COMPACT, TRANSPORTABLE NUCLEAR POWER SYSTEMS FOR RAPID DEPLOYMENT TO REMOTE LOCATIONS FOR INDUSTRY, OIL RECOVERY, MUNICIPALITIES AND DISASTER RELIEF

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Abstract

Very compact multi-megawatt nuclear reactor systems utilizing well developed commercial fuel, capable of rapid transport by truck or airplane to remote locations, are described. The reactor design can provide electric power and process space heat for many different purposes, including extraction of oil from oil sands, remote settlements, natural disaster emergencies, electrical grid stabilization, and developing countries. Reactors can also condense large amounts of potable water from the atmosphere, and manufacture vehicle fuel and ammonia fertilizer, using materials from the atmosphere. Designs for 10 and 50 MW(e) reactors are described. At mission conclusion, the shielded reactor can be quickly and safely transported away from its operating site, leaving no radioactivity or structures behind.

1. Introduction

Terrestrial nuclear power has concentrated on two areas – large central station plants, and propulsion of ships and submarines. A few small power reactors have operated in locations like Antarctica. However, the need for power and critical materials in remote locations and less developed countries has sparked interest in small nuclear power systems. They can also provide power to areas hit by hurricanes, earthquakes, tsunamis, and other disasters, and prevent failure of large regional electrical grid systems. Recent studies have focused on outputs from 10 MW(e) to several hundred MW(e).(1,2,3) While smaller than 1000 MW(e) LWRs, they still require large structures constructed in place, and operate for 30 years or more. Some designs are barge mounted, but they would be restricted to coastal, lake, or river regions. This study examines compact modular nuclear power systems that can be rapidly deployed to sites, using existing air and ground transport, to generate electric power, process heat for oil extraction, condense fresh water from the atmosphere, and manufacture fuel, fertilizer, and other needed materials. The reactor may operate for long periods, e.g., years, or short periods, e.g., months. At mission completion, the shut-down reactor is quickly and safely transported away. The reactor could also stay in place to generate power if an emergency occurs. These reactor systems are based on existing commercial nuclear technology. A baseline near term system using TRIGA nuclear fuel and an advanced, longer term system using TRISO particle fuel are described below.

2. Potential applications for compact, readily deployable reactor systems

Figure 1 illustrates five important applications for the DEER (Deployable Electric Energy Reactor) system. The first application is the supply of steam, hot water, and electric power for the extraction of oil from oil sands. Oil sands are a very large resource base for production of synthetic crude oil. The world's identified resources of crude bitumen are about 360 billion cubic meters[4], equivalent to over a trillion barrels of synthetic crude oil product, with 150 billion cubic meters in Canada. These recovery processes require an energy output of approximately 40% of the final synthetic crude calorific value for the various operations – mining, extraction, coking, and hydrotreating – to obtain the final synthetic oil product. This energy input comes from additional bitumen or natural gas. Using low cost thermal energy from DEER deployable reactors, instead of fossil fuel energy from the processes (i.e., recovery, extraction, hydrotreating), overall product cost can be reduced and environmental impacts lessened.

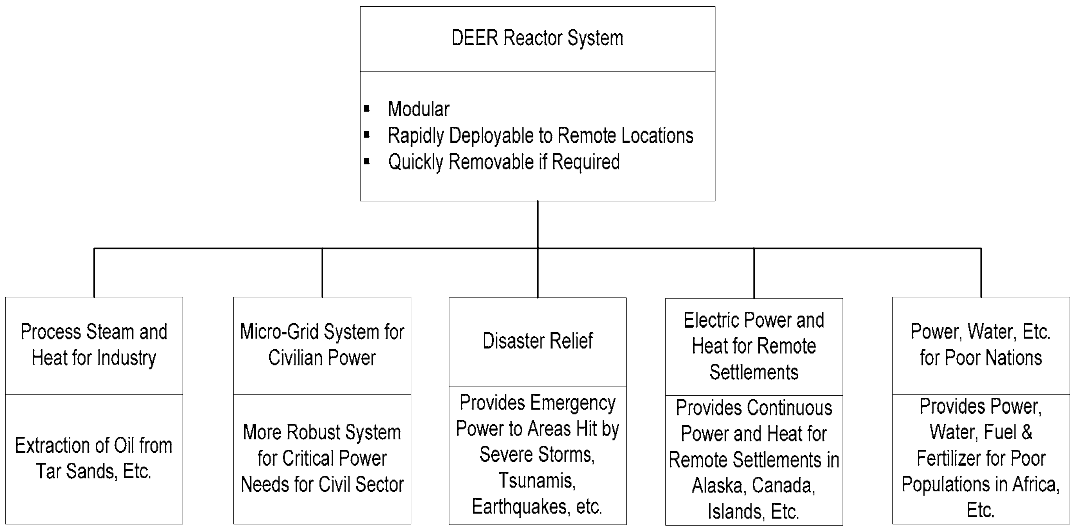

Fig. 1. Applications for DEER (Deployable Electric Energy Reactor) system.

A second application is for backup power if the main electrical grid were to collapse. The U.S. electric power grid is a very complex, highly interdependent network of large power plants and long transmission lines. Thousands of megawatts move hundreds of miles back and forth across the U.S. Disruptions have rapidly propagated through the electric infrastructure, causing major portions to fail. On August 14, 2003, a propagating outage from trees falling in Ohio shut off power to millions of people in a few minutes. Power disturbances cost the U.S. economy $100 billion annually, according to EPRI[5]. Recent 2008 Midwest ice storms cut off power to hundreds of thousands of customers for days. Power is usually restored in a few hours to days, since the causes are generally local and non-deliberate. However, terrorist physical attacks on power plants or transmission lines, or cyber attacks on the computer/control network, could shut down the grid for long periods. If much of the U.S. lost electric power for long periods due to terrorist attacks on the grid, or if there were nuclear, chemical, or biological attacks against metropolitan areas, there could be widespread panic, refugees, rioting and lack of food and fuel. Compact nuclear emergency power units could help to maintain social order, even if the grid failed for long periods.

