Thermal-hydraulic simulation of loss forced circulation in the TRIGA Mark I - IPR-R1

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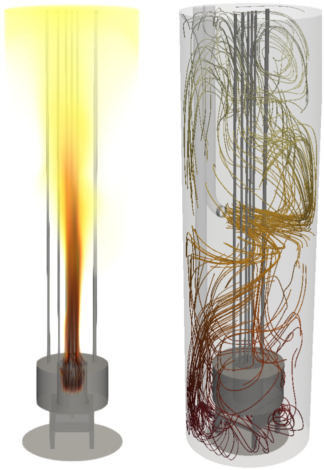
Objective

Reactor refrigeration

Study the thermal-hydraulic behavior inside the pool reactor by computational fluid dynamics considering two situations:

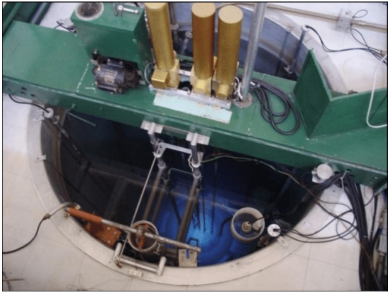
- Forced circulation. That is, when the external coolant circuit is available.
- Natural circulation. That is, when the external coolant circuit shut down.

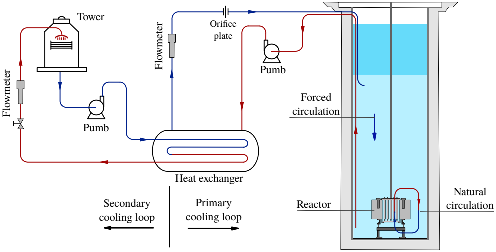


Introduction

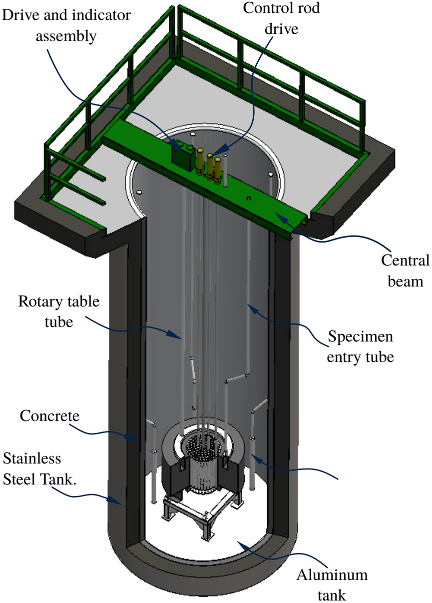
TRIGA Research Reactor *(Training Research Isotopes General Atomic)*

TRIGA reactors were designed and built by General Atomic. They are open-pool type reactors used for academic, research, material testing and isotope production purposes.



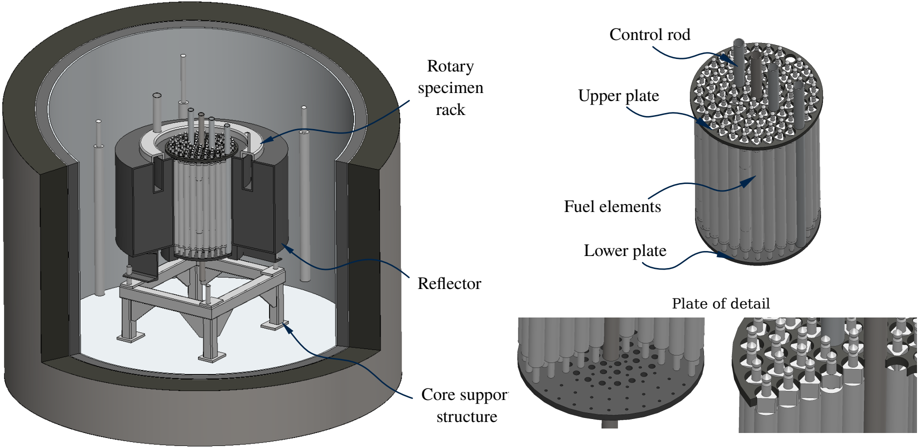


TRIGA IPR-R1 nuclear research reactor



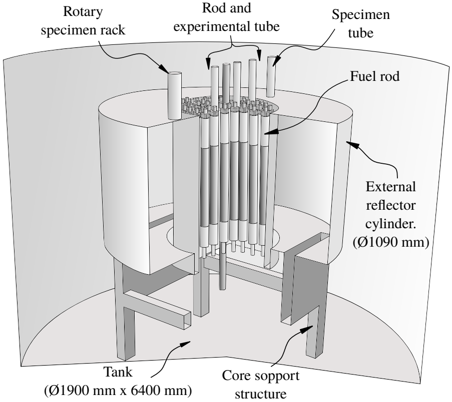
- The core of the reactor can house 91 rods, with 63 fuel elements, 23 false graphite elements, a neutron source, a central irradiation tube and 3 control rods.
- It is an upward flow reactor. That is, in normal operation the coolant flows from the bottom to the top of the core.

