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LIFE Materials: Thermomechanical Effects Volume 5 - Part I

M. Caro, P. DeMange, J. Marian, A. Caro, M. Fluss, L. Zepeda-Ruiz

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LIFE Materials: Thermomechanical Effects Volume 5 – Part I

TOPIC: LIFE Fuel

Magdalena Caro

With contributions from the Materials Science Team:
P. DeMange, J. Marian, A. Caro, M. Fluss, and L. Zepeda-Ruiz

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CHAPTER A: LIFE Requirements for Materials

Improved fuel performance is a key issue in the current *Laser Inertial-Confinement Fusion-Fission Energy* (LIFE) engine design. LIFE is a fusion-fission engine composed of a ~ 40-tons fuel blanket surrounding a pulsed fusion neutron source, see schematic representation in Figure 1. Fusion neutrons get multiplied and moderated in a Beryllium blanket before penetrating the subcritical fission blanket. The fuel in the blanket is composed of millions of fuel pebbles, and can in principle be burned to over 99% FIMA without refueling or reprocessing.

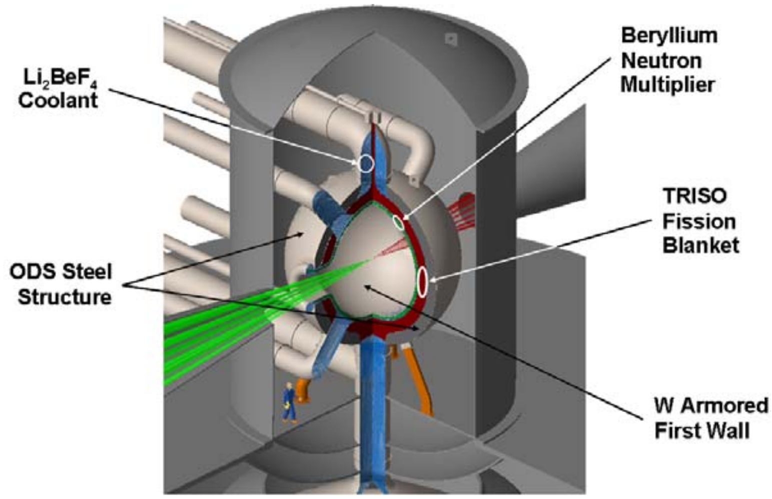

Figure 1: Schematic representation of LIFE engine [i].

In LIFE, the fuel blanket will have to achieve high burn-up, stand intense neutron radiation, and resist exposure to Flibe (Li_2BeF_4) forced-circulation coolant flow. LIFE fuel will have to enable operation for several tens of years without refueling, demonstrate tolerance to high temperature level (~760 ^oC), rapid thermal pulsing (ΔT ~ 30 K at 20 Hz), severe radiation dose (~300 dpa) and hostile chemical environment. Materials technology limits the design.

Different primary fuel sources are envisioned for the LIFE engine: Fertile fuels including depleted uranium (DU), natural uranium (NatU), and spent nuclear fuel (SNF) or fissile fuels such as low-enrichment uranium (LEU), excess weapons plutonium (WG-Pu), and excess highly-enriched uranium (HEU). The base case analyzed in this report considers DU uranium-oxicarbide (UCO) fuel, but several other cases are currently been studied with different fuel alternatives (UC, UO_2).

The relatively well-developed TRISO (Tristructural Isotropic) based fuel pebble bed is taken as reference fuel blanket. TRISO particle based fuel offers a path to reach very high burnups and extended core lifetimes. It is favored because there is a long time experience (> 40 years) on investigation of High Temperature Reactor (HTR) fuels in the world using the same elementary coated TRISO fuel particle: Germany (HTGR), US (NP-MHTGR), Japan (HTTR), Russia (HTGR), China (HTR-10). Also, there is also a long list of TRISO particle irradiation experiments. More than 100 fuel irradiation capsules and results have been obtained in reactor surveillance programs (Fort St. Vrain, Peach Bottom, AVR), relevant experiments in US are: NPR-1, NPR-2 (HFIR), and NPR-1A (ATR). Today, TRISO-Coated UO_2 in annular compacts are fabricated in Japan (Coated particle fabrication facility Nuclear Fuel Industries, Ltd. NFI), various kernels of TRISO-Coated particles in cylindrical compacts have been fabricated in ORNL, and TRISO particles with UO_2 and UCO kernels are fabricated by BWXT. In France, CEA has experimental coated particle facilities. South Africa fabricates TRISO-Coated UO_2 within the Pebble-Bed Project Pebble Bed Modular Reactor (PBMR).

Parameters in several concepts of TRISO particles in pebble bed reactors or in prismatic blocks are compared to those in LIFE engine in Table 1 [ii]. Temperatures in LIFE fuel blanket are lower than in other TRISO based reactors: Average temperature in the fuel blanket is ~ 660 ^{o}C, with fuel pebble surface and centerline temperatures, 699 ^{o}C and 763 ^{o}C, respectively. These occur at the front of the fuel blanket. Also, note that end-of -life (EOL) is assumed to be ~ 48 years of operation in the case of DU-LIFE engine, while in the LIFE engine based on fissile fuel EOL is much shorter (~ 5-7 years).

Table 1: Parameters in several concepts of pebble bed or prismatic block reactors compared to those envisaged in LIFE [ii]

	Japan	Germany	China	South Africa	France	HRB	VHTR	NP-MHTGR	LIFE Rev. 0	LIFE Rev. 1
Packing Fraction (%)	30	10	10	10	15		35	29	60	30
Power Density (MW/m^3)	6	3	3	3	6	6	6	6	200	100
Ave. Temp. (°C)	1200	1100	1100	1100	1200	1100	974	974	760	760
Burnup (%FIMA)	4	8	8	10	15	30	20	79	99	99
Fast Fluence (10^{25} n/m^2)	4	4	3	4	4	4	4	4	240	240
Damage (dpa)	5	5	3	5	5	5	5	5	310	310
Maximum FG Pressure (MPa)	15	15	15	15	15	15	20	20	160	160

Specific challenges faced by LIFE fuel are associated to the long lifetime and high burn-up ~ 99% FIMA required in the design, like the build up of gas pressure inside the TRISO particle reaching ~ 160 MPa. Buildup of gas pressure is a specific challenge faced by LIFE TRISO fuel. Under high burn-up conditions generation of gas (gaseous fission products Xe and Kr, oxygen released, etc.) can lead to mechanical failure of the fuel. TRISO fuel particles are envisaged as a viable solution for high-burn up fuel (up to max. 20 %FIMA) in the NGNP program. These particles can stand temperatures ~1600 ^{o}C and are designed not to crack due to the stresses from processes, such as differential thermal expansion or fission gas pressure. TRISO concept is based on a micro-fuel particle with a porous carbon buffer surrounded by 3 coating layers that have proved to successfully work as a tiny pressure vessel for each small fuel: A dense inner layer of pyrolytic carbon (PyC), followed by a ceramic layer of silicon carbide (SiC), followed by another dense outer layer of PyC. The advantage of this fuel form comes from the ability of the particle to maintain its integrity. Currently, intensive studies are conducted on TRISO fuel for Generation-IV nuclear power plants. LIFE engine will require new long-lived fuel forms capable of withstanding extreme environments.