The third application is rapidly deployed emergency power in natural disasters like hurricanes Katrina and Rita, the recent large tsunamis in Indonesia, and the earthquakes in Pakistan. At some point, major earthquakes will strike densely populated California and the Pacific Northwest.

The fourth application is for remote settlements where fossil fuels cost too much or are not available for power generation. Galena in Alaska has been proposed for the 10 MW(e) Toshiba 4S reactor.(1) The 4S system is large and heavy, not rapidly deployable, and requires considerable field construction. It is difficult to remove, and would operate for 30 years. Small, rapidly deployable reactors with minimal field construction appear very attractive in Alaska, Siberia, Canada, etc., for electricity and heat for the inhabitants, mining and industry.

The fifth application is for poor regions in Africa, Bangladesh, India, etc. Local populations there lack power, clean water, fuel for cooking and heating, and fertilizer to grow food. With electric powered dehumidifiers, fresh water can be condensed from the atmosphere. A 10 MW(e) system could produce 300,000 gallons a day of safe fresh water for drinking and irrigation in drought stricken areas. Hydrogen fuel can be produced by electrolysis (Figure 2) for cooking and heating.

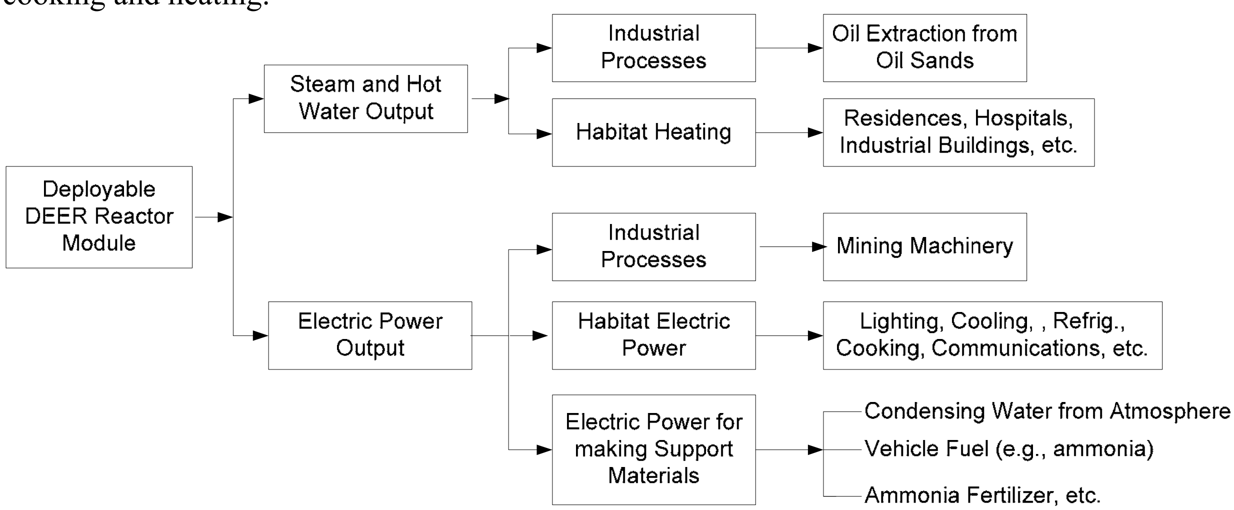

Figure 2. Flowsheet for production of electric power, process heat for extraction of oil from oil sands, fresh water from atmosphere condensation, vehicle fuel and fertilizer at remote or undeveloped locations using the DEER reactor system.

Large regions of Africa are being deforested due to the use of wood and charcoal for cooking and heating. Bottled hydrogen would curtail the need for charcoal and wood. Hydrogen combined with atmospheric nitrogen (Haber process) will produce vehicle fuel and fertilizer for crops. Ammonia can also be used as a practical vehicle fuel. Internal combustion engines based on the Otto or diesel cycle can operate using ammonia fuel with minor modifications. Ammonia fueled vehicles could transport people to schools, hospitals, work, etc. A 10 MW(e) reactor would produce fuel equivalent to 3000 gallons of diesel fuel per day. Ammonia fertilizer would greatly increase crop yields.

3. Application of the DEER reactor system to recovery of synthetic crude oil from oil sands

To recover synthetic crude oil from the bitumen in Canadian oil sands, large amounts of process heat and electric power are required. Table 1, taken from Probstein and Hicks Synthetic Fuels(4) illustrates the energy requirements for four options of recovery as a percent of the calorific value of synthetic crude oil integrated oil sands plants, as derived mainly from Canadian experience. The four options are: 1) mining bitumen with subsequent hot water extraction; 2) mining with coking; 3) in situ with steam flooding; and 4) in situ with combustion.

