

Preliminary Neutronic design of SPOCK reactor: a nuclear system for Space Power generation

N. Burgio*, M. Cumo+, A. Fasano+, M. Frullini+, A. Santagata*

*ENEA FPN FIS-ION CR Casaccia, Rome – Italy

+Department of Nuclear Engineering and Energy Conversion, University of Rome “La Sapienza” Rome – Italy

SPOCK (Space POver Core Ka) : Schematic view

SPOCK is guided by the general idea of keep out core the thermoelectric conversion devices and eventual propulsive systems. The main advantages are:

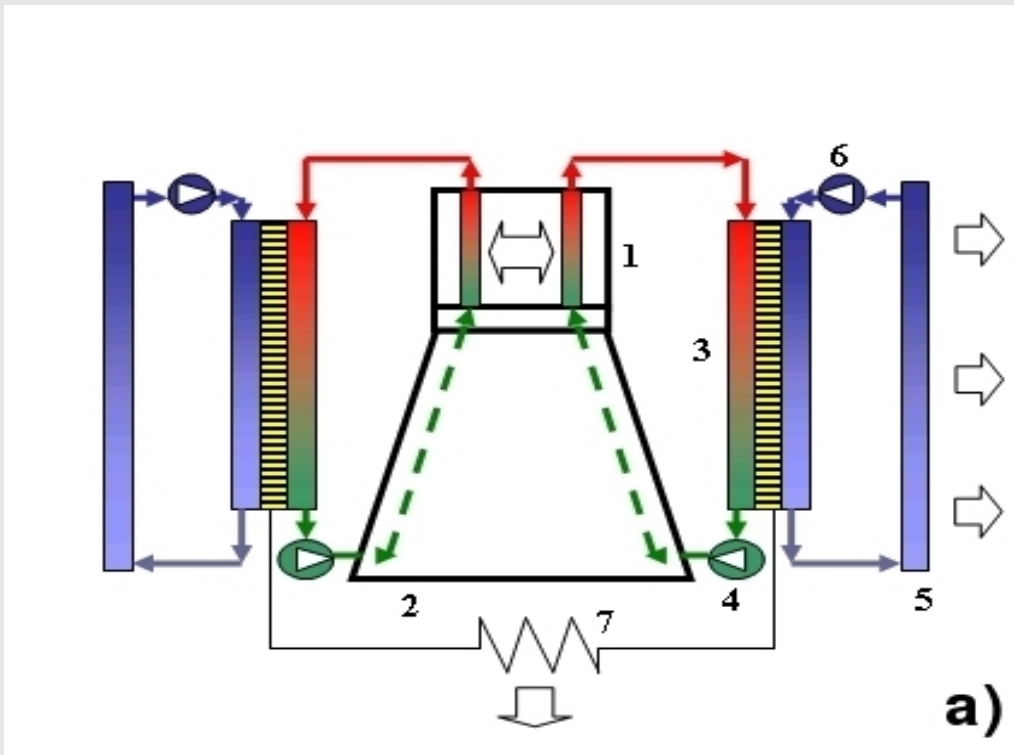
- Minor radiation damage of the devices (lifetime enhancement)
- Higher temperature jump,
- The core will be no charged with static and/or dynamic reactivity worth.

SPOCK would provides 350 kW of thermal power in order to generate 30 kW of electric power. (p-n junction thermoelectric converter with an efficiency of 9-11%).

The heat transfer to the hot side of the p-n junction (1150 – 1250 K) is ensured by a forced liquid Na circuit at 300 kPa of pressure.. Residual heat will be irradiated into space by radiative panels connected to the “cold” side of the p-n junction converter by secondary Sodium circuit (thermal range 650-750 K).

The circulation of Na coolant is ensured by ElectroMagnetic Pumps (EMP)

Mass/dimension ratio compatible with main launchers as NASA Space Shuttle System and ESA ARIANE-5 is highly recommended.