Thermo-mechanical challenges in the development of LIFE TRISO are related to the pulsed nature of the engine, which together with gas fission product (FP) production will induce static and dynamic stresses in the SiC layer inside the TRISO particle. The reference case assumes a 500 MW_{th} pulsed fusion source, i.e. 3.55E+17 *500 MW_{th}= 1.78E+20 n/s neutron source, with a repetition rate of 20 Hz. A 60 cm fission zone at the inner blanket with uranium fuel increases the fusion power to ~2300 MW_{th}. The pulse of neutrons entering the fission blanket translates into a temperature spike in the TRISO fuel kernel.

Enhancements to the traditional fuel design are sought to handle the high repetition rate and to bring a solution to the need of an extended fuel lifetime. Figure 2 shows a schematic view of a LIFE fuel pebble with TRISO particles dispersed inside an inert matrix coated with refractory metal or metal-carbide cladding compatible with molten salt. A robust particle is proposed with an enhanced SiC shell that is further coated with a protective PyC. A novel TRISO fuel particle with UOC as the fuel kernel and high temperature, high strength composites for cladding is envisaged [iii].

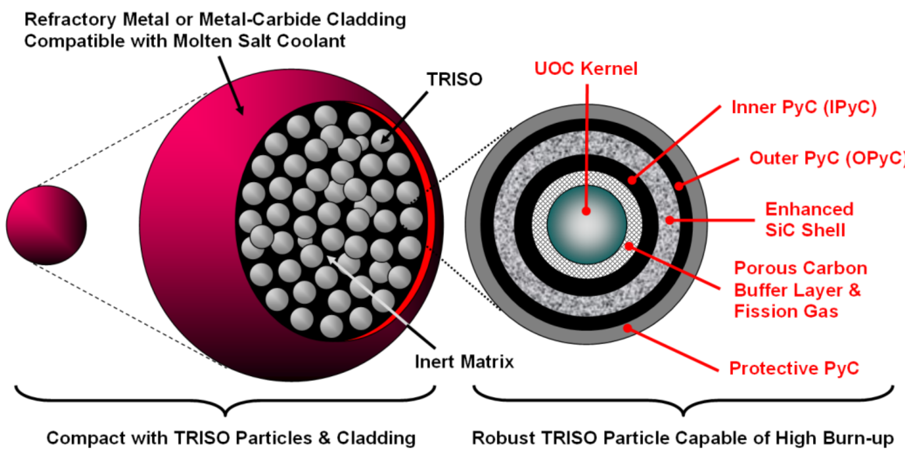

Figure 2: LIFE fuel pebble and cladding with robust TRISO particles dispersed inside an inert matrix. TRISO particles are coated with a protective PyC [iii].

The thermomechanical response (swelling/shrinkage, irradiation creep) of LIFE fuel after accumulation of a severe dose, with high fast fluence levels reaching ~ 240 x 10^{25} n/m^2, is a big concern. Total and fast EOL neutron fluence expected in the LIFE-DU fuel blanket are ~1 x 10^{24} n cm^{-2} and ~3 x 10^{23} n cm^{-2}, respectively [iv], with total and fast neutron flux F(E>0.1 MeV) ~ 8.8 x 10^{14} n cm^{-2} s^{-1} and ~ 8.8 x 10^{13} n cm^{-2} s^{-1}, respectively, see Figure 3.

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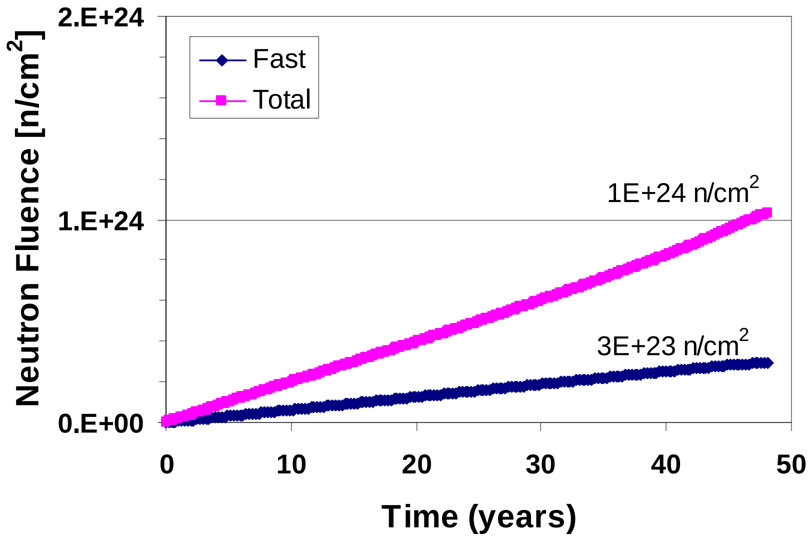


Figure 3: Neutron fast fluence F(E > 0.1 MeV) attains 3 x 10^{23} n/cm^2 at EOL, in LIFE-DU fuel blanket reference case vv2 [iv].

The hard neutron spectrum becomes a mixed-spectrum at EOL, see Figure 4. Note the 14 MeV neutron peak is a signature of LIFE engine.

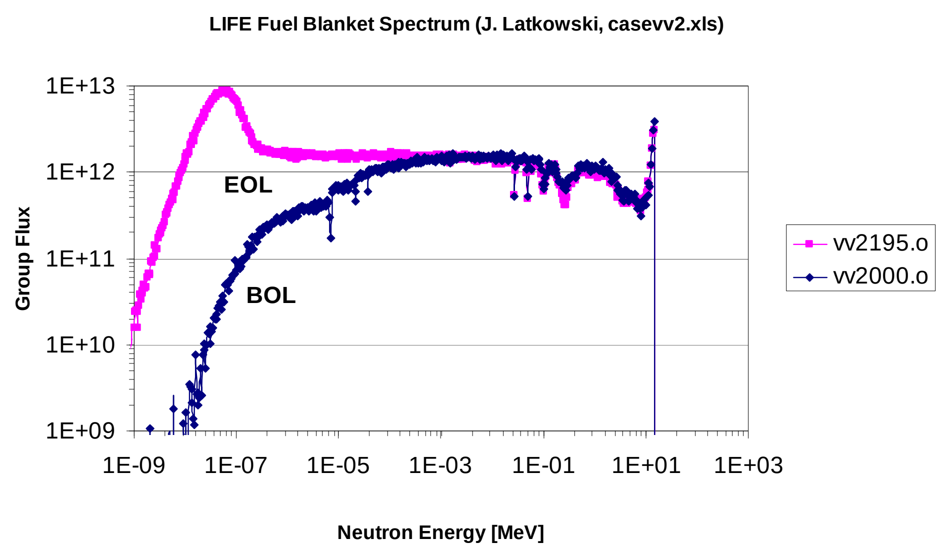


Figure 4: DU LIFE fuel blanket neutron spectrum at beginning (BOL) and end of life (EOL).

