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

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Abstract

SPOCK (Space POwer Core Ka) is an upgrade of the MAUS reactor that was conceived to generates, via thermoelectric conversion, 30 kW of electricity for space applications. Apart the power scale up, SPOCK is characterised by a forced circulation of the Na coolant into the core. The thermoelectric conversion will be performed out of core, by heat exchange with the primary coolant. The present paper was mainly dedicated on the development of SPOCK general concept and to the preliminary computer modelling for the set up of a calculation chain based on Monte Carlo (MCNPX 2.5.0) code and a thermohydraulic code (FLUENT 6.2.16). Early results were focussed to a critical revision of the nuclear data to be used in Monte Carlo estimations of SPOCK's neutronic performance in the challenging condition of a space mission. The very encouraging results allows us to discuss the future development lines of the SPOCK system and the creation of integrated design tool.

Keywords

Nuclear space reactor, MCNPX, criticality analysis, FLUENT.

Introduction

SPOCK (Space POwer Core Ka) is a fast, MOX fuelled, compact reactor controlled by absorption control rods located in the Be reflector, and cooled by liquid Na in forced circulation in order to supply an out of core thermoelectric converter for space applications. The main difference respect to his father MAUS [1-3] are: i) the power scale up at 30 kWe; ii) the forced circulation regime of the liquid Na coolant. SPOCK during the heart and launch operation must be maintained in sub-critical state and it will start up in the outer space at 40 K with the coolant in a solid state. Operating steady condition will be reach at 1300 K with the coolant in the liquid state. Obviously, the main difficult is to design the apparatus and components in a manner that all the possible transients during start up and steady state conditions will be properly controlled. Aim of this paper is to put the first cornerstone in the building of SPOCK design investigating the primary neutronic behaviour of the system coupled with some thermohydraulics effects. Neutronic effects at various overall temperature and density change were investigated by using MCNPX 2.5.0 code [4] criticality model of SPOCK. Some efforts were also directed in the simulation of local temperature effects on reactivity by coupling MCNPX model with the FLUENT 6.2.16 thermal hydraulic code.

1. Description of SPOCK concept

The SPOCK main components are: nuclear reactor core, pressurized reactor vessel for sodium forced liquid coolant, reflector, peripheral control rods, primary external circuit for energy converter devices (p-n junction thermal to electric converter), secondary thermal circuit to release waste heat not converted, radiator. Finally a system of ElectroMagnetic Pumps (EMP) to force the liquid sodium into two thermal circuits (see figure 1). The SPOCK fast nuclear reactor is the heat source for a thermoelectric power supply with is able to produce energy for more then 7 years. It provides about 350 kW of thermal power which is transferred through forced circuit of liquid sodium from the MOX fuel (UO_2 with 95 % enriched in U_{235}) to the hot side (thermal range 1150 – 1250 K) of the ex-core p-n junction thermoelectric conversion system with efficiency range of 9-11% which generates about 30 kW of electric power. The thermal power which is not converted is irradiated directly into space by conventional radiative panels which are connected to the “cold” side of the p-n junction converter by secondary Sodium circuit (thermal range 650-750 K). A shield and/or a structure separating the reactor from the payload is foreseen, to reduce the radiation dose to the payload. The electric power target of the SPOCK generator is 30 kW, during all the time of the spacecraft mission (7-10 years). A priority requirement for nuclear space system is the mass/dimension compatibility with more important launchers as NASA Space Shuttle System and ESA ARIANE-5. The electric power conversion system (p-n junction) are designed with absence of moving parts as hydraulic pumps in order to allow very high operation reliability. The reactor is contained in a pressurized vessel where liquid Sodium is maintained at 5 bar pressure when circulating as coolant. Sodium is used because of its low neutron capture cross section, high thermal conductivity, compatibility with materials of interfacing components and relatively low density. In the SPOCK configuration the fuel is UO_2 (highly enriched, 95%, in fissile) and fuel clad is made of Molybdenum, with Helium in the gap. Metallic beryllium has been chosen as reflector because of its optimal neutron reflecting characteristics, good resistance under irradiation, low density, and compatibility with other materials involved. The tentative SPOCK layout is guided by the general idea of keep out core the thermoelectric conversion devices and eventual propulsive systems. The main advantage are: i) minor radiation damage of the devices (lifetime enhancement) ii) The possible to work with an higher temperature jump, iii) the core will be no charged with static and/or dynamic reactivity worth.