- 1) Reactor Core. 2) Shield. 3)p-n junction thermoelectric converter.
- 4) ElectroMagnetic Pump (EMP) primary loop. 5) Radiator. 6) EMP secondary loop. 7) Electric External Load.

Space POver Core Ka (SPOCK): Design requirements

High power density, well known fuel behaviour, massive heat remotion, non interfering control rods motion.



- A fast, Metal OXide (MOX) fuelled, compact reactor controlled by absorption control rods located in a Be reflector, and cooled by liquid Na in forced circulation.

Assembling and launch safety requirements.



- SPOCK will be maintained in sub-critical state with the Na coolant in the solid state during launch operation.

Safe and reariable remote start up procedure.



- SPOCK will start up in the outer space at about 40 K with the coolant in a solid state. The full power criticality will be reach at 1300 K with the Na coolant in the liquid state.

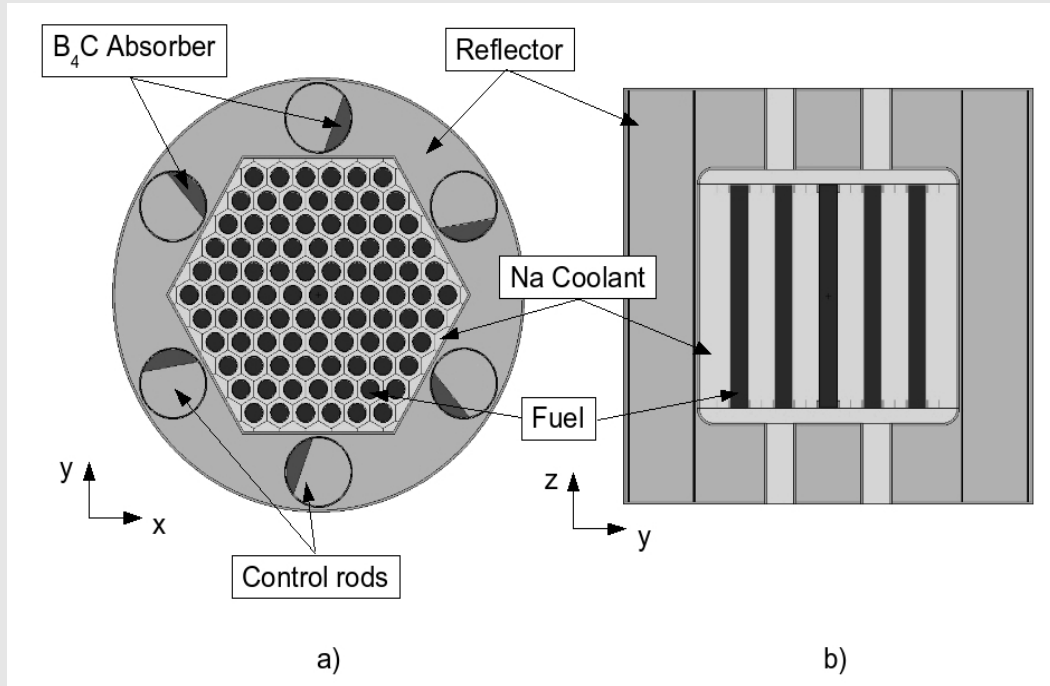
From design to safety analysis and plant control.



- All the possible transients during start up and the raise to the operative criticality conditions must be properly simulated and controlled.

Space Power Core Ka (SPOCK): The nuclear system

Having in mind the previous cited requirements, the basic dimensioning of the SPOCK core was carried out by using a Monte Carlo (MCNPX 2.5.0) criticality model.



- The core is constituted of 91 (95% ^{235}U enriched) cylindrical shaped fuel rods disposed on hexagonal rings and held between two Molybdenum grids.
- In the actual design stage, because of the better knowledge of UO_2 nuclear data, MOX is preferred to the low payload UN. More advanced fuels (and less proliferating) options will be considered in future..
- The reflector is made of a Be (thickness=8 cm).
- The final system shape is a cylinder (height=diameter=60 cm).

