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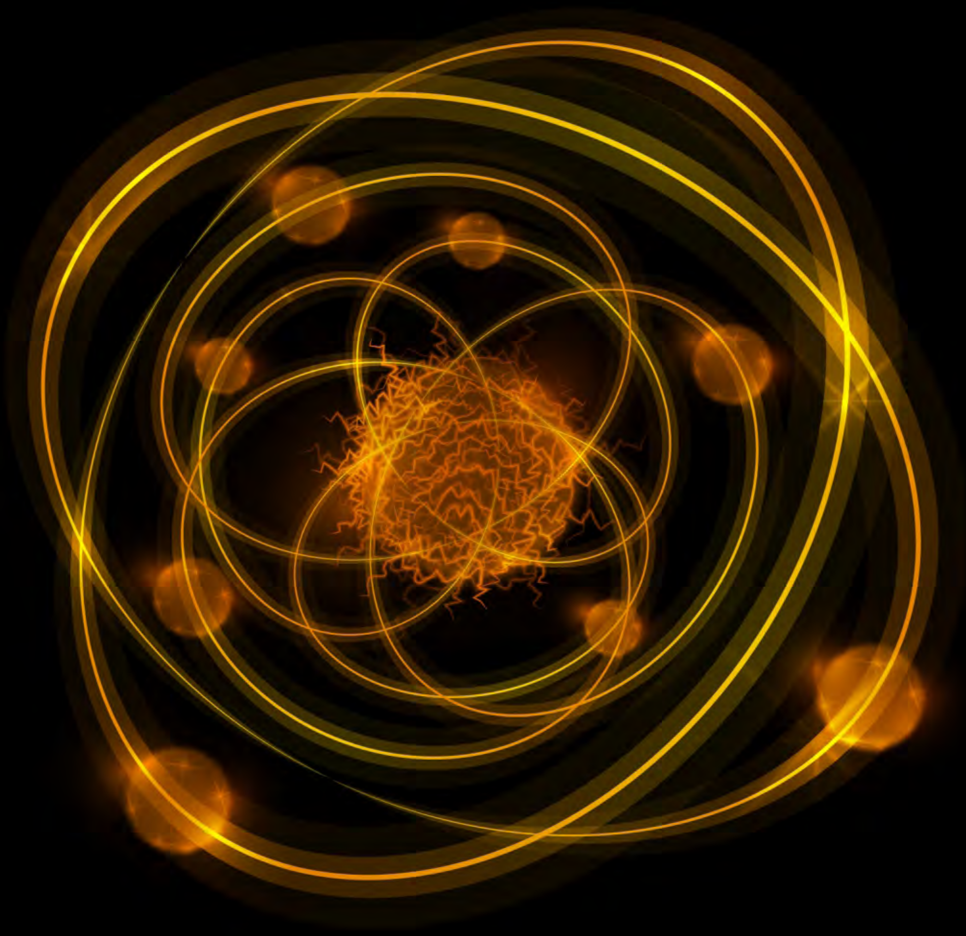

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Numerical Analysis of Heating Technique in Corium Melt Pool Convection Flow Field & Thermal Interaction in a Volumetrically Heated Molten Pool

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Abstract

In-Vessel Retention (IVR) is one of the existing strategies of severe accident management of LWR, which intends to stabilize and isolate corium & fission products inside the reactor pressure vessel (RPV) and primary containment structure. Since it has become an important safety objective for nuclear reactors, it is therefore needed to model and evaluate relevant phenomena of IVR strategy in assessing safety of nuclear power reactors. One of the relevant phenomena during accident progression in the oxidic pool is non-uniform high heat generation occurring at large scale. Consequently, direct experimental studies at these scales are not possible. The role computer codes and models are therefore important in order to transpose experimental results to reactor safety applications. In this paper, the state-of-the-art ANSYS FLUENT CFD code is used to simulate Non-uniform heat generation in the lower plenum by the application of Cartridge heating under severe accident conditions to derive the basic accident scenario. However, very few studies have been performed to simulate non-uniform decay heat generation by Cartridge heaters in a pool corresponding lower plenum of power reactor. The current investigation focuses on non-uniform heating in the fluid domain by Cartridge heaters, which has been done using ANSYS FLUENT CFD code by K-epsilon model. The computed results are based on qualitative assessment in the form of temperature and velocity contour and quantitative assessment in terms of temperature and heat flux distribution to assess the impact of heating method on natural convective fluid flow and heat transfer.

