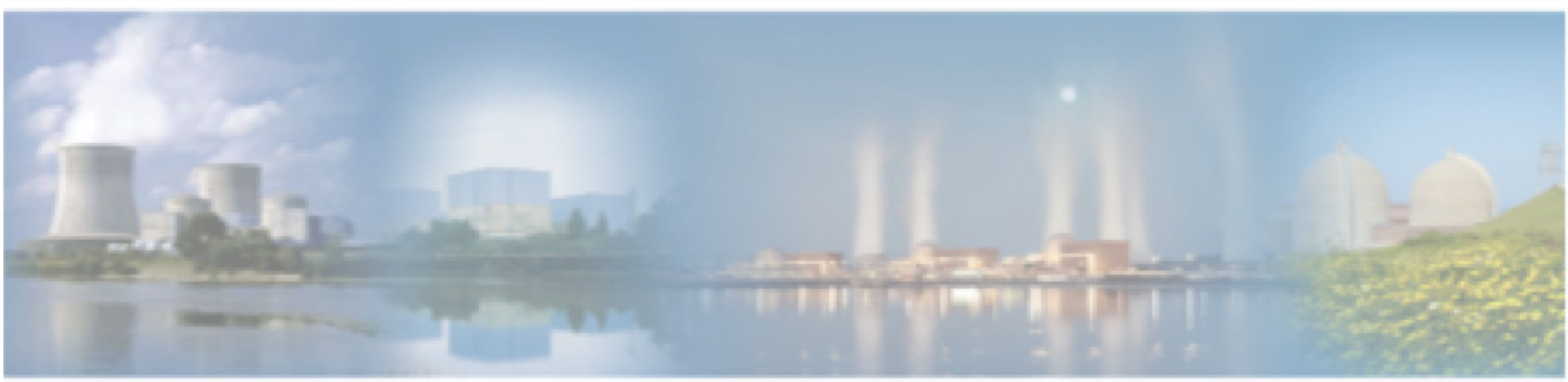
ORNL/TM-2016/ORNL/TM-2016/753

Light Water Reactor Sustainability Program

IMAC Database v.0.1. – Minerals

Yann Le Pape



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Light Water Reactor Sustainability Program
Fusion and Materials for Nuclear Systems Division

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ACRONYMS

ASR alkali-silica reaction

BASH Bourne-again shell

CBS concrete biological shield

hcp hardened cement paste

HLW high-level waste

IMAC Irradiated Minerals, Aggregates and Concrete

KJMA Kolmogorov-Johnson-Mehl-Avrami

LMA Levenberg-Marquardt algorithm

LWR light water reactor

LWRS Light Water Reactor Sustainability

MD molecular dynamics

mXRF micro X-ray fluorescence

ORNL Oak Ridge National Laboratory

QA quality assurance

RIVE radiation-induced volumetric expansion

TEM Transmission Electron Microscopy

VCS version control system

XML Extensible Markup Language

1. CONTEXT

Light water reactors (LWRs) concrete biological shields (CBSs) are exposed to high neutrons and gamma irradiations [Fukuya et al., 2002, Esselman and Bruck, 2013, Remec et al., 2016] potentially reaching levels for which degradation has been reported in the literature, i.e., 5×10^{18} n.cm^{-2} at $E > 0.1$ MeV [Hilsdorf et al., 1978, Seeberger and Hilsdorf, 1982]. Reviews of current knowledge on irradiated concrete can be found in [Willam et al., 2013, Rosseel et al., 2016]. At ~80 years of operation, it is estimated that the bounding fluence approaches 6×10^{19} n$^{E>0.1\ \mathrm{MeV}}$.cm^{-2}, i.e., about 12 times, the potentially critical dose for irradiation-induce damage onset (As countries other than the U.S. may consider different operation extension periods, the bounding fluence can be estimated proportionally). Susceptibility of concrete to neutron irradiation greatly varies as a function of its constituents, i.e., coarse aggregates, sand, and hardened cement paste (hcp). In particular, higher irradiation-susceptibility was found as a direct function of aggregates RIVE [Elleuch et al., 1972, Field et al., 2015, Le Pape et al., 2015], i.e., the propensity of swelling as a function of their minerals contents, structures and textures. Irradiation-induced amorphization, also referred to as *metamictization* when occurring naturally by α-decay in rocks bearing U, Th. . . , also induces significant density change, especially in silicates. For example, the maximum volumetric expansion of quartz and feldspars – a group of rock-forming tectosilicate minerals that make up as much as 60% of the Earth's crust [Clarke and Washington, 1924, Wedepohl, 1971] – has been shown to be as large as ≈18% [Primak, 1958, Zubov and Ivanov, 1966] and ≈8% [Krivokoneva, 1976], respectively, while the change of density in calcite remains rather low (≈0.3% according to [Wong, 1974]) Depending on the mineralogical content, considerable variations in aggregate RIVE [Dubrovskii et al., 1967, Kelly et al., 1969, Dubrovskii et al., 1970, Seeberger and Hilsdorf, 1982] have been observed as described in the comprehensive review by Field et al. [2015]. Moreover, some observed post-irradiation expansions exceed what is considered as detrimental by alkali-silica reaction (ASR) researchers (e.g., [Fournier and Bérubé, 2000, Rajabipour et al., 2015]). Because the CBS structural concrete is made of ≈ 70% of aggregates by volume, RIVE imposes severe stresses on the surrounding hcp leading to micro-cracking, or even fracturing [Le Pape et al., 2015, Giorla et al., 2016]. Because, for obvious economical reasons, the concrete used for the construction of any nuclear power plants structures is made with local materials, large variations of mineralogical composition of aggregate are expected causing major differences in terms of susceptibility against irradiation. Hence, the significance of irradiated structure depends directly on its constituents, and in particular on the aggregate-forming minerals composition, texture and volume fraction.

