

THE USE OF MOLYBDENUM-BASED CERAMIC-METAL (CerMet) FUEL FOR THE ACTINIDE MANAGEMENT IN LWRs

RADIOACTIVE WASTE
MANAGEMENT
AND DISPOSAL

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The technical and economic aspects of the use of molybdenum depleted in the isotope ^{95}Mo (DepMo) for the transmutation of actinides in a light water reactor are discussed. DepMo has a low neutron absorption cross section and good physical and chemical properties. Therefore, DepMo is expected to be a good inert matrix in ceramic-metal fuel. The costs of the use of DepMo have been assessed, and it was concluded that these costs can be justified for the transmutation of the actinides neptunium, americium, and plutonium.

I. INTRODUCTION

Radioactive waste of spent fuel represents a radiological risk for a long period of time ($>100\,000$ yr). The long-term radiotoxicity of this waste is mainly determined by the actinides plutonium and americium. Transmutation of these actinides offers a possibility for the reduction of the radiotoxicity of nuclear waste. Dedicated advanced systems, such as accelerator driven systems are suitable for the transmutation of actinides. However, because of the current unavailability of these systems and their relatively high development costs, these systems cannot be seen as short-term options for transmutation of plutonium and americium. Because of the large number of light water reactors (LWRs) worldwide, the use of LWRs might be a short-term option for the transmutation of Np, Pu, and Am.

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Transmutation of plutonium in mixed oxide (MOX) fuel is the first step, which is currently taken on a rather large scale. However, transmutation in LWRs does not significantly decrease the Pu stocks because of the presence of uranium in the MOX and the fact that in most LWRs only about one-third of the core contains MOX, while two-thirds contains UO_2 fuel. To try to significantly reduce the Pu stocks, several concepts are studied currently. Commissariat à l'Énergie Atomique in France investigates the assemblage plutonium advanced concept,¹ which is based on heterogeneous fuel elements containing, among others, Pu-containing ceramic-metals (CerMets), shaped in the form of an annulus or a cross. These shapes allow increasing the moderator/fuel ratio, which improves the safety characteristics of the reactor. Another innovative concept is the combined nonfertile and uranium (CONFU) fuel assembly concept, where $\sim 20\%$ of the uranium fuel rods are replaced by fuel rods containing Transuranic (TRU) elements.² In this concept the CONFU assembly can be designed to achieve an equilibrium state in terms of net generation of TRU nuclides and at the same time have acceptable reactivity control and thermal-hydraulic characteristics. Several institutes are studying the use of ceramic (oxide) materials as inert matrix, given the high melting points, low neutron absorption cross sections, and good chemical stability of some oxides. However, currently no single candidate has been identified that has proven to be able to fulfill all requirements in an economically viable manner in an LWR. The most promising ceramic-ceramic (CERCER) candidate for plutonium transmutation is so-called rocklike oxide (ROX) fuel, which is based on a ZrO_2 matrix.³

The transmutation of americium puts more severe demands on the fuel concept because of the large helium production, which can have the adverse effect of inducing

large swelling of the fuel.⁴ Because of this additional complexity, no matrix has yet been identified that is suitable for the transmutation of americium.

The use of a metal inert matrix might be an option to find a suitable concept for the transmutation of americium and plutonium in LWRs. The advantages of CerMet fuel⁵ lie in the fact that the metallic matrix is a potential supplementary barrier to fission-gas release and ensures excellent thermal conductivity, as well as forms a metal-to-metal contact for the cladding and the matrix, which makes pellet-cladding interaction highly improbable.

The main candidates to be used as the metal phase in an LWR can be grouped,⁵ depending on their neutron absorption cross section, as follows:

1. metals with a low neutron capture cross section, e.g., zirconium and silumin (88% Al, 12% Si) (Ref. 6)
2. metals with an intermediate neutron capture cross section, e.g., INCONEL[®]
3. metals with a high neutron capture cross section, e.g., Mo and stainless steel.

A collection of the main properties of candidate materials is given in Table I.