Keywords

IVR, ANSYS FLUENT, LWR, CFD Analysis, Core Degradation, RPV

1. Introduction

The in-vessel coolability & retention strategy is based on the idea of flooding the PWR vessel cavity with water either to submerge the vessel completely or at least to submerge the lower head. The lower head containing the melt pool is cooled from outside, which keeps the outer surface of the vessel wall cool enough to prevent vessel failure. The purpose of flooding is to delay the vessel failure by means of cooling through the reactor vessel wall [1]. Since, it (IVR) has become an important safety objective for nuclear reactors, it is therefore needed to model and evaluate the dynamics of associated phenomena of heat transfer processes in the corium melt pool and the influence of these phenomena on accident progression as shown in **Figure 1**.

One of the associated phenomena during accident progression in the oxidic pool is non-homogenous decay heat generation occurring at large scale. Consequently, direct experimental studies at these scales are not possible. The role computer codes and models are therefore important in order to transpose experimental results to reactor safety applications. In this paper, state of the art CFD code (ANSYS FLUENT) is used to simulate non-homogenous heat generation in the lower plenum by the application of Cartridge heaters under severe accident conditions to derive the basic accident scenario. At the same time, there is a clear need to understand natural convective fluid flow & heat transfer phenomena, since melt pool convection in the lower plenum of the RPV is one of the main contributor for the final state of the melt pool formation and its thermal loads on the lower head the along with core degradation and relocation, debris formation, and coolability. The progression of severe accident and the physical state of the molten pool depends on the heat transfer at the pool boundaries which is mostly controlled by In-vessel natural circulation [2].

The primary purpose of In-vessel natural circulation is to delay the overall heating of the core, due to the more effective heat removal from the hotter core regions to the colder core structures. As a result, radial temperature gradients in the core are reduced and the resulting heating pattern becomes much more uniform. A natural circulation regime is established in the molten pool, and the heat fluxes at the boundaries of the pool depend on the internal Rayleigh number.

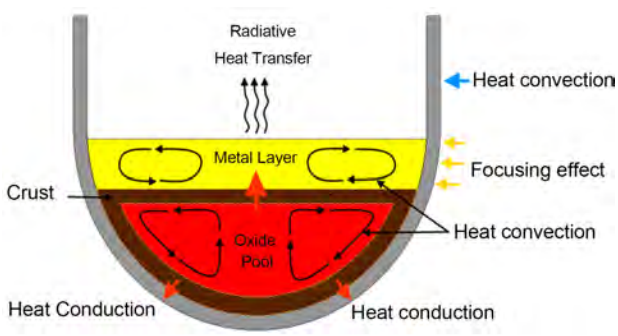

Figure 1. Schematics of IVR-ERVC concept.

The choice of Rayleigh number was determined mainly by the height of the pool and hence could not be varied much. This is usually modeled with standard heat transfer correlations applied at the external boundaries of the pool [3].

Examining relevant literatures, we have found that a number of research (RASPLAV [4], MASCA [5], BALI [6], SIGMA [7], LIVE [8], COPRA [9], SIMECO-II [10]) have been carried out in the area of corium behavior using different heating methods like electrode heating, wire heating and like this. Experimental work in this case is effective, but as we know, this type of experimental work with complex facilities is very tough to conduct under extreme condition. Moreover, carrying out these complex experiments are very expensive and time consuming. That means, direct experimental studies at these extreme conditions and scales are not feasible. Therefore, numerical models & methods are required to predict melt pool thermal hydraulics in which characteristics of ERVC condition including non-uniform heat generation must be considered since practically, heat generation in the lower plenum of the RPV during the accident progression is non-uniform.

After an intensive & careful assessment, it has been found that very few studies have been performed to simulate non-uniform decay heat generation by Cartridge heaters in a pool corresponding lower plenum of power reactor. The current investigation focuses on non-uniform heating in the fluid domain by Cartridge heaters, which has been done using ANSYS FLUENT CFD code [11] by K-epsilon turbulent model.

The computed results are based on qualitative assessment in the form of temperature and velocity contour and quantitative assessment in terms of temperature and heat flux distribution to assess the impact of heating method on natural convective fluid flow and heat transfer.

