Exploratory Design of a Reactor/Fuel Cycle Using Spent Nuclear Fuel Without Conventional Reprocessing – 13579

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ABSTRACT

General Atomics has started design of a waste to energy nuclear reactor (EM^2) that can use light water reactor (LWR) spent nuclear fuel (SNF). This effort addresses two problems: using an advanced small reactor with long core life to reduce nuclear energy overnight cost and providing a disposal path for LWR SNF. LWR SNF is re-fabricated into new EM^2 fuel using a dry voloxidation process modeled on AIROX/ OREOX processes which remove some of the fission products but no heavy metals. By not removing all of the fission products the fuel remains self-protecting. By not separating heavy metals, the process remains proliferation resistant.

Implementation of Energy Multiplier Module (EM^2) fuel cycle will provide low cost nuclear energy while providing a long term LWR SNF disposition path which is important for LWR waste confidence. With LWR waste confidence recent impacts on reactor licensing, an alternate disposition path is highly relevant.

Centered on a reactor operating at 250 MWe, the compact electricity generating system design maximizes site flexibility with truck transport of all system components and available dry cooling features that removes the need to be located near a body of water. A high temperature system using helium coolant, electricity is efficiently produced using an asynchronous high-speed gas turbine while the LWR SNF is converted to fission products. Reactor design features such as vented fuel and silicon carbide cladding support reactor operation for decades between refueling, with improved fuel utilization.

Beyond the reactor, the fuel cycle is designed so that subsequent generations of EM^2 reactor fuel will use the previous EM^2 discharge, providing its own waste confidence plus eliminating the need for enrichment after the first generation. Additional LWR SNF is added at each re-fabrication to replace the removed fission products. The fuel cycle uses a dry voloxidation process for both the initial LWR SNF re-fabrication and later for EM^2 discharge reuse. The EM^2 waste disposal profile is effectively only fission products, which reduces the mass (about 3% vs LWR), average half life, heat and long term radio-toxicity of the disposal.

Widespread implementation of EM^2 fuel cycle is highly significant as it would increase world energy reserves; the remaining energy in U.S. LWR SNF alone exceeds that in the U.S. natural gas reserves. Unlike many LWR SNF disposition concepts, the EM^2 fuel cycle conversion of SNF produces energy and associated revenue such that the overall project is cost effective. By providing conversion of SNF to fission products the fuel cycle is closed and a non-repository LWR SNF disposition path is created and overall repository requirements are significantly reduced.

INTRODUCTION

Nuclear spent fuel waste management has been an expensive and slowly evolving process. What is needed is to make a spent fuel waste program that has the ability to generate revenue, reducing the cost of spent fuel disposition. The spent fuel and depleted uranium have tremendous inherent energy potential; if tapped it can provide not only disposition but also provide energy for commercial markets. Frequently referred to as closing the fuel cycle, many processes have been proposed that can tap the inherent energy potential but all to date have not been cost effective. Further, aqueous reprocessing has significant non-proliferation challenges. With cost requirements in mind, the General Atomics' improved fuel cycle is centered around the Energy Multiplier Module (EM^2) reactor using a dry fission product removal from spent fuel.

ENERGY MULTIPLIER MODULE (EM^2) REACTOR CONCEPT

EM^2 is a compact helium-cooled fast reactor that augments its fuel load with either DU or UNF, which contain the additional ^{238}U to allow the reactor to both convert and burn fuel in situ. The basic construct of a 250 MWe module is presented in Fig. 1, showing a below-grade core flanked on one side by a closed cycle gas turbine power conversion unit (PCU) and on the other side by a direct reactor auxiliary cooling system (DRACS). The primary coolant system is enclosed by the containment, which is divided into three connected chambers with structural ligaments around the reactor chamber that also serve as shielding.

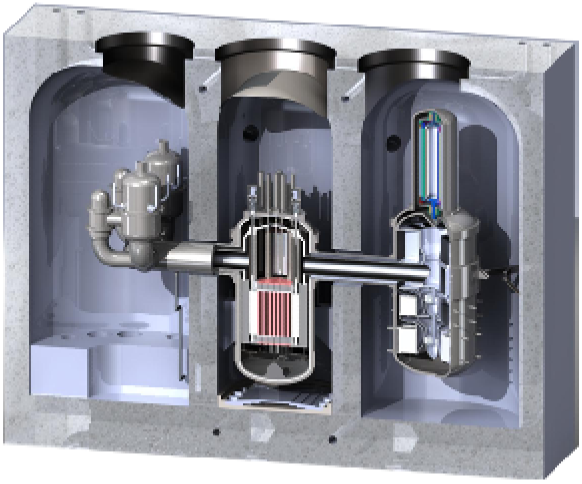

Fig. 1. 250 MWe EM^2 power module in a below-grade sealed containment.

Reactor Core System

A cutaway view of the reactor system is shown in Fig. 2. The reactor vessel is an internally insulated 4.7 m diameter, 10.6 m high structure constructed from standard SA533-Grade B plate steel. In contrast to conventional LWR vessels, this unit is of a size that can be manufactured by many vendors. All vessels are small enough to be shipped by truck to the construction site.

The EM^2 core, illustrated in Fig. 3, is divided into two sections: starter and fertile. The starter is the "critical" section of the reactor at beginning of life. It contains low enriched uranium (LEU) to initiate criticality and provide excess neutrons for converting fertile to fissile materials in the starter and fertile sections. The core contains 85 fuel assemblies arranged in a hexagonal prism. Seventy-nine assemblies contain 91 fuel rods, each 2.7 m long by 21.5 mm in diameter. A total of six assemblies in the core contain central voids for shutdown rod insertion. The clad is 1 mm thick ß-SiC composite, which is a high-temperature material that is also resistant to neutron damage [2]. The fuel is uranium carbide (UC) in the form of porous pellets. The pellets are annular with which provides a means for volatile fission products to escape to a fission product collection system. This alleviates the pressure buildup and reduces fuel swelling over the long core life.