The candidate metals to be used in an LWR and in a fast reactor are different. For fast reactor application the thermal neutron absorption cross section is less important, and therefore, metals with relatively high thermal neutron absorption cross sections and high melting temperatures (Cr, W, V) are proposed in addition to Zr (Refs. 7 and 8). Since the difference between DepMo and natural Mo is mainly the thermal neutron absorption cross section, it can be concluded that using DepMo instead of natural Mo has only a marginal impact on the neutronic conditions in a fast reactor. Therefore, this paper discusses only the application of DepMo under thermal conditions such as in an LWR.

For LWR application a metal with a low neutron cross section is required by the safety coefficients (Doppler coefficient, moderator coefficient, and void coefficient).⁹ However, the low cross-section metals (e.g., Al, Zr) have the disadvantages of low melting temperatures and/or a low chemical stability. Molybdenum depleted in the high neutron absorption cross-section isotope ⁹⁵Mo (called DepMo) is suggested as a suitable metal to be used in CerMet fuel for the transmutation of americium or plutonium in an LWR. The technical and economic aspects of the use of DepMo are discussed in Secs. II and III.

II. TECHNICAL ASPECTS

II.A. Isotopic Composition

Molybdenum has seven stable isotopes. Two isotopes, ⁹²Mo and ⁹⁴Mo, are lighter than ⁹⁵Mo, while four isotopes, ⁹⁶Mo, ⁹⁷Mo, ⁹⁸Mo, and ¹⁰⁰Mo, are heavier than ⁹⁵Mo. Because of this, DepMo can be produced and enriched in the light isotope ⁹²Mo and in the heavy isotopes ⁹⁸Mo and ¹⁰⁰Mo. To reduce the production costs of DepMo, both a light and a heavy fraction can be obtained from the same batch of starting material. These two fractions can thereafter be combined into a so-called “mixed fraction,” which is enriched in both ⁹²Mo and ¹⁰⁰Mo. The isotopic compositions of natural Mo, the light fraction, the heavy fraction, and the mixed fraction are schematically shown in Fig. 1 and Table II. It should be remarked that the isotopic compositions of the various types of DepMo are only shown as typical examples obtained from the tests made by Urenco. The exact composition of DepMo depends on the number of enrichment steps, which will be directly influenced by economic aspects.

TABLE I
Some Characteristics of UO₂ and of Candidate Metals to be Used in an LWR*

Material	Melting Temperature (°C)	Density (kg/m ³ at 20°C)	Thermal Conductivity (W/m·K at 400°C)	Thermal Cross Section (b)
Natural Mo	2600	10 200	123	2.65
Aluminum	660	2 710	228	0.23
Silumin		2 260	180	0.22
Zircaloy-4	1845	6 570	21.4	0.19
Type 304 stainless steel	1400	7 820	20.8	3
UO ₂	2800	11 000	4	12 ^a

*Most data originate from Porta et al.¹²

^aFor a ²³⁵U enrichment of 5%.

