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Document title

First comparison of the leachability behaviour of SiC and ZrC powder and kernels

Executive summary

At present, spent HTR fuel elements are considered for direct disposal in deep geological formations. From a chemical point of view, direct disposal of spent HTR fuel is justified by some favourable characteristics of HTR fuel elements, in particular the presence of chemically resistant coating layers around the radioactive fuel kernels such as SiC or the envisaged alternative ZrC which are further embedded in a highly stable graphitic matrix.
Recently, research has made dummy kernels with an external carbide coating, lacking the outer carbon layer, available for leachability studies.
In this study the chemical resistance of SiC and ZrC, both as powders and in the form of coating layer, is determined under repository conditions such as salt domes, granite-based repositories and clay formations.
Lifetimes between 1E3 and 1E4 years have been measured depending on the kind of repository and temperature. Depending on leachant type and temperature, either ZrC or SiC is to be preferred in terms of stability under contact with the leachant.
Results will be used for development of a model describing the disposal behaviour of HTR fuel elements.

Revisions

Rev.	Date	Short description	Author	WP Leader	SP Leader	Coordinator
00	14/02/2007	First issue	M.J. den Exter NRG	Name, Organisation *Signature*	Name, Organisation *Signature*	Name, Organisation *Signature*
01	01/03/2007	Second Issue		J. Fachinger FZJ		

First comparison of the leachability behaviour of SiC and ZrC powder and kernels

1.1 Objective

An open fuel cycle with direct disposal of conditioned or non-conditioned fuel elements is one of the back end options for spent HTR fuel elements as proposed in the EC. In order to develop a realistic descriptive model for the long term behaviour of spent HTR fuel in aqueous phases of host rock systems in terms of possible release of radionuclides, the behaviour of the fuel kernel and all subsequent coating layers under repository conditions need to be understood.
The carbide coating serves as a barrier for immobilising the fission products in HTR fuel. After ingress of naturally occurring fluids in the surrounding graphite through pores or damaged parts, the carbide layer is subjected to corrosion. The corrosion velocity of this layer is one of the most important parameters determining radionuclide release since it serves as a barrier to trap the formed fission products.
In recent years, zirconium carbide has come to fore as an alternative for the existing silicon carbide coating. Silicon carbide can form unwanted phases with fission products like silver, altering the integrity of the layer.
Data with respect to corrosion velocities of zirconium carbide is lacking and consequently, comparison between both carbides from a disposal point of view cannot be made. This report describes first results from corrosion studies, addressing both carbide materials.

The envisaged fuel elements for a HTR are shown in Figure 1. Coated fuel containing particles, consisting of several layered materials are distributed in graphite pebbles. The existing coated particles have an internal SiC layer that serves as fission product barrier. In Figure 1, the different coatings are shown.

The external pyrocarbon layer (PyC) present on existing coated particles prevent corrosion studies with respect to the SiC (or ZrC) layer since contact of an intact pyrocarbon coating prevents/limits water ingress and therefore contact of natural existing liquids with the carbide layer. In principle, the outer pyrocarbon coating may be removed by oxidation at elevated temperatures but this may change the state of the coating, e.g. by formation of silicon (or zirconium) oxide or oxicarbides. The formation of such reaction products will influence the corrosion velocity of the carbide layer.
Therefore, the need exists for coated particles where the external pyrocarbon coating has not been applied.

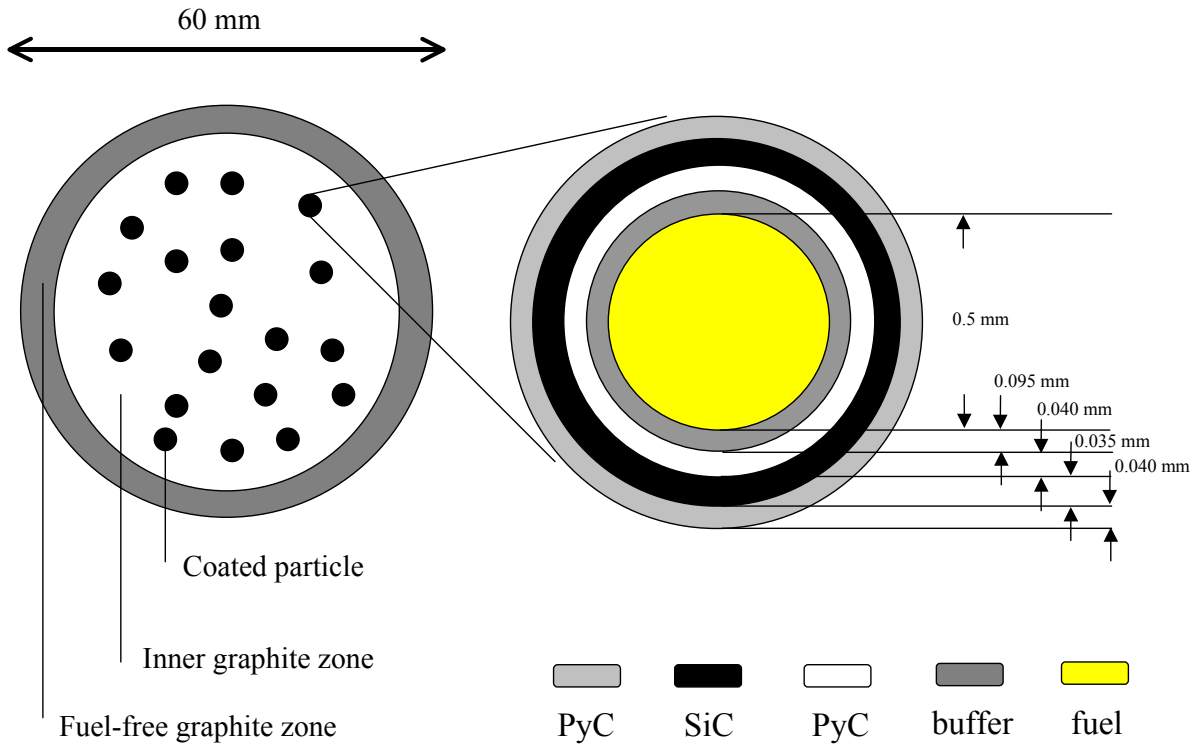


Figure 1: Pebbles (left) and fuel kernels (right) showing the subsequent layer materials

In recent years, novel coated particles have been produced. By interrupting the developed coating process, particles have become available lacking the outer pyrocarbon coating. This allows a thorough investigation of the corrosion resistance of the carbide layer and more realistic corrosion rates can now be measured, refining modelling data and improving the descriptive model for HTR fuel disposal behaviour.

1.2 Materials

1.2.1 Leachant specifications

Simulants for clay porewater and Q-brine were prepared by dissolving accurately weighted amounts of salts in demineralized water (>18 MΩ). The simulants were stored in PE vessels. Any contact with glass or Si/Zr-containing materials was avoided.

For clay porewater the following salts were used (mg/l given within the brackets): $MgSO_4$ (12.0), KCl (20.0), Na_2SO_4 (1.50), NaF (8.0), $NaHCO_3$ (1250), NaCl (44.0) saturated in $CaCO_3$ and filtered over a 0.45 µm cellulosenitrate filter (Schleicher&Sluell). Density: 1.0115 g/cm^3.
For Q-brine the following salts were used (g/l in brackets): NaCl (350), $CaCl_2.H_2O$ (3.12), Na_2SO_4 (3.04), K_2SO_4 (3.2) and $MgSO_4.7H_2O$ (2.52). Density: 1.2134 g/cm3. For Q-brine experiments at 90 °C, additional NaCl (36.0 g) and $CaSO_4.2H_2O$ (7.2 g) was added in order to keep the solution saturated in NaCl and $CaSO_4$.
For granite water, the demineralised water was used. Density: 1.0060 g/cm^3.

