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Research Article

Conceptual Study on Recriticality Prevention Core Having Duplex Pellets with Neutron Absorber in Outer Core in a Fast Reactor

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In a fast reactor, we evaluated a new core concept that prevents severe recriticality after whole-scale molten formation in a severe accident. A core concept in which Duplex pellets including neutron absorber are loaded in the outer core has been proposed. Analysis by the continuous energy model Monte Carlo code MVP using the JENDL-4.0 nuclear data library revealed that this fast reactor core has large negative reactivity due to fuel melting at the time of a severe accident, so that the core prevents recriticality. Regarding the core nuclear and thermal characteristics, the loading of Duplex pellets including neutron absorber in the outer core caused no significant differences from the normal core without Duplex pellets.

1. Introduction

In the Fukushima Daiichi Nuclear Power Plant accident, it is estimated that fuel melted and that molten fuel penetrated the pressure vessel and accumulated in a debris state at the bottom of the containment vessel. Even in this accident the possibility of recriticality depending on the conditions in the fuel melting state and the subsequent debris state has been pointed out.

Since a fast reactor core is not a minimum criticality system, it is essential to consider recriticality at the time of fuel melting. That is, since coolant is eliminated by molten fuel and the reactor core compacts, the neutron spectrum is hardened, so that there is a high possibility that recriticality will occur unless fuel is dispersed. For this reason, it is important to prevent recriticality in any fuel arrangement state such as fuel melting in the fast reactor. Many studies [1–5] on avoiding recriticality at the time of fuel melting have been published.

In the current large-scale reactor design, in order to avoid recriticality in a core damage accident, a fuel assembly provided with an internal duct [1, 2] or corium discharge tube [3] having a function of discharging molten fuel is adopted. Such empty ducts adopted in the core will reduce the power density or distort the power distribution. In the case of adopting the internal duct assembly, the core was designed by being paid attention to power distortion due to the arrangement of the internal channel, manufacturing difficulty, and rotational asymmetry at the refueling.

However, a measure to prevent recriticality even if molten fuel accumulates on the lower axial blanket in the core would further improve the safety of the fast reactor.

We discuss a concept aimed at preventing recriticality by adopting a core having Duplex pellets with neutron absorber. Figure 1 shows the concept of Duplex pellets with neutron absorber. Duplex pellets were studied for use in light water reactors [6, 7]. In PWR, studies on enriched uranium fuel with natural uranium in the center were conducted to keep the fuel center temperature low and to reduce the emission of fission product gas. In addition, in BWR, in order to reduce power peaking in the beginning stages of burnup, research on

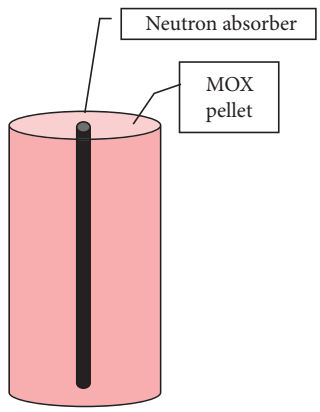

Figure 1: Concept of Duplex pellet with neutron absorber material. A hole with a diameter of approximately 1 mm is provided at the center of the fuel pellet.

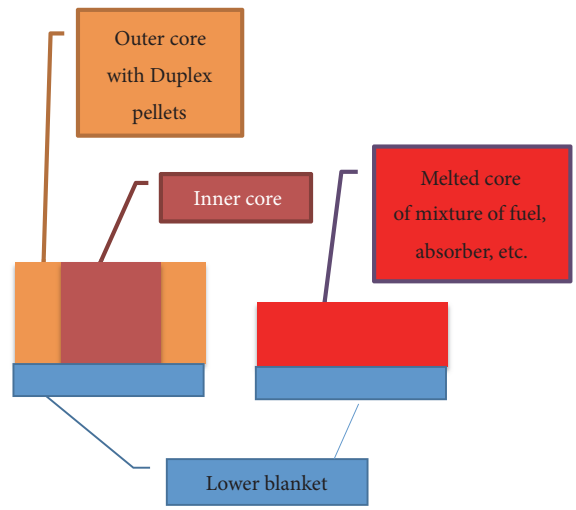

Figure 2: Concept of recriticality prevention with Duplex pellet with neutron absorber in the outer core of the fast reactor.