- Reactor control system is constituted by six Be drums located in the reflector. Each drum has a B_4C (neutron absorber) sector. When the absorber sector is in front of the core a full negative reactivity condition take place (**Maximum neutron absorption**). Conversely, when the Be sector is in front of the core the neutron were reflected back to the core generating a positive reactivity insertion (**Maximum neutron reflection**).

Space Power Core Ka (SPOCK): Preliminary Analysis

As already stated, it is highly recommended to have all the reactor core in a solid form during the launch phase.

Consequently

- Start up and power rise will be remotely controlled in a scenario where the fission heating has to be used to melt the total mass of the Na coolant and then its forced circulation will take place.
- Apart from expected feedback effect on the criticality conditions, there is the possibility that an ill-posed heat distribution hindered the total melt of the coolant and limits its circulation.
- In this condition the nuclear pile could arrive to criticality but the electrical power generation could fail.

The present analysis is mainly devoted to “collect” the basic information on the possibility that the coupling of neutronic transport Monte Carlo (MC) and Computational Fluid Dynamic (CFD) codes could simulate the given scenario and furnishes the main parameters to be used for system design.

Space POver Core Ka (SPOCK): Neutronic Modelling

The neutronic analysis was focussed to temperatures and material density effects on criticality in the wide range of conditions that SPOCK will experiment (k_{eff} estimation).

Tab. I Reactivity at different temperatures.

N.	Description	Temperature (K)	Sodium density (g/cm³)	k_{eff}
1	Maximum Reflection	50	1.008	1.06608±0.00026
2	Maximum Reflection	300	0.968	1.06438±0.00027
3	Maximum Reflection	1300	0.706	1.05606±0.00024
4	Maximum Absorption	50	1.008	0.97774±0.00024
5	Maximum Absorption	300	0.968	0.97624±0.00024
6	Maximum Absorption	1300	0.706	0.96515±0.00024

The system retains a sufficient criticality margin and the control drums were adequate to maintain the system in sub critical conditions in the entire range of explored temperatures.

Space POver Core Ka (SPOCK): Temperature effects on reactivity

As expected, the system reactivity decreases as temperature raise. In particular, reactivity raise of about 170 pcm when the temperature decrease from launch conditions (300 K) to space conditions (50 K). Conversely a net reactivity loss of 1100 pcm takes place when the system raises to the steady power condition (1300 K).

Tab. II Temperature effect on reactivity.

	Temperatures	Δk (pcm)	$\Delta k/\Delta T$ (pcm/K)
Maximum Reflection	300 K--> 50K	170±37	0.68±0.15
	50 K --> 1300 K	-1000±35	-0.802±0.028
Maximum Absorption	300 K--> 50K	150±35	0.6±0.14
	50 K --> 1300 K	-1259±34	-1.007±0.027

It is worth of noticing that the overall temperature effect can be divided into two contribution:

- Interaction of neutron with target nucleus (kinetic energy on the single hit).
- Change of the macroscopic cross section as consequence of bulk properties variation (frequency of the hit).

Space Power Core Ka (SPOCK): Temperature effects on Be reflector

Be, as light element, needs special temperature dependant cross section corrections to take into account the interaction of the structure with neutron. MCNPX properly simulated this behaviour when an additive set of temperature dependent cross sections, the so called $S(\alpha,\beta)$, were loaded for the specific elements.

Tab. III Beryllium $S(\alpha,\beta)$ effect on reactivity

Description	k_{eff}	k_{eff} (no Be $S(\alpha,\beta)$)	k_{eff} (pcm)
Maximum Reflection T=300 K	1.06438±0.00027	1.06414±0.00026	24±37
Maximum Absorption T=300 K	0.97624±0.00024	0.97577±0.00025	47±35
Maximum Reflection T=1300 K	1.05606±0.00024	1.05579±0.00026	27±35
Maximum Absorption T=1300 K	0.96515±0.00024	0.96512±0.00023	3±33

As expected for a fast reactor, the influence on reactivity of the $S(\alpha,\beta)$ cross sections is limited to a positive contribution of the order of 50 pcm. Due to the high fusion temperature no change of density was taken into account.