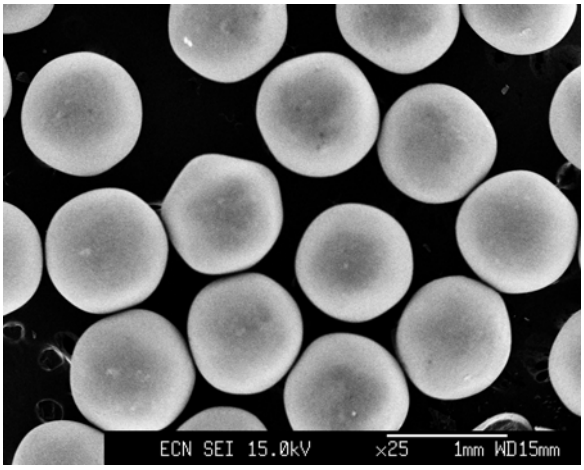
1.2.2 Powder and coated particle specifications/characterisation

The used carbide powders have the following specifications:

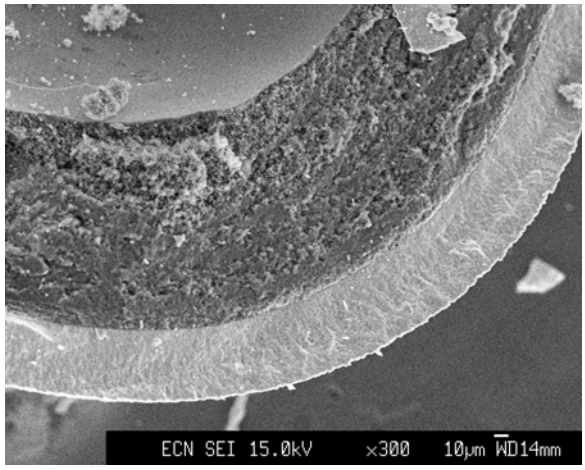
- Beta-SiC: Alfa-Aesar, 99.8% (metals basis), lot nr. J28G25, 1 micron particles $A_{spec.}$ = 12.91 m^2/gram
- ZrC: Alfa-Aesar, 99.5% (metals basis excluding Hf), Hf < 200 ppm, lot nr. I20P40 $A_{spec.}$ = 0.43 m^2/gram

The coated particles provided for corrosion studies have been prepared at CEA. The fuel section of both type of particles contains ZrO_2-Y_2O_3 from TOSOH. The SiC coated particles (prepared on 04/04/2002, amount: 500 gram) are coded: ZPDSIC 17. The ZrC coated particles (amount: 5 gram) have been sent to NRG on 13/12/2005 and are coded: DTEN/S3ME/LMIC, ZRC lot: 2. It is mentioned in the accompanying letter that these particles are from first test results and do not have to meet the exact requirements for future specifications like the exact stochiometry.

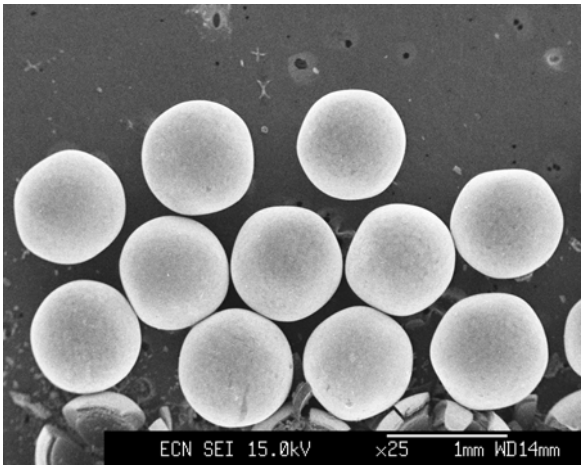
In Figure 2, SEM-images of an overview and cross-section are shown of both types of coated particles (as-received):

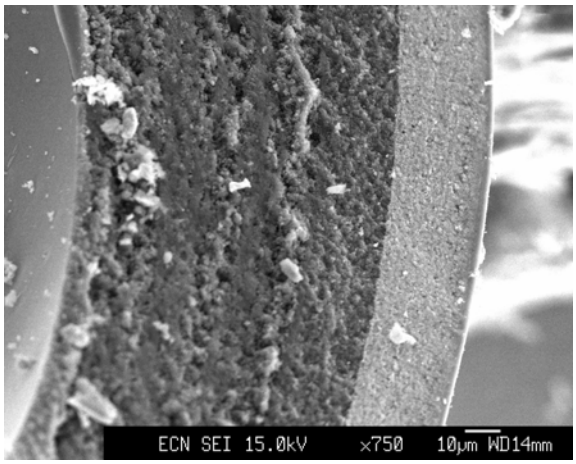


SiC overview



SiC cross-section





ZrC overview ZrC cross-section

Figure 2: SEM images of SiC- and ZrC-coated particles

As can be seen from the overview-images of both particle type, the particles are near (but not fully) spherical. Therefore, dimensional measurements have been carried out. In Figure 3, the results of measurements of the particle diameters of both coated particle types are presented. Here, light microscopy-images have been processed with Image Pro Plus software. The in the graph presented data are mean diameters ((maximum diameter + minimum diameter)/2) per counted particle. Averaged over about 100 counted particles per type, the following diameters are found:

- SiC average mean diameter: 0.98 ± 0.04 mm, maximum: 1.08 mm, minimum 0.77 mm
  average max. diameter : 1.00 ± 0.04 mm, average min. diameter : 0.96 ± 0.04 mm
- ZrC average mean diameter: 0.96 ± 0.03 mm, minimum: 0.86 mm, maximum: 1.03 mm
  average max. diameter : 0.98 ± 0.03 mm, average min. diameter : 0.94 ± 0.03 mm

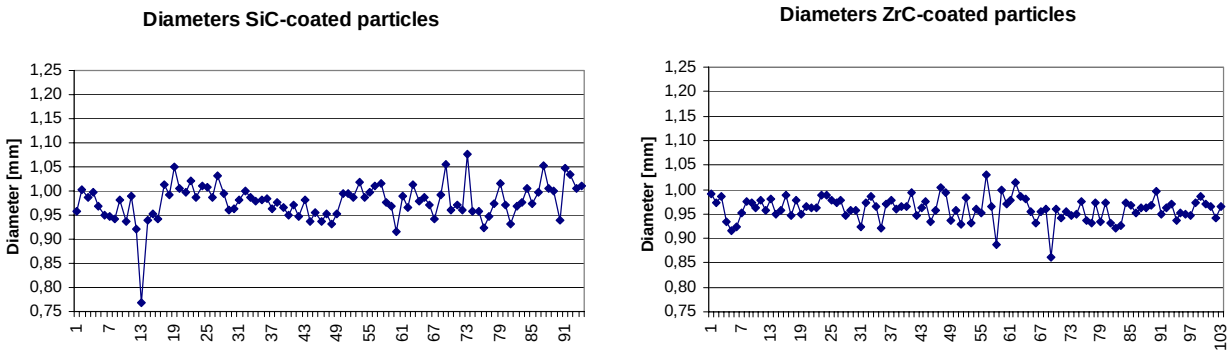


Figure 3: mean diameter of SiC- and ZrC-coated particles

Both types of particles have similar averaged deviations in the measured mean diameter although the ZrC-coated particles are slightly smaller. The spreading is shown in Figure 4.