Duplex pellets of MOX fuel with Gd_2O_3 at the center was also conducted.

In this study, a hole with a diameter of approximately 1 mm is provided at the center of the fuel pellet, and a neutron absorber such as Gd_2O_3 (absorption cross section of ^{157}Gd is approximately 800 barns for the fast neutron spectrum) is placed therein. In the core having Duplex pellets with neutron absorber, this fuel pellet has little influence on reactivity due to the self-shielding effect of the central neutron absorber.

In a severe accident, prior to formation of melt pool, the rapid power increase and the fuel melting and the movement of melt fuel occur, and it causes mixing of the melt core material. It is assumed that all core fuel melts together with the structural material and accumulates on the axial blanket surface, where it is prevented from being removed from the core. In the fuel molten state, it is believed that the central Gd_2O_3 melts and disperses together with molten fuel in a homogeneous manner. As the neutron absorber is homogeneously dispersed, the self-shielding effect disappears, the neutron absorption effect of the neutron absorber increases, and negative reactivity results.

Research has been conducted on the concept of a fast reactor core that prevents recriticality accident using Duplex pellets with neutron absorber [8]; however, the model adopted Duplex pellets with neutron absorber throughout the reactor core. Results showed that when the fuel and the neutron absorber were melted into a homogeneous mixture in all fuel pins throughout the core, the compaction reactivity was negative at approximately -1.6%$\Delta\rho$ while the burnup reactivity increased significantly. In addition, installing Duplex pellets with neutron absorber into all fuel assemblies would increase the manufacturing cost.

Therefore, as a new idea, we considered the use of Duplex pellets with neutron absorber only in the outer core of the reactor. In this study, we evaluated compaction reactivity at the time of fuel melting, burnup reactivity, void reactivity, and Doppler reactivity, which are important to core safety, thermal characteristics, etc. Figure 2 shows the concept of recriticality prevention using Duplex pellets with neutron absorber in the outer core of the fast reactor.

In this study, we propose a new core concept that prevents severe recriticality after whole-scale molten formation in a severe accident. It is clarified that the adoption of Duplex pellets with neutron absorber does not affect the safety and operating characteristics of the normal core without Duplex pellets.

2. Calculation Model

A method of filling oxide granules (Gd_2O_3) was selected on the basis of the behavior of the neutron absorber during normal operation and core melting. To arrange a core with Duplex fuel pellets, fuel filled with Gd_2O_3 granules in the center hole of MOX fuel pellets was placed in the outer core of the reactor. The density and melting point of Gd_2O_3 are 7.41 g / cm 3 and 2330°C.

A large fast reactor core with a thermal power of 3600 MW and an electric power of approximately 1500 MWe was used in this study. The reactor core has two homogeneous regions, core height is 80 cm, and the number of control rods is 55. The operation period is assumed to be 18 months.

Table 1 shows the specifications of the normal core and the core having Duplex pellets with neutron absorber. The k-eff value of the normal core is 1.0358. On the other hand, the k-eff value of the core having Duplex pellets with Gd_2O_3 is 1.0357. The k-eff values for both cores are almost same.

The compaction reactivity and core characteristics such as the breeding ratio, void reactivity, Doppler reactivity, etc. have been evaluated by the continuous energy Monte Carlo code MVP[9] using the JENDL-4.0 nuclear data library [10]. The accuracy of the evaluated reactivity was approximately 0.2%. Burnup calculation was executed by MVP-BURN code, which is the MVP's burning routine [8].

Table 1: Core specifications of normal core and the core having Duplex pellets with neutron absorber.

Item	Normal core without Duplex pellets	Core having Duplex pellets with neutron absorber in the outer core fuel
Reactor power (MWt)	3600	3600
Core height (cm)	80	80
Number of assemblies in inner/outer core	316/278	316/278
Assembly pitch	183.2	183.2
Diameter of fuel pin	8.8	8.8
Pu contents (wt%) in inner/outer core	18.3/22.9	18.3/22.9
Number of fuel pins in an assembly	271	271
Thickness of wrapper tube (mm)	5	5
Neutron absorber material in Duplex pellet	-	Gd_2O_3
Diameter of center hole in Duplex pellet (mm)	-	1
Location of assemblies with Duplex pellets	-	Outer core
Filling rate of neutron absorber material (%)	-	60

Table 2: Comparison of compaction reactivity between the core having Duplex pellets with neutron absorber in the inner and outer cores.