Process Options	**Mining**	**Extraction**	**Coking or Extraction/ Coking**	**Hydro-treating**	**Total**
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

Table 1. Illustrative energy requirements as a percentage of synthetic crude calorific value for major operations in integrated oil sands plants, as derived mainly from Canadian experience. [Taken from Probstein and Hicks, "Synthetic Fuels", Dover, 2006]

Process heat requirements are in the range of about 35-to-40 percent of the calorific value of the synthetic crude oil product, with the mix distribution depending on the process option. For processing oil sands, DEER reactors can supply either, depending on the process option : (A) steam and hot water; (B) steam, hot water, and electrical power; and (C) electrical power only. Hydrotreating involves reacting hydrogen with the process fluid to create the synthetic crude oil. In current operations, the hydrogen is generated either by steam reforming of natural gas, or by gasification of bitumen. Hydrogen can also be generated by electrolysis of water. Normally, this route is more expensive than using natural gas or bitumen. However, the DEER supply 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. Based on Probstein and Hicks(4) flow sheet for a 125,000 barrel per day synthetic crude oil plant using hot water extraction, the hot water input of 175,000 tons/day corresponds to a thermal energy requirement of 585 MW(th), the steam input of 11,300 tons/day corresponds to 419 MW(th), and the electrical inpact to make 391 tons of hydrogen per day by electrolysis, to 682 MW(e), based on electrolyzer efficiency of 80%.

Designs for 10 MW(e) and 50 MW(e) DEER reactors are presented below. However, the DEER-1 and DEER-2 systems can be readily scaled up to 100 MW(e) per reactor with an accompanying thermal hot water and steam output of 300 MW(th) per reactor. For the 125,000 barrel per day output, seven DEER reactors would provide the 391 tons per day of hydrogen output, plus 2100 MW(th) of process heat, considerably more than the ~ 1000 MW(th) required for the hot water extraction process. The in situ steam flooding extraction option requires about twice as much process heat as the hot water extraction option, making a good match for the combined DEER process heat/electrical output option. Oxygen from the electrolysis of water can also contribute to efficient processing of the oil sands.

The DEER system appears very cost effective. For a projected capital cost of $3000 per kW(e), the installed cost of the seven 100 MW(e) DEER reactors would be $2.1 billion. At a fixed charge of 7% per year, the corresponding capital cost is only $3.20 per barrel of product. Operating and fuel costs will add another few cents per barrel of output. Using DEER reactors for extraction of synthetic oil from oil sands has many advantages, including reductions in:

- greenhouse gas emissions
- amount of mining, particularly with in situ recovery
- amount of waste tailings
- process cost

The DEER reactor modular approach enables mass production of units that can be quickly installed when needed at low cost, and quickly removed when the application is finished, with no residual structures or radioactivity. In contrast, existing Light Water Reactors are very large, take a long time to construct, and are extremely difficult to dismantle and remove when finished.

4. The DEER concept

The DEER system is comprised of a reactor module, a power conversion module, a waste heat rejection module, and depending on needs of the operating site, a set of process modules, which can be used for production of fresh water, hydrogen fuel, and ammonia.

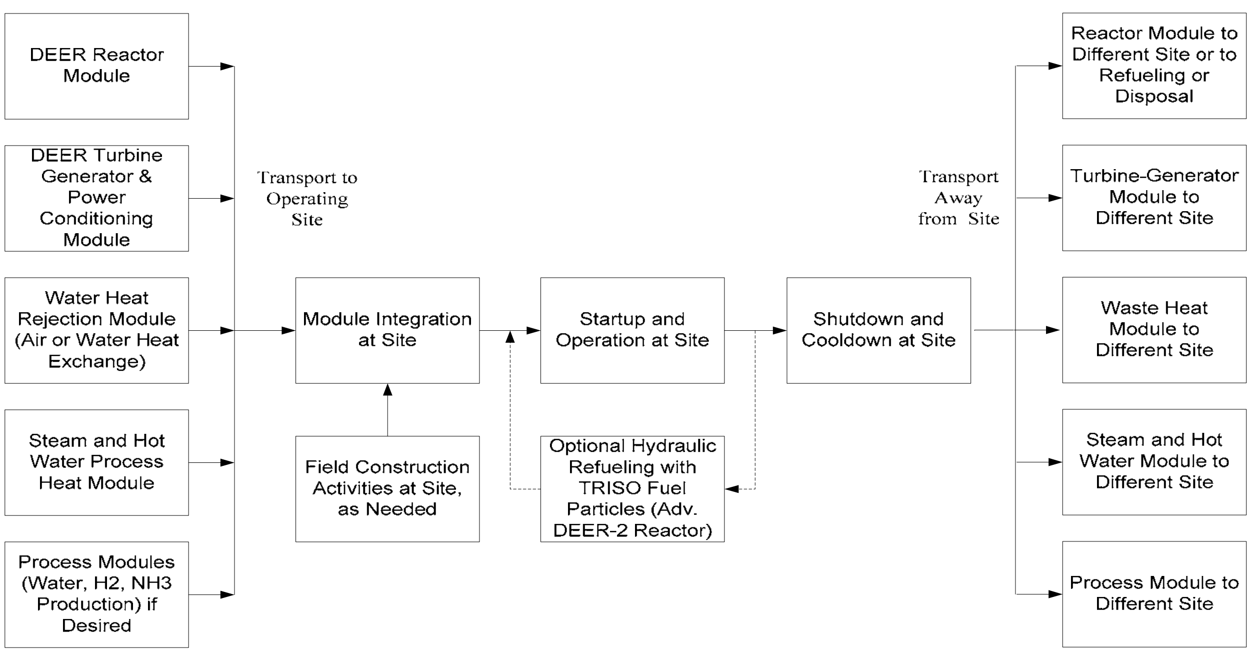

Figure 3. Flowsheet for installation and removal of Deployable DEER reactor system.

