



Glass formulation for nuclear waste containment

DE LA RECHERCHE À L'INDUSTRIE

Joint ICTP-IAEA International School on Nuclear Waste Vitrification – 23 - 27 Septembre 2019 - TRIESTE

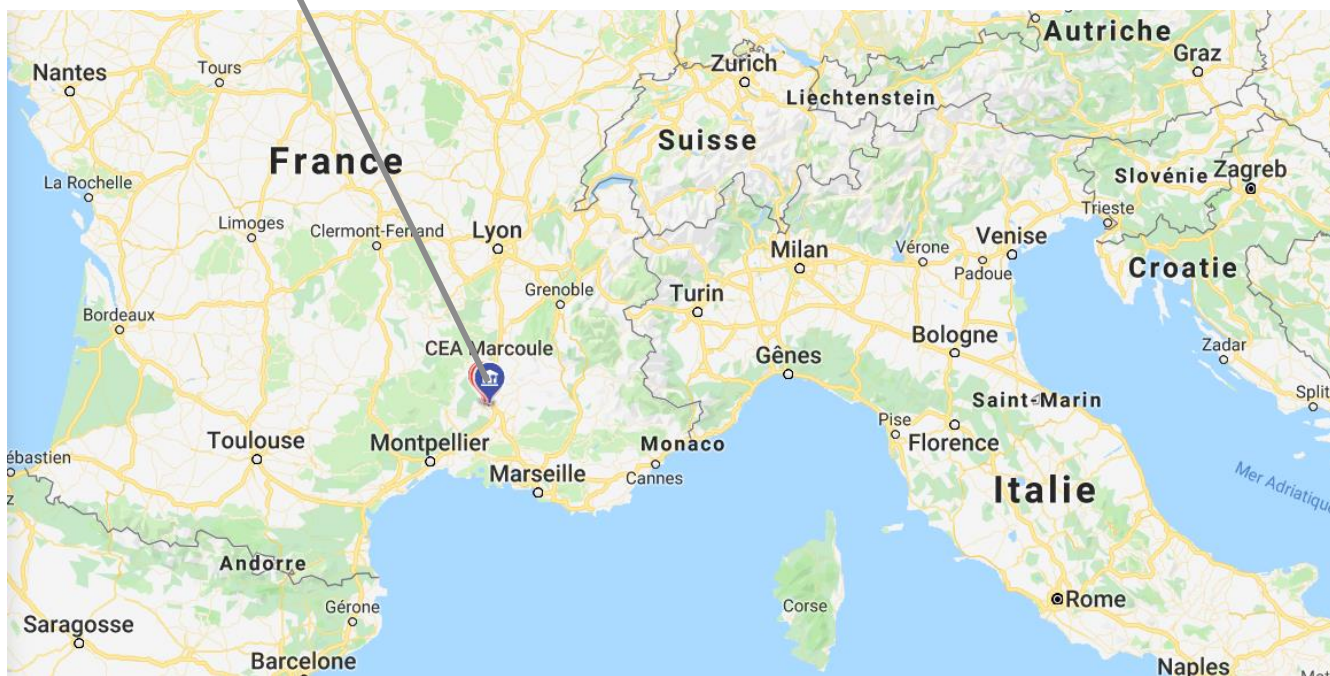
E. Régnier



CEA-Marcoule

Nuclear energy R&D

... since 1955



CEA Marcoule center (~5000 peoples)

Research facilities

ICSM Institut for
Separation Chemistry

Vitrification
Process development
Material science

Cementation
Decontamination

ATALANTE
Reprocessing
Separation chemistry
Conditioning matrices
Fuel fabrication
Interim storage of spent fuels

I. Nuclear waste to be vitrified

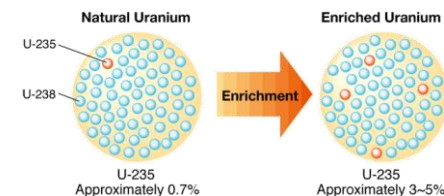
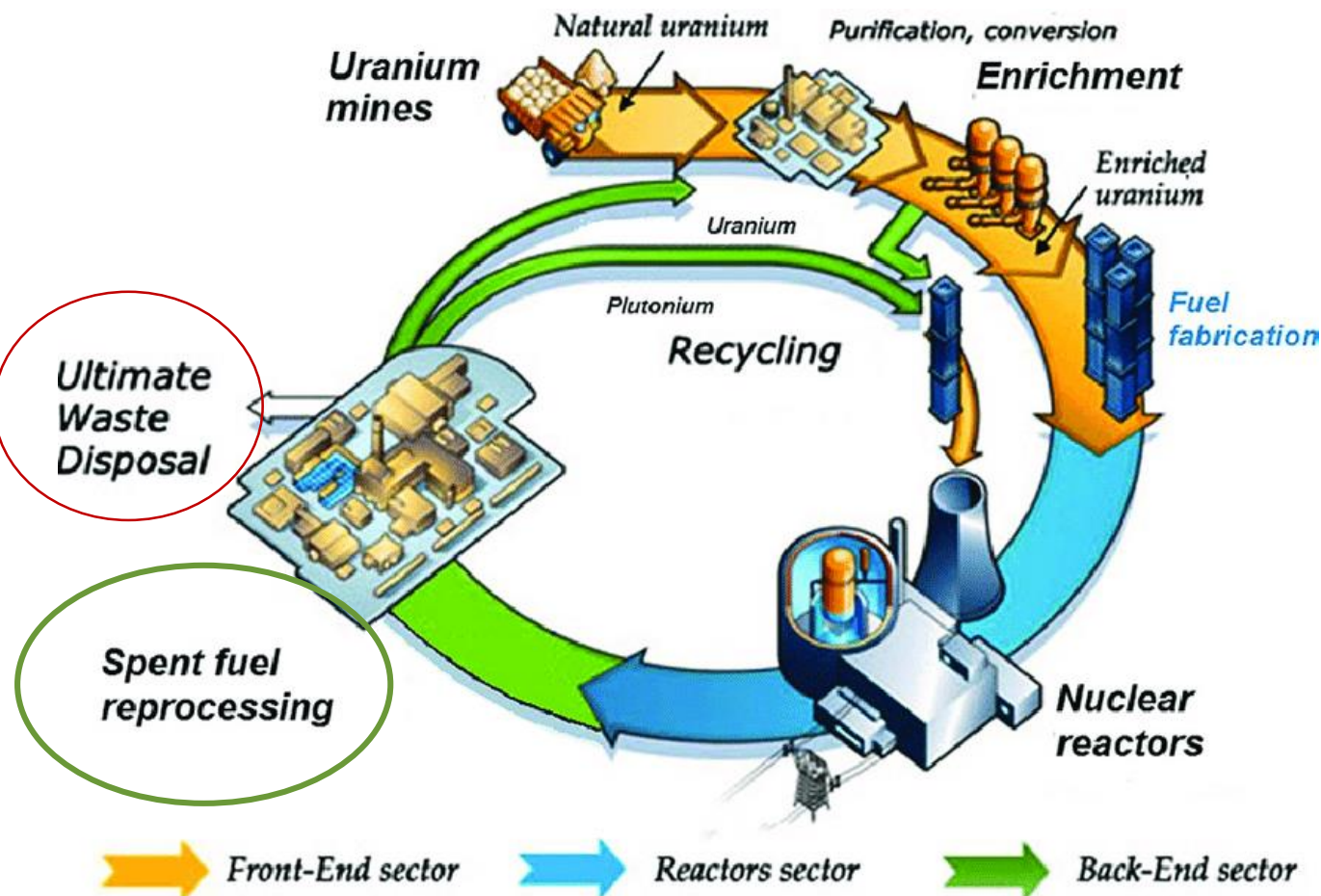
- 1) Origin of nuclear waste
- 2) Objectives of nuclear waste containment

II. Some basic knowledge on glass

- 1) Glass structure
- 2) Glass formers / modifiers / intermediates
- 3) Role of radioelements in the glass structure

III. How to formulate a nuclear glass?

- 1) Which constraints have to be respected?
- 2) Methodology to formulate a nuclear glass
- 3) CEA experience in nuclear glass formulation



<https://www.jnfl.co.jp/en/business/uran/>

⇒ Nuclear waste produced at all stages of the Nuclear Fuel Cycle (from mines to spent fuel reprocessing)

+ Decommissioning & Dismantling (D&D) operations

https://www.researchgate.net/figure/Uranium-and-nuclear-fuel-cycle-sectors_fig11_317779578

Waste classification

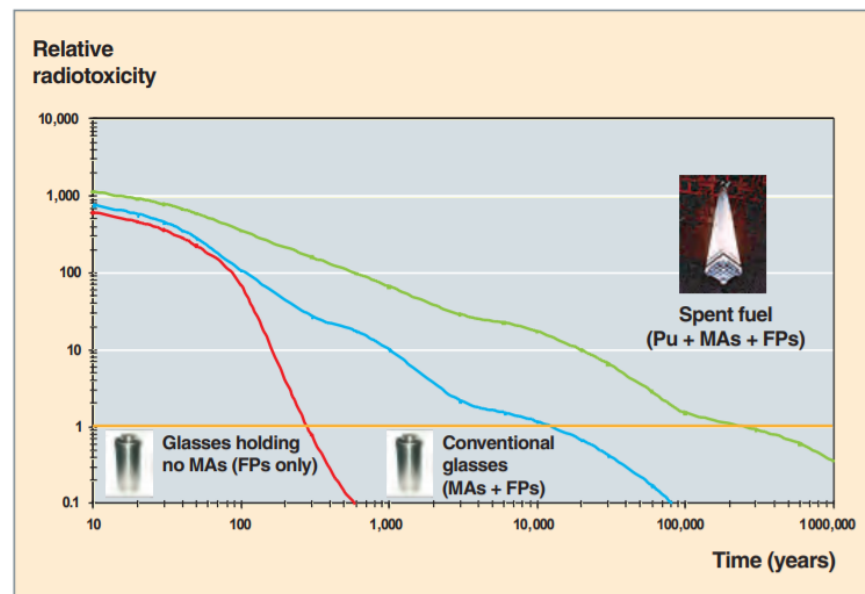
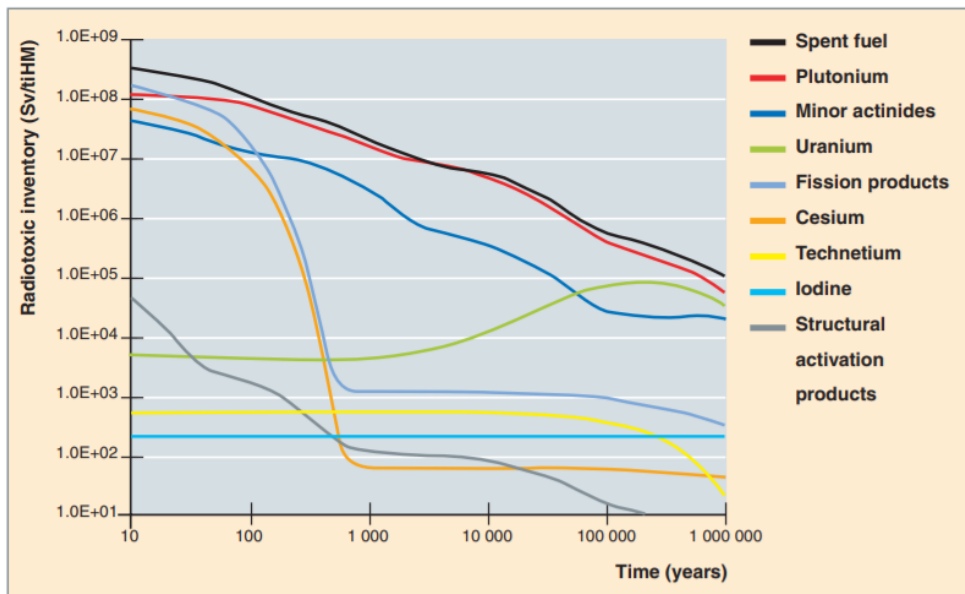
	Very short lived	Short lived	Long lived
Very low level (VLLW)	VSLW (managed first through on-site decay and then disposed of as conventional waste)	VLLW (disposed of at the CSTFA facility located in the Aube district)	
Low level waste (LLW)		LILW-SL (disposed of at the CSFMA facility (Aube))	LLW-LL (near-surface repository)
Intermediate level waste (ILW)		63 % vol but 0,02 % of radioactivity	ILW-LL (deep disposal, at 500 m, under dvpt)
High level waste (HLW)		HLW (deep disposal, at 500 m, under dvpt)	

Source : ANDRA, 2014

⇒ Used fuel reprocessing (PUREX process) ⇒ The resulting Fission Products (FP) / minor Actinids (mA) solutions are the main radioactive waste of the fuel cycle: 96 % of radioactivity (but 0,2 % vol)

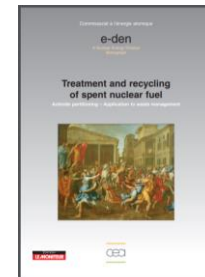
Radiotoxicity of HLW

Spent fuel / reprocessed spent fuel



⇒ Very important to propose a long term reliable solution for storage!