Item	Core having Duplex pellets with neutron absorber in the inner core	Core having Duplex pellets with neutron absorber in the outer core
Compaction reactivity(%$\Delta\rho$)	+4.0	-1.7

3. Results and Discussion

First, we compared the effect of Duplex pellets with neutron absorber on the compaction reactivity between the cases of loading in the inner and outer cores. Table 2 shows the comparison of compaction reactivity between the two cases having Duplex pellets with neutron absorber.

The compaction reactivity was found to be negative (-1.7%$\Delta\rho$) when Duplex fuel with neutron absorber was loaded into the outer core, while it was found to be positive (+4%$\Delta\rho$) when Duplex fuel with neutron absorber was loaded into the inner core.

In the case of loading Duplex fuel with neutron absorber into the inner core, it is estimated that the neutron absorber having negative reactivity spreads from a region having a higher reactivity worth in the inner core to a region having a lower reactivity worth in the outer core due to melting, causing positive reactivity. On the other hand, when the Duplex fuel with neutron absorber is placed only in the outer core, the neutron absorber spreads from a region of lower reactivity in the outer core to a region of higher reactivity in the inner core at the time of fuel melting, causing negative reactivity. That is, the compaction reactivity in case of loading Duplex pellets with neutron absorber in the outer core becomes negative.

Table 3 shows a comparison of the compaction reactivity for the normal core without Duplex pellets and the core having Duplex pellets with neutron absorber in the outer core. Figure 3 shows the MVP calculation model of the core having Duplex pellets with neutron absorber and the melted core. It is considered that the upper axial blanket will not melt due to low temperature and keep original form. For conservative evaluation of compaction reactivity, the upper axial blanket will not fall into melt pool.

The compaction reactivity of the normal core without Duplex pellets is positive (+3.9%$\Delta\rho$), while the compaction reactivity when the Duplex pellets with the neutron absorber are loaded on the outer core is negative (-1.7%$\Delta\rho$). It was revealed that the loading of the fuel having Duplex pellets with neutron absorber into the outer core of the fast reactor is effective in preventing recriticality.

Next, the core nuclear and thermal characteristics were evaluated when Duplex pellets with neutron absorber were loaded on the outer core of a fast reactor. Table 3 shows the core nuclear characteristics for the normal core without Duplex pellets and the core having Duplex pellets with neutron absorber in the outer core.

It was found that the void reactivity was nearly the same in the both cases.

Table 3: Results of compaction reactivity and nuclear characteristics of normal core and core having Duplex pellets with neutron absorber.

Item	Normal core without Duplex pellets	Core having Duplex pellets with neutron absorber in the outer core fuel
Compaction reactivity(%$\Delta\rho$)	3.9	-1.7
Doppler reactivity ($\times 10^{-3}\Delta\rho/(\Delta T/T)$)	-8.9	-8.1
Void reactivity (%$\Delta\rho$)	1.6	1.7
Breeding ratio	1.17	1.21
Burnup reactivity (%$\Delta k/kk'$/year)	2.26	2.33

