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Review Article

Review on Nanotechnology Applications in Nuclear Energy

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Abstract

Today, the need to transition away from our reliance on fossil fuels is growing increasingly urgent. Although the expansion of renewable energy and nuclear fusion & fission will likely be keys to achieving this goal, this rollout isn't happening fast enough to avoid catastrophic damages to societies and natural ecosystems in the near future. The use of the latest engineered nanomaterials in nuclear energy systems has opened doors for improving the performance and safety of nuclear power. Nuclear Nano Technology (NNT) deals with the use of the engineered nanomaterials & nano fluids for future nuclear energy applications. This literature review summarizes the recent and ongoing research in labs around the world on Nuclear Nano-Technology development, focusing on the use of nanomaterials in area of the phase change materials for enhancing their thermal conductivity and efficiency, nuclear fuel manufacturing, and their capacity for the improvement of the safety and performance of the future generation nuclear reactors, cladding for increasing safety and fuel burnup, structural material in nuclear reactors structures and reduce radiation effects.

Introduction

With the rising global energy demand, the potential of nuclear energy, as a low-carbon energy resource, is becoming more and more obvious. But if nuclear energy is going to achieve its full potential, four grand challenges such as the maximization of application of available nuclear fuel uranium, the lifetime maximization of today's nuclear power plants, the resistance towards nuclear proliferation, and the minimization of nuclear waste via reasonable reprocessing and treatment must be fulfilled. New types of materials with unique behaviors and functions are considered to be central to meet all the four challenges [1].

New capabilities in the synthesis and characterization of materials with controlled nano-scale structure offer tremendous opportunities for the development of tailored materials for fabrication of advanced nuclear fuels (with nano-scale control of composition), use of actinides in catalysis, efficient nano-scale sorbents for spent nuclear fuel reprocessing, advanced nuclear waste forms and convenient sensors for detection of radionuclides [1], nanofluid for cooling system, nanomaterials for reactor structural material such as cladding and vessel. Therefore, some countries with developed nuclear energy programs, such as the USA, attach great importance to the research of nanomaterials and nanotechnologies.

In its Research and Development Roadmap - Report to Congress dated April 2010, the Department of Energy (DOE) Office of Nuclear Energy clearly identified four research and development objectives, among which include, —Developing technologies and other solutions that can improve the reliability, sustain the safety, and extend the life of current nuclear reactors," —Develop Improvements in the Affordability of New Reactors," and —Develop Sustainable Nuclear Fuel Cycles" [2]. Scientific communities around the world are working towards achieving these objectives and demands in various ways, including via Nuclear Nano-Technology (NNT), which is an efficient tool and candidate for achieving the goal of utmost safety and performance.

Nanotechnology is one of the fastest growing new areas in science and engineering. The subject arises from the convergence of electronics, physics, chemistry, biology and material sciences to create new functional systems of nanoscale dimensions. Nanotechnology deals with science and technology associated with dimensions in the range of 0.1 to 100nm [3]. The ability to fabricate structures with nanometric precision is of fundamental importance to any exploitation of nanotechnology.

Nuclear Nano-Technology addresses the issue of performance and safety in nuclear energy systems from various angles and works in different areas to achieve it. In this literature review, the ongoing research in the field of NNT is grouped and reviewed under the following classifications or areas, where engineered nanoparticles, nanoscale materials, properties, or processes are used to enhance mechanical, chemical, physical, or thermo-hydraulic properties and performance in nuclear energy systems

Note that: It is almost impossible, to summarize all the important results in nanomaterials and nanotechnologies related to nuclear fuel cycle system in one short article. Thus, the advances we select for discussion are limited to nanostructured materials, fuel such as PCM, uranium oxide nanocrystals, Cladding, nanofluid for cooling system, structural material for fusion reactor.

Nanoencapsulation of PCMs for Advanced Thermal Energy Storage Systems

Due to the high demand for immediate power, renewable energies are not currently reliable or economically viable enough to fully replace oil, coal, and natural gas. Even if is sufficient, Because of their intermittent nature renewables cannot provide reliable electricity daily and throughout different seasons. Meanwhile, the development of advanced nuclear reactors can promise the stability of the electricity grid and as base-load. In addition to these, it is vital to develop energy storage systems to ensure clean energy can be provided around the clock.

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The major drawback of renewable energies such as solar power is their intermittency – when the sun is not shining, no energy can be produced. This is where thermal energy storage is of great importance. Excess of thermal energy can be stored using an energy storage media, which acts as an energy sink. The energy can then be released during peak hours to meet demand, known as peak shifting [4].

In particular, thermal energy storage (TES) provides several advantages when integrated with nuclear energy. First, nuclear reactors are thermal generators, meaning that fewer energy transformation mechanisms are required when thermal energy is used as the coupling energy resource. Second, TES systems would preserve nuclear energy in its original form (heat), enabling much more flexible use when the stored energy is recovered (e.g., electricity production or steam supply for industrial systems). Third, a thermal buffer allows a decoupling between the nuclear core and the power conversion unit that historically has dictated system operation [5].

TES performance depends on such criteria as type, size, storage medium and heat-transfer fluid (HTF) materials, ambient temperature, constant or variable working temperatures, and application [6]. All classifications of TES technologies are generally based on three common routes of energy storage: sensible heat, latent heat, and thermochemical energy.