Space Power Core Ka (SPOCK): Temperature effects on Na coolant

Na is enough heavy element to be considered totally decoupled from the chemical structure in its interaction with neutrons. Hence the Na microscopic cross section dependence from temperature is well described by perfect gas approximation (Doppler Broadening). The reactivity change connected with Na Doppler Broadening was analysed keeping constant the Na density and varying its temperature.

Tab. IV Doppler broadening effect on reactivity.

Temperature jump	Sodium coolant density (g/cm ³)	Maximum Reflection k _{eff} (pcm)	Maximum Absorption k _{eff} (pcm)
T=50 K-> T=300 K	1.008 (T=50 K)	53±38	30±35
	0.968 (T=300 K)	-10±37	15±35
T= 50 K->T=1300 K	1.008 (T=50 K)	309±36	151±34
	0.706 (T=1300 k)	312±35	175±34
T=300 K->T=1300 K	0.968 (T=300 K)	326±38	153±35
	0.706 (T=1300 K)	298±35	160±33

The maximum of reactivity change is of the order of 300 PCM for the transition of the system temperature from 300 to 1300 K (at constant Na density).

Space POver Core Ka (SPOCK): Temperature effect on Na coolant

The reactivity change connected with Na macroscopic cross section modification (transition of the bulk density with temperature) was analysed keeping constant the temperature (constant Doppler Broadening) and varying Na density.

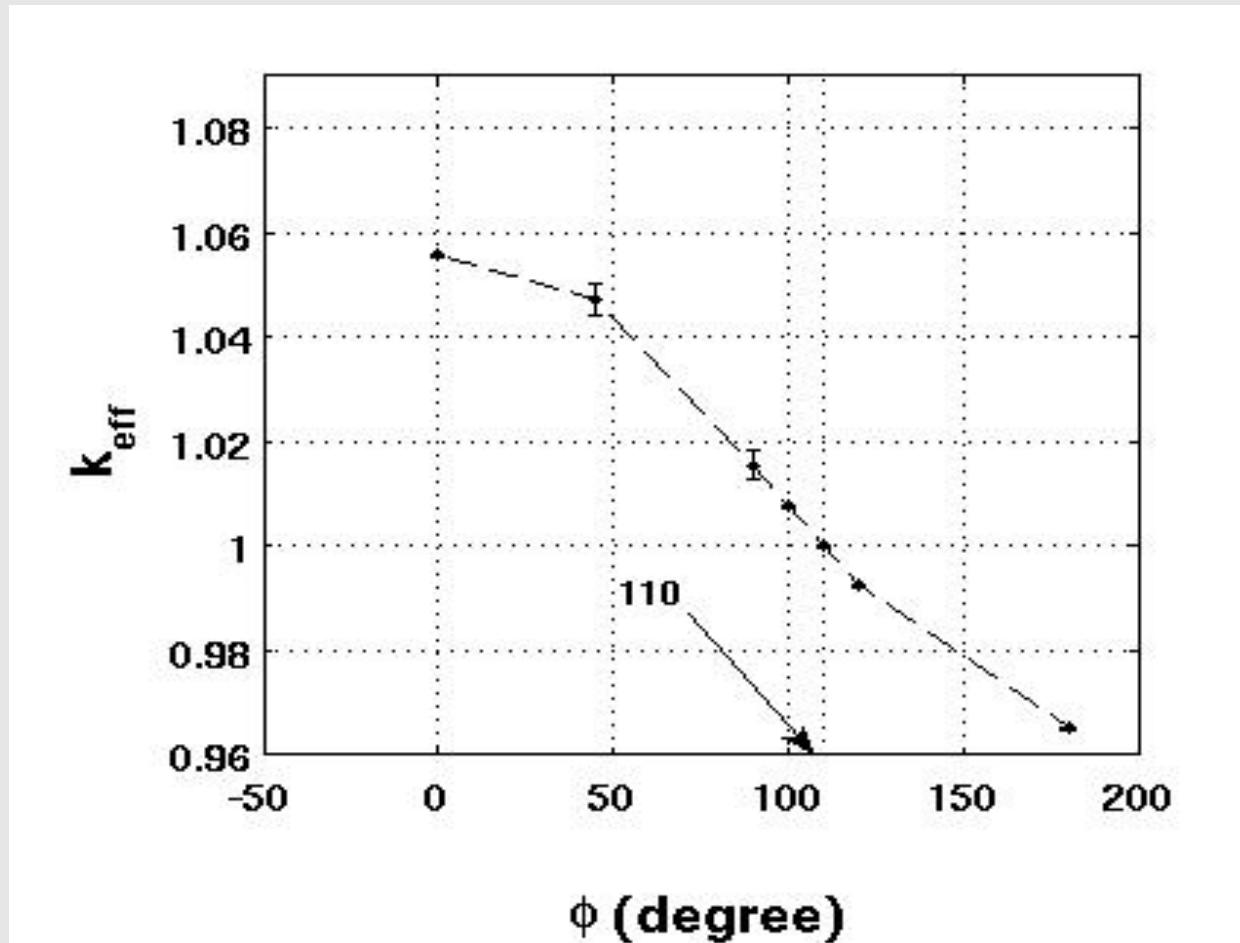
Tab. V Sodium density effect on reactivity.

