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Original

Non-destructive test of irradiated silicide fuel plate: Visual examination and digital X-ray radiography analysis

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Abstract: The development of high-density silicide fuels for research reactor RSG-GA Siwabessy has been conducted by increasing the fuel density. The fuel density of U_3Si_2/Al fuels was increased from 2.96 gU/cm^3 to 4.8 gU/cm^3 with potential effect on the cladding integrity and its geometric stability, so a post-irradiation examination is required. Non-destructive tests using digital X-ray radiography and visual inspection are the most important tests in performance evaluation of irradiated fuels. This research uses U_3Si_2/Al fuel plate with 4.8 gU/cm^3 density and 20% burnup as known as CBJJ249. Visual inspection of the fuel surface was performed in hot cell 102 and 103 using a camera through the hot cell window and dedicated manipulator intra-camera. X-ray radiography test was performed in hot cell 103 using digital x-ray radiography apparatus with parameters set at 120 kV and 1000 µA, respectively. The image analysis was later performed using an image processor, which involves the process of adjusting image contrast and histogram value to provide homogeneity and dimensional data of fuel plate. Based on visual inspections and digital x-ray radiography test, no significant surface defects and sub-surface defects were found. X-ray radiographic images clearly show a homogeneous fuel profile. Thus, it can be concluded that the U_3Si_2/Al fuel plate during irradiation on the RSG-GAS core has an incredibly satisfactory performance.

Keywords: Silicide fuel, visual examination, X-ray radiography, non-destructive test

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1. Introduction

Since 1999, the reactor core of the 30 MW multipurpose research reactor G.A. Siwabessy (RSG-GAS) BATAN was converted from using oxide fuel U_3O_8/Al into using silicide fuel U_3Si_2/Al with density 2.96 gU/cm^3 for better safety margin and improvement of the RSG-GAS performance (Soentono et al., 2004; Suripto & Mutalib, 2003). The silicide fuel U_3Si_2/Al with a density 2.96 gU/cm^3 was domestically produced and used in RSG-GAS until recent times. The success of 2.96 gU/cm^3 U_3Si_2/Al fuel brought BATAN to develop U_3Si_2/Al fuel with a higher uranium density of 4.8 gU/cm^3 for better performance and economic benefits related to fuel management. Three full-size U_3Si_2/Al fuel plates with uranium density of 4.8 g/cm^3 with code CBBJ249, CBBJ250, and CBBJ251 had been successfully fabricated in PTBBN BATAN and irradiated in the RSG-GAS in 2008 (Ginting et al., 1998). Irradiation was conducted at 15 MW power with an estimated burnup of 20% for CBBJ 249, 40% for CBBJ251, and 60% for CBBJ250 (Briyatmoko et al., 2015; Kadarusmanto et al., 2016).

Continuing the success in the post-irradiation examination (PIE) of CBJJ250 and CBJJ251 which was conducted previously, the PIE of CBJJ249 was conducted to obtain comprehensive performance data and fuel behavior during irradiation (Ajiriyanto et al., 2018; Artika et al., 2020; Ginting & Liem, 2015; Liem et al., 2013; Sihotang et al., 2022). Several studies related to the performance of silicide fuel and the effect of higher density, especially related to mechanical characteristics, have been widely investigated (Hofman et al., 2019; Keiser et al., 2020; Yang et al., 2021). The objective of this study is to observe the anomalies possibilities and dimensional stability of silicide fuel CBJJ249 after being irradiated in the RSG-GAS based on a non-destructive test. The PIE data will become part of the requirements document for the preparation of fuel certification.

2. Materials and methods

The post-irradiation examination (PIE) was conducted after U_3Si_2/Al fuel plate with a density of 4.8 gU/cm^3 and 20% burnup was irradiated in RSG-GAS previously and sent to the Radiometallurgy Installation (RMI) hot cell via the transfer channel. In the preliminary stages of PIE, the fuel plate was characterized using a non-destructive test which includes visual examinations and digital X-ray radiography test. Visual examination along the fuel surface was conducted using a dedicated periscope in the operating area of hot cell 102 and documented with a Canon 7 DSLR camera through the hot cell window and dedicated real-time camera.

