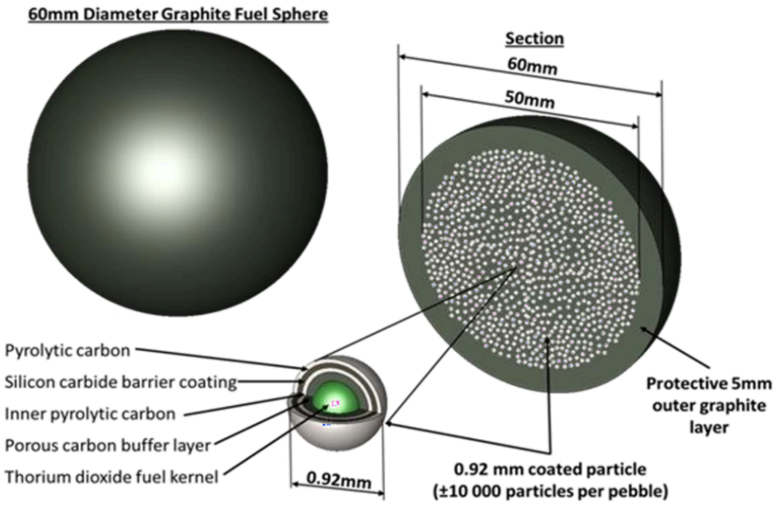
TRISO fuel primer

Background

Tristructural-isotropic (TRISO) fuel is a type of micro-particle fuel. A particle (see diagram below) consists of a kernel of UO_X fuel (sometimes UC or UCO), which has been coated with four layers of three isotropic materials deposited through fluidized chemical vapor deposition (FCVD). The four layers are a porous buffer layer made of carbon that absorbs fission product recoils, followed by a dense inner layer of protective pyrolytic carbon (PyC), followed by a ceramic layer of SiC to retain fission products at elevated temperatures and to give the TRISO particle more structural integrity, followed by a dense outer layer of PyC.

Thousands of these TRISO particles are then combined into spherical balls (or other prismatic form factor) wrapped in graphite:



TRISO fuel particles are designed not to crack due to the stresses from processes such as differential thermal expansion or fission gas pressure (at temperatures up to 1600 °C). This means that the radioactive fuel will be contained under any conceivable scenario – loss of power, loss of control systems, earthquakes, flooding etc. The use of TRISO fuel means that the reactor and the power plant are “walk-away safe”. Two such reactor designs are the prismatic-block gas-cooled reactor (such as the GT-MHR) and the pebble-bed reactor (PBR). Both of these reactor designs are high temperature gas reactors (HTGRs) – the use of gas rather than water as a coolant means that it is possible to locate the reactors in arid or cold environments not suitable for a PWR.

TRISO fuel particles were originally developed in the United Kingdom as part of the Dragon reactor project, following the suggestion of the inclusion of the SiC as a diffusion barrier by D. T. Livey. TRISO was mass produced for the first time to fuel the THTR-300 powerplant in Germany, using both uranium and thorium as kernel fuel. It was operational from 1986-89, but then shut down following a change in German government policy following Chernobyl.

This is ironic given that such an accident would not have been possible with a TRISO reactor.

Interest in TRISO has revived in the last 5 years as the realization that advanced (passively safe) nuclear reactors are the best way to overcome concerns about the danger of nuclear power and to ensure its broader application for power needs globally. Currently, TRISO fuel compacts are being used in some experimental reactors, such as the HTR-10 in China and the high-temperature engineering test reactor in Japan. In the United States, spherical fuel elements utilizing a TRISO particle with a UO_2 and UC solid solution kernel are being used in the Xe-100, and Kairos Power is developing a 140 MWE nuclear reactor that uses TRISO.

Why TRISO is so important

TRISO fuel is the most important component of a TRISO based AMR. Getting the TRISO fuel certified is the most important step in getting the AMR certified. Why? Because a TRISO based AMR is Gen IV passively safe (walkaway safe, some might say inherently safe) owing to the TRISO fuel.

TRISO's ability to shield the uranium inside from conditions outside and to prevent radioactive material from leaking out means that the self-stabilizing effects of temperature on fission can be fully utilized. Even if the traditional cooling/dampening methods (graphite rods, pressurised gas cooling) are disabled and temperatures rise in the reactor, the increase in temperature (from its standard working temperature of 780 C up as high as 1600 C) means that the uranium will start to absorb more neutrons via the Doppler Effect, thereby reducing the rate of fission.

This would not be possible in a traditional PWR (pressurized water reactor) because the increase in temperature needed for the uranium to absorb more neutrons would also have melted key components in the reactor.

Not only is TRISO fuel the critical safety component, it is also the most important cost component – over the lifetime of an AMR, TRISO fuel will represent 65-75% of the total cost of the reactor. So manufacturing TRISO fuel consistently and cheaply will determine the success of any AMR project.

At the German AMR project, the South Africa AMR project and at the Chinese AMR project many years of research and development has been going into manufacturing TRISO. Using different form factors, using different kernel fuels and scaling up production. This typically starts out with modifying off the shelf equipment to make it suitable for TRISO production, but often end up designing and manufacturing their own equipment from scratch.

How is TRISO made

TRISO is a long multi-faceted process requiring a mix of different chemical engineering and deposition processes. The main steps are as follows

1. Kernel Manufacturing – drops of molten heavy metal (UO2 or UCO or ThO2) are created (sparged) and then cooled in a tower.

