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論 文 内 容 要 旨

Fast breeder reactor (FBR) can generate not only electric power but also nuclear fuel material, plutonium (Pu), more than the amount consumed in the reactor operation. Research and development for commercialization of FBR have proceeded extensively, where the FBR is regarded as one of the important energy sources for future sustainable development.

Plutonium consists of around sixty to seventy percent of the main fissile isotope ^{239}Pu, and the remainder contains the higher-mass Pu isotopes (^{240}Pu, ^{241}Pu, and ^{242}Pu). Since the commercial FBR is required to achieve a high fuel burnup (targeted to 150 GWd/t in core average) from the economical points of view, the higher-mass Pu becomes more important for accurate prediction in the fuel burnup calculation. Moreover, FBR has to manage a wide variety of fuel nuclide composition recovered from the spent fuel of light water reactors (LWRs). So, in some instances, it may use a highly-degraded Pu from high-burnup LWR or LWR-MOX spent fuel which contains a certain amount of higher-mass Pu.

Besides the breeding capability, more extensive and higher performances are required for the future essential energy generating system. One of them is the nuclear transmutation of long-lived minor actinide nuclides (MA: Np, Am, Cm) which are to be contained in the high-level radioactive waste. Thanks to the abundant neutron economy, FBR is suitable for the transmutation of MA ensuring the compatibility with breeding.

Therefore, this study deals with the advanced FBR core design focusing on the higher-mass Pu and MA nuclides. The necessary reactor core physics studies have also been performed regarding the validation or improvement of inaccurate nuclear data of those nuclides. In particular, the following study items are included: (1) Reactor core physics study on higher-mass plutonium, (2) Validation of MA nuclear data by PIE analysis, (3) Advanced FBR core design for MA transmutation, (4) Advanced FBR core design for nuclear non-proliferation. The main results are summarized below.

(1) Reactor core physics study on higher-mass plutonium

The French CIRANO experimental programme carried out at the MASURCA facility provides an extensive validation database for important aspects of plutonium burning fast reactor core physics. Fuel substitution reactivity worths between various types of plutonium fuel were examined in a small central zone, in which a wide range of plutonium isotopic vector from 8 to 35% of ^{240}Pu contents was covered. The experimental information of higher-mass plutonium is worthwhile for development of commercial FBRs accepting degraded plutonium.

An analysis of the CIRANO experiment was performed by using the Japanese standard FBR core calculation scheme with the Japanese evaluated nuclear data, JENDL-3.2. Cross-section adjustment technique was employed for the consistency check between the set of FBR core integral experimental analyses (235 data) and the present one. Cross-section adjustment also enabled us to deduce the trend for improvement of nuclear data, especially for ^{240}Pu cross sections.

As a result, a good consistency between those experimental analyses was confirmed. The following ^{240}Pu cross-section changes were observed by the adjustment calculation: the fission cross section increased by 8-9% in the energy range of 20-100 keV, whilst increased by 0.2-0.5% around 1 MeV; the average number of neutrons per fission increased by about 2% uniformly in energy; the capture cross section showed a decrement of a few to 10% in the energy range of 20 keV to a few MeV. The uncertainty induced from ^{240}Pu nuclear data was successfully reduced.

The experimental analysis results were also devoted to the development of an adjusted cross section for FBR so that the experimental information could be reflected back into the core design calculations. The adjusted cross section called ADJ2000R that includes the CIRANO experimental information on higher-mass plutonium has been used in the commercial FBR core design in the FBR cycle technology development project in Japan, as well as the advanced FBR core design in this study.

(2) Validation of MA nuclear data by PIE analysis

In order to validate or improve the inadequate nuclear data, the PIE (post irradiation experiment) analyses on MA samples irradiated at the experimental fast reactor "JOYO" was performed. It was found that the isomeric ratio of ^{241}Am capture reaction lied around 0.85 (defined as ^{242}Am / (^{242}Am+^{242m}Am)) in the core central region. However, the isomeric ratio obtained from JENDL-3.3 was about 0.7, while ENDF/B-VI gave about 0.8. The necessity of re-evaluation of isomeric ratio data in those libraries was suggested. After that, the revision of ^{241}Am isomeric ratio was performed in the major nuclear data libraries (ENDF/B, JENDL, JEFF) one after the other, and any of them was changed close to 0.85 in fast reactor energy region.