In sensible TES, energy is stored by changing the temperature of a storage medium such as water, air, oil, rock beds, bricks, sand, or soil. The amount of energy input to TES by a sensible heat device is proportional to the difference between the storage final and initial temperatures, the mass of the storage medium, and its heat capacity [6]. Each medium has its own advantages and disadvantages. For example, water has approximately twice the specific heat of rock and soil. The relatively low heat capacity of rocks and ceramics (~0.84 kJ/kg C) is somewhat offset by the large temperature changes possible with these materials, and their relatively high densities (Tomlinson and Kannberg, 1990). sensible heat storage technologies consist of a storage medium (liquid or solid), a container (usually a tank), and a heat transfer fluid. The heat transfer fluid absorbs the thermal energy from the heat source and transfers it to the storage medium. It can also do the same thing in reverse: namely, absorb heat from the storage medium and deposit it to a heat user [5]. the existence of a thermal gradient across storage is desirable. Maintaining thermal stratification is much simpler in solid storage media than in fluids.

Latent heat storage refers to heat transfer associated with phase transitions, which cannot be detected with a thermometer. Latent heat storage is more efficient and has a far superior storage density than sensible heat storage. Materials that utilize latent heat storage are known as phase change materials (PCMs).

Currently, low-temperature latent heat storage systems are already commercialized and have been commissioned in various residential, commercial, and industrial facilities for heating and cooling peak load shifting [5].

latent heat storage systems for use in higher temperature NPPs may cause additional challenges. latent heat storage systems for high-temperature applications has been remained at the laboratory scale for validation in relevant environments with TRL 5.

Thermochemical energy storage (TCES) utilizes a reversible chemical reaction and takes the advantage of strong chemical bonds to store energy as chemical potential. Compared to sensible heat storage and latent heat storage, this theoretically offers higher energy density with minimum energy loss during long-term storage due to the temperature-independent means of storage [7]. Current challenges regarding thermochemical storage technologies include the high cost of such systems and the technical complexity and finding the appropriate reversible chemical reaction for the energy source involved in their use. TCES technologies are mainly divided into two groups, thermochemical sorption storage system and chemical reaction storage system.

Thermochemical reactions are used as thermochemical materials (TCM) at high temperatures (more than 400°C) and the enthalpy of the reaction is located in a high range (from 80 to 180 kJ/mol). In addition, since the products of the reaction must be store separately, the systems that use TCM to store energy can be applied as seasonal storage systems (Michel et al., 2012).

Phase change materials

When a material melts or vaporizes, it absorbs heat; when it changes to a solid (crystallizes) or to a liquid (condenses), it releases this heat without changing in temperature. This phase change is used for storing heat in PCMs in the thermal energy storage (TES) systems.

Characteristics of PCM differs for material from organic (paraffins, polymers, alcohols, fatty acids), inorganic (i.e. salt, salt hydrates) and eutectics (mixtures of inorganics and/or organics) group. Phase change materials can be classified based on the type of transition: solid-liquid, solid-solid, liquid-gas [8]. Typical PCMs are water/ice, salt hydrates, and certain polymers. Since energy densities for latent TES exceed those for sensible TES, smaller and lighter storage devices and lower storage losses normally result. Like ice and water, eutectic salts have been used as storage media for many decades. one important application of PCMs was in association with space technology, with NASA sponsoring a project on PCM applications for thermal control of electronic packages [8].

There are some proprieties required for PCMs used in TES systems [9,10]:

a) melting point
b) high heat of fusion
c) high thermal conductivity in both phases
d) non-toxicity, non-flammability and lack of explosive properties during normal use
e) compatibility with container material
f) small volume change during the transition
g) stability after many work cycles
h) small temperature difference between the melting and solidification points
i) reasonable price

Many characteristics are desired of a PCM. Since no material can satisfy all of the desires, the choice of a PCM for a given application requires careful examination of the properties of the various candidates, weighing of their relative merits and shortcomings, and, in some cases, a certain degree of compromise.

Factors involved in the selection of heat storage materials include cost, storage density and reliability.

The most frequently employed PCMs for medium- and high-temperature applications were recognized as salt-based, metallic, inorganic compounds, and eutectic. The potential of medium-high melting temperature PCMs is often limited by barriers such as low thermal conductivity and low efficiency of PCM storage systems. Some past studies have therefore looked at various methods of enhancing their thermal conductivity with materials such as metal particles, carbon, and ceramic-based additives [11].

Nano-size storage media or PCM particles and capsules

PCM size has a significant effect on heat transfer rates between PCMs and HTFs (Heat Transfer Fluid), and affects the HTF pressure drop. PCM particle (or capsule) size also affects the total heat capacity of a flowing fluid in which tiny PCM particles are dispersed as a secondary refrigerant. As these factors affect the performance of a plant integrated with a TES system, the impact of PCM size is evident [8].

In recent years, there has been considerable interest in shape-stable composite PCMs and encapsulation of PCMs within a solid shell. the encapsulation of PCMs into micro and nano-capsules is possessing 'smart shell' properties, see figures 1 & 2.

Nanoencapsulation is one of the most promising solutions to increase the efficiency of PCMs, both organic and inorganic. It promotes high specific surface area, prevents exchange of encapsulated material with the environment, controls heat exchange across the capsule shell and initiates congruent melting/crystallization due to the small core size. Energy nanocapsules can find new application fields in thermal energy storage, such as cascaded multi-temperature energy systems, additives to thermal paints or other building materials, etc. [4].