Figure 3 shows the flowsheet for deployment, operation, and eventual removal of the compact DEER nuclear power system. The various modules are delivered by available transport, either trucks or aircraft. The reactor module is described later. The steam turbine-generated power conversion modules(s) and process heat modules are integrated with the reactor module at the site, as are the waste heat rejection module(s). The waste heat rejection module(s) would condense the turbine exhaust steam using cooling water, if available, or by using an air cooled heat exchanger. With water cooling, the thermal cycle efficiency is ~ 30%, typical of LWR conditions. Using air cooling, turbine exhaust pressure is higher, e.g., ~ 15 psi (100° C) with lower thermal cycle efficiency, ~ 25%. If desired, the process modules for fresh water hydrogen and ammonia would also be shipped. These use standard industrial process equipment. After several days' integrating the modules, the DEER system would begin operation. Field construction would principally be enclosures for the modules, simple covered sub-surface pits lined with concrete produced locally.

The baseline DEER-1 is a fully sealed reactor using TRIGA fuel. It is not refueled at the site. After reaching its reactivity limited lifetime, the reactor module would be transported away for refueling or disposal and a new module brought to the site if desired. For disaster relief, one reactor module per mission would probably be sufficient. For power/water/fuel/fertilizer production, additional modules might be necessary. The removed DEER-1 module has an integral gamma shield that limits radiation dosage to handling and transport personnel to values well below existing guidelines. There is no residual radioactivity at the operating site after the end of the mission. The advanced DEER-2 system uses TRISO fuel particles that are hydraulically unloaded from the reactor after shutdown, enabling periodic refueling even though the reactor vessel is sealed. The particle unloading/loading uses small diameter pipes that are valved shut during operation. Spent TRISO fuel particles are loaded into a compact, fully shielded transport cask. The integral shield for the DEER-2 reactor weighs much less than that for DEER-1. The DEER-2 reactor can remain at a site for as long as power output is needed.

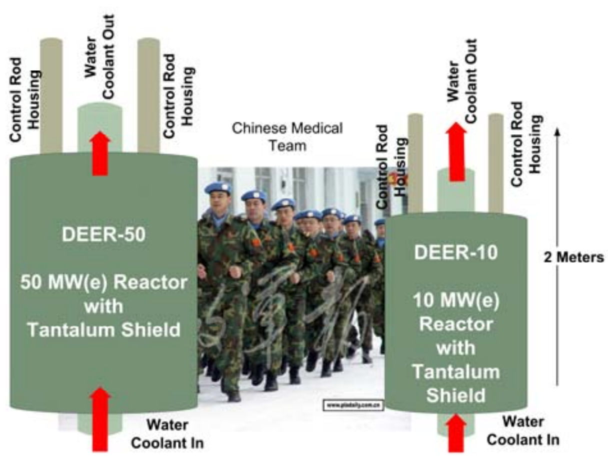

Figure 4. Overall scale of DEER-1 modules (includes shielding).

Figure 4 shows the scale of the DEER-1 reactor modules. The 10 MW(e) module's thermal power is 40 MW(th), based on a cycle efficiency of 25%, and a turbine exhaust pressure of 15 psi for waste heat reaction to the atmosphere. The larger module's thermal power is 200 MW(th) with an output of 50 MW(e). If water cooling is available, the power outputs would be 12 MW(e) and 60 MW(e) respectively. The TRIGA DEER-1 reactor is very attractive. TRIGA reactors have operated safely and reliably for decades at many locations around the World without problems, routinely providing very large bursts of neutrons. They safely handle prompt criticality insertions of six dollars with pulsed power increases to ~ 20,000 megawatts, inherently shutting down without damage. Fuel temperatures can reach 1200 K with no release of fission products. TRIGA reactors are primarily used for research and not power production. However, designs of TRIGA power reactors have been carried out.(3) Because of its inherent safety, extensive operating experience, and operation simplicity, TRIGA has been selected for the baseline DEER-1 system.

The advanced DEER-2 reactor uses well developed TRISO fuel particles. However, instead of imbedding them in graphite blocks or pebbles, the TRISO particles are packed into fuel elements and directly cooled by water. The Particle Bed Reactor (PBR) was a very high performance nuclear rocket developed in the DOD/SNTP (Space Nuclear Thermal Propulsion) program. In the PBR, TRISO derived fuel particle elements were cooled by 1000 psi hydrogen propellant, with outlet temperatures of ~ 3000 K. PBR blow-down tests demonstrated fuel element power densities of 30 megawatts(th) per liter.(6) The power density in the water cooled DEER-2 reactor fuel elements is much less than in the PBR, e.g., 0.5 MW(th) per liter vs. 30 MW(th) per liter. Much higher power densities are possible for the DEER-2 reactor; however, the fissionable loading would be used up too quickly. The packed particles in the DEER-2 fuel elements can be hydraulically unloaded and fresh particles loaded back in, enabling the reactor to be periodically refueled without opening the pressure vessel. Ten (10) and 50 MW(e) designs of the DEER-1 and DEER-2 power levels bracket the range of interest for deployable systems. If more than 50 MW(e) is desired at a site, additional units would be deployed.

5. The DEER-1 baseline reactor system

Table 2 lists the principal parameters for the 10 and 50 MW(e) designs.