Gas production in the fuel (He/dpa ratio ~ 2 and H/dpa ratio ~ 4) will affect the long-term material properties. Displacement damage rate in Carbon in the fuel is ~ 7

DPA after a year of operation and remains almost constant. The value was obtained using the fuel neutron spectrum of reference case casevv2 mentioned above, and cross sections for Carbon with threshold displacement energy Ed = 20 eV [v]. Using the same spectrum and SPECTER code [vi] the gas production (He and H) in Silicon facing the same neutron environment as in LIFE TRISO particles, was calculated as a function of time, see Table 2 and Figure 5 [vii]. Results show ~ 8 appm of He and ~ 139 appm H have been produced after a year of operation; hydrogen gas production remains higher and reaches ~ 7000 appm at EOL. Values are much lower for case dg2 with 30% packing fraction (note that input time data for the dg2 case was only provided up to ~25 years but it is reasonable to extrapolate it to ~ 3500 appm at EOL)..

Table 2: Radiation Damage in Silicon in LIFE DU Fuel Blanket

Silicon in LIFE Fuel Blanket	1 year	50 years
Fast Fluence (n/cm^2)	7.66E+20	2.92E+23
Damage (dpa)	6	394
He (appm)	88	4245
H (appm)	139	6806

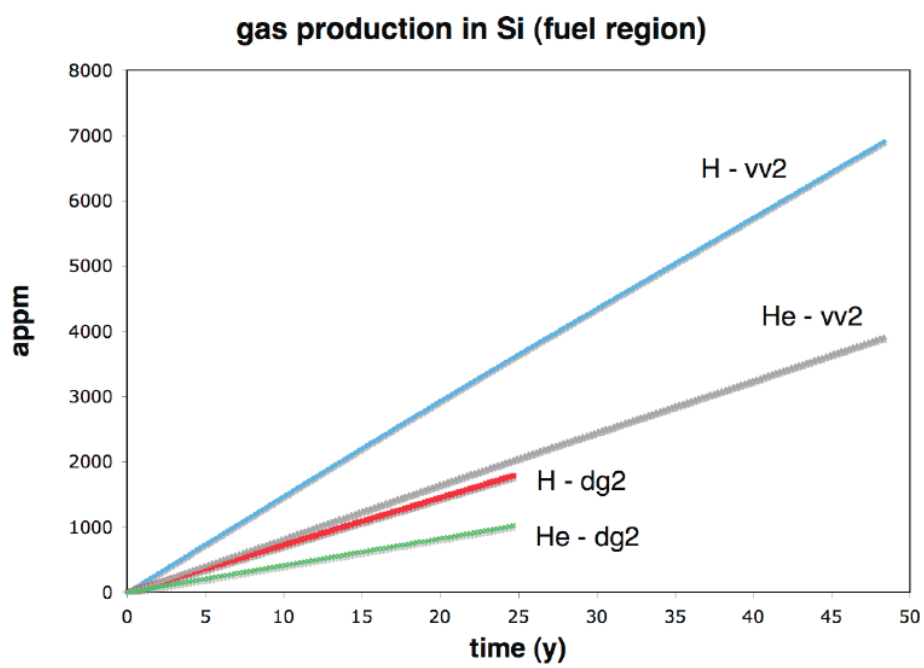


Figure 5: Gas production in Si inside TRISO fuel in LIFE for 60% packing fraction (case vv2) and 30% packing fraction (case dg2) [vii].

The consequence of main irradiation conditions in LIFE will be an essential input to the thermomechanical model of LIFE TRISO fuel together with multi-dimensional failure mechanisms, like shrinkage of PyC layers, debonding between PyC and SiC layers, deviations from spherical shape of the particle, and kernel migration (Amoeba effect) which may also play a role in the particle failure rate. A thermo-mechanical model of TRISO particle that includes these multi-dimensional effects and thermal pulsing is currently being developed using a 3D finite element engineering hydrocode [viii]. As we shall see in what follows the thermo-mechanical response of PyC layers is complex, in part due to the inherent PyC anisotropy and to shrinking/swelling due to radiation damage and relaxation effects introduced by irradiation-induced creep. Complex synergistic effects of these variables with stress amplitudes due to thermal pulsing are currently being investigated in the case of intact TRISO and in the presence of cracks in IPyC layer [ix].

Finally, note that traditional failure mechanisms fail to explain the TRISO particle failure rate seen in several experiments, for example the failure rate obtained in NPR-1A experiment conducted in the 90's, in the ATR reactor (USA). Capsule irradiations in NPR-1A experiment were part of a larger demonstration and qualification program for HEU-UCO fuel under normal and accident conditions for the New Production Modular High Temperature Gas-Cooled Reactor (NP-MHTGR) [x]. Among other issues mentioned in INEEL report [x], two are of relevance here:

- Irradiation-induced changes in the pyrocarbons played a dominant role in the failure of the fuel particles

- Future particle fuel designs should consider the performance of the entire system of coating layers with respect to particle integrity under irradiation.

From these bullets we conclude, that a detailed thermomechanical modeling of LIFE fuel is necessary to identify the key constrains for its design. Ideally, the goal is to have a model that, given an input fuel pebble, (TRISO particle, pebble environment and irradiation condition specifications) predicts the actual failure process. We are developing such a platform. It will cover the most important thermomechanical aspects of LIFE fuel, some inherent to the nature of the pulsing source, others linked to the layered coating of the fuel (debonding, asphericity, crack propagation, etc.). The 3D finite element engineering hydrocode, ABAQUS [xi] and ANSYS [xii] are proposed as part of the platform that will be needed to design and optimize our high performance LIFE fuel. The 3D finite element engineering hydrocode is built to handle dynamic mechanical deformation at extreme pressure and temperatures, and as we will see in the next section has proved to be the perfect tool to accurately model the effects of thermal pulsing, pressure and mechanical stresses. The thermo-mechanical hydrocode capabilities allow modeling debonding of PyC and SiC layers in TRISO particles (see Figure 6), where the SiC layer experiences concentrated stresses associated with shrinkage cracks; these stresses are relieved after complete debonding occurs [xiii].

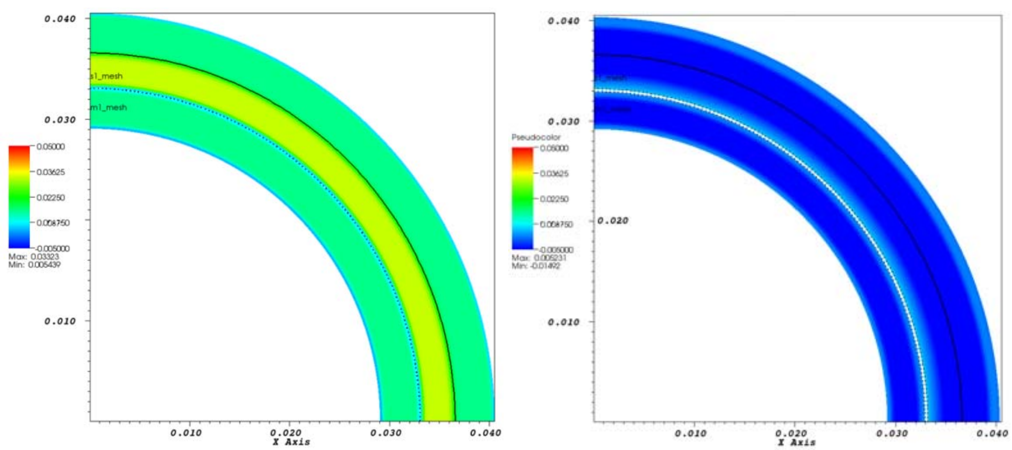


Figure 6: a) Stresses at debonding threshold, b) Stresses are relieved after complete debonding occurs in TRISO particle (see layer separation shown in white)

Swelling and creep are standard elements in ABAQUS and ANSYS. These codes are used by the industry to design fuel pins/elements for nuclear power plants. Preliminary calculations show agreement with the finite element engineering hydrocode for the IAEA Benchmark Cases 1,2 and Case 3 with PyC and SiC layered particle [xiv,xxxviii].