New methodology for capsule production needs to be developed further, such as complex emulsions, layer-by-layer assembly, microfluidics and industrial-scale sonication. These high-throughput manufacturing methods will lead to simple and wide-scale fabrication of PCM nano-capsules, reducing costs and increasing viability [4].

Nanomaterials are able to enhance the effective thermal conductivity of heat transfer fluids (HTFs). Factors of Nanomaterials Affecting the Specific Heat Capacity are included the Size of nanomaterials and Nanomaterial concentration.

Discrepancies in the particle size-dependent specific heat capacity of molten salts have been found in literature, which may result from the variation of materials and/or methods used in different experiments. Noticeably different results of the effect of nanomaterial concentration on the variation of specific heat capacity of molten salts were reported by many researchers. It has been found that the largest enhancement of specific heat capacity was usually achieved at a concentration of 1 wt.%, but not constricted to the same kind of nanomaterials in different studies [12].

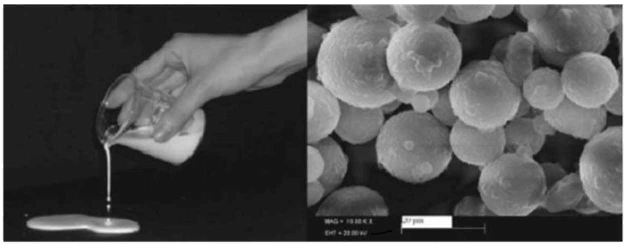

Figure 1: Flowing Micro/Nanoecapsulated PCM as a phase-change slurry (Wang et al., 2008a).

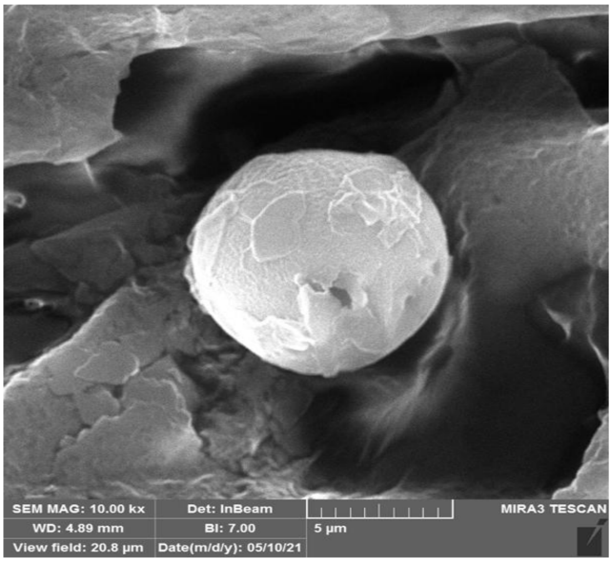

Figure 2: SEM image of microcapsules PCM for TES system.

Nanofluids Application in Reactor Cooling System

Nuclear power plants can be considered as the safest and most reliable facilities in the world. But these days a lot spoken about the accidents that have potential to happen, which people and the environment can adversely be affected. In PWR nuclear reactors all the designers' efforts are to prevent the two-phase flow to occur. So, the pressure in the core is set in a point to don't let the fluid to boils and became steam.

Nuclear reactions can be associated with high heat energy release. Extracting such energy efficiently requires the use of high-rate heat exchangers. Conventional heat transfer fluids, such as water and oils are limited in their thermal conductivity, and hence nanofluids have been introduced lately to overcome such limitation. By suspending metal nanoparticles with high thermal conductivity in conventional heat transfer fluids, thermal conductivity of the resulting homogeneous nanofluid is increased. Heterogeneous nanofluids offer yet more potential for heat transfer enhancement. By stratifying nanoparticles within the boundary layer, thermal conductivity is increased where temperature gradients are highest, thereby increasing overall heat transfer of a flowing fluid. In order to test the merit of this novel technique, a numerical study of a laminar pipe flow of a heterogeneous nanofluid was conducted. Effect of Iron-Oxide distribution on flow and heat transfer characteristics was investigated. With Iron-Oxide volume concentration of 0.009 in water, up to 50% local heat transfer enhancement was predicted for the heterogeneous compared to homogeneous nanofluids. Increasing the Reynolds number is shown to increase enhancement while having negligible effect on pressure drop. Using permanent magnets attached externally to the pipe, an experimental investigation conducted at MIT nuclear reactor laboratory for similar flow characteristics of a heterogeneous nanofluid have shown up to 160% enhancement in heat transfer. Such results show that heterogeneous nanofluids are promising for augmenting heat transfer rates in nuclear power heat exchanger systems. Critical heat flux (CHF) is the thermal limit of a phase change phenomenon where boiling occurs during heating, which suddenly decreases the efficiency of heat transfer. CHF is one of the key parameters that by exact calculation of it can be a good support to covers the safety functionality of nuclear reactors.

