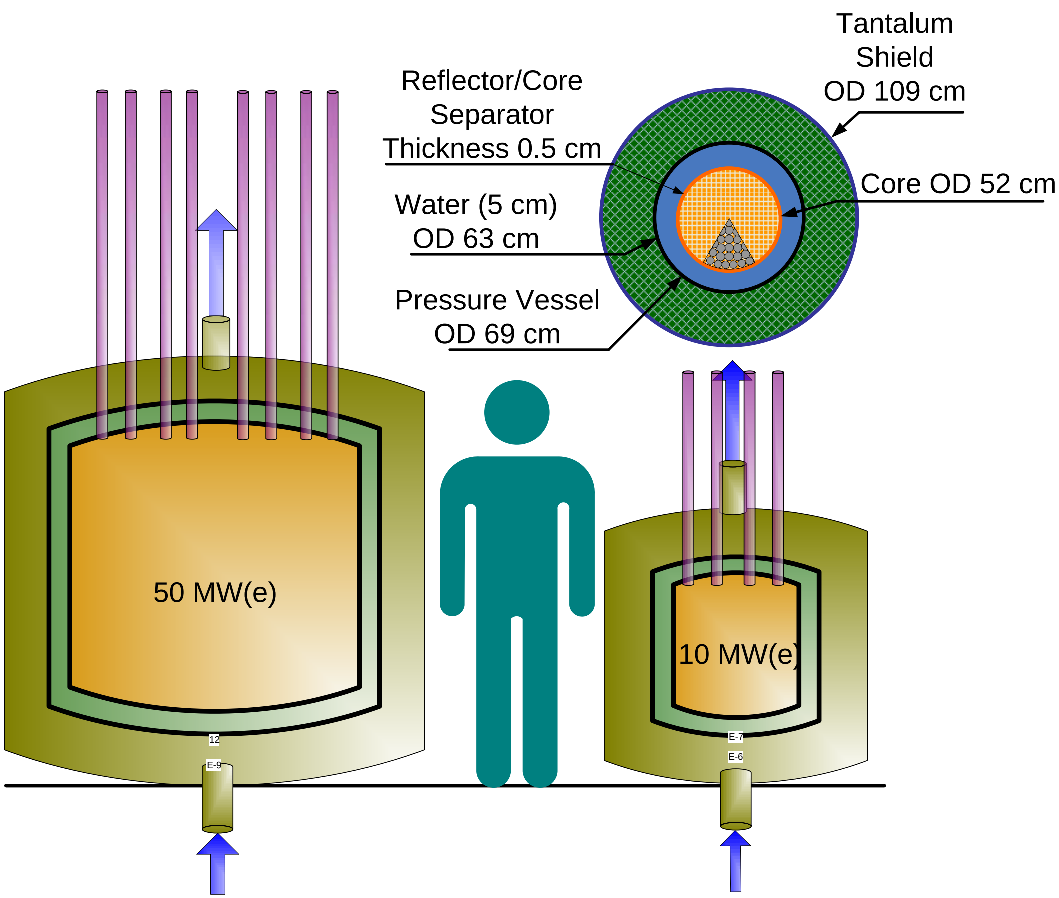


- Excellent Retention of Fission Products
- Non-Weapons Grade Fuel 20% Enriched,
- Minimal Testing of TRIGA® Fuel required for DEER System

DEER

deployable electric energy reactor

2078 fuel elements in 10 MWe unit



40 metric ton

14 metric ton

- Reactor Neutronic Performance is Predicted with High Accuracy using 3D Monte Carlo Codes and Detailed Representation of 3D Geometry
  - MCNP Code Calculates Initial Reactor Criticality, Power Distribution, Control Rod Effectiveness, etc.
  - MonteBurns Code Provides Fuel Burn up, Criticality, Control, and Power Distribution over Expected Operating Period
- 3D MCNP Code Determines Shielding Requirements for:
  - Operation at Full Power
  - Transport of Shut-Down Reactor
- Reactor Thermal-Hydraulics is Accurately Calculated using standard Heat Transfer Codes