Sodium density jumps (g/cm ³)	T (K)	Maximum Reflection Δk_{eff} (pcm)	Maximum Absorption Δk_{eff} (pcm)
d=1.008 -> d=0.968	50	160±36	166±34
	300	1353±36	1447±33
d=1.008 -> d=0.706	50	1314±36	1434±33
	1300	1311±36	1410±33
d=0.968 -> d=0.706	300	1129±37	1268±34
	1300	1158±37	1262±34

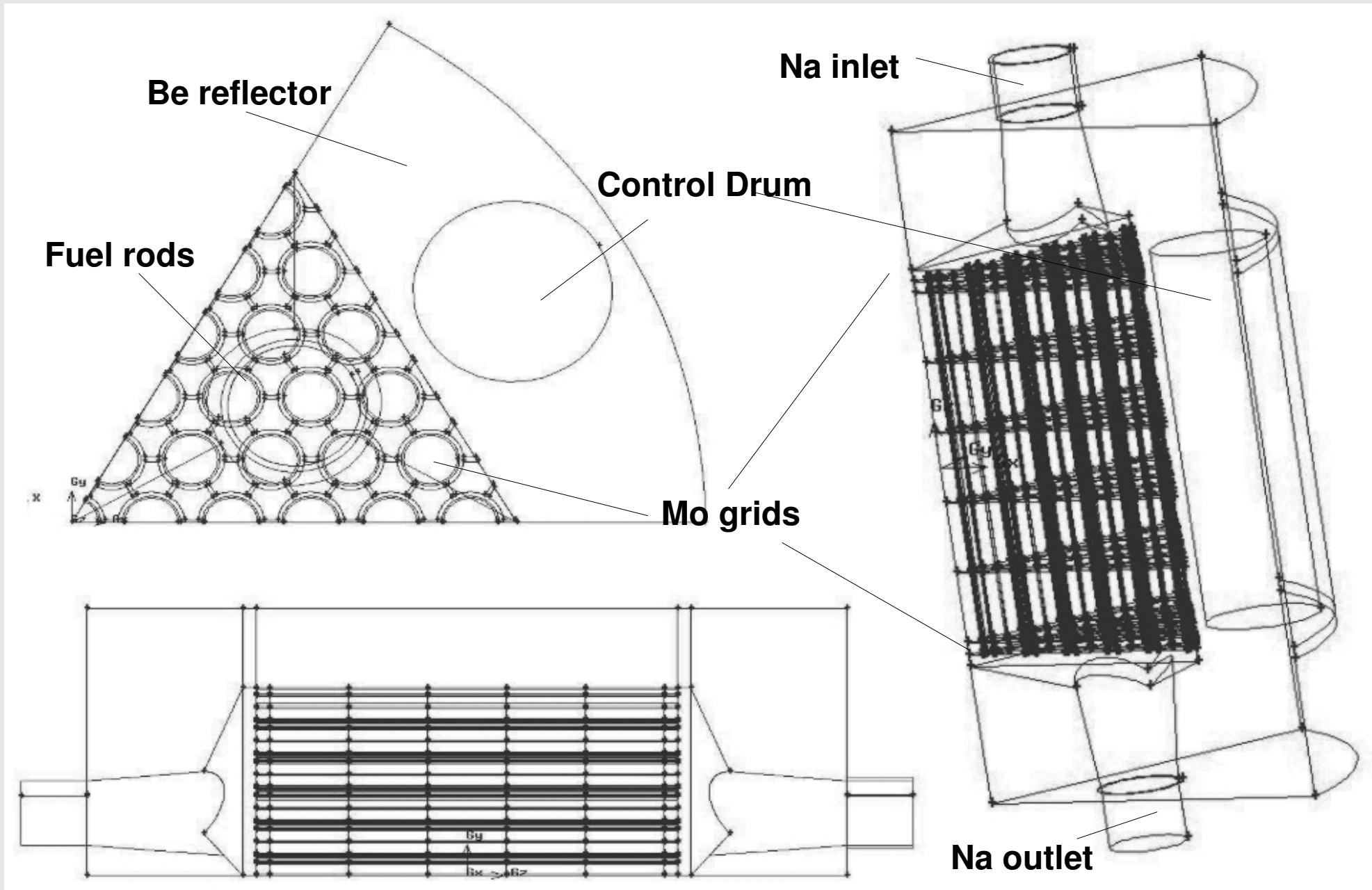
The main contribution to the reactivity is represented by density effects and, secondary, by Doppler broadening.