Source : <https://hal-cea.archives-ouvertes.fr/cea-01153306/file/cea6-en.pdf>



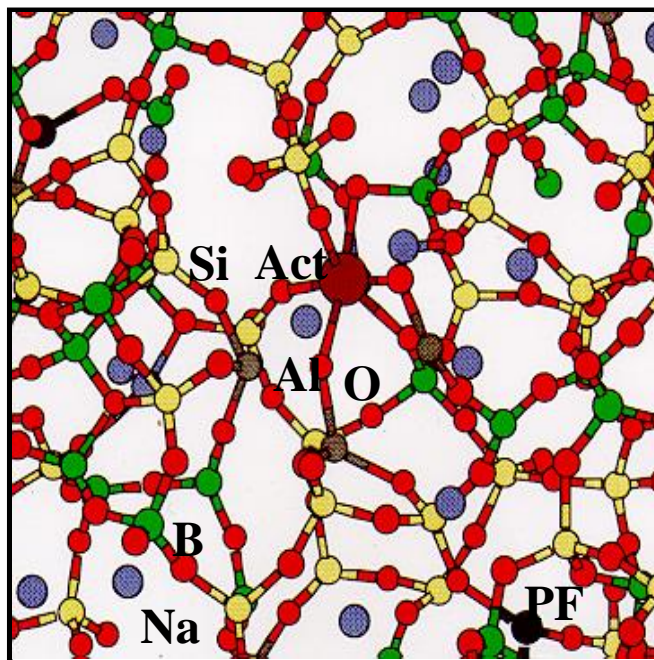
- ▶ The highly radioactive and very complex FP **solutions** are produced by the PUREX process. They contain ~40 chemical elements that must be **continuously stirred and cooled** to dissipate their thermal power.
- ▶ Conserving them in the liquid state is **not a sustainable option** => France (as well as US, UK, Canada) began to study solidification process in the 50's.

Fission Product / minor actinides solution

<div><div></div><div><div>1</div><div>H</div><div>Hydrogen 1.00794</div></div></div>	<div><div></div><div><div>2</div><div>He</div><div>Helium 4.003</div></div></div>	<div><div></div><div><div>3</div><div>Li</div><div>Lithium 6.941</div></div></div>	<div><div></div><div><div>4</div><div>Be</div><div>Beryllium 9.012182</div></div></div>	<div><div></div><div><div>5</div><div>B</div><div>Boron 10.811</div></div></div>	<div><div></div><div><div>6</div><div>C</div><div>Carbon 12.0107</div></div></div>	<div><div></div><div><div>7</div><div>N</div><div>Nitrogen 14.00674</div></div></div>	<div><div></div><div><div>8</div><div>O</div><div>Oxygen 15.9994</div></div></div>	<div><div></div><div><div>9</div><div>F</div><div>Fluorine 18.9984032</div></div></div>	<div><div></div><div><div>10</div><div>Ne</div><div>Neon 20.1797</div></div></div>	<div><div></div><div><div>11</div><div>Na</div><div>Sodium 22.98976928</div></div></div>	<div><div></div><div><div>12</div><div>Mg</div><div>Magnesium 24.3050</div></div></div>	<div><div></div><div><div>13</div><div>Al</div><div>Aluminum 26.9815385</div></div></div>	<div><div></div><div><div>14</div><div>Si</div><div>Silicon 28.0855</div></div></div>	<div><div></div><div><div>15</div><div>P</div><div>Phosphorus 30.973761</div></div></div>	<div><div></div><div><div>16</div><div>S</div><div>Sulfur 32.06</div></div></div>	<div><div></div><div><div>17</div><div>Cl</div><div>Chlorine 35.4527</div></div></div>	<div><div></div><div><div>18</div><div>Ar</div><div>Argon 39.948</div></div></div>	<div><div></div><div><div>19</div><div>K</div><div>Potassium 39.0983</div></div></div>	<div><div></div><div><div>20</div><div>Ca</div><div>Calcium 40.078</div></div></div>	<div><div></div><div><div>21</div><div>Sc</div><div>Scandium 44.955910</div></div></div>	<div><div></div><div><div>22</div><div>Ti</div><div>Titanium 47.867</div></div></div>	<div><div></div><div><div>23</div><div>V</div><div>Vanadium 50.9415</div></div></div>	<div><div></div><div><div>24</div><div>Cr</div><div>Chromium 51.9961</div></div></div>	<div><div></div><div><div>25</div><div>Mn</div><div>Manganese 54.938045</div></div></div>	<div><div></div><div><div>26</div><div>Fe</div><div>Iron 55.845</div></div></div>	<div><div></div><div><div>27</div><div>Co</div><div>Cobalt 58.933200</div></div></div>	<div><div></div><div><div>28</div><div>Ni</div><div>Nickel 58.6934</div></div></div>	<div><div></div><div><div>29</div><div>Cu</div><div>Copper 63.546</div></div></div>	<div><div></div><div><div>30</div><div>Zn</div><div>Zinc 65.39</div></div></div>	<div><div></div><div><div>31</div><div>Ga</div><div>Gallium 69.723</div></div></div>	<div><div></div><div><div>32</div><div>Ge</div><div>Germanium 72.61</div></div></div>	<div><div></div><div><div>33</div><div>As</div><div>Arsenic 74.92160</div></div></div>	<div><div></div><div><div>34</div><div>Se</div><div>Selenium 78.96</div></div></div>	<div><div></div><div><div>35</div><div>Br</div><div>Bromine 79.904</div></div></div>	<div><div></div><div><div>36</div><div>Kr</div><div>Krypton 83.80</div></div></div>	<div><div></div><div><div>37</div><div>Rb</div><div>Rubidium 85.4678</div></div></div>	<div><div></div><div><div>38</div><div>Sr</div><div>Strontium 87.62</div></div></div>	<div><div></div><div><div>39</div><div>Y</div><div>Yttrium 88.90585</div></div></div>	<div><div></div><div><div>40</div><div>Zr</div><div>Zirconium 91.224</div></div></div>	<div><div></div><div><div>41</div><div>Nb</div><div>Niobium 92.90638</div></div></div>	<div><div></div><div><div>42</div><div>Mo</div><div>Molybdenum 95.94</div></div></div>	<div><div></div><div><div>43</div><div>Tc</div><div>Technetium (98)</div></div></div>	<div><div></div><div><div>44</div><div>Ru</div><div>Ruthenium 101.07</div></div></div>	<div><div></div><div><div>45</div><div>Rh</div><div>Rhodium 106.42</div></div></div>	<div><div></div><div><div>46</div><div>Pd</div><div>Palladium 106.42</div></div></div>	<div><div></div><div><div>47</div><div>Ag</div><div>Silver 107.8682</div></div></div>	<div><div></div><div><div>48</div><div>Cd</div><div>Cadmium 112.411</div></div></div>	<div><div></div><div><div>49</div><div>In</div><div>Indium 114.818</div></div></div>	<div><div></div><div><div>50</div><div>Sn</div><div>Tin 118.710</div></div></div>	<div><div></div><div><div>51</div><div>Sb</div><div>Antimony 121.760</div></div></div>	<div><div></div><div><div>52</div><div>Te</div><div>Tellurium 127.60</div></div></div>	<div><div></div><div><div>53</div><div>I</div><div>Iodine 126.90447</div></div></div>	<div><div></div><div><div>54</div><div>Xe</div><div>Xenon 131.29</div></div></div>	<div><div></div><div><div>55</div><div>Cs</div><div>Cesium 132.90545</div></div></div>	<div><div></div><div><div>56</div><div>Ba</div><div>Barium 137.327</div></div></div>	<div><div></div><div><div>57</div><div>La</div><div>Lanthanum 138.90485</div></div></div>	<div><div></div><div><div>72</div><div>Hf</div><div>Hafnium 178.49</div></div></div>	<div><div></div><div><div>73</div><div>Ta</div><div>Tantalum 180.9479</div></div></div>	<div><div></div><div><div>74</div><div>W</div><div>Tungsten 183.84</div></div></div>	<div><div></div><div><div>75</div><div>Re</div><div>Rhenium 186.207</div></div></div>	<div><div></div><div><div>76</div><div>Os</div><div>Osmium 190.23</div></div></div>	<div><div></div><div><div>77</div><div>Ir</div><div>Iridium 192.217</div></div></div>	<div><div></div><div><div>78</div><div>Pt</div><div>Platinum 195.078</div></div></div>	<div><div></div><div><div>79</div><div>Au</div><div>Gold 196.96655</div></div></div>	<div><div></div><div><div>80</div><div>Hg</div><div>Mercury 200.59</div></div></div>	<div><div></div><div><div>81</div><div>Tl</div><div>Thallium 204.3833</div></div></div>	<div><div></div><div><div>82</div><div>Pb</div><div>Lead 207.2</div></div></div>	<div><div></div><div><div>83</div><div>Bi</div><div>Bismuth 208.98038</div></div></div>	<div><div></div><div><div>84</div><div>Po</div><div>Polonium (209)</div></div></div>	<div><div></div><div><div>85</div><div>At</div><div>Astatine (210)</div></div></div>	<div><div></div><div><div>86</div><div>Rn</div><div>Radon (222)</div></div></div>	<div><div></div><div><div>87</div><div>Fr</div><div>Francium (223)</div></div></div>	<div><div></div><div><div>88</div><div>Ra</div><div>Radium (226)</div></div></div>	<div><div></div><div><div>89</div><div>Ac</div><div>Actinium (227)</div></div></div>	<div><div></div><div><div>104</div><div>Rf</div><div>Rutherfordium (261)</div></div></div>	<div><div></div><div><div>105</div><div>Db</div><div>Dubnium (262)</div></div></div>	<div><div></div><div><div>106</div><div>Sg</div><div>Seaborgium (263)</div></div></div>	<div><div></div><div><div>107</div><div>Bh</div><div>Bohrium (262)</div></div></div>	<div><div></div><div><div>108</div><div>Hs</div><div>Hassium (265)</div></div></div>	<div><div></div><div><div>109</div><div>Mt</div><div>Mendelevium (266)</div></div></div>	<div><div></div><div><div>110</div><div></div><div>(269)</div></div></div>	<div><div></div><div><div>111</div><div></div><div>(272)</div></div></div>	<div><div></div><div><div>112</div><div></div><div>(277)</div></div></div>	<div><div></div><div><div>113</div><div></div><div></div></div></div>	<div><div></div><div><div>114</div><div></div><div></div></div></div>	<div><div></div><div><div>58</div><div>Ce</div><div>Cerium 140.116</div></div></div>	<div><div></div><div><div>59</div><div>Pr</div><div>Praseodymium 140.90768</div></div></div>	<div><div></div><div><div>60</div><div>Nd</div><div>Niodymium 144.24</div></div></div>	<div><div></div><div><div>61</div><div>Pm</div><div>Promethium (145)</div></div></div>	<div><div></div><div><div>62</div><div>Sm</div><div>Samarium 150.36</div></div></div>	<div><div></div><div><div>63</div><div>Eu</div><div>Europtium 151.964</div></div></div>	<div><div></div><div><div>64</div><div>Gd</div><div>Gadolinium 157.25</div></div></div>	<div><div></div><</div>
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The aim is to confine radionuclides by establishing chemical bonds



Remind: ~40 elements in the waste solution

► The program began by attempting to produce synthetic minerals such as mica $K[Si_3Al][Mg_3]O_{10}(OH)_2$ or feldspar $((Na,K)AlSi_3O_8)$, but glass soon proved to be the only material capable of immobilizing all the elements present in such complex solutions.

Mica-phlogopite



⇒ Choice of glass in Canada, France, US, Germany, USSR.

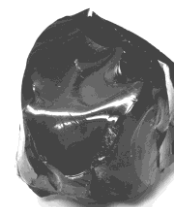
► In France, the first radioactive glass was synthesized at laboratory scale at CEA in 1957

⇒ **Birth of vitrification in the 50's**

⇒ **A new application of the glass was born: containment glasses**

⇒ Needs of R&D on:

- Material (specific composition of nucl. glass, long term behavior)
- Process



I. Nuclear waste to be vitrified

- 1) Origin of nuclear waste
- 2) Objectives of nuclear waste containment

II. Some basic knowledge on glass

- 1) Glass structure
- 2) Glass formers / modifiers / intermediates
- 3) Role of radioelements in the glass structure

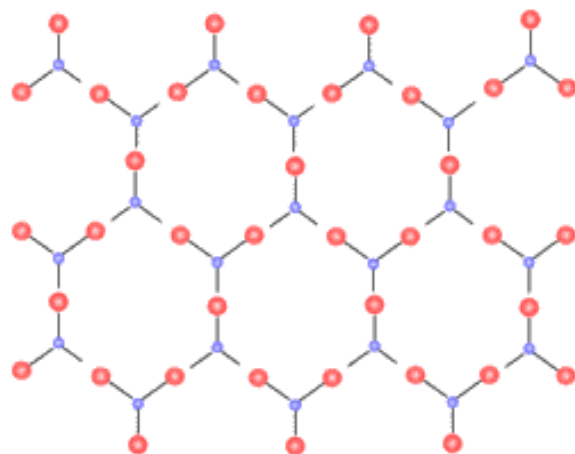
III. How to formulate a nuclear glass?

- 1) Which constraints have to be respected?
- 2) Methodology to formulate a nuclear glass
- 3) CEA experience in nuclear glass formulation

Glass structure: a disordered structure

Cristallized state (SiO_2):

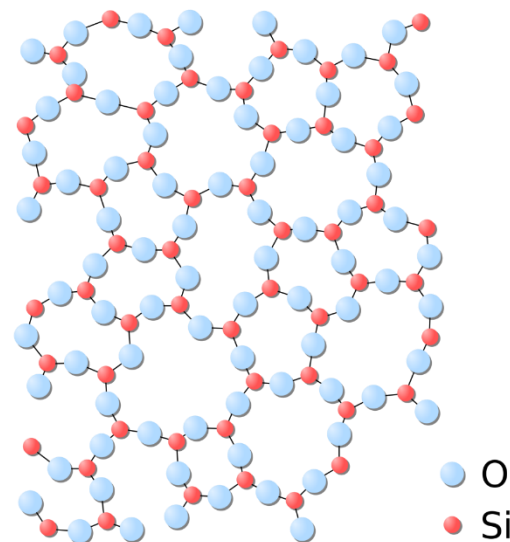
- Repetition of elementary patterns
⇒ **Ordered material**



● Oxygen
● Silicium

Vitreous state (SiO_2):

- Assembly of connected polyhedra
⇒ **No long range order**



Thanks to its disordered structure, glass is able to incorporate many different elements within its structure. However, the role of each element in this structure differs from an element to another.

