Study of various options for final disposal of HTR coated particles
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ABSTRACT

In the frame of the RAPHAEL European project, the back end of the fuel cycle is addressed concerning mainly open cycles: direct disposal of spent fuel or of separated constituents (fuel matrix, particles, compacts or pebbles). One of the objectives is study and compare potential matrixes and their fabrication routes for incorporation separated particles. The direct disposal of used prismatic fuel blocks (or graphite pebbles of PBMR’s) is not considered due to of the large volume of fuel to dispose of.

While the immobilization of reprocessing residues in glass may follow largely existing processing schemes, employed for LWR fuel waste, the direct embedding of particles in glass without reprocessing seems also be feasible if reprocessing of certain spent fuel kernel types would not be beneficial, due to the high burn-up. However, other matrix SiC may be considered as potential matrix material as well.

The embedding of fuel particles would allow for a strong volume reduction compared with the direct disposal of fuel pebbles or compacts.

Concerning encapsulation in glass, large scale radioactive production experience and favorable disposal properties make glass a primary choice as confinement matrix. The product is capable to withstand groundwater attack for many hundreds of thousands of years. Alteration of by water will lead to the transformation of the glass into a dense gel like alteration phase which most likely will maintain strong confinement properties of fuel particles.

Vitrification of fuel particles was achieved via two methods: glass melting and sintering. Inert fuel particles and a borosilicate glass were used. With oxidizing lass melting at 1200°C-1300°C floatation and decomposition of carbon and silicon carbide occurred, leading to CO2 gas formation. Thermal pre-treatment of the particles lead by oxidation to the removal of the outer pyrocarbon layer, but glass/SiC contact remained weak. The sintered glass at 700°C showed better embedding properties of the fuel particles despite higher porosity compared to glass made by melting. Aqueous leaching properties of sintered glass were similar to those of melted glass.

The lower operation temperature makes the use of sintered glass an interesting option to conserve as much as possible the strong confinement properties of the fuel particles.

Embedding in SiC is investigated as alternative method. This material would be also capable to withstand a groundwater attack for a long time.

Conventional methods for SiC production, such as liquid sintering or hot pressing are not applicable when processing spent coated particle fuel. These methods hold the danger of damaging the particles and release fission products, either due to the high temperature (1800°C-2000°C) or the high pressure applied. In order to maintain integrity of the coated particles, a mild processing method for the production of the composite material is required. The route tested is the production of green bodies from well-dispersed aqueous SiC and graphite powder slips to which particles were added. These green bodies are subsequently infiltrated and reaction-bonded with molten silicon. The samples produced show no fractures and the new SiC matrix is grown together with the outer pyrocarbon layer of the fuel particle.

The properties of this matrix are under investigation to compare them with the glass matrix.

INTRODUCTION

The specific advantages which contribute to the increasing interest of HTRs result mainly from their basic concept, which distinguishes them from all other types of reactors: a refractory fuel in the form of sealed coated particles dispersed within a graphite matrix. From the point of view of the fuel cycle, this unique fuel design allows for a great flexibility in the choice of fissile and fertile materials mixtures which can feed these reactors and permit also a wide choice in the management of these materials (see ref [1] for an in depth analysis of this issue).

These sub-millimeter coated particles, called Triso particles, consist of a spherical fuel kernels surrounded by a thin layer of buffer carbon (BC), a layer of inner pyrolytic carbon (IpYC), a layer of silicon carbide (SiC) and an outer layer of pyrolytic carbon (OpYC). These layers exhibit excellent tightness against radionuclide release during high temperature reactor operation, but they can also provide long term confinement properties which can
prevent radionuclides release during the final disposal of the used fuel.

Strategically, there are three options for spent fuel management: long-term onsite storage, reprocessing, final disposal in a geological repository. An overview of these issues has been provided in ref [2] and reprocessing option has been analysed in particular in ref [3]. One can just remind here that treatment for recycling may be an interesting option because it allows the recovery of recyclable materials contained in the fuel (for example the residual enriched uranium of HTR’s is significantly higher than in LWR fuel and could justify the recovery of this fissile materials for recycling). Reprocessing also permit optimization of waste management by sorting and conditioning the various kinds of waste according to their potential hazards, in order to dispose them safely for the environment. To this regard, the vitrification process has been widely recognized as the preferred option for the conditioning of fissions products and long lived actinides coming from reprocessing of used nuclear fuel. Indeed, the glass matrix offers unique performances of stability and durability in the long term. However, other matrix such as SiC, Al2O3, or synroc may be considered as potential matrix material as well.