Space POver Core Ka (SPOCK): Control rods regulation

In order to evaluate the control drums position compatible with the core critical state at the nominal operating temperature (1300 K) a last set of criticality simulations was performed with a progressive rotation of the control drums. In this coarse approximation the control drums were rotated simultaneously of the same angular quantity. The criticality state was obtained at 110 degree of rotation.

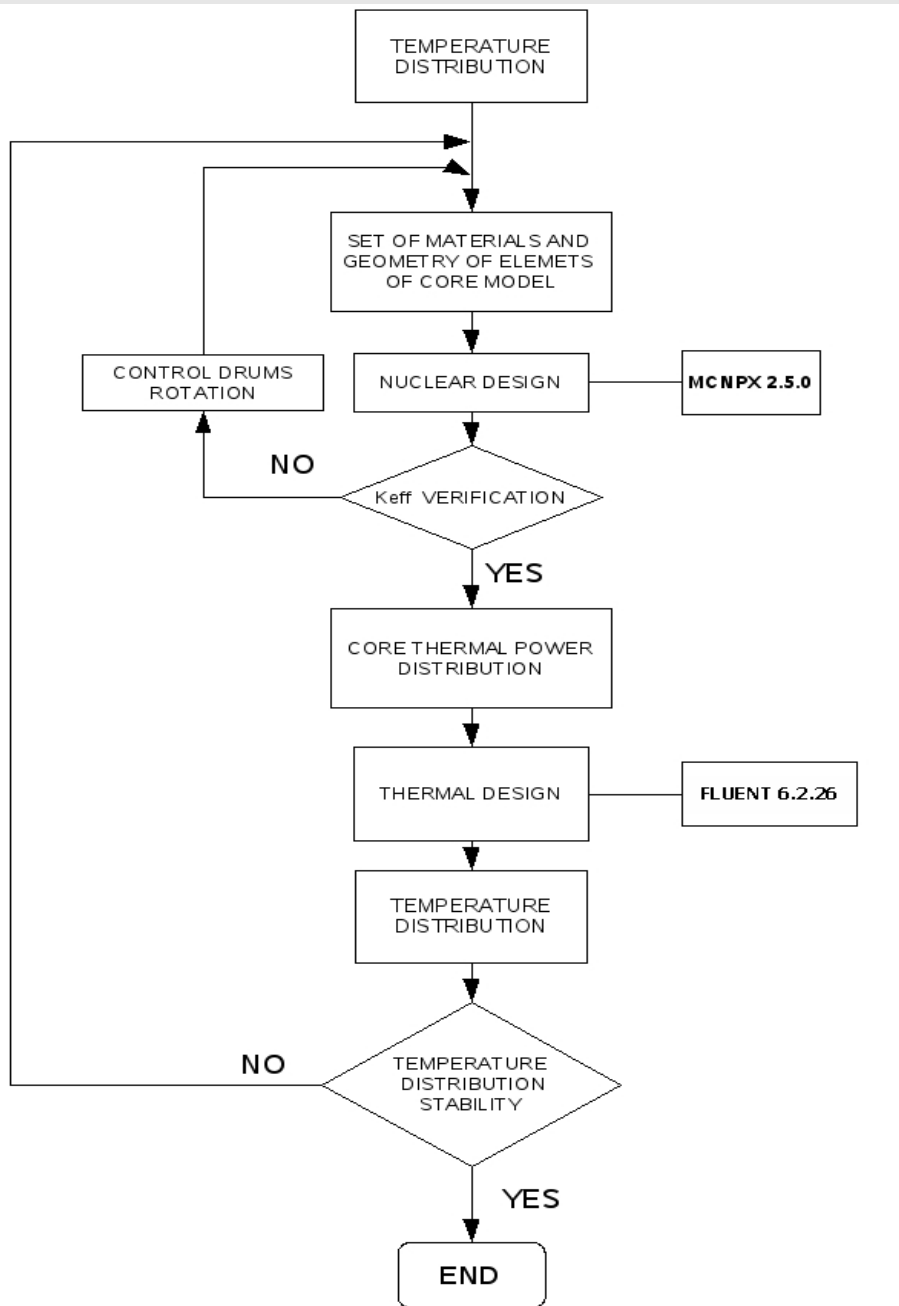


Space POWER Core Ka (SPOCK): Thermal hydraulic modelling



FLUENT simulation was carried out on a geometric element of 1/6th of the total system.