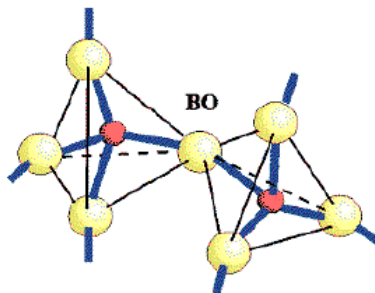
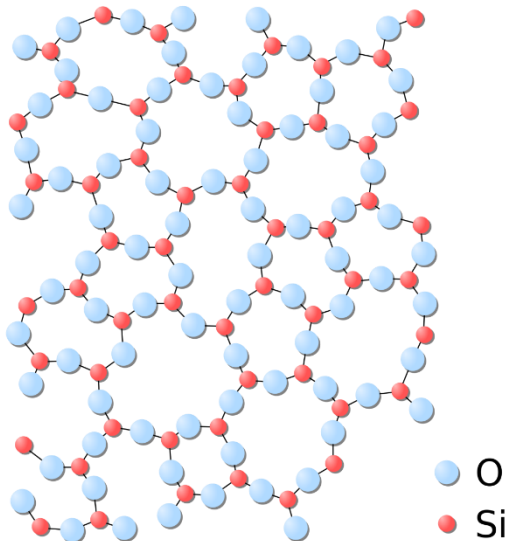
- Network formers -



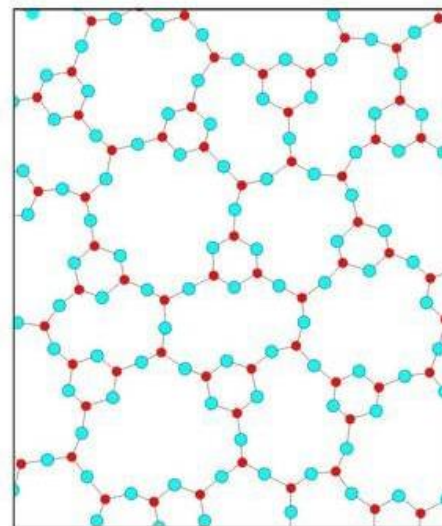
⇒ Able to form a glass alone (iono-covalent links)

⇒ SiO_4 , BO_4 / BO_3 ... polyhedra linked by their tops

SiO_2 glass



$\text{SiO}_2\text{-B}_2\text{O}_3$ glass



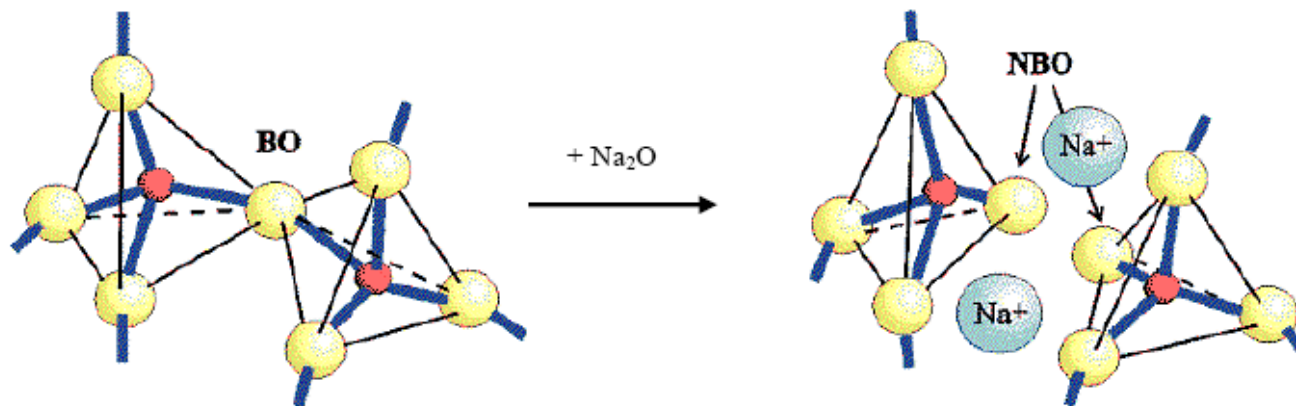
Edited by:
Adrian C. WRIGHT, Steven A. FELLER
and Alex C. HANNON

- Network modifiers -

Alkaline, Alkali earth, some transition elements and rare earths

- ⇒ Are not able to form glasses alone (cristallize) (ionic links)
- ⇒ In glass network: break the bonds

example of Na^+ in SiO_2 glass



Effect on the glass properties:

- Decrease the melting temperature
- Decrease the glass viscosity
- Decrease the chemical durability

- Intermediate elements -



⇒ Are not able to form glasses alone (cristallize)

⇒ Can reinforce or break the bonds (depends on their content, on glass composition...)

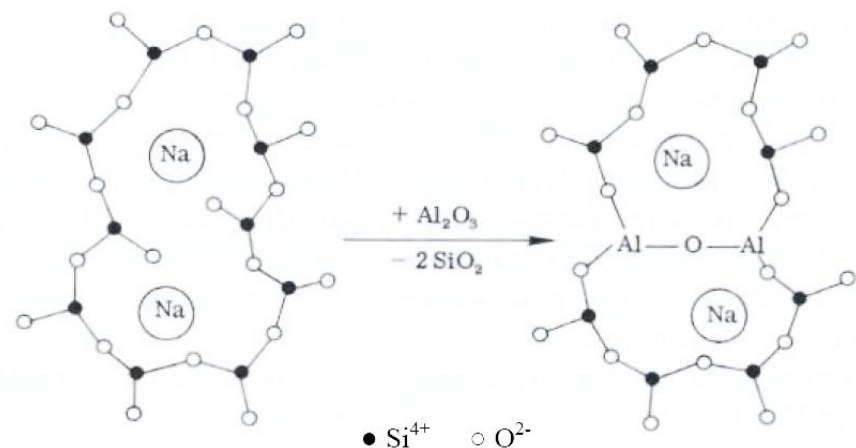
Case of Al_2O_3

⇒ Can form $[\text{AlO}_4]^-$ tetrahedrons as well as $[\text{SiO}_4]^-$ if positive charges are available

⇒ Possible with alkaline ions

⇒ But if $\text{Al}_2\text{O}_3/\text{A}_2\text{O} < 1$, then not enough alkalines to compensate $[\text{AlO}_4]^-$ charges

⇒ $\text{Al} \rightarrow [\text{AlO}_6] = \text{modifier}$.



- Summary -

Formers	Intermediates	Modifiers
SiO_2	Al_2O_3	Li_2O
GeO_2	PbO	Na_2O
B_2O_3	ZnO	K_2O
P_2O_5	CdO	CaO
As_2O_3	TiO_2	BaO
As_2O_5		
V_2O_5		

(can be found in every books on glass science)

2) Role of radioelements in the glass structure

Fission Product / minor actinides solution

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<div><div></div><div>11</div><div>Na</div><div>Sodium</div><div>22.9897701</div></div>	<div><div></div><div>12</div><div>Mg</div><div>Magnesium</div><div>24.3050</div></div>											<div><div></div><div>13</div><div>Al</div><div>Aluminium</div><div>26.9815385</div></div>	<div><div></div><div>14</div><div>Si</div><div>Silicon</div><div>28.0855</div></div>	<div><div></div><div>15</div><div>P</div><div>Phosphorus</div><div>30.973761</div></div>	<div><div></div><div>16</div><div>S</div><div>Sulfur</div><div>32.066</div></div>	<div><div></div><div>17</div><div>Cl</div><div>Chlorine</div><div>35.4527</div></div>	<div><div></div><div>18</div><div>Ar</div><div>Argon</div><div>39.948</div></div>											
<div><div></div><div>19</div><div>K</div><div>Potassium</div><div>39.0983</div></div>	<div><div></div><div>20</div><div>Ca</div><div>Calcium</div><div>40.078</div></div>	<div><div></div><div>21</div><div>Sc</div><div>Scandium</div><div>44.955910</div></div>	<div><div></div><div>22</div><div>Ti</div><div>Titanium</div><div>47.867</div></div>	<div><div></div><div>23</div><div>V</div><div>Vanadium</div><div>50.9415</div></div>	<div><div></div><div>24</div><div>Cr</div><div>Chromium</div><div>51.9961</div></div>	<div><div></div><div>25</div><div>Mn</div><div>Manganese</div><div>54.938049</div></div>	<div><div></div><div>26</div><div>Fe</div><div>Iron</div><div>55.845</div></div>	<div><div></div><div>27</div><div>Co</div><div>Cobalt</div><div>58.933200</div></div>	<div><div></div><div>28</div><div>Ni</div><div>Nickel</div><div>58.6934</div></div>	<div><div></div><div>29</div><div>Cu</div><div>Copper</div><div>63.546</div></div>	<div><div></div><div>30</div><div>Zn</div><div>Zinc</div><div>65.39</div></div>	<div><div></div><div>31</div><div>Ga</div><div>Gallium</div><div>69.723</div></div>	<div><div></div><div>32</div><div>Ge</div><div>Germanium</div><div>72.61</div></div>	<div><div></div><div>33</div><div>As</div><div>Arsenic</div><div>74.92160</div></div>	<div><div></div><div>34</div><div>Se</div><div>Selenium</div><div>78.96</div></div>	<div><div></div><div>35</div><div>Br</div><div>Bromine</div><div>79.904</div></div>	<div><div></div><div>36</div><div>Kr</div><div>Krypton</div><div>83.80</div></div>											
<div><div></div><div>37</div><div>Rb</div><div>Rubidium</div><div>85.4678</div></div>	<div><div></div><div>38</div><div>Sr</div><div>Strontium</div><div>87.62</div></div>	<div><div></div><div>39</div><div>Y</div><div>Yttrium</div><div>88.90585</div></div>	<div><div></div><div>40</div><div>Zr</div><div>Zirconium</div><div>91.224</div></div>	<div><div></div><div>41</div><div>Nb</div><div>Niobium</div><div>92.90638</div></div>	<div><div></div><div>42</div><div>Mo</div><div>Molybdenum</div><div>95.94</div></div>	<div><div></div><div>43</div><div>Tc</div><div>Technetium</div><div>(98)</div></div>	<div><div></div><div>44</div><div>Ru</div><div>Ruthenium</div><div>101.07</div></div>	<div><div></div><div>45</div><div>Rh</div><div>Rhodium</div><div>102.90550</div></div>	<div><div></div><div>46</div><div>Pd</div><div>Palladium</div><div>106.42</div></div>	<div><div></div><div>47</div><div>Ag</div><div>Silver</div><div>107.8682</div></div>	<div><div></div><div>48</div><div>Cd</div><div>Cadmium</div><div>112.411</div></div>	<div><div></div><div>49</div><div>In</div><div>Indium</div><div>114.818</div></div>	<div><div></div><div>50</div><div>Sn</div><div>Tin</div><div>118.710</div></div>	<div><div></div><div>51</div><div>Sb</div><div>Antimony</div><div>121.760</div></div>	<div><div></div><div>52</div><div>Te</div><div>Tellurium</div><div>127.60</div></div>	<div><div></div><div>53</div><div>I</div><div>Iodine</div><div>126.90447</div></div>	<div><div></div><div>54</div><div>Xe</div><div>Xenon</div><div>131.29</div></div>											
<div><div></div><div>55</div><div>Cs</div><div>Cesium</div><div>132.90545</div></div>	<div><div></div><div>56</div><div>Ba</div><div>Barium</div><div>137.327</div></div>	<div><div></div><div>57</div><div>La</div><div>Lanthanum</div><div>138.9055</div></div>	<div><div></div><div>72</div><div>Hf</div><div>Hafnium</div><div>178.49</div></div>	<div><div></div><div>73</div><div>Ta</div><div>Tantalum</div><div>180.9479</div></div>	<div><div></div><div>74</div><div>W</div><div>Tungsten</div><div>183.84</div></div>	<div><div></div><div>75</div><div>Re</div><div>Rhenium</div><div>186.207</div></div>	<div><div></div><div>76</div><div>Os</div><div>Osmium</div><div>190.23</div></div>	<div><div></div><div>77</div><div>Ir</div><div>Iridium</div><div>192.217</div></div>	<div><div></div><div>78</div><div>Pt</div><div>Platinum</div><div>195.078</div></div>	<div><div></div><div>79</div><div>Au</div><div>Gold</div><div>196.96655</div></div>	<div><div></div><div>80</div><div>Hg</div><div>Mercury</div><div>200.59</div></div>	<div><div></div><div>81</div><div>Tl</div><div>Thallium</div><div>204.3833</div></div>	<div><div></div><div>82</div><div>Pb</div><div>Lead</div><div>207.2</div></div>	<div><div></div><div>83</div><div>Bi</div><div>Bismuth</div><div>208.98038</div></div>	<div><div></div><div>84</div><div>Po</div><div>Polonium</div><div>(209)</div></div>	<div><div></div><div>85</div><div>At</div><div>Astatine</div><div>(210)</div></div>	<div><div></div><div>86</div><div>Rn</div><div>Radon</div><div>(222)</div></div>											
<div><div></div><div>87</div><div>Fr</div><div>Francium</div><div>(223)</div></div>	<div><div></div><div>88</div><div>Ra</div><div>Radium</div><div>(226)</div></div>	<div><div></div><div>89</div><div>Ac</div><div>Actinium</div><div>(227)</div></div>	<div><div></div><div>104</div><div>Rf</div><div>Rutherfordium</div><div>(261)</div></div>	<div><div></div><div>105</div><div>Db</div><div>Dubnium</div><div>(262)</div></div>	<div><div></div><div>106</div><div>Sg</div><div>Seaborgium</div><div>(263)</div></div>	<div><div></div><div>107</div><div>Bh</div><div>Bohrium</div><div>(262)</div></div>	<div><div></div><div>108</div><div>Hs</div><div>Hassium</div><div>(265)</div></div>	<div><div></div><div>109</div><div>Mt</div><div>Meitnerium</div><div>(266)</div></div>	<div><div></div><div>110</div><div></div><div></div><div>(269)</div></div>	<div><div></div><div>111</div><div></div><div></div><div>(272)</div></div>	<div><div></div><div>112</div><div></div><div></div><div>(277)</div></div>	<div><div></div><div>113</div><div></div><div></div><div></div></div>	<div><div></div><div>114</div><div></div><div></div><div></div></div>															
															<div><div></div><div>58</div><div>Ce</div><div>Cerium</div><div>140.116</div></div>	<div><div></div><div>59</div><div>Pr</div><div>Praseodymium</div><div>140.90766</div></div>	<div><div></div><div>60</div><div>Nd</div><div>Neodymium</div><div>144.24</div></div>	<div><div></div><div>61</div><div>Pm</div><div>Promethium</div><div>(145)</div></div>	<div><div></div><div>62</div><div>Sm</div><div>Samarium</div><div>150.36</div></div>	<div><div></div><div>63</div><div>Eu</div><div>Europium</div><div>151.964</div></div>	<div><div></div><div>64</div><div>Gd</div><div>Gadolinium</div><div>157.25</div></div>	<div><div></div><div>65</div><div>Tb</div><div>Terbium</div><div>158.92534</div></div>	<div><div></div><div>66</div><div>Dy</div><div>Dysprosium</div><div>162.50</div></div>	<div><div></div><div>67</div><div>Ho</div><div>Holmium</div><div>164.93032</div></div>	<div><div></div><div>68</div><div>Er</div><div>Erbium</div><div>167.26</div></div>	<div><div></div><div>69</div><div>Tm</div><div>Thulium</div><div>168.93421</div></div>	<div><div></div><div>70</div><div>Yb</div><div>Ytterbium</div><div>173.04</div></div>	<div><div></div><div>71</div><div>Lu</div><div>Lutetium</div><div>174.967</div></div>
<div><div></div><div>90</div><div>Th</div><div>Thorium</div><div>232.0381</div></div>	<div><div></div><div>91</div><div>Pa</div><div>Protactinium</div><div>231.03588</div></div>	<div><div></div><div>92</div><div>U</div><div>Uranium</div><div>238.0289</div></div>	<div><div></div><div>93</div><div>Np</div><div>Neptunium</div><div>(237)</div></div>	<div><div></div><div>94</div><div>Pu</div><div>Plutonium</div><div>(244)</div></div>	<div><div></div><div>95</div><div>Am</div><div>Americium</div><div>(243)</div></div>	<div><div></div><div>96</div><div>Cm</div><div>Curium</div><div>(247)</div></div>	<div><div></div><div>97</div><div>Bk</div><div>Berkelium</div><div>(247)</div></div>	<div><div></div><div>98</div><div>Cf</div><div>Californium</div><div>(251)</div></div>	<div><div></div><div>99</div><div>Es</div><div>Einsteinium</div><div>(252)</div></div>	<div><div></div><div>100</div><div>Fm</div><div>Fermium</div><div>(257)</div></div>	<div><div></div><div>101</div><div>Md</div><div>Mendelevium</div><div>(258)</div></div>	<div><div></div><div>102</div><div>No</div><div>Nobelium</div><div>(259)</div></div>	<div><div></div><div>103</div><div>Lr</div><div>Lawrencium</div><div>(262)</div></div>															