2. MOTIVATIONS AND OBJECTIVES

The DOE LWRS Program Materials and Aging Degradation Pathway has developed a holistic approach, based on materials characterization and modeling, to assess the susceptibility of concrete against irradiation effects and the structural significance of irradiated concrete biological shield in light water reactors (LWRs). – Fig. Figure 1. This approach aims at using experimental data collected in test reactors, and possibly after harvesting from in-service reactor, to help the development and the validation of irradiated concrete models to be utilized for the structural assessment of any specific LWR CBS.
The development of a materials database is central in order to:

1. Connect materials characterization and modeling tools with reliable irradiated properties;
2. Facilitate data searching for correlation analysis;
3. Validate irradiated concrete models, in particular, upscaling models (micromechanics or meso/micro-scale numerical models), i.e, minerals → aggregate → concrete; and,
4. Assess the susceptibility of a specific aggregate or concrete against irradiation.

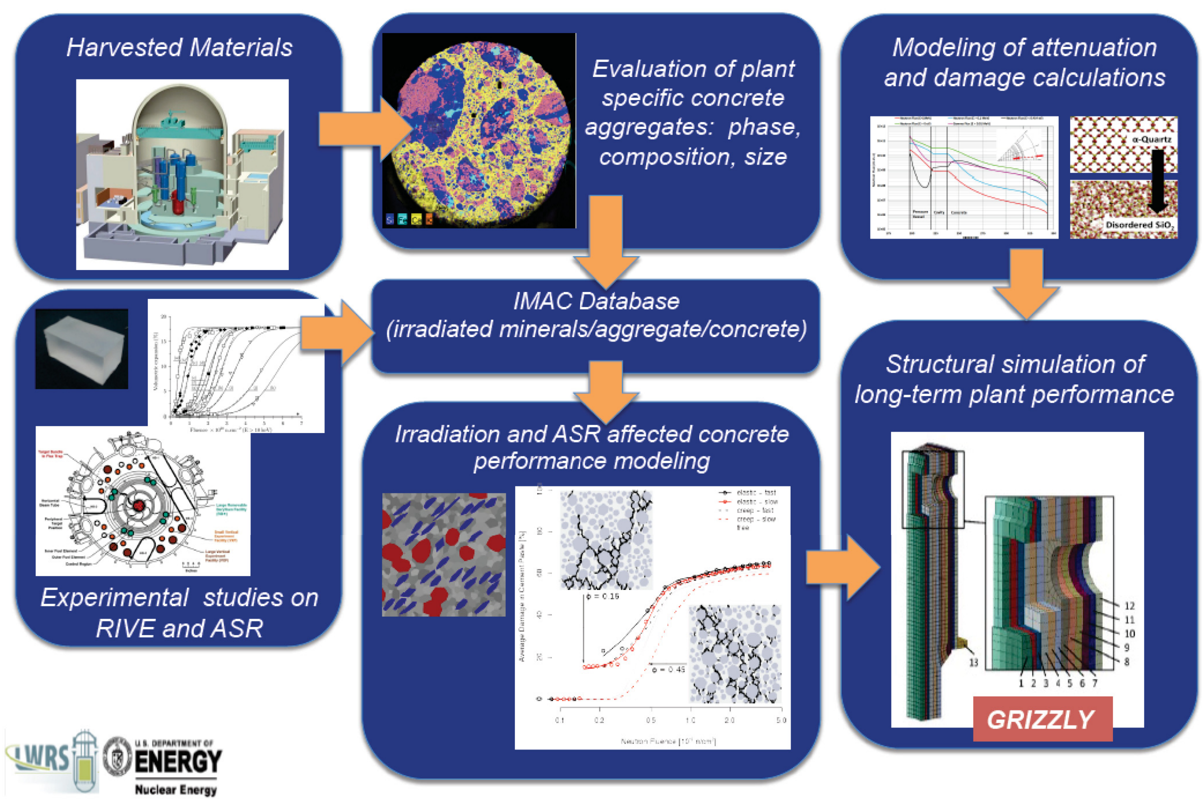


Figure 1. Risk-assessment of the irradiation effects on concrete and theirs structural significance. DOE LWRS Strategy.

A number of irradiated concrete and aggregate properties (compressive and tensile strength, Young modulus, loss of mass and radiation-induced expansion) have been previously collected [Field et al., 2015]. Although likely-silicate-bearing aggregates were found to be more RIVE-prone than likely-carbonate-bearing aggregates, it appears that the ASTM classification[ASTM C294-12] of aggregates for concrete fails to define the resistance of aggregates against neutron irradiation. Typical examples can be found in Gray [1971] where different aggregates categorized as *limestone*, i.e, primarily carbonated rocks, exhibit very low expansions, as expected for carbonates, to high linear expansions >1%. The lack of information on the detailed mineralogical contents result in inherent limitations when interpreting the data, in particular, with regard to the large observed scatter. Moreover, the representativity of irradiated aggregate or concrete data against the actual concrete composition used for CBS is more difficult to assess.

Hence, to develop a more rational classification of irradiation-sensitive aggregate, the Light Water Reactor Sustainability (LWRS) Program approach is to adopt a "bottom-to-top" methodology aiming at characterizing irradiated mineral analogues, as a first step, before studying irradiated aggregates. i.e., understanding and modeling the interactions between rock-forming minerals, in a second step, and finally, address irradiated concrete using tools previously developed [Le Pape et al., 2015, Giorla et al., 2015, 2017].