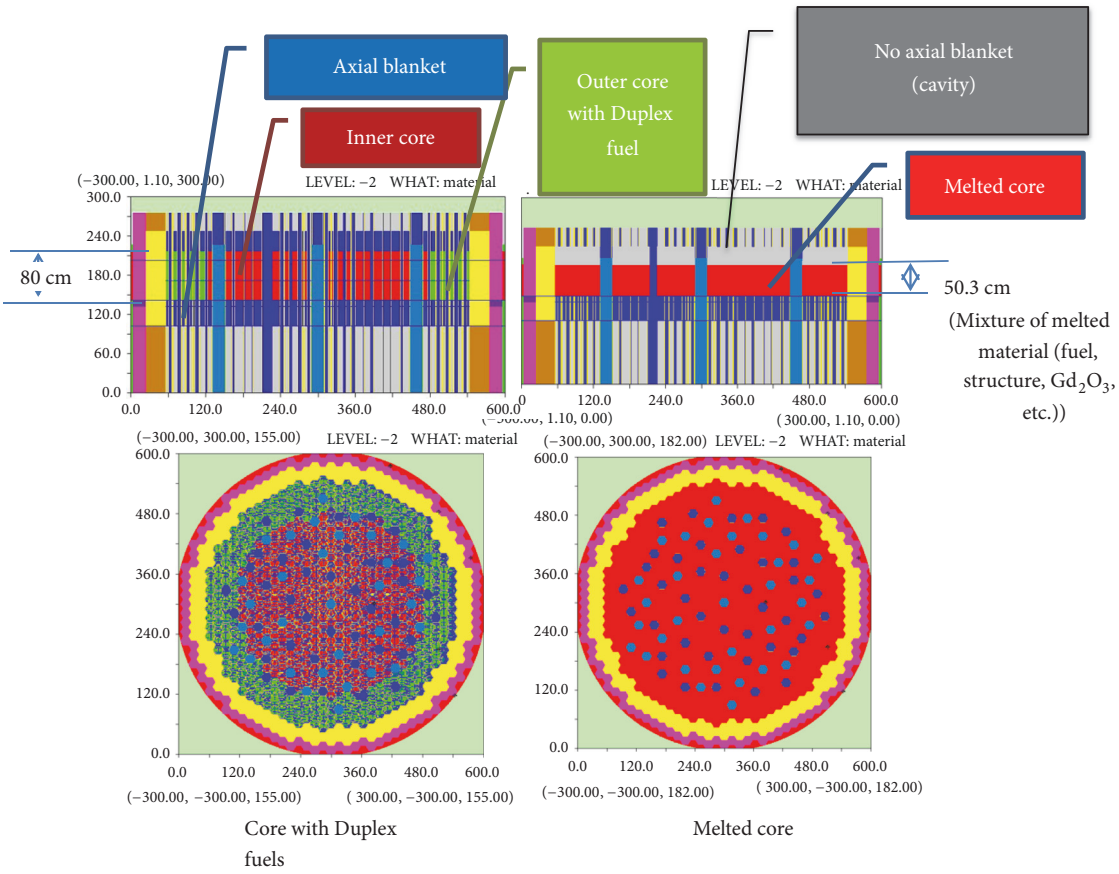

Figure 3: MVP calculation model of the core having Duplex pellets with neutron absorber and the melted core. The vertical and horizontal cross-sections of the two cores.

The Doppler reactivity is more negative in the case of loading Duplex pellets including neutron absorber into the outer core than it is in the case of the normal core. It is estimated that the decrease in the absolute value of Doppler reactivity due to the absorption of low energy neutrons, i.e., hardened neutron spectrum, is greater than the increase in the absolute value of Doppler reactivity due to the rise in the power of the inner core.

The breeding ratio is greater in the case of loading Duplex pellets including neutron absorber into the outer core than in the case of the normal core. It is estimated that the breeding ratio in the axial blanket is greater in the inner core having less neutron leakage. Therefore, when loading Duplex pellets including neutron absorber in the outer core, it is thought that the breeding ratio increased due to the increasing power of the inner core.

The burnup reactivity was nearly the same in the both cases.

According to the burnup calculation, it was found that the depletion of ^{157}Gd under irradiation was about 5% for 18