This paper, deals with the final disposal option of the spent fuel. In fact, in this option, the direct disposal of used prismatic fuel blocks (or graphite pebbles of PBMR’s) is not considered as a promising route because of the large volume of fuel to dispose of. This is because of the fact that, in a prismatic fuel block, Triso particles containing the nuclear fuel itself represents only 9 wt% of the total volume of the fuel, the rest being graphite (91% of the volume).

Thus, the first stage is a treatment of the used graphite blocks (or graphite pebbles) in order to separate Triso coated particle from the graphite. Then, once these coated particles are isolated, two options can be contemplated :

1. The first one is an encapsulation of the coated particles in an appropriate container before final disposal. However, in this option, the very long-term tightness of the container must be demonstrated as well as the long-term resistance to leaching of coated particles themselves.

The second option is the immobilization of coated particles in borosilicate glass or SiC before geological disposal. The vitrification process may be achieved via two methods : glass melting and sintering. Embedding coated particles in SiC matrix is currently investigated as alternative method since this material is also capable to withstand a groundwater attack for a long time.

This paper is focused on the study of these options. The studies were performed in the context of the European project “Raphael: reactor for process heat, hydrogen and electricity production”.

**PRETREATMENT**

For some embedding experiments, the TRISO-particles were heat-treated in an ATG apparatus to remove the OPyC coating without removing the SiC layer. The results are shown in Fig. 1 as mass loss as a function of heat duration. Four cycles of heating at 600°C over 24h were necessary to complete oxidation of OPyC. No significant mass loss occurred between 20 and 24h. The mass loss (0.16 mg) for a single TRISO-particle is similar to the theoretical one (0.185 mg).

**Fig. 1** Mass loss of a TRISO-fuel particle during heating at 600°C under oxygen atmosphere (TGA).

SEM examination of the heat-treated TRISO-particle showed the absence of the OPyC layer (Fig. 2), confirming the complete oxidation to likely carbon monoxide CO [4]. EDS analysis of the particle surface showed that the SiC layer was little affected by the oxidation as indicated by presence of only traces of SiO2 due to SiC oxidation. For most of the particles rapid oxidation of OPyC was obtained in a furnace heated at 1100°C for 3h. Complete oxidation of OPyC was confirmed by EDS analysis of the particle surface under the SEM.

**Fig. 2**: SEM micrograph of a heat-treated TRISO-UO2 particle showing the complete oxidation of OPyC layer.
VITRIFICATION

In the present chapter we report on the immobilization of TRISO-UO₂ particles in glass for an eventual geological disposal. Industrial glasses were proven to be efficient matrices for fission products and actinides immobilization in most of the countries reprocessing civilian and military spent nuclear fuels (France, Germany, Belgium, United Kingdom, United States, Japan, Russia etc.) [5]. Large-scale radioactive production experience and favorable disposal properties make glass a primary choice as confinement matrix. The glass product is capable to withstand groundwater attack for many hundreds of thousands of years. Alteration of glass by water will lead to the transformation of the glass into a dense gel-like alteration phase which most likely will maintain strong confinement properties of fuel particles. Hence, the glass constitutes an additional barrier for particles protection against groundwater corrosion and radionuclides dispersion in environment.

Experimental

The glass matrix used for vitrification was provided by CEA. The composition is given in Table 1. The Tg is 528±8°C, density is 2.48 g.cm⁻³ and the melting temperature is about 1200°C. The glass was used in the form of two powders: Ø<63 µm and 40 µm <Ø<140 µm corresponding to a BET surface area of 0.49 and 0.27 m².g⁻¹, respectively. Non-irradiated TRISO-UO₂ fuel particles were used with a diameter < 1 mm and a density of 3.59±0.1% g.cm⁻³. In some vitrification tests pretreated TRISO particles without the outer pyrocarbon layer (OPyC) were used.

Tab. 1: Glass composition used for vitrification

<table>
<thead>
<tr>
<th>Oxide</th>
<th>% weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>58.84</td>
</tr>
<tr>
<td>B₂O₃</td>
<td>18.15</td>
</tr>
<tr>
<td>Na₂O</td>
<td>7.00</td>
</tr>
<tr>
<td>CaO</td>
<td>5.23</td>
</tr>
<tr>
<td>Li₂O</td>
<td>2.56</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>4.28</td>
</tr>
<tr>
<td>ZnO</td>
<td>3.24</td>
</tr>
<tr>
<td>ZrO₂</td>
<td>0.70</td>
</tr>
</tbody>
</table>

Two vitrification options were tested: melting under oxic conditions at 1250-1300°C and sintering at T< 700°C. In each vitrification test about 10-20 fuel particles were used with few grams of glass. Prior to sintering, powdered glass and fuel particles were mixed at room temperature and the mixture was compacted with a pressure of 400 bars. The resulting pellets were heated at 700°C for a few minutes and then sintered at 680°C for 3h. After cooling, the melted and sintered composite samples were cut and polished to 3 µm for surface analyses and leaching experiments.

