Registered Office
Herrmann-Debrouxlaan 40
1160 Brussel – Belgium

Foundation of Public Utility
VAT BE 406.568.867

Research Centres
Boeretang 200
2400 Mol – Belgium

Chemin du Cyclotron 6
1348 Ottignies-Louvain-la-Neuve – Belgium

Reference N°	Creation Date	
SCK CEN/46155164	2021-11-02	
Alternative Reference N°	Revision	Version
N/A	1.0	1
ISC	Revision Status	
Public	Approved	

REPORT ON U3Si2-Al DISPERSION FUEL FOR HIGH-POWER RESEARCH REACTORS .pdf

Authors*
Leenaers Ann

Approval information for current revision*

Name	Outcome	Date
Marc Verwerft	Approved	2021-12-14

Change log*

Revision	Version	Status	Date	Description of change
1.0	1	Approved	2021-11-02	

REPORT ON U_3Si_2-Al DISPERSION FUEL FOR HIGH-POWER RESEARCH REACTORS

Yeon Soo Kim, A. Oaks, B. Ye, L. Jamison, K. Mo, Y. Miao,
Z. Mei, G. Hofman, A. Yacout
Argonne National Laboratory (ANL)
9700 S. Cass Ave, Argonne, IL 60439 – USA

A. Robinson, D. Keiser
Idaho National Laboratory, P.O. Box 1625, Idaho Falls, ID 83415-6188 – USA

A. Leenaers
Nuclear Materials Science Institute, SCK•CEN, Boeretang 200, 2400 Mol – Belgium

ABSTRACT

The primary focus points of a report entitled “Technical Basis Report on Low Enriched Uranium Silicide-Aluminum Dispersion Fuel for High Power Research Reactors” are described in this paper. In the US Reactor Conversion program, U_3Si_2-Al dispersion fuel was developed. In 1988, the US NRC’s safety evaluation report (NUREG-1313) concluded that U_3Si_2-Al plate-type fuel was acceptable for use in research and test reactors with uranium densities up to 4.8 gU/cm^3 in the meat at the power level investigated in the demonstration tests. Fuel performance at the power conditions included in NUREG-1313 are summarized. As interest has recently been revived for higher power applications of this fuel, the effect of high-power conditions on fuel performance is addressed. In addition, the effect of U-densities higher than 4.8 gU/cm^3 is discussed. Knowledge gap items associated with higher power and higher U-density applications are identified together with the proposed resolution methods.

1. INTRODUCTION

A report on U_3Si_2-Al dispersion fuel in a plate form has been drafted as this fuel is undergoing renewed interest in potential applications for high power conditions, extending those evaluated in NUREG-1313 [1]. This fuel was licensed for use with uranium densities up to 4.8 gU/cm^3, at the power level interrogated in the demonstration test (peak heat flux ≤ ~140 W/cm^2 and peak fuel temperature ≤ ~130 °C). Since the publication of NUREG-1313, more test data for this fuel, particularly at high powers, have become available.

The main objective of this report is to produce a stand-alone data compilation that enables review and analysis of the available higher-power data, extended from the data used for the qualification of this fuel in 1988. It is also indirectly intended to serve as a supporting document of the technical basis for future reactor-specific fuel qualification reports, in support of regulatory licensing activities for reactor conversions.

Knowledge gaps for higher-power applications of the fuel have been identified and indicate the desired work areas in the near future. Methods to resolve the information gaps are proposed.

The structure of this report is as follows:
Chapter 1: Background and basic information for the report are given.
Chapter 2: Fuel fabrication methods are described.
Chapter 3: Characterization of the as-fabricated fuel system is described.