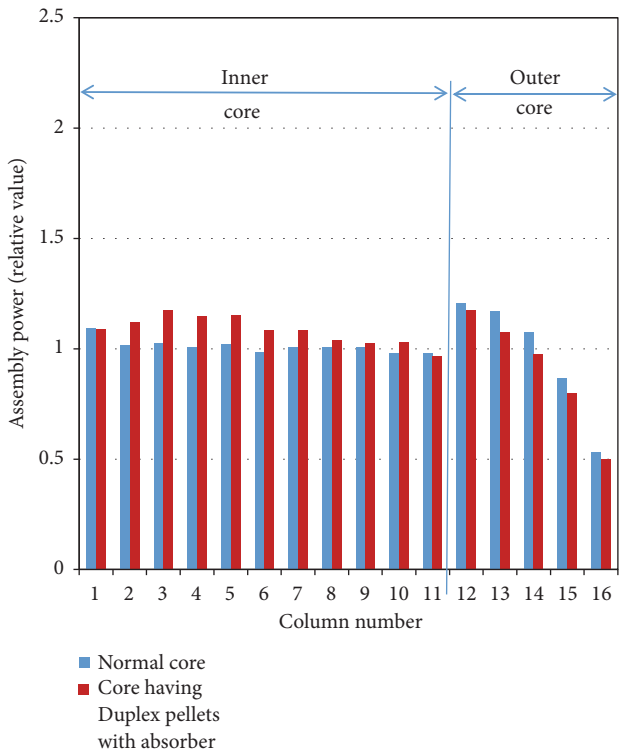

Figure 4: Comparison of assembly power between the normal core without Duplex pellets and the core having Duplex pellets with neutron absorber. The difference in the assembly power between both cores is insignificant.

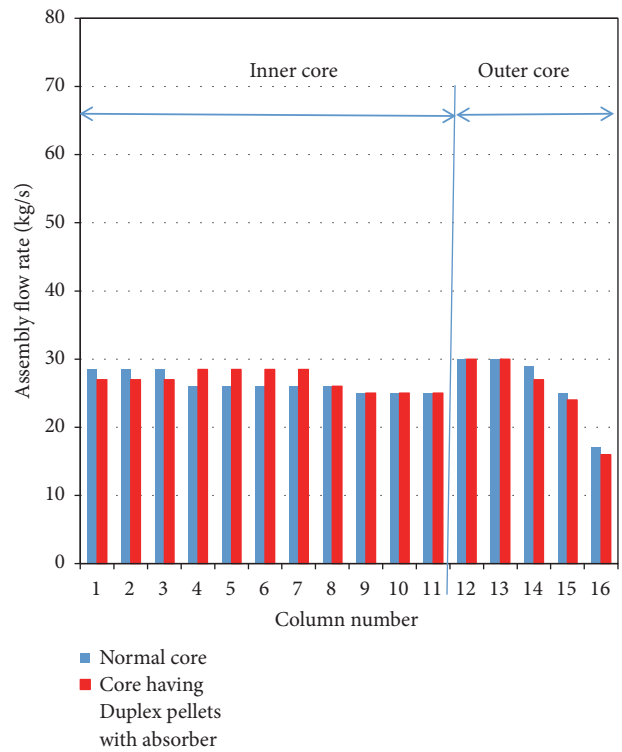

Figure 5: Comparison of assembly flow rate between the normal core without Duplex pellets and the core having Duplex pellets with neutron absorber.

months. It is considered that the reactivity effect of mixing Gd_2O_3 with fuel was not large different for the irradiated core and for the initial core.

Evaluation of the core characteristics revealed that even when Duplex pellets including neutron absorber were loaded in the outer core, there were no significant differences from the normal core without Duplex pellets from the viewpoint of core characteristics and that satisfactory operation is likely.

Figure 4 shows the comparison of assembly power between the normal core without Duplex pellets and the core having Duplex pellets with neutron absorber. The assembly power of the outer core loaded with Duplex pellets including the neutron absorber is generally lower than that of the outer core in the normal core. On the other hand, the assembly power of the inner core of the core loaded with Duplex pellets including the neutron absorber is greater. However, since the central diameter of the neutron absorber is 1 mm and the loaded amount of absorber is small, the difference in the assembly power between both cores is insignificant.

Figure 5 shows the comparison of assembly flow rate between the normal core without Duplex pellets and the core having Duplex pellets with neutron absorber. Since the influence on the flow distribution is small, the maximum flow rate is nearly the same in both the cores. The pressure loss of the core loaded with Duplex pellets including the neutron absorber is 0.18 MPa, which satisfies the design condition.

From the viewpoint of thermal characteristics, there is no significant difference between the normal core without Duplex pellets and the core loaded with Duplex pellets including the neutron absorber.

Regarding the behavior under irradiation of Gd_2O_3, based on the reference [11] and thermodynamic calculation, it is estimated that Gd_2O_3 remains stable in the central region of MOX fuel even under irradiation.

The interaction between Gd_2O_3 and the minor actinides and fission products formed during MOX fuel irradiation is estimated not to make oxidation by thermodynamics calculation.