Numerous neutron-irradiated minerals RIVE are scattered in the public 'Western' literature, e.g., [Wittels, 1957, Primak, 1958, Wong, 1974, Seeberger and Hilsdorf, 1982]... along with on-going irradiated minerals analogues study at Oak Ridge National Laboratory (ORNL) [Rosseel, 2016]. In addition, more recently, Russian literature was made available to the LWRS Program researchers. These data are extremely valuable as varied minerals, aggregates formed with similar minerals, and concrete made with the same aggregate were tested in similar irradiation conditions. It must also be noted that past research programs related to high-level waste (HLW) storage resulted in the publication of data on the resistance of minerals against ion-irradiation [Eby et al., 1992, Dran et al., 1992]. More recently, electron-irradiation amorphization of minerals was also studied [Muto and Maruyama, 2016]).

However, limited data on irradiated elastic properties are still available: all elastic tensor constants, c^*_{ij}, [Mayer and Gigon, 1956, Mayer and Lecomte, 1960, Zubov and Ivanov, 1967] are available for irradiated quartz only. On-going experiments of mineral analogues aims at providing elastic properties for other minerals. It must also be said that molecular dynamics (MD) can help estimate RIVE amplitude and the c^*_{ij} constants of irradiated minerals (in particular, where data is missing), although, some uncertainties about the energy potential in complex crystalline system limit the use of these results.

Finally, the experimental characterization of rock-forming minerals in concrete aggregate using, for example micro X-ray fluorescence (mXRF) and petrographic analysis, requires elements and oxides compositions data.

The Irradiated Minerals, Aggregates and Concrete (IMAC) database aims a collecting all the aforementioned scattered information and data using a systematic approach, including the use of publicly available standard format to export the database and the documentation of the original sources. The database development tools and schedule are provided in sections 3. and 6., respectively.

3. DEVELOPMENT TOOLS

The IMAC database is currently hosted on an internal server at ORNL: `https://code-int.ornl.gov/ylb/IMAC_database`. Access is currently limited to a small number of developers. However, a public release is envisioned for Summer 2017. For the sake of increased quality assurance (QA), the database is being developed and managed by `GitLab` `https://about.gitlab.com/`, a web-based version control system (VCS) `Git` `https://git-scm.com/` repository manager with wiki and issue tracking features, using an open source licence. Any committed change, i.e., addition/modification of new/existing data and features, is tracked and recorded. The database uses primarily `Scilab` `http://www.scilab.org/`, a free open source software for numerical computation, similar to `MathLab`, to:

1. Input and structure data in the database,
2. Export the database in Extensible Markup Language (XML) files to allow the use of the third-parties software such as finite element code, and,
3. Export the database in LaTeX-format automatically-generated documentation.

The data structures generated in `Scilab` can advantageously be utilized by upscaling micromechanics-type analysis, e.g, [Le Pape et al., 2015]: minerals → aggregate → concrete.
The IMAC repository currently includes the following folders:

`bib` contains the bibliographic database `IMAC.bib`, using BiBTeX reference management software (`http://www.bibtex.org/` – For the sake of convenience, the installation of a graphical application for managing BiBTeX files is recommended: e.g., `JabRef`, `http://www.jabref.org/`, an open software using `Java`). Whenever accessible, copies of the original data sources, i.e., journal articles, proceedings, and sometimes books, are stored in `bib/pdf`. This feature allows future verification of anomalous or suspicious data. Note that BiBTeX citations entries correspond strictly to the cross-reference entries in the database `.sci` files to exchange information between the bibliographic database and the *materials* database

`doc/pub` contains the LaTeX file `IMAC_database.tex` necessary to compile the database in `.pdf` format. Note that `IMAC_database.pdf` being automatically generated, some information can be redundant. For example, each of the < 21 elastic constants data of the minerals includes the information on the experimental technique used (In most cases, the same technique was used to derive all elastic constants of the same mineral). That information is repeated in the exported file. The main reason for these duplications in the `.sci` data files is to ensure that each data point is correctly and thoroughly informed in its data structure to permit efficient data search.

`minerals` contains the minerals database *per se*. Each mineral corresponds to a specific folder name, e.g., `minerals/albite`, containing multiples data files (generally `.sci` files, although some information can also be stored in `.txt` (plain text) files when appropriate, e.g., long tables or figure captions. or `.png` image files, for scanned figure before digitization). For each mineral, a master `Scilab` file loads all information/data. The name of the master file corresponds to the folder name, i.e., the mineral names, e.g., `minerals/albite/albite.sci`.
XML exports also use the mineral names, e.g., `minerals/albite/albite.xml`.
LaTeX exports use the extension `_pub.tex`, e.g., `minerals/albite/albite_pub.xml`.

`scilab` contains `Scilab` executable files need to run the database. In particular, loading the database library and exporting the minerals database are performed by launching quick-screen-minerals.sce in a Scilab console, after configuring and launching environment_variable.sci (See config).

config contains only one configuration file, environment_variable.sci, to be edited by each user to provide information about the path to the IMAC database end export options.

lib contains all Scilab functions library files necessary for description of the data structures, e.g., mineral_template.sci, exports, e.g., xml_export.sci. It also contains Bourne-again shell (BASH) scripts to extract some general information from publicly-accessible minerals web-database, e.g., mineral_classification.sh.

reactors contains currently one file only: list_reactors.sci linking test reactor names and channels to codes used in the database. Future developments envision to add information on the neutron fluence spectrums.