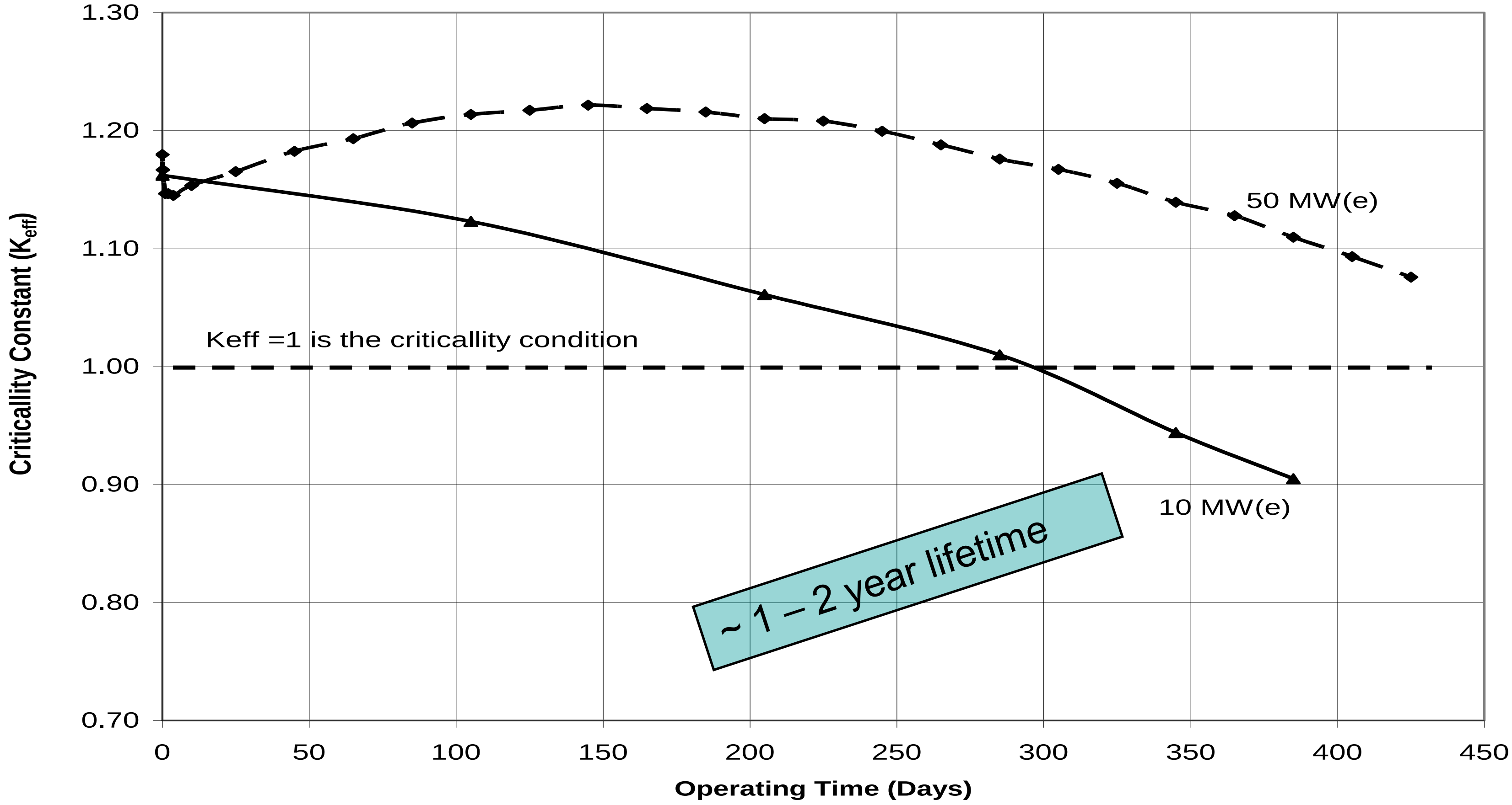
DEER (TRIGA® Fuel) Reactor Parameters

Thermal Power (MWt)	**200**	**40**
Electric Power (MWe)	**50**	**10**
Cycle Efficiency	**25%**	**25%**
Reactor OD(cm)	**124**	**63**
Module OD (cm) (20 cm thick tungsten shield)	**174**	**109**
Core OD, cm	**120**	**53**
Core Length (cm)	**120**	**60**
Fuel Element Diameter (cm)	**1**	**0.9**
Fuel Elements in Core	**5149**	**2078**
Uranium in UZrH1.8 Fuel (Wt. %)	**30**	**30**
Uranium in Core, kg (20% U-235)	**226**	**37**
Weight w/Fuel, metric tons	**7.4**	**1.3**
Module Weight w/Tungsten Shield, metric tons	**40**	**13**

Comparison of GA Research and DEER TRIGA® Reactors

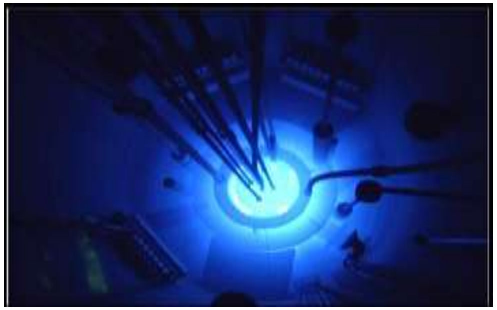
Component	TRIGA® Research Reactor	TRIGA® DEER REACTOR
Nuclear Fuel	$UZrH_{1.8}$ Fuel, 1 cm Diameter Fuel Elements	Same
Coolant Type	Water	Same
Coolant Pressure and Temperature	1 atm, < 100°C	100 atm, 300°C
Peak Power Density in Fuel Elements	400 megawatts per liter	0.8 megawatts per liter
Peak Temperature Inside Fuel Element	1200°C	700°C
Type of Operation	Thousand of Pulses per Year	Steady State

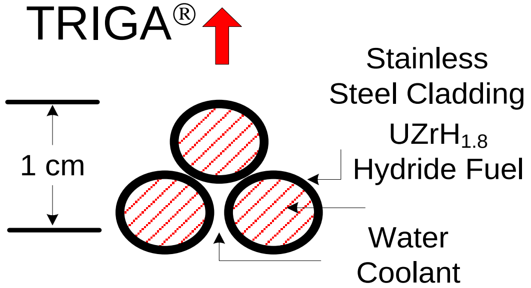
K_{eff} vs. Operating Time for DEER with TRIGA® Fuel at 10 MWe and 50 MWe Output.



In operation, the reactor control rods are used to control K_{eff}

Three Nuclear Fuel Options





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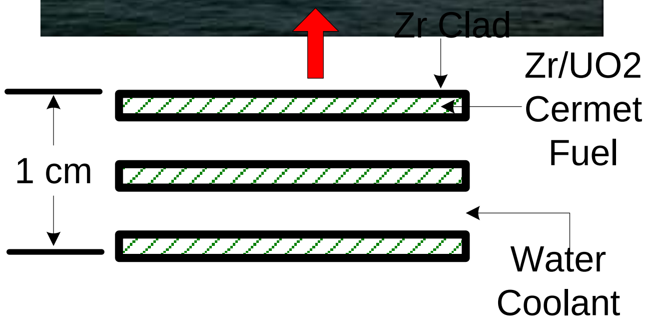

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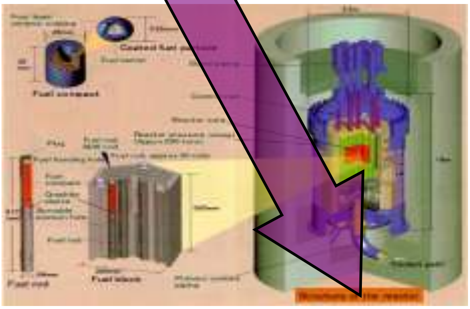