Leaching experiments were used to qualify the hydrolytic stability of the glass product. Experiments were conducted with glass powder or composite materials and pure water in 50 mL Teflon® containers at 92±2°C. Solid to solution volume ratios (SA/V) of 10 - 40000 m⁻¹ were used. Tests durations ranged between 1-56 days. The leached quantities of boron and lithium from the glass, used as corrosion tracers, were analyzed by Inductively Coupled Plasma Mass Spectrometry (ICP-MS) with an error of ±5-10%. No leaching of embedded fuel particles is expected under these conditions.

Polished composite materials were analyzed using a JSM 5800 LV JEOL scanning electron microscope (SEM) equipped with a Kevex Energy Dispersive X-ray spectrometry (EDS) system. Thin sections of standard phases were used to obtain quantitative analyses. Corroded glass and composite samples were also observed under the microscope. On polished thin section the error is about ±5%.

Results

Vitrification by melting: All glass melting attempts with untreated TRISO-particles were unsuccessful because of floatation and sorption of particles on the crucible or the steel mold because the glass melt does not wet the carbon coating. Some improvement was achieved with pretreated samples in which case the glass melt comes indirect contact avec le SiC. Light microscope images of pretreated and untreated TRISO-particles are shown in Fig. 3. Some particles are completely embedded in the glass matrix (Fig. 3a) while others floated on the glass surface and caused some fracturing (Fig.3b). All around the particles the reaction of the OPyC layer with dissolved oxygen in the glass melt or the oxide content of the melt caused the formation of gas bubbles of CO [4] developed, thus increasing the mechanical stress at the glass/particle interface during cooling (Fig. 3c).
Detailed SEM images of the glass/particle interface are given in Fig. 4, showing large gas bubbles around the TRISO-particle. Higher magnification shows no direct contact between the glass and the SiC (Fig. 4b). In case of direct contact between the glass melt and the SiC of pretreated particles, the SiC show only slow oxidation. Partial oxidation of SiC and SiO2 formation did not improve the adherence between the glass silica network and pretreated TRISO-particle surface. Fractures in the glass matrix and low coating capability of melted glass may facilitate exposition of TRISO-particles to environmental agents such as air or water humidity. Extended exposition (1-2h) of TRISO-particles to the glass melt had led to the complete oxidation of TRISO-coatings. The remaining bare fuel kernels settled down in bottom of the crucible.

**Fig. 4** SEM micrograph of a TRISO-particle immobilized in melted glass (a). Interface glass/TRISO-particle (b)

Vitrification by sintering: Because of difficulties encountered in experiments with melted glass due to high processing temperatures (1200-1300°C) under oxic conditions, we studied the possibility of using sintered glass for TRISO-particles immobilization. The sintered composite material is shown in Fig. 5. Unlike the melted glass, the sintered glass presents a homogenous morphology without fractures. A cross section through the composite shows good coating properties of the glass without macroscopic bubbles around the TRISO-particle. The cold pressing did not cause any fractures in the particles. Furthermore, the results obtained with inert (Fig. 6a) and heat-treated TRISO-particle (Fig. 6b) are similar, suggesting that no heat treatment is necessary to immobilize the particles in the sintered glass.

**Fig. 5** Sintered glass

**Fig. 6** SEM micrograph of triso particles embedded in sintered glass

SEM observation of the interface of the TRISO-particles with the sintered glass shows a direct glass coating of the OPyC (Fig. 7a) or the SiC (Fig. 7b), due to cold pressing. The sintered glass contains some remaining microporosity.

**Fig. 7:** SEM micrographs showing the good coating properties of the glass for the inert (a) and heat-treated (a) TRISO-particle.

