How can traveling wave reactors solve nuclear energy issues?

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Traveling Wave Reactors (TWRs) offer a promising approach to improving sustainability and safety in nuclear energy, though it faces challenges. Professor Di Yun from Xi'an Jiaotong University discusses a novel 'Tai-Chi' technology designed to tackle key R&D issues related to TWR

With rising electricity demands all over the globe and abnormal climate patterns due to carbon emissions, nuclear power is being valued as a vital electricity generation source. Having experienced the Three Mile Island accident, the Chernobyl accident, and the Fukushima accident, the safety standards and measures taken by the nuclear industry have taken a huge leap to become more systematic and mature. However, there are still some hardcore issues that nuclear power needs to overcome, among which the most imminent ones are scarce uranium resources, disposition of nuclear wastes, and climbing costs as the safety measures of the current nuclear systems become more stringent.

A traveling wave reactor (TWR), often known as the breeder-burner wave reactor, was proposed and developed to address the need for green sustainability, inherent safety, and nuclear non-proliferation in nuclear energy development. TWRs are named for their continuously moving neutron 'burning' zone, continuously consuming new nuclear fuel zones and creating a spent nuclear fuel zone after burning.

As a result, the spent nuclear fuel is significantly reduced, and lower toxicity nuclear wastes are generated compared to many other reactor types. It is also possible to optimize the design of the TWR reactor using different fuels, including natural uranium, depleted uranium, spent fuel, low-enriched uranium, and even thorium, based on different needs, hence reducing costs on the nuclear fuel fabrication side. TWR has outstanding advantages: ultra-high nuclear fuel utilization: up to 50-70 folds that of the current light water reactor fleet, high system thermal efficiency, simple control and long-term self-stabilizing operation, and ultra-long lifetime extending to about four times or above of the current limit set for fast neutron reactors by the International Atomic Energy Agency (IAEA), etc. Once proposed, it was widely regarded as the ultimate form of fission nuclear reactors. Once realized, the TWR technology will disruptively break the current contradiction between safety and economy faced by existing Generation III and IV nuclear reactors.

However, the development of TWR is currently very limited worldwide. This is because TWR sets very strict requirements on its nuclear fuels. Due to its extensive fuel life, nuclear fuels for TWRs must survive 40-60 years of in-reactor operation. The resulting impacts on the nuclear fuel materials are extremely severe: large amounts of fission gases are accumulated in the fuel, leading to strong fuel swelling; a very high dose of fast neutron irradiation brings about severe irradiation damage to the nuclear fuel cladding materials, and extensive long life leads to accumulation of corrosion effects. Any of the above effects alone would be challenging enough for nuclear fuel engineers not to discuss the combination of all three. Nuclear fuel developers have been puzzled by these issues for a long time, and the R&D efforts to TWR have almost completely stopped.

Five-element technological blueprint

In 2022, the research team led by Professor Di Yun at Xi'an Jiaotong University of China proposed a fresh new idea to solve the above-mentioned issues: an approach linked to the renowned Chinese Kungfu element 'Tai-Chi.' The technical details are outlined in a scientific paper published in MRS Bulletin (A novel approach on designing ultrahigh burnup metallic TWR fuels: Upsetting the current technological limits, MRS Bulletin, Impact Section, Volume 48, November 2022). Since then, the team has been researching and further developing this technology into a five-element technological blueprint.

The five leading technologies are:
1) High zirconium metallic nuclear fuels for extensive fuel burn-up, 2) In-pile annealing technology to heal irradiation effects in nuclear fuel cladding materials, 3) Self-healing of oxide film by short-term high-temperature operation, 4) Collected fission gas to monitor fuel temperature on the fly during high-temperature operations, and 5) Operation experience accumulation-based self-learning of nuclear fuel performance models to high fuel burn-up. The fuel design utilizes a high zirconium nuclear fuel, U-50Zr, relying on its low intrinsic fuel swelling. The key element to this technology is the intentional introduction of high-temperature operations, which is usually feared in nuclear reactors, to simultaneously treat the cladding irradiation effects and oxide film degradation by corrosion. This high-temperature operation is only possible when the nuclear fuel has a melting temperature high enough and a negative temperature feedback coefficient, which is what U-50Zr fuel possesses.

With the layout of the technological blueprint, the team has been pushing steadily on all five fronts: a large amount of corrosion and high-temperature treatment experiments have been conducted to elucidate the characteristics of the material that best supports the self-healing technology and the exact high-temperature at which the operation needs to be undertaken has been determined. In-pile irradiation experiments have been planned to help optimize the material's composition to achieve the near-complete healing of irradiation effects. An experimental apparatus has been set up to demonstrate the feasibility of monitoring fuel temperatures on the fly with gas pressure measurements. A fuel performance platform that encompasses the Artificial Intelligence algorithms of self-learning is also being developed. The team expects significant progress in the next three to five years, and a mature technological roadmap will be envisioned.

In summary, TWR is the ultimate nuclear fission reactor technology that solves all significant existing problems for nuclear electricity generation. A team led by Professor Di Yun at Xi'an Jiaotong University of China is now pushing for the development of a novel

‘Tai-Chi’ technology that is believed to be capable of resolving the key issues faced by the R&D of TWR. The team welcomes domestic and international collaborations to push this technology forward.

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