The performance model will incorporate the irradiation effects at severe high fast doses as well as damage effects due to He and H production. Extrapolated correlations will have to be used for this purpose. These models have an intrinsic importance. The state-of-the-art "atomistic" modeling capabilities that are available to assess cladding and structural materials performance (Ferritic-martentisic steels, etc.) are not yet available for fuels. The experimental work reported in the literature is at present the only thing that we can rely on and is not enough because the requirements imposed on LIFE fuel go beyond the available experimental data-base range. We will have to rely on thermomechanical models to assess the fuel performance in this regime.

CHAPTER B: Summary of Existing Knowledge

The current LIFE concept assumes a ~ 60 cm thick fuel blanket located behind a beryllium blanket. The fuel is assumed to be in the form of pebbles containing TRISO fuel pellets embedded in a graphite matrix. A thin ~ 3 mm-thick oxide-dispersed-strengthened (ODS) ferritic/martensitic (F/M) steel wall separates both blankets. The fuel blanket contains ~ 7 million fuel pebbles are immersed in molten Flibe coolant. The reference case assumes a fuel zone that consists of 60 %vol. pebbles + 40 % Flibe, see Table 3 [xv]. Different packing fractions are under consideration (60 %, and 30 %).

Table 3: Pebble Dimensions, TRISO Packing Fraction, LIFE Pebble and TRISO Steady-State and Pulse Temperatures [xv].

Pebble diameter	2 cm
TRISO packing	60%*
TRISO/pebble	4887
Pebble packing in blanket	60%*
Steady-state maximum pebble temperatures:	
> Surface	699 C
> Centerline	763 C
Maximum pebble thermal pulse:	
> Centerline	21 C
> Surface	6 C

Several thousand (~ 4887) TRISO particles are dispersed inside a ~ 2 cm diameter fuel pebble. TRISO particles consist of a fuel kernel ~300 micrometers in diameter, surrounded by ~102 micrometers-thick porous carbon layer (buffer), which is usually followed by 3 coating layers: an inner pyrolytic carbon (IPyC), silicon carbide, and an outer layer of pyrolytic (OPyC), see Figure 7.

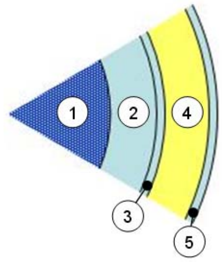


Figure 7: Schematic representation of LIFE TRISO particle: 1) Kernel, 2) Buffer, 3)IPyC, 4) SiC, 5)OPyC [xv].

At present the base case considers a ~5 micrometers-thick inner pyrocarbon (IPyC), and a ~90 micrometer-thick SiC but it does not incorporate the last layer (OPyC); in this case the TRISO particle becomes a BISO, see Table 4.

Table 4: Dimensions and Materials in LIFE Concept

Region	Description	Density (kg/m3)	Inner radius (μm)	Thickness (μm) **
1	UCO kernel	10500	0	600 ϕ
2	Porous PyC buffer	1100	300	102
3	Inner PyC	1950	402	5
4	SiC	3217	407	90
5	Outer PyC	1950	497	0*

Inert matrix fuel (IMF) kernels with carbon-diluted fuel ~500 micrometers in diameter are also envisaged. IMF kernels are important because they might be the answer to high burn-up and high temperatures. Ongoing research programs like the one cited in reference [xvi], provide results from irradiations with accelerators, or in research reactors like in HFR at Halden. Still there are open questions in this new field of research relative the fuel behavior under power transients, the change in thermal conductivity with irradiation, fission gas retention potential, the possibilities to enhance the plutonium loading and burning efficiency by modification of the additives [xvi]. Both TRISO and IMF solid fuels thermo-mechanical survivability is further challenged in LIFE engine by the high rate pulsed 20-Hz operation of its intense neutron source. In what follows we analyze these new limiting conditions in a typical TRISO.

Heat Analysis

Transient and spatial temperature profiles were calculated by R. Abbott for a fuel particle inside the most vigorously heated pebble of the pebble bed blanket [xvii]. Figure 8 shows the temperature history for several cases with different neutron heating pulse time: 1, 10, and 20 microseconds. In this calculation, BISO particles have been simulated that consist of a fuel kernel 200-300 micrometers in diameter surrounded by a 90 micrometer-thick porous carbon layer (buffer). The ensemble is further surrounded by 3 coating layers: a 40 micrometer-thick inner pyrocarbon (IPyC), 35 micrometer-thick silicon carbide (SiC) and 40 micrometer-thick outer pyrocarbon (OPyC).

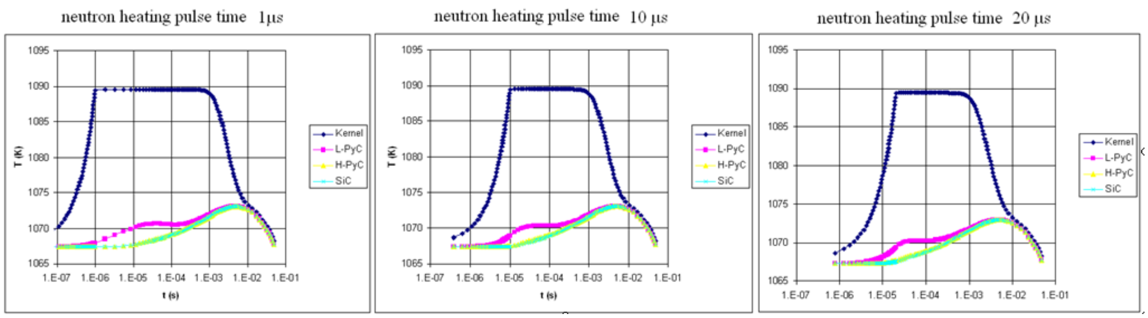


Figure 8: Temperature history inside the BISO particle: UO_2 kernel (blue), buffer (magenta), inner pyrocarbon (yellow), and SiC (green) layers [xviii].

All cases assume a BISO particle consisting of a UO_2 kernel, buffer, inner pyrocarbon and SiC layers (UO_2/L-PyC/H-PyC/SiC/C with dimensions ~149/~52/~5/~44/~27 μm). Note that an outer layer of Carbon was added to the outside of the particle to represent matrix material. Simulations show that energy is deposited in the kernel within ~ 20 microseconds. The temperature raise in the kernel is ~ 21 ^{o}C. The temperature rises by ~ 6 ^{o}C in SiC after 5 miliseconds, see Figure 9.