In the next step, the fuel plate was transferred to hot cell 103 with a transport trolley for digital X-ray radiographic testing using the Diondo X-ray inspection system. X-ray radiography test was performed with voltage and current parameters set at 120 kV and 1000 μA, respectively. The radiographic image was further analyzed to obtain data on the homogeneity of fuel meat distribution, the possibility of sub-surface defects, and post-irradiated dimensions of the fuel plate.

3. Result and discussion

Post-irradiation examination on fuel plate U_3Si_2/Al density of 4.8 gU/cm^3 with 20% burn up was a part of the analysis and evaluation of fuel performance during irradiation at RSG-GAS. This silicide fuel plate with the code CBJJ249 was part of the test fuel element, which was irradiated simultaneously with two other fuel plates, namely CBJJ250 and CBJJ251. The non-destructive testing process including visual examination and digital X-ray radiographic testing as a preliminary stage of PIE is shown in Figure 1.

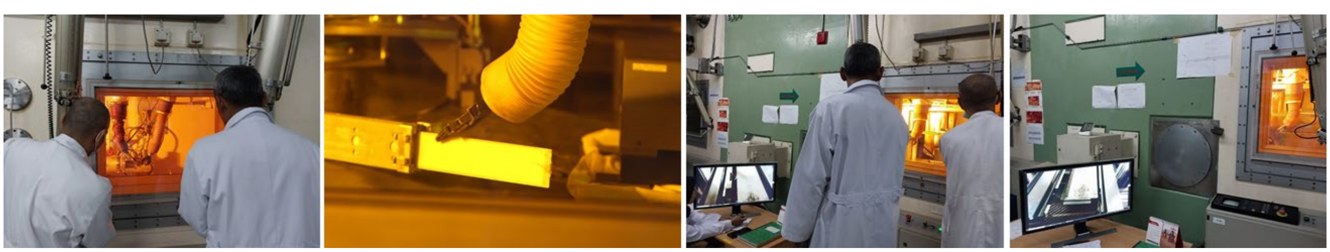


Figure 1. Non-destructive test of CBJJ249 in RMI hot cell.

3.1. Visual examination

Visual examinations of the CBJJ249 fuel plate were conducted in hot cell 102 IRM using a digital camera equipped with a macro lens to obtain visual details of the fuel surface. The results of visual examinations on the fuel surface are shown in Figure 2 below.

Besides using a digital camera placed outside the hot cell, visual examinations were also made using a dedicated camera in the slave-arm manipulator hot cell 10. The development of the visual examination method by adding a camera to the slave-arm manipulator was not only for easier handling but also expected to reduce the effect of the refraction of the hot cell lead glass when visual examinations were made using a digital camera through the hot cell window. The results of visual examinations using a real-time camera dedicated to the slave-arm manipulator are shown in Figure 3.

Based on the results of visual examinations that have been made on the fuel surface as shown in Figure 2 and Figure 3, it is generally seen that there were indications of discoloration which are thought to be caused by handling effects, during sampling from the RSG-GAS core, transferring from RSG-GAS to RMI hot cells, transferring between hot cells in RMI and handling during testing. In addition, observations using a real-time in-cell dedicated camera produce clearer visuals so that on the fuel surface, several points are thought that have occurred the formation of an oxide layer. Further analysis of the possibility of the formation of an oxide layer on the fuel surface will be conducted through destructive testing, especially metallography testing. As confirmation of visual examinations as part of the non-destructive test data, the test was continued using digital X-ray radiography conducted in hot cell 103.