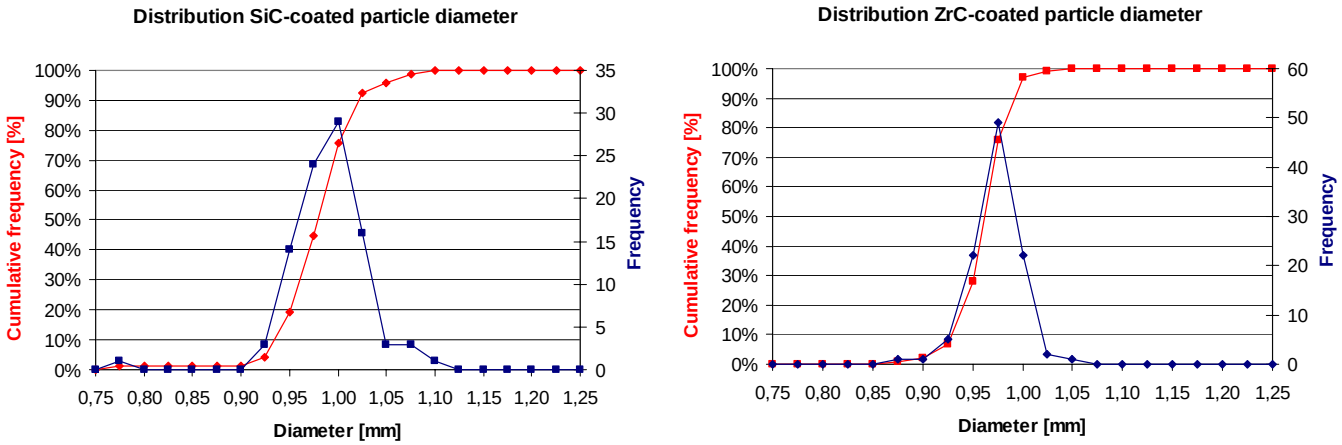


Figure 4: Particle diameter distribution

Because of the fact that breaking of the particles for obtaining parts of the carbide-layer for dimensional measurements results in fragments of different sizes with different orientations, it is not possible to use a similar procedure as for the overall particle size measurement. Therefore, carbide layer thickness measurements have been performed, based on a few SEM-images only where the orientation of the fragments is sufficient for an estimate. Based on these measurements, the following estimated layer thickness is found:

- SiC: ~ 45 micrometer
- ZrC: ~ 30 micrometer

In order to investigate the roundness of the particles (sphericity), the averaged difference (ADif) between the measured maximum diameter and the minimum diameter per particle has been calculated and the maximum (Dif_{max}) and minimum (Dif_{min}) difference of the population of measured amount of particles:

- SiC: ADif = 0.043 ± 0.017 mm, Dif_{max} = 0.118 mm, Dif_{min} = 0.020 mm
- ZrC: ADif = 0.042 ± 0.014 mm, Dif_{max} = 0.081 mm, Dif_{min} = 0.019 mm

From these calculations, it appears that both particle types have a similar roundness although for the SiC-coated particles Dif_{max} is slightly higher. It should however be kept in mind that one particle in the measured particle population that may deviate, will change the values for Dif_{max} and Dif_{min}. Accordingly, the averaged values are leading. From these observations, both particle types do not differ.

X-ray diffraction measurements were carried out on a Bruker D8-Advance diffractometer for a monolayer of coated particles (see Figure 5). The measuring time amounted to 16 hours for ZrC-coated particles and 10 hours for SiC-coated particles (step size 0.050 °). The results are presented in Figure 3. Disregarding some visible reflections of the graphite part and zirconium

oxide centre part, both diffractograms reflect the proper phase. The lattice parameters determined after refinement (Si-NIST as standard, Pawley method) are:

- SiC: a-axis = 4.36557(14) Å, cell volume = 83.1999(81) $Å^3$
- ZrC: a-axis = 4.70753(20) Å, cell volume = 104.323(13) $Å^3$

The SiC-coating consists of stoechiometrical cubic SiC. For the ZrC-coating (cubic), the stoechiometry may vary from $ZrC_{0.70}$ to ZrC and cannot be determined more accurately with the prevailing method. Since the carbide is extremely poorly dissolvable, attempts will be undertaken to use Laser-Ablasion combined with ICP-MS for elemental analysis.

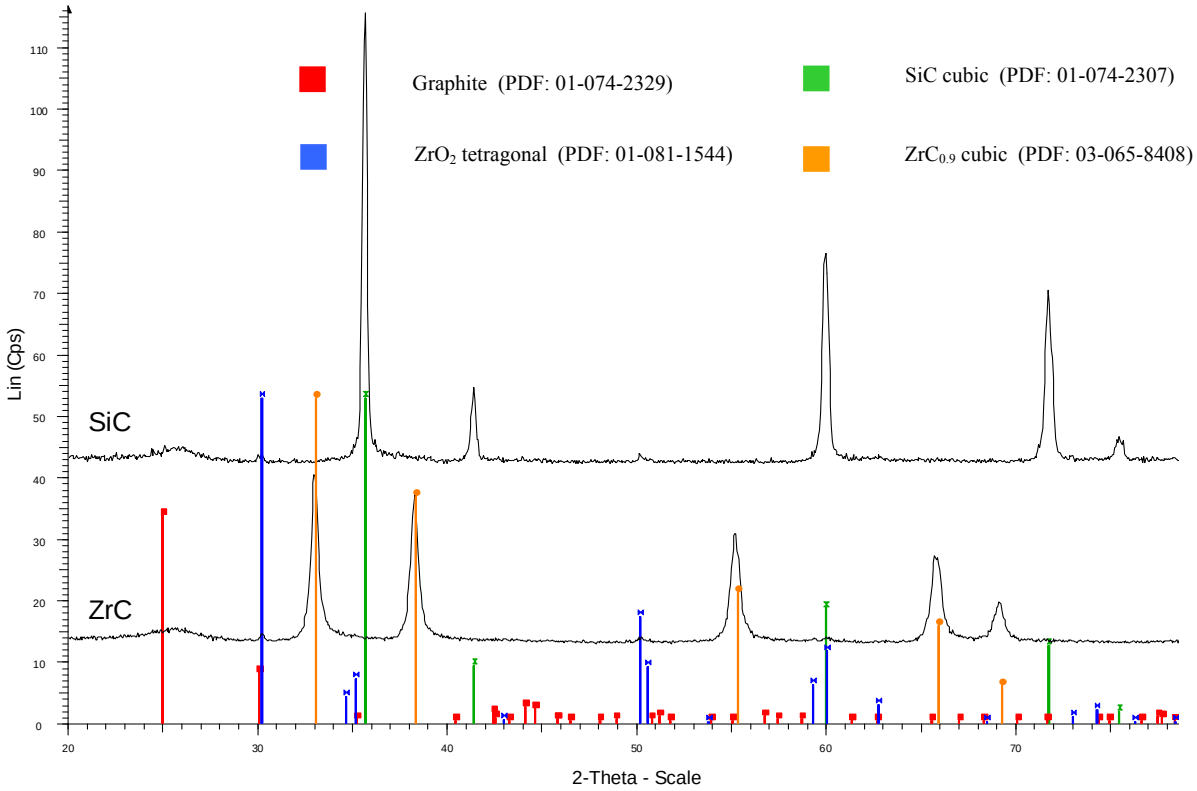


Figure 5: X-ray diffraction patterns of ZrC and SiC

Presuming perfect spherical particles, a core of fully Y-stabilized zirconia with a density amounting to 95% of the theoretical density and PyC- and carbide-coatings with an uniform layer thickness of the specifications as shown in Figure 1, the following data applies:

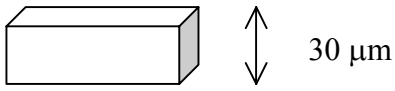
Table 1: specifications of spherical ZrC and SiC-coated particles

	SiC	ZrC
Weight of 1 particle (gram)	8.41 E-4	1.09 E-3
Amount of particles in 1 gram	1189	918
Surface area of 1 particle (cm^2)	2.22 E-2	2.22 E-2
Surface area of 1 gram particles (cm^2)	2.64 E1	2.03 E1

1.3 Calculation procedure of lifetimes

The following assumptions have been made with respect to calculating lifetimes of the SiC and ZrC layer from corrosion data obtained for the powder samples:

- uniform leaching rate without pit corrosion
- stoechiometry (Si=C, Zr=C)
- minimum density SiC = 3.18 g/cc (HTR-F specifications*), TD = 3.21 g/cc
  minimum density ZrC = 6.67 g/cc*, TD = 6.73 g/cc
- deviation in lifetime = 5% (based on detection deviation of ICP-AES)
- SiC/ZrC layer thickness: 30 µm



* the minimum density is defined as 99.07 % of the theoretical density (TD); accordingly, for ZrC the same percentage has been chosen. XRD-analysis confirms an X-ray density of 6.66 g/cc.