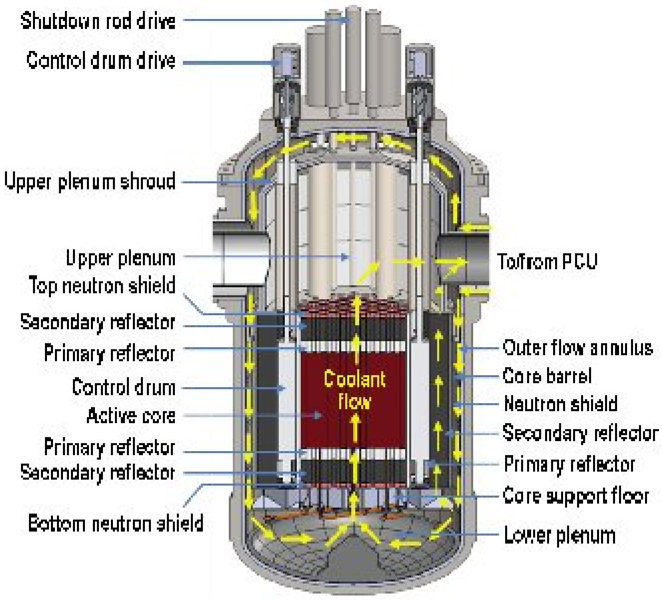

Fig. 2. Cutaway of EM^2 reactor system.

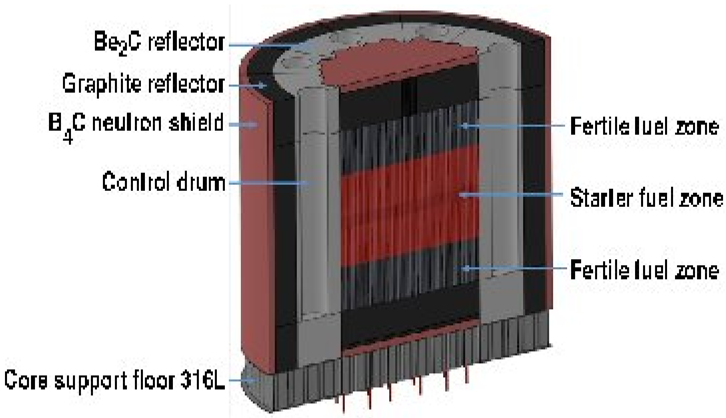

Fig. 3. EM^2 core arrangement composed of starter and fertile sections. (The shapes of the fissile and fertile sections are only schematically illustrated.)

The core is surrounded by a reflector which consists of an inner section of canned Be_2C and an outer section of graphite. These reflector materials are highly neutron-economic and keep the core neutron leakage under 2%. Owing to power peaking around the core periphery, the starter fuel adjacent to the reflector has a reduced enrichment, leading to a spatially flat power profile that results in relatively uniform irradiation rates everywhere within the core; this precludes the need for fuel shuffling. Six rotatable drums are embedded in the reflector to provide reactivity control during normal power operation. Table I summarizes materials used for EM^2 core design and selection bases.

TABLE I. Materials Used for EM^2 Core Design.

Component	Material	Characteristics
Fuel	Uranium carbide	High density (13.63 g/cm^3), high melting point (2350°C), high thermal conductivity (16-17 W/m·K), little or no fuel restructuring, low fission gas release and significant fuel swelling
Cladding	Silicon carbide	High dissociation temperature (2730°C), high thermal conductivity, high-temperature strength, low thermal expansion, resistant to chemical reaction and neutron damage
Coolant	Helium	Single phase gas, inert, compatible with materials (not activated) enables direct power conversion, minimal void coefficient
Control absorber	Boron carbide	90%-enriched ^{10}B, strong neutron absorber, high melting point (2763°C)
Reflector	Beryllium carbide	High melting point (2100°C), low neutron absorption, neutron multiplication
Reactor vessel	Steel	SA533-Grade B ASME Section II qualified

Power Conversion System

The PCU is based on a direct Brayton cycle. Hot helium from the core is expanded directly through the turbine to drive the generator and compressor. A recuperator recovers heat from the turbine exhaust that is at too low a pressure to accomplish efficient conversion to mechanical energy. The water-cooled precooler provides the cycle heat rejection. Figure 4 shows a cutaway of the PCU vessel, which contains all components that are in contact with primary coolant. The turbine-compressor-generator is on a single vertical shaft that is suspended by active magnetic bearings. The generator is located in a separate, connected vessel at the top. A dry-gas shaft seal isolates the helium in the generator cavity from the primary coolant.

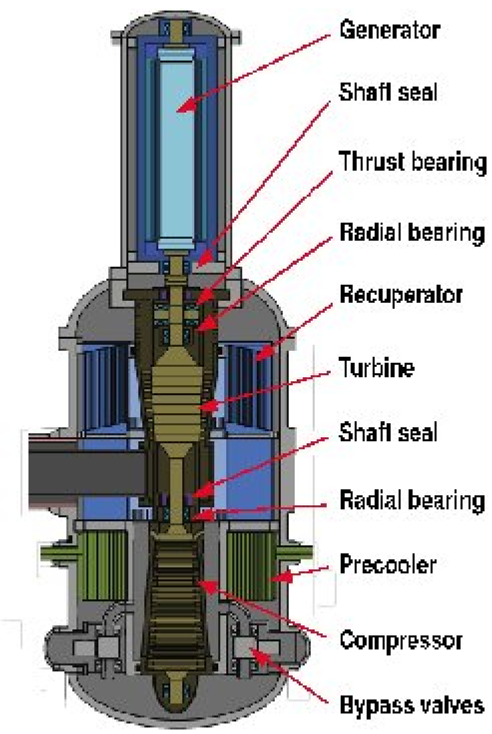

Fig. 4. PCU and generator cutaway.