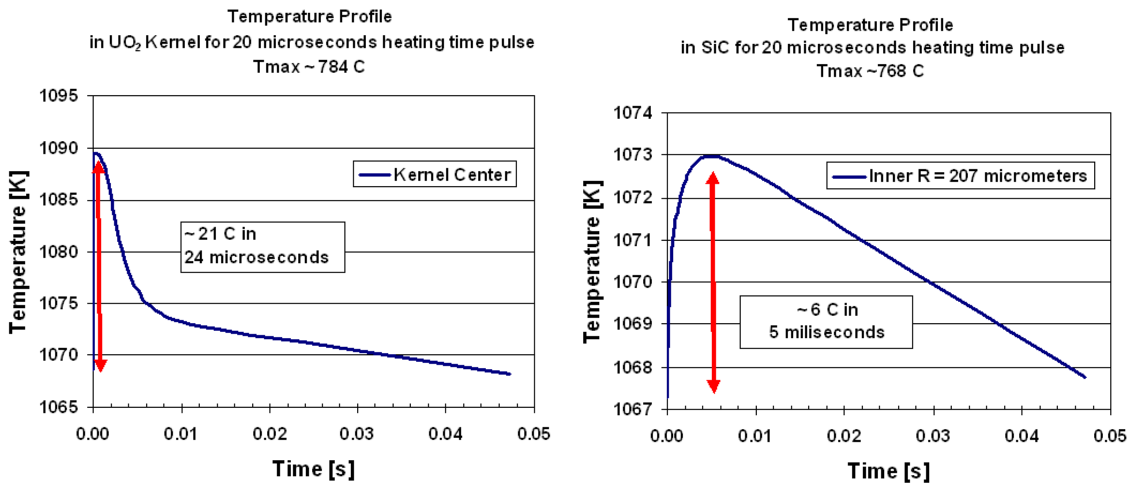


Figure 9: Temperature rise in fuel kernel and SiC, used in the stress analysis.

Note that the temperature falls back down to its starting point by the time of the next pulse.

Thermal Stress Analysis

In addition to static stress due to fission gas accumulation, thermal pulsing at 20 Hz generates dynamic stress in the TRISO particle. Therefore, a preliminary model has been set up to study the mechanical response of TRISO facing two sequential pulses [xix]. To do so a 3D finite element engineering hydrocode was used. As was mentioned before, the finite element hydrocode that treats fluid and elastic-plastic response of materials. Equation of state tables (LEOS database) were used for UO_2, Buffer (Foam CHO, 85% C), I/OPyC (graphite), SiC, Carbon. The calculation assumed constant shear modulus and yield strength, constant thermal conductivity, and heat capacity. Boundary conditions included a profile for the temperature versus time and radial position applied to each TRISO layer, and a constant pressure of 75 MPa applied to UO_2 kernel. A schematic view of the 3D representation [xix] is given in Figure 10.

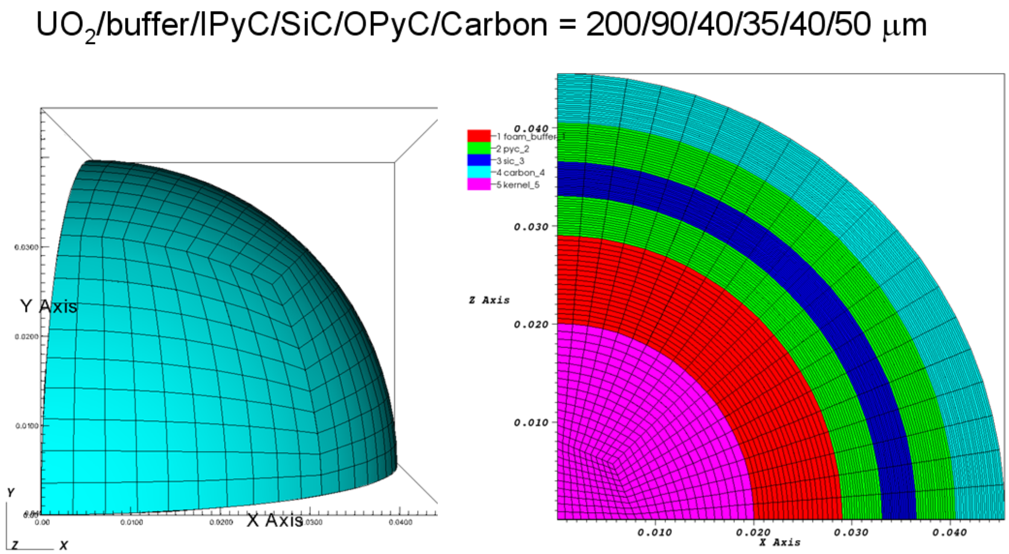


Figure 10: Schematic 3D representation of TRISO particle, with kernel (magenta), buffer (red) and coating layers IPyC and OPyC (green) and SiC (dark blue). Note the outer graphite layer (light blue) is added to represent the pebble matrix.

Preliminary results indicate that stress amplitudes due to thermal pulsing are ~5 MPa, for both tangential and radial components in each TRISO layer, see Figure 11.

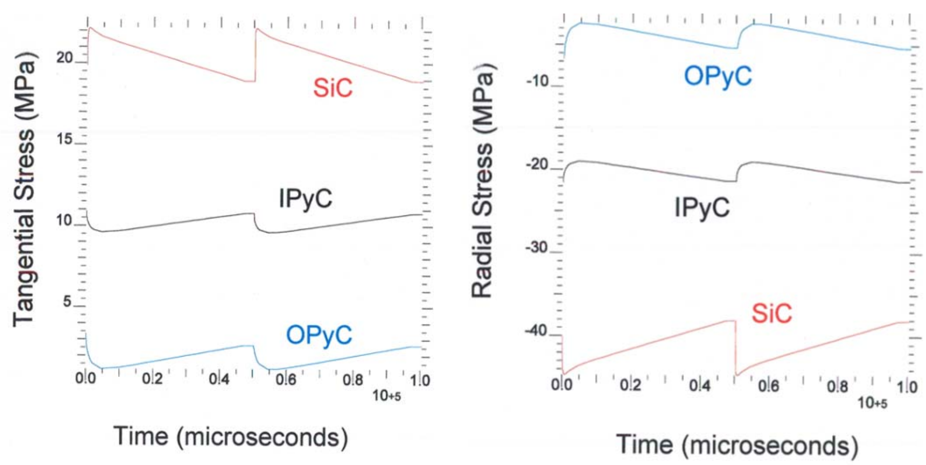


Figure 11: Tangential and Radial Stress as a function of time inside SiC, IPyC and OPyC layers.

It is important to note that fatigue (~ 10^9 pulses to reach EOL) is a key issue in evaluating TRISO particle lifetime. To our knowledge there is limited data on monolithic SiC fatigue [xx]. The situation in SiC is different from that of metals, where even at relatively low stress, dislocation move and pile-up, introducing changes in the microstructure leading to metals failure under the load, usually by crack propagation at an existing flaw or crack, or by failure of the grain boundaries. More research is need on SiC microstructure evolution in the case of TRISO in LIFE engine. If SiC microstructure does not evolve, then SiC lifetime is assured, except for considerations of environmental issues such as corrosion.