The volume of a SiC or ZrC layer of 30 micron thickness and 1 m^2 surface area amounts to 3.1 E^{-5} m^3. The SiC and ZrC content within this volume (based upon the minimal density as formulated in HTR-F) is 95.4 gram and 200.01 gram, respectively. The lifetime of the layer has been calculated presuming a uniform leaching rate over the specified surface area which is constant over the period of the experiment. Leaching rates, normalised to the specific surface area of the material, can then be recalculated to a maximum lifetime expressed in years of according to the following equations:

- lifetime SiC (years) = (95.4) / leach rate ($g/m^2/d$) / 365
- lifetime ZrC (years) = (200.01) / leach rate ($g/m^2/d$) / 365

The same method is used for the coated particles. The surface area used is based on spherical particles (see data Table 1).

1.4 Leaching procedure and equipment

1.4.1 Static leach experiments

A: SiC and ZrC powder and coated particles

Static leach experiments are carried out using the following method:

Static corrosion experiments on accurately weighted amounts of SiC powder, ZrC powder and coated particles were performed in PTFE containers (Nalgene). The containers were pretreated as described in the ASTM-C 1220-92 standard test. Each container was weighed accurately before and after the leaching period so as to ensure that evaporation of the leachants did not occur. After the preset contact time period, the powder was separated from the leachate, accomplished by filtering over a 0.45 µm cellulose nitrate filter (Schleicher&Sluell). The Si or Zr content in the aqueous phase was determined by ICP-AES analysis. The Si and Zr content of the leachants were measured also and serve as a blanc correction on the ICP-AES data.

Then, the Nalgene vessels were treated ultrasonically for 5 minutes with a known amount of diluted nitric acid for additional ICP-AES measurements so as to check if the vessel walls contain leached material that has reprecipitated e.g. as colloidal oxidic particles.
In order to establish a suitable concentration of nitric acid, capable of selectively dissolving colloidal zirconia particles without dissolving possible ZrC-particles that remained adhered at the vessel walls after filtration, the following experiment was conducted:

- 0.01 gram of a 20wt% Nyacol colloidal sol of zirconia (particle size ~5 nm) was dissolved in 15 gram of diluted nitric acid varying in molarity between 0.16 and 5. The zirconium content was determined using ICP-AES analysis after filtration over a 0.45 micron filter;
- The similar procedure was carried out but 0.01 gram of ZrC powder was added. The amount of ZrC used would increase the zirconium concentration in the liquid phase for about a factor 6 if the ZrC would dissolve.

In Figure 6, the results of the analyses are presented in terms of the percentage of the measured zirconium concentration to the theoretical expected concentration according to the weight amounts of sol and amount of diluted nitric acid versus the used nitric acid concentration. From the figure, it can be seen that the measured concentration for the dissolved zirconia sol matches the expected concentration (within accuracy of the analysis) over the entire molarity range. The result for the combined experiment (sol plus ZrC powder) is similar, proving that the ZrC is not dissolving and the method selectively dissolves the colloidal zirconia particles only.

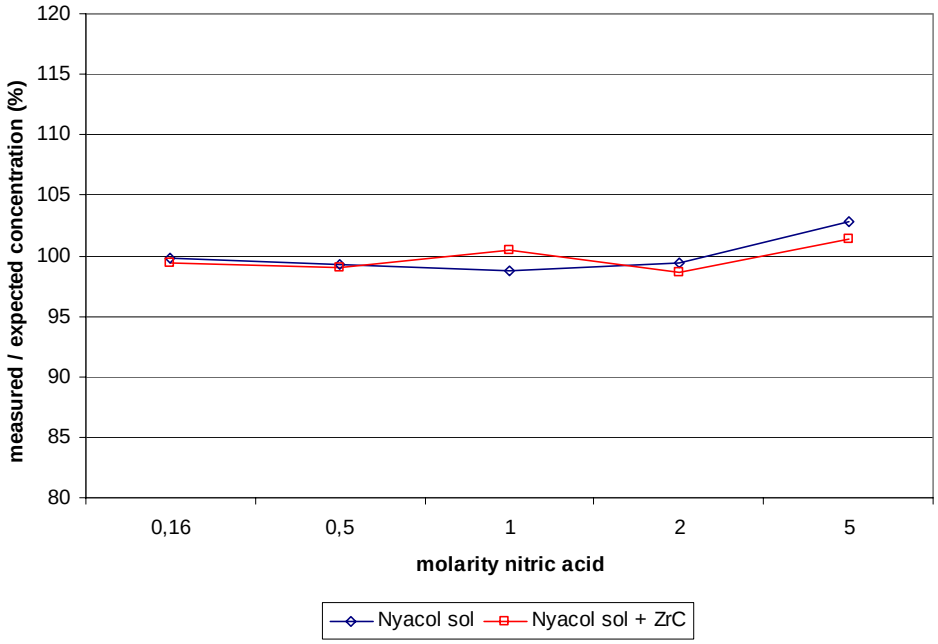


Figure 6: Selectivity in dissolving ZrO_2 sol particles and ZrC versus molarity of nitric acid

From the data it was decided to wash the vessels directly after removal of the leachate from the vessel with a weighted amount of 1.0 molar nitric acid and wash the particles similarly with a 0.16 molar nitric acid solutionwith known weight to check if colloidal particles may be adhered to the powder or coated particles. Both washing solutions were filtered over a 0.45 micron filter prior to the ICP-AES analyses.

The amount of leachant used was weighed, based on the required volume and its density. For the SiC powder (BET specific surface area: 12.908 m^2/gram), 10 ml leachant per 0.05 gram of powder was applied (surface-to-volume ratio S/V = 64540 m^{-1}), similar to the ratio used in the HTR-N/N1 programme. Accordingly, 10 ml leachant per 0.05 gram was applied for all experiments with ZrC powder. Based on its specific surface area (BET: 0.4301 m^2/gram), this results in a S/V = 2151.

Experiments under oxidizing conditions have been carried out by weighing the samples and leachants in air and closure of the vessels in air. For the corrosion experiments under inert/reducing atmosphere, all materials and leachants were posted into the glove box and weighed there. The glove box contains 2 ppm of oxygen as a maximum. In order to maintain reducing conditions, NaS was added to the leachants in an amount of 25.73 ppm, 25.42 ppm and 29.50 ppm for granite water, Q-brine and clay pore water, respectively.

For weighing the powders, an antistatic ring was used, connected to the balance, since both ZrC and SiC powders tend to be static.

A special oven has been designed that can be placed inside an argon filled glove box for carrying out corrosion experiments under inert/reducing atmosphere. The oven has dimensions that allow moving inside and outside the box through the lock for maintenance. The oven controller is compact and smaller than the oven and is placed inside the glove box as well. The oven is isolated sufficiently for keeping the temperature of the argon atmosphere inside the box below 30°C. The oven is suitable for containing 15 Nalgene vessels at the same time. In Figure 7 and 8, the design of the oven and the glove box is shown.