Nanofluids are engineered colloidal suspensions of nanoparticles in water and exhibit a very significant enhancement (up to 200%) of the boiling critical heat flux (CHF) at modest nanoparticle concentrations ($0.1% by volume). Since CHF is the upper limit of nucleate boiling, such enhancement offers the potential for major performance improvement in many practical applications that use nucleate boiling as their prevalent heat transfer mode. The Massachusetts Institute of Technology is exploring the nuclear applications of nanofluids, specifically the following three:

a) main reactor coolant for pressurized water reactors (PWRs)

b) coolant for the emergency core cooling system (ECCS) of both PWRs and boiling water reactors

c) coolant for in-vessel retention of the molten core during severe accidents in high-power-density light water reactors

The main features and potential issues of these applications are mentioned. The first application could enable significant power uprates in current and future PWRs, thus enhancing their economic performance. Specifically, the use of nanofluids with at least 32% higher CHF could enable a 20% power density uprate in current plants without changing the fuel assembly design and without reducing the margin to CHF. The nanoparticles would not alter the neutronic performance of the system significantly. A RELAP5 analysis of the large-break loss-of-coolant accident in PWRs has shown that the use of a nanofluid in the ECCS accumulators and safety injection can increase the peak-cladding-temperature margins (in the nominal-power core) or maintain them in uprated cores if the nanofluid has a higher post-CHF heat transfer rate. The third application can increase the margin to vessel breach by 40% during severe accidents in high-power density systems such as Westinghouse AP-1000 and the Korean APR-1400. In summary, the use of nanofluids in nuclear systems seems promising; however, several significant gaps are evident, including, most notably, demonstration of the nanofluid thermal-hydraulic performance at prototypical reactor conditions and the compatibility of the nanofluid chemistry with the reactor materials. These gaps must be closed before any of the aforementioned applications can be implemented in a nuclear power plant [13].

Development of Nanomaterials for Structural Materials and Nuclear Fuels in Nuclear Industry

The use of nanomaterials to improve properties and develop new materials for different applications are accomplished in two ways adding to the alloys and surface coating. Also, the features of the structure and properties of nanopowders provide the possibility of developing new materials for nuclear power industry and improving materials already used in this industry.

At present the limitation of maximum fuel burn-up is connected with relatively low radiation resistance of structural materials for fuel pin claddings and low heat resistance of wrappers of fuel assemblies.

It has been experimentally shown that the use of nanopowders is promising for the modernization of the technology of a uranium-containing fuel for nuclear reactors and for the improvement of its parameters. These powders in the nanocrystalline state can be sintered and compact pellets can be obtained. Similar prospects have been demonstrated for the modernization of neutron-absorber pellets of controlling rods by changing boron carbide to dysprosium hafnate [14]. Nano-Technology Engineered

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Fuels designed or produced with nanotechnologies can enhance service lives, avoid losses during the fabrication process, and avoid the potential for failure in normal or accidental conditions, such as increased fission gas retention, plasticity, radiation tolerance, and heat transfer capability, as well as reduced fuel cladding chemical and mechanical interactions. As a result, the fuel burnup is improved and the refueling period increases.

The main factors which determine the radiation resistance of structural materials for nuclear reactor are: void swelling, radiation creep, high- and low-temperature radiation embrittlement and also the radiation stability of structure and properties of material in the field of neutron irradiation.

Steel is the widely used material in nuclear power plants. The utilization of nanoparticles in the steel will help in enhancing the mechanical, thermal, and physical properties of the steel. The structural failure of the steel is due to cyclic loading. This delivers a considerable impact on the nuclear power plant's life-cycle. This may result in crack initiation. The addition of copper nanoparticles in steel minimizes surface unevenness. This results in the confinement of the number of stress risers and further fatigue cracking [15].

Controlling radiation-induced defects via interfaces plays a crucial role in the removal of damages and also transmits stability in nano-particles under certain circumstances where bulk materials demonstrate void swelling and/or embrittlement. Nanostructured metals and composites suggest a way to accomplish this goal because they comprise interfaces that attract, absorb and annihilate the line and defects [16].

Nanoparticles are able to shift some mechanical and physical specifications of materials towards specific purposes and to improve some parameters such as mass attenuation coefficient at nuclear facilities due to high ratio of surface to volume [17]. The different NPs have been used in concrete mixtures as shield in order to improve both the mechanical properties and pore structure of the concrete [18] This feature is useful to design a shield in nuclear science which merely change the mixed-material density nonlinearly.

Advanced fuels for utilization in advanced reactors have a good technology maturity relative to the fuel cladding. Meanwhile, the development of cladding with high creep strength and maintaining swelling resistance can speed up the commercialization process of the technology.

High-Cr F/M steels exhibit superior swelling resistance which should allow for higher burn-up and increase safety margins. However, their strength is limited for higher temperatures (typically above 650ºC). Oxide Dispersed Strengthened (ODS) alloy versions of ferritic steels, reinforced by a distribution of nano-oxides (or nano-clusters, NC), show higher creep strength and maintain swelling resistance, making them good candidates for the cladding of advanced fast reactors (LFR and SFR cladding).

Therefore, ODS ferritic and F/M steels are envisioned as reference cladding for high burn-up fuel in fast reactors [19]. Nanostructured Ferritic Steels (NFSs) with 12-14 wt% Cr have attracted widespread interest for potential high-temperature structural and fuel cladding applications in advanced nuclear reactors. The properties of the NFSs depend on the composition that mainly consists of Cr, Ti, W or Mo, and Y_2O_3 as alloying constituents [20].

A major effort of research is being invested in developing fewer brittle ceramics forms such as composite ceramics, or nano-structured plastic ceramics.

Ceramic materials are needed for very high temperature components (> 1000°C) such as heat exchangers and thermal insulations in the primary system, as well as core components such as control rod sheath (V/HTR and GFR) and fuel constituents (GFR as shown in figure 3) [21].

Long-term experiments such as neutron irradiation experiments, creep tests and long-period corrosion and aging tests, are necessary to assess the performance of structural material of advanced nuclear systems with high efficiency and high burn-up.

