Nuclear Engineering and Design 335 (2018) 279–290

Contents lists available at ScienceDirect

Nuclear Engineering and Design

journal homepage: www.elsevier.com/locate/nucengdes

Sodium-cooled fast reactor pin model for predicting pin failure during a power excursion

K. Herbreteau[a,*], N. Marie[a], F. Bertrand[a], J-M. Seiler[b], P. Rubiolo[c]

[a] CEA, DEN, DER, SESI, F-13108 Saint Paul lez Durance, France
[b] Scientific Advisor, France
[c] LPSC, IN2P3, CNRS, 53, avenue des Martyrs, F-38026 Grenoble, France

ARTICLE INFO

Keywords:
Severe accident
Sodium-cooled fast reactor
Power excursion
Design oriented physical tool

ABSTRACT

Within the framework of the Generation IV Sodium-cooled Fast Reactor (SFR) in which the CEA (French Commissariat à l'Energie Atomique et aux Energies Alternatives) is involved, the French innovative reactor design behavior under severe accidents conditions has to be assessed. Such accidents have mainly been simulated with mechanistic calculation tools (such as SAS-SFR and SIMMER-III). As a complement to these codes, which provide reference accidental transient calculations, a new physico-statistical approach is being developed at CEA; its final objective being to derive the variability of the main results of interest to quantify the safety margins. This approach requires fast-running tools to simulate extended accident sequences, by coupling models of the main physical phenomena with advanced statistical analysis techniques. The tool enables to perform a large number of simulations in a reasonable computational time and to describe all the possible scenario progressions of the hypothetical accidents. This general approach, combining mechanistic codes and evaluation tools, has already been conducted for some accidental initiator families (USAF – Unprotected SubAssembly Fault (Marie et al., 2016) and ULOF – Unprotected Loss Of Flow (Droin et al., 2017). In this context, this paper presents a physical tool (numerical models and result's assessment) dedicated to the simulation of the beginning of the primary phase of the Unprotected Transient OverPower accidents (i.e. before failure of sub-assembly wrapper).

At the beginning of this primary phase, the fast increase of nuclear power induces a strong temperature rise in the fuel pellets leading to strong mechanical and thermal loads on the cladding which could lead to clad failure or/and fuel meltdown. These phenomena are described and modelled analytically in single pin geometry in accordance to the level of details required to catch all the decisive phenomena.

Slow power increase transients, such as control rod withdrawal, and fast power increase transients have been investigated in the past. Experimental validation on CABRI (experimental reactor dedicated to safety studies) and CESAR (Circuit d'Etude de l'ébullition du Sodium lors d'un Accident de Réactivité) experiments were carried out focusing on the amount of molten fuel formed during the transient, on the propagation of the void front in the channel in case of sodium boiling and on the pin failure mechanisms. Furthermore, a comparison of the physical tool calculation results was performed against reference accident SIMMER-III calculations.

The tool is demonstrated to be able to predict the radial propagation of the molten zone in the fuel pin, the pin failure mechanism and void front propagation with a discrepancy of less than 10%. In the future, this physical tool, associated with a point kinetic neutronic model, will be used to simulate the global core behavior under an UTOP transient following a ramp excursion.

1. Introduction

The current main objective of the French Generation IV project is to design a new reactor based on improved technologies in terms of safety and reliability at an industrial scale. Among other concepts, the Sodium-cooled Fast Reactor (SFR) has been selected for its ability to

Abbreviations: BFC, Bottom of Fissile Column; CESAR, Circuit d'Etude de l'ébullition du Sodium lors d'un Accident de Réactivité; OCARINa, Outil de Calcul Analytique Rapide pour les Insertions de réactivité dans un réacteur à neutrons rapides refroidis au sodium (Na) (Fast-running analytical tool dedicated to power excursion simulation for sodium-cooled fast reactor); PCMI, Pellet-Clad Mechanical Interaction; PIRT, Phenomena Identification and Ranking Table; PPN, Peak Power Node; SCRAM, Safety Control Rod Axe Man (emergency shutdown); SFR, Sodium Fast Reactor; TFC, Top of Fissile Column; (U)LOF, (Unprotected) Loss Of Flow; (U)SAF, (Unprotected) SubAssembly Fault; (U)TOP, (Unprotected) Transient OverPower

* Corresponding author.
E-mail address: kevin.herbreteau@cea.fr (K. Herbreteau).

https://doi.org/10.1016/j.nucengdes.2018.05.023
Received 6 March 2018; Received in revised form 18 May 2018; Accepted 22 May 2018