3.2. Digital X-ray radiography

As a form of confirming the conclusions of the visual examination results, testing using digital X-ray radiography was conducted on silicide fuel plate CBJJ249 in hot cell 103. In addition to confirming that the indication of discoloration on the fuel surface was the impact of the handling manipulator, not the effect of the irradiation process at RSG-GAS, X-ray radiographic testing was conducted to ensure whether there was diffusion of meat into the cladding. The X-ray radiographic image for the CBJJ249 fuel plate is shown in Figure 4. The radiographic image clearly shows that there are no sub-surface defects caused by irradiation. Based on these facts, the indications that appear in visual examinations on the fuel surface are the effects of handling during the transfer and testing processes.

One of the characteristics that must be observed from irradiated fuel plates is the homogeneity of meat distribution and cladding integrity. Homogeneity can be determined based on image processing from X-ray radiography using image processing software from gray value analysis. The fuel plate homogeneity profile based on the gray value at several locations is shown in Figure 5.

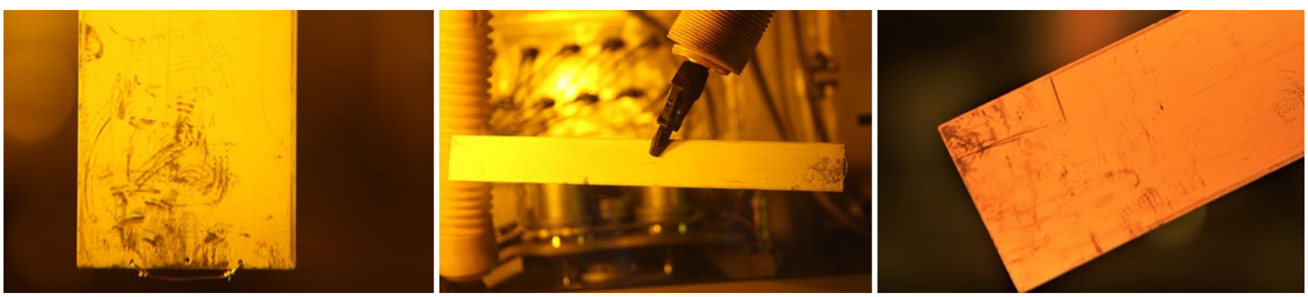


Figure 2. Visual examination of CBJJ249 fuel plate.

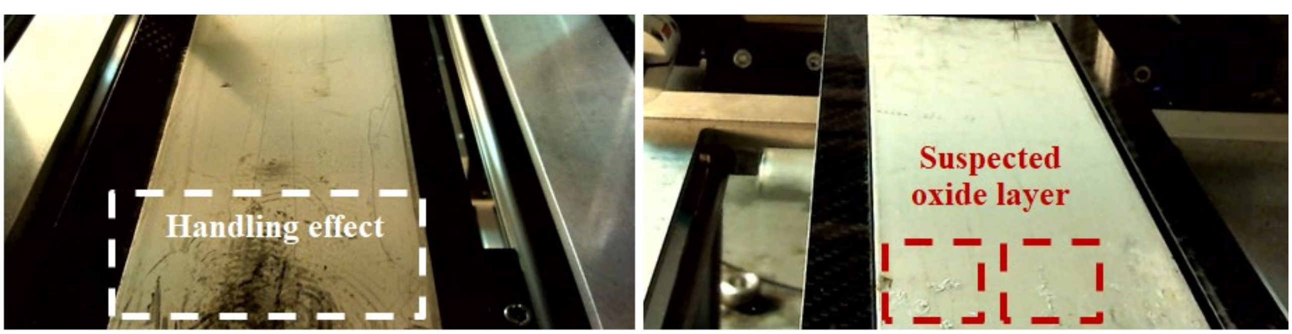
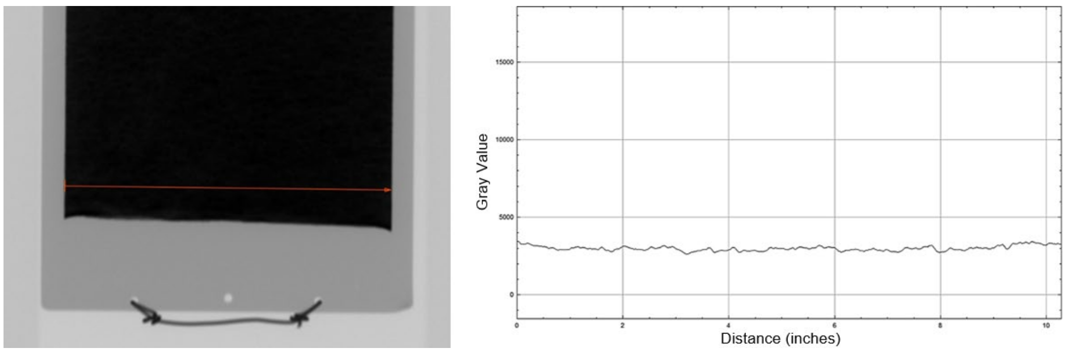