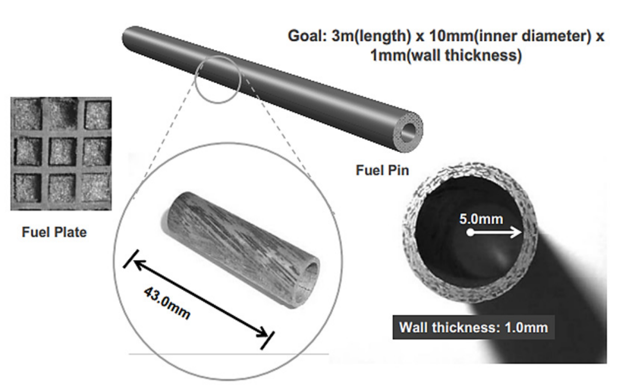

Figure 3: 2-D SIC/SIC fuel pin or fuel plate for GFR [20].

Nanomaterials Application in Fusion

For the nuclear fusion reaction, the light nuclei must come close enough to each other and weld together. The requirement is that the nuclei have high kinetic energy so they can overcome the mutual Coulomb repulsion.

One way to provide this energy is to heat the fuel to a temperature of about 100 million degrees Celsius, about 16 times the temperature of the Sun's core. Therefore, such a reaction is called a thermonuclear fusion reaction.

Deuterium (D ≡ ^{2}H) and tritium (T ≡ ^{3}H) fusion reaction has the largest cross-section and the lowest required plasma temperature among other fusion reactions [22].

$$D + T \rightarrow {}^{5}He \rightarrow {}^{4}He\ (3.5\ MeV) + {}^{1}n\ (14.1 MeV)$$

At such a high temperature, the fusion reaction fuel turns into an ionized gas called plasma, the fourth state of matter (Figure 4) [23].

Harnessing of hot plasma by material walls is not possible. Therefore, two methods have been researched and developed: Magnetic Confinement Fusion (MCF) and Inertial Confinement Fusion (ICF) [24].

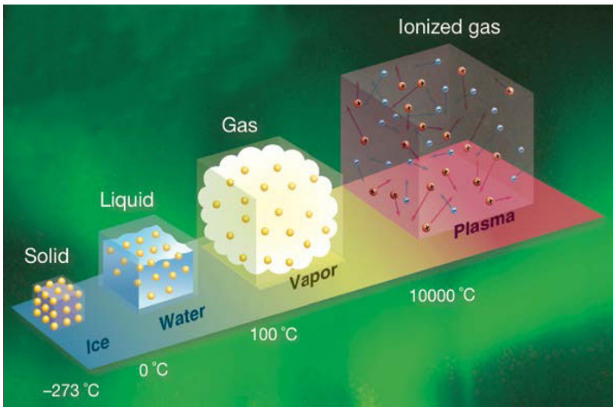

Figure 4: A boiling mixture of charged particles, plasmas can be considered the 4th state of matter

Achieving fusion energy as a commercial and economical energy source has not been achieved until today, and scientists have a long but clear road ahead. The world community's magnetic confinement nuclear fusion effort in the first global international project, ITER (International Thermonuclear Experimental Reactor, a fusion tokamak experiment to generate 500 MW of fusion power with high gain Q>10, fusion/external heating power), is proof of this claim. The results of R&D show that the energy supply activities through nuclear fusion will reach an unprecedented level of engineering and technological achievements in this century. Nuclear energy-driven magnetic confinement is on the verge of achieving breakeven via donut shape device known as Tokamak, a toroidal apparatus for producing controlled fusion reactions in hot plasma (Figure 5).

Magnets produce magnetic fields that will initiate, confine, shape, and control the plasma. A Central Solenoid (CS), a magnet carrying an electric current, creates a second magnetic field along the "poloidal" direction. The divertor situated at the bottom of the vacuum vessel extracts heat and ash produced by the fusion reaction, minimizes plasma contamination, and protects the surrounding walls from thermal and neutronic loads. The vacuum vessel is torus-shaped and double-walled. The vacuum vessel provides a high-vacuum environment for the plasma, improves radiation shielding and plasma stability, acts as the primary confinement barrier for radioactivity, and provides support for in-vessel components such as the blanket and the divertor.

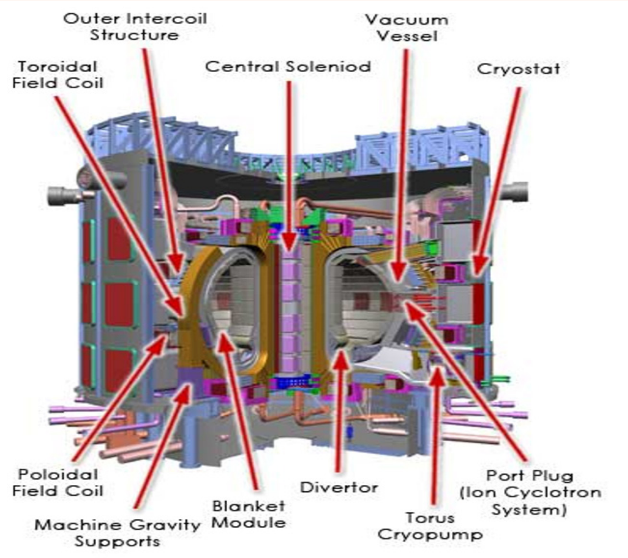

Figure 5: A tokamak is a device which uses a powerful magnetic field to confine plasma in the shape of a torus.