Reactor Parameters	50 MW(e)	10 MW(e)
Thermal Power MW(th)	200	40
Cycle Efficiency	25%	25%
Reactor OD (m)	1.24	0.63
Module OD (m) with 0.2 (m) Tungsten Shield	1.74	1.09
Reactor Core OD (m)	1.20	0.53
Reactor Core Length (m)	1.20	0.6
Fuel Element Diameter (cm)	1.0	0.9
# of Fuel Elements in Core	5149	2078
Wt. % Uranium in $UZrH_{1.8}$ Fuel	30	30
Wt. of Uranium in Core, kg (20% U-235 Enrichment)	226	37
Reactor Wt. w/Fuel, metric tons	7.4	1.3
Module Wt. w/Tungsten Shield, metric tons	40.0	13

Table 2. Design parameters for the DEER-1 reactor.

Figure 5 shows a cross section view of the 10 MW(e) DEER-1 reactor design based on TRIGA fuel rods. Very detailed Monte Carlo neutronic codes model the actual 3-dimentional geometry of the reactor core and reflector, using experimentally measured cross sections over the complete energy spectrum. The MCNP Monte Carlo code(7) models criticality, power distribution, control rod worth, void coefficient, temperature coefficient, etc. with great accuracy, while the Monte

Burns Monte Carlo code[8] follows the neutronic behavior of the reactor over its operating life, as the U-235 fuel burns out and fission products build up. Three dimensional Monte Carlo neutronic analyses are very accurate and predict reactor performance with high precision. Monte Carlo predictions of the various neutronic parameters for the SNTP/PBR nuclear propulsion reactor, which was comparable in size to the DEER-1 reactors, agreed at the 1% level with experimental measurements on the actual PBR critical assemblies.[6]

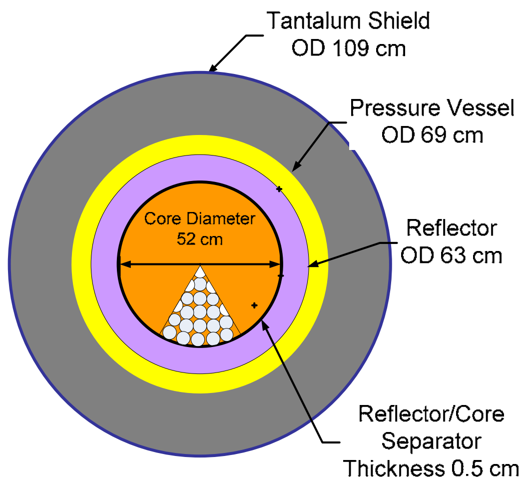

Figure 5. Near-term DEER-1 reactor design, cross sectional view [10 MW(e) system].

Figure 6 shows the criticality constant, K_{eff} as a function of time for the 10 and 50 MW(e) designs, as predicted by the MCNP and Monte Burns codes. The DEER-1 reactor operates as long as K_{eff} is greater than, or equal to 1.00.[When K_{eff} is greater than 1.00, control rods keep the operation K_{eff} = 1.00.] The DEER-1 fuel contains a burnable neutron poison to minimize the swing in K_{eff} over reactor lifetime. For the 10 MW(e) design, K_{eff} reaches its limit of 1.00 after 300 days of full power operation. At this point, the DEER-1 reactor would be removed and transported to a site to be refueled or decommissioned.

The 50 MW(e) reactors operate considerably longer, well over 425 days. (The Monte Burns analysis was stopped at 425 days; however, it could probably reach almost 600 days before replacement.) If the reactor does not always operate at full output, the reactor module would not require replacement until its integrated output reached 300 full power days for the 10 MW(e) design and ~ 600 full power days for the 50 MW(e) unit. Also, the designs assume a 30 weight percent loading of uranium in the $UZrH_{1.8}$ hydride fuel. Higher uranium weight loadings are practical, up to at least 45%, which could double operational lifetime. The DEER-1 fuel enrichment is 20% U-235, which is not usable for nuclear weapons. Twenty percent (20%) enriched fuel is widely used and does not require safeguards. When the DEER-1 reactor is shut down and transported away from its operating site, thermal energy generation will continue from the radioactive decay of its fission products. This small afterheat continues to decrease with time after shutdown. For the10 MW(e) DEER-1 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.

The DEER-1 reactors have an enclosing thick tungsten or tantalum gamma shield that attenuates the external dose from the radioactive fuel inside the shut down reactor, so that personnel can safely remove and transport it away from the site. Figure 7 shows the gamma dose in rads per day as a function of distance from the shield surface, based on a 20 centimeter thick tungsten shield at 2.3 days after shutdown. For the 10 MW(e) reactor, at 10 feet the radiation dose is 0.05 rad per day. The allowable dose for radiation workers is 5 rads per year. To receive this dose, the worker would have to remain at 10 feet from the shield for 100 days, assuming the dose rate stayed constant at the 2.3 day level. However, since the afterheat and gamma photon release rate rapidly decrease with time, the worker would not receive 5 rads no matter how long he/she stayed there. The dose rate for the 50 MW(e) reactor is ~ 0.25 rad per day. At 10 feet for 20 days, a worker would receive 5 rads at the 2.3 day release rate. However, since the photon release rate decreases with time, the worker would not receive 5 rads, even if he/she stood there for a year. At 20 feet away, dose rate would drop by a factor of four. It thus appears that handling and transport personnel can remove a shut-down DEER-1 reactor from its operating site without a harmful radiation dose.