2. Coated Particle Manufacturing – the kernels of heavy metal are coated with in turn a porous carbon buffer layer, an inner pyrolitic carbon layer (IPyC), a silicon carbide barrier coating (SiC) and then an outer pyrolitic carbon layer (OPyC). The resulting coated (TRISO) particles are less than 1mm across.
3. Fuel Sphere Manufacturing – 60mm shells with 5mm thickness are cast from matrix graphite and then filled to create with approximately 10,000 of these coated particles to create a TRISO pebble

Vigorous QC is required at each step of this process. Any rejected kernels, CPs or FSs are recycled.

American vs European TRISO Production Methods

Two ways have been developed to produce in TRISO which are generally described as the American and the European (or German) methods. In general the lines have been built so far in the US conform to the American method. There are important differences between the two outlined in the table below:

Aspect	US Style TRISO	European Style TRISO	Main Difference
Manufacturing Approach	Batch process with intermediate quality checks, leading to weaker inter-layer bonding and higher defect rates.	Uses Safe Geometry to create full-scale continuous processes – coating ensures seamless layer integration and superior durability.	Batch offers flexibility; continuous ensures higher reliability and scalability.
Kernel Material	UCO (Uranium Oxycarbide): Higher thermal conductivity but increases kernel migration and gas release risks.	UO2 (Uranium Dioxide): Stable performance with lower gas release and better in-reactor reliability. Proven compatibility with all combinations of LEU, HALEU, and ThO2.	UCO has better heat management; UO2 is more versatile and stable under irradiation.
Performance Metrics	Higher fission gas release and frequent irradiation-induced failures.	Three orders of magnitude lower fission gas release and excellent irradiation performance.	European TRISO excels in reliability; US TRISO has niche thermal advantages.
Scalability	Limited scalability for large SMR deployment.	Proven industrial-scale production for high-demand scenarios.	European TRISO scales better; US TRISO fits small-scale or experimental needs.

UCO vs UO2

The biggest difference between the American and European methods (which in turn explains a lot of the other differences between the two) is that the former uses UO2 as its kernel fuel input and the latter uses UCO (Uranium Oxycarbide). UO2 is more widely available but has been proven to more unstable in a TRISO context. As the DOE mentioned in a recent report:

“When the uranium in a uranium dioxide (UO 2) molecule splits, the oxygen ions released can react with carbon in the pyrolytic layers to form carbon monoxide (CO) gas,” the DOE said. *“At very high burnup, the accumulated CO gas may exert excessive pressure on the*

particle coatings and cause them to fail. The UCO mixture limits the amount of free oxygen released from the kernel, enabling higher burnups to be achieved, as has been confirmed during post-irradiation examination of TRISO fuel."

Moving from Batch to Continuous Production

All existing TRISO lines are batch. This is the logical process technology when the quantities of TRISO involved are small, as TRISO form factor and performance are being perfected and cost is not a major consideration. But when you need to produce fuel for dozens or even 100s of TRISO based SMRs then you need to move from 1-2kg a day to 10/20/50 kg a day.

At this point the amount of uranium present in the plant passes critical levels. Safety in production becomes a primary concern. To manage this it is essential to use "Safe Geometry". This means ensuring that there is no possible place along the production line where a critical amount of uranium could build up, even in the event of a complete production line breakdown.

The other issue with a move to continuous production methods is that the tooling required is totally different. Our team has spent years of research in testing and modifying the equipment required for this shift.

Kernel Fuel: HALEU, LEU and Thorium Mixes

The reality of reactor design depends on neutron management at a millimeter spatial resolution in all three dimensions. The specific location of fissile isotopes within the core will drive this distribution. Fuel pellets could be fabricated of the same composition for the entire core—that is, each fuel pellet would contain a prescribed fraction of thorium and uranium. The second option would be fabricating pure thorium dioxide separately, such that both uranium and thorium fuel pellets would be used to construct the core. In practice this is much easier to achieve with a TRISO design than with traditional PWR fuel rods.

TRISO Fuel Certification

For any AMR using TRISO-based fuel, obtaining certification for the TRISO fuel is a crucial step in the overall reactor certification process. The multi-step certification process ensures the fuel meets the rigorous safety and performance standards required for operation in AMRs, being a key component of the renowned safety features of the reactor. The process combines historical data from past programs, rigorous testing, guided by regulatory frameworks set forth by the U.S. Nuclear Regulatory Commission (e.g. NUREG-2246) and other international entities.

Key Certification Requirements

The certification process for TRISO fuel is centered around a regulatory framework focused on demonstrating the ability to retain fission products and perform safely under normal operating conditions and during accident scenario testing. The process is based on work performed by past reactor programs, integrating lessons learned and optimizing the TRISO fuel to meet specific operational requirements.

Performance, Quality and Safety Testing

TRISO fuel certification revolves around confirming the radionuclide retention capabilities of the fuel. The multi-layered coating of the fuel kernel is critical to prevent the release of radiation during normal and accident scenarios. The fuel undergoes extensive irradiation testing and post-irradiation examination to evaluate the fuel's integrity and effectiveness of the multi-layer radiation retention capabilities.

Additionally, as part of the certification, quality assurance is evaluated at every stage of the fuel fabrication process to ensure low defect levels and that the coating layers are applied uniformly.

Citations

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