For ^{241}Am capture cross section, good agreement between calculation and experiment within 10-15% was observed, which significantly contributed to the rational design especially for the highly-concentrated americium target described in the next study item.

Moreover, the analysis results showed the ^{244}Cm capture cross section in ENDF/B-VI was overestimated by about 50%, and the ^{245}Cm capture cross section in JENDL-3.3 by about 30%. The experimental information of ^{244}Cm capture cross section is quite valuable and it contributes to the improvement of prediction accuracy of decay heat of MA-bearing fuel.

Prior to the above-mentioned PIE analyses, a burnup sensitivity analysis on a commercial FBR was carried out to clarify the dependence of core characteristics on nuclear data libraries and to evaluate their uncertainties induced by nuclear data. These uncertainties were compared with the target accuracy, and then the influential nuclear data were selected to assign higher priority in the validation work. As a result, the following nuclear data in the energy range of 100 eV to 1 MeV were found to be improved to at least from 1/2 to 1/3 of the prior uncertainty level: the isomeric ratio of ^{241}Am capture reaction, the capture cross section of ^{243}Am, the capture cross section of ^{242}Cm, and the capture cross section of ^{244}Cm.

(3) Advanced FBR core design for MA transmutation

As a new method for MA recycling in FBR, this study proposes a heterogeneous MA-loading core concept that uses highly-concentrated americium containing fuel (Am target). Americium content in heavy metal was assumed in the range of 10 to 20 wt% in accordance with the target development scope. It has been found that the ring-shaped target loading pattern between inner and outer core region has favorable MA transmutation performance without any significant deterioration in core neutronics characteristics compared to the reference homogeneous MA-loading case. It should be noted that the Am targets in this loading pattern can contribute to the suppression of the core power distribution change along with burnup. A series of core design including the core neutronics, thermal hydraulics, and fuel integrity evaluations was carried out for a representative Am-target loading case. It turns out to be possible to design Am-target subassembly that can cope with the issues brought by highly-concentrated americium, i.e., the deterioration of thermal physics properties and the accumulation of helium gas inside the target fuel pin. This study showed that an Am-target design modification by increasing the number of target pin and the cladding thickness is a feasible measure to cope with them.

Based on a three-dimensional core neutronic calculation, a thermal-hydraulic evaluation, and a fuel integrity evaluation, a detailed core design evaluation was performed for the representative Am-target loaded core in which the Am content of the target is set to 20 wt%. The core and fuel specifications have been determined to satisfy the design requirements and conditions for a commercial FBR core. And as a result, the heterogeneous Am-target loading core becomes to have much enhanced design feasibility, and hence it can be considered as an alternative option for MA recycling in fast reactor with a benefit of the small-scale MA fuel cycle systems.

(4) Advanced FBR core design for nuclear non-proliferation

Plutonium used as the core fuel of FBR is usually "reactor grade," where the reactor grade Pu contains a certain amount of higher-mass plutonium so that ^{240}Pu isotopic fraction is more than 18% according to the conventional classification. On the other hand, in the blanket surrounding the core fuel, uranium is converted into higher grade Pu than reactor grade, in which the proportion of fissile isotopes is more than 90%.

As measures in response to concerns about nuclear proliferation due to higher grade Pu, the rigorous safeguards by the

International Atomic Energy Agency (IAEA) and the physical protection of nuclear materials essentially keep the system's proliferation resistance at a high level. Moreover, it is possible to keep the Pu products in the fuel cycle system at reactor grade by reprocessing the blanket together with the core fuel. Nevertheless, in a future commercial era when a number of FBRs are deployed, society may come to demand a more enhanced proliferation resistance level. As an example of a way to cope with that situation, this study investigated a core design that reduces the attractiveness of nuclear material (that is, which prevents the production of higher grade Pu) while avoiding serious deterioration in core performance, fuel fabrication, fuel handling, and so on. As a result, the following three methods (i) to (iii) were found to be feasible.

Method (i) is to load the blanket with Pu, whereupon the blanket becomes low-enriched fuel with Pu enrichment of 3-5%. No higher grade Pu emerges because from the outset the generated Pu is naturally mixed with the reactor grade Pu added initially.

In method (ii), MA on the order of 2-4% produces ^{238}Pu, the decay heat of which is considered to make a large contribution to nonproliferation characteristics. It should be noted that this method is subject to limitations in terms of the MA supply, because MA with low decay heat is necessary from the viewpoint of fuel fabrication and handling. After preliminary evaluation of the attractiveness of Pu for methods (i) and (ii), it is foreseen that it is sufficiently possible to reduce the attractiveness of the nuclear material to the same level as core fuel.