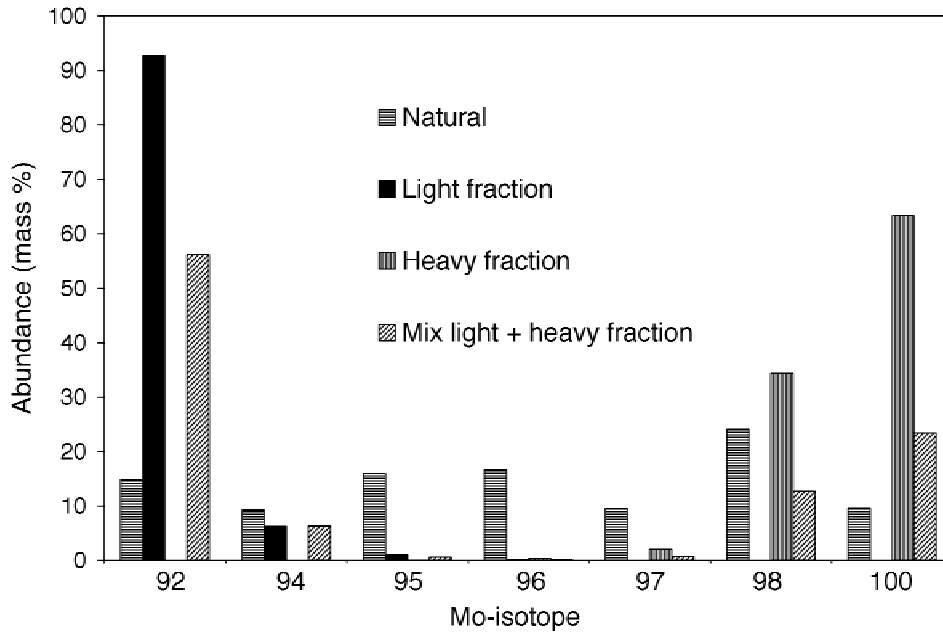


Fig. 1. Approximate isotopic compositions of natural Mo and of DepMo (light, heavy, and mixed fraction).

TABLE II

The Abundance of the Mo Isotopes in Natural Mo and in the Various Types of DepMo

Molybdenum Isotope	Isotopic Composition (at.%)			
	Natural	Light	Heavy	Mixed Light + Heavy
92	14.84	93	0	56
94	9.25	6	0	6
95	15.92	1.0	0.03	0.6
96	16.68	0.07	0.3	0.14
97	9.55	0	2	0.7
98	24.13	0	34	13
100	9.63	0	63	23

II.B. The Neutronic Aspects of DepMo

The relatively high neutron cross section of natural Mo (due to ⁹⁵Mo) has the drawback that a high concentration of fissile atoms has to be used to obtain sufficient reactivity. Putting these high concentrations into the fuel might have several adverse effects on the neutronics parameters such as Doppler coefficient, moderator coefficient, and void coefficient.⁹ In this section the influence of using DepMo instead of natural Mo on the cross section of the molybdenum is studied.

The impact of the isotopic composition on the neutron absorption cross sections has been studied for LWR

typical conditions. Since the cross sections are energy dependent, a typical LWR spectrum in 172 energy groups was used to study this impact. Table III shows the fluxes of the 172 energy groups summed in three energy groups (thermal, epithermal, and fast). The energy-averaged neutron absorption cross sections have been computed in the three energy groups. These computations have been done by multiplying the 172 energy group fluxes with the absorption cross sections and normalizing with the flux in the various LWR energy groups. For these computations neutron absorption cross-section data from JEF-2.2 (Ref. 10) have been used. No self-shielding has been taken into account. The resulting energy-averaged neutron absorption cross sections are shown in Fig. 2 and Table IV.

The neutron absorption cross sections shown in Table IV for the thermal range are somewhat different from those on the Karlsruhe Nuclide map.¹¹ This is because the data shown in Table IV are integrated over the

TABLE III

LWR-Typical Fluxes for Three Energy Groups

Energy Range	Flux (m ⁻² s ⁻¹)
Thermal (10 ⁻⁵ eV < E < 0.625 eV)	2.34 × 10 ¹⁷
Epithermal (0.625 eV < E < 0.1 MeV)	3.25 × 10 ¹⁷
Fast (E > 0.1 MeV)	3.15 × 10 ¹⁷
Total (10 ⁻⁵ eV < E < 20 MeV)	8.74 × 10 ¹⁷