As the irradiation proceeds, internal gas pressure continually builds up inside the TRISO particle. Noble fission product gases (Xenon, and Krypton) are released to the void volume in the fuel particle and stresses develop on the IPyC/SiC/OPyC "containment vessel". The EOL internal pressure in the SiC layer of a typical German TRISO fuel is ~ 5 MPa, see Table 5. The pressure in the proposed GT-MHTGR TRISO fuel reaches ~ 8.5 MPa [xxi]. Note in Figure 12, the high contribution of CO gas formation to the total internal pressure in UO_2 TRISO fuel. In UCO fuels, it is assumed that there is no free oxygen available to form CO or CO_2.

Table 5: Typical TRISO Internal Pressure at EOL

	Fuel	**Kernel Diameter [micrometers]**	**Temperature [C]**	**% FIMA**	**EOL Internal Pressure [MPa]**
German TRISO	8% UO_2	500	900	8.5	5
GT-MHTGR TRISO (HRB-21 Exp.)	19.7% UCO	350	1200	21	8.5

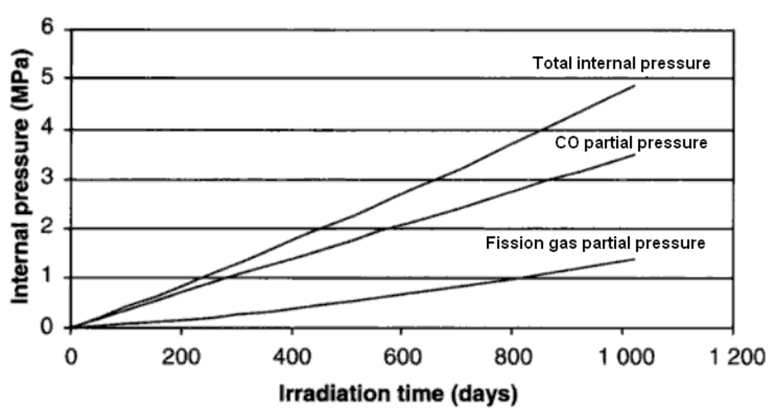


Figure 12: Internal gas pressure in a typical German TRISO

The fission gas pressure accumulated is much larger in LIFE fuel after 99% burnup (i.e. after ~ 48 years). The EOL internal pressure in the enhanced LIFE TRISO particle with a 90 micrometer SiC_f/SiC fiber composite (UCO DU fuel, 600 micrometers diameter kernel, 99% FIMA) is ~ 184 MPa, see Table 6, where for this example the TRISO particle is assumed to face an off-normal condition reaching T ~ 1200 ^oC (1473 K); i.e nominal operating temperature ~ 750 ^oC (1023 K) plus a temperature rise of ~ 177 ^oC (450 K). In the calculation, the amount of gas produced at EOL is assumed to be ~ 9.81 x 10^{-4} mol/g (n_{Kr} ~ 7.05 x 10^{-5} mol/g; n_{Xe} ~ 9.1x 10^{-4} mol/g).

Table 6: Enhanced LIFE TRISO particle with SiC_f/SiC fiber composite [xxii]

	r_i (cm)	r_o (cm)	δr (cm)	V_{void} (cm^3)	V (cm^3)	Vol %	φ (g/cm^3)	m (g)	P (MPa)
UCO	0.0000	0.0300	0.0300		1.131E-04	21.99	10.5	1.19E-03	
Buffer	0.0300	0.0402	0.0102	6.93E-05	1.590E-04	30.93	1.1	1.75E-04	
IPyC	0.0402	0.0407	0.0005		1.028E-05	2.00	1.95	2.00E-05	
SiCf-SiC	0.0407	0.0497	0.0090		2.318E-04	45.08	3.3	7.65E-04	184
Total			**0.0497**		**5.142E-04**	**100**		**2.15E-03**	

Solid fission products as well as the gas production need to be considered in the loading of the TRISO particle shell. The volumetric change in solid material will be very large at 99% burnup. Experimental measurements of UO_2 kernel swelling indicate values are in the range of 0.6 to 1.5% deltaV/V per atom percent burnup [xxiii]. At 20 %FIMA, this amount of swelling corresponds to a 6 to 30% increase in the volume of the kernel. Fuel swelling rates of 9% to 14% per year are reported for UC at 1100 ^oC [xxiv]. Solid fission product fuel swelling reduces the void volume available in the particle. Internal gas pressure increases leading to kernel/coating layer mechanical interaction and particle failure. In LIFE TRISO design the porosity of the carbon buffer layer accommodates the kernel volume expansion. In the example of Table 6, kernel swelling decreases the volume available for the fission gases to occupy, the void volume available becomes Vvoid ~ 4.29 x 10^{-5} cm^3 [xxv] and the fission gas pressure increases to ~ 297 MPa.

CHAPTER C: Identification of Gaps in Knowledge & Vulnerabilities

With this in mind, adding burnup and temperature dependent swelling and creep models to the 3D finite element engineering hydrocode is recommended. The performance model should also contain information on the materials microstructure behavior under irradiation. We conclude that TRISO coatings can support high pressures generated by high burnup because SiC retains high strength as a function of fluence or temperature.

At present, particle failure is modeled in pebbled bed and prismatic configurations using fuel performance codes, such as Idaho National Laboratory's PARFUME (PARticle Fuel ModEl) [xxvi-xxviii] or TIMCOAT [xxxiv-xxxxi]. The available literature agrees in that traditional failure mechanisms (pressure vessel failure) in standard TRISO particles cannot explain the experimentally found particle failure. Several other multi-dimensional failure mechanisms have to be taken in account like, shrinkage cracks in PyC layers, debonding of layers, and deviation of the particle from spherical shape, kernel migration, etc.

Part of the work underway aims to incorporate all TRISO physics in the 3D finite element engineering hydrocode simulation:

- Swelling – Crystal elasticity/plasticity model: input anisotropic elastic / thermal expansion coefficients
- Debonding of layers – critical tensile strength, pressure
- Kernel migration – anisotropic pressure input
- Anisotropy of TRISO particle (as-manufactured) – oblong mesh

Shrinkage and swelling of the PyC layers of the fuel particle affects the amount of stress experienced by the SiC layer. This fact plays a most important factor in TRISO failure. Fluence (time) dependent correlations to represent PyC shrinkage/swelling have been developed based on empirical fits to the data compiled by CEGA Corporation [xxix]. Radial and tangential PyC shrinkage/swelling correlation expressed in terms of strain is shown in Figure 13 for fast fluences up to ~ 4.5 x 10^{25} n/m^2 [xxx]. PyC shrinks in the tangential direction (tangential strains are always negative). PyC first shrinks and then swells in the radial direction. In the figure, BAF (Bacon Anisotropy Factor) indicates the degree of PyC anisotropy: a high BAF value corresponds to high PyC anisotropy (red curve); a more isotropic PyC (blue curve) is desirable for long TRISO lifetimes.