4. CURRENT DEVELOPMENT STATUS

The December 2016 release includes *minerals* data only. **Currently, the IMAC database contains only 42 minerals which corresponds to about 120 Mb of source code files, `pdf` documentation, and 72,000 lines of XML output data**. The number of imported mineral may seem poor compared to the >4,500 different known minerals. However, it must be noted that this database is oriented toward concrete aggregate. In that regards, more than 90% on the crust is composed of silicate minerals. Most abundant silicates are feldspars – plagioclase ($approx$40%) and alkali feldspar (≈10%). Other common silicate minerals are quartz (≈10%) pyroxenes (≈10%), amphiboles (≈5%), micas (≈5%), and clay minerals (≈5%) [Wedepohl, 1971]. The rest of the silicate family comprises 3% of the crust. Only 8% of the crust is composed of non-silicates, i.e., carbonates, oxides, sulfides. . . Although the IMAC database is subject to expansion in the future, the current list of minerals covers, to a large extent, concrete aggregate-forming minerals. Minerals currently available in IMAC are albite, analcime, andesine, ankerite, anorthite, anorthoclase, augite, biotite, bromellite, bronzite, bytownite, calcite, cassiterite, chamosite, clinochlore, cordierite, corundum, diopside, dolomite, enstatite, fluorapatite, forsterite, hematite, hornblende, hydroxylapatite, labradorite, lizardite, magnesite, magnetite, microcline, muscovite, nepheline, oligoclase, orthoclase, periclase, phlogopite, pyrope, quartz, rutile, sanidine, siderite, silica (amorphous), and, spinel.

5. PRELIMINARY INTERPRETATION OF THE RIVE DATA

On-going studies aims to analyze the minerals RIVE data by series or groups (e.g., Dana's [Dana, 1892] new classification) and provide best-fit parameters assuming two different isothermal RIVE models (S-shaped curve – details of the equations not given here): (1) **(Z)** Zubov and Ivanov's model [Zubov and Ivanov, 1966], or, (2) **(N)** Kolmogorov-Johnson-Mehl-Avrami (KJMA) nucleation-growth model [Kolmogorov, 1937, Johnson and Mehl, 1939, Avrami, 1939, 1940, 1941]. , in conjunction with different three temperature-dependent RIVE models: (1) **(L)** linear[Le Pape et al., 2016], or, (2) **(A)** activation energy, or, (3) **(D)** Denisov's tabulated values. . The RIVE data from the IMAC database are fitted with combined models (ZL), (ZA), (NA) and (ZD) neutrons and all fluence are normalized [Denisov et al., 2012] at $E > 10$ keV. Because of the uncertainties related to the *average irradiation temperature*, temperature is analyzed as a probabilistic variable.
For the sake of illustration, the analysis made on irradiated plagioclases (feldspars) is presented. Feldspars ($KAlSi_3O_8$ - $NaAlSi_3O_8$ - $CaAl_2Si_2O_8$) are a group of rock-forming tectosilicate minerals that make up as much as 60% of the Earth's crust [Clarke and Washington, 1924, Wedepohl, 1971] Feldspars crystallize in both intrusive and extrusive igneous rocks, are also present in many types of metamorphic rock, and are also found in many types of sedimentary rocks. Feldspars are generally separated in two groups: plagioclase (Pl, sodium-calcium bearing minerals, triclinic) and alkali feldspar, also known as potash feldspars, or K-feldspar (Kfs, sodium-potassium bearing minerals, triclinic or monoclinic). The two groups meet at the high-sodium end-members, i.e., albite (Ab), oligoclase (Olg) and anorthoclase (Ano) – Figure 2. The regression model

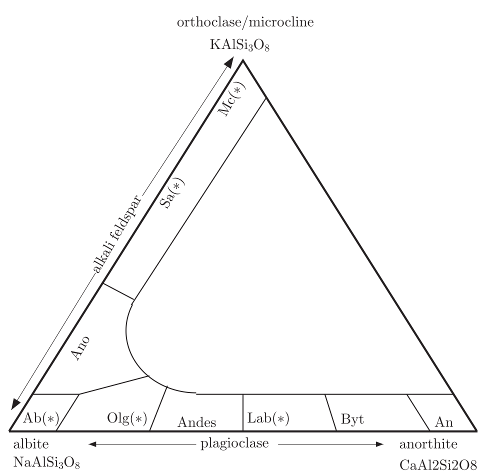
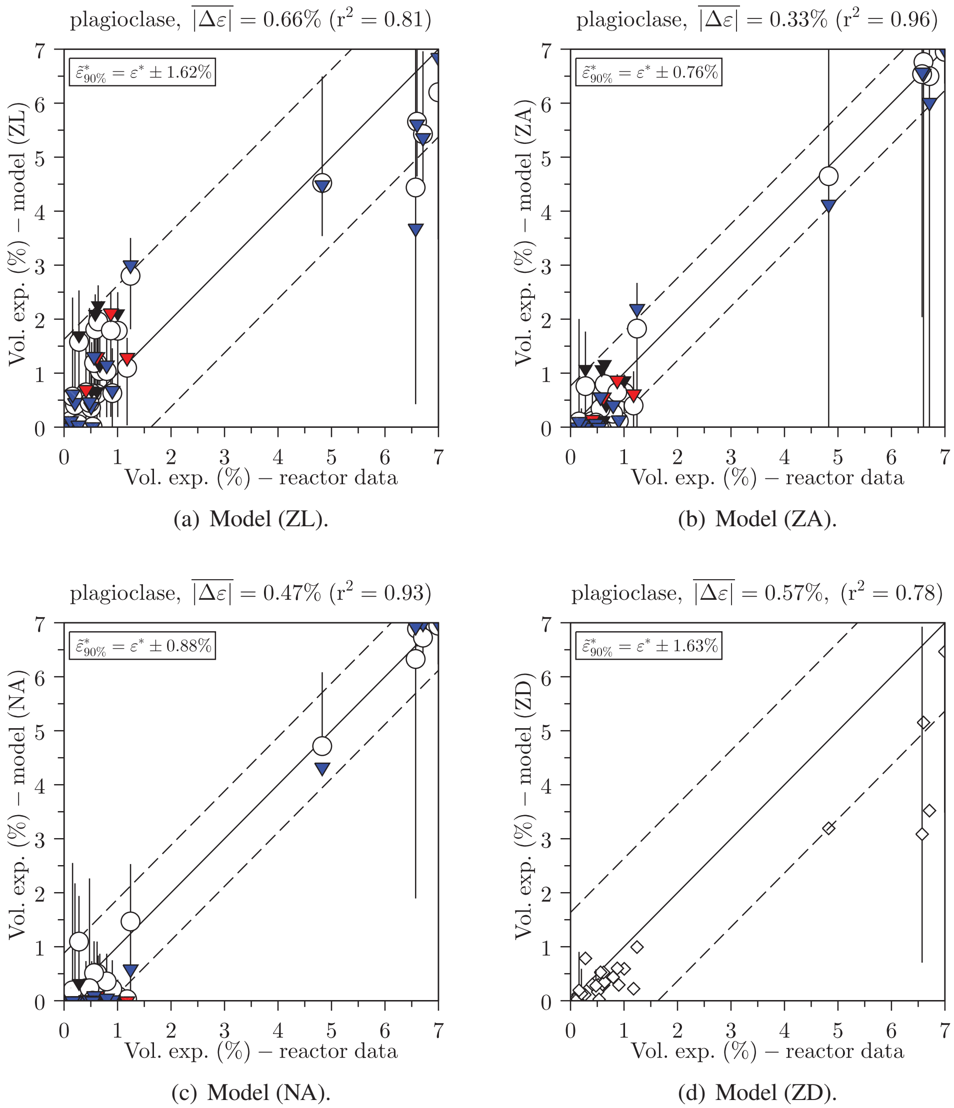