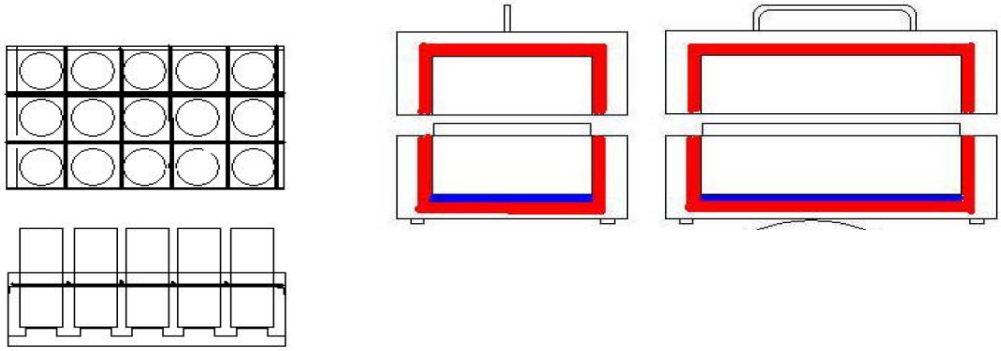


Figure 7: Design of the oven for corrosion studies under inert atmosphere

Figure 8: Argon-filled glove box for corrosion studies under inert atmosphere

B: coated particles

For all corrosion experiments with coated particles (the particles have a very low geometrical surface area), a S/V of 2000 (m^{-1}) was applied. This allows all particles to be well below the liquid surface so that all particles are properly into contact with the leachant. The procedure is similar to the one applied for the powder samples.

1.4.2 Long-term leaching

Little is known with respect to the corrosion mechanism. When converting measured corrosion rates to lifetimes of the coating layer, the presumption is made that uniform corrosion takes place (see section on lifetime calculations). This, however, is an uncertainty. It may well be the case that instead of uniform corrosion over the entire exposed surface area into contact with the leachant, pit-corrosion occurs where the exposed surface area is corroded on distinct places, causing the formation of pinholes. This would decrease the lifetime of the coating layer. Since the carbide layers are extremely resistant against corrosion, short-term corrosion experiments corrode insufficient material to be able to see surface changes. For this reason, long-term dynamic experiments have been set up (exposure time 1 year). After the time of exposure, the surface of the particles will be thoroughly investigated to see if pit-corrosion occurs. For this, friction damage to the surface of the particles has to be prevented. During exposure, the particles must remain at place without rubbing against each other because of the leachant flow.

Dynamic long-term leach experiments have been started (starting date December 2005) as follows: SiC-coated particles are placed in a closed packing order in special designed acetal columns. In Figure 9, the design of the columns is shown. Acetal is used since it is fully free of silicon or zirconium.

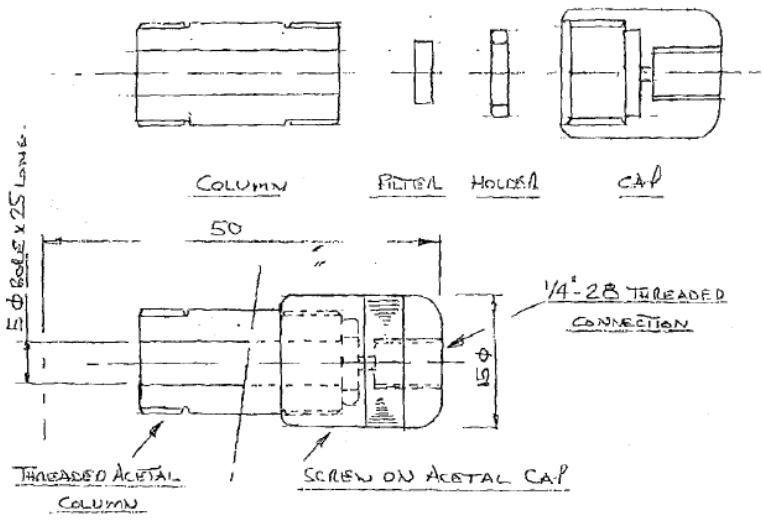


Figure 9: Design of vessels for long-term leach experiments

The columns serve to keep the coated particles at place without movement of the particles caused by the leachant flow, therefore minimising friction and damage of the coating surface. In Figure 10, the set-up including the pump system is shown. The pump is specially designed for minimising pulsation behaviour, accomplished by a relatively flat rotation wheel with a small curving radius. The pump velocity amounts to 1.0 ml/min. Each vessel is connected with tubing to a second vessel, which is used for filling the system. This way, several experiments can be conducted simultaneously.

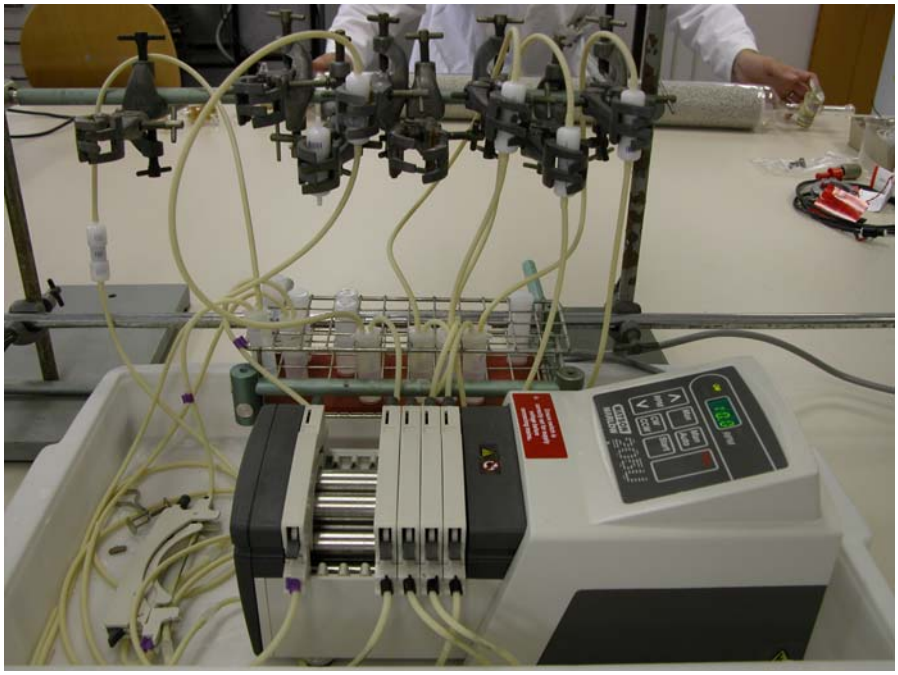


Figure 10: Long-term corrosion set-up

The amount of coated particles is ca. 0.86 gram per vessel. Because of the volume of connecting tubing, the amount of leachant volume is ~12.5 ml per vessel, resulting in a S/V= 360. The experiments with SiC-coated particles (25°C, all three leachant types) will be stopped at the end of 2006 when the leachants will be investigated for their corrosion product content and the surface of the particles will be examined. Beneficial is that at the same time, data is gathered for corrosion rates under flow conditions. Experiments with ZrC-coated particles can only be started when sufficient material becomes available. Since three pump-positions are empty, these experiments can start directly after supplying material.

1.5 Corrosion results

1.5.1 Comparison corrosion rates of SiC and ZrC powder under reducing conditions

In Figure 11 and 12, the leach rates and calculated lifetimes (see section 1.3 for the calculation method) for SiC and ZrC powder under reducing conditions are shown. Detailed values can be found in annex 1.

