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MATERIALS FOR ADVANCED FUSION AND FISSION REACTORS

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ABSTRACT

Structural materials represent the key for containment of nuclear fuel and fission products as well as reliable and thermodynamically efficient production of electrical energy from nuclear reactors. Similarly, high-performance structural materials will be critical for the future success of proposed fusion energy reactors, which will subject the structures to unprecedented fluxes of high-energy neutrons along with intense thermo-mechanical stresses. Advanced materials can enable improved reactor performance via increased safety margins and design flexibility, in particular by providing increased strength, thermal creep resistance and superior corrosion and neutron radiation damage resistance. In many cases, a key strategy for designing high-performance radiation-resistant materials is based on the introduction of a high, uniform density of nano-scale particles that simultaneously provide good high temperature strength and neutron radiation damage resistance.

Keywords: Corrosion, Fission, Fusion, Nano-Scale Particles, Neutrons, Radiation

I. INTRODUCTION

Advanced Nuclear Materials discusses the major classes of materials suitable for usage in nuclear fission, fusion reactors and high power accelerators, and for diverse functions in fuels. The work addresses the full panorama of contemporary international research in nuclear materials, from Actinides to Zirconium alloys. Considerable changes in the operating performance of fission reactors, along with advances in the plasma physics knowledge required for heating and controlling fusion energy reactions suggest that fission and fusion energy can be important components of the overall energy portfolio for the 21st century and beyond. Advanced materials can enable improved reactor performance via increased safety margins and design flexibility, in particular by providing increased strength, thermal creep resistance and superior corrosion and neutron radiation damage resistance.

II. FISSION

A power reactor core contains fuel rods with a height of ~4 m and diameter ~1 cm. As illustrated in Fig. 1, a wide range of structural materials are used for a diverse variety of roles in fission reactors. The fuel cladding serves to reliably contain the fuel and radioactive fission products while efficiently transferring the intense nuclear heat from the fuel to the coolant. The typical heat flux through the cladding is ~1 MW/m^2 (~1% of the heat flux at the surface of the sun). Zirconium alloys are used as fuel cladding in most commercial reactors, due to their compatibility with $UO_2$and water, their adequate thermal conductivity and ease of manufacturing. A large number of these reactors are based on uranium dioxide fuel pellets arranged in long cylinders (“fuel rods”) with surrounding flowing water channels.