Chapter 4: Fuel performance is discussed.
Chapter 5: Data and correlations of the properties of the fuel system are discussed.
Chapter 6: Fuel performance during off-normal states is addressed.
Chapter 7: Summary
Appendix: Gap analysis table

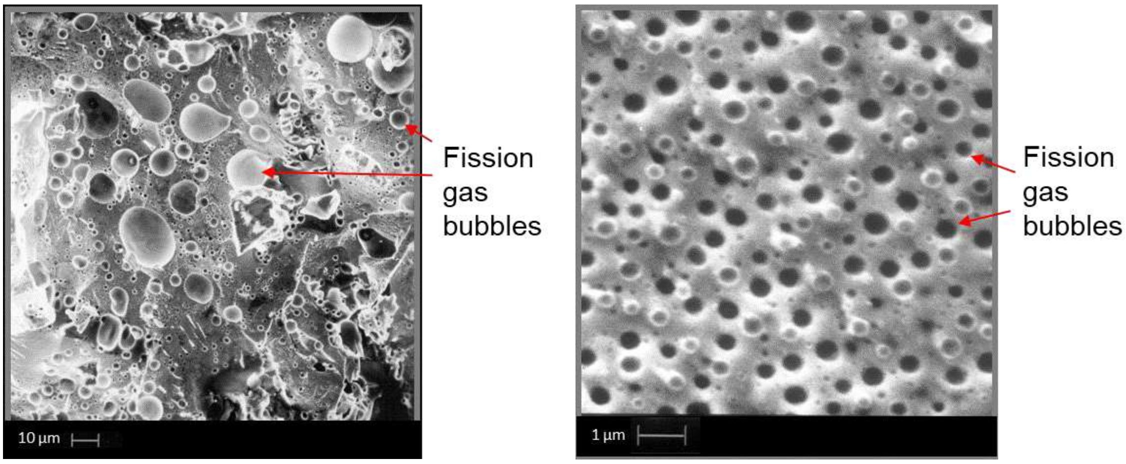
2. U_3Si_2-Al PERFORMANCE

2.1 Lower Power Conditions

The crystalline U-Si fuel compounds (U_3Si, U_3Si_2 and USi) that form during fabrication, transform to non-equilibrium mixtures of amorphous U_3Si, U_3Si_2 and USi under irradiation at relatively low research reactor temperature conditions. When irradiated fuel is discussed, the amorphous states of those mixtures are of particular importance. A fuel particle can be a mixture of amorphous U_3Si, U_3Si_2, and USi phases, each of which exhibits different fission gas bubble behavior. Therefore, the size of fission gas bubbles (FGB) can be drastically different locally depending on the local chemistry.

Low power conditions discussed in this section are for those interrogated in the past demonstration tests included in NUREG-1313 (having a heat flux ≤ ~140 W/cm^2 and a peak fuel temperature ≤ ~130 °C) [1],[2].

U-Si fuel meat swelling under low power conditions is primarily due to fuel particle swelling, since the effect of interaction layer (IL) growth between the fuel particles and the aluminum matrix is small. FGB swelling is the primary contributor to fuel particle swelling at high burnup. The kinetics of FGB growth is known to be dependent on the Si content in the fuel particle. The size of the FGB in U_3Si_2 is much smaller than that in U_3Si (See Figure 1).



(a) U_3Si (90% LEU burnup) (b) U_3Si_2 (90% LEU burnup)

Figure 1: SEM images of the fractured surfaces of U-Si fuels irradiated at ~100 °C in ORR. Note the difference in magnification [2].

In a lower magnification optical microscopy (OM) image (Figure 2), the microstructure of U_3Si_2-Al exhibits large FGB that are in-homogeneously distributed throughout the fuel meat. The non-uniform distribution of the large FGB implies that they are related to the local fuel chemistry. Nominally, U_3Si_2 alloy contains a fraction of lower-Si content alloys such as U_3Si, which shows higher FGB swelling.