Cooling water circulating through the vessel's double steel walls will remove the heat generated during operation. Several openings, or ports, in the vacuum vessel provide access for remote handling operations, diagnostics, heating, and vacuum systems. The blanket modules that completely cover the inner walls of the vacuum vessel protect the steel structure and the superconducting toroidal field magnets from the heat and high-energy neutrons produced by the fusion reactions. As the neutrons are slowed in the blanket, their kinetic energy is transformed into heat energy and collected by the water coolant. One of the primary roles of blanket tokamaks built in the future is the production of tritium required for the fusion reaction through the interaction of fusion neutrons with the lithium compounds used in the blanket structure [25].

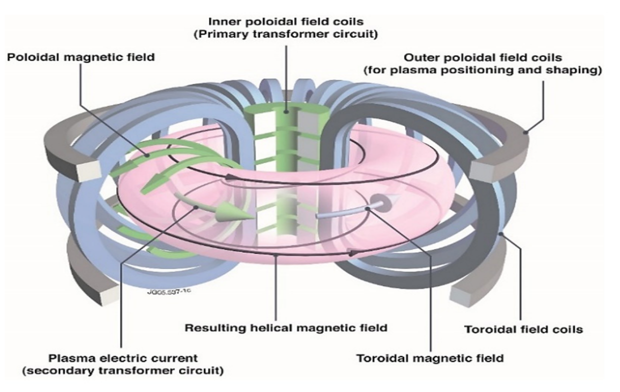

Figure 6: Magnetic Fields which confine plasma in a torus shape.

As mentioned, in a tokamak, magnetic fields are used to harness the plasma (Figure 6). In these configurations, a poloidal magnet creates toroidal field lines. Toroidal field lines alone cannot trap ions. Since ions and electrons rotate in different directions, they also move in opposite directions, and this causes the separation of charges. The separation of charges causes the formation of an electric field and instability in the plasma. This causes the plasma to collide with the chamber's walls, a type of disturbance. It is necessary to use a poloidal magnetic field to prevent the plasma from hitting the walls, to prevent excessive charge separation, and to balance the plasma pressure with the magnetic forces. In a tokamak, this field is generated by the plasma flow in the torus direction. Central Solenoid (CS) induces this current in the plasma.

High-energy neutrons of 14.1MeV are the main products of the DT fusion reaction. These uncharged non-ionizing particles leave the plasma containing charged particles without interaction and leave their kinetic energy in the wall surrounding the plasma. This heat is then transferred to a liquid or gas coolant and converted into electrical power by conventional systems. Also, neutrons provide the tritium required for fusion reaction through interaction with lithium used in the structure of blankets. In addition, through interaction with multipliers such as Be and Pb, neutrons cause neutron multiplication in the blanket structure, which is essential for the self-sustaining production of tritium. In addition to these, neutrons also have destructive effects. Tokamak structural materials exposed to high-energy neutron radiation suffer from radiation damage, such as displacement per atoms (dpa), and the production of gases such as hydrogen and helium, and lose their properties [26]. To meet this challenge, several materials – both structural and functional – are required to be developed.

Nanomaterials for magnetic confinement fusion

Although tremendous work has been achieved in the past decades in MCF, there remain significant challenges - particularly materials' role in designing future nuclear fusion energy reactors. As the materials have to face the high-energy neutrons, structural materials have to have radiation resistance apart from other properties, and the functional materials the required level of integrity. Part of this challenge is the extreme power exhaust on the surfaces of the walls that make up the fusion reactor, limiting the reactor's lifetime and operation. Fusion reactors are built to contain the plasma, and large-scale erosion of the wall material results in quenching the plasma energy in the reactor's core, limiting its operation. So, the walls of the plasma container have to be very strong. The coupling of the fusion plasma and its interface with the wall material is complex. Hydrogen and helium particles from the burning plasma implant on the material walls lead to erosion and poisoning of the plasma edge.

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Due to the complex and massive structure of nuclear fusion reactors, several materials – both structural and functional – are required to be developed. Recently, some studies have been done to utilize nanotechnology to address and improve plasma-facing materials for use in a fusion device.

The first wall of the Tokamak is the nearest wall to the plasma and, therefore, experiences high radiation damage due to the high energy neutrons. The critical issues related to the first wall materials include their transmutation and displacement damage due to the high-energy neutrons, and gas (Helium and Hydrogen) production because of the reactions of the neutrons with the atoms constituting the first wall. He (helium) Production rate in the material, due to its irradiation by the 14.1 MeV neutrons, is very high (in the range of 200-600 ppm/yr for steel) and, therefore, in its lifetime of 30 years, the material is likely to accumulate huge amounts of He [27].

Tungsten is considered the primary choice for this part of the tokamak due to its high melting temperature, good thermal conductivity, low swelling, and low tritium trapping.