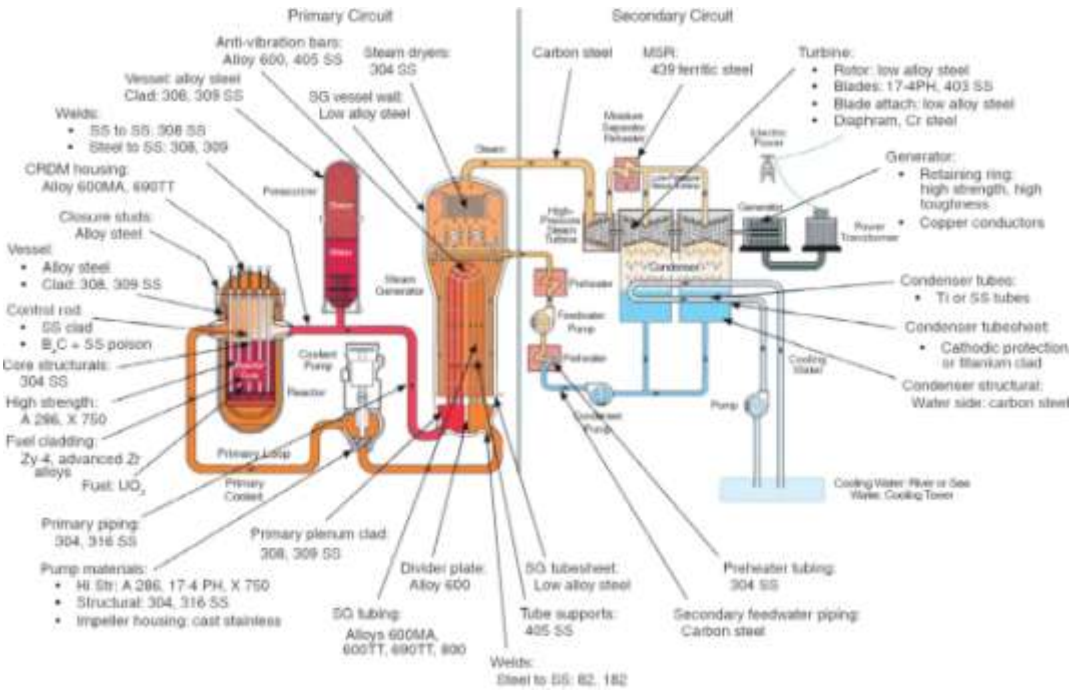


Fig.1: Diverse range of structural materials used in fission reactors

The fuel remains in the reactor for several years, with the cladding being subjected to high temperatures (3500C-4000C), mechanical stress, and intense radiation. Main problem includes oxidation, hydriding, build-up of low thermal conductivity corrosion deposits, and effect of hydrogen on cracking and corrosion. These core internal structures must reliably operate for over 30 years in a high radiation environment (resulting in higher accumulated doses than the fuel cladding in many cases) at ~300 °C without substantial dimensional changes or degradation in mechanical properties due to stress corrosion cracking or radiation damage. The reactor pressure vessel (quenched and tempered Mn-Mo-Ni low-alloy pressure vessel steel) serves as the critical safety boundary between the reactor and the environment, and is generally considered the key lifetime-limiting (irreplaceable) component for a nuclear reactor. Major concern is loss of fracture toughness due to radiation-induced defect cluster hardening and radiation-induced precipitation. The embrittlement is monitored by regular mechanical property testing of specimens located at the inside wall of the pressure vessel. Piping and heat exchanger materials (ferritic steels and Ni-base alloys such as Alloy 600 and 690) are designed to enable reliable and thermodynamically efficient conversion of thermal energy from the reactor into steam that drives turbines to generate electricity. Due to desire for reliable operation for decades at elevated temperatures in an aqueous environment at 300 to 350 °C, main concerns for the piping and heat exchanger materials include thermal aging and complex water chemistry issues that may induce corrosion or stress corrosion cracking. Aqueous corrosion is a complex form of degradation that is dependent on temperature, material condition, material composition, water purity, water pH, water impurities, and dissolved gas concentrations. The predominant corrosion mechanism varies with location in the reactor core and multiple mechanisms may be simultaneously operating[1 and 2]

III. FUSION

Continuous advancement over several decades has taken fusion researchers to the brink of demonstrating the plasma physics feasibility of fusion energy via magnetically-confined and inertially confined concepts. A schematic of a prototypic magnetic fusion energy reactor is shown in Fig.2. The fusion reactions are induced within a toroidal-shaped high temperature ionized plasma that is shaped by powerful toroidal and poloidal field magnets. The heat and energetic neutrons produced by the deuterium-tritium (D-T) fusion reaction are absorbed by the surrounding first wall, blanket, and divertor components. The fusion reaction occurs inside a vacuum vessel to prevent atmospheric contamination of the D-T plasma. The major functions of the blanket region are to efficiently capture the energy produced by the fusion reactions and transfer the heat to a coolant for electricity generation, and to create and extract fresh tritium fuel (by utilizing nuclear transmutation reactions with lithium-containing liquid or solid materials) to enable continuous operation of the fusion energy system. A wide variety of structural materials, reactor coolants, and tritium generation materials systems have been evaluated for potential use in future fusion reactors. Table 1 summarizes the material combinations that are considered to be the most promising based on thermodynamic efficiency, neutronics, chemical compatibility, and other engineering considerations