TRIGA IPR-R1 nuclear research reactor



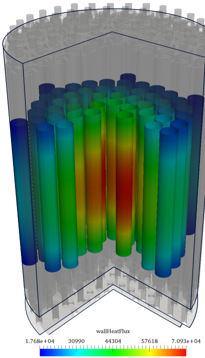
Reactor features

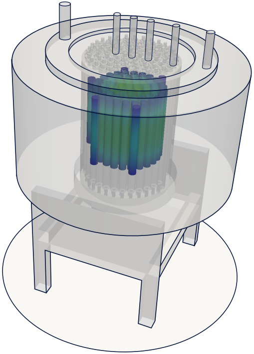
Thermophysical properties	
Heat capacity Cp_a	4183 $(J/kg.K)$
Pressure P_a	1 (atm)
Dynamic viscosity μ	797.7×10^{-10} $(N.s/m^2)$
Prandtl numberPr	5.42
Density of ref. rho_{ref}	995 (kg/m^3)
Temperature of ref. T_{ref}	302 (K)
Thermal expansion β	0.305×10^-3 $(1/K)$
Geometric and operation parameters	
Thermal Power P_t	100 (kW)
Number of fuels N_c	63
Number graphite elements/others N_g	28
Diameter of the pool D_t	1900 (mm)
Total pool height L_t	6400 (mm)
Core diameter D_n	441 (mm)
Reflector diameter D_r	1090 (mm)

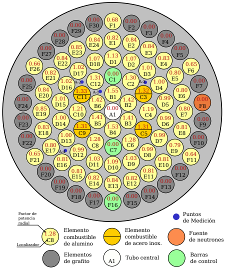


Power distribution

A total power of 100 kW was imposed, with a sinusoidal profile for axial distribution and with a radial distribution obtained from literature simulation and experimental data (*Dalle*, 2002).







Governing Equations

Simulations were performed using the compressible Boussinesq solver (buoyantPimpleFoam) to estimate the density variations.

1. Continuity equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_j)}{\partial x_j} = 0 \tag{2.1}$$

2. Momentum equation:

$$\frac{\partial (\rho u_j)}{\partial t} + \frac{\partial (\rho u_j u_i)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}(\tau_{ij} + \tau_{t,ij}) + \rho g_i \tag{2.2}$$

3. Energy equation (written in terms of enthalpy):

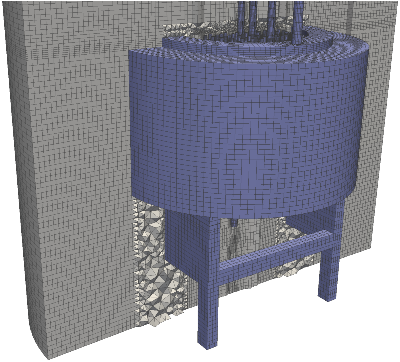
$$\frac{\partial (\rho h)}{\partial t} + \frac{\partial}{\partial x_j}(\rho h u_j) - \frac{\partial p}{\partial t} = \frac{\partial}{\partial x_k}\left(\kappa_{eff}\frac{\partial T}{\partial x_k}\right) \tag{2.3}$$

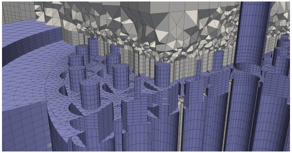
   $\kappa_{eff} = \alpha_{eff}\rho Cp$ is the effective conductivity, α_{eff} is the effective thermal diffusivity and Cp the specific heat.