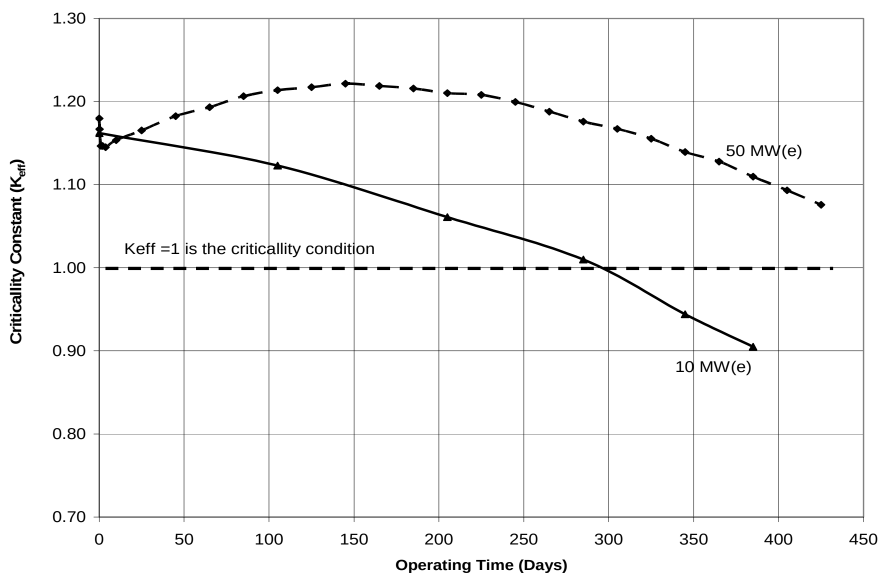

Figure 6. K_{eff} vs. operating time for DEER-1 using TRIGA fuel at 10 MW(e) output. [In operation, the reactor control rods are used to control K_{eff}.]

The temperature distribution along the fuel element located at the center of the DEER-1 reactor core, which has the greatest power density, has been analyzed as a function of distance from the coolant inlet. Maximum temperature at the center of the fuel element is 970 K, well below the maximum temperature capability of the TRIGA fuel, and comparable to the maximum temperature for steady state operation in previous TRIGA reactor designs. The heat transfer analyses determine the ΔT from the center of the hydride fuel to the outer surface of the fuel, the ΔT between the outer surface of the hydride and the inner surface of the stainless steel cladding, the ΔT across the water film from the outer surface of the cladding to the bulk of the water coolant. The largest ΔT is that between the center of the hydride fuel and its outer surface, being about 200 K at the center of the reactor. The analysis was for a thermal power of 50 MW, an early design version of the 10 MW(e) unit. The present thermal rating is 40 MW(th), which reduces each of the ΔT's by a factor of 0.8, making the maximum fuel temperature ~ 900 K.

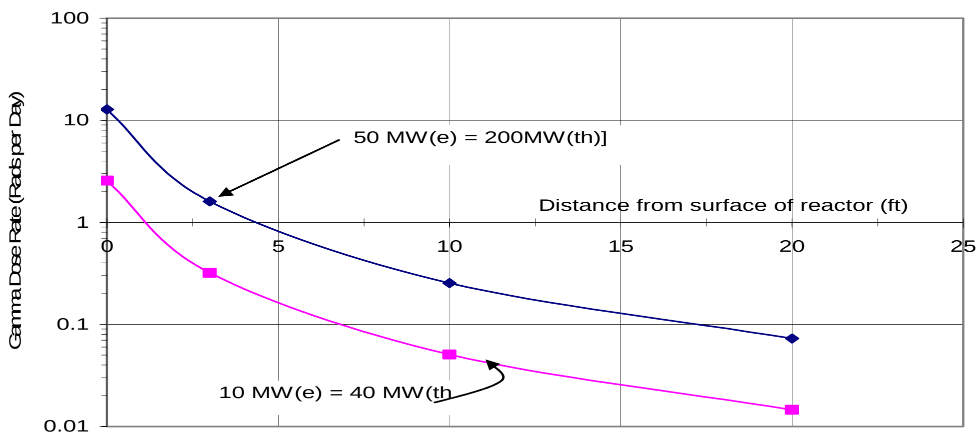

Figure 7. Gamma dose rates after 1000 hours of operation as a function of the distance from the surface of the reactor. Calculation is based on a 20 cm thick tungsten shield with 2.3 days of reactor shutdown. The gamma attenuation factor inside the reactor is assumed to be 10.1.

Besides providing electric power and process heat, the DEER-1 reactor can produce potable water, plus manufacture hydrogen and ammonia fuel using N_2 extracted from the atmosphere and hydrogen generated by electrolysis of water. The amount of water condensed is very large, even in very hot, dry climates. At 100° F and 10% humidity, for example, one megawatt of electric power can condense out 25,000 gallons of potable water per day. Hydrogen would be generated by using either high temperature solid electrolyzer units operating on steam or lower temperature PEM electrolyzers. Nitrogen (N_2) would be extracted from the atmosphere using cryogenic distillation or by an absorption/desorption process. The N_2 would react with hydrogen by the standard Haber process to make ammonia.

6. The DEER-2 advanced reactor system

Figure 8 illustrates the advanced DEER-2 reactor in which TRISO particles can be hydraulically unloaded and loaded. The inlet water coolant flows along the central cylindrical channels inside the particle bed fuel elements and then radially outwards through the annular packed particle beds, removing the fission heat from the TRISO particles. The annular particle bed is held between two coaxial cylindrical porous frits, which form the fuel element. The pressure drop for water flow through the frits is designed to be several times greater than the pressure drop through the particle bed so that each local portion of the bed experiences the proper water flow rate, and the temperature of the water coolant existing through the outer frit is essentially the same everywhere in the reactor. The same flow approach was used for the SNTP/PBR nuclear propulsion engine. Frits were manufactured and tested that could control individual coolant flows at every (r,θ,Z) location on each fuel element in the reactor core, so that the outlet coolant was at the same temperature everywhere. To hydraulically unload the fuel particles from the element, the reactor is shut down and water coolant flows in through the inlet at the bottom of the element (Figure 8), fluidizing the settled particle bed and causing the particles to flow out with the water through the top of element into an external spent fuel storage cask. To hydraulically load fresh fuel particles into the DEER-2 reactor, the fluidized particles are introduced into the top of the elements. The down-flowing particles are then trapped by the porous frit at the bottom of each element, building up the annular bed in the element.