2. Description of SPOCK nuclear system

As shown in figure 2, cylindrical shaped fuel rods are disposed on hexagonal rings surrounded by the reflector and held between two Molybdenum grids. The fuel, clad and grid materials have been chosen taking into account the high temperature of the Na coolant. The in-core circulation of the liquid Na will be ensured by electromagnetic pumps (EMP). The critical mass is obtained with 91 $U0_2$ fuel rods, that in this first design stages are preferred to low payload UN fuel, because of the superior knowledge on the related nuclear data. In further development of the systems, when the conceptual relation between the various components behaviour will became clear, more advanced fuels options will be considered. The reflector is made of a Be (thickness = 8 cm) that surrounding the core gives the final shape of a cylinder (height = diameter = 60 cm) to the system. The reactor control is based on neutron absorption/reflection realized by 6 rotating drums located into the reflector. As reported in figure 2a), the Be control drums have B_4C (neutron absorber) sectors, when the drums were rotated to orientate the absorber sector in front of the core a negative reactivity condition take place (Maximum neutron absorption). Conversely when the neutron absorber sectors are oriented in the opposed direction, the neutron were reflected back to the core by Be reflector, generating a positive reactivity insertion (Maximum neutron reflection).

3. Preliminary Analysis

Generally speaking, it is highly recommended to have all the reactor core in a solid form during the launch phase. This safety requirement could introduces some drawbacks in the neutronic design of the systems. Start up and power rise will be remotely controlled in a scenario where the fission heating as to be used to melt the Na coolant that only after a given amount of time will be ready to begin forced circulation. Apart from expected feedback effect on the criticality conditions, there is the possibility of that an hill-posed heat distribution avoids the total melt of the coolant and limits its circulation. In this condition, at least, the nuclear pile could arrives to criticality but the electrical power generation fails. The present analysis is mainly devoted to “collect” the basic information on the possibility of both neutronic transport Monte Carlo codes and thermohydraulics codes to simulates the above cited scenario and furnishes the main parameters to be used, later, for the set up of the control system.