The PCU incorporates several features that distinguish it from previous Brayton cycle designs. The turbo-compressor-generator is a variable speed machine operating above synchronous frequency. Speed control is used to track load changes rather than the more traditional approaches of turbine bypass or primary coolant pressure changes bringing several advantages. The diameters of the turbine, compressor and generator are reduced by the inverse of the design rotational speed, so that the overall size and weight is greatly reduced relative to a synchronous machine. The primary system temperatures are maintained at near constant levels over the full turn-down ratio, and the thermodynamic efficiencies are high at the lower power levels. The variable, non-synchronous operation is made possible by commercial power inverters that convert variable frequency input to grid frequency at 99% efficiency.

The generator incorporates a permanent magnet (PM) rotor that eliminates the I^2R losses associated with a wound rotor and exciter. The PMs are attached to the rotor by a proprietary high strength fiber winding that was developed by General Atomics for military applications. This approach further reduces the radial build and allows the PCU to be small enough to be road transportable.

Direct Reactor Auxiliary Cooling System (DRACS)

The DRACS is designed to remove the core residual heat when the reactor is in a shutdown mode and the PCU system is not available for heat removal. The DRACS consists of two parallel loops, each loop being designed to provide adequate cooling operating by itself for the operational modes of: i) pressurized cool-down using helium with or without the helium circulator and water pumps operating (active or passive modes) and ii) depressurized cool-down at atmospheric pressure along with operation of the helium circulator. The DRACS is made up of various components such as multi-tube helical coil helium-to-water heat exchanger (illustrated in Fig. 5), a backup maintenance helium circulator, a water-to-air heat exchanger, a natural draft cooling tower, water pumps, and ducts and pipes as needed to connect the various components.

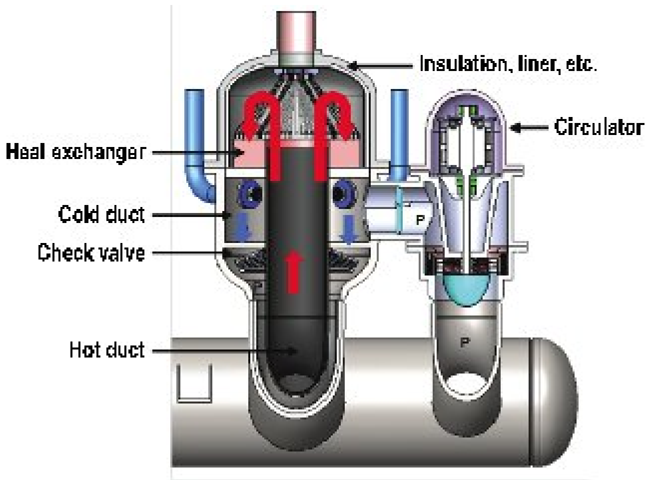

Fig. 5. DRACS heat exchanger cutaway.

Primary Coolant System

The reactor produces 500 MWt and is cooled by helium coolant pressurized to 1900 psia (13.1 MPa). The average core outlet temperature is 850°C. During normal operation, hot helium from the top of the core flows to the PCU to drive the turbo-compressor and submerged generator. During both normal and abnormal shutdown, the hot helium flows by natural convection to the 100% redundant DRACS. The primary coolant helium is maintained free of oxidants as well as any circulating radioactivity by a helium purification system.

EM^2 PERFORMANCE

Neutronics Performance

Core modeling has determined that criticality is maintained for more than 30 years without refueling or fuel shuffling, as shown in Fig. 6, which plots effective multiplication factor vs full power run time. This results from a careful shaping of fissile (LEU) and fertile (DU) fuel sections to balance the reactivity growth from production of new fissile fuel with the reactivity decrements from fuel depletion and fission product accumulation. The very low temporal gradients and the very limited dynamic range of the reactivity (<3%) over multiple decades permit reactivity control by control drums embedded in the reflector. This approach helps maintain a vertically symmetric burnup profile although the vertical temperature gradient will cause a small amount of asymmetry.

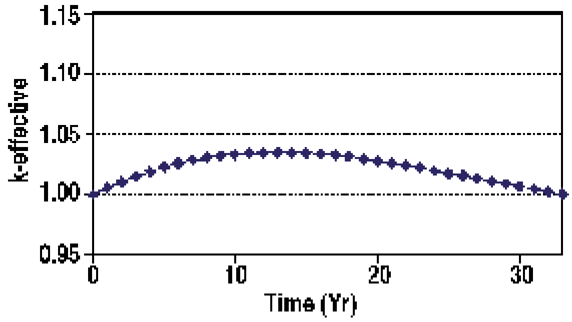

Fig. 6. Neutronics calculation showing a 30+ year core life and the tight control range of k-effective for EM^2 core fueled with LEU and DU.

Figure 7 shows the fractional contribution of key fissile isotopes to total core power as a function of life for a LEU/DU loading. Initially, most of the power comes from ^{235}U in the starter. After about ten years, converted fuel contributes the largest energy fraction; averaged over the life cycle, the majority of the energy is produced by the original fertile material. Direct fast-fission of the ^{238}U produces about 20% of the energy. End-of-cycle burnup is approximately 140 GW-days/MT, more than double that of any LWR. Additional gain in uranium utilization stems from the high thermal to electric conversion efficiency of 53%.

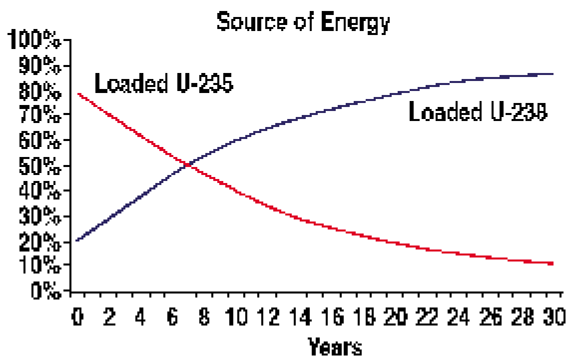

Fig. 7. Fractional contribution of loaded material to core power over time.