Remind

Network formers: SiO_2 , B_2O_3 , GeO_2 , P_2O_5

Network modifiers:

Alkaline, Alkali earth,
some **transition elements**
and **rare earths**

Intermediates: Al_2O_3 , ZnO , ZrO_2 , PbO , TiO_2

⇒ Most of the elements present in the FP solutions:
unknown behavior in glass (no data from traditional glass industry)
⇒ Knowledge had to be acquired

2) Role of radioelements in the glass structure

Fission Product / minor actinides solution

<div>1</div> <div>H</div> <div>Hydrogen</div> <div>1.00794</div>		<div>2</div> <div>He</div> <div>Helium</div> <div>4.003</div>																													
<div>3</div> <div>Li</div> <div>Lithium</div> <div>6.941</div>		<div>4</div> <div>Be</div> <div>Beryllium</div> <div>9.012182</div>												<div>5</div> <div>B</div> <div>Boron</div> <div>10.811</div>	<div>6</div> <div>C</div> <div>Carbon</div> <div>12.0107</div>	<div>7</div> <div>N</div> <div>Nitrogen</div> <div>14.00674</div>	<div>8</div> <div>O</div> <div>Oxygen</div> <div>15.9994</div>	<div>9</div> <div>F</div> <div>Fluorine</div> <div>18.9984032</div>	<div>10</div> <div>Ne</div> <div>Neon</div> <div>20.1797</div>												
<div>11</div> <div>Na</div> <div>Sodium</div> <div>22.98976928</div>		<div>12</div> <div>Mg</div> <div>Magnesium</div> <div>24.3050</div>												<div>13</div> <div>Al</div> <div>Aluminium</div> <div>26.9815385</div>	<div>14</div> <div>Si</div> <div>Silicon</div> <div>28.0855</div>	<div>15</div> <div>P</div> <div>Phosphorus</div> <div>30.973761</div>	<div>16</div> <div>S</div> <div>Sulfur</div> <div>32.066</div>	<div>17</div> <div>Cl</div> <div>Chlorine</div> <div>35.4527</div>	<div>18</div> <div>Ar</div> <div>Argon</div> <div>39.948</div>												
<div>19</div> <div>K</div> <div>Potassium</div> <div>39.0983</div>	<div>20</div> <div>Ca</div> <div>Calcium</div> <div>40.078</div>	<div>21</div> <div>Sc</div> <div>Scandium</div> <div>44.955910</div>	<div>22</div> <div>Ti</div> <div>Titanium</div> <div>47.867</div>	<div>23</div> <div>V</div> <div>Vanadium</div> <div>50.9415</div>	<div>24</div> <div>Cr</div> <div>Chromium</div> <div>51.9961</div>	<div>25</div> <div>Mn</div> <div>Manganese</div> <div>54.938049</div>	<div>26</div> <div>Fe</div> <div>Iron</div> <div>55.845</div>	<div>27</div> <div>Co</div> <div>Cobalt</div> <div>58.933200</div>	<div>28</div> <div>Ni</div> <div>Nickel</div> <div>58.6934</div>	<div>29</div> <div>Cu</div> <div>Copper</div> <div>63.546</div>	<div>30</div> <div>Zn</div> <div>Zinc</div> <div>65.39</div>	<div>31</div> <div>Ga</div> <div>Gallium</div> <div>69.723</div>	<div>32</div> <div>Ge</div> <div>Germanium</div> <div>72.61</div>	<div>33</div> <div>As</div> <div>Arsenic</div> <div>74.92160</div>	<div>34</div> <div>Se</div> <div>Selenium</div> <div>78.96</div>	<div>35</div> <div>Br</div> <div>Bromine</div> <div>79.904</div>	<div>36</div> <div>Kr</div> <div>Krypton</div> <div>83.80</div>														
<div>37</div> <div>Rb</div> <div>Rubidium</div> <div>85.4678</div>	<div>38</div> <div>Sr</div> <div>Strontium</div> <div>87.62</div>	<div>39</div> <div>Y</div> <div>Yttrium</div> <div>88.90585</div>	<div>40</div> <div>Zr</div> <div>Zirconium</div> <div>91.224</div>	<div>41</div> <div>Nb</div> <div>Niobium</div> <div>92.90638</div>	<div>42</div> <div>Mo</div> <div>Molybdenum</div> <div>95.94</div>	<div>43</div> <div>Tc</div> <div>Technetium</div> <div>(98)</div>	<div>44</div> <div>Ru</div> <div>Ruthenium</div> <div>101.07</div>	<div>45</div> <div>Rh</div> <div>Rhodium</div> <div>102.90550</div>	<div>46</div> <div>Pd</div> <div>Palladium</div> <div>106.42</div>	<div>47</div> <div>Ag</div> <div>Silver</div> <div>107.8682</div>	<div>48</div> <div>Cd</div> <div>Cadmium</div> <div>112.411</div>	<div>49</div> <div>In</div> <div>Indium</div> <div>114.818</div>	<div>50</div> <div>Sn</div> <div>Tin</div> <div>118.710</div>	<div>51</div> <div>Sb</div> <div>Antimony</div> <div>121.760</div>	<div>52</div> <div>Te</div> <div>Tellurium</div> <div>127.60</div>	<div>53</div> <div>I</div> <div>Iodine</div> <div>126.90447</div>	<div>54</div> <div>Xe</div> <div>Xenon</div> <div>131.29</div>														
<div>55</div> <div>Cs</div> <div>Cesium</div> <div>132.90545</div>	<div>56</div> <div>Ba</div> <div>Barium</div> <div>137.327</div>	<div>57</div> <div>La</div> <div>Lanthanum</div> <div>138.9055</div>	<div>72</div> <div>Hf</div> <div>Hafnium</div> <div>178.49</div>	<div>73</div> <div>Ta</div> <div>Tantalum</div> <div>180.9479</div>	<div>74</div> <div>W</div> <div>Tungsten</div> <div>183.84</div>	<div>75</div> <div>Re</div> <div>Rhenium</div> <div>186.207</div>	<div>76</div> <div>Os</div> <div>Osmium</div> <div>190.23</div>	<div>77</div> <div>Ir</div> <div>Iridium</div> <div>192.217</div>	<div>78</div> <div>Pt</div> <div>Platinum</div> <div>195.078</div>	<div>79</div> <div>Au</div> <div>Gold</div> <div>196.96655</div>	<div>80</div> <div>Hg</div> <div>Mercury</div> <div>200.59</div>	<div>81</div> <div>Tl</div> <div>Thallium</div> <div>204.3833</div>	<div>82</div> <div>Pb</div> <div>Lead</div> <div>207.2</div>	<div>83</div> <div>Bi</div> <div>Bismuth</div> <div>208.98038</div>	<div>84</div> <div>Po</div> <div>Polonium</div> <div>(209)</div>	<div>85</div> <div>At</div> <div>Astatine</div> <div>(210)</div>	<div>86</div> <div>Rn</div> <div>Radon</div> <div>(222)</div>														
<div>87</div> <div>Fr</div> <div>Francium</div> <div>(223)</div>	<div>88</div> <div>Ra</div> <div>Radium</div> <div>(226)</div>	<div>89</div> <div>Ac</div> <div>Actinium</div> <div>(227)</div>	<div>104</div> <div>Rf</div> <div>Rutherfordium</div> <div>(261)</div>	<div>105</div> <div>Db</div> <div>Dubnium</div> <div>(262)</div>	<div>106</div> <div>Sg</div> <div>Seaborgium</div> <div>(263)</div>	<div>107</div> <div>Bh</div> <div>Bohrium</div> <div>(262)</div>	<div>108</div> <div>Hs</div> <div>Hassium</div> <div>(265)</div>	<div>109</div> <div>Mt</div> <div>Meitnerium</div> <div>(266)</div>	<div>110</div> <div></div> <div></div> <div>(269)</div>	<div>111</div> <div></div> <div></div> <div>(272)</div>	<div>112</div> <div></div> <div></div> <div>(277)</div>	<div>113</div> <div></div> <div></div> <div></div>	<div>114</div> <div></div> <div></div> <div></div>																		
																		<div>58</div> <div>Ce</div> <div>Cerium</div> <div>140.116</div>	<div>59</div> <div>Pr</div> <div>Praseodymium</div> <div>140.90765</div>	<div>60</div> <div>Nd</div> <div>Neodymium</div> <div>144.24</div>	<div>61</div> <div>Pm</div> <div>Promethium</div> <div>(145)</div>	<div>62</div> <div>Sm</div> <div>Samarium</div> <div>150.36</div>	<div>63</div> <div>Eu</div> <div>Europium</div> <div>151.964</div>	<div>64</div> <div>Gd</div> <div>Gadolinium</div> <div>157.25</div>	<div>65</div> <div>Tb</div> <div>Terbium</div> <div>158.92534</div>	<div>66</div> <div>Dy</div> <div>Dysprosium</div> <div>162.50</div>	<div>67</div> <div>Ho</div> <div>Holmium</div> <div>164.93032</div>	<div>68</div> <div>Er</div> <div>Erbium</div> <div>167.26</div>	<div>69</div> <div>Tm</div> <div>Thulium</div> <div>168.93421</div>	<div>70</div> <div>Yb</div> <div>Ytterbium</div> <div>173.04</div>	<div>71</div> <div>Lu</div> <div>Lutetium</div> <div>174.967</div>
																		<div>90</div> <div>Th</div> <div>Thorium</div> <div>232.0381</div>	<div>91</div> <div>Pa</div> <div>Protactinium</div> <div>231.03588</div>	<div>92</div> <div>U</div> <div>Uranium</div> <div>238.0289</div>	<div>93</div> <div>Np</div> <div>Neptunium</div> <div>(237)</div>	<div>94</div> <div>Pu</div> <div>Plutonium</div> <div>(244)</div>	<div>95</div> <div>Am</div> <div>Americium</div> <div>(243)</div>	<div>96</div> <div>Cm</div> <div>Curium</div> <div>(247)</div>	<div>97</div> <div>Bk</div> <div>Berkelium</div> <div>(247)</div>	<div>98</div> <div>Cf</div> <div>Californium</div> <div>(251)</div>	<div>99</div> <div>Es</div> <div>Einsteinium</div> <div>(252)</div>	<div>100</div> <div>Fm</div> <div>Fermium</div> <div>(257)</div>	<div>101</div> <div>Md</div> <div>Mendelevium</div> <div>(258)</div>	<div>102</div> <div>No</div> <div>Nobelium</div> <div>(259)</div>	<div>103</div> <div>Lr</div> <div>Lawrencium</div> <div>(262)</div>