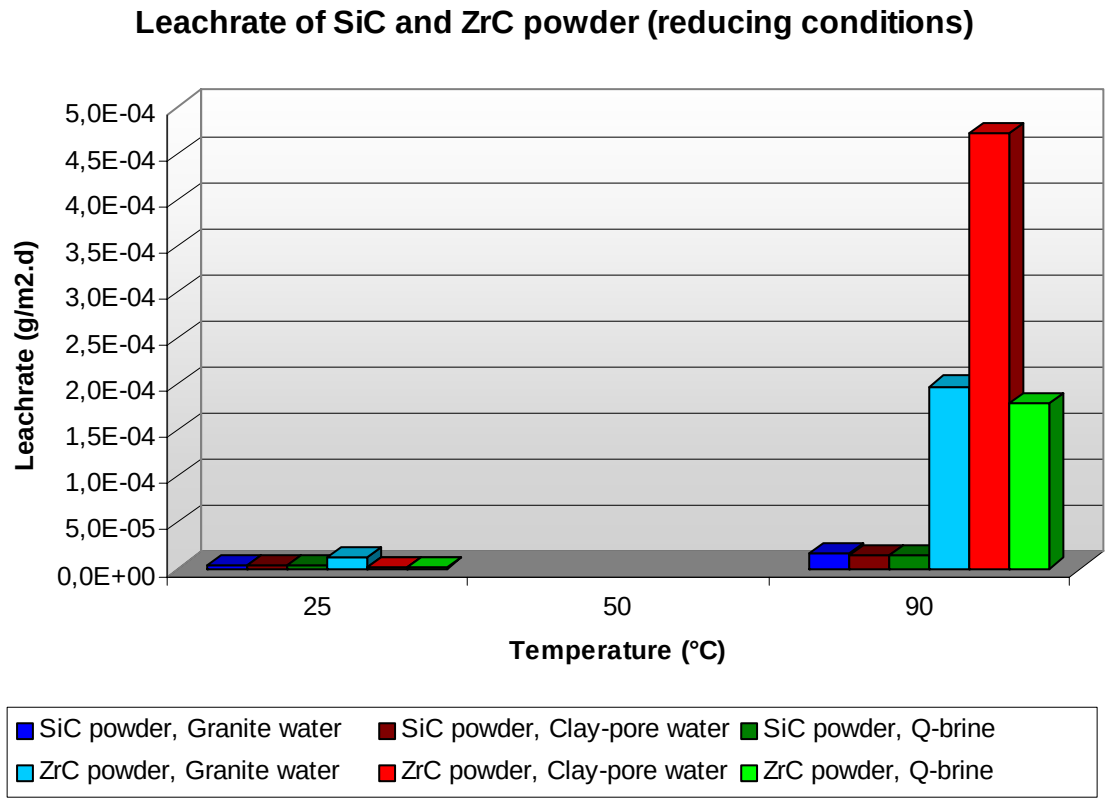


Figure 11: Leach rates of ZrC and SiC powder

As can be seen from Figure 11, leach rates, as expected, increase upon a temperature increase for both types of carbides. Striking is that for the zirconium carbide, leach rates are a bit smaller then for the silicon carbide at 25°C, except in granite water, while the increase in corrosion rate upon increasing the temperature is factors higher. This reduces the lifetime of ZrC to a high extend. At 25°C, the calculated lifetimes for SiC amount to ~10.000 years while for ZrC powder, these values are about a factor 10 higher, depending on the leachant type. At 90°C, the lifetime of SiC drops to about 20% of the lifetime determined at 25°C (similar

reduction for all leachant types) while for ZrC lifetime values drop to 1/350 of the values at 25°C for clay-pore water and Q-brine and 1/17 of the value at 25°C for granite water. Data for corrosion experiments at 50°C will be available before the end of 2006.

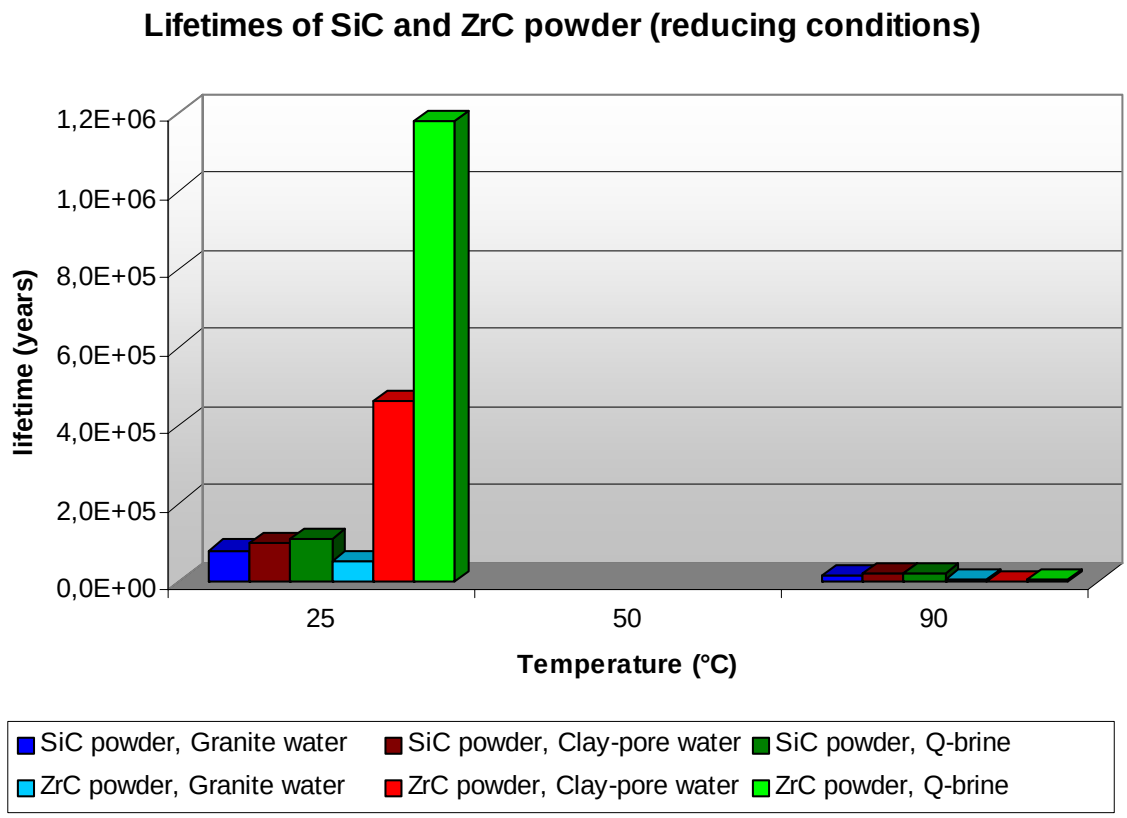


Figure 12: Calculated lifetimes for ZrC and SiC powder

So, under reducing conditions, the ZrC powder is more corrosion resistant at low temperatures but at higher temperatures, SiC powder proves to be more stable.

1.5.2 Comparison corrosion rates of SiC-coated particles and SiC powder under oxidizing conditions

In Figure 13 and 14, the measured leach rates and calculated lifetimes of both SiC-coated particles and SiC powder (reaction-sintered) under oxidizing conditions are shown. The data for the SiC powder has been taken from the 5th Framework HTR-N/N1 project