4. To model the turbulence the standard $\kappa - \epsilon$ model was used

Numerical Model

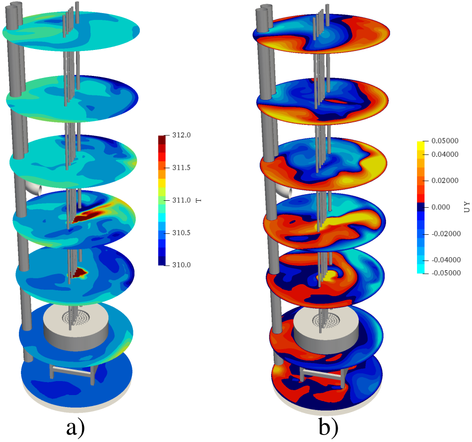
- **Computational domain:** extruded meshes combined with non-structured meshes were used. Total mesh size: 6,978,842 cells.
- **Perforated support plates:** They were represented through porous media regions using the Darcy-Weisbach approach.
- **Heat transfer:** The floor and lateral walls were assumed as Adiabatic while a constant convective coefficient was used for modeling the heat loss through the free surface.
- **Parallel computing:** 20 nodes (80 processors) in CIMEC cluster (16 hr of calculus for each 1 hr of simulation).





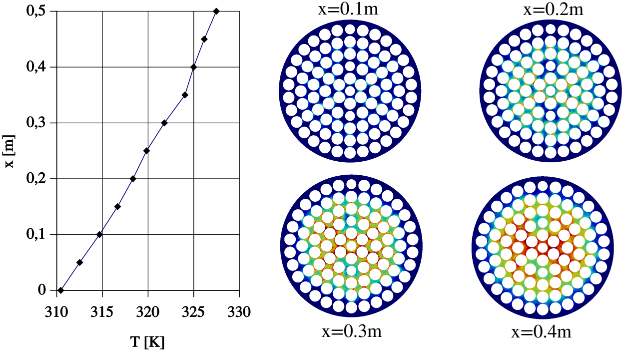
Results - Forced circulation

- **Temperature:** The variations at the cross sectional planes are less than 2K and they become lower at the top side.
- **Velocity:** Blue zones correspond to downward flow and red zones to upward flow. The minimum and maximum values are between -50 mm/s to 50 mm/s.At the upper half side the flow ascends close the wall and descends through the center.



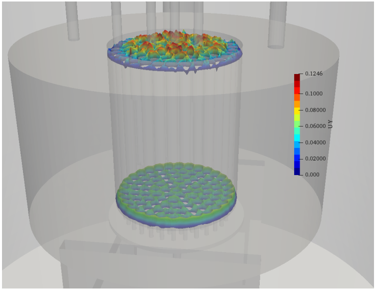
Forced circulation

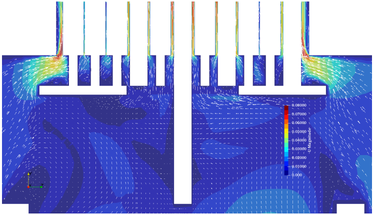
- **Core:** Along the axial direction the temperature increases almost linearly from 310K to 330K.
- **Radial temperature distribution:** It is clearly a consequence of the pin power distribution and the location of the control and stainless steel rods.



Forced circulation

- **Core inlet:** The highest velocities are close to the periphery because of the opening windows.
- **Core outlet:** There is not a smooth velocity profile. Maximums are in the center with many peaks at the high pin power locations.
- **Core inlet:** The coolant flows mostly by the opening windows with an average velocity of 40 mm/s rising to 80 mm/s close to the rods. On the other hand, the velocity at central perforated plate remains less than 10 mm/s, but this is due to the porous media representation.

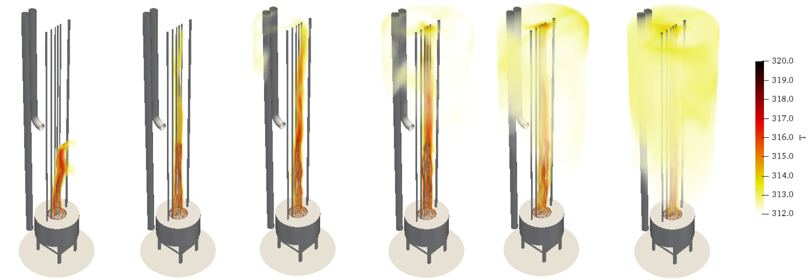




Natural circulation

Evolution of pool heating

- In normal operation (t=28000s) the hot plume is mixed with the cold inlet.
- Once forced flow shut down the plume ascends up to the free surface, where only a fraction of the heat is transferred to the environment.
- the temperature increases progressively with heat rate of 5.2K per hour. After 960s (16 min) the temperature increases around 2K in the upper part of the pool.

