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Power transient analysis of fuel-loaded reflector experimental devices in Jules Horowitz Material Testing Reactor

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ABSTRACT

The Jules Horowitz Reactor (JHR) is designed to be the 100 MW Material Testing Reactor (MTR) which achieves the most important experimental capacity in Europe. It has been conceived to perform several irradiation tests at a time – taking advantage of many positions both in the core and in the reflector. The locations inside the reflector zone may utilize an intense thermal neutron flux to test the properties of fuel materials and to produce radioisotopes for medical purposes. High sample irradiation rates are achieved in the reflector area and a relevant power can be generated here, due to fissile materials inside these fuel test samples: about 60 kW for ADELINE test devices, some 120 kW for MADISON and up to about 650 kW for MOLFI. Then, power transient analyses are requested for these devices, mainly in connection with the reactor shutdowns. Energy deposition in the fuel samples – which are placed in the reflector – has been evaluated considering both normal operation and different reactor shutdown procedures. The analysis has been carried out by dividing the reactor system into two portions: the core as a neutron source and the reflector as a subcritical system. First, core power transients have been simulated by means of DULCINEE point kinetics code. Then, the neutron flux inside the reflector has been evaluated through the Monte Carlo transport code TRIPOLI 4.8, starting from the previously computed source. Both nominal operation and different configurations of control rod insertions have been taken into account. This evaluation provided a description of core-device coupling in terms of flux shape in the reflector. Main focus is on power deposition in samples which is of course affected by flux shape. Thus, point kinetics approach has been applied to the core as a source irradiating the samples that are considered coupled through the parameters evaluated by Monte Carlo. Power transients have been calculated both for energy deposition due to neutron-induced fission reactions and for gamma radiation as well. Results matched technical needs for the cooling loops optimization and the safety scenarios.

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1. Introduction

Research and development in nuclear technology is mainly aimed at the optimization and the enhancement of power plants design and operation. Therefore, several tests are needed to qualify the structural materials and to characterize the fuel behavior during nominal conditions or accident scenarios.

Then, several experiments are carried out in Material Testing Reactors (MTRs) to achieve neutron flux and gamma irradiation which are representative of nuclear power plants. A decade ago, the French Atomic Energy Commission (CEA) has launched the construction of a new research facility in Cadarache research center. The Jules Horowitz Reactor (JHR) is intended to be the MTR which achieves the most important experimental capacity in Europe (Bignan et al., 2012).

The irradiation positions placed inside the core of the JHR have been designed to reach elevated dose rates, taking advantage of a high power and a quite hard neutron spectrum. In addition, a significant thermal flux has been envisaged within the reflector area. In these reflector positions, the fuel materials are tested by means of particular devices for nominal operations, power transients and accident simulations.

High experimental capability is achieved inside the reflector, since several fuel pins and fissile samples are charged and irradiated at the same time. Then, a significant power is released also in these devices: about 60 kW for ADELINE test devices, some