Nomenclature

ρ	density [kg/m^3]
Cp	specific heat [J/kg/K]
k	thermal conductivity [W/m/K]
T	temperature [K]
P	volumetric power source [W/m^3]
H	enthalpy [J/kg]
L	latent heat of vaporization [J/kg]
H_{lsat}	enthalpy at saturation [J/kg]
x_{th}	thermodynamic quality [-]
G	flow rate [kg/m^2/s]
S	cross section [m^2]
φ	heat flux [W/m^2]
ε	strain [–]
σ	stress [Pa]
σ_{eq}	von Misès stress [Pa]
σ_y	yield strenght [Pa]
σ_{UTS}	Ultimate Tensile Stress [Pa]
σ_{ii}	stress in the direction i∊[r, θ, z] [Pa]
r	radius [m]
θ	polar angle [-]
z	height [m]
E	Young's modulus [Pa]
K	hardening modulus [Pa]
α	average thermal expansion coefficient [K^{-1}]
n	gaseous fission products quantity [mol]
R	gas constant [J/mol/K]
V	volume [m^3]
P_{cavity}	pressure in the molten cavity [Pa]
P_{vf}	vapor pressure of the fuel [Pa]
P_{max}	maximal power [W]
P_0	nominal power [W]
t_{Pmax}	time at the power peak [s]
$t_{failure\ exp}$	experimental clad failure time [s]
$t_{failure\ OCARINa}$	OCARINa clad failure time [s]
$z_{failure\ exp}$	experimental clad failure height [m]
$z_{failure\ OCARINa}$	OCARINa clad failure height [m]

secure the nuclear fuel resources and to manage radioactive waste by minor actinides transmutation. A major innovation of the new SFR

French concept concerns the core, which is characterized by a very low (even negative) sodium void worth. More specifically, this feature has a strong impact on the severe accident sequences especially regarding the material heating-up and on the global core power evolution (Bertrand et al., 2015). In the framework of safety studies devoted to the Unprotected Transient OverPower (UTOP, or power excursion), a physical tool, called OCARINa (Outil de Calcul Analytique Rapide pour les Insertions de réactivité dans un réacteur à neutrons rapides refroidi au sodium (Na)), is being developed in order to allow to derive the variability of the main results of interest and to quantify the design of safety margins for the severe accident studies. This is not achievable with current mechanistic tools requiring high CPU time.

In the very past, the methodology used in design studies and safety analysis of SFR was only based on one most damaging accidental scenario (Waltar and Reynolds, 1981), reasonably bounding (expert judgment), and mainly because its calculation required an assessment of a large range of phenomena likely to occur during the accidental sequences. This reference bounding transient was simulated by mechanistic codes such as SAS-SFR (Lemasson and Bertrand, 2014) and SIMMER-III (Kondo et al., 1996), which describe the dynamic behavior of a highly complex system, including time-dependent coupling between neutron kinetics and multi-component thermalhydraulics.

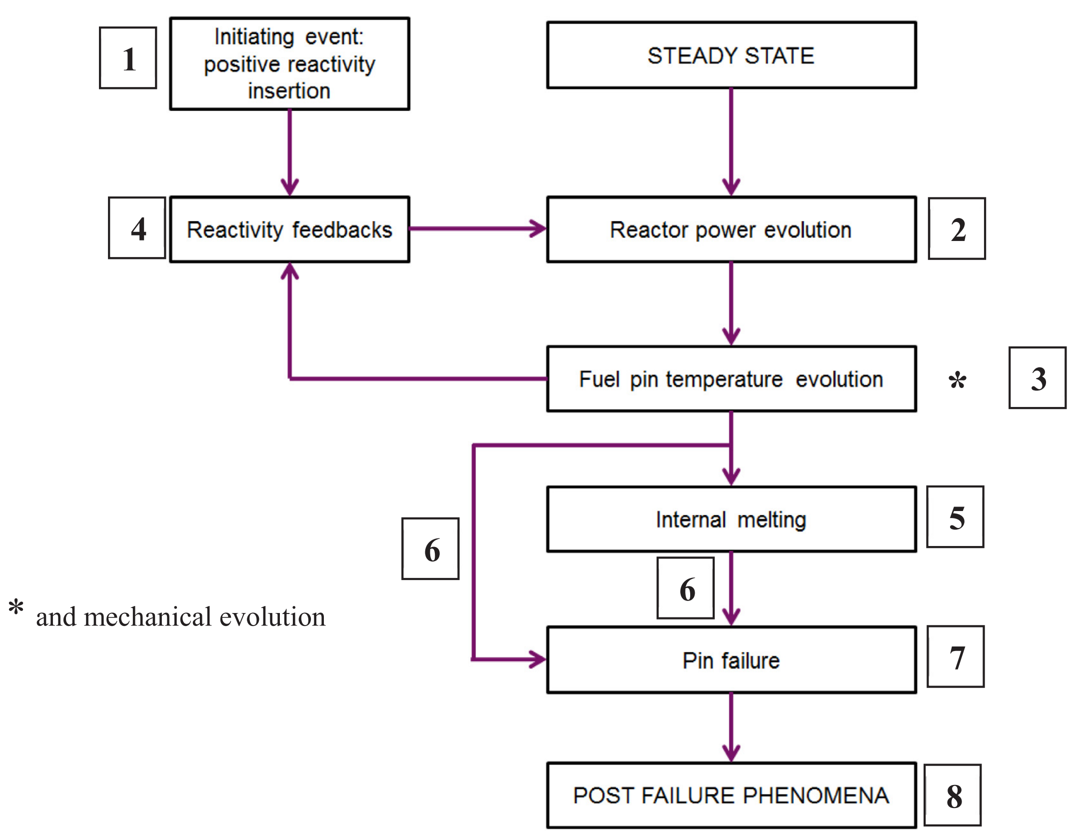

Fig. 1. Phenomenological event tree for the beginning of the primary phase of an UTOP transient in a SFR reactor.