Method (iii) uses a radial blanket-free core that is made possible by modifications of the core fuel specifications to maintain breeding performance. Method (i) or (ii) can be applied to the axial blanket if necessary.

This study showed that any of these methods can be expected to enhance the nonproliferation characteristics with respect to the isotope composition of Pu while satisfying the performance requirements of a commercial FBR.

In conclusion, this study has produced much progress in the validation and improvements of nuclear data for higher-mass Pu and MA which have importance in the advanced FBR core design. Useful knowledge was also obtained by the burnup sensitivity analysis and the evaluation of uncertainty induced by their nuclear data. Those results were reflected back into the core design calculation method, and hence contributed to the rational core design. The core design study proposed the new MA loading method and the non-proliferation core concepts, which resulted in the improvements of the advanced FBR core concept with enhancing its attractiveness.

論文審査結果の要旨

発電しながら燃料の増殖が可能な高速増殖炉は、将来の基幹電源として研究開発が進められてきた。近年は増殖に加え、経済性、廃棄物管理性、核不拡散性などの観点から高い性能を有する先進的高速炉の必要性が高まっていた。本研究では、先進的高速炉の性能向上に重要な役割を果たす高次プルトニウム（Pu）とマイナーアクチニド（MA）に着目した炉心設計の高度化を行うとともに、合理的な炉心設計に不可欠な核設計精度の確保を目的とした高次 Pu と MA に係る炉物理研究を行っている。本論文はその成果をまとめたものであり、全文５章よりなる。

第１章は序論であり、本研究の背景と目的について述べている。

第２章においては、実験データが不足し十分活用されていなかった高次 Pu に関する炉物理実験データを拡充し、高速炉核設計への反映を行った。さらに、高速炉エネルギー領域における ^{240}Pu の核分裂あたりの平均中性子発生数の過小評価、^{240}Pu の捕獲反応断面積の過大評価が示唆されること等を明らかにし、核データ改善のための傾向を把握した。

第３章においては、MA サンプルの照射試験解析によって、^{241}Am 捕獲反応の核異性体比が高速炉エネルギー領域において約 0.85 であることを明らかにし、米国をはじめとする核データライブラリの見直しに波及する影響を与えた。^{241}Am 捕獲反応に関する実験解析結果は、第４章で述べる高含有 Am ターゲット燃料装荷炉心の合理的な設計に極めて重要な寄与をはたした。また、使用済燃料の崩壊熱等の精度向上に寄与する Cm 同位体の捕獲反応断面積が、いくつかの核データライブラリにおいて著しく過大評価であることも明らかとなった。なお、上記の照射試験解析に先立ち、炉心特性について核データに起因する不確かさと核データ必要精度を定量化し、MA サンプル照射試験等における測定の優先順位や測定精度の設定へ活用した。

第４章の先進的高速炉の炉心設計においては、上記の高次 Pu や MA の測定結果を炉心設計手法に反映させながら、幅広い観点からの炉心設計検討を行った。特に高含有率の Am ターゲットを用いた MA の新しい非均質装荷方法として、内側炉心と外側炉心の境界付近に Am ターゲットをリング状に装荷する方法を提案し、従来のターゲット装荷法で問題であった出力ミスマッチが大きくなる、炉心構成が複雑になるといった課題を解消できる見通しを得た。核不拡散性向上炉心の検討においては、物質障壁の観点から核物質魅力度を下げるために、ブランケットにおける高グレード Pu の生成を防止する炉心設計を、炉心性能や燃料製造・取扱い等に深刻な影響を与えない範囲で検討し、ブランケットへの Pu 添加、ブランケットへの MA 添加、径方向ブランケット削除炉心、の各方法の実現可能性を明らかにした。

第５章では、本研究の結論を述べている。

以上、本論文では、先進的高速炉の炉心設計において重要な高次 Pu と MA の核データの妥当性検証と精度向上が進展するとともに、核データ起因誤差の評価においても有用な知見が得られた。本論文は先進的高速炉の炉心設計に反映して、Am ターゲットの新しい装荷法や、核不拡散性向上の新しい炉心概念を構築しており、魅力ある先進的高速炉の炉心設計の高度化に貢献するのみならず、原子炉工学の発展に大いに寄与するものである。

よって、本論文は博士（工学）の学位論文として合格と認める。