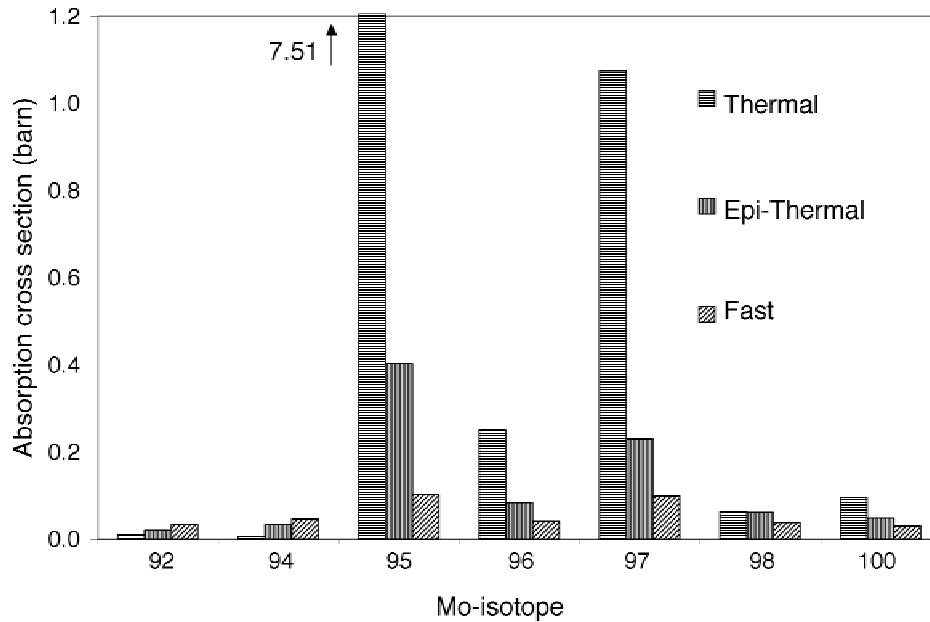


Fig. 2. The absorption cross section for thermal neutrons of the Mo isotopes. The neutron absorption cross section of ⁹⁵Mo in the thermal energy group is 7.51 b, which lies outside the figure.

complete thermal energy group ($10^{-5} \text{ eV} < E < 0.625 \text{ eV}$), while the Karlsruhe Nuclide map shows the value for one specific energy (2200 m/s).

Table IV and Fig. 2 show that the neutron absorption cross sections of ⁹⁵Mo in the thermal and epithermal energy group are significantly higher than those of the other Mo isotopes. In the fast energy group the differences are less pronounced. The importance of the neutron absorption cross sections in the various energy groups is dependent on the isotopic composition of the molybdenum and the neutron fluxes in these groups. Combining the isotopic abundance (Table II), the neutron absorption cross sections (Table IV), and the fluxes in the three groups (Table III), yields the neutron ab-

sorption rates for the three neutron energy groups. The isotopic average of the cross sections for natural, light, heavy, and mixed Mo are shown in Table V. These data show that natural Mo has a much higher cross section than the light, the heavy, and the mixed Mo.

Table V shows that under LWR conditions the neutron absorption in the light DepMo is about ten times smaller than in natural Mo. For heavy DepMo the neutron absorption cross section is about seven times smaller, and in mixed DepMo the absorption is about nine times smaller. Table V also shows that for natural Mo the neutron absorption in the thermal energy group is much larger than in the other energy groups, while for the three types of DepMo, this difference is much smaller.

TABLE IV

The Neutron Absorption Cross Sections of the Mo Isotopes in the Thermal, Epithermal, and Fast Energy Groups

Molybdenum Isotope	Neutron Absorption Cross Section (b)		
	Thermal Range ($10^{-5} \text{ eV} < E < 0.625 \text{ eV}$)	Epithermal Range ($0.625 \text{ eV} < E < 0.1 \text{ MeV}$)	Fast Range ($E > 0.1 \text{ MeV}$)
92	0.01	0.02	0.03
94	0.01	0.03	0.05
95	7.51	0.40	0.10
96	0.25	0.08	0.04
97	1.08	0.23	0.10
98	0.06	0.06	0.04
100	0.10	0.05	0.03

TABLE V

Isotopic Average of the Cross Sections for Natural, Light, Heavy, and Mixed Mo in the Three Energy Groups*

Molybdenum Composition	Thermal Range (10^{-5} eV < E < 0.625 eV)	Epithermal Range (0.625 eV < E < 0.1 MeV)	Fast Range (E > 0.1 MeV)	Sum of the Energy Ranges
Natural	1.000	0.128	0.054	1.182
Light	0.062	0.026	0.035	0.123
Heavy	0.079	0.058	0.034	0.171
Mixed	0.065	0.038	0.035	0.138

*The data have been normalized to the value for natural Mo in the thermal energy group.

Because of the low cross sections of DepMo, which are similar to those of silicon and zirconium, the use of DepMo is expected to largely overcome the neutronics problems of CerMets based on natural Mo. The exact consequences of the use of DepMo on the neutronics behavior will depend strongly on the layout of the fuel and the reactor in which this fuel is used and will therefore require detailed neutronics computations.