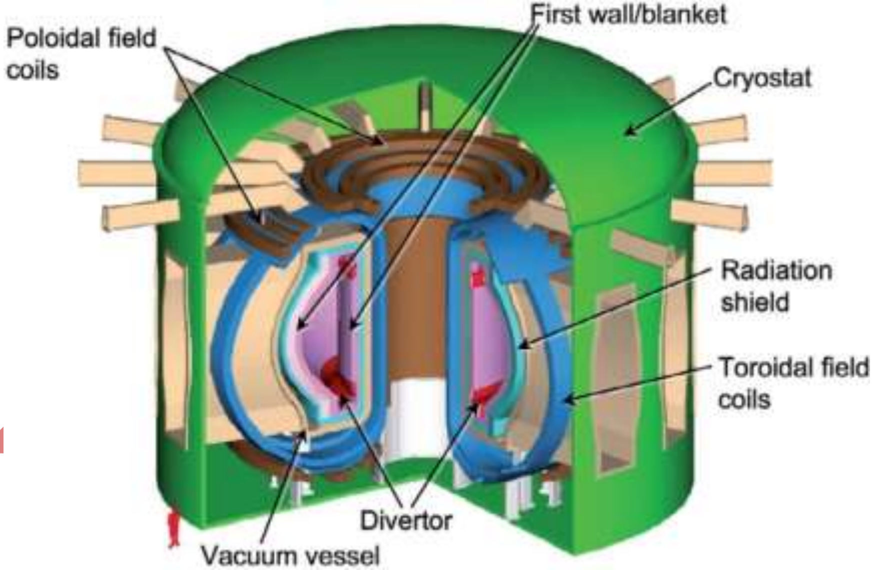


Fig.2: Schematic Diagram of Fusion Reactor

material	Li/Li	He/PbLi	He/Li Ceramic	FLiBE
Ferritic steel			✓	
V alloy		✓		✓
SiC/SiC				✓

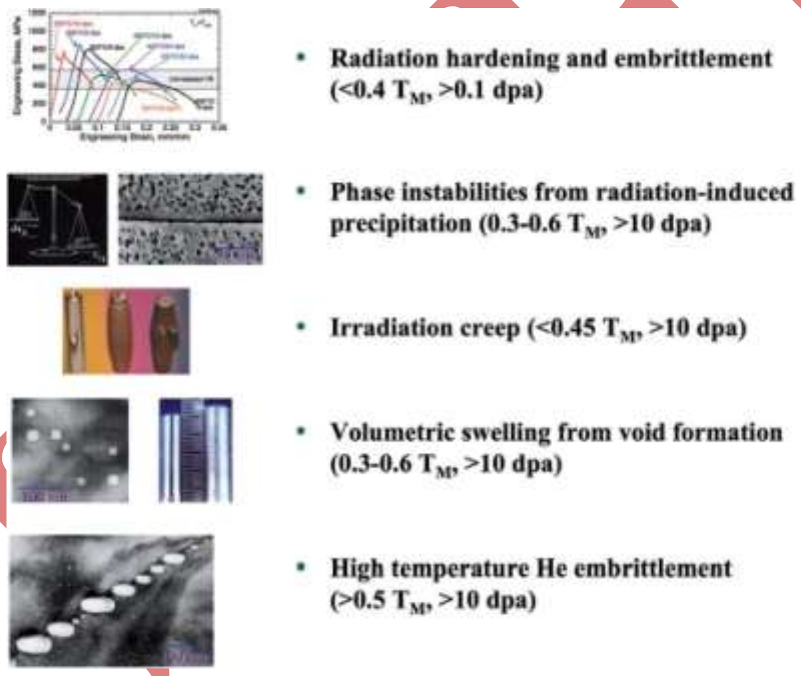
TABLE 1.

Summary of leading proposed structural materials, coolant and tritium generation concepts for fusion energy systems [3 and 4]. The filled cells in the table indicate material combinations that are under consideration for fusion energy blankets. FLiBe is a LiF- BeF$_2$molten salt.