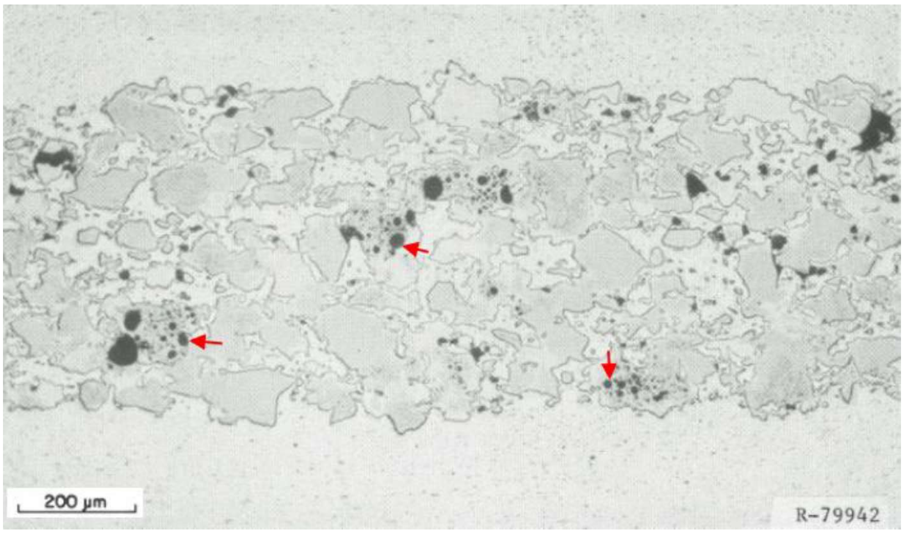


Figure 2: OM image of U_3Si_2-Al in BSI-201 at 71% LEU burnup. The red arrows mark large FGB [2].

A study at SCK•CEN (Belgium) showed that the size of the FGB is dependent on the Si content of the fuel particles they occupy, although the fuel is a nominal U_3Si_2-Al dispersion (Figure 3) [3]. Figure 3 shows that minor fuel phases such as USi and U_3Si are also found in U_3Si_2-Al dispersion fuel. The FGB are round in USi and U_3Si_2, but they take various shapes in U_3Si, implying signs of FGB coalescence.

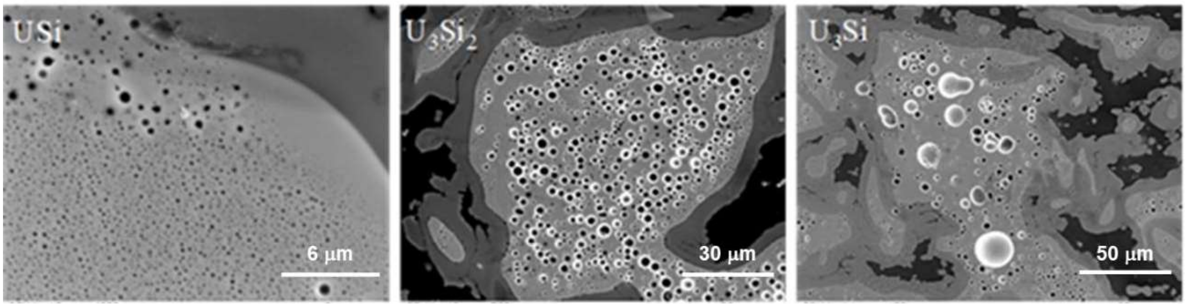


Figure 3: SEM images of fuel particles showing the differences in FGB generated in the USi, U_3Si_2 and U_3Si phases contained in a nominal U_3Si_2-Al dispersion fuel irradiated to a burnup of ~86% at ~130 °C. Note the difference in magnification.

The effect of Si content in U-Si fuel on overall fuel particle swelling is evident in Figure 4. The alloys with the least Si (indicated by the blue box in the figure legend) generally swell at a higher rate. This enhanced swelling is associated with a pronounced coarsening and coalescence of the fission gas bubbles (see the image of U_3Si in Figure 3). The data for higher Si content fuels such as U_3Si_2 and USi do not deviate much from the dashed line for swelling due to solid fission products (the lowest possible fuel swelling) up to 100% LEU burnup, indicating no sign of breakaway swelling. The volume fraction of heterogeneously large FGB is still small, and more importantly the FGB are contained within the fuel particles as is shown in Figure 2 and Figure 3(U_3Si).