Fuel Performance

Materials performance is key to the multi-decade lifetime limit established by the neutronics. All structural materials in the core, including the fuel cladding, are SiC composite. This material is unusually radiation-tolerant, especially in the temperature range of interest for gas-cooled reactors where annealing effects come into play [3]. Although there is no in-core data that extends to the full life of EM^2, the data that does exist suggests that the changes in constitutive properties saturate at low displacement per atom (DPA) levels. Swelling from helium and hydrogen produced by neutron bombardment is another major concern for material life. This is not life-limiting in EM^2 because the carbon in the core softens the neutron spectrum, resulting in a very low population of neutrons above the energy threshold for transmutation events in SiC.

Another potentially life-limiting problem is the chemical interactions between the fuel and the clad at high burnup. There is very limited data at the burnup values pertinent to long core life operation characteristic of EM^2. However, Fig. 8 provides some indirect evidence that this issue is not likely to be a showstopper. This figure illustrates a cross section of a Tri-structural-isotropic (TRISO) fuel particle that has been subjected to unusually high burnup of ~70% [4] at higher temperatures (1,600°C) than EM^2 clad will experience (<1,100°C). The figure shows that some of the protective layers surrounding the fuel kernel have been breached, but the SiC layer (the bright white circle in the figure) remains intact. Clad life can also be limited by the buildup of pressure within the fuel from gases produced either as fission products or in the decay chains of fission products. This is avoided in the EM^2 design by use of annular fuel pellets that enable venting these gases from fuel elements into a trapping system external to the reactor.

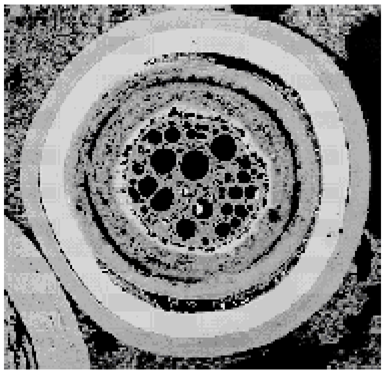

Fig. 8. TRISO particle subjected to deep burn showing the intact SiC layer after 70% burnup (white) [4].

Safety Performance

The EM^2 reactor is designed to meet all relevant U.S. Nuclear Regulatory Commission (NRC) requirements for licensing in the U.S. including risk-informed design. The “relevancy” of these requirements to small modular reactors (SMRs) is currently under review, particularly with respect to shared facilities, services and staffing. In the interim, the EM^2 safety design effort to-date has mainly been on the reactor system, containment and DRACS. The EM^2 safety philosophy is built on three premises:

(i) Passive safety features are the main line of defense against all abnormal and accident conditions including “beyond design basis events”.
(ii) All safety-related systems, including passive safety features, must be regularly tested.
(iii) A comprehensive statusing system shall be implemented to provide regularly updated information on the conditions of the fuel clad, primary coolant pressure boundary and containment.

The safety features of EM^2 are summarized as follows:

(i) Because of very large ^{238}U loading, the reactor core has a high negative temperature coefficient through the core life. When combined with the high fuel and clad temperature limits, the negative temperature coefficient enables the reactor to sustain an anticipated transient without scram (ATWS) by reducing the fission power to zero as the core heats up.
(ii) Normal reactivity control and shutdown is through rotational action of the control drums. A diverse backup shutdown system is composed of six shutdown rods which are lowered into the core for shutdown. Both drums and rods will actuate by gravity in the event of a loss of signal to the drive motors.
(iii) Core decay heat is normally removed by the PCU. In the event of a reactor shutdown, supplemental rotational energy to provide flow is provided by motoring the generator. If the PCU is not available, shutdown heat removal is provided by two auxiliary circulators that provide forced flow from the core to the DRACS water-cooled heat exchangers (HXs).

(iv) If the PCU and auxiliary circulators become unavailable, core afterheat is removed by natural convection of helium to either of the two 100% water-cooled DRACS HXs. The DRACS water loops also operate by natural convection and reject heat to the air via a water/air HX. The cooldown transient following shutdown from 100% power is shown in Fig. 9 for the assumption of only one DRACS HX in operation. The peak fuel temperature is steadily reduced to shutdown conditions 500°C in 20 minutes. No damage is incurred to the reactor during this transient. The cooling operation is completely passive - no electric power or operator actions are required.

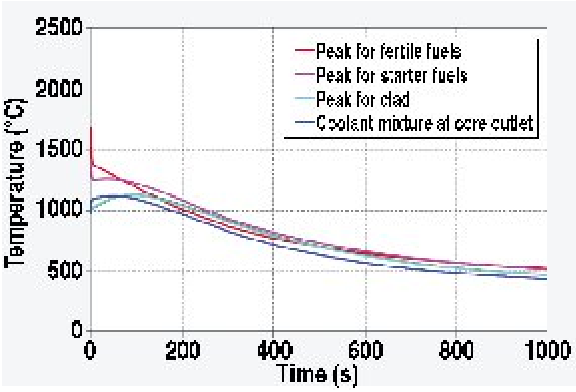

Fig. 9. Pressurized natural convection cool-down on one DRACS loop.

EM^2 Operational Performance

Due to its high temperature and direct cycle, EM^2 operates at about 53% efficiency using conventional cooling tower (evaporative cooling). This high efficiency is an important economic improvement. However, for site flexibility where water conservation is important, the high temperature features of EM^2 allow use of a dry cooling cycle for about a 4% penalty in efficiency but with a significant reduction in water use. The ability to separate the nuclear reactor site from water locations opens many potential new sites, in lower population density regions.

The smaller number of components, which are all sized for truck transportation, allows a new level of modular construction approach to reduce construction cost and schedules.