2. Computation Platform

Governing Equations

Energy transport occurs by conduction, convection and radiation. In order to simulate the heat transfer and the convective flows, the complete three-dimensional time dependent equations are involved as below [12]:

Mass equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho U) = 0$$

Momentum equation:

$$\frac{\partial \rho U}{\partial t} + \nabla \cdot (\rho U \times U) = \rho g + \nabla \cdot (-P\delta + \mu \nabla U)$$

Energy conservation equation:

$$\rho C_V \left(\frac{\partial T}{\partial t} + U \cdot \nabla T \right) = -\nabla \cdot (-k \nabla T + q_r) + \mu \phi - p \nabla \cdot U + Q_V$$

where,

$\frac{\partial T}{\partial t}$, is the local derivative, which is physically the time rate of change of temperature with time, $\frac{\partial \rho}{\partial t}$, is the time rate of change of density (kg/m^3) with time, $-\nabla \cdot q_r$ is the energy source per unit volume supplied locally by radiation to each volume element d_V, g is the gravitational acceleration if the weight of the fluid is only the body force, C_V is the specific heat (J/Kg/K), U is the characteristic velocity, μ is the dynamic viscosity (Pa.sec), Q_V is the internal volumetric heat source (W/m^3). Where, means density, heat capacity, room temperature, time, heat conductivity, heat source. Each part of the room is a sub-domain and these subdomains are solved in parallel.

In order to numerically solve the governing equations, a control volume approach is used. The three-dimensional Reynolds-Averaged Navier-Stokes (RANS) equations along with the momentum and continuity equations were solved using the commercial CFD code. The model employs the control-volume technique and the Semi-Implicit Method for Pressure-Linked Equations (SIMPLE) velocity-pressure coupling algorithm with the second order upwind discretization. The standard k-e transport model is used to define the turbulence kinetic energy and flow dissipation rate within the model. The gravity acts in the negative direction.

3. Working Domain & Boundary Conditions

The main part of the facility is a slice type test section, which is a semi-spherical lower head water cooled vessel, representing lower head of a typical PWR pressure vessel, as shown in Figure 2.

A volumetric heat source (Q_v) is implemented in the fluid domain. A water-cooling system is used to maintain isothermal boundary condition surrounding the test section.

Boundary conditions applied: The computation is executed under the following boundary conditions (Table 1) to study the influence of a boundary temperature mode. Such change of the boundary mode causes an essential change of the flow structure especially in the area adjacent crust-vessel interface.

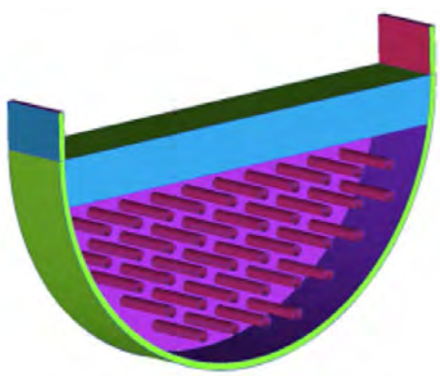

Figure 2. Model of the fluid domain.

Table 1. Applied boundary conditions in the fluid domain.

Location/Position of the domain	Type of BC	Applied value
Front & Back surface of the oxide layer	External emissivity External radiation temperature	$\varepsilon = 0.5$ t = 298 K
Top metal surface	External emissivity External radiation temperature	$\varepsilon = 0.15$ t = 298 K
Front & Back surface of the metal layer	External emissivity External radiation temperature	$\varepsilon = 0.15$ t = 298 K
Vessel outer surface	Isothermal boundary condition by natural circulation of water	T = 343 K

4. Discussion & Analysis

Figure 3 presents the different locations of the heating sources inside the 3D-semicircular object where the thirty-six heaters are installed to analyze the thermal phenomena and the fluid flow among the sources.

In the lower part of the cavity, the fluid is thermally stratified and flow field is almost steady. The upper part is under influence of large vortex structures that are triggered by Rayleigh-Tailor instabilities at the cooled top as shown in Figure 3.

It is noticeable that the higher temperature is observed in the center of semi-circular boundary. The temperature field of the oxide layer of the Figure 3 has a significant characteristic that the magnitudes of the temperature is high on the close enclosure of oxide layer due to the thermal stratification effect on the other hand there is noticeable amount of decrement is seen in the peripheral zone of the 3D-semicircular object for the convection through the wall of the test vessel.