Figure 2. Feldspar ternary diagram (sodium-calcium–potassium). (∗) indicates minerals for which RIVE data are available. Ab: albite, An: anorthite, Andes: andesine, Ano: anorthoclase, Byt: bytownite, Lab: labradorite, Mc: microcline, Olg: oligoclase, Sa: sanidine

results for plagioclases expansions are presented in the scatter plots Figure 3 and in Table 1. The most *reliable* expansion model was found to be model (ZA) with $r^2 = 0.96$ and a 90% confidence intervale error of 0.76%. Similar on-going analysis are being performed on other silicates and carbonated groups. These minerals-RIVE models will be used in subsequent analysis/modeling of the irradiated aggregates to be implemented in phase 2 (v0.2) of the IMAC database.



(a) Model (ZL). (b) Model (ZA). (c) Model (NA). (d) Model (ZD).

Figure 3. Scatter plot (plagioclase). (○): Mean calculated expansions, i.e., $\bar{\bar{\varepsilon}}^*$. (▼): albite; (▼): labradorite; (▼): oligoclase: Calculated expansions assuming the mean values of the best-fit parameters. (◇): expansion at mean temperature (model ZD only). Vertical bar: min./max. calculated expansions (temperature uncertainties). Dashed lines: model error at a 90% interval confidence (See equation provided in upper-left corner of the plot).

Table 1. Plagioclases: Best-fit parameters, regression coefficients and errors. $^{(\dagger)}$: $n^{E>10\text{ keV}}.pm^{-2}{}^{\circ}C^{-1}$, $^{(\ddagger)}$: $n^{E>10\text{ keV}}.pm^{-2}$, $^{(*)}$: K. $\tilde{\varepsilon}^*_{90\%} = \varepsilon^* \pm \text{err}$

model	parameters				err	$\overline{\lvert\Delta\varepsilon\rvert}$	r^2
	$a_c^{(\dagger)}$	$b_c^{(\ddagger)}$	$a_L^{(\dagger)}$	$b_L^{(\ddagger)}$			
(ZL)	0.0173 (39%)	-0.7672 (51%)	0.0330 (20%)	-0.1765 (386%)	1.62%	0.67%	0.82
	Φ_c $^{(\ddagger)}$	$E_{a,c}/R$ $^{(*)}$	Φ_L $^{(\ddagger)}$	$E_{a,L}/R$ $^{(*)}$			
(ZA)	0.1451 (66%)	3728 (44%)	1.6110 (16%)	2118 (18%)	0.76%	0.34%	0.96
	Φ_c $^{(\ddagger)}$	$d^{(\#)}$	$E_{a,c}/R$ $^{(*)}$				
(NA)	1.7034 (20%)	9.3311 (164%)	2172 (17%)		0.88%	0.47%	0.94
	Tabulated values in Denisov's et al.						
(ZD)					1.64%	0.47%	0.79

The interpretation of highly-valuable data from the Russian literature provide new perspectives on irradiated minerals and guidance on the susceptibility of aggregates against irradiation:

- The susceptibility (ε^*_{max}) of silicates against neutron-irradiation can be ranked as follows: quartz ($\approx$ 18%) > feldspar ($\approx$ 8%) > pyroxene ($\approx$ 3%). Due their nearly perfect basal cleavage, micas RIVE data are subject to large uncertainties.
- The susceptibility (ε^*_{max}) of carbonates against neutron-irradiation, much lower than for silicates, seems to vary slightly with the substitution of calcium by magnesium: dolomite/siderite ($\approx$ 0.7%) > calcite/magnesite ($\approx$ 0.4%).

6. FY2017 DEVELOPMENT SCHEDULE

IMAC v.0.1 – Minerals (December 2016): This document.

IMAC v.0.2 – Aggregate (April 2017): A first database of irradiated concrete properties has been created at ORNL [Field et al., 2015]. The development task will consist in (1) creating a more advanced data structure to include additional properties and metadata, (2) transferring the previously acquired data in IMAC, and, (3) including addition data from the Russian and German literature.

IMAC v.0.3 – Concrete (August 2017): A first database of irradiated concrete properties has been created at ORNL [Field et al., 2015]. The development task will consist in (1) creating a more advanced data structure to include additional properties and metadata, (2) transferring the previously acquired data in IMAC, and, (3) including addition data from the Russian literature.