ENERGY MULTIPLIER MODULE FUEL CYCLE

Figure 10 illustrates a closed fuel cycle based upon a presumed 60% extraction of every fission product at each cycle. The end-of-life discharge from the 1st core is used as the starter for the next 1.2 cores. LEU (or other fissile material) is required for the first core, but no fissile addition is needed for follow-on cores, only fertile addition. Modeling has verified that such a fuel cycle reaches steady state conditions in a few generations.

An important feature of this type of reactor is that enriched fuel is only needed in the first generation. Widespread implementation of this technology would eliminate the need for the world to have any additional enrichment plants, independent of the extent to which nuclear energy supplies the world's energy needs. This would reduce the proliferation risks associated with the front end of the fuel cycle compared to the conventional approach adopted today.

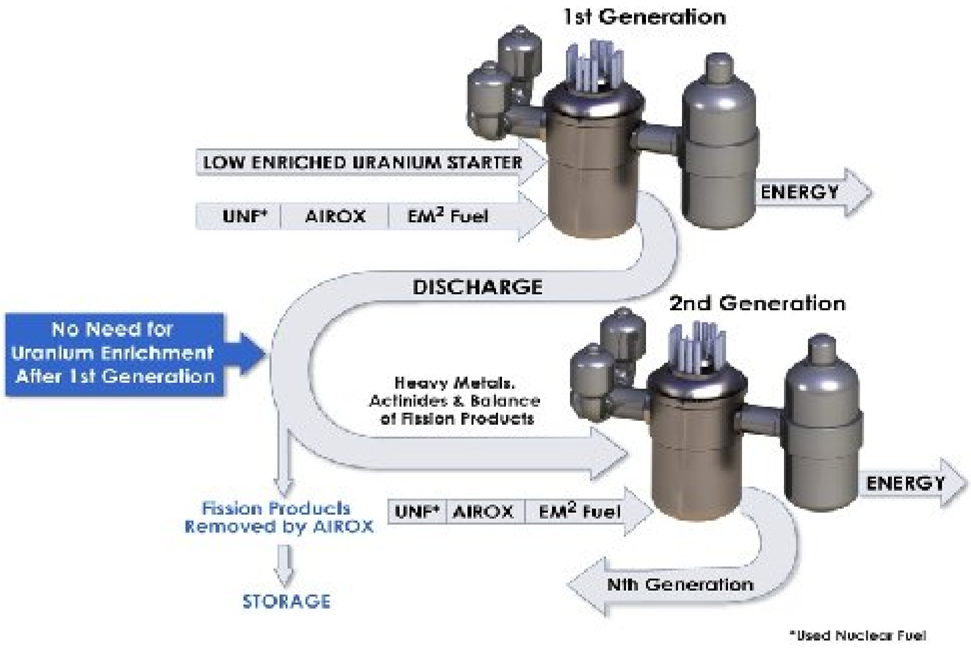

Fig. 10. Illustration of EM^2 closed fuel cycle without conventional reprocessing.

EM^2 REFABRICATION OF SPENT FUEL

The process for making EM^2 fuel is illustrated in Fig. 11. Uranyl-nitrate particles containing carbon are made through a sol-gel process. After drying and calcining, the particles are in the form of an oxide with carbon. The particles are then heated to convert them to UC. The particles are then sintered into an annular pellet with a pre-determined porosity. The tubular SiC composite clad is made separately. After inserting pellets into the SiC composite tube, end caps are applied and sealed. However, the key difference between EM^2 and today's reactors is its ability to use refabricated spent nuclear fuel.

Technological advances will need to be demonstrated for recycling used nuclear fuel (UNF). A simple process such as voloxidation or AIROX [5], is adequate to reformulate LWR UNF to have satisfactory reactivity in an EM^2 core. This process eliminates fission products that are volatile at less than 600^{o}C but no heavy metals. A schematic illustration of the enhanced voloxidation method of recycling both LWR and EM^2 discharged fuel into EM^2 fuel is shown in Fig. 12. After piercing the clad, oxidizing and reducing gases are introduced to pulverize the fuel pellet and leave the heavy metals in an oxide form. A significant number of fission products are also released during this process. Additional gases are introduced to react with remaining fission products to form volatile compounds such that they can also be released at varying process temperatures. The fission product compounds are collected on adsorber beds. Heavy metals including uranium, plutonium and other transuranics remain as oxides mixed with unreleased fission products. This mixture is the feedstock for the EM^2 fuel fabrication process.

Although voloxidation can convert end-of-cycle EM^2 fuel into a viable "driver" fuel, it does not separate out all fission products, and the reformulated fuel can only operate a finite number of cycles before the fuel form will be unacceptably degraded in reactivity through buildup of fission products that displace burnable fuel. The number of usable cycles for EM^2 used fuel can be extended indefinitely by a process that removes at least 40% of every fission product.

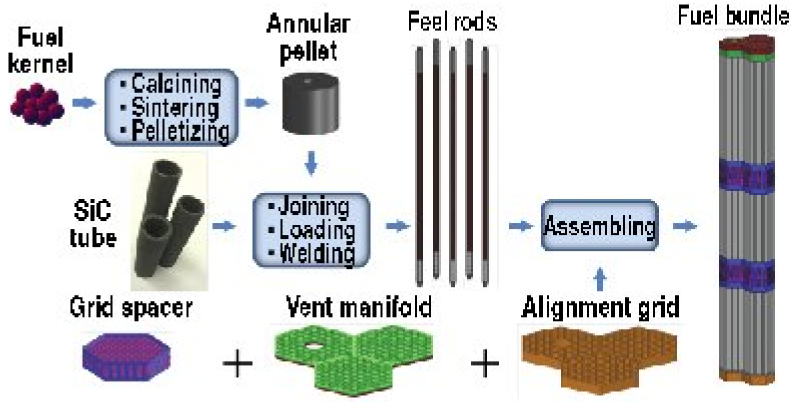

Fig. 11. EM^2 fuel manufacturing process.