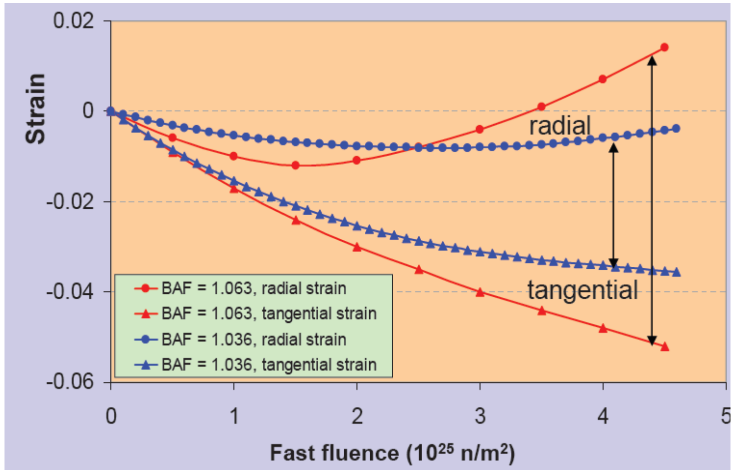


Figure 13: Radial and tangential strains in PyC as a function of fast fluence F(E > 0.18 MeV) [xxx].

Figure 14 shows that as neutron irradiation proceeds, PyC shrinkage provides a strong compressive stress in the SiC layer, which is desirable. The reported stress calculations were performed using finite element code PISA code [xxxi] for the case of a 100% TRU kernel with PyC seal coating and ZrC (120 micrometers in diameter) followed by a 100 micrometer-thick buffer, and IPyC/SiC/OPyC with dimensions 35/35/40 micrometers, respectively. PISA [xxxi] is a coupled, thermal-stress finite element code used by General Atomics (GA) for fuel particle design and development. The calculation assumes an irradiation temperature T = 1000 ^{o}C. Gas pressure develops inside the TRISO particle due to FP generation, reaching ~7.2 MPa at EOL, and ~10.6 MPa during EOL accident, see detail in Figure 8 of the final SiC layer in tension (tangential stress in SiC reaching ~ + 25 MPa at fast fluence ~ 3.3 x 10^{21} n/cm^2) at which point the particle fails. Experiments show that if the shrinkage is too large then the tangential stresses that develop in the PyC are high enough to cause cracking in the PyC layer. PyC cracks lead to stress concentrations in the SiC layer high enough to cause failure of that layer, too.

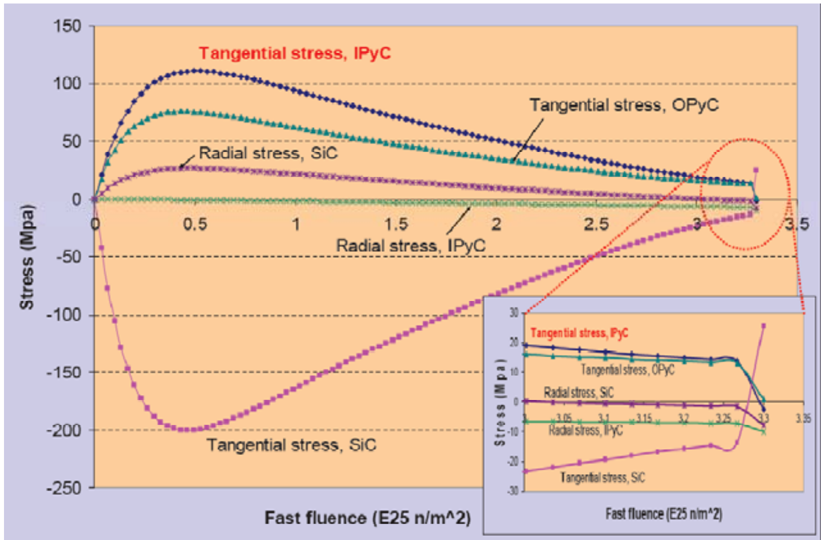


Figure 14: Stress in IPyC, SiC and OPyC as a function of fast fluence F (E > 0.18 MeV) [xxxi].

Swelling and creep modules, standard modules in several finite element codes, are not yet available in the 3D finite element hydrocode. These are needed in the hydrocode models of intact and cracked particles: see for example the development of stress concentrators in IPyC cracked layers in Figure 15 [xxxii].

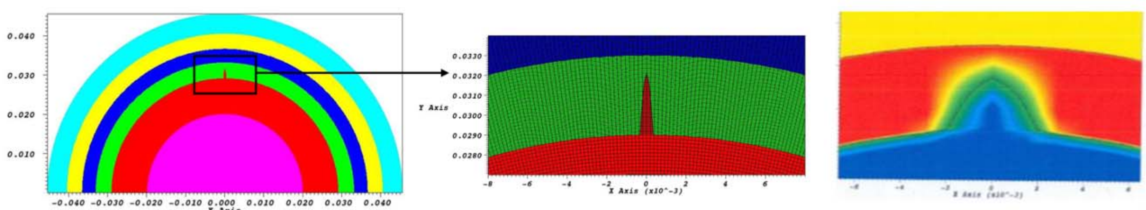


Figure 15: Geometry and pseudo-color scale map showing pressure gradient surrounding crack during thermal pulsing of TRISO particle with cracked IPyC layer [xxxii].

CHAPTER D: Strategy and Future Work

An exceptionally robust fuel form must be developed to stand the fast neutron flux and very high burn-up (~ 99%) required in LIFE engine. 75-80% burnup has been attained in plutonium-bearing (but non-breeding) nuclear fuel. Fort Saint Vrain is an example of a reactor that used TRISO-coated highly enriched uranium fuel but did not achieve such high burnup. The extension of the fissile TRISO experience to a TRISO fuel based on depleted uranium and suitable material coatings poses extreme challenges on the materials side.

A preliminary design for a new LIFE fuel pebble is envisaged [xxxiii]. The design assumes a 2-cm in diameter spherical compact fuel. The reference configuration, shown in Figure 16, considers the central cavity filled with porous carbon core, followed by sacrificial SiC and PyC transition layers. Several coatings surround this kernel. A spherical shell fuel leads to slightly lower temperatures inside the kernel. The kernel is surrounded by SiC acting as sacrificial layer, ZrC as diffusion barrier and PyC as transition layer. A high strength SiC_f/SiC fiber wrap and refractory-metal corrosion-resistant fuel cladding.