The temperature distribution of the top side of the metal layer is demonstrated in the Figure 4. As a result of metal to metal conduction between the metallic layer of the steel to the vessel wall radially, while the radiative heat transfer is negligible. So, the temperature of center of the oxide layer has not decreased significantly compare to the adjacent region of metal oxide layer. In addition, the heat is also transferring from the salt of the molten pool to the oxide layer.

In the metal layer, the heat from the lower oxide layer passes through the entire contact surface, and it is then emitted from the metal layer upwards (by radiation) and transversely to the wall of the reactor vessel. The metal layer receives heat from the corium pool and performs Rayleigh-Benard convection transferring heat transversely to the vessel wall. Due to a rather low radiative heat transfer from the top of the metal layer, most of the power received is transferred radially to the vessel wall, which is then subject to a highly elevated high heat flux. This heat flux focusing is most intense for a thin metal layer since the transverse area for heat transfer is smaller.

Temperature distribution of the mid plane of molt pool presents in Figure 5. For the sake of the conduction heat transfer from oxide layer to wall solid boundary layer, this pattern of the temperature is simulated.

Figure 5 shows the temperature and the heat flux distribution of metallic layer as well as oxidic pool. Since the conduction is the most dominating mode of heat transfer from the metal oxide layer to the boundary of the test wall, the temperature and heat flux of the oxide layer of the steel is lower than the constituents of the different layers of the molten pool. The temperatures of the different layer of the semi-circular vessel pool is non-uniform because of the density difference of the molten salt, the convection heat transfer from the molten salt to the lower head plenum inner boundary, and the heat addition to the steel oxide layer from the salt of the pool.

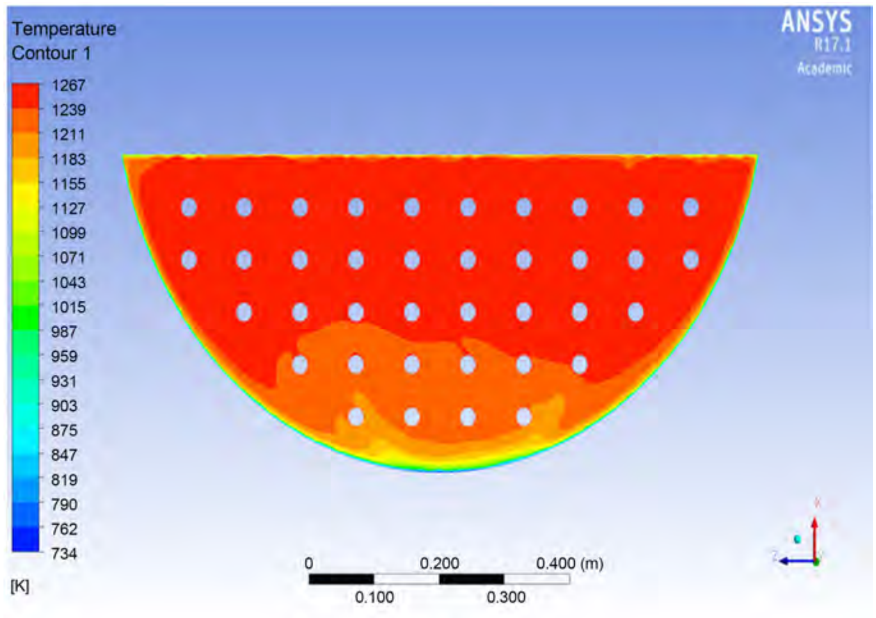

Figure 3. Stratified layer in the oxide layer.