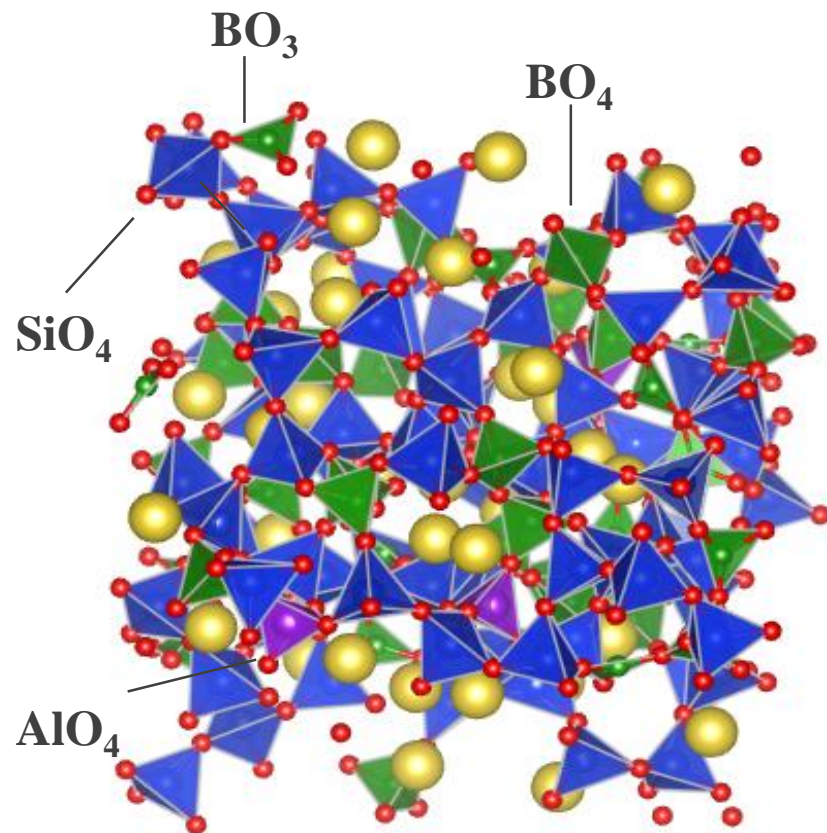
Knowledge acquired for nuclear borosilicate glass

Transition elements mainly act as intermediate elements. They have almost no impact on glass durability and viscosity, but can crystallize (cf. spinel).

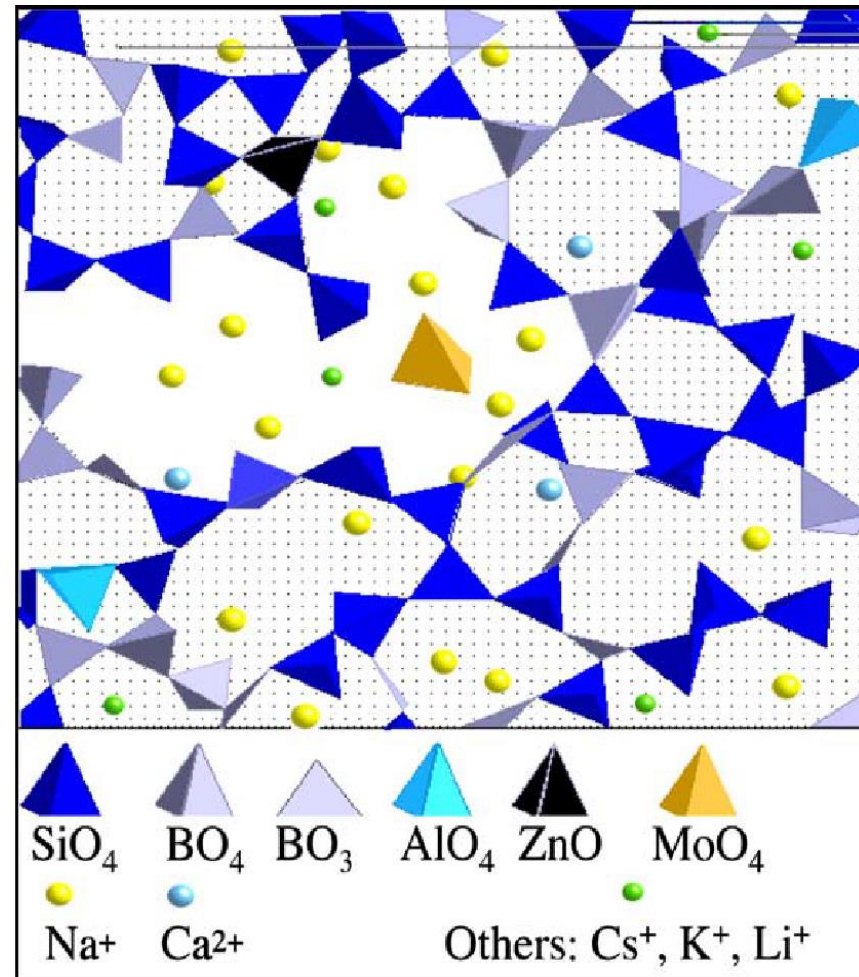
Fission products will generally act as intermediate elements. They tend to increase the resistance of glasses against water corrosion, increase glass viscosity and tend to lead to phase separation (Mo) or crystallization (RE_2O_3 , Ce, Mo).

Specific case of platinum elements: insoluble elements in borosilicate glasses. They have almost no impact on glass corrosion by water, modify the glass rheology, and act as nucleating agents for crystallization.

More complex glasses?



Complex glasses \Rightarrow a combination between an experimental approach / a statistical approach / basic knowledge on glass science is needed



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- 2) Methodology to formulate a nuclear glass
- 3) CEA experience in nuclear glass formulation

When formulating nuclear glasses:

- Elements coming from the waste solution are sustained:

Fission products / minor actinides solutions (FPS)



1 H Hydrogen 1.00794																	2 He Helium 4.003
3 Li Lithium 6.941	4 Be Beryllium 9.012182																
11 Na Sodium 22.98976928	12 Mg Magnesium 24.3050																
19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.955910	22 Ti Titanium 47.867	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938049	26 Fe Iron 55.845	27 Co Cobalt 58.933200	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.723	32 Ge Germanium 72.61	33 As Arsenic 74.92160	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.80
37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90585	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybdenum 95.94	43 Tc Technetium (98)	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.90550	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760	52 Te Tellurium 127.60	53 I Iodine 126.90447	54 Xe Xenon 131.29
55 Cs Cesium 132.90545	56 Ba Barium 137.327	57 La Lanthanum 138.9055	72 Hf Hafnium 178.49	73 Ta Tantalum 180.9479	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.078	79 Au Gold 196.96655	80 Hg Mercury 200.59	81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.98038	84 Po Polonium (209)	85 At Astatine (210)	86 Rn Radon (222)
87 Fr Francium (223)	88 Ra Radium (226)	89 Ac Actinium (227)	104 Rf Rutherfordium (261)	105 Db Dubnium (262)	106 Sg Seaborgium (263)	107 Bh Bohrium (262)	108 Hs Hassium (265)	109 Mt Meitnerium (266)	110 (269)	111 (272)	112 (277)	113	114				
58 Ce Cerium 140.116	59 Pr Praseodymium 140.90765	60 Nd Neodymium 144.24	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92534	66 Dy Dysprosium 162.50	67 Ho Holmium 164.93032	68 Er Erbium 167.26	69 Tm Thulium 168.93421	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967				
90 Th Thorium 232.0381	91 Pa Protactinium 231.03588	92 U Uranium 238.0289	93 Np Neptunium (237)	94 Pu Plutonium (244)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (251)	99 Es Einsteinium (252)	100 Fm Fermium (257)	101 Md Mendelevium (258)	102 No Nobelium (259)	103 Lr Lawrencium (262)				

Constraint 1:

All elements from the nuclear waste have to be incorporated in the glass structure

Constraint 2:

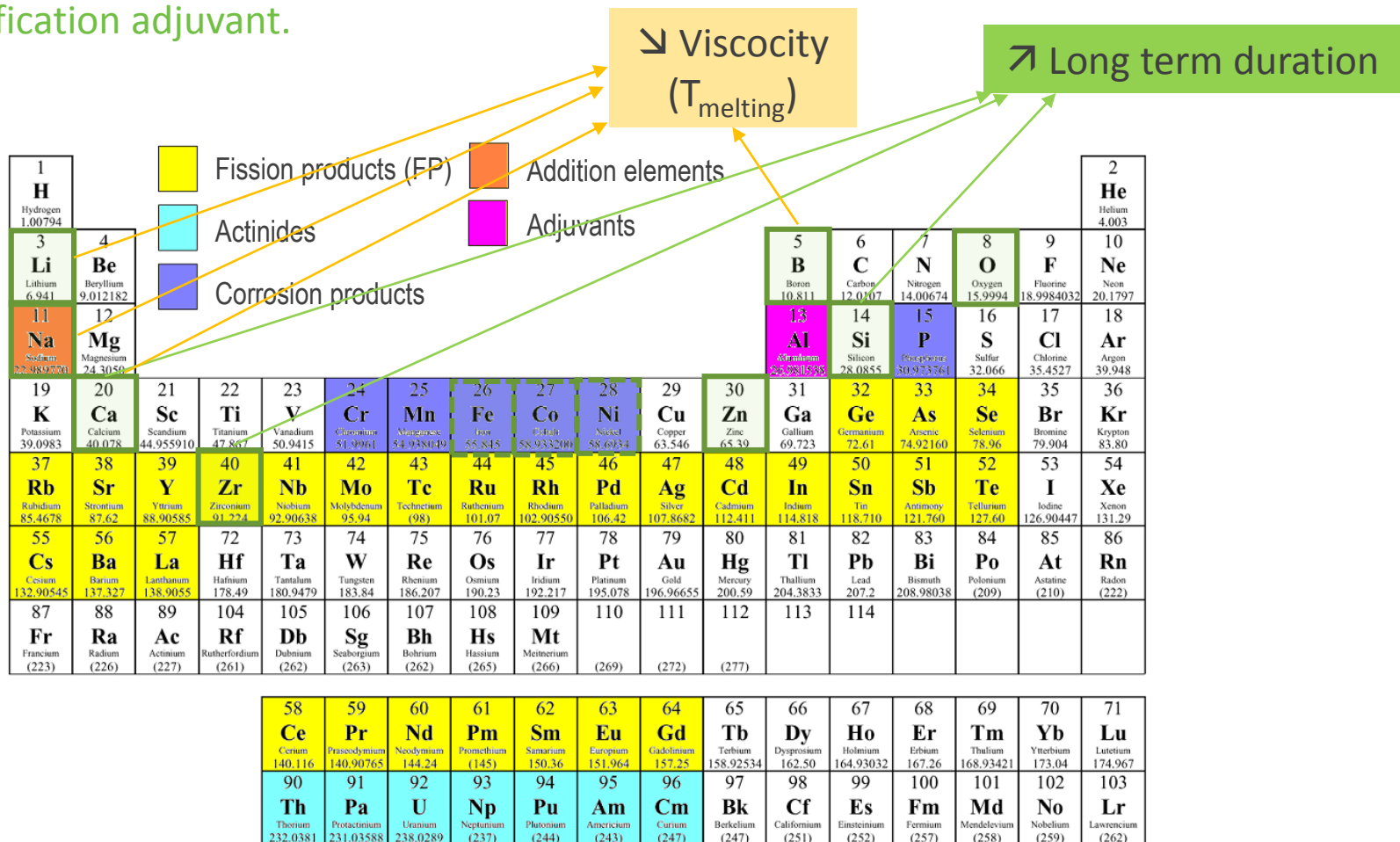
Loading rate has to be maximized to minimize storage cost

NB:

These elements are not glass formers

When formulating nuclear glasses:

- Elements coming from the waste solution are sustained,
- Glass formers (generally absent from the waste solution) have to be added
= vitrification adjuvant.



