# MFront: an open-source code generation tool for the rigorous management of material knowledge in the PLEIADES and MAP platforms

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1. **Introduction**

Numerical simulations of nuclear fuel elements made with the applications developed in the PLEIADES platform, which is co-developed by EDF, CEA and FRAMATOME, requires an advanced description of the evolution of materials under irradiation [[1](#ref-marelle_new_2016)].

Those materials may be made of ceramics, metals, composites and their evolution is influenced by the myriad of phenomena occurring during the irradiation of the fuel elements, such as viscoplasticity, damage, phase transitions, swelling due to solid and gaseous fission products, etc.

To make things even more complex, this evolution must be described during events which can have a typical time scale of a microsecond for some off-normal scenarios such as reactivity initiated incidents and time scale of many years in normal operating conditions.

The knowledge on those materials has been acquired through numerous experiments and are summarized by mathematical representation of various kinds that must be implemented numerically.

Inside the PLEIADES platform, the numerical implementation of material properties, point-wise physico-chemical models and mechanical behaviours is delegated to the MFront open-source code generator[[1]](#footnote-2) [[2](#ref-helfer_introducing_2015)], the presentation of which is the object of Section 2. The versatility of MFront and its ability to be used in many different languages and solvers allow and easy transfer of complex implementations between academic and industrial partners.

The development of fuel performance codes inside the PLEIADES platform is driven by stringent qualification requirements. So do engineering studies built on top of the Materials Ageing Plateform (MAP), developped by EDF [[3](#ref-latourte:hal-00836332)]. This observation led to a common effort by CEA, EDF and FRAMATOME to build a rigorous material knowledge management

strategy from experimental data to engineering studies. The result of this effort is discussed in Section 3. In this context, several tools, built on top of MFront and the Salomé platform have been released as open-source projects.

1. **An updated overview of the MFront code generator**

MFront is a code generation tool dedicated to material knowledge (material properties, behaviours, point-wise models) which special focus on mechanical behaviours for which MFront has been applied to a large number of phenomena, including:

* Damage, plasticity, viscoplasticity at the macroscopic scale.
* Hyper-plasticity and hyper-viscoplasticity.
* Single crystal plasticity and viscoplasticity [[4](#ref-portelette_crystal_2018)].
* Homogeneization.
* Generalized behaviours used for example in variational approaches to fracture, Cosserat media, micromorphic approaches or strongly coupled multi-physics models (solved in a monolithic manner).

Many examples and tutorials are available in the MFront gallery[[2]](#footnote-3). The list of publications using MFront highlights the diversity of the potential applications and the wide range of its academic and industrial users which goes far beyond the realm of nuclear industry[[3]](#footnote-4).

The main goals of the development of MFront are:

* Ease of use through the use of tensorial objects to mimic as much as possible the mathematical expressions and the notion of Domain Specific Languages (DSLs) (see Section 2.1) and bricks (see Section 2.1.1). DSLs and bricks eliminate boiler plate code and numerical details to let the user focus on the physics to be treated.
* Numerical efficiency. The underlying linear algebra library, called TFEL/Math leverages many advanced techniques (template metaprogramming, expression templates, loop unrolling, tag dispatching, etc.) to achieve high performances. Interested reader may refer to the various benchmarks available on the MFront website which compares MFront implementations to legacy implementations in various mechanical solvers.
* Code quality. An extensive documentation and many tutorials are available. More than (18,000) unit tests have been introduced which provide an extensive coverage of the facilities provided by MFront.
* Portability. This term may have two meanings regarding MFront:
  + MFront is available on a wide range of operating systems (LiNuX, Mac Os, Windows, FreeBSD, etc.) and is compatible with all major C++ compilers (gcc, clang, icc, Visual Studio, etc.).
  + Implementations based on MFront are written independently of any solver or programming language. MFront provides so-called interfaces which are used to generate code for a specific solver or programming language (see Section 2.2).
  1. **Domain specific languages**

MFront provides several Domain Specific Languages (DSLs) which are meant to simplify the implementation of a given material knowledge. Apart from a DSL dedicated to material properties and a DSL to simple point-wise models, all the other DSLs are related to the implementation of (mechanical) behaviours. The most useful ones simplify the integration of the constitutive equations using implicit schemes[[4]](#footnote-5), which are usually more efficient than other methods and also give access to the so-called consistent tangent operator [[5](#ref-simo_consistent_1985)].

* + 1. **Behaviour bricks**

In many cases, the implementation can be further simplified by making assumptions on the behaviour treated. In MFront, this defines the role of behaviour bricks.

For example, the StandardElasticity brick[[5]](#footnote-6) can be used to simplify implicit implementation of strain based behaviours based on the following very common assumptions:

* The total strain can be additively split in an elastic part and an inelastic part.
* The relationship between the stress and the elastic strain is given by the Hooke law.

The StandardElasticity brick allows to focus on the implementation of the constitutive equations related to the inelastic part of the strain and automatically provides support for plane stress and the computation of the consistent tangent operator.

* + 1. **Example of the StandardElastoViscoplasticity brick**

The StandardElastoViscoplasticity brick provides a rich catalog of inelastic (plastic and viscoplastic) flows that can be composed with several standard isotropic and kinematic harderning rules, as detailed in the online documentation[[6]](#footnote-7).