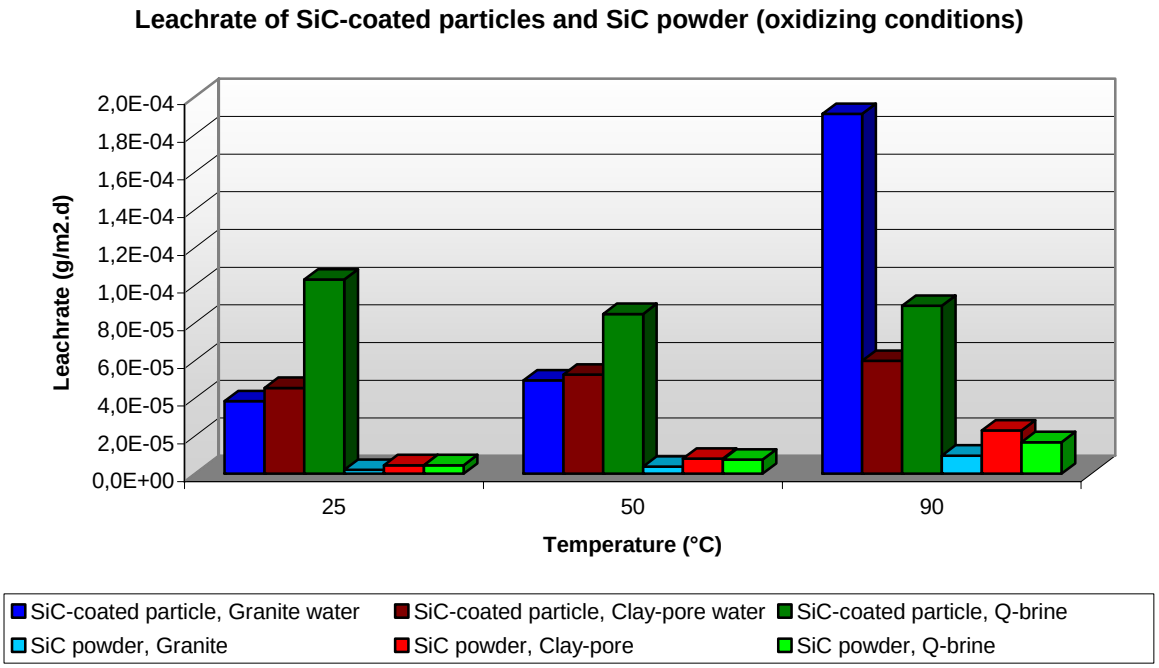


Figure 13: Leach rates of SiC-coated particles and SiC powder

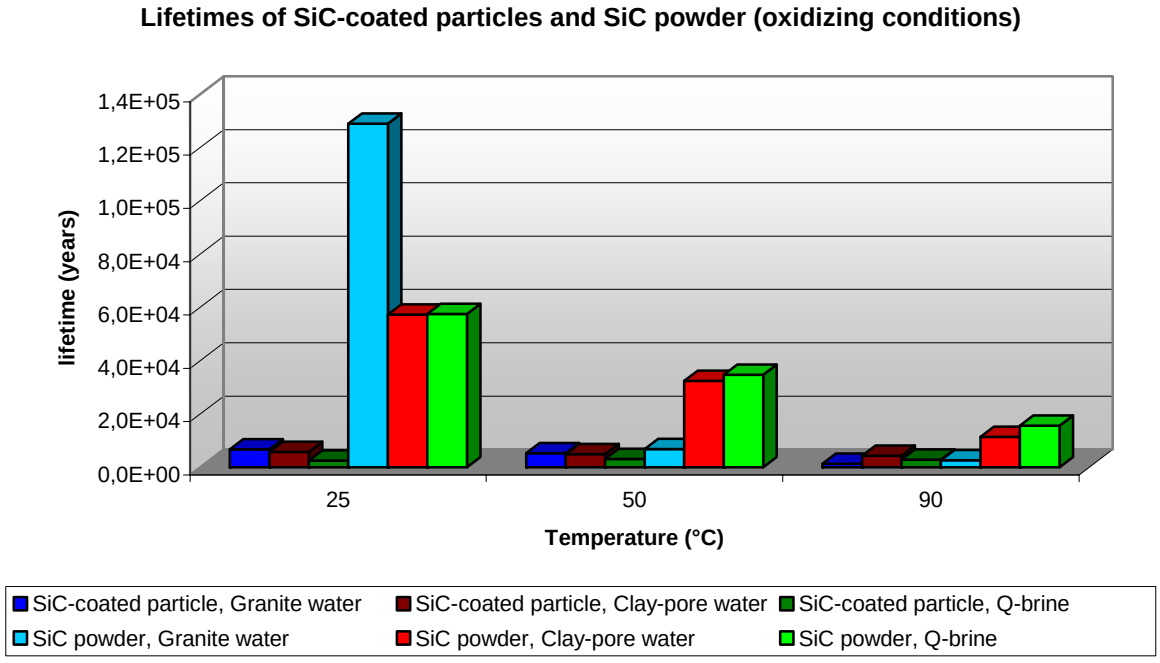


Figure 14: Lifetimes of SiC-coated particles and SiC powder

The SiC powder investigated is reaction-sintered powder. The SiC-coating of the particles has been produced by chemical vapour depositio (CVD).

For both type of materials, the leach rates decrease as expected at higher temperatures. The measured leachtrates for the SiC powder, however, are one order of magnitude lower then for the coated particle. The leach rates are normalized to the specific surface area. For the coated particle, the specific (accessible) surface area is unknown. Therefore, for the particles the geometrical surface area has been used in the calculations. When the actual surface area would be larger then the geometrical surface area, which can be expected, the calculated leach rates for these particles would decrease. For obtaining similar values for both materials however, the actual surface area of the coated particle must be 10-20 times higher then the geometrical surface area. From SEM observations, this does not seem to be very realistic for a rather smooth surface area is visible.

In the HTR-N/N1 project it was found that, although data is minimal because few material was available at the time, CVD produced SiC with known specific surface area shows lifetimes of 1-5 E3 years under oxidizing conditions (see annex 2), similar values as the SiC-coated particles. Apparently, CVD-produced SiC is less corrosion resistant then the reaction-sintered material. Although speculative, structural differences like microporosity, defects in the lattice-structure or trace amounts of impurities may change the chemical interaction between material and leachant constituents.

1.5.3 First leach rate data for ZrC powder under oxidizing conditions

In Figure 15, first results are presented for measured leach rates for ZrC powder under oxidizing conditions, based on the Zr-content of the leachates only.

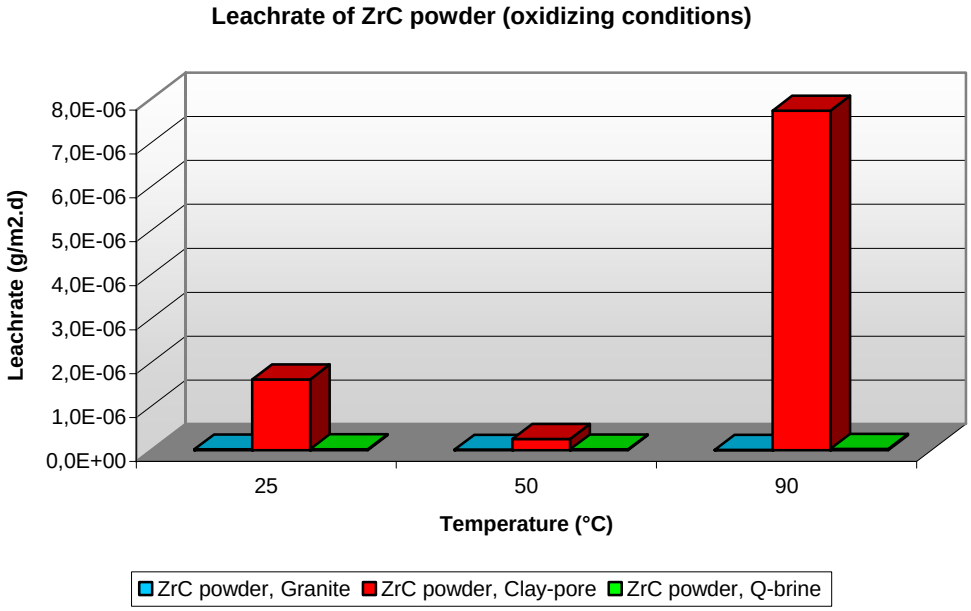


Figure 15: Leach rates for ZrC powder under oxidizing conditions

Because of an error, the amount of leached material present on the vessel walls after the contact period for these experiments has not been measured. Therefore, these corrosion experiments will be repeated before the end of 2006. However, the data calculated from the content of the leachates (see annex 1) is presented here anyway. Since in all conducted experiments with the different materials, it is found that up to 20% of the leached silicon or zirconium is present at the vessel walls, the presented data are only indicative. However, when taking this amount as an estimate into account, still extremely low leach rates (1E-8 g/m2.d) are found, much lower then for SiC powder under similar atmospheric conditions. It may very well be the case that formation of a thin zirconium dioxide-layer under oxidic conditions is preventing corrosion. In case of silicon carbide, silicium dioxide may be formed, which is less stable then its zirconium-counterpart. Repeating the corrosion experiments with analysis of the vessel walls included in the procedure will provide correct leach rate data.
It is striking that for clay-pore water, much higher leach rates are found, an order of 2 in magnitude higher. An explanation has not been found yet but likely constituents in the clay-pore water disturb the alteration of the external surface of the carbide, e.g. prevent formation of a closed oxide-layer. Execution of a new set of corrosion experiments shall reveal if this phenomenon is reproducible.