An aspect in the use of molybdenum that requires some attention is the production of the long-lived radioactive isotope ^{99}Tc (half-life is 2.1×10^5 yr), due to neutron capture in ^{98}Mo . Production of one radioisotope during the transmutation of the other isotope is of course an unfortunate side effect. Simple neutronics computations show that for a typical DepMo-based fuel (containing the mixed fraction), the amount of ^{99}Tc produced from fission of the Pu present in the fuel is one to two orders of magnitude larger than the amount of ^{99}Tc produced from neutron capture in ^{98}Mo . This shows that the production of ^{99}Tc from neutron capture in ^{98}Mo is only of minor importance. Using solely the molybdenum isotopic fraction enriched in the light isotope ^{92}Mo prevents the formation of ^{99}Tc but will increase the costs of the DepMo somewhat.

II.C. Fuel Behavior of Mo-Based CerMets

II.C.1. Behavior During Normal Operation

The behavior of natural molybdenum-based CerMet fuels during neutron irradiation in the SILOE experimental reactor has been studied by Dehaut et al.¹² The fissile phase in these CerMets was UO_2 particles (36 vol%, 19.6% ^{235}U) with a typical size of 100 to 150 μm . The irradiation duration was 104.5 full-power days, causing a burnup of 55.4 MWd/kg U. The CerMet fuel stack was equipped with central thermocouples, which showed that the high thermal conductivity of molybdenum caused a low fuel temperature. This low fuel temperature decreases the fission-gas release. The dimensional stability of the aforementioned Mo/ UO_2 fuel is observed to be very good. The CerMet microstructure did not change during the irradiation. Given the low fission-gas release, the high thermal conductivity, and the good dimensional

stability, it can be expected that the maximum burnup that can be achieved with a Mo-based CerMet is very high.

II.C.2. Behavior During Accident Conditions

For the introduction of CerMet fuel, the good behavior of the fuel during accident conditions is crucial. An overview of the parameters of importance to the behavior under accident conditions is given by Porta et al.¹³ for natural molybdenum and other metals. It is of importance to ascertain that the fuel keeps sufficient integrity during accident conditions, such as loss-of-coolant accidents and reactivity initiated accidents. The high melting temperature and the low thermal expansion of Mo are important safety features of Mo-based CerMets.

Bonnet et al.¹⁴ discussed that having a ceramic phase with a higher density (g/cm^3) than the metal phase in CerMet has adverse safety consequences in case of a meltdown. Such a density distribution would for instance be present in a PuO_2 /Zircaloy CerMet. Because of the difference in density, there exists a serious risk of recriticality during a meltdown accident since all fissile material might collect at the bottom of the reactor vessel with a metal phase present on top of the fissile phase. In case the density of the ceramic phase is similar to that of the metal phase (e.g., MOX/DepMo) or lower (ROX/DepMo), this risk would be much smaller.

Another important safety aspect is the compatibility of Mo with the water coolant in the case of failure of the cladding of the fuel pin, both during normal irradiation and during accident conditions. This corrosion aspect and other safety aspects of Mo-based fuel should be studied in more detail and will be strongly dependent on parameters such as the fraction of the reactor core loaded with this type of fuel.

II.D. Fuel Concept

To be able to make an assessment of the economic aspects of the use of DepMo, a fuel rod and a fuel assembly design should be proposed. For the fuel assembly the CONFU design² is assumed in which 80% of the fuel rods contains UO_2 pellets and 20% of the rods contains

TRU-based pellets. The fraction of TRU oxides in the TRU pellets is 12 vol%, from which a CerMet can be proposed as containing DepMo (70 vol%) and $(\text{TRU}_{0.36}, \text{Er}_{0.03}, \text{Y}_{0.07}, \text{Zr}_{0.54})\text{O}_{2-x}$ fissile particles (30 vol%). From an economic point of view, the above assumption that 70 vol% of the fuel rod contains DepMo might be conservative, but detailed fuel behavior studies are required to determine the lower limit of the DepMo fraction, which still gives reliable fuel behavior. The fuel structure and the fuel behavior are expected to be similar to that of the UO_2/Mo fuel described by Dehaut.¹² The pellets are assumed to be solid and to have an outer diameter of 8 mm. The aim of introducing the aforementioned fuel characteristics is only to compare the costs of DepMo with the total costs of electricity generation. The authors do not suggest that this concept is the optimum concept for the use of DepMo in an LWR.