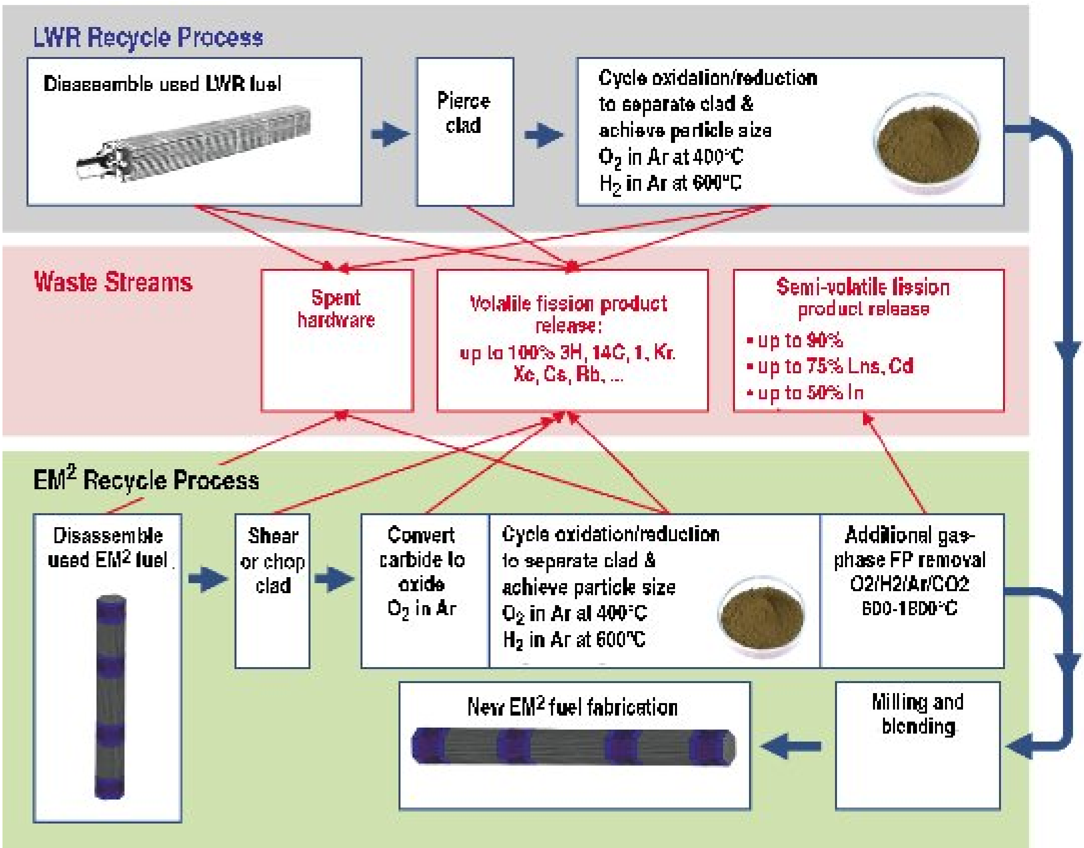

Fig. 12. Adaptation of voloxidation process to proliferation resistant re-fabrication of LWR and EM^2 fuel.

Light Water Reactor Spent Fuel

In the U.S. alone there is over 70,000 tonnes of spent fuel at the reactor sites in either spent fuel pool or dry cask storage (Fig. 13). The cessation of the Yucca Mountain project will create demand for alternative disposition options of the spent fuel from today's commercial reactors. As 95% of the initial energy still remains stored in the spent fuel (if used in EM^2), then implementation of this reactor concept opens the door for LWR spent fuel use. Rather than using the funds collected for spent fuel disposition in Yucca Mountain, these funds could be more effectively used to fund the difference in re-fabrication cost of LWR spent fuel versus natural or depleted uranium. After use in the EM^2, the LWR spent fuel becomes EM^2 spent fuel (discussed below).

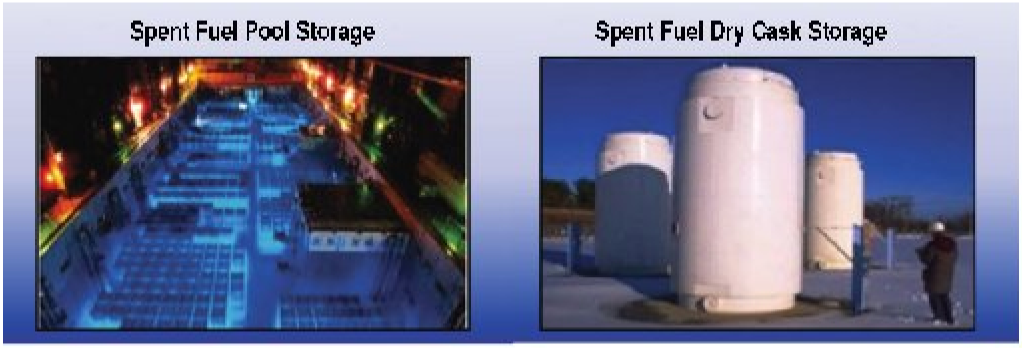

Fig. 13. U.S. Spent Fuel in Pool or Dry Casks provide an available resource for EM^2.

The energy content in the U.S. spent fuel is 0.8 Trillion Barrels of Oil Equivalent, which is equivalent to 42% of the total U.S. fossil energy reserves (coal, natural gas and oil). This resource is readily accessible and under the responsibility of the U.S. government.

Depleted Uranium

Depleted uranium (DU) does not get the attention of spent nuclear fuel, but the U.S. inventory is ten times larger than spent nuclear fuel (Fig. 14). Further, it is easier to re-fabricate into EM^2 fuel. After use in the EM^2, the DU becomes EM^2 spent fuel (discussed below).

The energy remaining in U.S. depleted uranium is about 9 Trillion Barrels of Oil Equivalent, effectively four to seven times the combined U.S. energy reserves of coal, oil and natural gas (Fig. 15). This resource is readily accessible and under the responsibility of the U.S. government.