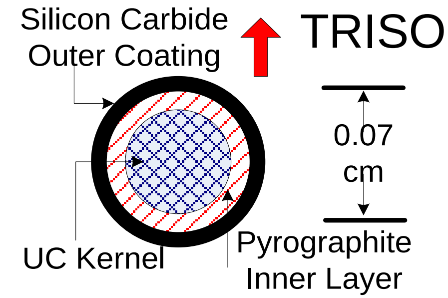

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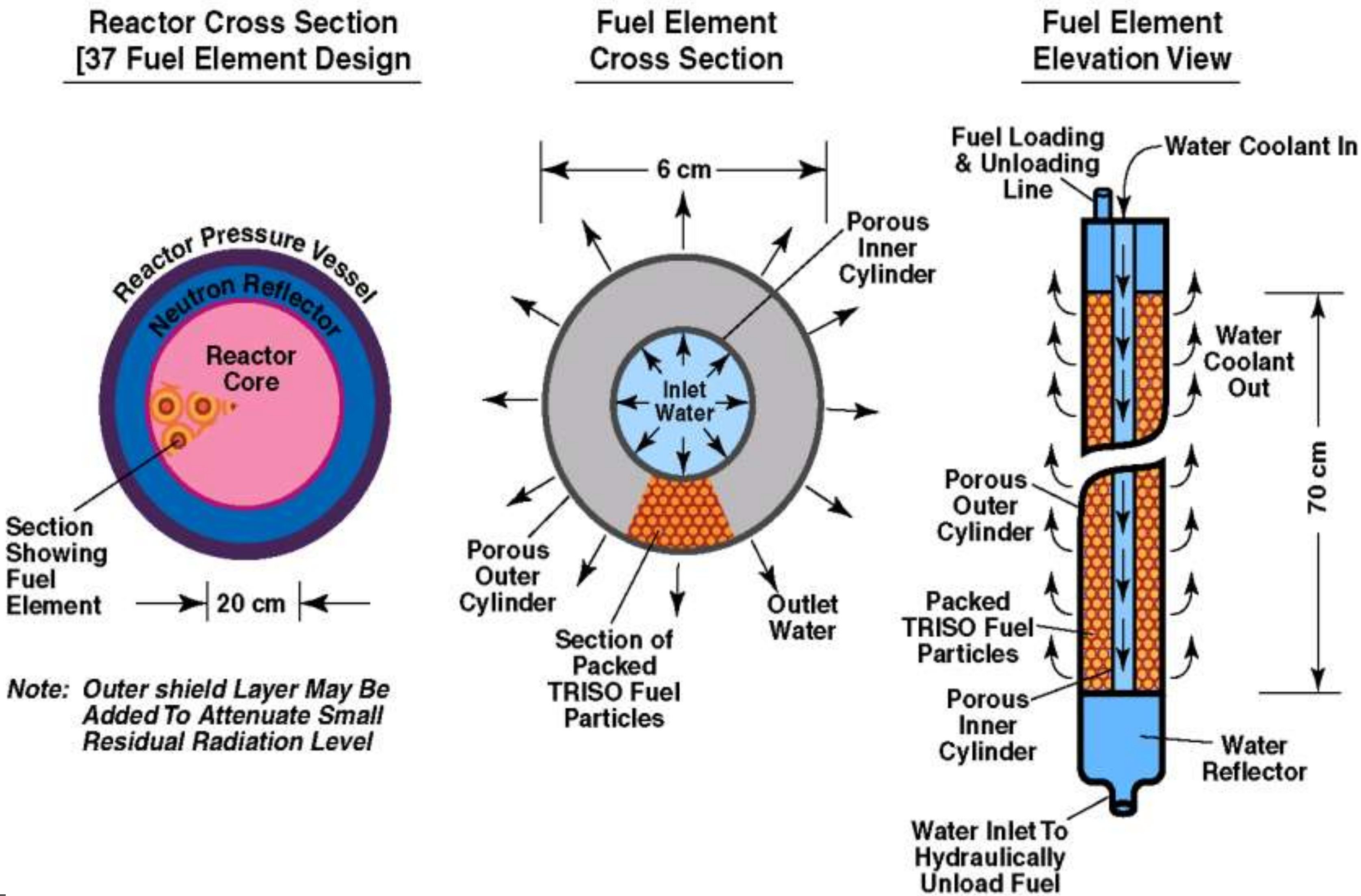
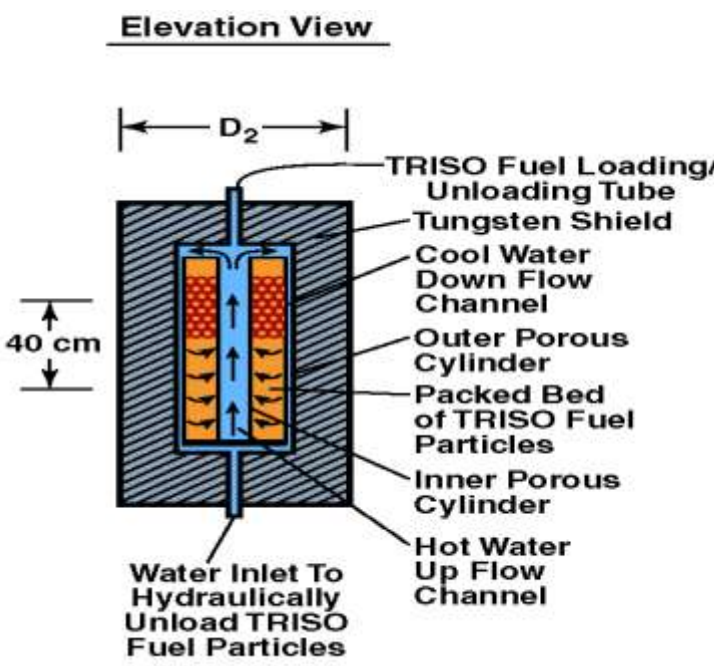
TRISO Fuel Selected for Advanced DEER System

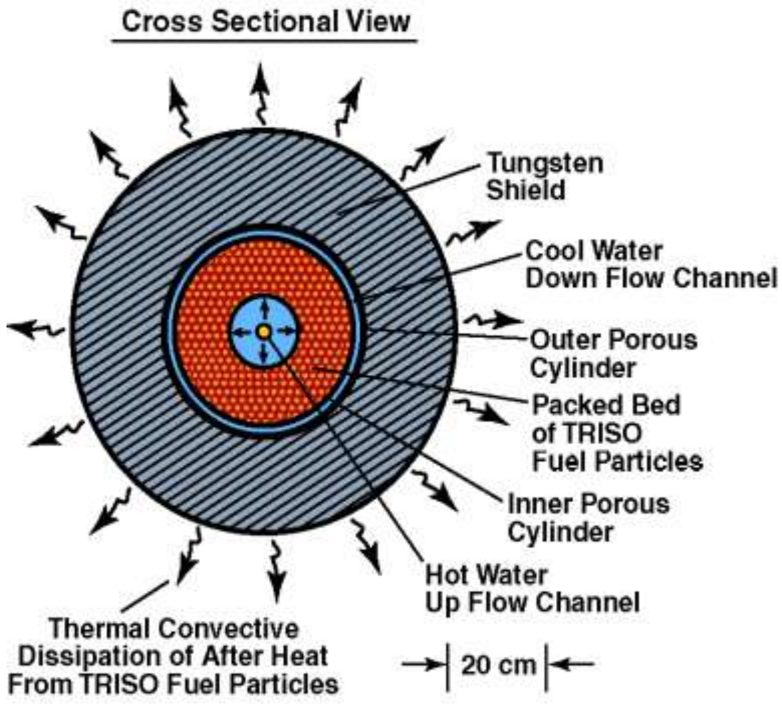
- TRISO Fuel Enables very Compact, very Lightweight, High Power Advanced DEER Reactor Systems
  - Packed Beds of **TRISO Fuel Particles** would be Directly Cooled by Water
  - Core Power Densities can be >> 1 MW(th)/Liter
- TRISO Particles can be Hydraulically Loaded into, and Unloaded from, DEER Reactors
  - Spent Fuel Particles transferred to Small Transport Cask in a Few Hours and Rapidly Transported away from Site
  - After TRISO Particles are Removed, Residual Radioactivity in Reactor System is Much Less
  - Reactor can be Re-Loaded with Fresh, Non-Radioactive TRISO® Particles, or Removed from Site
- TRISO Particles Have Excellent Retention of Fission Products