This brick has been recently extended to porous plasticity for the description of ductile failure.[[7]](#footnote-8)

The StandardElastoViscoplasticity brick allows a simple declarative syntax of complex mechanical behaviours as demonstrated by the following example which implements a non-associated plastic behaviour based on the Mohr-Coulomb:

@Brick StandardElastoViscoPlasticity{  
 stress\_potential : "Hooke" {  
 young\_modulus : 150.e3,  
 poisson\_ratio : 0.3  
 },  
 inelastic\_flow : "Plastic" {  
 criterion : "MohrCoulomb" {  
 c : 3.e1, *// cohesion*  
 phi : 0.523598775598299, *// friction angle or dilatancy angle*  
 lodeT : 0.506145483078356, *// transition angle*   
 a : 1e1 *// tension cuff-off parameter*  
 },  
 flow\_criterion : "MohrCoulomb" {  
 c : 3.e1, *// cohesion*  
 phi : 0.174532925199433, *// friction angle or dilatancy angle*  
 lodeT : 0.506145483078356, *// transition angle*   
 a : 3e1 *// tension cuff-off parameter*  
 },  
 isotropic\_hardening : "Linear" {R0 : "0"}  
 }  
};

**2.2 Portability of MFront implementations**

Implementations of MFront are translated into a set of C++ sources specific to the targeted language or solver through the notion of interfaces.

* + 1. **Available interfaces for mechanical behaviours**

For mechanical behaviours, MFront provides interfaces to a large number of solvers:

* Industrial nuclear fuel performance codes such as Cyrano [[6](#ref-petry_cyrano3_2015)], Copernic [[7](#ref-garnier_copernic_2004-1)] and Galileo [[8](#ref-vioujard_galileo_2010)].
* Open-source or research finite element solvers, such as [Cast3M](http://www-cast3m.cea.fr/), [code\_aster](https://www.code-aster.org/), [Europlexus](http://www-epx.cea.fr/), [CalculiX](http://www.calculix.de/).
* Commercial finite element solvers such as [Abaqus/Standard](https://www.3ds.com/fr/produits-et-services/simulia/produits/abaqus/), [Abaqus/Explicit](https://www.3ds.com/fr/produits-et-services/simulia/produits/abaqus/), [Ansys](https://www.ansys.com/), [ZMAT](http://zset-software.com/)
* Fast-Fourier Transform solvers such as TMFTT and [AMITEX\_FFTP](http://www.maisondelasimulation.fr/projects/amitex/general/_build/html/index.html).

Experimental interfaces are being considered for [diana-fea](https://dianafea.com/), [COMSOL Multiphysics](https://www.comsol.fr/comsol-multiphysics) and [LS-DYNA](http://www.lstc.com/products/ls-dyna).

* + 1. **The MFrontGenericInterfaceSupport (MGIS) project**

The MFrontGenericInterfaceSupport (MGIS) project has been initiated as an answer to the growing interest for coupling MFront with various open-source and commercial solvers [[9](#X01552cf3f0482bc543468319cc90e64d47a06e6)]. This project is written in C++ and provides bindings for C, Python, Fortran and Julia.

MGIS has been integrated in many project, with various level of integration and maturity, including: [OpenGeoSys](https://www.opengeosys.org/), [mgis.fenics](https://thelfer.github.io/mgis/web/mgis_fenics.html), [mfem-mgis](https://github.com/thelfer/mfem-mgis), XPer [[10](#ref-perales:hal-01899269)], [MoFEM](http://mofem.eng.gla.ac.uk/mofem/html/) [[11](#ref-Kaczmarczyk2020)], [Kratos Multiphysics](https://github.com/KratosMultiphysics/Kratos), [JuliaFEM](https://github.com/JuliaFEM/MFrontInterface.jl), [OOFEM](http://www.oofem.org/), [NairnMPM](http://osupdocs.forestry.oregonstate.edu/index.php/NairnMPM), [Disk++](https://github.com/wareHHOuse/diskpp), etc…

* + 1. **Legacy implementations**

MFront may also be used as a wrapper to share legacy implementations [[12](#ref-helfer_using_2020)]. A typical use case is to wrap an implementation written in fortran for the umat interface proposed by Abaqus/Standard.

Using MFront as a wrapper allows users of solvers interfaced with MFront, notably those using [MGIS](https://github.com/thelfer/MFrontGenericInterfaceSupport) to have access to an outstanding collection of behaviour implementations.

It also allows a transition from an existing implementation to an MFront implementation and validate the new implementation both in terms of physical results and numerical performances. Hopefully, the latter may be more efficient and maintanable.

1. **Material knowledge management within the PLEIADES and MAP platforms**

MFront is one of the basic tools used to build a rigorous material knowledge management strategy within PLEIADES platform. Such strategy is essential for the verification and validation of fuel performances codes. The same concerns are shared by the MAP platform which provides advanced constitutive laws to support EDF engineering studies.

A working group, called VAES, a french acronym for Separated Effect Validation, composed by members of CEA, EDF and FRAMATOME has been constituted to:

* Provide common file format to store experimental data, MFront implementations, unit tests and identify the parameters of constitutive equations.
* Ensure a consistent path from experimental data to nuclear fuel elements simulation codes. The same implementation used for the identification of the material parameters of the constitutive equations must be used in all the solvers and fuel performance codes of interest.
* Create continuous integration projects, such as MFrontGallery[[8]](#footnote-9), with can execute appropriate unit-tests which guarantee the non-regression of the results as MFront and the solvers of interest evolve.

In this process, the identification has been identified as a crucial step. A dedicated tool, called LC0D, based on several open-source dependencies such as MFront and ADAO, has been developed.

1. **Conclusions**

The MFront code generator is a major building block of the PLEIADES platform.

Since MFront has been released in open-source in late 2014, a large community of users from the academic and industrial world well beyond the scope of the nuclear industry has grown.

Thanks to MFront versatility and portability, in the sense detailed in Section 2, a rigorous material knowledge management is being developed by CEA and its industrial partners and applied to the fuel performance codes developed within the PLEIADES platform.

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