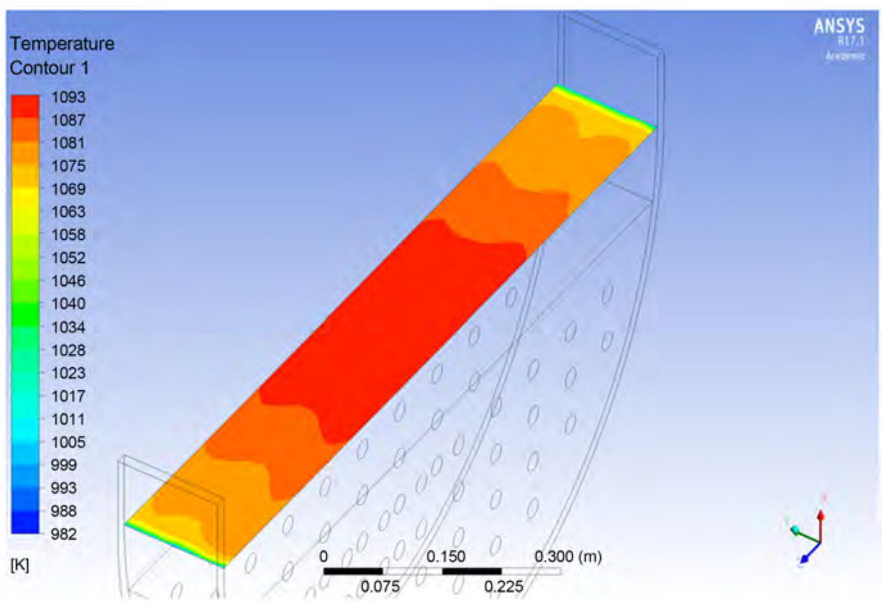

Figure 4. Top view of the metal layer.

The solid simulant corium is melt down by the application of heating elements due to conduction between surface contact of heating rods and solid corium. As a result, the simulant corium is turned liquid, which takes 6000 sec to reach thermal equilibrium position in the molten pool. As we use heating elements as external heating source, the fluid flow motion is caused by free convection. Because of density difference of the liquid corium, an upward motion of liquid corium is generated and that is why the temperature becomes higher in the interface between oxide and metal. The magnitude of the velocity becomes higher (as shown in **Figure 6**) at the vicinity of the vessel-debris interface because of the heating free zone, and at the interface the velocity of liquid corium

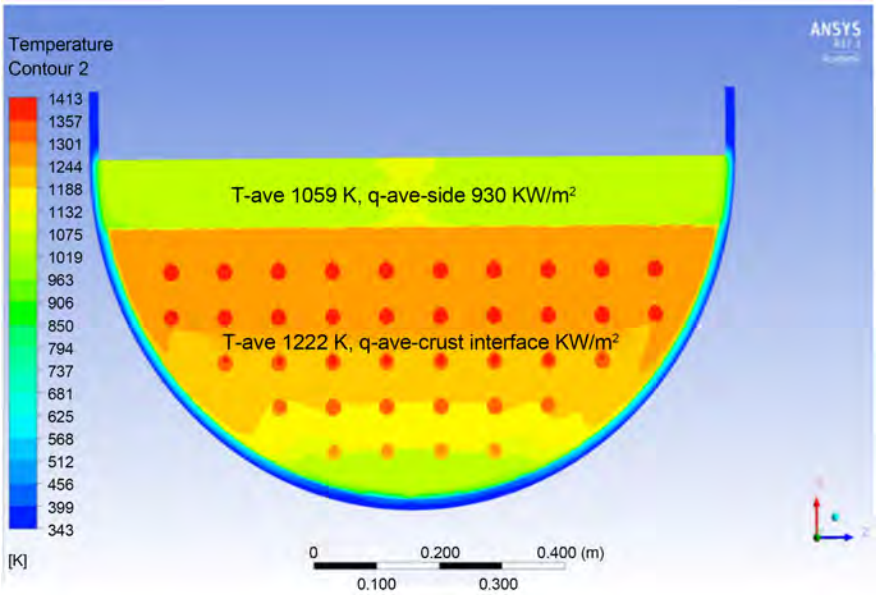

Figure 5. Illustration in-vessel temperature and heat flux of the oxidic & metallic layer.