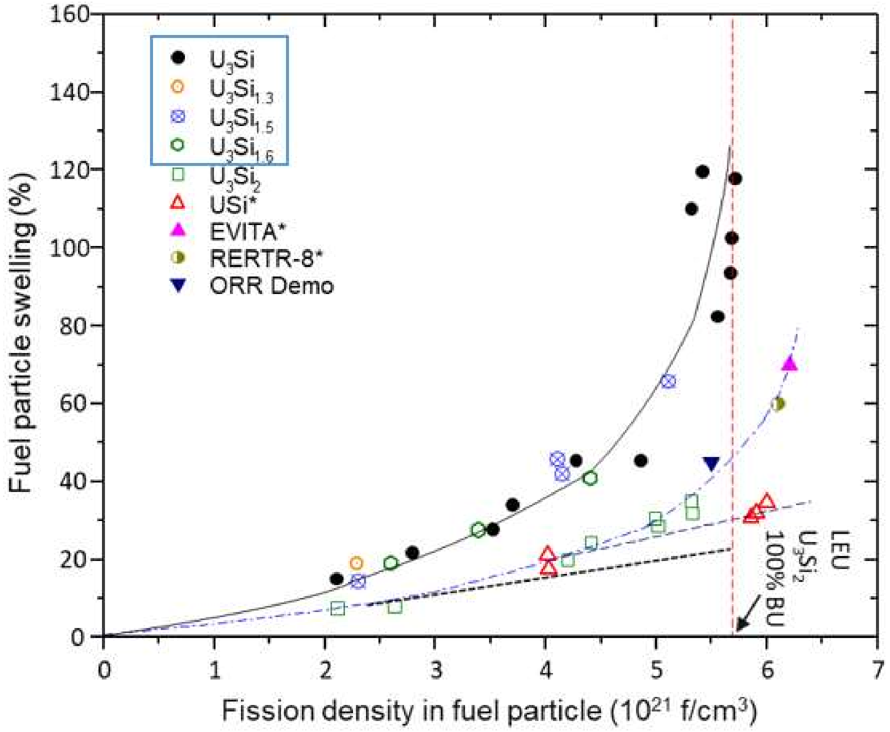


Figure 4: Fuel particle swelling in various U-Si/Al dispersion fuel plates. The Si/U ratios are nominal values. (* Enriched in U-235 higher than 20%). EVITA [4], RERTR-8 [5] and ORR Demo [6] are U_3Si_2. The data for EVITA and ORR Demo are from full size plates; all other listed data are from reduced size plates. The dashed black line indicates swelling from only solid fission products.

2.2 High Power Conditions

High power conditions discussed here refer to irradiation studies with higher fission rates and fuel temperatures, but the same level of burnup as those discussed in Sect. 2.1.

Higher fission rates and temperatures do not appear to change the kinetics of FGB swelling significantly [2]. However, the IL growth rate is enhanced by higher fission rates and particularly higher temperatures. Under these conditions, the IL growth consumes the Al matrix more rapidly and, in some extreme cases, a complete depletion of matrix Al occurs. Continued irradiation under these conditions causes the IL density to increase (due to continued diffusion of the Al from the IL to the fuel), and pores to develop at the previous fuel particle surfaces (Figure 5). The formation of this pore type can lead to pillowing due to the fuel overheating as a result of the decreased thermal conductivity in the fuel meat.