III. ECONOMIC ASPECTS

III.A. The Costs of Depletion of Mo

Several techniques exist for the enrichment/depletion of isotopes. A technique to deplete relatively large amounts of medium- and heavy-weight isotopes is gas ultracentrifuge. This technique is used for the enrichment and depletion of uranium and several stable isotopes (e.g., zinc and iridium). The main producers of stable isotopes are some companies located in Russia, and Urenco in the Netherlands. The depletion of Mo, using MoF_6 as a process gas, has been studied by Urenco. Apart from economies of scale, the costs are determined by two parameters:

1. The degree of depletion in the isotope ^{95}Mo . In this paper a depletion between 0% ^{95}Mo (heavy fraction) and 1% ^{95}Mo (light fraction) is used since this gives a strong decrease in absorption cross section at reasonable costs.

2. The composition of the remaining isotopes shows that there exist both lighter and heavier isotopes than ^{95}Mo , and therefore, both a light Mo fraction and a heavy Mo fraction can be obtained, which are both depleted in ^{95}Mo . From an economic point of view, it is most interesting to mix these fractions into the mixed fraction shown in Fig. 1 and Table II.

Good test results were obtained by Urenco, showing that a cost price target of 10 euros/g for DepMo (1% ^{95}Mo) is achievable, assuming a production of several tonnes per year.

III.B. The Costs of Applying DepMo

For the fuel characteristics mentioned in Sec. II.D, the amount of DepMo required per meter fuel rod is ~ 350 g, which costs ~ 3500 euros/m. Since the CONFU assembly contains only 20% rods containing TRU nuclides, the costs (average over TRU rods and UO_2 rods) are 700

euros/m. Assuming a typical burnup of 50MWd/kg UO_2 and a thermal-to-electrical conversion of 33%, the cost contribution of DepMo to the electricity costs amount to 0.003 euro/kW·h. The costs of electricity produced by a standard LWR using UO_2 are ~ 0.04 euro/kW·h (Ref. 15).

The production of molybdenum-based CerMet fuel is relatively simple¹⁶ since molybdenum is ductile and not very sensitive to oxygen, which allows fuel fabrication using the standard technique of powder mixing and sintering. Therefore, when large-scale production is made of DepMo-based fuels, it is likely that the production costs are not much higher than those of the production of other types of plutonium- or americium-containing fuels. Since the fuel behavior of DepMo-based fuel is expected to be better than that of UO_2 , MOX, or CERCER-based transmutation fuels, part of the additional costs of 0.01 euro/kW·h might be compensated for by better fuel behavior, which would allow higher fuel powers and higher burnups.

From this discussion we conclude that the costs of DepMo are not excessively high and justify further study into the technical details of the use of DepMo for the transmutation of Pu or Am in for instance LWRs.

IV. CONCLUSIONS

An overview has been given of both the technical and economic aspects of using DepMo in CerMet fuel in an LWR. It is concluded that DepMo might be a suitable metal in CerMet fuel with plutonium- or americium-containing ceramics. More detailed studies will be required on aspects such as corrosion rates of molybdenum, detailed fuel rod layout, neutronics, and irradiation behavior.

REFERENCES

1. B. GASTALDI, J. PORTA, C. KRAKOWIAK-AILLAUD, and L. BUFFE, "APA: Alternative Concept, Neutronics Optimisation of a Cruciform Geometry," *Proc. 7th Inert Matrix Fuel Workshop (IMF7)*, Petten, the Netherlands, October 25–26, 2001, Nuclear Research and Consultancy Group (2001).
2. E. SHWAGERAUS, P. HEJZLAR, and M. S. KAZIMI, "A Sustainable PWR Fuel Cycle with Complete TRU Recycling Using Fertile Free Fuel," *Proc. Int. Congress Advances in Nuclear Power Plants (ICAPP '03)*, Cordoba, Spain, May 4–7, 2003 (CD-ROM).
3. T. YAMASHITA, K. KURAMOTO, H. AKIE, Y. NAKANO, N. NITANI, T. NAKAMURA, K. KUSAGAYA, and T. OHMACHI, "Rock-Like Oxide Fuels for Burning Excess Plutonium in LWRs," *Proc. Workshop Advanced Reactors with Innovative Fuels (ARWIF 2001)*, Chester, United Kingdom, October 22–24, 2001, Nuclear Energy Agency (2001).
4. R. J. M. KONINGS, R. CONRAD, G. DASSEL, B. J. PIJL-GROMS, J. SOMERS, and E. TOSCANO, "The EFTTRA-T4