IMAC v.1.0 – public release (September 2017): This version of the database will be put on a publicly-accesible server.

References

ASTM C294-12. *Standard Descriptive Nomenclature for Constituents of Concrete Aggregates*. Committee C09, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959, USA.

M. Avrami. Kinetics of phase change. I. General theory. *Journal of Chemical Physics*, 7(12):1103–1112, 1939.

M. Avrami. Kinetics of phase change. II. Transformation-time relations for random distribution of nuclei. *Journal of Chemical Physics*, 8(2):212–224, 1940.

M. Avrami. Kinetics of phase change. III. Granulation, phase change, and microstructure. *Journal of Chemical Physics*, 9(2):177–184, 1941.

F. Clarke and H. Washington. The composition of the Earth crust. Technical report, United States Geological Survey, 1924.

E. Dana. *The system of mineralogy*. John Wiley & Sons, New York, sixth edition with appendices i, ii, and iii edition, 1892.

A. Denisov, V. Dubrovskii, and V. Solovyov. *Radiation Resistance of Mineral and Polymer Construction Materials*. ZAO MEI Publishing House, 2012. in Russian.

J.-C. Dran, J.-C. Petit, T. Pro, J.-M. Lameille, and M. Montagne. Radiation enhanced solubility of calcite: implications for actinide retention. *Nuclear Instruments & Methods in Physics Research*, B65:330–334, 1992.

V. Dubrovskii, S. Ibragimov, M. Y. Kulakovskii, A. Y. Ladygin, and B. Pergamenshchik. Radiation damage in ordinary concrete. *Atomnaya Énergiya*, 23(4):310–316, October 1967.

V. Dubrovskii, B. Pergamenshchik, V. Korenevskii, and V. Perevalov. Change of concrete aggregate properties under effect of neutron irradiation. *Concrete and Reinforced Concrete*, 9:25–27, 1970. in Russian.

R. Eby, R. Ewing, and R. Birtcher. The amorphization of complex silicates by ion-beam irradiation. *Journal of Materials Research*, 7(11):3080–3102, 1992.

L. Elleuch, F. Dubois, and J. Rappeneau. Effects of neutron radiation on special concretes and their components. *Special Publication of The American Concrete Institute*, 43:1071–1108, 1972.

T. Esselman and P. Bruck. Expected condition of concrete at age 80 of reactor operation. Technical Report A13276-R-001, Lucius Pitkins, Inc., 36 Main Street, Amesbury, MA 01913, September 2013.

K. Field, I. Remec, and Y. Le Pape. Radiation Effects on Concrete for Nuclear Power Plants, Part I: Quantification of Radiation Exposure and Radiation Effects. *Nuclear Engineering and Design*, 282: 126–143, 2015.

B. Fournier and M. A. Bérubé. Alkali-aggregate reaction in concrete: a review of basic concepts and engineering implications. *Canadian Journal of Civil Engineering*, 27(2):167–191, 2000.

K. Fukuya, H. Nakata, K. Fujii, I. Kimura, M. Ohmura, H. Kitagawa, T. Itoh, and K. Shin. Radiation field analyses in reactor vessels of PWRs. *Institute of Nuclear Safety System Journal*, 9:153–161, 2002. URL `http://www.inss.co.jp/e/seikae/journal9e/j9_16e.htm`.

A. Giorla, M. Vaitová, Y. Le Pape, and P. Štemberk. Meso-scale modeling of irradiated concrete in test reactor. *Nuclear Engineering and Design*, 295:59–73, 2015.

A. Giorla, Y. Le Pape, and H. Huang. Meso-scale modeling of irradiation in pressurized water reactor concrete biological shield. In V. Saouma, J. Bolander, and E. Landis, editors, *Proceedings of FraMCoS-9*, Berkeley, CA, May-June 2016. IA-FraMCoS. doi: 10.21012/FC9.238. URL http://www.framcos.org/FraMCoS-9.php#gsc.tab=0.

A. Giorla, Y. Le Pape, and C. Dunant. Computing creep-damage interactions in irradiated concrete. *Journal of Nanomechanics and Micromechanics*, 2017. Accepted.

B. Gray. The effects of reactor radiation on cement and concrete. In *Proceedings of an Information Exchange Meeting on 'Results of Concrete Irradiation Programmes'*, volume EUR 4751 f-e, Brussels, Belgium, April 19 1971. Commission des Communautés Européennes.

H. Hilsdorf, J. Kropp, and H. Koch. The effects of nuclear radiation on the mechanical properties of concrete. *Special Publication of The American Concrete Institute*, 55:223–254, 1978.

W. Johnson and R. Mehl. Reaction kinetics in processes of nucleation and growth. *Transactions of the American Institute of Mining and Metallurgical Engineers*, 135:416, 1939.

B. Kelly, J. Brocklehurst, D. Mottershead, and S. McNearney. The effects of reactor radiation on concrete. In *Proceedings of the Second Information Meeting on Pre Stress Concrete and Reactor Pressure Vessels and their Thermal Isolation*, volume EUR-4531, pages 237–265, Brussels, 1969.

A. Kolmogorov. A statistical theory for the recrystallization of metals. *Bulletin of the Academy of Sciences, USSR, Physics Series*, 1:355–359, 1937.

G. Krivokoneva. Structural changes in feldspars under impact of radiation. *Crystal Chemistry and Structural Features of Minerals*, Leningrad, Nauka:75–79, 1976. (In Russian).

Y. Le Pape, K. Field, and I. Remec. Radiation Effects in Concrete for Nuclear Power Plants - Part II: Perspective from Micromechanical Modeling. *Nuclear Engineering and Design*, 282:144–157, 2015.