DEER Advanced Reactor Using Hydraulic Loading/Unloading of TRISO Nuclear Fuel Particles



10 MW(e) Advanced DEER-2 System Transport Cask





TRISO® Fueled DEER Reactor Parameters

Based on Fuel Elements with Hydraulically Loaded/Unloaded TRISO Particles

TRISO Reactor Parameters	***DEER-10***	***DEER-50***
Thermal Power (MW)	40	200
Cycle Efficiency (%)	25	25
Reactor OD (cm)	65	92
Core OD (cm)	45	71
Reactor Core Length (cm)	100	176
# of Fuel Elements in Core	37	91
Fuel Element OD (cm)	6	6
Thickness of TRISO Bed in Fuel Element (cm)	1.45	1.45
Avg. Power Density in TRISO Bed MW(th)/liter	0.78	0.78
Initial U-235 Loading in Core (kg)	14.6	73
50% Burnup Lifetime (months)	6	6
Weight of Reactor including Fuel (metric tons)	**1.25**	**4.5**

Unique Market Sectors

- Military and National Security
  - Domestic Military Bases
  - Forward Operating Bases
  - Overall Grid Vulnerability
- Process Heat
  - Chemical/Industrial
- Commercial Power
- Power for Remote Locations
- Potable Water, Desalination, Fertilizer
- Oil Recovery