Chemical durability tests with composite materials are ongoing: The results of glass corrosion experiments with composite materials show dissolution rates of glasses below 1 g.m$^{-2}$.d$^{-1}$. The dissolution rate of sintered glass is a little higher than that of melted glass. This can be attributed to underestimation of calculated geometric surface area due to the presence of microporosity in sintered glass. Nevertheless, both dissolution rates of composite products are similar or a little lower than those obtained for glasses with similar compositions [6] and indicate good chemical durability of melted and sintered composite materials. The corrosion rates were too low to allow for the detection of any uranium in the leaching solution. More work is necessary to identify its confinement properties with respect to corrosion of coated particles.

**Summary on vitrification**

The preliminary results described in this work show that confinement of TRISO-fuel particles in a glass matrix is possible. With the present data using an oxidizing melt process, immobilization of the particles in sintered glass appears to be more promising than in melted glass. Identified advantages of sintered glass are: 1) low processing
temperature in air that better preserves the TRISO-particles, 2) good coating properties, 3) no heat treatment of TRISO-particles is required prior to vitrification and 4) good chemical durability. The quality of sintered glass can still be improved to reduce the porosity by optimizing the sintering time, processing temperature and perhaps sintering under pressure and at temperature. Vitrification by melting is possible but requires high processing temperatures of about 1150 °C in inert atmosphere conditions to prevent rapid oxidation of TRISO-coatings and ultimately fuel kernels. Oxidation of the particle coating may release volatile radionuclides including $^{129}$I, $^{134}$,$^{135}$,$^{137}$Cs and maybe $^{36}$Cl. In an industrial vitrification plant it is expected that Cs can more easily be incorporated into the glass but this is much more difficult for $^{129}$I. Though vitrification of irradiated TRISO-particles was not tested it is expected that the sintered glass remains stable under high radiation doses. In fact, this glass is being used as additive for high-level waste vitrification in France (R7T7 nuclear waste glass). The R7T7 glass holds an initial specific activity of alpha emitters of 1.7TBq, a beta-gamma activity of 110TBq and a thermal load of 13.5 W per liter of glass. If similar activity loading and heat production is envisioned for coated particle loaded glass this suggests that each liter of our sintered composite glass can be used to immobilize $2.7 \times 10^5$ TRISO-particles (UOX fuel, burnup 19% FIMA, initial enrichment 10%, 3 years of decay, H. Werner – personal communication) corresponding to volume fraction of coated particles of about 16% and an average distance between the surfaces of two particles of 0.8 mm. Nevertheless, tests with real active material are necessary to confirm this argumentation.

**EMBEDDING IN SiC**

Silicon carbide (SiC) is a prevalent material for many technological applications because of its excellent mechanical, chemical and thermomechanical properties. Ceramic based on SiC is characterized by extreme hardness (9.5–9.75 Mohs), high thermal conductivity, relatively low thermal expansion and chemical durability. In general, SiC is not stable in oxidising environment, but the thermodynamic stable SiO$_2$-layer formed by oxidation largely passivates the surface and prevents further oxidation [7,8]. Owing to its favourable properties even at high temperatures, silicon carbide (SiC) is used as coating material for the HTR TRISO-fuel kernels. Therefore, SiC ceramics can be also considered as a long-term stable matrix for radioactive waste proposed for final disposal.

However, it is necessary to be careful at the selection of methods for ceramic fabrication. Conventional methods for SiC production, such as liquid sintering or hot pressing are not applicable when processing spent coated particle fuel. These methods hold the danger of damaging the particles and release fission products, either due to the high temperature (1800-2000°C for liquid sintering) or the high pressure applied.

The most suitable option for spent HTR fuel incorporation is the reaction-bonded silicon carbide. Reaction-bonded SiC (RBSiC) is produced by infiltration of Si/C-green bodies with molten Si. The SiC is thus formed out of the elements silicon (Si) and carbon (C) by the weakly exothermic reaction. The reaction needs about several minutes to complete and starts after the melting point of Si (1414°C) [9-13] The reaction conditions of 1600°C for 20 minutes in vacuum atmosphere as proposed by Paik et al. [14] were found suitable for the given application.

The advantage of RBSiC is the little or no shrinkage of the composite, so near-net shaped green bodies can be produced. The green body has to hold the necessary amount of pores for the infiltration process. Molten Si has the favourable features of low viscosity, high surface tension and wettability, ensuring the short infiltration times of a few minutes.

Therefore, the reaction zone is at the Si-C interface and the chemical reaction needs to be maintained by the diffusion of Si-atoms through the novel SiC into the carbon. The added SiC powder initialises heterogeneous nucleation of novel β-SiC on the original α-SiC grains. This deposition preferably takes place on fine original SiC particles with high surface area [15, 16]. Unreacted Si (usually around 2-12%) remains in the SiC as intergranular phase resulting in a non-porous body [17].