Y. Le Pape, A. Giorla, and J. Sanahuja. Combined effects of temperature and irradiation on concrete damage. *Journal of Advanced Concrete Technology*, 14(3):70–86, 2016. doi: doi:10.3151/jact.14.70.

G. Mayer and J. Gigon. Effets des neutrons rapides sur quelques constantes physiques du quartz cristallin et de la silice vitreuse. *Le Journal de Physique et le Radium*, 18:109–114, 1956.

G. Mayer and M. Lecomte. Effet des neutrons rapides sur le quartz cristallin et la silice vitreuse. *Le Journal de Physique et le Radium*, 21(12):846–852, 1960.

S. Muto and I. Maruyama. Electron irradiation-induced density change of natural rock minerals, α-quartz, orthoclase, and muscovite. 70th Cement Technology Tournament Abstracts, 2016. 1317:120-121.

W. Primak. Fast-neutron-induced changes in quartz and vitreous silica. *Physical Review*, 110(6):1240–1254, 1958. ISSN 0031-899X.

F. Rajabipour, E. Giannini, C. Dunant, J. H. Ideker, and M. D. Thomas. Alkali-silica reaction: current understanding of the reaction mechanisms and the knowledge gaps. *Cement and Concrete Research*, 76: 130–146, 2015.

I. Remec, T. Rosseel, K. Field, and Y. Le Pape. Characterization of radiation fields for assessing concrete degradation in biological shields of NPPs. In *9th Topical Meeting of the Radiation Protection and Shielding Division of the American Nuclear Society – (RPSD-2016)*, Paris, France, October 3-6 2016.

T. Rosseel. Status report on the second single variable mineral analogue experiment. Technical Report ORNL/TM-2016/285, Oak Ridge National Laboratory, June 2016.

T. Rosseel, I. Maruyama, Y. Le Pape, O. Kontani, A. Giorla, I. Remec, J. Wall, M. Sircar, C. Andrade, and M. Ordonez. Review of the current state of knowledge on the effects of radiation on concrete. *Journal of Advanced Concrete Technology*, 14:368–383, 2016. Accepted.

J. Seeberger and H. Hilsdorf. Einfluß von radioactiver Strahlung auf die Festogkeit and Struktur von Beton. Technical Report NR 2505, Institut für Massivbau and Baustofftechnologie, Universität Karlsruhe, 1982.

K. Wedepohl. *Geochemistry*. Holt, Reinhart and Winston, 1971.

K. Willam, Y. Xi, and D. Naus. A review of the effects of radiation on microstructure and properties of concretes used in nuclear power plants. Technical Report NUREG/CR-7171 ORNL/TM-2013/263, U.S. Nuclear Regulatory Commission, Washington, DC 20555-0001, November 2013.

M. Wittels. Structural behavior of neutron irradiated quartz. *Philosophical Magazine*, 2:1445–1461, 1957.

C. Wong. Neutron radiation damage in some birefringent crystals. *Physics Letters A*, 50(5):346, 1974.

V. Zubov and A. Ivanov. Expansion of quartz caused by irradiation with fast neutrons. *Soviet Physics Crystallography*, 11(3):372–374, 1966.

V. Zubov and A. Ivanov. Elasticity of quartz irradiated with fast neutrons. *Soviet Physics Crystallography*, 12 (2):313–314, Sept.-Oct. 1967.