Several designs were reported to mitigate the radiation damage that occurs when tungsten is exposed to high-heat and high-flux plasma in fusion devices which would result in greater radiation-tolerant tungsten materials. Low-Z films on tungsten, tungsten composites and alloys are currently some emergent plasma-facing component designs, which require additional doping or deposited elements to tungsten. Formation of ultrafine (grains of less than 500nm) and nanocrystalline (grains of less than 100nm) tungsten, on the other hand, is an alternative solution which does not require the addition of another element. By going to nanoscale grains, grain boundary area is increased which can act as helium particle sinks. Grain boundaries are considered a strong trap for helium particles. Although not mitigating surface changes under He irradiation completely, this approach could yield an increased particle fluence threshold for forming fuzz and other known surface morphology changes if the same were dominated by helium bubble formation mechanisms. In addition to providing sinks for helium particles, grain boundaries are known to be effective sinks for other defects. Grain boundaries can lead to improved radiation-tolerant materials. Grain boundaries were demonstrated to absorb interstitials formed due to collision cascades, and later re-emit them to combine with vacancies that approach grain boundaries. This can contribute to a denuded zone (few tens of nm from grain boundaries) where zero or a low concentration of bubbles is observed under helium irradiation. Furthermore, ultrafine and nanocrystalline tungsten has improved strength, ductility and fracture toughness compared to commercial tungsten materials (large grain materials with average grains >5–10μm). Thus, ultrafine and nanocrystalline tungsten should be investigated as candidate for Plasma Facing Materials [28].

Oxide dispersion strengthened alloys (ODS alloys) typically consist of a high temperature metal matrix - such as iron aluminide, iron chromium, iron-chromium-aluminum, nickel chromium or nickel aluminide - with small (5-50nm) oxide particles of alumina (Al_2O_3) or yttria (Y_2O_3) dispersed within it Iron-based and nickel-based oxide dispersion strengthened alloys exhibit good corrosion resistance and mechanical properties at elevated temperatures. These alloys also show excellent creep resistance, which stems partly from the dispersion of oxide and other particles, and partly from the very large elongated grain structure.

ODS materials as structural material in fusion reactors would allow the operating temperature to increase up to 650°C. It was illustrated that ODS steels possess high temperature strength by maintaining the ductility even at wide temperature range and the range can be further expanded for the application of fusion reactors [29].

A novel Ferritic ODS material with the chemical composition (Fe–13/18CrWTi), which acquires high chromium content, was tailored for the intended applications in high-temperature nuclear reactors. In order to make the materials compatible to be used in fusion reactors, the material was modified slightly by including nanoclusters (NCs). Homogeneous microstructure was observed with very fine grains broadened in the hot extrusion direction. The NCs were found within the matrix. The ODS material showed an enhanced tensile strength for temperature 750°C with ductility as expected for this type of material [30]. irradiation creep can be considered of technical relevance in advanced fast fission reactors and fusion plants [31]. Thus, evidence suggests that the nano-structured dispersoids in the Ferritic/Martensitic steels show improved mechanical properties and radiation resistance based on the size of the particles and distribution of the particles in the matrix.

Nanomaterials for laser-driven nuclear fusion

Using a compact but powerful laser to heat arrays of ordered nanowires, CSU scientists and collaborators have demonstrated micro-scale nuclear fusion in the lab. They have achieved record-setting efficiency for the generation of neutrons - chargeless sub-atomic particles resulting from the fusion process.

Laser-driven controlled fusion experiments are typically done at multi-hundred-million-dollar lasers housed in stadium-sized buildings. Such experiments are usually geared toward harnessing fusion for clean energy applications. In contrast, Rocca's team of students, research scientists and collaborators, work with an ultra-fast, high-powered tabletop laser they built from scratch. They use their fast, pulsed laser to irradiate a target of invisible wires and instantly create extremely hot, dense plasmas - with conditions approaching those inside the sun. These plasmas drive fusion reactions, giving off helium and flashes of energetic neutrons.

Inertial confinement works in a pulsed mode, where small portions of fuel are compressed and heated by powerful laser pulses so rapidly that a significant fraction of the atoms fuse as the superheated plasma expands. The energy released during the explosive process is limited by the mechanical, thermal, and radiation characteristics of the fusion chamber and is typically of the order of a few hundred megajoules.

Laser induced Inertial Confinement Fusion (ICF) is in a new exciting stage of development, due to the enormous increase of laser power, in particular due to the Extreme Light Infrastructure (ELI) Laboratories in the EU.

A diagram of the process of an inertial confinement fusion device has shown in figure 7 in four steps, respectively: a) lasers bombard the target fuel pellet b) the outer layer of fuel breaks down into a plasma, detonating outward and compressing inward c) the inner gas also forms a plasma, following the detonation shockwave d) once sufficient temperature and density are achieved, fusion reactions are achieved. Also, it has been shown a schematic of the Laser Inertial Confinement Fusion-Fission Energy (LIFE) Reactor conceived at Lawrence Livermore National Laboratory (LLNL) in figure 8.

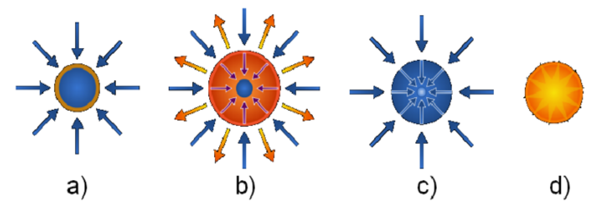

Figure 7: Process of an inertial confinement fusion device.

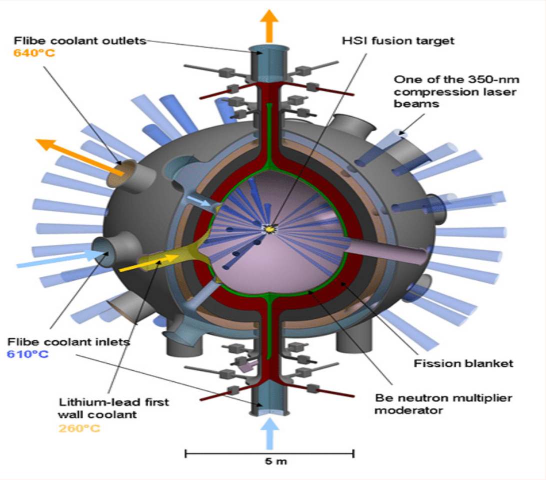

Figure 8: Schematic of the Laser Inertial Confinement Fusion-Fission Energy (LIFE) Reactor.