In order to maintain integrity of the coated particles, a mild processing method for the production of the composite material is required. Thence, the route envisaged in this report is the production of green bodies from well-dispersed aqueous SiC and graphite powder slips to which TRISO coated particles were added. These green bodies are subsequently infiltrated and reaction-bonded with molten silicon.

The production of dense and homogeneous green bodies depends on the following factors: interparticle potentials, particle size distribution, particle shape, solid loading, amount of dispersant and driving force. Inhomogeneities in the green bodies, such as carbon islands, should be avoided and the colloidal processing of ceramic powders facilitates this. The use of bimodal SiC mixtures increases the packing density and provides narrow pore size distributions. [18-22] In aqueous suspensions, SiC tends to oxidise at the surface, which might influence the infiltration and reaction-bonding process [7]. The usually applied procedure for slip casting occurs with the aid of plaster moulds. The mould dehumidifies the slip via capillary action. As the green bodies ought to be produced in the SiC crucibles utilized for reaction bonding, the water was largely removed by filtration.

Furthermore, the particles have a tendency to agglomerate by virtue of the prevailing van der Waals forces. In order to stabilise a suspension, this interaction
SiO$^-$ formation results in a negative $\zeta$-potential, a measure for the electrostatic repulsion forces between two particles. The superposition of the attractive and repulsive potential energies between two particles (DLVO-theory) results in formation of an energy barrier preventing particle agglomeration and ensuring a stable suspension when the $\zeta$-potential is higher than +/- 30 mV. Electrostatic stabilisation of SiC suspensions with low viscosities usually can be achieved at a pH 10-11.5. Basic SiC-slurries are in general strongly thixotropic, so the mixture should be continuously moved. [7] More problematic is the proper dispersion of carbon present in the slips. Homogeneous mixing with the SiC particles and segregation prevention during drying process must be assured. Carbon is hydrophobic, badly wettable and has high homoflocculation tendencies. [14, 9] Carbon does not react with water under normal conditions and not at all with alkaline solutions. However, the above for SiC described reaction with oxygen absorbed or in solution may occur and lead to $\text{CO}_2$ and high $\zeta$-potentials in highly alkaline solution. [23] Furthermore, addition of dispersants may yield stable suspensions by charging the particle surface and/or steric hindrance. Polyethyleneimine (PEI) is a commonly used dispersant for ceramic colloidal processing. In acid and weak basic region PEI is a positively charged polyelectrolyte and adsorption on the SiC surface might lead to charge reversal, the stabilisation takes place by electrosteric hindrance. [24-26]

Experimental approach to SiC embedding

Silicon powder, $\alpha$- Silicon carbide and Graphite flakes supplied by Alfa Aesar with purity of 99% and higher were used as initial materials. The powders were consequently mixed for 3 hours in the ball mill.

For the samples 1 and 2, the slip was produced by mixing the powders with NaOH solution (pH ~ 10 – 11). A third slip was prepared with 1%wt. PEI instead of NaOH (sample 3). Then the slip was mixed with of UO$_2$-TRISO coated particles. This mixture was subsequently filtered in a device specially designed for this purpose.

Sample 1 was produced from 2 g slip and 0.5 g coated particles. Sample 2 and 3, in contrast, contained about 1 g of coated particles for about the same amount of slip. Thereafter, the green body was dried in the desiccator at 95°C in a standard SiC crucible (Wacker Ceramics, inner diameter – 10 mm, outer diameter – 20 mm, height – 25 mm).

Silicon powder was added above the green compacts in the crucible. Then the samples were reaction bonded in the oven under vacuum (2 mbar). The program was as follows: heating with 400°C per hour to 1600°C, dwell for 0.5 hour at 1600°C and cool down to room temperature with 200°C per hour.

Results on SiC embedding

Several test samples with different coated particles loads and dispersing conditions were successfully fabricated by the slip casting / reaction bonding route. During fabrication it was observed that the slips in basic media (NaOH) are easily filterable, whereas the slips containing PEI are a more problematic. The macromolecular dispersant prevents the water removal. When PEI is present, the coated particles are more wettable.

A comparison of sample height of the green body and ceramic after reaction bonding does not reveal any valuable dimension changes. This shows, that near-net shape production is possible via reaction bonding.