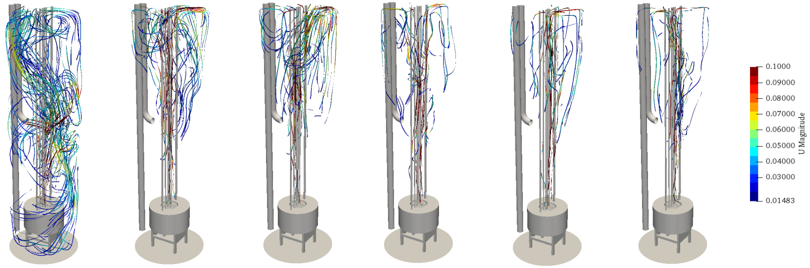


t = 28000s t = 29204s t = 29554s t = 29904s t = 30254s t = 30604s

Forced vs Natural circulation

Evolution of velocity pattern

- In contrast to the quite-steady and ordered plume, the downward flow is unstable. The flow ascend in the central zone with high velocity and slowly descend close to the laterals.
- Flow transition from forced to natural circulation takes place quickly. In 500s the hot plume due to the outlet core coolant reach a fluid flow stationary condition.



t = 28000s t = 29204s t = 29554s t = 29904s t = 30254s t = 30604s

Forced vs Natural circulation

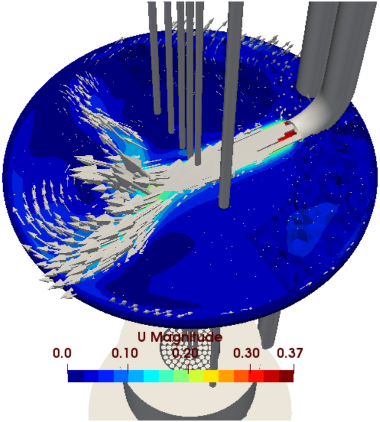
Streamlines videos

Video streamlines Velocity

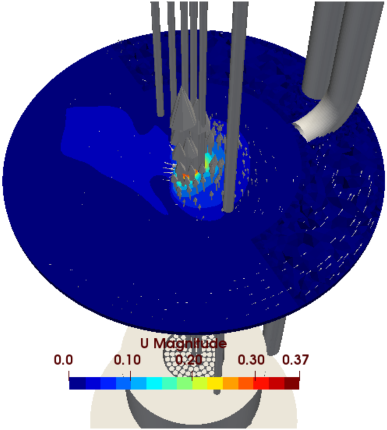
Video streamlines Temperature

forced vs natural circulation- inlet

- **Forced flow:** The inlet flow dominates and the the central plume is moved toward the pool wall.

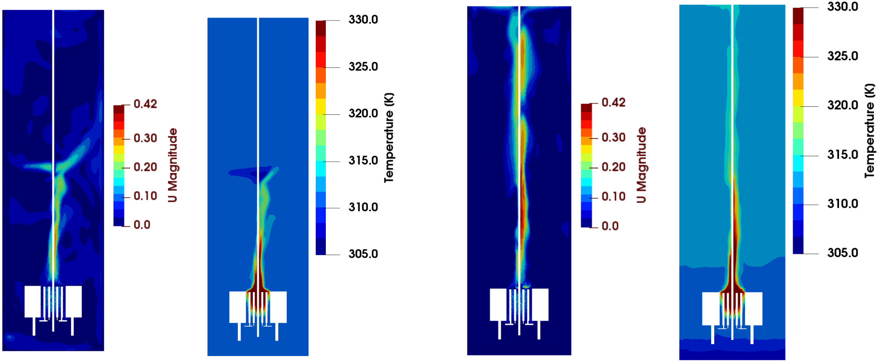


- **Natural circulation:** The fluid motion is mainly due to the ascending central plume and the helical descending flow.



Forced vs natural circulation- Velocity

- **Forced circulation:** The inlet flow dominates and the the central plume is displaced toward the pool wall.
- **Natural circulation:** The motion is mainly due to the ascending central plume.



Conclusions

- In this work, the cooling capacity of the TRIGA-Mark I reactor was studied by CFD. Two operation conditions at full power were evaluated: forced circulation and natural circulation. The model allowed us to analyze the transition from forced to natural flow.
- Steady-state forced circulation conditions were achieved after simulate around 7 hr of operation, getting a high mixing and quite complex flow pattern.
- On the other hand, once the forced circulation shut down, an organized flow characterized by a central upwards plume was achieved. In this situation an almost constant heating rate of 5.2K per hour was obtained.
- 4- The heat exchange at the free surface was less than 5 kW, which was less than 5 % of the total power in the core.

Thank you for your attention!

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