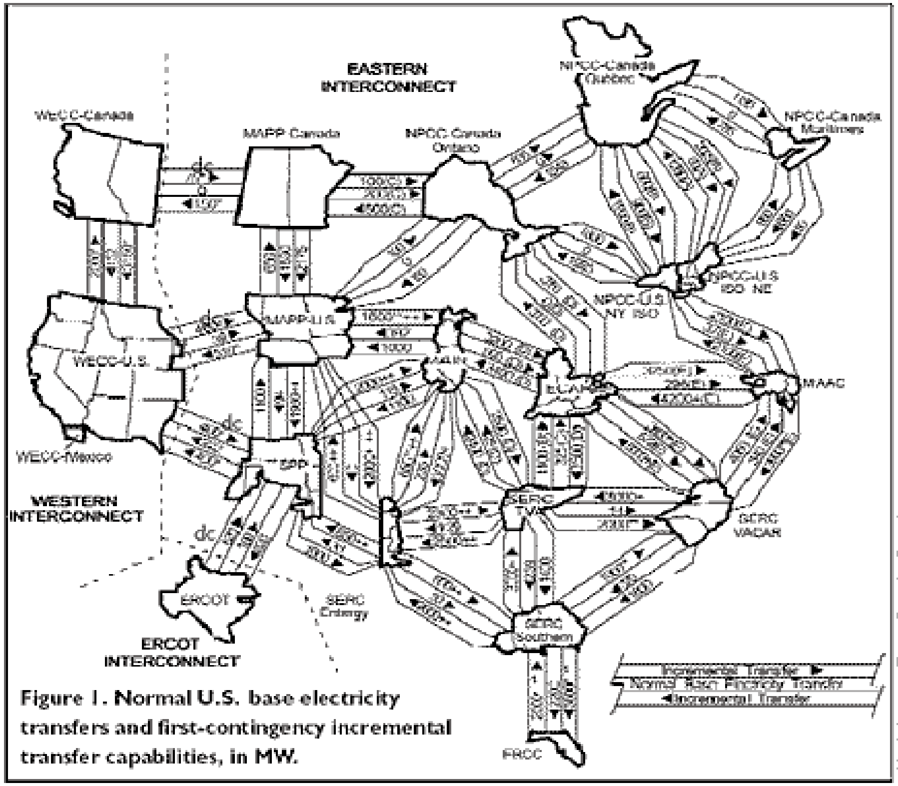
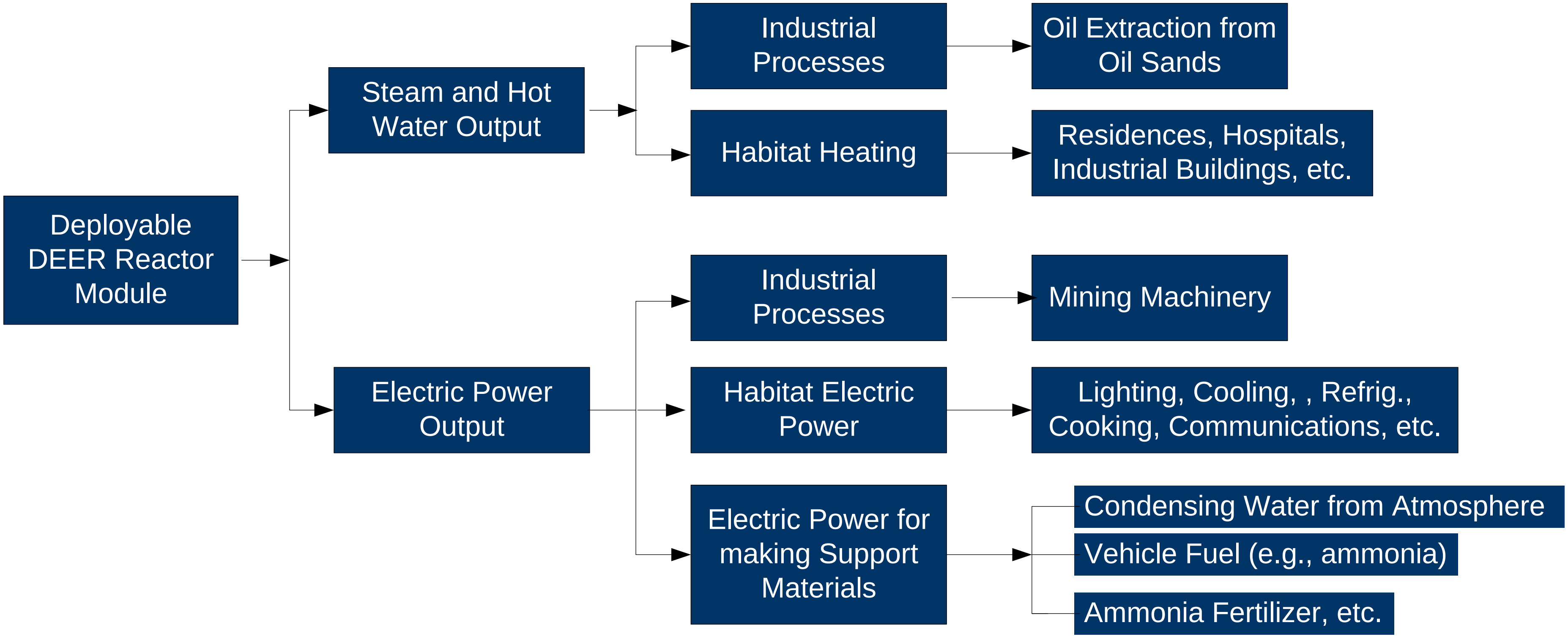
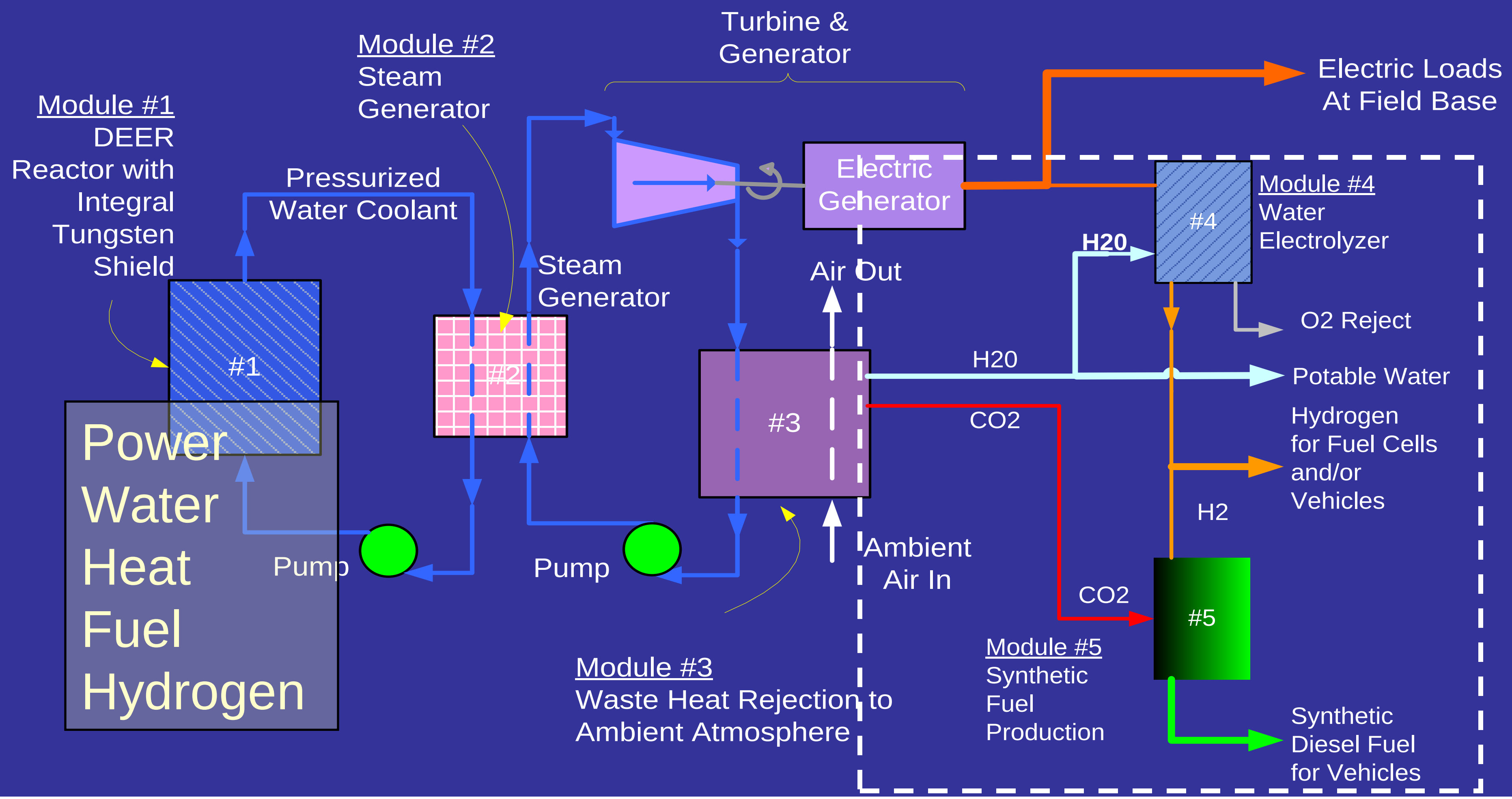


Figure 1. Normal U.S. base electricity transfers and first-contingency incremental transfer capabilities, in MW.