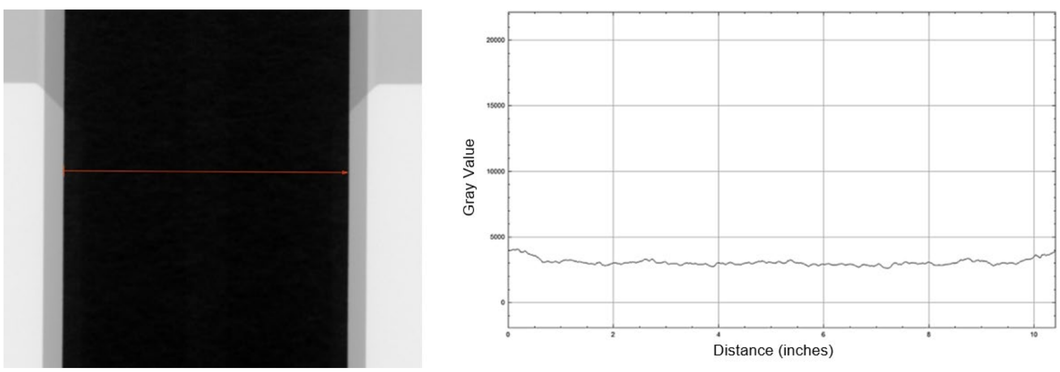
Figure 3. Visual of fuel surface by a dedicated real-time camera.

(a) (b) (c)

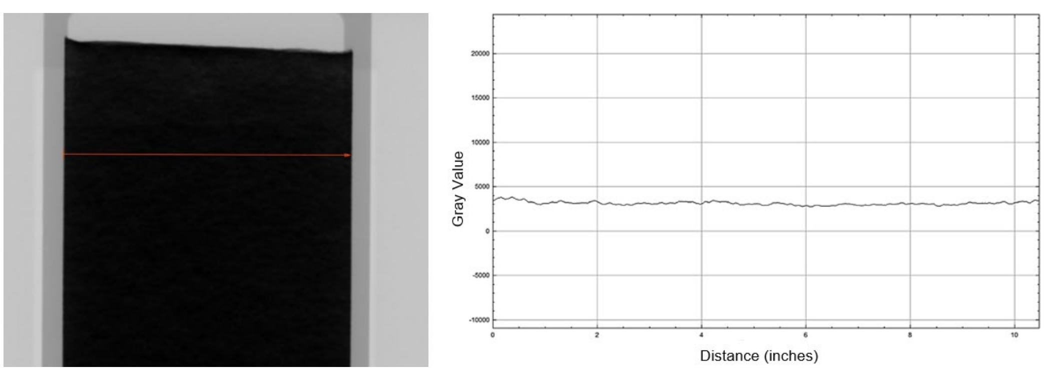
Figure 4. X-ray radiographic image at the top (a); middle (b); and bottom (c) of fuel plate.



(a)



(b)



(c)

Figure 5. Gray value analysis in the horizontal direction of the meat at the *top*(a); *middle* (b); and *bottom* of fuel plate (c).