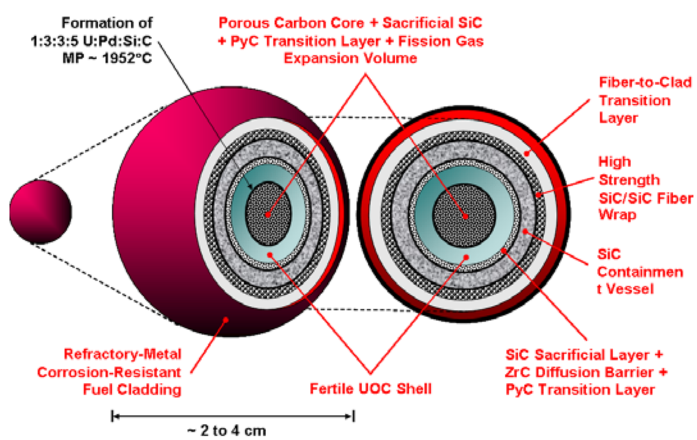
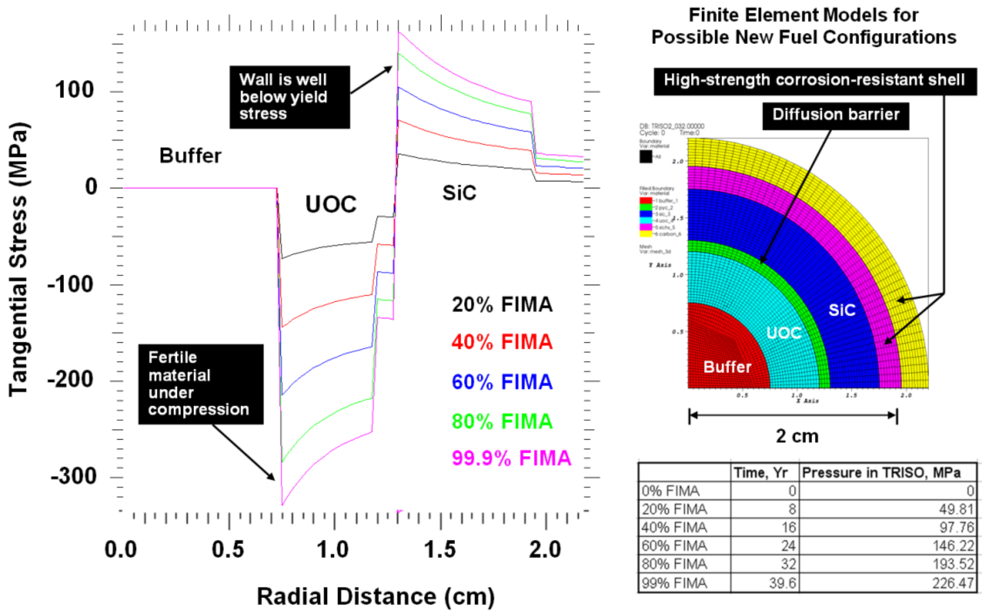


Figure 16: Reference spherical compact fuel [xxxiii]

Preliminary results for this design (see Figure 17) indicate tangential stress at the SiC_f/SiC wall increases as pressure build-up increases but remains below the SiC_f/SiC strength.



	Time, Yr	Pressure in TRISO, MPa
0% FIMA	0	0
20% FIMA	8	49.81
40% FIMA	16	97.76
60% FIMA	24	146.22
80% FIMA	32	193.52
99% FIMA	39.6	226.47

Figure 17: Tangential stress inside fuel pebble at different points in time [xxxiv].

Stress calculations have been done for a spherical fuel with an empty space at the center, namely a Spherical Hollow Compact (SHC) [xxxv]. The spherical kernel is followed by a buffer. The cavity at the center of the kernel allows for kernel swelling up to 99% burnup and together with the buffer leaves enough space for fission gas release. In the SHC case the buffer is made of porous ZrC, thick enough to accommodate fission product recoils. The buffer layer is followed by a SiC_f/SiC composite which works as "containment vessel" and provides the structural strength at high burn-up. Finally, an outer layer (Carbon or Carbon composite) protects the whole fuel pebble from wear and damage.

Thermomechanical modeling of LIFE SHC fuel is currently underway using the 3D finite element thermo-mechanical hydrocode seeking to identify the key constrains for its design. Input from neutronic calculations (power densities) and thermal distribution (temperatures at the center and surface of the pebble) will be used to perform a stress analysis during a transient thermal pulse to help define pebble dimensions and composition. The hydrocode model accounting for stresses associated with 1) gas buildup, and 2) thermal pulses, will be complemented by ABAQUS calculations to account for 3) radiation swelling.

Note that SiC/SiC composites are known for their excellent thermal shock and thermal fatigue resistance, and for their excellent fracture properties and fracture toughness (~ 25 MPa $m^{1/2}$) with strength and fracture toughness independent of temperature up to the limit of the fiber stability [xxxvi]. However, radiation damage data is scarce and will be needed to calibrate the thermomechanical model and reach the final objective of predicting the pebbles time to failure. Fiber shrinking and swelling under irradiation should be small enough not to cause stress-induced debonding of the fiber/matrix interphase. Differential materials response of fiber, fiber/matrix interphase (fiber coating), matrix, is expected to affect the composite when exposed to the thermal-mechanical loads prevailing in the pulsed LIFE engine. Other issues identified are common to the NGNP materials program, like cost of fabrication, joining methods, and factors limiting the range of operation, e.g. thermal conductivity of SiC_f/SiC composites which decreases with temperature and irradiation (~20 W/m-K at 1000 °C).

Finally data on the composite response under irradiation is scarce. Composites produced with the advanced fibers, Hi-Nicalon Type S and Tyranno-SA have been irradiated and the test results showed no loss in strength up to a dose of 10 dpa [xxxvii], see Figure 18.

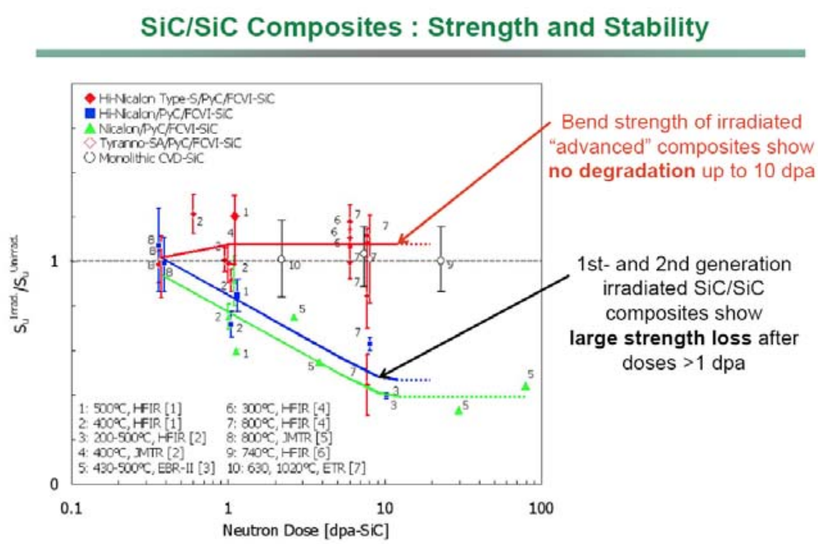


Figure 18: Ratio of ultimate strength of irradiated and unirradiated composites as a function of neutron dose [xxxxvii].

The conclusion in reference [xxxvii] is that limited existing data suggests continuous fiber ceramic matrix composites, such as SiC_f/SiC, exhibit very good thermal shock characteristics but most data was obtained for - ΔT conditions as a result of quenching from an elevated temperature. Thermal shock in a fission reactor will result from loss of coolant and will result in a + ΔT. One study was reported for SiC_f/SiC composites given a +ΔT with no loss in strength following 25 cycles at a heating rate of 1700°C/s. Monolithic SiC failed in 1.5 cycles at a heating rate of 1400°C/s. Thermal fatigue test results also suggest that SiC_f/SiC composites will exhibit little or no degradation for 100's of cycles.

Recommendations for future work are linked to incorporating fluence and temperature radiation swelling, irradiation and thermal creep, and performing analysis of different postulated fuel forms that would have the chance of working to 99% burnup. We will continue the validation of our methods (a 3D finite element engineering hydrocode, ABAQUS, ANSYS, etc.) and models against the standard benchmarks [xxxviii]. As we write this topical report, candidate fuel/coating combinations for an advanced, coated-fuel for LIFE engine are being evaluated with thermomechanical models being developed for both: the new HSC fuel pebble and the enhanced TRISO Pu fuel.

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