DEER Applications



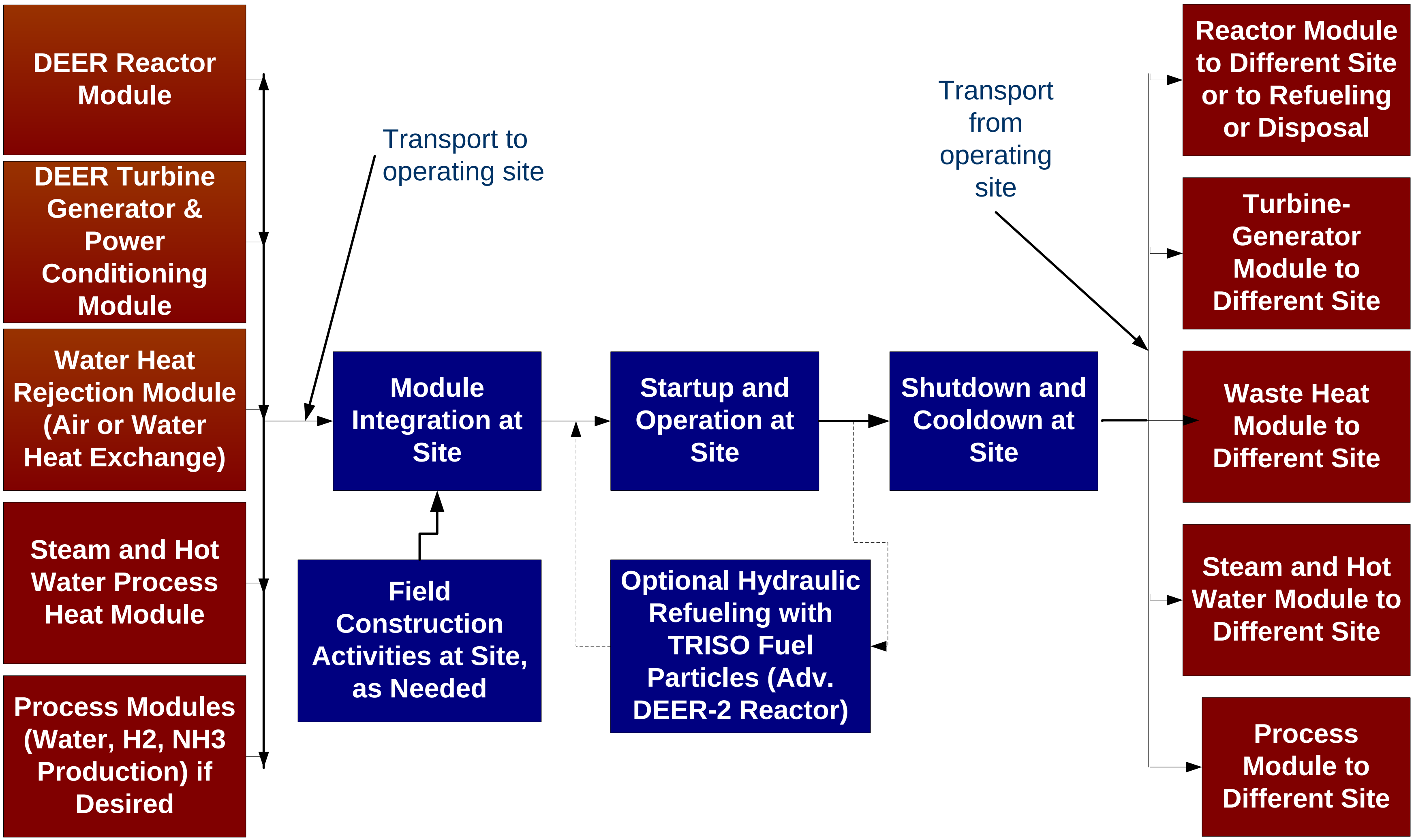
Functional Processes for Fuel and Power Generation Using the Compact DEER Deployable Reactor System



The Product Add-Ons

Production	10 MW(e)	50 MW(e)
JP-8 Fuel	3,000 gallons per day	15,000 gallons per day
Potable Water [40°C, 23% humidity atmospheric conditions in Iraq]	430,000 gallons per day*	2,150,000 gallons per day*