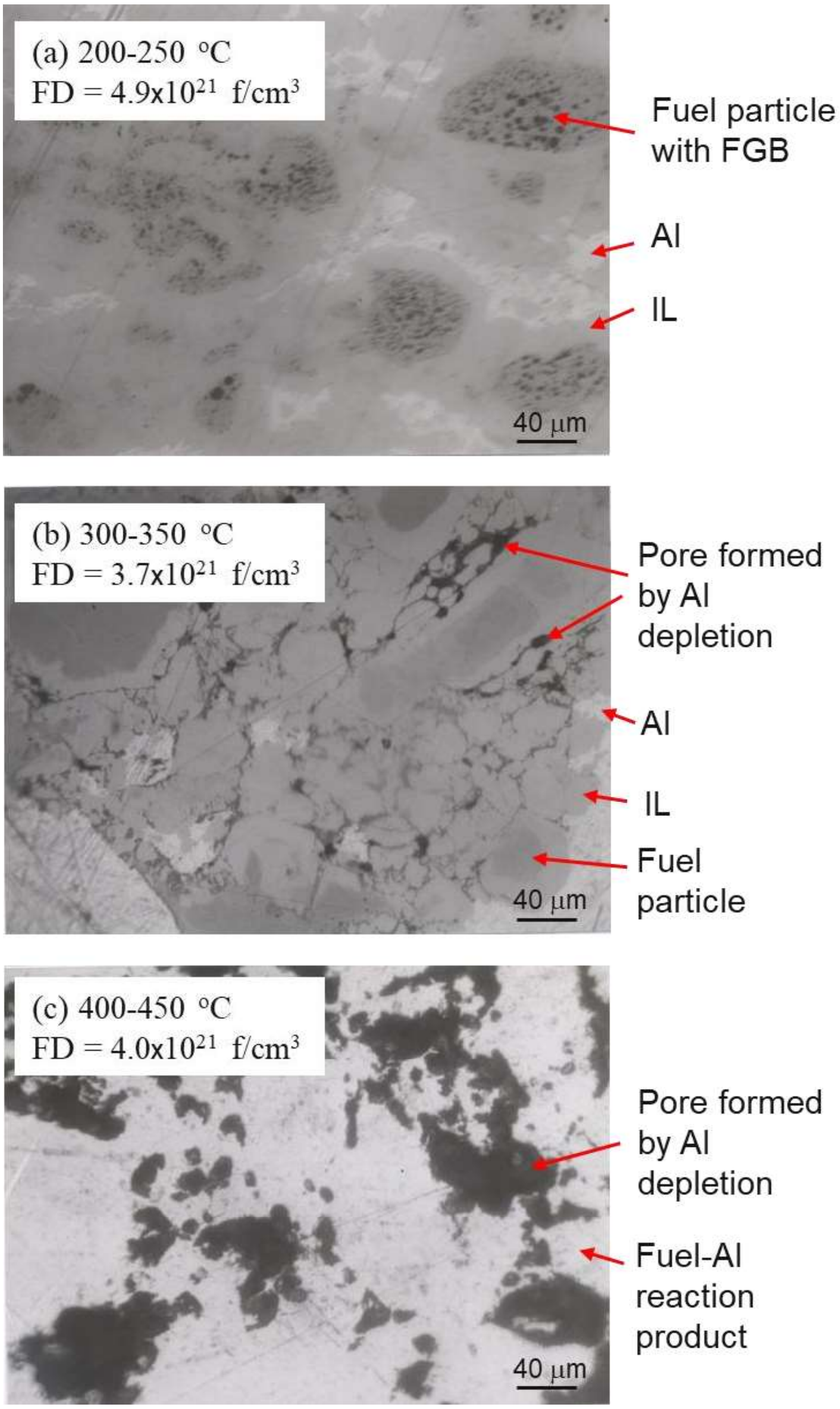


Figure 5: Low-enriched U_3Si_2-Al dispersion fuel samples with 4.8 gU/cm^3 irradiated for 23 effective full power days (EFPD) at the indicated fuel temperatures. Temperatures were controlled during the irradiation, so they are not proportional to fission densities (FD) [7].

2.3 Effect of Uranium Density

When the U-density of U_3Si_2-Al dispersion fuel increases, the thermal conductivity and initial Al volume fraction of the fuel meat decrease. The majority of in-pile test data are for U-density of 4.8 gU/cm^3-fuel meat. Although limited, there are some data for U-densities higher than 4.8 gU/cm^3. The test in the ORR [2] included miniplates with higher U-densities up to 5.7 gU/cm^3. At low temperatures (≤ ~130 °C), the increase in U-density exhibited no significant impacts on fuel performance [2].

Although there was minimal impact of increasing the U-density in the fuel at lower powers, at high powers the U-density can significantly impact the fuel performance. The increased surface area and decreased Al matrix increases the rate at which the matrix is consumed by IL formation, leading to large pores (as seen in Figure 5(c)). For U-density of 6.1 gU/cm^3 under high power [8], complete depletion of the Al matrix occurred at 25% burnup (FD = 1.3×10^{21} f/cm^3, peak temperature reaching ~420 °C), a much lower burnup than when depletion occurs at lower power (see Figure 5 (c)). Note that the test conditions of the test of Ref. [8] are different from those of the test shown in Figure 5 (c), making direct comparisons difficult. Establishing a U-density threshold for each power regime is desirable. A systematic set of data and a thorough evaluation of irradiation parameters are needed in order to compile this information.