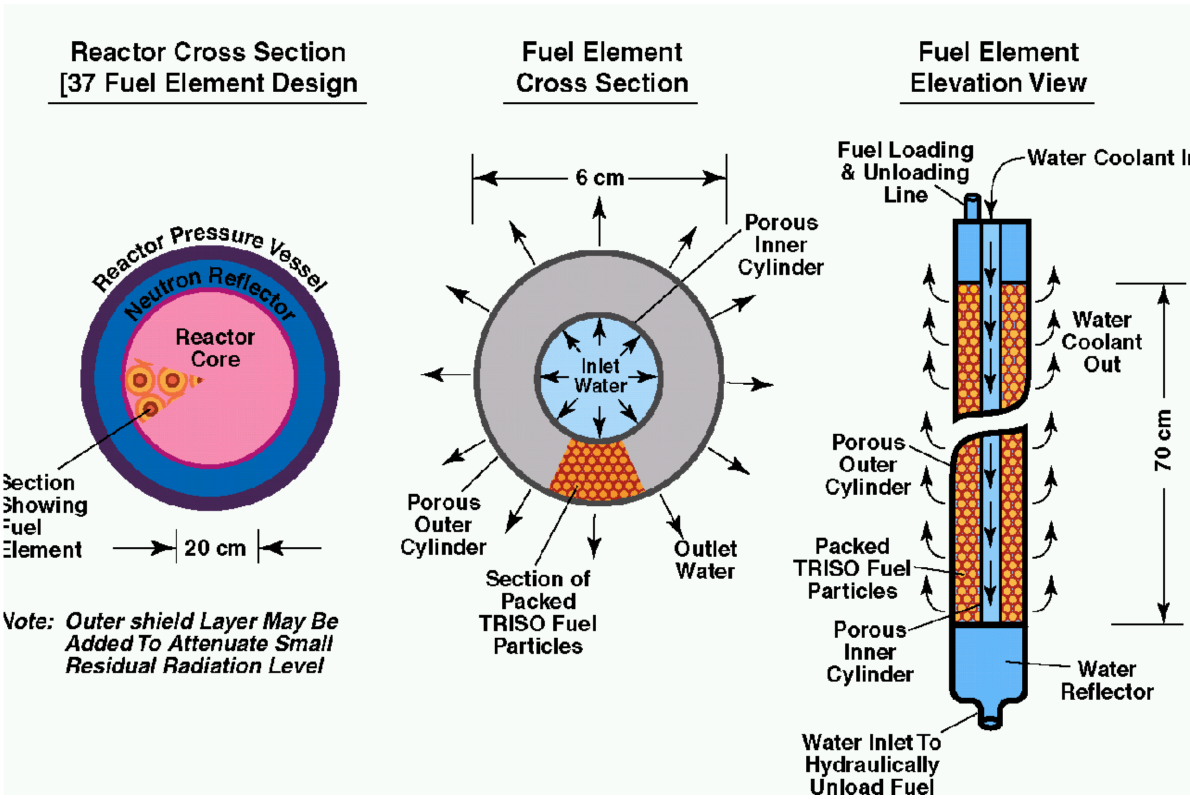

Figure 8. DEER-2 Advanced Reactor design using hydraulic loading/unloading of TRISO nuclear fuel particles.

Figure 9 shows an elevation view of the fuel storage/transport cask for the 10 MW(e) DEER-2 TRISO reactor. The spent TRISO fuel particles are immersed in liquid water inside the enclosing tungsten shield/container vessel. The shield attenuates the gamma radiation enough from the fission products that the handling/transport personnel do not receive excessive radiation dosages. The decay heat deposited in the TRISO fuel particles (primarily from beta particle decay, which is about one-third of total decay heat) is transferred to the water bath in which the particles are immersed, and then by convection to the tungsten shield. This energy, plus the gamma energy deposited in the tungsten, is then conducted through the tungsten shield to the outer surface of the cask. From there, natural convection, which may be augmented by fans, transfers the thermal energy to the ambient atmosphere. Natural convection currents in the water bath appear sufficient to transfer the thermal energy to the inner surface of the tungsten shield; if they are not sufficient, they could be augmented with a small electrically powered circulator. Table 3 shows the parameters for the 10 and 50 MW(e) advanced DEER-2 reactors. The advanced reactors are significantly smaller and much lighter than their near term designs because of the higher power density in the reactor core and the elimination of the integral tungsten shield.

While shielding is still needed for the fuel storage/transport cask, the size and weight of its shield is considerably smaller than that for the DEER-1 reactor.