High-performance structural materials will be critical for the future success of proposed fusion energy reactors, which will subject the structures to unprecedented fluxes of high-energy neutrons along with intense thermo-mechanical stresses and high temperature coolants that may induce corrosion [3, 6, 7, 9,10]. The high average neutron energy associated with the deuterium-tritium fusion reaction compared to fission tends to produce much higher levels of transmutant solutes such as H and He in the structural materials that generally magnify radiation-induced degradation processes. Consideration of this reduced-activation mandate, along with the requirement for high performance, leads to three major options for fusion structural materials. Ferritic/martensitic steel (where high activation solutes such as Mo and Nb in commercial steels are replaced by W and V) is the most mature option[5,10,11,12,] Oxide dispersion strengthened steel represents a promising future higher-performance option if non-uniformity, joining, and high cost can be resolved. Refractory alloys based on either vanadium or tungsten alloys represent a higher performance, higher risk option. Vanadium alloys are preferred for self-cooled lithium blanket systems, but are not effective with other blanket concepts[5]. SiC/SiC ceramic composites offer the potential for the highest thermodynamic efficiency and best safety and waste disposal margins, but are least developed for large-scale structural applications.

IV. RADIATION DAMAGE

The kinetic energy of the neutrons produced by the fission and fusion reactions is sufficient to dislodge substantial numbers of atoms in structural materials from their lattice sites over the projected operating lifetimes of the reactors, creating defects associated with the missing lattice atoms (vacancies) and the dislodged atoms that reside in the lattice interstices (self-interstitial atoms, SIAs). The amount of radiation damage from these ballistic collisions is quantified in terms of displacements per atom (dpa). A damage level of 1 dpa corresponds to “stable” displacement of every atom from its lattice site. For reactor operating temperatures, there is sufficient thermally activated diffusion of the radiation-induced defects to enable recombination of many of the vacancies and SIAs so that the retained displacement damage is a fraction of the dpa value. An important strategy for designing radiation resistant materials is to promote very efficient recovery of the defects: Very little can be done to alter the instantaneous displacement damage from exposure to energetic neutrons, but substantial resistance to radiation damage can be engineered by efficiently facilitating the recombination of these defects. Considering that dimensional instabilities above a few percent generally cannot be tolerated in large-scale engineering structures and that future reactor designs call for structural materials that will be exposed to damage levels in excess of 100 dpa, the challenge is to develop materials with “self-healing” defect recombinations. It is a challenge that engineered defect recombination structures must be resistant to the vigorous transient (~1 fs to 1 ps) atomic mixing that occurs within fast neutron-induced displacement cascades; the magnitude of this transient atomic mixing is roughly two orders of magnitude higher than the dpa value[16,18,19] and could result in dispersal or dissolution of nano-scale precipitate structures. Radiation damage poses five main threats to the operation of structural materials, emerging at different operating temperatures and damage levels. These phenomena are summarized in Fig.3. At low temperatures (below 0.3–0.4 TM, where TM is the absolute melting temperature), radiation-induced defect clusters (predominantly created directly in displacement cascades) serve as strong obstacles to dislocation motion. This radiation hardening is usually accompanied by substantial reductions in uniform elongation and macroscopic work hardening capacity, and can induce loss of fracture toughness in body centered cubic metals and alloys. Since the radiation hardening emerges at relatively low doses (0.001 to 0.1 dpa), radiation hardening and embrittlement often defines the lower operating temperature limit for structural materials in neutron irradiation environments. At intermediate temperatures, three distinct radiation effects phenomena are of potential significance for doses above ∼1 to 10 dpa: radiation-induced segregation and precipitation (0.3–0.6 TM) that can lead to localized corrosion or mechanical property degradation such as grain boundary embrittlement, void swelling from vacancy accumulation (0.3–0.6 TM) that can create unacceptable volumetric expansion, and radiation induced creep and/or anisotropic growth (0.2–0.6 TM) that can produce dimensional expansion along directions of high stress and/or specific crystallographic directions. At very high temperatures (>0.5 TM) and under applied mechanical stress, helium produced by neutron transmutation reactions in the structural material may migrate to grain boundaries and form cavities, thereby causing inter-granular fracture with limited ductility in stressed materials. This high temperature helium embrittlement of grain boundaries typically emerges for helium concentrations above 10 to 100 appm (∼1 to 100 dpa depending on material and neutron spectrum) and becomes increasingly severe with increasing temperature and applied stress and decreasing deformation rate. Along with chemical compatibility and thermal creep strength, high temperature helium embrittlement may define the maximum allowable operating temperature for a structural material in neutron irradiation environments.



