is preferable to substitute better than Ni cation into spinel ferrite structure. In addition, it is because of that the electrostatic repulsive force between the colloidal oxide particles and fuel cladding surface becomes lower as the zinc concentration increases in the primary coolant. However, both physical and chemical properties of already-deposited crud were not changed from that before immersion test in coolant containing zinc. It would possibly be because the immersion time of 500 h is not enough zinc ion to substitute to Ni ion in nickel ferrite crud or the electrostatic force between corrosion product particles and crud surface is weaker than that between those and clad surface.

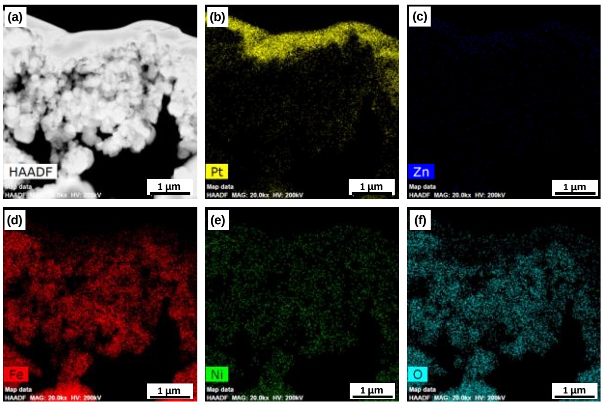

Fig. 9 (a) STEM images and (b-f) TEM-EDS elemental mapping results of crud after immersion test in PWR primary coolant containing 60 ppb Zn.

4. Conclusions

We have investigated the effect of zinc concentration on crud layer deposited on fuel cladding tube through immersion test in simulated primary coolant containing zinc contents of 10 ppb and 60 ppb. The change in surface morphology and porosity of crud layer is not found after immersion test in the primary coolant containing for 500 h. The zinc content was not found in cruds immersed in the primary coolant containing both 10 ppb and 60 ppb zinc. In addition, the XRD characteristic peaks of the immersed cruds in zinc addition are same with that of as-deposited crud. Therefore, it is considered that the zinc added to the primary water does not affect to the crud already deposited on fuel cladding regardless of its concentration at least less than 60 ppb.

Acknowledgments

This work was financially supported by the Korea Hydro & Nuclear Power Co., Ltd. of the Republic of Korea (L18S061000). This work was also supported by the National Research Foundation of Korea (NRF) grant funded by the government of the Republic of Korea (2017M2A8A4015159).

REFERENCES

[1] M. P. Short, The particulate nature of the crud source term in light water reactors, J. Nucl. Mater. Vol. 509, pp. 478, 2018.

[2] S. Odar, Crud in PWR/VVER coolant, Vol. 1, Technical Report, ANT Int'l, Sweden, 2014.

[3] J. A. Sawicki, Evidence of Ni_2FeBO_5 and m-ZrO_2 precipitates in fuel rod deposits in AOA-affected high boiling duty PWR core, J. Nucl. Mater., Vol. 374, pp. 248, 2008.

[4] I. Betova, M. Bojinov, P. Kinnunen, T. Sarrio, Zn injection in Pressurized Water Reactors-laboratory tests, field experience and modelling, Research Report, VTT-R-05511-11, VTT, Finland, 2011.

[5] J. Deshon, D. Hussey, B. Kendrick, J. McGurk, J. Secker, M. Short, Pressurized water reactor fuel crud and corrosion modeling, JOM Vol. 63 (8), pp. 64, 2011.

[6] S. Uchida, Y. Asakura, H. Suzuki, Deposition of boron on fuel rod surface under sub-cooled boiling conditions - an approach toward understanding AOA occurrence, Nucl. Eng. Des. Vol. 241, pp. 2398, 2011.

[7] N. Cinosi, I. Haq, M. Bluck, S. P. Walker, The effective thermal conductivity of crud and heat transfer from crud-coated PWR fuel, Nucl. Eng. Des. Vol. 241, pp. 792, 2011.

[8] K. Edsinger, C. R. Stanek, B. D. Wirth, Light water reactor fuel performance: current status, challenges, and future high fidelity modelling, JOM Vol. 63, pp. 49, 2011.

[9] S. Bushart, PWR Operating Experience with Zinc Addition and the Impact on Plant Radiation Fields, EPRI, Palo Alto, USA, 1003389, 2003.

[10] S. Holdsworth, F. Scenini, M. G. Burke, G. Bertali, T. Ito, Y. Wada, H. Hosokawa, N. Ota, M. Nagase, The effect of high-temperature water chemistry and dissolved zinc on the cobalt incorporation on type 316 stainless steel oxide, Corr. Sci. Vol. 140, pp. 241, 2018.

[11] X. Liu, X. Wu, E.-H. Han, Electrochemical and surface analytical investigation of the effects of Zn concentrations on characteristics of oxide films on 304 stainless steel in borated and lithiated high temperature water, Electrochim. Acta Vol. 108, pp. 554, 2013.

[12] S. E. Ziemniak, M. Hanson, Zinc treatment effects on corrosion behavior of 304 stainless steel in high temperature, hydrogenated water, Corr. Sci. Vol. 48, pp. 2525, 2006.

[13] H. Kawamura, H. Hirano, S. Shirai, H. Takamatsu, T. Matsunaga, K. Yamaoka, K. Oshinden, H. Takiguchi, Inhibitory effect of zinc addition to high temperature hydrogenated water on mill-annealed and prefilmed Alloy 600, Corrosion Vol. 56, pp. 623, 2000.

[14] L. Zhang, K. Chena, J. Wang, X. Guo, D. Dua, P. L. Andresen, Effects of zinc injection on stress corrosion cracking of cold worked austenitic stainless steel in high-temperature water environments, Scr. Mater. Vol. 140, pp. 50, 2017.

[15] H. S. Kim, H. B. Lee, J. Chen, C. Jang, T. S. Kim, G. L. Stevens, K. Ahluwalia, Effect of zinc on the environmentally-assisted fatigue behavior of 316 stainless steels in simulated PWR primary environment, Corr. Sci. Vol. 151, pp. 97, 2019.

[16] R. S. Pathania, B. Cheng, M. Dove, R. E. Gold, C. A. Bergmann, Evaluation of zinc addition to the primary coolant of Farley-2 PWR, Proc. Int'l Symposium Fontevraud IV, SFEN, Fontevraud, pp. 959, 1998.

[17] E. Kolstad, W. J. Symons, K. Bryhn-Intebrigsten, B. C. Oberlander, Evaluation of Zinc Addition on Fuel Cladding Corrosion at the Halden Test Reactor, EPRI, Palo Alto, USA, TR-106357, 1996.

[18] J. Gorman, Overview Report on Zinc Addition in Pressurized Water Reactors, EPRI, Palo Alto, USA, 1009568, 2004.

[19] K. S. Kim, S. H. Baek, H.-S. Shim, J. H. Lee, D. H. Hur, Effect of zinc addition on fuel crud deposition in simulated PWR primary coolant conditions, Annals, Nucl. Energy Vol.146, pp. 107643, 2020.
[20] H. Kawamura, Effect of Low DH Concentration on Crud Deposition on heated Zircaloy-4 in Simulated PWR Primary Water, Proc. Int'l Conf. Nucl. Plant Chemistry, Paris, France, 2012.