3. U_3Si_2-Al PROPERTIES

The properties of U_3Si_2, matrix Al, and the U_3Si_2-Al meat composite necessary for fuel designs and safety analyses were compiled in the report. Primarily, only un-irradiated material properties are available. Many of the material properties are considered to be insensitive to irradiation. However, thermal conductivity, density, and heat capacity may change due to irradiation, for which no data are currently available. These items are identified as gaps.

4. GAP ANALYSIS AND METHODS OF RESOLUTION

The availability of fuel performance information and thermo-physical properties of U_3Si_2-Al under higher power conditions are summarized in Table 1. The proposed methods and plans to resolve the data gaps are also included. Note here that there are on-going irradiation tests of the U_3Si_2-Al system at those higher power conditions in BR-2 (e.g., HiPROSIT experiment [9]), which are expected to fill in some of the data gaps identified in the table. Only limited data from the EVITA testing are currently available, but included in the table in case more data become available in the future.

Table 1: Gap analysis and resolution methods

Topic	Gap reason	Method to fill gap
Specifications	- No gap for currently qualified fuel, but modification for high power use may be needed. - Inspection methods to be developed with fabricators.	- Decide when new data are available
Fuel meat swelling at high power conditions	- Quantitative meat swelling data for high-power tests are needed. - FGB swelling at higher power is not quantitatively known.	- Existing test data from BR2 [8] - EVITA data - On-going Tests at BR2
Interdiffusion reaction between U_3Si_2 and Al at high temperatures	- Al matrix consumption kinetics is critical to sound fuel performance, but data are scarce at high temperatures.	- Existing test data from BR2 [8] - EVITA data - On-going Tests at BR2
Effect of higher fuel loading at high power conditions	- Performance data on the effect of U-loading higher than 4.8 gU/cm^3 at high power (or high temperature) are needed. - A threshold function on fuel loading versus power may be desirable.	- Thorough re-analysis of existing data from legacy tests from ORR and BR2 - On-going tests at BR2
Fuel meat creep	- The effect of this phenomenon is not fully understood. - Quantitative creep data are not available.	- Thorough re-analysis of existing data from legacy tests from ORR and BR2 - EVITA data - On-going tests at BR2
Effect of burnable absorber (BA) addition	- Some studies are available for low-power tests, but more data are needed at high power conditions.	- On-going tests in BR2
Un-irradiated U_3Si_2 thermal conductivity	- Data for bulk U_3Si_2 are tentatively used for U_3Si_2 powder. Values for the powder may be different.	- Measurement of particulate U_3Si_2
Irradiated U_3Si_2 thermal conductivity	- No measured data are available. - Modeling may be more time and cost effective.	- Low scale modelling - Measurement of irradiated fuel
Density of irradiated fuel meat	- Some measurement data are available. - More measurement data are needed. - Modeling may help.	- On-going tests in BR2 - Model needs to be verified with measured data
Heat capacity of irradiated fuel meat	- Heat capacity of irradiated fuel meat changes by meat density change (e.g., FGB). - No measurement data are available. - Modeling may be a realistic option.	- Modelling may be needed - Measurement of irradiated fuel
Properties of EU cladding materials	- EU cladding (AG3NE or AlFeNi) data are less known than US test cladding AA 6061.	- Collaboration with CEA and SCK CEN
Blister threshold temperature	- Low power data exist. - Plates irradiated at high power may have different blister temperatures.	- Collaboration with CEA and SCK CEN

5. SUMMARY

A report on U_3Si_2-Al dispersion fuel has been drafted. A brief summary of the report focusing on fuel performance and properties of the fuel is presented. The data gaps to establishing a technical basis of this fuel performance at higher power conditions are identified and the resolution methods of the gaps are proposed.