Major critical chemical elements coming from nuclear waste to be vitrified**Mo**Phase separation and
molybdates crystallization**Ru, Pd, Rh, Ag**Chemical reactivity, particle
settling, electrical conductivity,
viscosity**Nd, La, Pr, Ce, P**

Apatite crystallization

Fe, Ni, Cr

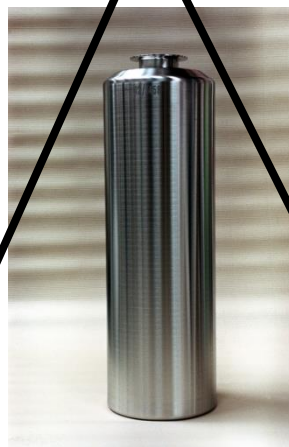
Spinel crystallization

Ru, Cs, Tc

Volatility

Waste incorporation in the glass

- * Solubility of radioelements in glass
(Mo, transition metals, rare earths, actinides, SO_4 , Ag,...)
- * Reactivity waste – glass adjuvant

**Technical feasibility at industrial scale**

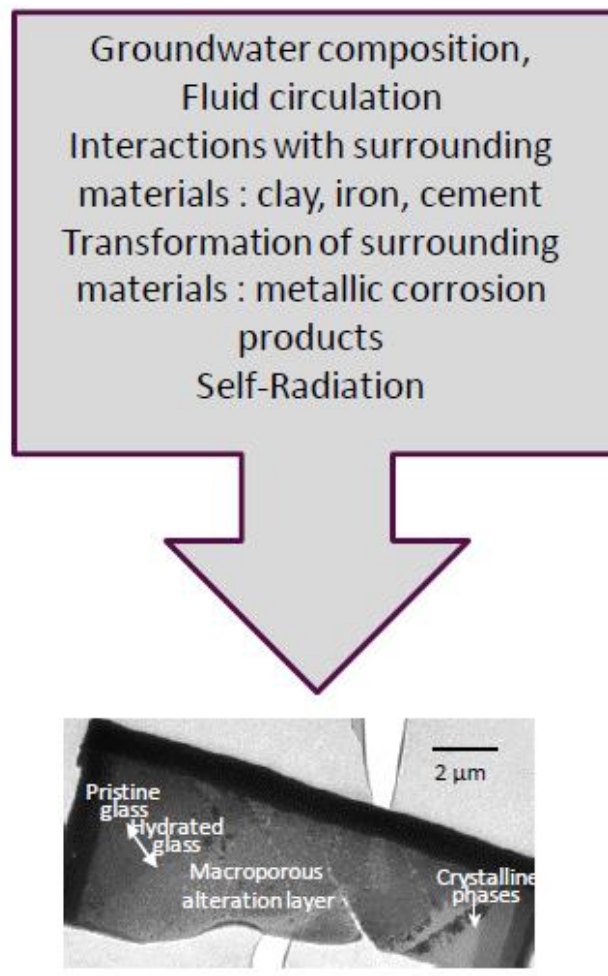
- * T_{melting}
- * Rheology (cf. cast possibility),
- * Redox
- * Reactivity (cf. production capacity)
- * Thermal and electrical conductivities

Long term behavior of glass (storage)

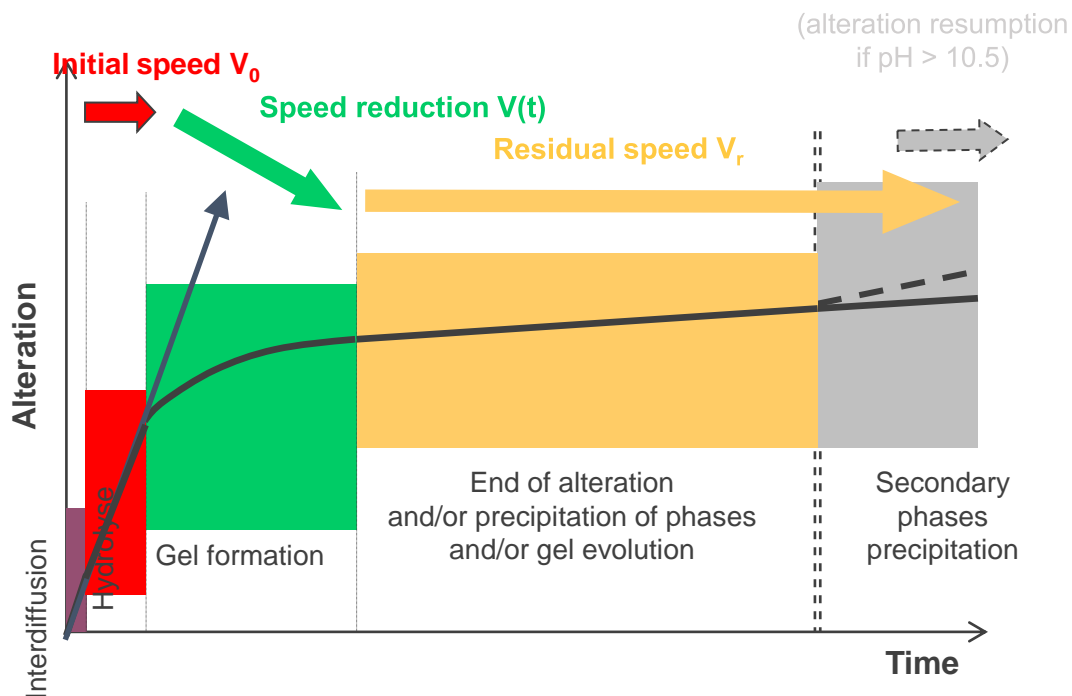
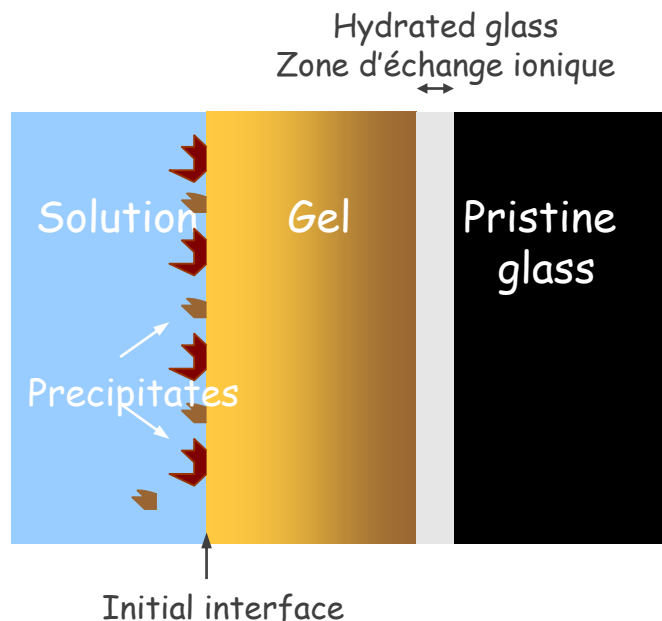
- * Thermal stability
- * Chemical durability
- * Auto-irradiation resistance

Cf. Christian LADIRAT talk

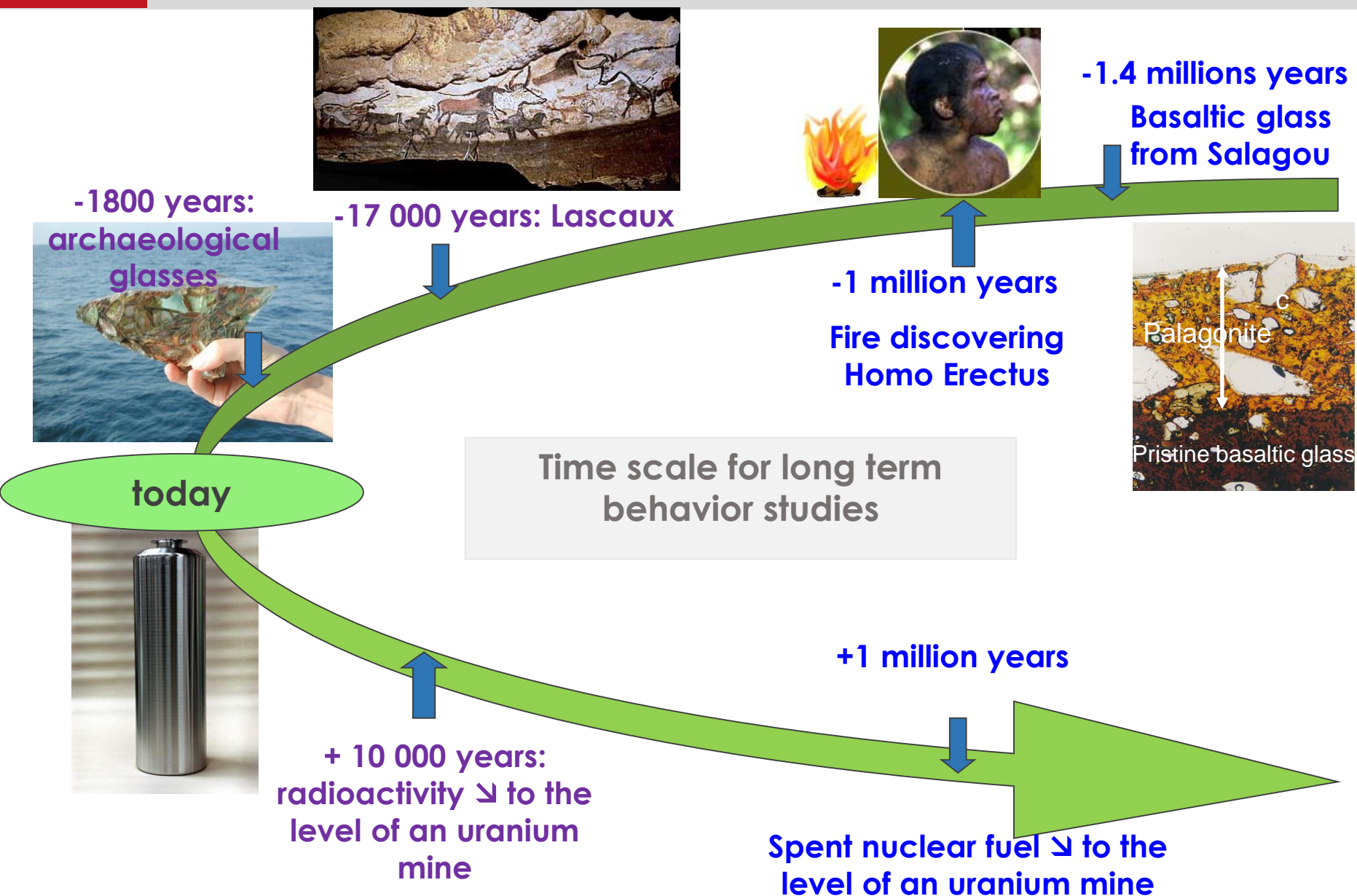
Glass – water interactions => RN release from the package



Glass – water interactions => RN release from the glass package



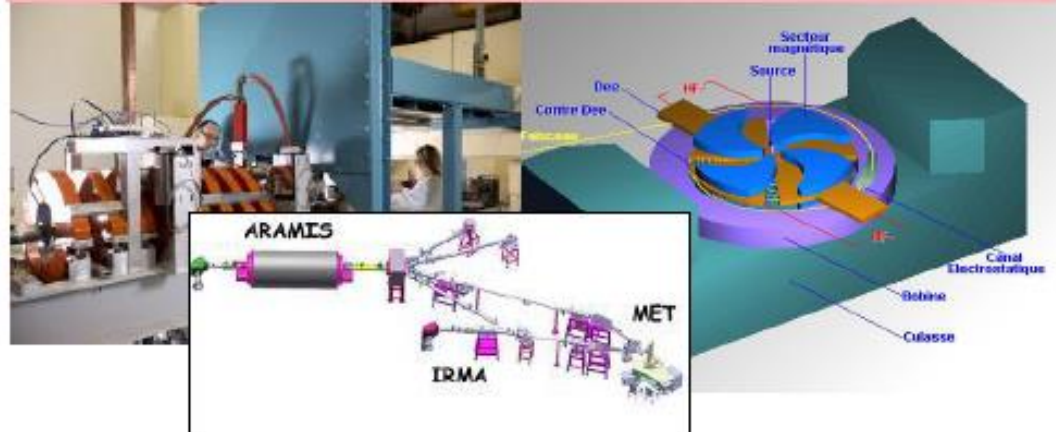
The RN release speed depends on glass composition, but also groundwater composition, fluid circulation, interactions with surrounding materials (clay, iron, cement), transformation of surrounding material (metallic corrosion, self-irradiation...)



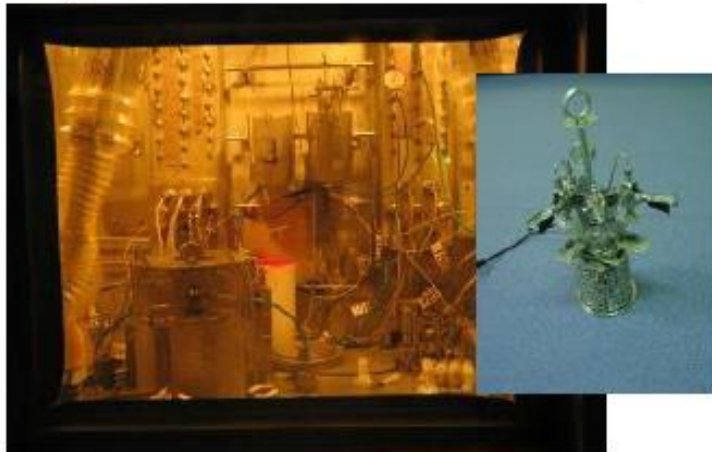
Doped glasses (^{244}Cm , ^{238}Pu , ^{239}Pu ,...)