The gray value data along the horizontal direction of the meat at several positions shows homogeneous results with homogeneity value at top, middle and bottom of fuel plate are 4.35%, 3.89% and 3.19%, respectively. The maximum acceptable limit for the homogeneity of meat distribution is set at 20%, so that the results of the homogeneity analysis show that the homogeneity of irradiated CBJJ249 still meets the acceptance requirements. In addition, there is no visible diffusion of fuel meat towards the cladding which indicates that the integrity of the cladding is still well maintained. The other indication of the nuclear fuel cladding integrity, the dimensional consistency during the irradiation process must be met. The dimensional consistency of irradiated CBJJ249 was analyzed using X-ray radiographic images. Several crucial points in dimensional consistency have been measured and shown in Figure 6. The meat width of the fabricated silicide fuel U_3Si_2/Al fuel plates with a uranium density of 4.8 g/cm^3 is in the range of 62.3 to 62.4 mm, so based on measurements made on irradiated CBJJ249 with an average meat width of 62.36 mm, the requirements for dimensional consistency of the fuel have been met. These results are supported by the results of irradiated fuel thickness measurements which still meet the acceptance requirements. The additional thickness of the irradiated CBJJ249 only reaches 0.36% of the 20% permitted swelling limit (Nampira & Ismarwanti, 2014; Supardjo et al., 2021).

4. Conclusions

The post-irradiation examination by non-destructive tests of the CBJJ249, U_3Si_2/Al fuel element plate with a density of 4.8 gU/cm^3 at 20% burn up can be observed visually, evaluated using digital X-ray radiography, and analyzed using image processor. Non-destructive test results show CBJJ249 has excellent performance during irradiation on the RSG-GAS core with no significant anomalies, homogeneous distribution of meat, good cladding integrity, and dimension stability.

Conflict of interest

The authors have no conflict of interest to declare.

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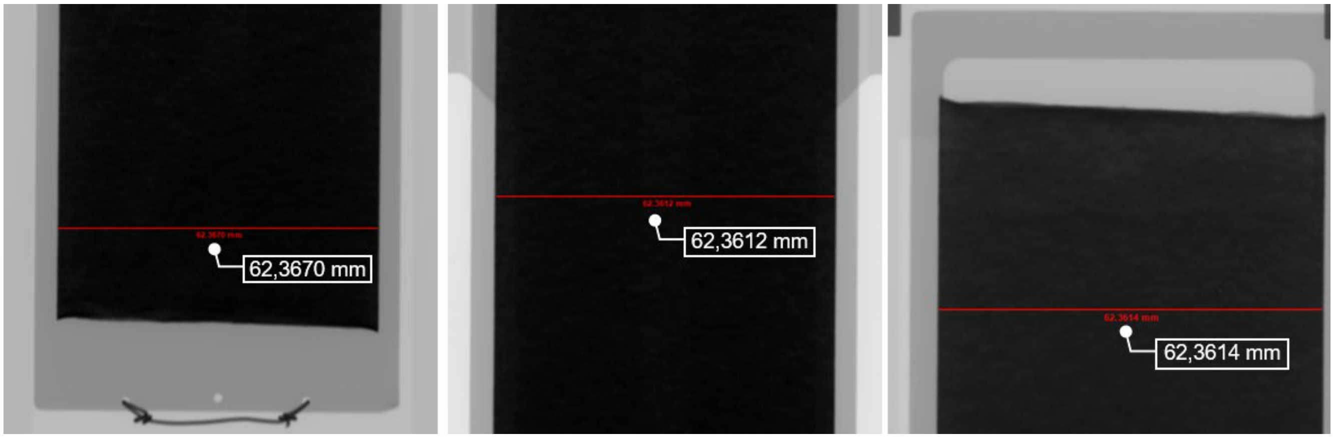

(a) (b) (c)

Figure 6. Meat-width measurement of irradiated CBJJ249 based on X-ray radiographic image at the top (a); middle (b); and bottom (c) of fuel plate.

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