Fig. 14. Depleted uranium – future EM^2 energy source.

EM^2 Spent Fuel

After energy production in EM^2 for decades the fuel can no longer sustain critical operations. Therefore after a suitable cooling period, the fuel can undergo re-fabrication (Fig. 12) and with the addition of fertile material (additional LWR spent fuel or natural/depleted uranium), can be loaded into an EM^2 reactor for additional decades of energy generation. This process removes a portion of the fission products which: (1) leaves the fuel self protecting due to the remaining fission products, (2) provides a waste stream effectively free of heavy metals which simplifies disposition storage time and other requirements, and (3) allows fuel fabrication without separation of heavy metals, reducing a proliferation concern.

This process also allows for second and later generations of EM^2 to operate without the need of further uranium enrichment. Enrichment is a major cost contributor to the fuel cycle cost, which partially offsets the cost of re-fabrication in a fuel line designed for the intrinsic radioactivity of the spent fuel.

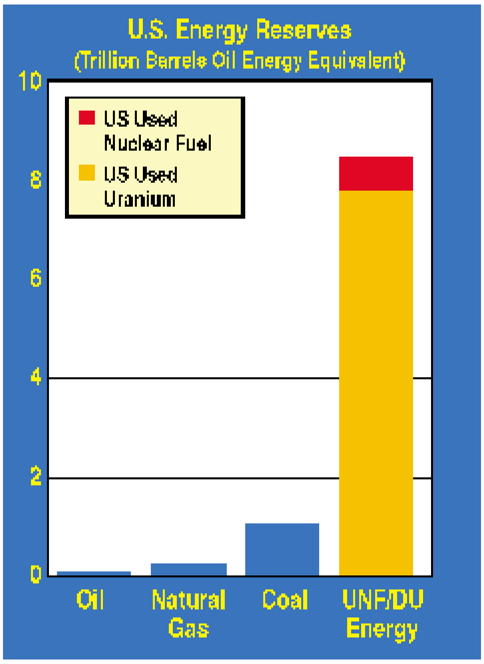

Fig. 15. Energy content of U.S. fossil fuel reserves and DU/SNF inventories.

BENEFITS FROM ENERGY MULTIPLIER MODULE IMPLEMENTATION

World Energy Benefits

One overall measure of the efficiency of an energy producing technology is the energy multiplication, defined as the ratio of the net useful energy supplied by a power plant over its operating life to the total energy invested in building, fueling, operating, and decommissioning that plant. As illustrated in Fig. 16, nuclear energy, embodied in LWR technology, compares favorably to fossil fuel options in both energy efficiency and capacity. Fifty years ago, the energy multiplication of all fossil fuel options was about 50, while that for nuclear energy was about 15. Oil and natural gas energy multiplication have dropped steadily in the intervening years as the easily tapped resources have been exhausted; they now have energy multiplications in the 10-20 range. During this same period, the energy multiplication of nuclear energy has increased by a factor of approximately four, owing to the use of more energy efficient centrifuge enrichment and to higher average burnup. Nuclear energy multiplication now approaches that of coal and exceeds that of all energy sources except for a few hydroelectric plants [1]. EM^2 is an alternative approach to nuclear power generation in which this figure of merit is increased by a factor of two.

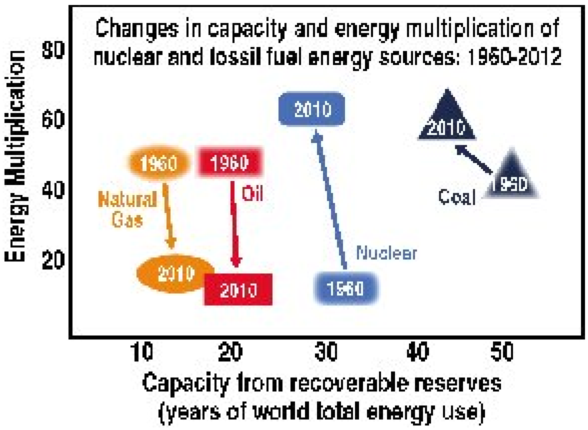

Fig. 16. Historical trends in capacity and energy multiplication of fossil and nuclear energy sources.

The capacity plotted in Fig. 16 presumes that the entire world's energy needs are met by the single energy resource in question and the value of that resource equal to the world's recoverable reserves. The figure shows that the capacity (measured in years of current world total energy use) in 2010 approximates that in 1960 for each fuel, which means that the reserves have increased in line with world energy usage. The cost of each energy source has increased substantially during this period. In simplistic terms, the cost increase for oil and natural gas stems from more difficult extraction, while for coal and nuclear, this increase is due largely to additional regulatory demands and labor costs that have risen faster than inflation. Coal has the highest capacity, but environment concerns may not allow full utilization of this resource.

The capacities for each fuel are only a few decades, and it can be expected that energy prices will continue to rise as these resources are depleted. Among these fuels, only nuclear has the potential to meet the world's energy needs beyond the present century. Today's nuclear technology merely extracts 0.5% of the energy in the uranium mined for this purpose. Furthermore, the thermal energy produced in this manner is converted to useful energy at a low efficiency compared to modern fossil plants because of temperature limitations inherent in the use of water as the coolant. Advanced nuclear technologies that go beyond these limitations have been explored for decades, but none are close to widespread usage. For example, breeder reactors convert fertile fuel to fissile fuel, which is then extracted by reprocessing and burned in other reactors. This approach does not appear to be destined for wide adoption because it is regarded as very costly and because it poses a serious risk of proliferating the availability of nuclear materials for potential clandestine uses.

Benefits from LWR Spent Fuel Disposition

Today's spent nuclear fuel is distributed in most U.S. states (Fig. 17). By removing spent nuclear fuel and utilizing it as energy in EM^2, this "waste" which has been a responsibility for the government but a burden for the utilities can become a resource where it is slowly converted to fission products while provide centuries of useful energy.