DEER Installation and Removal

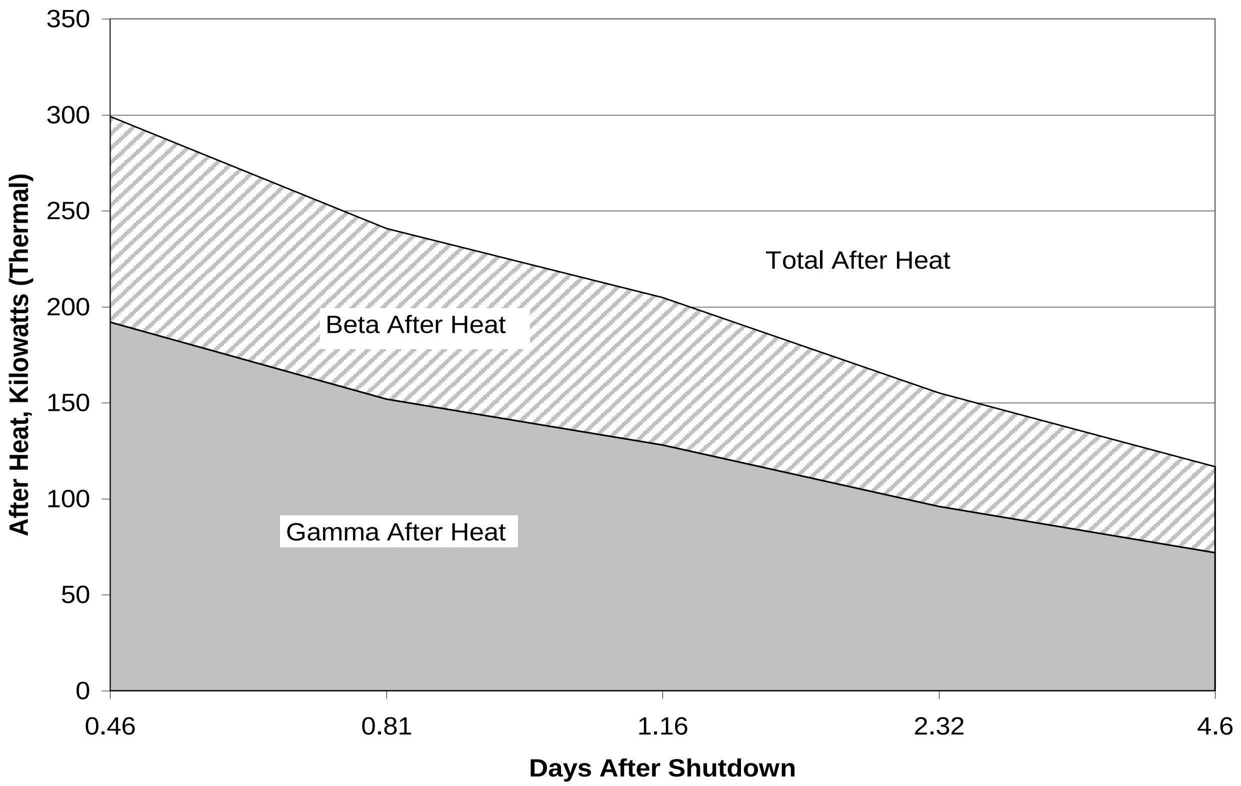


Thermal Afterheat

thermal power following shutdown for the 10 MW(e) DEER reactor

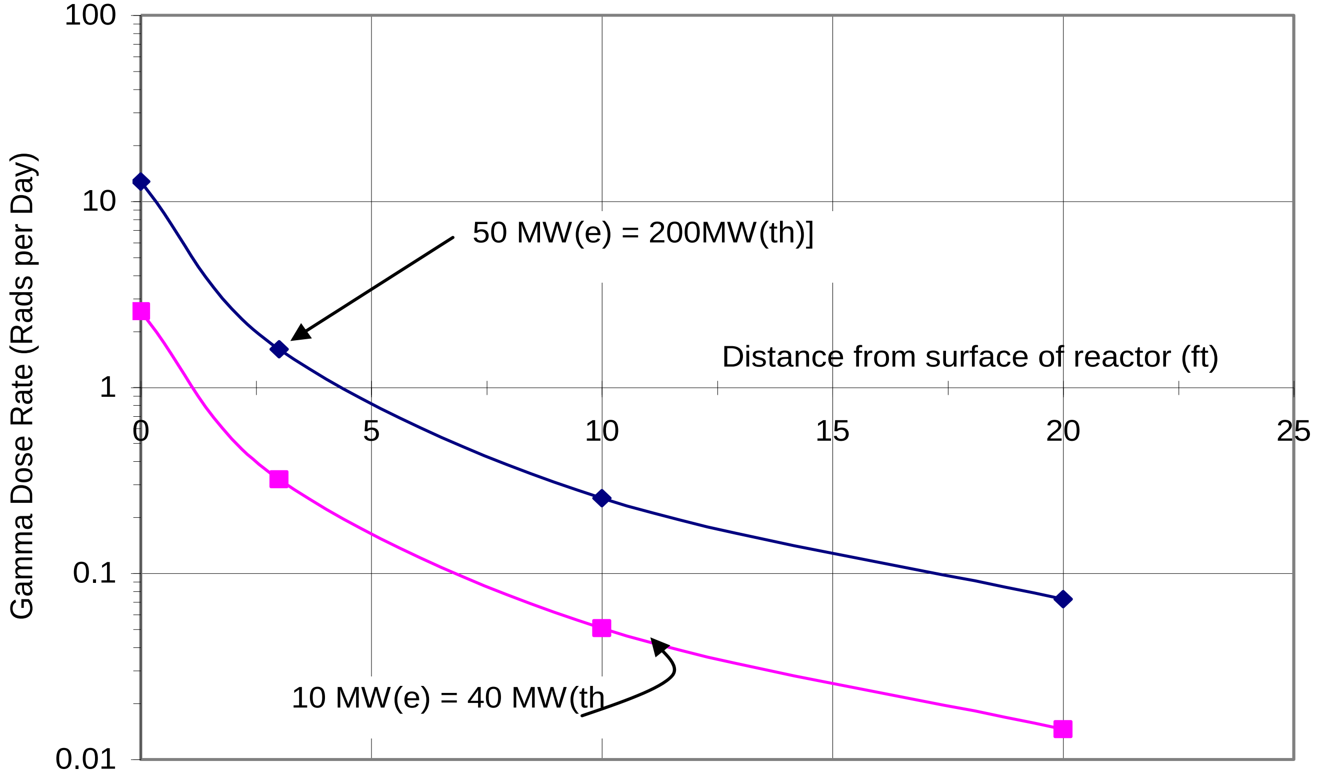
Two days after shutdown, the thermal power is 150 kilowatts, about 0.3% of the 40 megawatts generated at full power.

Approximately one-third is from short range beta particles, which stop inside the reactor, and two-thirds is from gamma photons, which require shielding



Gamma Dose Rate

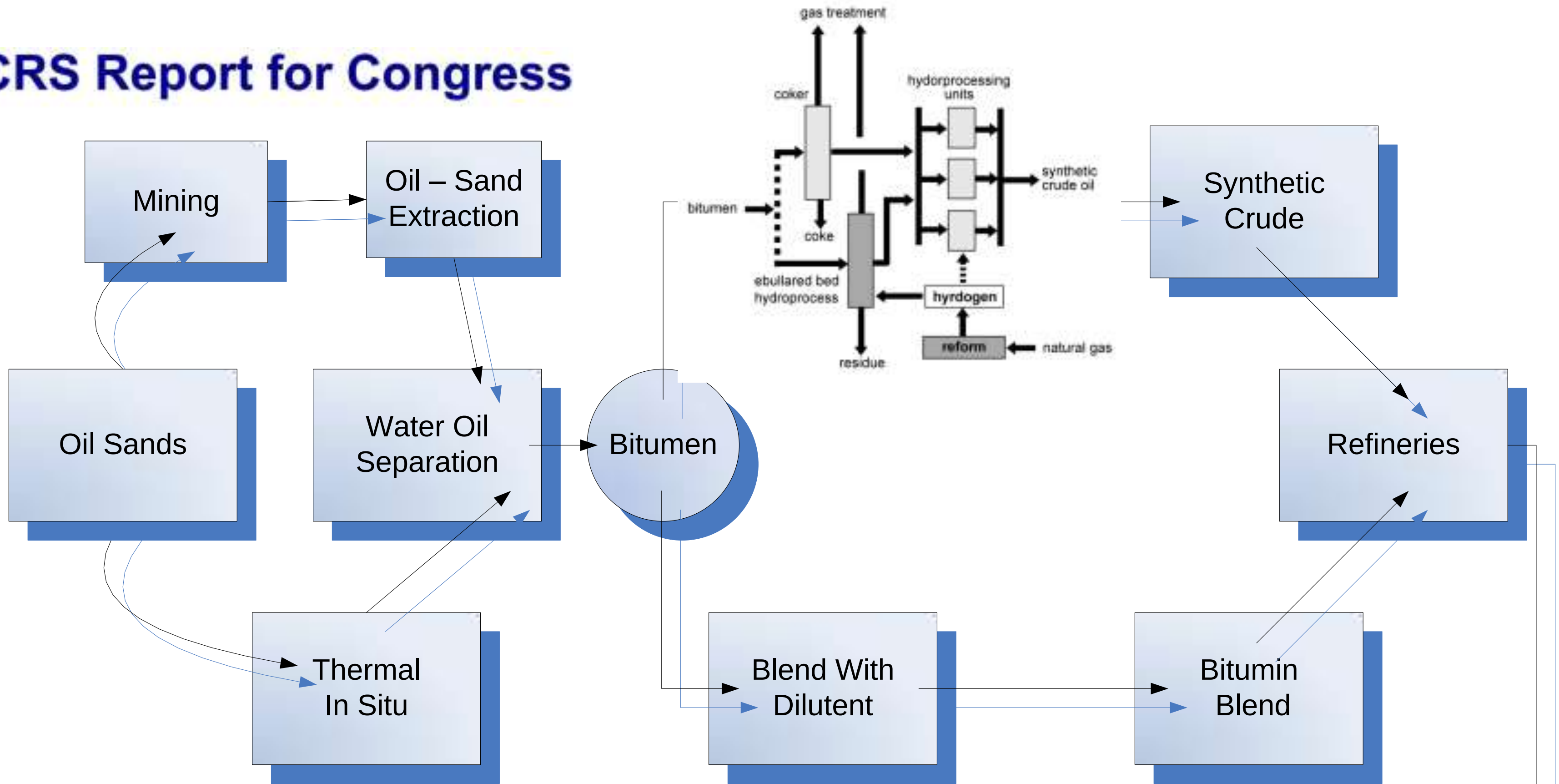
Gamma dose rates after 1000 hours of operation as a function of the distance from the surface of the reactor. Calculation is based on a 20 cm thick tungsten shield with **2.3 days after reactor shutdown**. The gamma attenuation factor inside the reactor is assumed to be 10:1