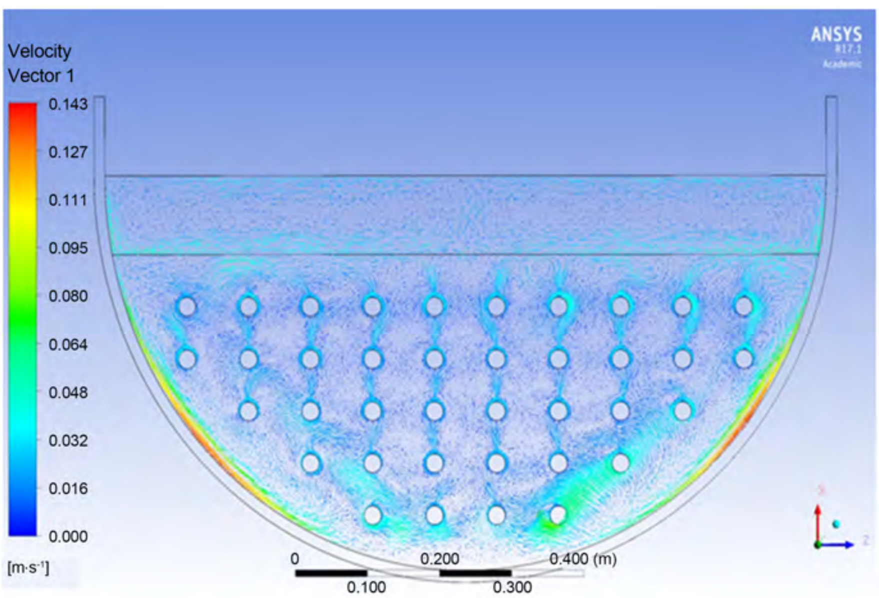

Figure 6. Velocity field in the molten pool.

is zero for no slip condition. The flow behavior has a significant effect on the heat transfer behavior of the internal heated melt pool. Therefore, it is necessary to obtain the clear flow behavior of large scale internal heated melt pool.

Figure 6 presents flow pattern, developed in the space between heaters. We experience chaotic motion of fluid because of the presence of heating source and irregular fluid motion inside heaters. Consequently, stream-lines follows different paths inside heaters. Heat concentration phenomena is noticed at the contact of the heating elements because of no slip condition.

5. Conclusions

We have simulated natural convection heat transfer in the corium fluid pool, embedded with cartridge heaters. The main issues related to the evaluation of heat transfers at the boundaries of a stratified molten pool in the vessel lower head have been addressed. Based on the studies and considerations deducted from the results of the models, implemented in ANSYS FLUENT code, the issues with large impact on the heat flux distribution to the vessel wall have been highlighted. In particular, the following points are identified.

As can be seen, minimum heat (162 KW/m^2) is removed through metal-debris interface since thermal conductivity of the debris is less. Because of focusing effect, maximum heat (930 KW/m^2) is removed through metal-vessel interface. It is also found that max heat is concentrated along heaters-debris interface as heat is being generated by the cartridge heaters.

This work can be further investigated applying CFD, CFD++, CFX and STAR CCM+.

Acknowledgements

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Nomenclature

α	Thermal diffusivity, $\lambda/(c\rho)$
β	Thermal expansion coefficient, 1/K
Cp	Specific heat, $J{\cdot}Kg^{-1}{\cdot}K^{-1}$
η	Dynamic viscosity, mPa·s
H	Height of the pool, m
λ	Thermal conductivity, $W{\cdot}m^{-1}{\cdot}K^{-1}$
υ	Kinematic viscosity, η/ρ
Nu	Nusselt number, $qH/\Delta T\lambda$
ρ	Density, kg/m^3
Pr	Prandtl number, υ/α
q	Heat flux, $Watt/m^2$
Ra	Relaigh number, $g\beta QH^5/\alpha\lambda\upsilon$
Q	Volumetric heat source, W/m^3
L	Characteristic length, m
V	Volume of the pool, m^3
R	Radius of the pool, m
g	Gravitational acceleration, m/s^2
T	Temperature, K
Gr	Grashof number $gH^3\alpha\Delta T/\upsilon^2$

List of Acronyms

NPP	Nuclear Power Plant
PWR	Pressurized Water Reactor
BWR	Boiling Water Reactor
LWR	Light Water Reactor
PECM	Phase Change Effective Convectivity Model
CFD	Computational Fluid Dynamics
RPV	Reactor Pressure Vessel
IVMR	In-vessel Melt Retention
SA	Severe Accident
SAM	Severe Accident Management
ERVC	External Reactor Vessel Cooling
DNS	Direct Numerical Method
FEM	Final Element Method
CHF	Critical Heat Flux
LOCA	Loss of Coolant Accident
SIMECO	Simulation of Melt Coolability
COPO	Corium Pool (experimental program)
BALI	Bain Liquide (experimental program)
LIVE	Large Scale Experiment on In-Vessel Retention
MASCA	Material Scaling project (experimental program)
VVER	Vodo-Vodyanoi Energeticheshy Reactor
COPRA	Corium Pool Research Apparatus