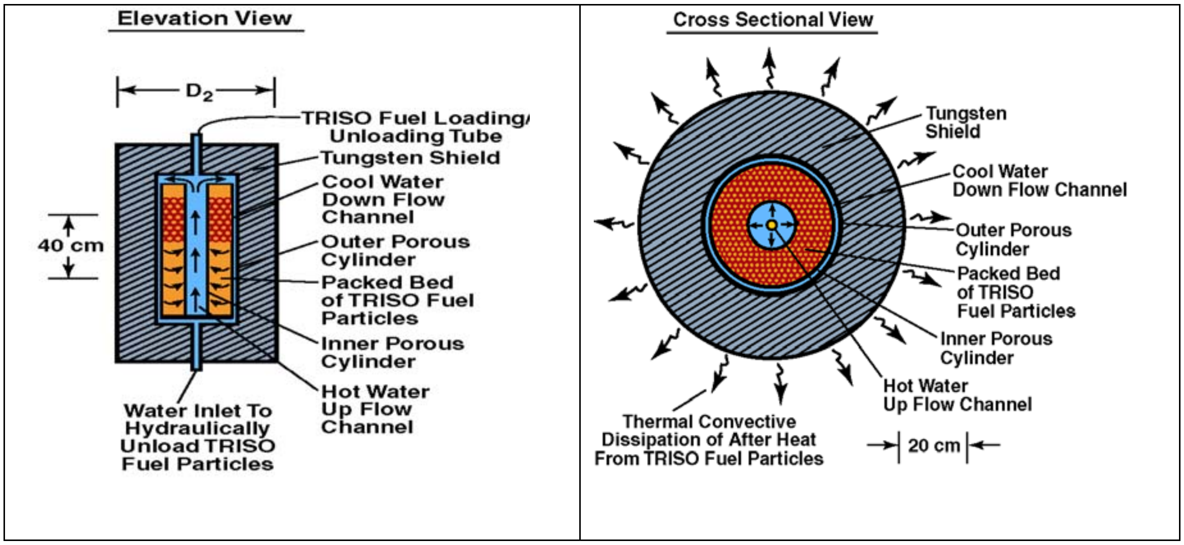

Figure 9. Elevation and cross sectional views of the 10 MW(e) Advanced DEER system transport cask.

Reactor Parameters	DEER-10	DEER-50
Thermal Power (MW)	40	200
Cycle Efficiency (%)	25	25
Reactor OD (m)	0.65	0.92
Reactor Core OD (m)	0.45	0.71
Reactor Core Length (m)	1.00	1.76
# of Fuel Elements in Core	37	91
Fuel Element OD (cm)	6.0	6.0
Thickness of TRISO Bed in Fuel Element (cm)	1.45	1.45
Average Power Density in TRISO Bed MW(th) / liter	0.78	0.78
Initial U-235 Loading in Core (kg)	14.6	73.0
50% Burnup Lifetime (mos.)	6	6
Weight of Reactor, incl. Fuel (metric tons)	1.25	4.5

Table 3. Parameters for Advanced Reactor based on fuel elements with hydraulically loaded/unloaded TRISO particles.

7. DEER technology issues and development requirements

The principal technology areas are nuclear fuel, reactor neutronics, thermal hydraulics, and the hydraulic unloading/loading of TRISO fuel particles for the Deer-2 reactor. Power conversion, waste heat rejection, and process modules use existing technology; their only issue is to be as compact and light as possible. In regard to fuel, the TRIGA fuel for DEER-1 is commercially available and does not need further development.(3) The TRISO fuel for DEER-2 is also fully developed.[2] However, testing with flowing hot water coolant is needed to show that there are no particle corrosion problems. These tests can be done using non-nuclear simulated fuel elements. In regard to reactor neutronics, Monte Carlo computer codes can predict neutronic parameters, i.e., K_{eff}, void and temperature coefficients, power distributions, burnup behavior, etc., quite accurately. Nonetheless, the predictions still need verification by low power critical assembly tests before constructing full scale, full power, actual DEER test reactors.

The third area is thermal hydraulics. Thermal hydraulic predictions – heat transfer rates, pressure drops, fuel temperatures, etc. – are usually good, but they also require experimental verification. Non-nuclear testing of electrically heated fuel element assemblies at the temperature and pressure environment in the DEER-1 and DEER-2 reactors would be carried out prior to constructing actual DEER test reactors.

The fourth area is the hydraulic unloading and loading of TRISO particles in DEER-2. [The TRIGA elements in DEER-1 remain fixed in place throughout the operating cycle, and are not an issue.] Experimental tests on packed bed fuel elements are needed to verify that they can be unloaded and loaded with TRISO particles. Initial tests would be on individual elements and small assemblies of elements. However, after settling on the best design approach, tests on a full scale, non-nuclear mockup of the DEER-2 reactor core would be desirable. In addition, nuclear tests on individual DEER-2 fuel elements are also desirable. As with the neutronic and thermal hydraulic tests, the hydraulic particle unloading/loading tests should be carried out before constructing actual DEER-2 test reactors.

8. Conclusions

The feasibility of compact, deployable power reactors for a range of applications, including process heat and power for oil extraction from oil sands, local civilian micro-grids, emergency power in areas hit by natural disasters, remote locations such as Alaska, and developing countries that need power for humanitarian purposes, has been examined. The reactor designs presented are based on commercial, well developed nuclear fuel and power conversion technologies that have excellent safety and environmental performance. Two designs, one at 10 MW(e) [40 MW(th)] and other at 50 MW(e) [200 MW(th)] have been developed. The deployable reactors can be quickly transported to and from their operating sites using existing truck or aircraft transport vehicles. The reactors use non-weapons grade, 20% enriched fuel, and operate without refueling. The reactors have integral gamma shields that enable them to be transported away from their operating site at the end of their scheduled operational lifetime with external radiation dosage rates that are within acceptable guidelines. The reactor designs presented appear to be practical, and could be quickly developed for implementation.

9. Acknowledgements

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