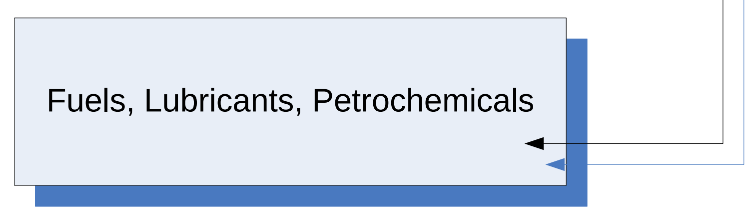


Maximum permissible dose is 5 rem per year

Oil Sands Processing Chain

CRS Report for Congress





North American Oil Sands: History of Development, Prospects for the Future
Marc Humphries, Analyst in Energy Policy Resources, Science, and Industry Division
Updated January 17, 2008

Role of DEER in Oil Recovery

DEER reactors can supply either :

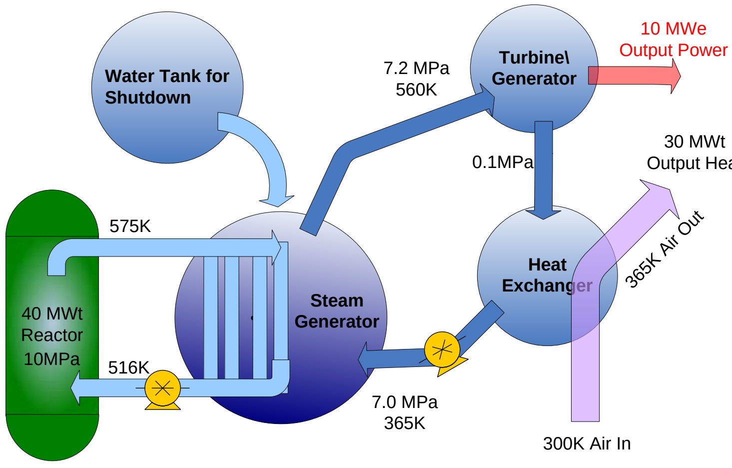
(A) steam and hot water;

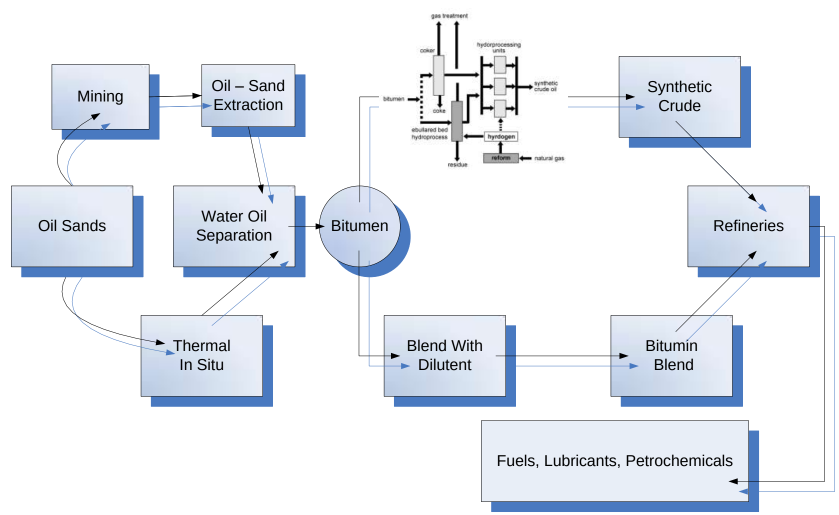
(B) steam, hot water, and electrical power; and

(C) electrical power only

Percent caloric value of operations as % of synthetic crude energy	Mining	Extraction	Coking or Extraction /Coking	Hydro-treating	Total
Process Options	**Surface Mining**				
1 Hot Water	10	13	7	10	40
2 Direct Coking	10	--	15	10	35
	In Situ Recovery				
3 Steam Flooding	--	26	7	10	43
4 Combustion	--	--	13-25	10	23-35

Probstein and Hicks, "Synthetic Fuels", Dover, 2006





DEER option B offers a low cost way to make hydrogen for hydrotreating. The turbine exhaust pressure is set relatively high, e.g., above 1 atmosphere, which results in steam and hot water for options 1 and 3 in processing the oil sands, while still enabling the generation of substantial amounts of electric power to be used for electrolyzing water to make hydrogen.

Summary

- Safe compact deployable 10 to 50 MWe reactors with integral radiation shield can be prebuilt and transported to and from locations where and when they are needed.
- Two designs are presented that differ in type of fuel, fuel handling and overall system weight.
- Applications are
  - Military
  - Industrial
  - Humanitarian
  - Dedicated industrial process heat and electric
  - Off grid power applications