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A solution could be found through a new approach to fusion, where nuclear fuel is ignited more efficiently by rapid laser pulses when inserting nanoparticles in the target.

The mass of a single inertial confinement fusion fuel pellet is just a few milligrams, while the compression and fusion reaction occurs on the timescale of several nanoseconds. Potentially, such compact fusion reactors utilizing small-size fuel pellets may be a viable route toward commercially viable nuclear fusion. However, the successful application of this approach is hindered by the hydrodynamic instabilities in the rapidly compressed plasma of the fuel pellet caused by the high-intensity laser beams.

Recently, Nano-Plasmonic Laser Inertial Fusion Experiments (NAPLIFEs) was proposed [32,33] as an improved way to achieve laser-driven fusion in a nonthermal, collider configuration where implanted nano-antennas regulated and amplified the light absorption in the fusion target [L.P. Csernai et al., Phys. Wave Phenom. 28, 187–99 (2020)].

In the NAPLIFE project, new ideas of nano-plasmonic amplification in a layered flat target with variable absorptivity to reach simultaneous ignition were applied. The idea is to disperse gold rod-shaped nanoparticles throughout the target material (deuterated polystyrene in this case). The incident laser radiation would excite plasmonic resonance (collective oscillation of the free electrons) in the nanoparticles [34].

during pulses lasting for just a few nano seconds, some parts of the fuel will be more compressed than others – leading to a flow named a ‘Rayleigh-Taylor instability’. to avoid instability in the fuel by integrating specialized nanoparticles, In the experiments, it has been synthesized a number of golds nanorods measuring just with a length and width of only a few nanometers (Figure 9). As these rods dissolved in the liquid polymer precursor, they then dispersed to adopt a uniform distribution.

The researchers continue to explore more exotic plasmonic nanostructures, like spheres or torus-shaped nanoparticles, that can further enhance the energy absorption of the fuel target and bring us closer to achieving controlled nuclear fusion. Note that with the help of light, electrons on the surface of a metal can be forced to move like waves, in which thinning and thickening alternates. Named a “surface plasmon”, this new type of charge movement has shorter wavelengths than those of the light used to excite the metal surface.

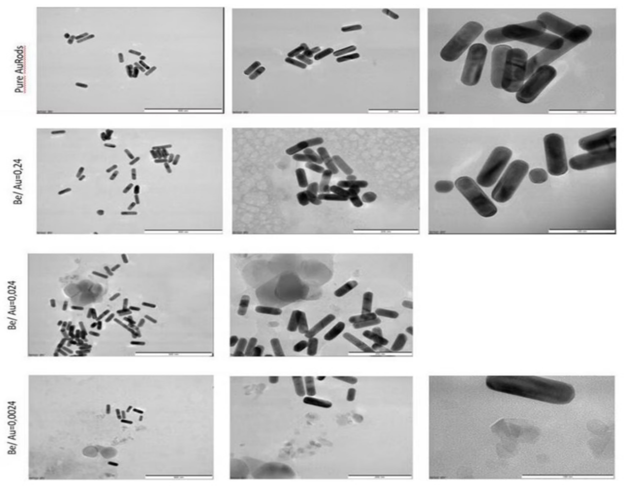

Figure 9: TEM (tunneling electron microscopy) images of various gold nanorods (Source: researchoutreach.org).

Conclusion

The basic research progress has been highlighted in nanomaterial and nanotechnologies for advanced nuclear fuel fabrication, structural and operational material such as cladding and cooling fluid for fission and fusion reactors and Thermal Energy Storage for advanced reactor.

It is clear that improvements are needed for all, from the manufacture of nuclear fuel to structural materials and other applications, and a slight improvement in each of these areas will certainly contribute to the advancement of performance and safety in nuclear energy systems. there are many hurdles to tackle before nanoparticles can be safely and effectively used in operating power plants and other sectors of nuclear industry. Scaling up particle production to the large volumes of particles necessary for implementation in a power plant is expensive and labor intensive. New synthesis infrastructures may be necessary for large-scale production of these tiny particles. Additionally, broad adoption of this technology will not occur until significant cost savings are proven effective at a functioning plant. As a result, particles must be made available at a cost reasonable for adoption.

In addition to cost-benefit analysis, extensive testing must be performed to ensure long-term application of these particles does not threaten the operational safety of the plant. To accomplish this, smaller scale reactors (research reactors) may test these particles over the course of years to track the impacts of long-term use. Potential pitfalls include increased corrosion, system clogging, and nanoparticle leakage into wastewater. Corrosion engineers will be needed to validate the degree to which nanoparticles contribute to the overall aging of reactors in which they are used.

It seems that development of new nanomaterials and using nanoparticles in nuclear power plant construction increases safety, stability, and durability, and also minimizes the tedious work of regular inspection. However, from the point of view of current international research status, nanomaterials and nanotechnologies in the field of nuclear energy are infancy in term of technology readiness level. there are still huge key scientific issues that should be addressed. With the deepening of the further research work, the advantages of nanomaterials and nanotechnologies will be found out step by step.

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