- **Radiation hardening and embrittlement (<0.4 T_M, >0.1 dpa)**
- **Phase instabilities from radiation-induced precipitation (0.3-0.6 T_M, >10 dpa)**
- **Irradiation creep (<0.45 T_M, >10 dpa)**
- **Volumetric swelling from void formation (0.3-0.6 T_M, >10 dpa)**
- **High temperature He embrittlement (>0.5 T_M, >10 dpa)**

Fig.3: Threats to Operation Of Structural Materials

V. METHODS TO ENHANCE STRUCTURAL MATERIAL PROPERTIES FOR FUSION AND FISSION REACTORS

Known structural materials have limited operating temperature ranges where they can be utilized in a neutron irradiation environment [14] as summarized in Fig.4 for moderate damage levels of 10 to 50 dpa. At low temperatures, the low ductility associated with low temperature radiation hardening creates conditions where modified (larger safety margin) engineering design rules must be used. In cases where fracture toughness is reduced by low temperature irradiation, the operating temperature is restricted to higher temperatures where embrittlement does not occur for anticipated normal and transient operating conditions. The upper operating temperature limit is typically determined by thermal creep strength or high temperature helium embrittlement considerations. Advanced materials can enable improved reactor performance via increased safety margins and design flexibility, in particular by providing increased tensile strength, thermal creep resistance and superior neutron radiation damage resistance. A key strategy for designing high-performance radiation-resistant materials is based on the introduction of a high, uniform density of nano-scale particles that simultaneously serve as obstacles to dislocation motion (providing high strength) and point defect recombination centers (providing good radiation damage resistance)[13,15]. This shows that it may be possible to develop alloys with highly improved mechanical properties compared to conventional alloys by appropriate use of either evolutionary ingot-based steel metallurgy or alternative processing techniques such as powder metallurgy production of oxide dispersion strengthened steels. In either approach, development of a high density of thermally stable, nano-scale hardening centers produces good mechanical properties. The 14YWT nanocluster-strengthened alloy also exhibits very good high temperature particle stability and thermal creep strength, and has demonstrated good resistance to low-temperature neutron irradiation embrittlement in preliminary low-dose irradiation tests. Limited success has also been obtained in creating high strength structural alloys that simultaneously convey improved high temperature oxidation resistance.