- Experiment on Americium Transmutation,” *J. Nucl. Mater.*, **282**, 159 (2000).
5. J. PORTA and A. PULL, “U-Free Pu Fuels for LWRs—The CEA/DRN Strategy,” *Proc. Workshop Advanced Reactors with Innovative Fuels (ARWIF 1998)*, Villigen, Switzerland, October 21–23, 1998, Nuclear Energy Agency (1998).
 6. V. TROYANOV, V. POPOV, and IU. BARANAEV, “Cer-Met Fuel in a Light Water Reactor: A Possible Way to Improve Safety. Part I. Fabrication and Characterization,” *Proc. 6th Inert Matrix Fuel Workshop (IMF6)*, Strasbourg, France, May 30–June 2, 2000, *Prog. Nucl. Energy*, **38**, 267 (2001).
 7. J. ROUAULT, J. C. GARNIER, N. CHAUVIN, and S. PIL-LON, “Programme on Fuels for Transmutation: Present Status and Prospects,” *Proc. Int. Conf. Back-End of the Fuel Cycle: From Research to Solutions (Global 2001)*, Paris, France, September 9–13, 2001 (2001) (CD-ROM).
 8. A. VASILE, G. RIMPAULT, J. TOMMASI, C. DE SAINT JEAN, M. DELPECH, K. HESKETH, H. M. BEAUMONT, R. SUNDERLAND, T. NEWTON, P. SMITH, W. MASCHKE, D. HAAS, Ch. DE RAEDT, G. VAMBENEPE, and J. C. LEVE-FRE, “Fast Reactors Fuel Cycle: Core Physics Results from the CAPRA/CADRA Programme,” *Proc. Int. Conf. Back-End of the Fuel Cycle: From Research to Solutions (Global 2001)*, Paris, France, September 9–13, 2001 (2001) (CD-ROM).
 9. S. BALDI and J. PORTA, “Elements of Comparison Between Different Inert Matrix Fuels as Regards Plutonium Utilisation and Safety Coefficients,” *Proc. 6th Inert Matrix Fuel Workshop (IMF6)*, Strasbourg, France, May 30–June 2, 2000, *Prog. Nucl. Energy*, **38**, 375 (2001).
 10. “The JEF-2.2 Nuclear Data Library,” JEFF report 17, Organization for Economic Cooperation and Development Nuclear Energy Agency (2000).
 11. Karlsruhe Nuclide Map, Forschungszentrum Karlsruhe Germany (1995).
 12. PH. DEHAUDT, A. MOCELLIN, G. EMINET, L. CAILLOT, G. DELETTE, M. BAUER, and I. VAILLARD, “Composite Fuel Behaviour Under and After Irradiation,” *IAEA-TECDOC-970*, p. 23, International Atomic Energy Agency (1997).
 13. J. PORTA, C. AILLAUD, and S. BALDI, “Composite Fuels: Neutronic Criteria for Selection of Matrix, Core Control, Transients, and Severe Accidents,” *Proc. 7th Int. Conf. Nuclear Engineering (ICONE-7)*, Tokyo, Japan, April 19–23, 1999.
 14. M. BONNET, S. BALDI, and J. PORTA, “Progress in CerMet Core Modelling to Calculate Severe Accidents,” *Proc. 6th Inert Matrix Fuel Workshop (IMF6)*, Strasbourg, France, May 30–June 2, 2000, *Prog. Nucl. Energy*, **38**, 387 (2001).
 15. “Accelerator-Driven Systems (ADS) and Fast Reactors (FR) in Advanced Nuclear Fuel Cycles,” Nuclear Energy Agency (2002).
 16. The EUROPEAN TECHNICAL WORKING GROUP ON ADS, “A European Roadmap for Developing Accelerator Driven Systems (ADS) for Nuclear Waste Incineration,” ENEA, Italy, (2001).

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