At low power conditions (having a heat flux ≤ ~140 W/cm^2 and a peak fuel temperature ≤ ~130 ^{o}C), U_3Si_2 fuel performs well, showing low and stable fuel swelling up to 100% LEU burnup. FGBs were small and, more importantly, they were contained within the fuel particles. At the combination of higher power conditions and temperatures, while the kinetics of FGB swelling does not appear to change significantly, enhanced IL growth consumed the Al matrix more rapidly and, in some extreme cases, a complete depletion of matrix Al occurred. Al matrix depletion and subsequent pore formation in the meat could potentially lead to pillowing.

Increasing the U-density was not significantly disadvantageous to fuel performance under low power conditions. However, at high power conditions, the increased U-loading could have a more significant effect on fuel performance by increasing the potential for a more rapid depletion of the Al matrix and needs further investigation. The effects of the combination of high power and high temperature will be further clarified with the availability of the data from the on-going and planned irradiation tests.

ACKNOWLEDGMENTS

This study was sponsored by the U.S. Department of Energy, National Nuclear Safety Administration (NNSA), Office of Material Management and Minimization (NA-23) Reactor Conversion Program.

The submitted manuscript has been created by the UChicago Argonne, LCC as Operator of Argonne National Laboratory under contract No. DE-AC-02-06CH11357 between the UChicago Argonne, LLC and the Department of Energy. The U.S. Government retains for itself, and others acting on its behalf, a paid-up, nonexclusive, irrevocable worldwide license in said article to reproduce, prepare derivative works, distribute copies to the public, and perform publicly and display publicly, by or on behalf of the Government.

REFERENCES

[1] U.S. Nuclear Regulatory Commission, "Safety Evaluation Report related to the Evaluation of Low-Enriched Uranium Silicide-Aluminum Dispersion Fuel for Use in Non-Power Reactors," NUREG-1313, 1988.

[2] J.L. Snelgrove, R.F. Domagala, G.L. Hofman, T.C. Wiencek, G.L. Copeland, R.W. Hobbs and R.L. Senn, "The Use of U_3Si_2 Dispersed in Aluminum in Plate-Type Fuel Elements for Research and Test Reactors," ANL/RERTR/TM-11, 1987.

[3] A. Leenaers, E. Koonen, Y. Parthoens, P. Lemoine, S. Van den Berghe, Journal of Nuclear Materials, vol. 375, p. 243, 2008.

[4] M.-C. Anselmet, M. Ripert, P. Lemoine, E. Koonen, W. Claes, F. Geens and S. Van den Berghe, "Qualification of the JHR fuel elements under JHR operating conditions," in Transactions of International Topical Meeting on Research Reactor Fuel Management (RRFM 2013), St. Petersburg, Russia, April 21, 2013.

[5] Yeon Soo Kim, G.L. Hofman, J. Rest and A.B. Robinson, "Temperature and Dose Dependence of Fission-Gas-Bubble Swelling in U_3Si_2," Journal of Nuclear Materials, vol. 389, p. 443, 2009.

[6] G.L. Copeland, R.W. Hobbs, J.L. Snelgrove and G.L. Hofman, "Performance of Low-

Enriched U_3Si_2-Aluminum Dispersion Fuel Elements in the Oak Ridge Research Reactor," Argonne National Laboratory, ANL/RERTR/TM-10, 1987.
[7] G.L Hofman, J. Rest, J.L. Snelgrove, T. Wiencek, "Aluminum- U_3Si_2 Interdiffusion and Its Implications for the Performance of Highly Loaded Fuel Operating at the Higher Temperatures and Fission Rates," RERTR Meeting, Oct. 7 – 10, 1996
[8] A. Leenaers, S. Van den Berghe, E. Koonen, P. Jacquet, C. Jarousse, B. Guigon, A. Ballagny and L. Sannen, "Microstructure of U_3Si_2 Fuel Plates Submitted to a High Heat Flux," Journal of Nuclear Materials, vol. 327, no. 2-3, pp. 121-129, 2004.
[9] S. Valance, H. Breitkreutz, Y. Calzavara, M. Hrehor, F. Huet, et al., "LEU fuels for medium and high power research reactors in Europe project LEU-FOREvER," International Topical Meeting on Research Reactor Fuel Management, ENS, Munich, Germany, Mar. 11 – 15, 2018.