Figure 8 shows the cut samples 2 and 3. Both show a quite homogeneous distribution of coated particles throughout the sample section. The coated particle load is lower in sample 3. It should be possible to
increase the coated particle load in samples with PEI. Sample 3 shows some greenish deposits after reaction bonding. This is most probably originating from the evaporation and decomposition of the dispersant. It was earlier assumed, that the heating process would already remove the organic polymer before the reaction bonding takes place. However a careful removal of the dispersant will be necessary and the procedure should be revised.

Figure 9 shows the optical microscopies of the samples 9 (a-c) and 3 (d-f). In both samples pores, excess carbon or metallic (Si) inclusions are present indicated by the dark dots. In the figures b, d and e bottom and wall parts of the crucible are shown for comparison. The bottom section with no reacted material is related to the rough green body bottom surface. In contrast to the crucible, the RBSiC contains more pores/inclusions. It is clearly visible that the dispersion with PEI results in compacts with less quality. The quality of Sample 2 is much better and can be produced more easily than the samples dispersed with PEI. Thus, from the present point of view, dispersion at pH 10-11 seems to be most appropriate.

The experiments conducted until now indicate that the following solid / coated particle loads are suitable for the production of RBSiC/coated particle compacts and probably can be even increased. A proof of this assumption is the presence of free Si in the ceramics.

Figure 9: Optical microscopies of sample 2 (a-c) and sample 3 (d-f)

The surprisingly high quality of the novel SiC implies that possibly an excess amount of pores is present for infiltration. This would make the usage of binder, also considering the problems evolving for further processing, unnecessary and the amount of carbon should be increased. The experiments conducted show that it is possible to produce high-quality ceramic composites of coated particles and silicon carbide via the reaction-bonding route.

Summary and conclusions on embedding in SiC

The experiments conducted show that it is possible to produce high-quality ceramic composites of coated particles and silicon carbide via the reaction-bonding route.
In general, there is a good junction between the coated particles and the matrix SiC, which originates from the reaction of the outer pyrocarbon layer with the liquid silicon. The coated particle content in the SiC matrix is about 40 vol.% and they distribute uniformly. This solid load with coated particles can probably be increased.

Dispersion in basic media (NaOH) delivers the better results for the production of SiC/coated particle composites. The optimum pH for dispersion and the amount of eventually added dispersant depends on particle size and isometry and should be determined for each system. The measurement of the pH dependency of the viscosities (should be minimum) and $\zeta$-potential of the solution for different dispersants and dispersant concentrations is an important prerequisite for the optimisation of the slip stability and thus the quality of the composite.

As the experiments performed shall only give a first insight how SiC/ coated particle-compacts can be produced, further examinations and possibly adaptations of the chosen parameters are necessary.

Basic investigations of the mechanical stability are still running. First results indicate high stability. However the mechanically stability could probably increased by reducing the amount of residual Si, if necessary. However further research needs to be carried out in order with respect to mechanical stability and water permeability.

Very interesting results may be obtained when the experiments are performed with dummy kernels without the outer PyC layer. The coated particles may be loose there outer pyrocarbon layer during the isolation process from the matrix graphite. Therefore, it is of huge importance if this is of influence for the ceramic composite formed.

One disadvantage is the sintering temperature of about 1600°C, which is identical with the accepted temperature limit during reactor operation. The feasibility of lower sintering temperatures just above the melting temperature of Si (1400°C) should be tested.

A last step will be the development a procedure, which is suitable for a large-scale application. This should provide a reliable option for the final disposal of HTR waste.

**OVERALL CONCLUSIONS**

One concept for the final disposal of HTR fuel is to remove the graphite for a strong volume reduction and then to encapsulate the coated particles in a stable matrix. The incorporation of TRISO coated particles into a stable matrix may be employed to decrease the risk of radionuclide release from the final repository: low porosity, high chemical and radiation stability, mechanical and thermal properties, providing reliable isolation from the biosphere on the geological time scale.

The preliminary results show that confinement of TRISO particles in a glass or in a SiC matrix is possible. With present data, immobilization of the particles in sintered glass appears to be more promising than in melted glasses. Glass matrix is already a reference for conditioning fission products coming from reprocessing of used nuclear fuel and offers unique performances of stability and durability in long term. Embedding SiC delivers high ceramic composites of coated particles and silicon carbide via the reaction bonding route. First results indicate high stability. The sintering temperature: 1600°C is identical with the accepted temperature limit during reactor operation. A suitable procedure will be developed for an industrial application. The long term behavior of the encapsulated particles will be compared to the behavior of vitrified LWR waste in same disposal conditions.
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