The additional studies are needed to check whether Gd_2O_3 remains at its initial location during irradiation.

We also think that the additional studies are needed to check whether distribution of Gd_2O_3 in the molten core is homogeneous.

4. Conclusions

To enhance the safety of a fast reactor, we studied a new core concept that prevents recriticality even when fuel melts in an accident. A core concept in which Duplex pellets including neutron absorber are loaded in the outer core has been proposed. As a result of analysis using the continuous energy Monte Carlo code MVP using the JENDL-4.0 nuclear data library, it was found that the present fast reactor core has a large negative compaction reactivity due to fuel melting at the time of an accident, so that the core does not

reach recriticality. Regarding the core nuclear and thermal characteristics, even when Duplex pellets including a neutron absorber were loaded in the outer core, it was found that there were no significant differences from the normal core without Duplex pellets and that satisfactory operation is likely.

As a result of this study, we confirmed the possibility of creating a new fast reactor concept which prevents recriticality due to negative compaction reactivity when fuel melts during an accident and does not affect the core nuclear and thermal characteristics during normal reactor operation.

In the future, we have a plan to conduct melting experiments of mixing Gd_2O_3 and MOX using simulated materials. We also think that it is necessary to perform the detail calculation and experimental verification for MVP code.

Data Availability

The data used to support the findings of this study are available from the corresponding author (Toshio Wakabayashi) upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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References

[1] T. Mizuno and H. Niwa, "Advanced MOX core design study of sodium-cooled reactor in current feasibility study on commercialized fast reactor cycle system in japan," *Nuclear Technology*, vol. 146, no. 2, pp. 143–145, 2004.

[2] Japan Atomic Energy Agency, "Fast reactor cycle technology development project (FaCT Project) -phase 1 report," JAEA-Evaluation 2011-003, 2011.

[3] F. Serre, F. Bertrand, A. Bachrata et al., "France-japan collaboration on severe accident studies for ASTRID: outcomes and future work program," in *Proceedings of ICAPP 2017*, pp. 24–28, Fukui, Japan, 2017.

[4] S. Maeda, M. Suzuki, T. Kaito, K. Tanaka, and T. Abe, "Concept and development status of fast breeder reactor fuels in the fact project," in *Fast Reactors and Related Fuel Cycles: Safe Technologies and Sustainable Scenarios FR13, Proceedings of an International Conference*, vol. 2, IAEA, Paris, France, 2013.

[5] K. Chitose, H. Mochizuki, and N. Takaki, "Thermal-hydraulic feasibility study of a convex shaped fast reactor core," in *Proceedings of the 5th International Symposium on Innovative Nuclear Energy Systems, INES-5*, Ookayama Campus, Tokyo Institute of Technology, Japan, 2016.

[6] M. Kato and K. Kamimura, "Development of duplex typE MOX-GD2O3 fuel for water reactor," in *Technical Commitee Meeting on Advances in Pellet Technology for Improved Performance and High Bumup*, Tokyo, Japan, 1996.

[7] S. Li, D. Wang, W. Guo, and Y. Jiang, "Analysis and prospect of the duplex fuel pellets of LOWI type for water-cooled reactors," in *Proceedings of the 24th International Conference on Nuclear Engineering*, North Carolina, NC, USA, 2016.

[8] T. Yokoyama and T. Wakabayashi, "Fast reactor core concept for preventing re-criticality accidents employing duplex pellets with absorber," in *ICONE23-1008, Proceedings of ICONE-23 23rd International Conference on Nuclear Engineering*, Chiba, Japan, 2015.

[9] T. Mori and M. Nakagawa, "Mvp/gmvp: general purpose Monte Carlo codes for neutron and photon transport calculations based on continuous energy and multi-group methods," in *JAERI-Data/Code–94–007*, 1994.

[10] K. Shibata, O. Iwamoto, T. Nakagawa et al., "JENDL-4.0: a new library for nuclear science and engineering," *Journal of Nuclear Science and Technology*, vol. 48, no. 1, pp. 1–30, 2011.

[11] A. Ishimi, K. Katsuyama, Y. Kihara, and H. Furuya, "Fuel performance of hollow pellets for fast breeder reactors," *Journal of Nuclear Science and Technology*, vol. 53, no. 7, pp. 951–956, 2016.