3.1 Neutronic modelling

A preliminary, not reported, set of Monte Carlo simulations allowed the calculations of the fissile mass, optimal fuels lattice geometry, reflector thickness and control drums geometry that constitutes the bases of the reactor system. Thus, accordingly to Spock concept, the reactor components and materials (core, reflector, control rods and coolant) relevant for its neutronic characterization were implemented on a new MCNPX 2.5.0 input deck. At this stage, the goal of the neutronic analysis was to identify behaviour differences induced by temperatures and density effects related to the different phases of the mission by using, as overall parameter, the estimated k_{eff} value. The MCNPX 2.5.0 simulations were carried out by using the KCODE routine with 10^3 refinement cycles (10^4 fission points sample for each cycle) on a 16 cpus parallel computer with a typical standard deviation of $2x10^{-4}$. For each case, the criticality reservoir was estimated by the calculation of two k_{eff} values: i) in maximum reflection condition, where control drums offer the Be sector to the core, ii) in maximum absorption condition, where control drums offer the B_4C absorber to the core. In each run the system was assumed to be in isothermal state. As reported in Table I, 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. As expected (see Table II) , 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). The overall temperature effect on reactivity could be further subdivided in different contributions related with the direct neutron–nuclei interactions at the given temperature and the macroscopic effect related with change of physical bulk properties such as atomic densities of the materials (mainly for Na coolant). The first effect strongly depends on the energies of incoming neutron: if the approaching neutron has an associated energy in the thermal range (0.01 to 4 eV) and the target nucleus is a light one, the collisions is influenced by the phononic band of the material whose states strongly depends on temperature, otherwise the collision is influenced by the translational degree of freedom of the target nucleus that can be considered as unbounded (Doppler Broadening effect). In principle MCNPX 2.5.0 corrects the cross section for both kind of thermal effects, but the temperature correction in phononic band requires additive cross section data from separated evaluation, the so called $S(\alpha,\beta)$ cross sections that are not available for all light materials in all temperature ranges. At this point in time, for our models, the only $S(\alpha,\beta)$ that are of interest are the one of Be at the temperatures of 300 and 1300 K. From the data reported in Table III, 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 that can be pretty controlled by the control rods worth. In order to split the Doppler Broadening to density change effects on reactivity, different sets of criticality simulations with concerted change of temperature and density were executed. Table IV reports the k_{eff} change induced by Doppler broadening for all the combination of jumps of the system temperature between 50, 300 and 1300 K at constant Na density. The density effects reported in Table V on k_{eff} were calculated from a second set of simulations executed at constant temperatures for all the combinations of jumps of Na density between 1.008, 0.968 and 0.706 g/cm3. The principal contribution to the reactivity change is mainly represented by Sodium density effects and secondary by Doppler broadening, whereas only a minor reactivity change is related to the phononic band interaction that take place in the reflector. 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. Figure 3 reports the estimated values of k_{eff} versus the rotation angle starting from 0 degree (maximum reflection) to 180 degree (maximum absorption). The criticality state was obtained at 110 degree of rotation.

3.2 Thermal hydraulic modelling

For a preliminary design of the SPOCK space generator, an iterative calculation system based on MCNPX 2.5.0 and FLUENT 2.2.16 codes was used, as shown in figure 4. The sequence calculation is based on many steps of refinements. In the first step a MCNPX 2.5.0 KCODE calculation was initiated with the control drums position compatible with a critical state having the entire core system (coolant, fuel rods, grids,..) at 1300 K. From this simulation the energy deposited on five axial segments of each fuel rod were evaluated. The so obtained heat source was given as input to FLUENT 1.2.16 code that, by using the set above cited thermo hydraulic characteristic reported, solve the heat transport equations obtaining a set of correlated temperatures for each element. This temperature field was used as input for a KCODE simulation where the criticality state was further refined. Again, a new set of deposited energy was used to define the fluent heat source. The iterations continue until a stable answer was obtained from both the codes. It is worth of mention that, due to the cylindrical symmetry of the SPOCK system, the FLUENT simulation was carried out on a geometric element of 1/6th of the total system (see figure 1). For the design specification of a mass flow of 0.3 kg/sec of the sodium coolant and an inlet temperature of 1150 K the iterative scheme 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.

4. Development requirement

In order to proceed to a more detailed analysis of the present steady state power condition and of the more onerous simulation of the “start up and raise to power” operations, an automation of the iterative scheme between MCNPX and FLUENT simulations will become mandatory. The general idea is to use a master control program, that managing the two codes as task processes, will be able to evaluate the goodness of the output results and would consequently expand or contract the number of requested iterations for a satisfactory convergence of the results. Another important item will be the cross check between different nuclear dataset in order to minimize the uncertainties that will come from different data evaluation. Finally some calculation chains will be developed to evaluate shielding requirement and burn-up figures.

5. Conclusions

The concept of SPOCK space nuclear system for power generation was presented along with the calculation tools necessary for coupled neutronic thermohydraulic calculations. From the preliminary simulations the main parameter that influence system reactivity are the coolant density and temperature whereas, neutronic effect of the other systems components appear to be of little or negligible influence. It is worth of noticing that the coupled neutronic-termohydraulic simulation converges to an outlet sodium temperatures of 1300 K that would be used in out core thermoelectric conversion by an appropriate semiconductor device.