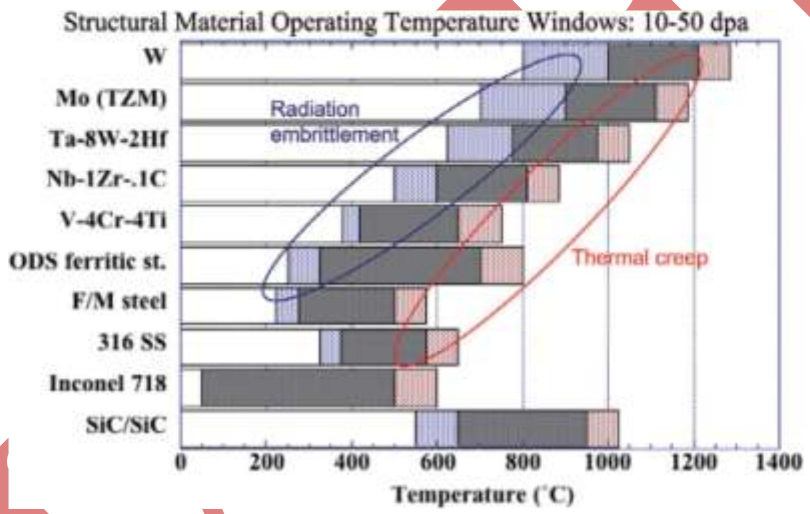


Fig.4: Materials Vs Temperature (Estimated Operating Temperature Windows {Dark Shaded Regions} For Structural Materials .The Light Blue and Red Regions Represent Lower and Upper Temperature)

Development of structural materials for large-scale energy application is a long and costly process, due to the extended period to develop a new alloy followed by an even longer proof testing period to validate the performance of the material in prototypic environments for appropriate licensing authorities. For example, Fig.5 shows the historical rate of progress in improving the upper operating temperature limit of steels for general (non-nuclear) structural applications has averaged ~2.5 °C/year for the past 60 years. Materials science tools such as computational thermodynamics and multi-scale radiation damage computational models, in conjunction with focused experimental validation studies (non-irradiation and irradiation environments), may offer the potential to reduce the time period to develop and qualify structural materials for advanced nuclear energy systems. It is seen that many structural materials currently being used in fission reactors are based on alloys that were originally developed in the 1950s and 1960s.

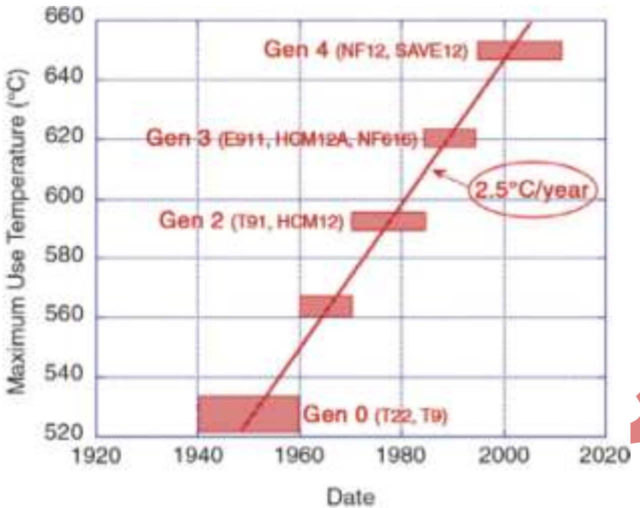


Fig.5 Upper Operating Temperature Limit Of Steels For General Structural Applications.

There are numerous examples where high-performance materials are being developed with the assistance of modern materials science tools [12, 13, 15]. For example, first principles atomistic modeling results provided important insight that the formation of highly stable nanoscale clusters enriched in Y, Ti and O from initial Y2O3 and Fe-Ti master alloy powders in a nanocluster-strengthened ferritic steel may have been enabled by the high concentration of vacancies produced during ball milling as part of the powder metallurgy processing of this steel. This nanocluster-strengthened ferritic steel has exhibited very high strength and good fracture toughness down to 120 K, and did not exhibit the sharp degradation in fracture toughness following neutron irradiation to moderate doses near 300 °C that caused embrittlement in conventional ferritic/martensitic steel. Similarly, ultra-high strength precipitation-hardened steels with adequate fracture toughness have recently been developed by carefully controlling the formation of fine-scale (Mo, Cr)2C precipitates Fig.6 compares the fracture toughness versus tensile strength behavior for the Aermet precipitation-strengthened steel and the 14YWT nanocluster-strengthened steel with the behavior for conventional bainitic and ferritic-martensitic steels. In all steels, the classic tradeoff between high strength and high toughness is evident. However, the critical tensile strength above which fracture toughness is reduced to low values is approximately 700 MPa in the conventional steels, whereas it is nearly 2000 MPa in the nanocluster-strengthened and fine-scale (Mo, Cr)2C strengthened steels.