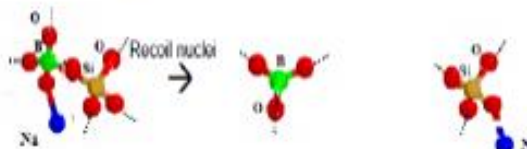
Irradiation facilities



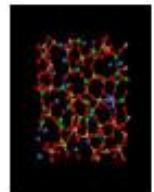
Leaching tests and measurements (effect of dose and dose rate)



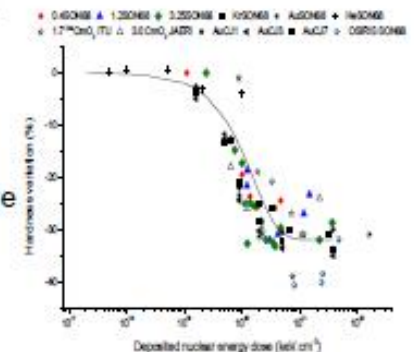
Damage / properties modelling



MD simulation of
displacement cascade:
accumulation of ballistic
disordering



- ❑ Thermal phase → local melting → network reorganization (rapid thermal quenching)
- ❑ Stabilization of a new structural state when all the volume has been damaged one time ($\sim 4 \times 10^{18} \alpha/\text{g}$)
- ❑ Stabilization of macroscopic properties (density, hardness...)



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How to formulate a nuclear glass?

⇒ No unique formulation methodology

Nuclear Glass formulation depends on:

- the type of waste (composition, variability, radioactivity level)

- * **FP solution** => limited composition domain
- * **rinse flows,**
- * **D&D operations,** } Compositions not as precisely defined as for FPS
- * **technologic waste** => Metallic phase, organic elements, minerals...

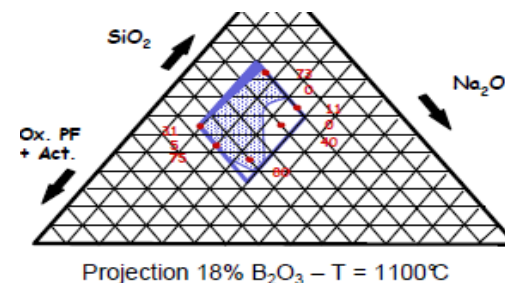
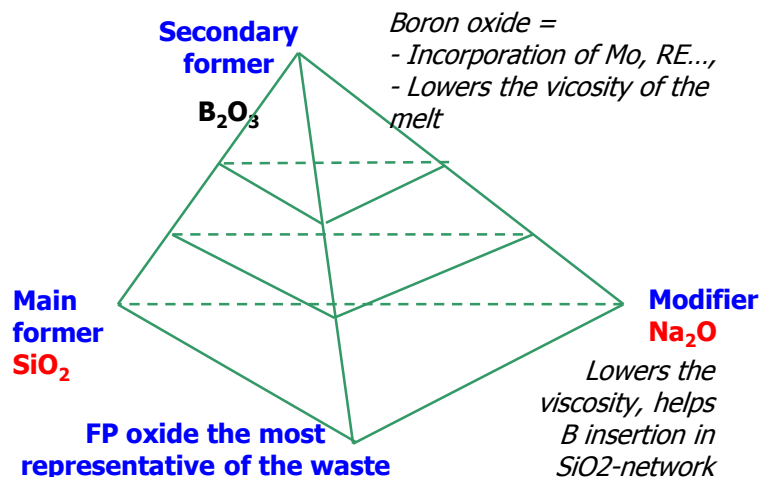
=> Reducing conditions

- the type of process

- * **hot metallic crucible** => cast, mechanical stirring
- * **CCIM** => cast, induced currents, mechanical stirring
- * **In-can melter (resistif furnace)** => no cast

⇒ Formulating a nuclear glass requires:

- A clear description of the waste (nature, composition, variability, radioactivity level...)
- A good knowledge on glass structure (⇒ identify key elements, define how to simplify the glass composition for specific studies,...)



- A good knowledge of process constraints (T_{max} , cast / no cast, redox conditions...)

⇒ a combination between an experimental approach / a statistical approach / basic knowledge on glass science is needed

Methodology

1) Waste features

- Nature
- Mean composition
- Variability

2) Process constraints

- Max T_{melting}
- Cast ?
- Melt homogeneity needed?

3) Long term behavior constraints

- Long term / middle term performances
- Homogeneous glass / crystallized glass

4) Define a few reference glass compositions based on

- Mean waste composition
- Capitalized knowledge on glass formulation
- Glass formulation modelling (cf statistical approach – see Damien PERRET talk)

5) Test these few reference glass compositions

- Glass elaboration
- Glass characterization
- First long term behavior tests

Lab scale
(inactive materials)



Technological scale
(inactive materials)



Long term behavior (water
intractions + radiations)



Specification document



Industrialization



Nuclear glass formulation: methodology

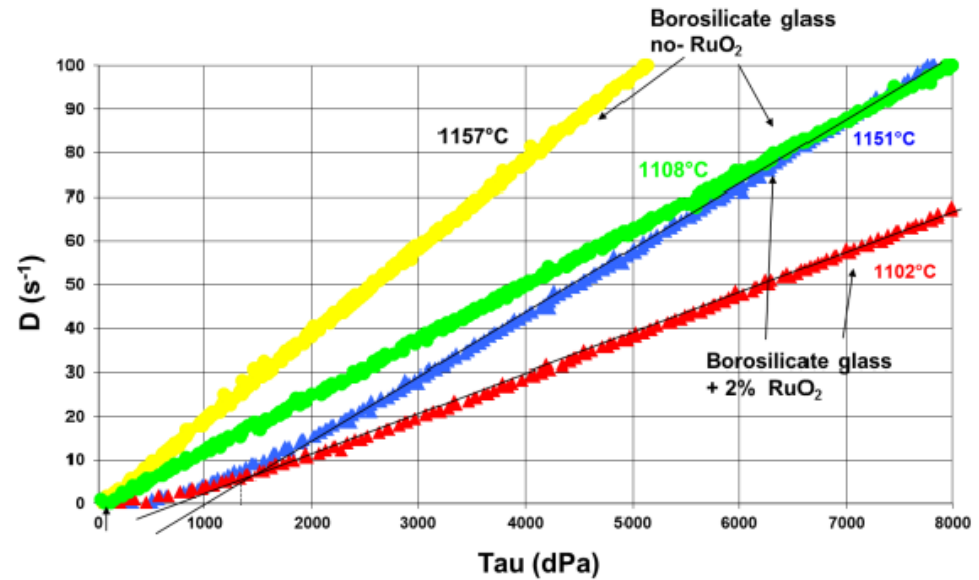
Glass melting at lab scale



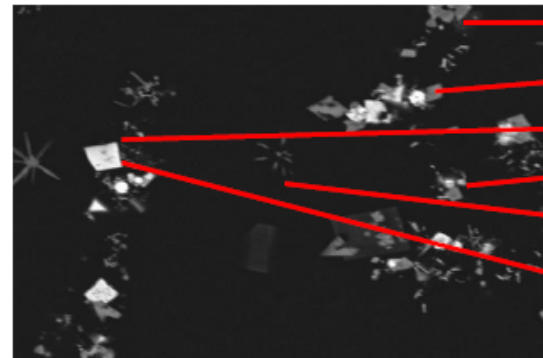
Viscosity



Melting process can be impacted by noble metal content in glass melt
(Convection, Pouring rate, Capacity)

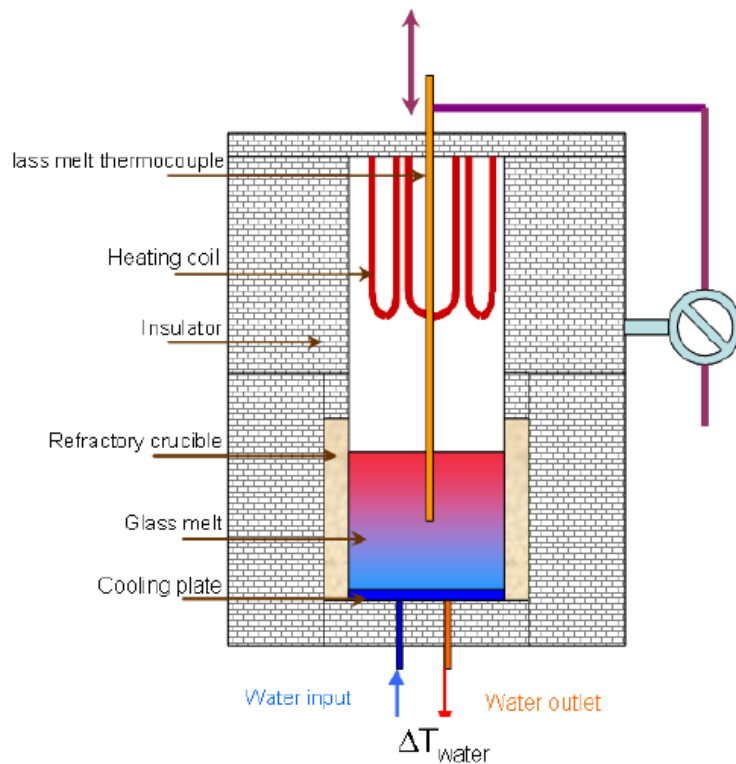


Micro-homogeneity

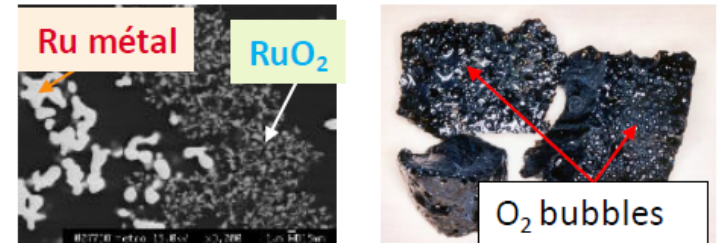


- Chromites
- Palladium-Tellure
- Cerium oxide
- RuO₂
- Silicophosphate
- Ca-molybdate

Thermal conductivity



Redox properties



Process parameters

- Melter atmosphere
- Temperature

Input data

- Glass frit composition
- (Fe²⁺/Fe³⁺) in glass frit
- Waste composition
- Nitrate concentration

Thermodynamic data on redox equilibria in the glass

- Fe²⁺/Fe³⁺
- Ce³⁺/Ce⁴⁺
- Cr³⁺/Cr⁶⁺
- Mn²⁺/Mn³⁺
- Ni²⁺/Ni³⁺
- Ru⁰/Ru⁴⁺.....

Oxygen fugacity in the final glass

Final redox ratio $M^{m+}/M^{(m+n)+}$ of multivalent elements in the glass

Examples of glass formulations

FP solutions

- * Precisely defined and nearly constant for given spent fuels (slowly evolving with increased burn-ups)
- * Long term reliability needed (Hot metallic crucible / CCIM)
- * Furnace process with glass casting

⇒ Borosilicate glass

- * Homogeneous melt (except platinoids elements)
- * limited crystallization in the final glass
- * Loading factor up to 18 wt%

*Examples of glass formulations*Legacy waste: Molybdenum-rich fission product solutions (UNGG fuels)

- * Highly corrosive ILW glass, low solubility of Mo into BSG

⇒ Designing a glass-ceramic melted material

- * Homogeneous melt (1250°C)
- * Crystallization with cooling
- * Loading factor up to 13 wt%

Examples of glass formulations

ILW waste contaminated with alpha emitters

- * Mainly arising from glove boxes used for MOX production (Melox facility)
- * Organic matter (30%) + metals (70%): gloves, power cables, metallic material or tools, dusters...

⇒ Aim:

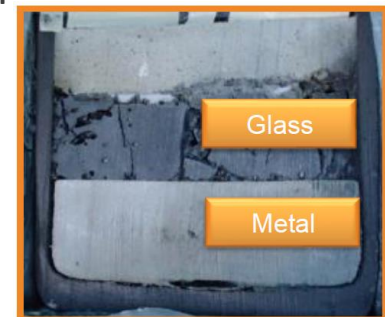
- * **Volume reduction**
- * **Organics destruction**
- * **Immobilization of TRU into a durable matrix**

⇒ **Formulation of a new glass / metal package**

- * Suitable for actinide incorporation : RN shall be confined in the glassy phase, not in the metallic part => Partition coefficients are understudy, depending on compositions

* **Description of a new ILW waste package**

- Leaching behaviour of the vitreous phase
- Corrosion mechanisms of the metallic part of the package
- Combination of both parts in expected disposal conditions