1.6 Preliminary conclusions

Although not all corrosion experiments are finished and some experiments will be repeated, first leach rates have been measured for SiC-coated particles and SiC/ZrC powder. From the obtained data, lifetimes have been calculated of 1E3 to 1E4 years for a 30 micron thick layer, provided that uniform corrosion takes place. Long-term leaching results may provide more inside in the corrosion mechanism.
Under reducing conditions, at low temperatures, lower leach rates for the ZrC powder are found then for SiC powder but at higher temperatures, the opposite is found.

Annex 1: Leach rates and lifetimes calculated from ICP-AES analysis results (corrected for blancs)

Temp. (°C)	Leachant	Days of exposure	Atmosphere	Status	Leach rate (g/m2.d)	Lifetime (years)	Leach rate (g/m2.d)	Lifetime (years)
					(based on leachate only)		(based on total analysis)	
					SiC powder			
25	Granite	80	Ar/NaS	finished	3.23E-6	8.09E4	3.40E-6	7.70E4
25	Clay-pore	80	Ar/NaS	finished	2.62E-6	9.96E4	2.75E-6	9.52E4
25	Q-brine	80	Ar/NaS	finished	2.39E-6	1.09E5	3.05E-6	8.58E4
50	Granite	80	Ar/NaS	running				
50	Clay-pore	80	Ar/NaS	running				
50	Q-brine	80	Ar/NaS	running				
90	Granite	80	Ar/NaS	finished	1.55E-5	1.69E4	1.71E-5	1.53E4
90	Clay-pore	80	Ar/NaS	finished	1.19E-5	2.19E4	1.47E-5	1.78E4
90	Q-brine	80	Ar/NaS	finished	1.25E-5	2.09E4	1.45E-5	1.81E4
					ZrC powder			
25	Granite	40	Air	Finished, repeated	1.86E-8	2.94E7	n.m.	n.m.
25	Clay-pore	40	Air	Finished, repeated	1.61E-6	3.41E5	n.m.	n.m.
25	Q-brine	40	Air	Finished, repeated	2.48E-8	2.21E7	n.m.	n.m.
50	Granite	40	Air	Finished, repeated	1.09E-8	5.03E7	n.m.	n.m.
50	Clay-pore	40	Air	Finished, repeated	2.56E-7	2.14E6	n.m.	n.m.
50	Q-brine	40	Air	Finished, repeated	1.94E-8	2.82E7	n.m.	n.m.
90	Granite	40	Air	Finished, repeated	1.04E-8	5.27E7	n.m.	n.m.
90	Clay-pore	40	Air	Finished, repeated	7.73E-6	7.09E4	n.m.	n.m.
90	Q-brine	40	Air	Finished, repeated	2.97E-8	1.84E7	n.m.	n.m.

Temp. (°C)	Leachant	Days of exposure	Atmosphere	Status	Leach rate (g/m2.d)	Lifetime (years)	Leach rate (g/m2.d)	Lifetime (years)
25	Granite	80	Ar/NaS	finished	1.09E-5	5.03E4	1.14E-5	4.81E4
25	Clay-pore	80	Ar/NaS	finished	1.19E-6	4.61E5	1.26E-6	4.35E5
25	Q-brine	80	Ar/NaS	finished	4.63E-7	1.18E6	5.11E-7	1.07E6
50	Granite		Ar/NaS	running				
50	Clay-pore		Ar/NaS	running				
50	Q-brine		Ar/NaS	running				
90	Granite		Ar/NaS	finished	1.41E-4	3.87E3	1.98E-4	2.76E3
90	Clay-pore		Ar/NaS	finished	4.05E-4	1.35E3	4.72E-4	1.16E3
90	Q-brine		Ar/NaS	finished	1.15E-4	4.76E3	1.79E-4	3.07E3
					SiC-coated particles			
25	Granite	80	Air	finished	1.58E-5	1.66E4	3.85E-5	6.79E3
25	Clay-pore	80	Air	finished	3.03E-5	8.62E3	4.55E-5	5.74E3
25	Q-brine	80	Air	finished	3.29E-5	7.94E3	1.03E-4	2.53E3
50	Granite	80	Air	finished	2.74E-5	9.53E3	4.95E-5	5.28E3
50	Clay-pore	80	Air	finished	3.96E-5	6.60E3	5.26E-5	4.97E3
50	Q-brine	80	Air	finished	4.21E-5	6.20E3	8.48E-5	3.08E3
90	Granite	80	Air	finished	1.76E-4	1.49E3	1.91E-4	1.37E3
90	Clay-pore	80	Air	finished	3.30E-5	7.91E3	5.99E-5	4.36E3
90	Q-brine	80	Air	finished	3.93E-5	6.65E3	8.91E-5	2.93E3
25	Granite	80	Ar/NaS	running				
25	Clay-pore	80	Ar/NaS	running				
25	Q-brine	80	Ar/NaS	running				
50	Granite	80	Ar/NaS	running				

Temp. (°C)	Leachant	Days of exposure	Atmosphere	Status	Leach rate (g/m2.d)	Lifetime (years)	Leach rate (g/m2.d)	Lifetime (years)
50	Clay-pore	80	Ar/NaS	running				
50	Q-brine	80	Ar/NaS	running				
90	Granite	80	Ar/NaS	to be repeated*				
90	Clay-pore	80	Ar/NaS	to be repeated*				
90	Q-brine	80	Ar/NaS	to be repeated*				
					Zr-coated particles **			

* malfunction of oven
** waiting for more material
n.m. not measured

Annex 2: SiC powder corrosion data in air (reaction-sintered SiC and CVD SiC)

Temp. (°C)	Leachant	Days of exposure	Atmosphere	Status	Leach rate (g/m2.d)	Lifetime (years)	Leach rate (g/m2.d)	Lifetime (years)
					Reaction-sintered		CVD	
25	Granite	40	Air	HTR-N/N1	2.03E-6	1.29E5	7.23E-6	3.62E4
25	Clay-pore	40	Air	HTR-N/N1	4.56E-6	5.73E4	2.05E-5	1.27E4
25	Q-brine	40	Air	HTR-N/N1	4.55E-6	5.75E4	4.70E-5	5.56E3
50	Granite	40	Air	HTR-N/N1	3.84E-6	6.80E3	1.14E-4	2.29E3
50	Clay-pore	40	Air	HTR-N/N1	8.07E-6	3.24E4	7.95E-5	3.29E3
50	Q-brine	40	Air	HTR-N/N1	7.54E-6	3.47E4	8.92E-5	2.93E3
90	Granite	40	Air	HTR-N/N1	9.64E-6	2.70E3	1.81E-4	1.44E3
90	Clay-pore	40	Air	HTR-N/N1	2.30E-5	1.14E4	1.54E-3	0.17E3
90	Q-brine	40	Air	HTR-N/N1	1.68E-5	1.56E4	3.52E-4	0.74E3