Space Power Core Ka (SPOCK): MC-CFD Coupling



Iterative calculation system

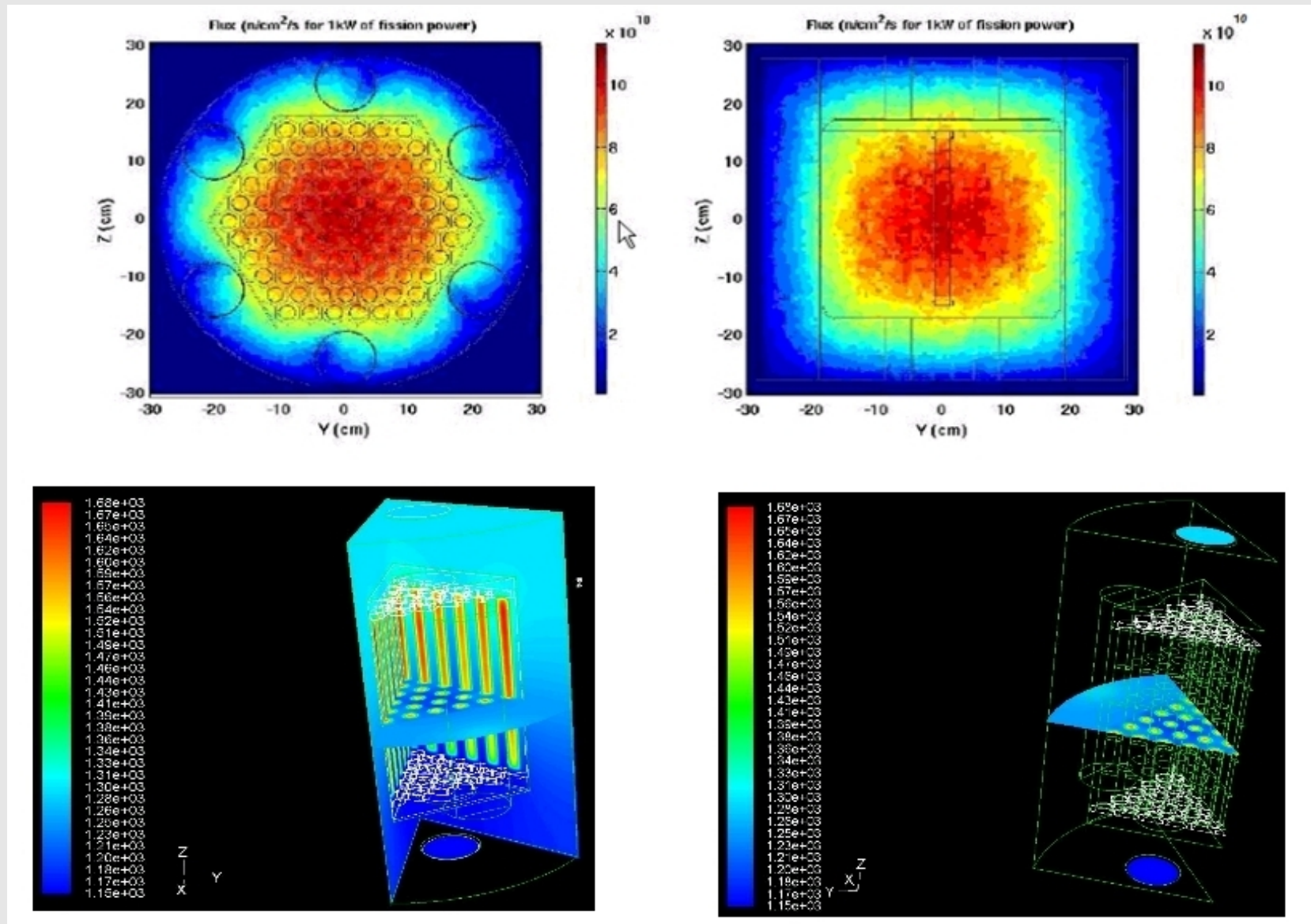
- Obtain a first estimation of Fission Heating Distribution from Monte Carlo Calculation
- FLUENT solve the heat transport equations for the Fission Heating Source.
- The set of correlated temperatures for each element was used in a new Monte Carlo calculation to adjust criticality level.
- A refined Fission Heating distribution is obtained and used to define the fluent heat source.
- The iterations continue until a stable solution was obtained.

Remark

The data flow is realized interactively by the user!

Space Power Core Ka (SPOCK): MC-CFD Coupling results

A mass flow of 0.3 kg/sec of the sodium coolant and an inlet temperature of 1150 K led to the final outlet coolant temperature of 1300 K and a temperature field with an hottest fuel rod zone (1680 K) located in the “upper part “ of central ring



Space Power Core Ka (SPOCK): Development requirement

In the light of the future design development that requires feedback between CFD and MC codes (transient analysis), an automation of the iterative scheme will become mandatory.

Works are in progress in the implementation of Control and Coupling (CO&CO) program whose major features are:

- Management of MC and CFD codes as task processes.
- Communication between tasks (CFD and MC coupling).
- Test convergence criteria and adaptive iterations strategy (tasks control).

A version zero of the CO&CO program is under testing on a very simple stationary problem and it has given promising results.

Space Power Core Ka (SPOCK): Conclusions

- The concept of SPOCK space nuclear system for power generation was presented along with the simulations tools necessary to implement coupled MC-CFD calculations.
- The system reactivity is mainly influenced by Na coolant density change whereas, neutronic effect connected with other systems components appear to be of little or negligible influence.
- The outlet sodium temperature of 1300 K is assumed for the future dimensioning of an out of core thermoelectric converter based on an appropriate semiconductor device (work in progress).