A APPENDIX A: AGGREGATES AND MINERALS HIERACHICAL CLASSIFICATION

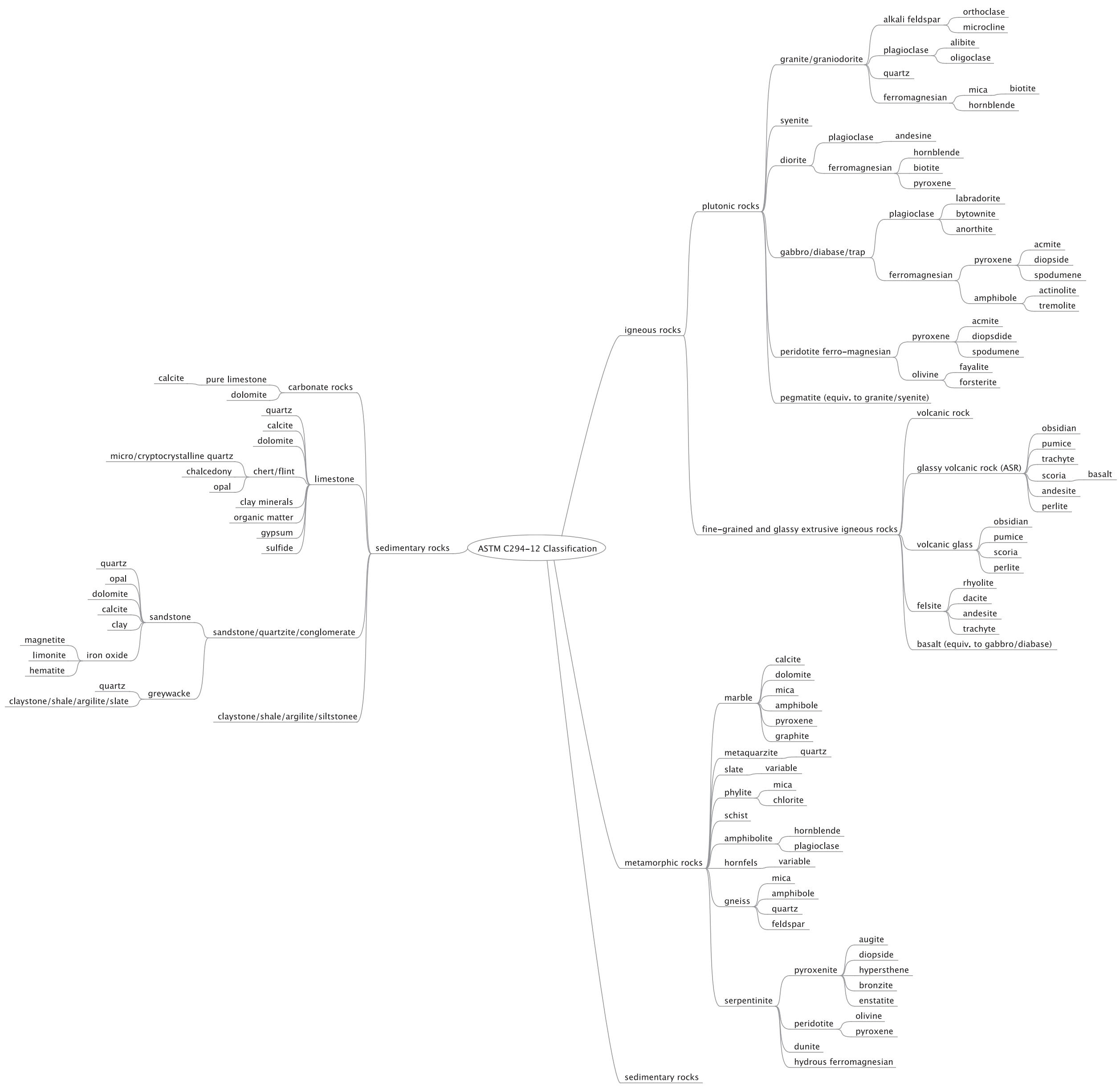


Figure 4. ASTM C294 hierarchical classification of aggregate used in concrete. The ramification extremities show the possible minerals constitutive of the rocks.

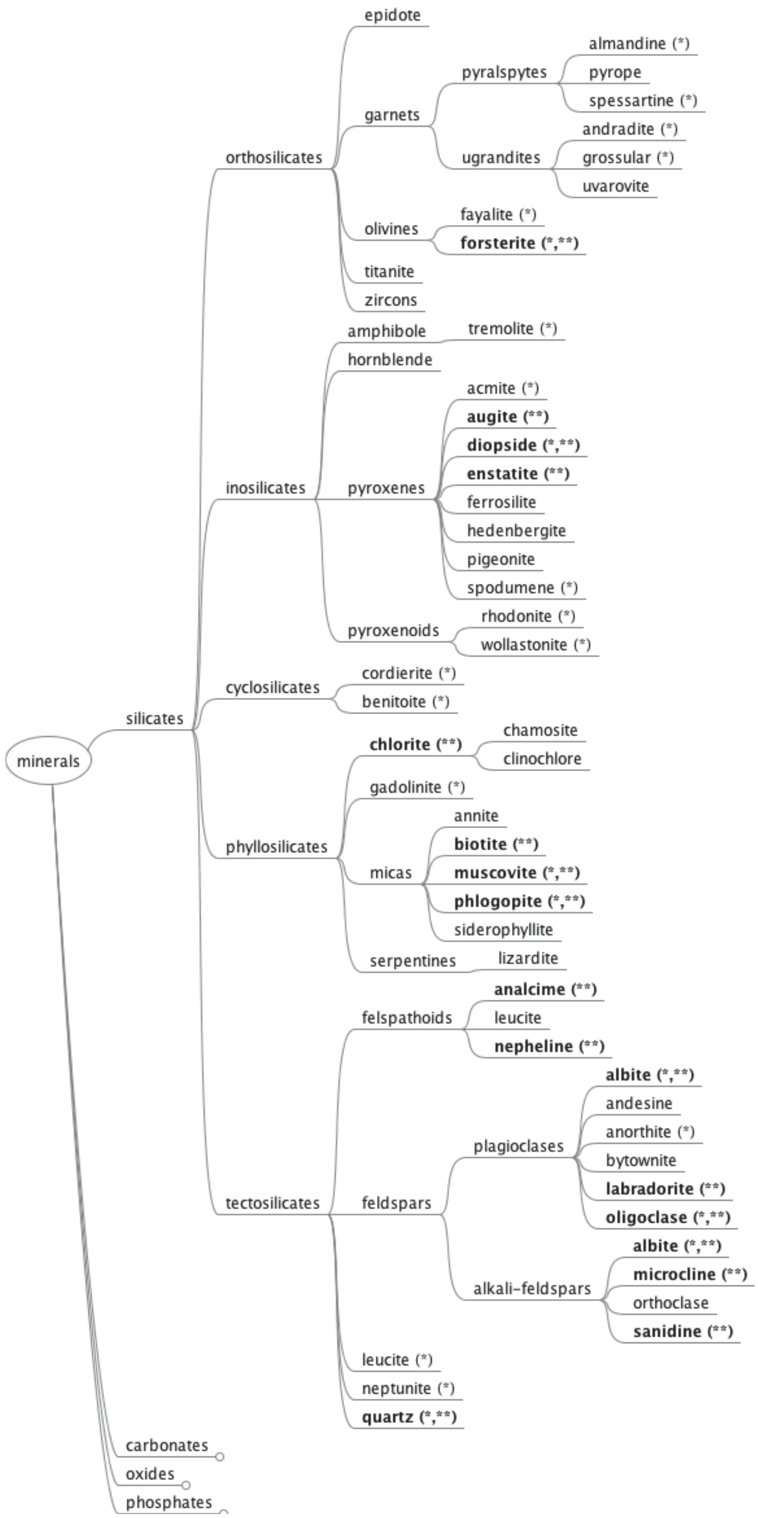


Figure 5. Hierarchical classification of silicates (non exhaustive list). (*) indicates available data obtained by ion-beam irradiation, i.e., critical amorphization dose; (**) corresponds to available data obtained by neutron irradiation.