Examples of glass formulations

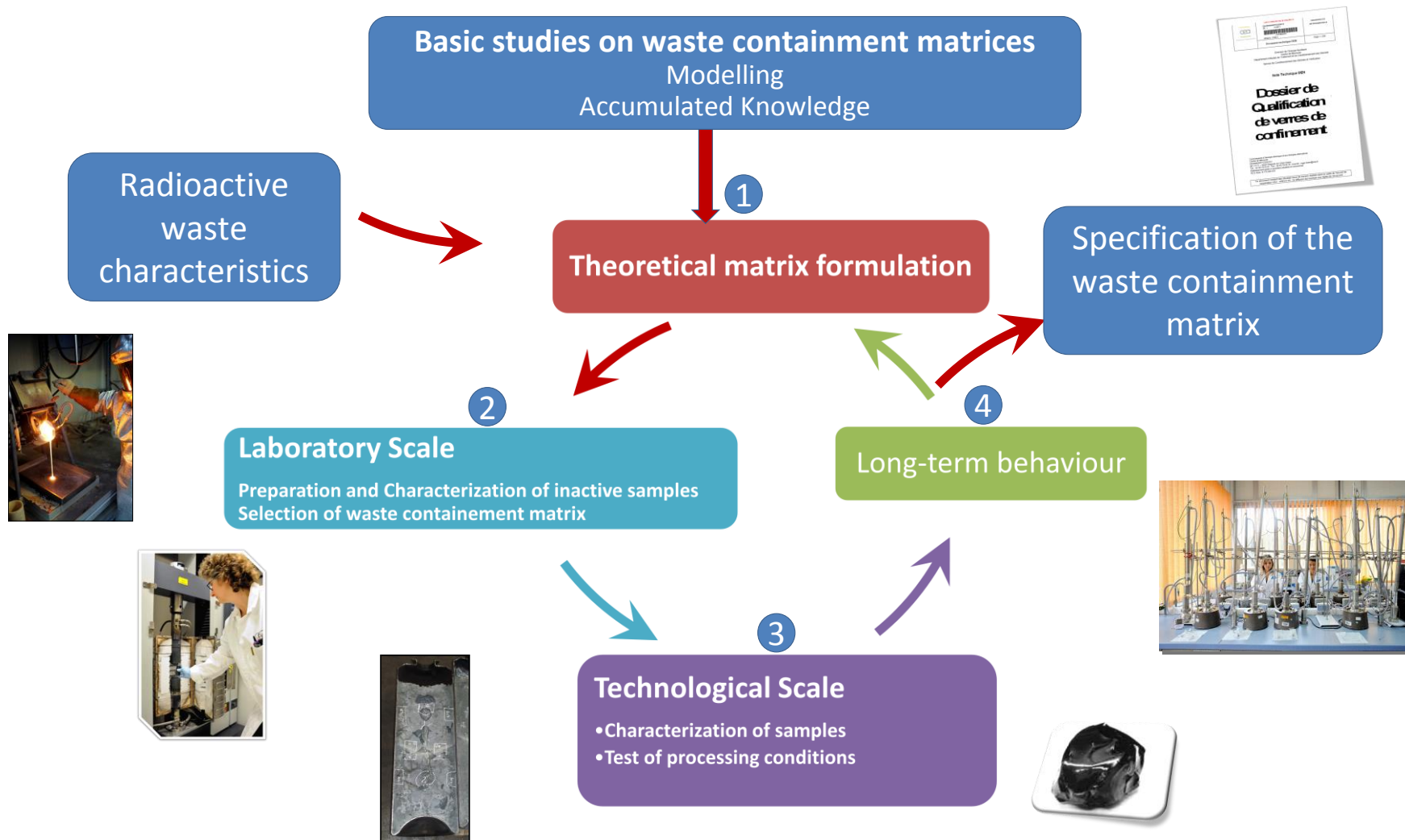
D&D operations, including legacy waste management

Material and process specification

- * Flexible and adjustable to waste with a composition poorly defined : mixed effluents such as zeolites, co-precipitation sludges, powders of fuel debris (FP and alpha components)
- * Final waste package must be suitable with existing routes and/or on-site storage facilities
- * Compact size of the process, compliant with existing hot cells under dismantling
- * “Dismantling tool” that shall be itself dismantled after use (for re-use)
- * Low quantities of secondary waste
- * Minimum investment and operation cost

Glass formulation challenge:

- * Glass formulation that can be melted at low T to avoid Cs volatilization
- * Suitable for P, Zr and Mo, elements that have a low solubility in borosilicate glasses
- * Compliant with variations of the feeding stream, characteristic of old deposits remaining in facilities that have been shut down, currently underdismantling



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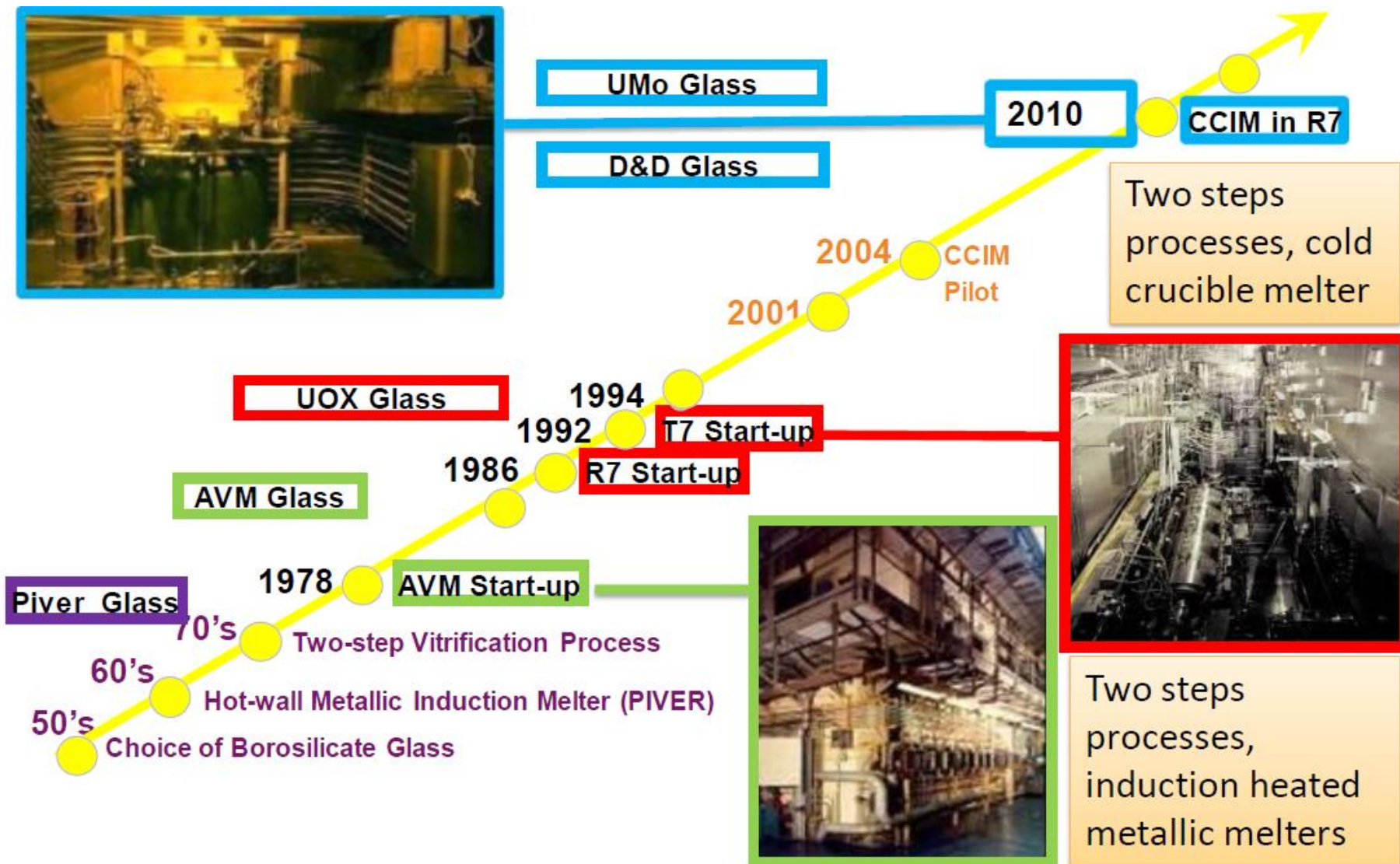
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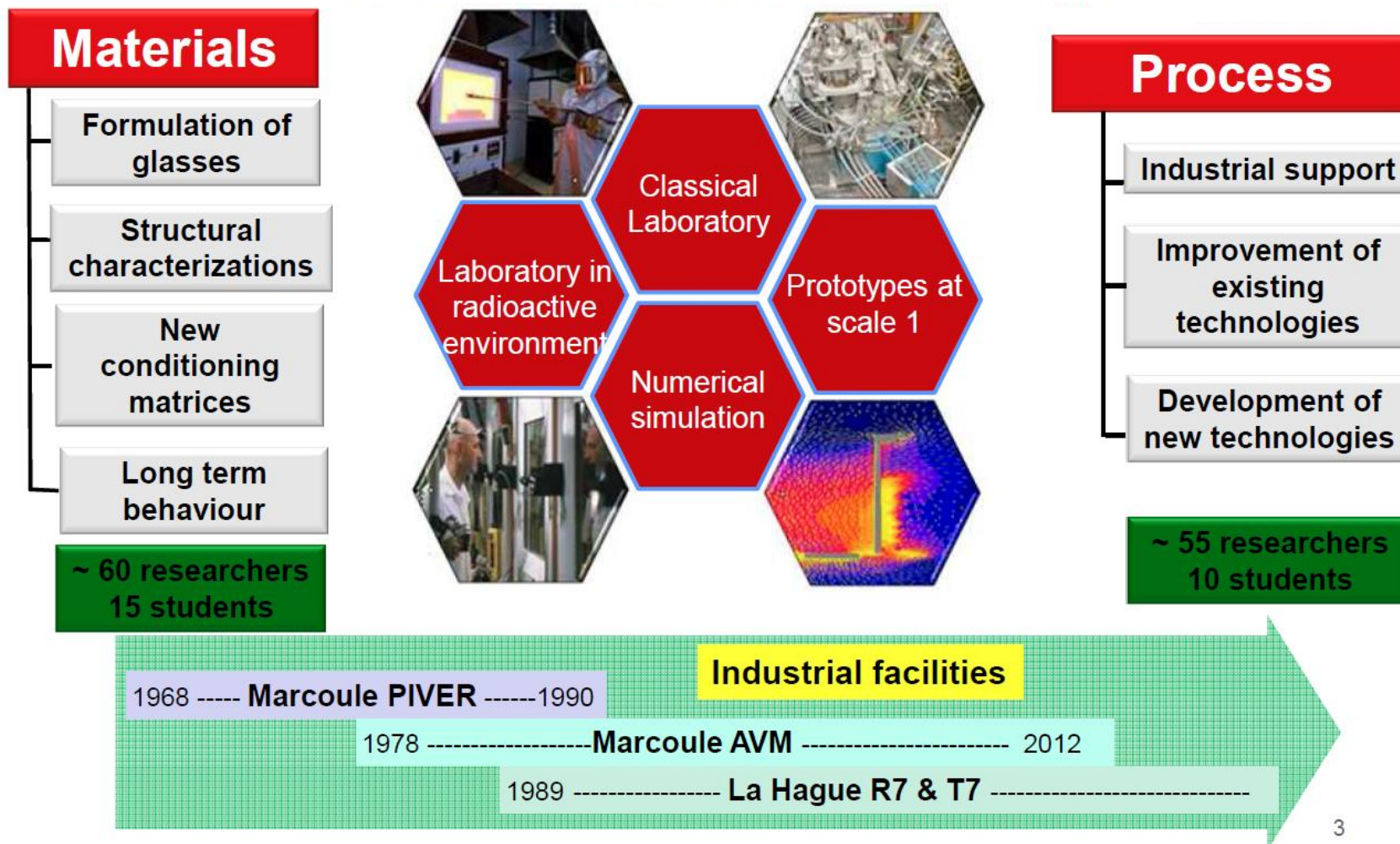
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HLW vitrification: from research to industry

From laboratory scale to industrial prototype

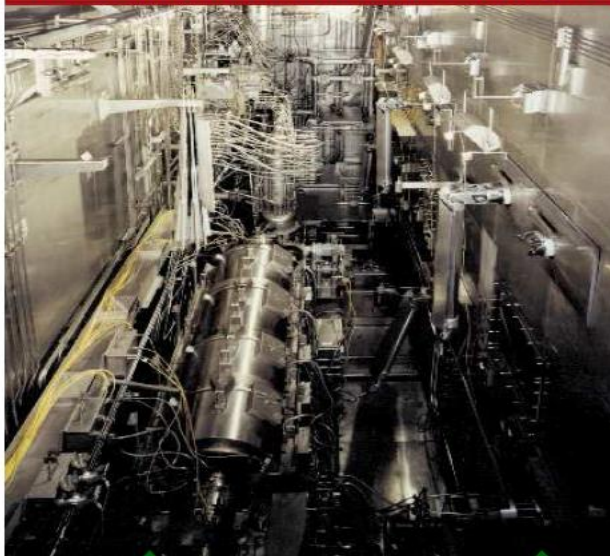


R&D in support of vitrification processes

**Vitrification
prototype
PEV Marcoule**



Hot cell for vitrification: La Hague



**Support scale 1
Non-radioactive
environment**

**Support
Radioactive
environment**

**Vitrification prototype in hot cell
DHA Atalante**



- ❑ More than 50 years of R&D on glass formulation / vitrification process at CEA
- ❑ Vitrification of 95% of the radioactivity coming from fuel recycling
- ❑ Production sites : Marcoule (1978 – 2010) La Hague (since 1989),

	Canisters (Number)	Mass of glass (Metric ton)	Activity (TBq)
AVM	3306	1220	22×10^6
R7T7	17667	7032	269×10^6
Total	20973	8252	291×10^6



- ❑ Continuous adaptation and evolution of the process up to industrial scale
- ❑ 6 specifications of nuclear glass approved by the safety authority

► **Keys to success in HLW vitrification:**

- A major program of sustained and continuing R&D (rather than by fits and starts)
- Continuous interaction between “material definition”, “technological research” and “long-term behavior”;
- Strong synergy with industry (ORANO) leading to the creation of a Joint CEA-ORANO Vitrification Laboratory in 2010.

Thanks for your attention

Acknowledgments



Glass elaboration and characterization

V. Ansault, T. Blisson, M. Chartier, V. Debono, S. Mure, J. Renard, C. Vallat

R&D scientists from CEA Marcoule

J. Agullo, O. Delattre, J.L. Dussossoy, M. Fournier, I. Giboire, I. Hugon, A. Laplace, C. Laurin, M. Neyret, D. Perret, O. Pinet, J. Renaud, E. Sauvage, S. Schuller, S. Vaubailon, F. Bart, C. Ladirat, N. Godon