In the wake of the Yucca Mountain decisions, there is a resulting degree of uncertainty of waste confidence for commercial reactor spent nuclear fuel. The implementation of the EM^2 program, as a disposition path for LWR spent nuclear fuel, would provide waste confidence long before the first EM^2 was in operation.

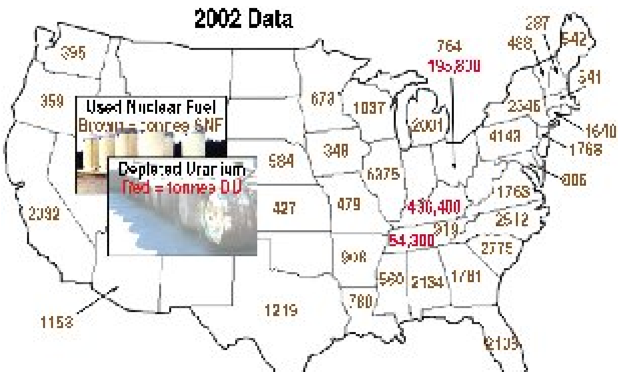

Fig. 17. Spent Fuel and Depleted Uranium Locations (tonnes as of 2002).

EM² Proliferation-Resistance Benefits

Fast reactors are considered synonymous with proliferation challenges in many circles, but the energy spectrum of the neutrons is not tied to the reprocessing. EM² provides a more benign approach to using LWR SNF. While no nuclear fuel cycle is completely "proliferation proof", EM²'s elimination of the need for enrichment after the first generation provides a net proliferation resistance benefit to the fuel cycle. In addition, EM² minimizes spent fuel production producing wastes that are primarily short-lived fission products. Also, from a safeguards perspective the elimination of refueling every 18 months simplifies assurance against material diversion by limiting periods of access within the reactor vessel.

The fact that heavy metals are never removed at any stage of the process is another major proliferation resistance advantage. It is also noted that end-of-cycle EM² fuel elements meet the International Atomic Energy Agency (IAEA) definition of self-protection (1 Sv/h at 1 m) for thirty years after removal from the core [7]. Because reformulated fuel still contains fission products, it has a similar self-protection feature. The fact that sophisticated remote handling equipment is needed to deal with both beginning-of-cycle (after the first generation) and end-of-cycle fuel is another proliferation-resistance merit.

EM² Waste Reduction Benefits

Because EM² can burn virtually any fertile or fissile fuel including transuranics, it opens up the possibility of eventually reducing the nation's nuclear waste burden. If end-of-cycle EM² cores can be remanufactured into fuel for a subsequent cycles, the net waste generated per cycle can be greatly reduced. This is illustrated in Fig. 18, which compares the mass of waste generated in LWRs with that of a number of EM² reactors of the same net electric power output.

In principle, every heavy metal isotope will eventually burn in an EM² core. The waste products requiring disposition in a geological repository can be reduced further by fission product separations technologies. Only 3% of the mass of EM² fission products represents long-lived isotopes, primarily ^{99}Tc and ^{129}I. Because actinides dominate both the decay heat and the spent nuclear fuel long term radio-toxicity, managing fission product-dominated waste stream is significantly easier and much less expensive than managing today's actinide-dominated waste stream.

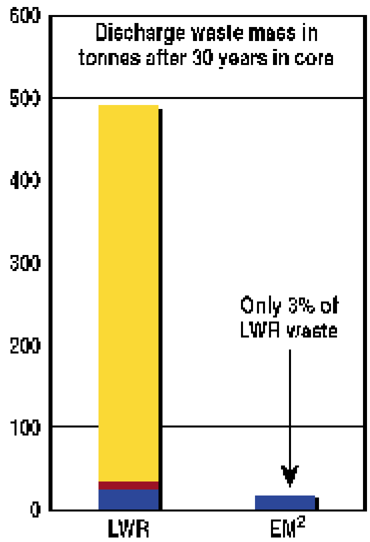

Fig. 18. Comparison of the net waste in tons after 30 years of operation for 1.2 GWe advanced LWR and EM² plants.

EM² Economic Benefits

The physical size of all the EM² subsystems is compatible with factory fabrication and truck transportation to the site. The use of small, modular equipment allows nuclear plant providers to take advantage of more cost-effective manufacturing and assembly line fabrication practices. Minimizing the on-site workload also reduces the time required for overall plant construction. Power plant complexes can be built up over time with much smaller capital cost increments, based upon individual 250 MWe stages. Together with the aforementioned reduced construction time, this significantly reduces the cost and difficulty associated with financing, which today is a major impediment to utility commitment for new nuclear plants. Note that, in contrast to small modular LWR concepts, the energy conversion efficiency is much higher in EM^2 (i.e. ~70% higher). This has a powerful impact on plant economics.

Based upon its attributes, EM^2 offers distinct advantages compared to LWRs in most areas that serve as cost drivers for providing energy. These areas include (on a per unit power delivered basis) the amount of materials required for construction, the amount of real estate needed for the plant, the life cycle cost of fuel, the on-site labor, the cost of money, the cost of waste handling, and the cost of heat rejection. These considerations provide a basis for optimism that the economics of EM^2 will be very attractive, perhaps competitive with U.S. natural gas fired energy sources, today's lowest cost energy technology.

CONCLUSION

Convert and burn reactors derive considerably more energy from a given amount of uranium so they will exhibit energy returns on investment significantly higher than LWRs. Even a first generation EM^2, i.e. one without fuel reformulation, will have an energy multiplication in excess of 100, a figure that is at least double that of all fossil fuels. As previously mentioned, it extends the capability of uranium reserves to meet world energy demand from a century to millennia.

Unlike many LWR SNF disposition concepts, the EM^2 fuel cycle conversion of SNF produces energy and associated revenue. By providing conversion of SNF to fission products the fuel cycle is closed and a significantly less burdensome LWR SNF disposition path is created.

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