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The development of high density, low enriched fuel for the conversion of research reactors

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The development high density LEU fuels was initiated by the U.S. Reduced Enrichment for Research and Test Reactors (RERTR) program, established in 1978 to address a concern about the proliferation of HEU in civil commerce. Its goal was to enable research and test reactors to convert to, or back to, LEU by developing higher-density fuels that could accommodate the required increase in 238U and that could be used without significant performance loss or cost increase.

Initially the program concentrated on the densest uranium silicide phase (U3Si) dispersed in aluminium as the prime candidate for development. The next-lower-density silicide phase, U3Si2, was also tested.
Rapidly international cooperation started up for development of the silicide dispersion fuels.

However the main silicide fuels being tested for use in plate-type fuel elements, U3Si-Al and U3SiAl-Al, had shown fission gas bubble growth in the fuel particles by at ˜ 85% burn up in LEU. Fortunately, U3Si2-Al fuel was found stable at a burn up of at least 90%, so further development was concentrated on U3Si2-Al fuel. The development of this fuel evolved without major drawbacks, and in 1988, the NRC gave a generic approval for use of U3Si2-Al dispersion fuel at 4.8 gU/cm3 in its licensed research and test reactors. This fuel gained worldwide acceptance and many research and test reactors, with powers up to 50 MW, have been converted since 1988 using U3Si2-Al fuel.
In Canada AECL developed and qualified U3SiAl-Al and U3Si-Al dispersions for its reactors, which use pin-type fuel elements. Later, AECL also qualified U3Si2-Al fuel in MAPLE-type pins.
The one negative aspect of the silicide fuels was the formation of silica gel during dissolution of spent fuel during reprocessing. - The problematic of the closure of the LEU fuel cycle will also be addressed in the paper.

High-power-density research and test reactors could not be converted with U3Si2 as they require higher-density fuels. A fuel loading of 6.5-8.5 gU/cc is required for most of these reactors; some of them require even higher densities only achievable with alternative fuel designs, such as the monolithic UMo. So the fuel developers community started the development of very-high-density fuels. High-uranium-content alloys, such as UMo and UNbZr with uranium contents of 90 w% or higher were considered. Guided by past experience with fast reactor fuels, UMo was adopted as the primary candidate for a very-high-density fuel by the U.S. RERTR program.

The initial irradiation tests of UxMo dispersions showed the fuel to perform satisfactorily with $x \geq 6$.
There was however considerably more interaction between the fuel and the aluminium matrix than there had been for the silicide fuel, but it was thought that this problem could be overcome.

Sometime later the U7Mo dispersion fuel system qualification experienced a number of unexpected setbacks, mainly related to the formation of an interaction layer around the fuel grains. The particular power regime at which the high density U7Mo fuel needs to operate, present a particular challenge compared to the U3Si2 qualification process.
Several remedies for this failure mechanisms were proposed and tested. Silicon addition to the matrix or coating of the fuel grains (E-FUTURE and SELENIUM) have clearly improved the behaviour up to 60% burn up. However, beyond these fission densities, fuel plates are still found to show rapid swelling. The tests with coated UMo fuel also show an accelerating swelling in function of burn up at these elevated fission densities, but were not followed by pillowing. The current working hypothesis is that we are facing intrinsic properties of the atomised U7Mo fuel, where the onset and progress of recrystallization of the fuel may eventually cause swelling rates to exceed the mechanical capabilities of the irradiated dispersion UMo meat. The recrystallization threshold and evolution can be influenced by changing the UMo microstructure to eliminate Mo inhomogeneity and enlarge grains, which may hold promise to reduce the swelling rate at high burn up to within acceptable limits for the mechanically weakened matrix.

Presently both dispersion and monolithic fuels are being pursued in parallel.
Qualification of UMo dispersion fuel is being pursued by the European HERACLES program. The U.S. program has a collaborative relationship with the HERACLES program. Two irradiation campaigns are presently foreseen to test and optimize the various remedies and deepen the basic understanding of the failure mechanisms. The fabrication process may have to integrate additional steps: atomization, coating, heat treatment.

Qualification of UMo monolithic fuel is strictly within the U.S. program at the present time, aimed at the conversion of five U.S. research and test reactors. The efforts are mainly concentrated on the industrialization of the fabrication process.

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