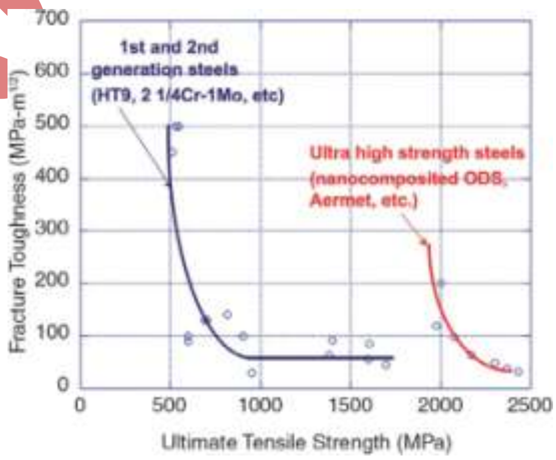


Fig.6 Fracture toughness versus Ultimate tensile strength

5.1 Future Fuel Concepts Under Consideration

UO2 – Zircaloy (Base Case)

UO2-FeCrAl(oxidation resistant Steel)

FCM-FeCrAl Fully Ceramic Microencapsulated Fuel

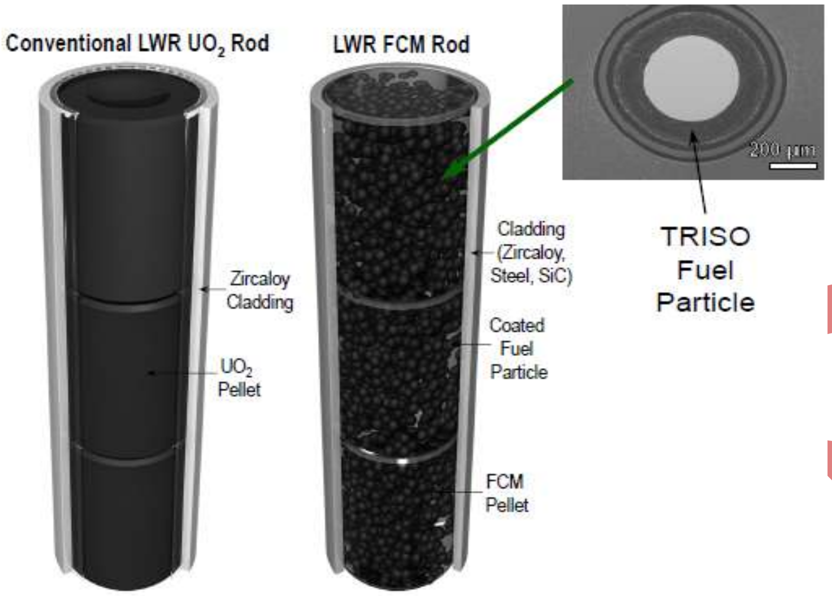


Fig.7: Cross-sectional view of fuel rod

VI. CONCLUSION

For fission and fusion energy systems to reach their full potential, high performance structural materials are needed that encompass improved mechanical strength, fracture toughness, good radiation resistance, and corrosion resistance. Development of a high density of uniformly distributed nanoscale hardening centers that are stable to thermal coarsening and radiation-induced growth or shrinkage is an attractive method to create a high-performance radiation resistant material. Emerging results from several classes of ferritic and austenitic steels suggest that substantial improvement in the performance of structural materials might be achievable. Considerable experimental validation will be needed to demonstrate the superior stability of these new alloys under prolonged exposure to high temperatures, mechanical stress, and neutron irradiation. Substantial improvement in the performance of structural materials can be achieved in a timely manner with a science-based approach like -Design of nanoscale features in structural materials confers improved mechanical strength and radiation resistance .Selection of accident-tolerant fuel options for light water fission reactors.

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