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Nomenclature

List of utilized symbols

$\phi(\mathbf{r},E,\hat{\mathbf{\Omega}},t)$, v	neutron angular flux and velocity
$\underline{L}$	leakage operator
$\underline{M}$	total multiplication operator
$\underline{M}_p$	prompt multiplication operator
$\underline{M}_d$	total delayed multiplication operator
$\underline{M}_{d_i}$	delayed multiplication operator for group i
β	delayed neutron fraction
β_i	delayed neutron fraction for group i
ν	neutron emitted per fission
Σ_f	macroscopic fission cross section
Σ_t	macroscopic removal cross section
Σ_s	macroscopic scattering cross section
χ_p	prompt emission spectrum
χ_{d_i}	delayed emission spectrum for group i
λ_i	neutron precursors decay constant for group i
$c_i(\mathbf{r},t)$	delayed neutron precursors concentration for group i
$q(\mathbf{r},E,\hat{\mathbf{\Omega}},t)$	neutron source
$w(\mathbf{r},E,\hat{\mathbf{\Omega}},t)$	weight function
$\psi(\mathbf{r},E,\hat{\mathbf{\Omega}},t)$	flux shape
$A(t)$	flux amplitude
ρ	reactivity
β_{eff}	effective delayed neutron fraction
β_{eff_i}	effective delayed neutron fraction for group i
Λ	effective generation time
$C_i(t)$	total neutron precursors for group i
$S(t)$	total neutron source
$\phi^\dagger(\mathbf{r},E,\hat{\mathbf{\Omega}},t)$	adjoint neutron flux
$\underline{L}^\dagger$	adjoint leakage operator
$\underline{M}^\dagger$	adjoint total multiplication operator
$k^\dagger$	first adjoint eigenvalue
$\hat{\phi}(\mathbf{r},E,\hat{\mathbf{\Omega}},t)$	flux first eigenfunction
$P(t)$	total core power
E_D	fission energy deposition
ε	power coefficient
$\alpha(\psi)$	neutron flux coupling coefficient
$C_i^*(t)$	total neutron precursors consistent with $P(t)$ for group i
$P(t)_d$	total device power
$C_{d_i}^*(t)$	total device neutron precursors consistent with $P_d(t)$ for group i
ρ_d	device reactivity
$\beta_{d_{eff}}$	device effective delayed neutron fraction
$\beta_{d_{eff_i}}$	device effective delayed neutron fraction for group i
λ_{d_i}	device neutron precursors decay constant for group i
Λ_d	device effective generation time
$S_{core}(t)$	device external source (from core)
T	material temperature
ρ_{th}	material density
c_v	specific heat capacity
λ_{th}	heat conductivity
q_{th}	heat source for unit volume
T_f	average fuel temperature
T_c	average cladding temperature
T_w	average coolant temperature
$T_{w_{in}}$	coolant inlet temperature
$T_{w_{out}}$	coolant outlet temperature
m_f	single plate fuel mass
m_c	single plate cladding mass
m_w	single plate domain coolant mass
$\dot{m}_w$	single plate coolant mass rate
c_f	fuel specific heat capacity
c_c	cladding specific heat capacity
c_w	coolant specific heat capacity
α	fuel-clad heat transfer coefficient
$\dot{Q}_p$	heat generation in single plate
h	cladding-fluid convection coefficient
A_f	single plate fuel external surface
A_c	single plate cladding external surface

120 kW for MADISON and up to about 650 kW for MOLFI for Mo99 production. Technical design and strict safety and regulatory constraints require an analysis of power transients during shutdowns even inside these samples.

Therefore a model has been developed and a calculation procedure has been setup with the purpose to make it implementable in similar cases, provided the increasing nominal power in future MTRs.

Point kinetics approach for transient description of the whole system is not capable of providing detailed results for each device, and in particular for all fuel pins which are loaded inside these experimental positions. In fact, point kinetics method considers neutron flux shape as a constant during a certain period of simulation time.

Conversely, the actual flux shape inside the reflector is modified by the insertions of control rods during shutdowns. Then, point kinetics approach would neglect this aspect which may be, in principle, relevant for a correct simulation of devices power during shutdowns.

The deposition of energy – which is the effective focus of the simulation – is in fact related to flux shape. We will refer to flux shape all along the present discussion – about core-reflector system – in order to discuss also spatial description of power deposition in the reflector. Indeed, energy deposition is related to flux through interaction cross-sections and energy deposition values.

Thus, the system has been thought of as split in two components: first the core which is the neutron source and then the reflector which is the second portion and that is an irradiated – strongly subcritical – system.

During the first part of present calculation procedure, power transients – only for the JHR core – have been evaluated by means of point kinetics DULCINEE code (Dutraive et al., 1970). In the second part, the evolution of core power has been considered as an external source for every device placed in the reflector.

The link between the source provided by the core and the irradiated reflector devices is evaluated in terms of the ratio between the power of each device related to total core power. The meaning of this parameter – and its evolution during transients – is somehow the effect of flux shape variation. This core-reflector coupling is utilized for the power calculation in reflector devices – regarding energy deposition in reflector.

The variation of flux shape inside the reflector and the related modification of the energy deposition have been computed by means of the Monte Carlo neutron transport code TRIPOLI 4.8 (Petit and Hugot, 2011). Nominal conditions have been considered, therefore the power of the devices has been estimated for the configurations after shutdowns (control rod insertions).

The explained approach is based on the utilization of Monte Carlo code. This tool has been considered suitable for a complex three-dimensional geometry – even compared to spatial dynamics solutions. Reflector samples have been thought of as very small subcritical systems irradiated by a strong external neutron source, whose impact is defined through said core-reflector coupling.

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