References

[1] Caira M., Cumo F., Gandini A., Naviglio A. , “MAUS: a fast nuclear reactor for space electric generation”, *Energia nucleare,* 10(2), 1993.

[2] Cumo M., Frullini M., Gandini A., Garofalo F., Mattu F., Naviglio A. et al., “Nuclear Reactor for Electric Power Generation in Space Application”, Proceedings of the Space Nuclear Conference 2005 San Diego, California, June 5-9, 2005, on CD-ROM Paper 1133.

[3] Cumo M., Frullini M., Gandini A., Naviglio A., Sorabella L., “MAUS-1,5 nuclear reactor for space electric power”, 12th International Conference on Emerging Nuclear Energy Systems (ICENES’2005) Brussels, Belgium, August 21–26, 2005, on CD-ROM, SCK•CEN, Mol, Belgium (2005).

[4] Denise B. Pelowitz, editor “MCNPX USER’S MANUAL Version 2.5.0” April 2005 LA-CP-05-0369.

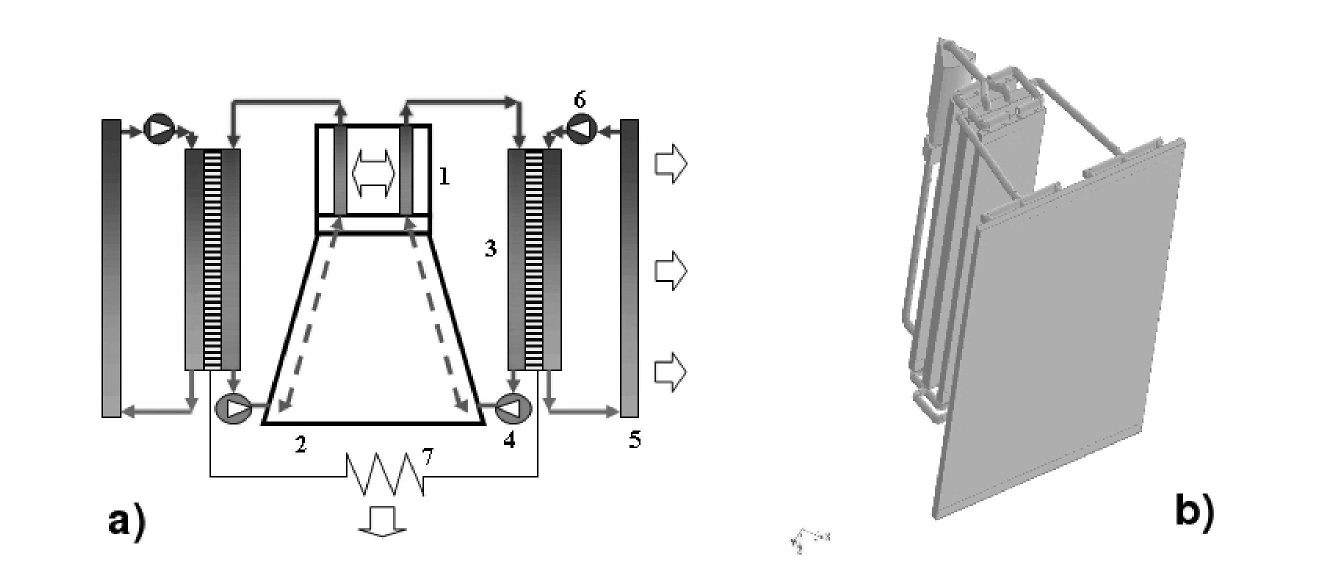
Figure caption

Figure 1: a) Schematic view of the SPOCK main components 1: reactor, 2: shield, 3: p-n junction thermoelectric converter, 4: EMP primary loop, 5: radiator, 6: EMP secondary loop, 7: External Load. b) 3-D detailed drawings of the same components (only 1/6th of the generator is represented).

Figure 2: Layout sections of SPOCK nuclear system.

Figure 3: Criticality evaluation for different rotation angle of control drums.

Figure 4: Flow chart of the iterative calculation procedure.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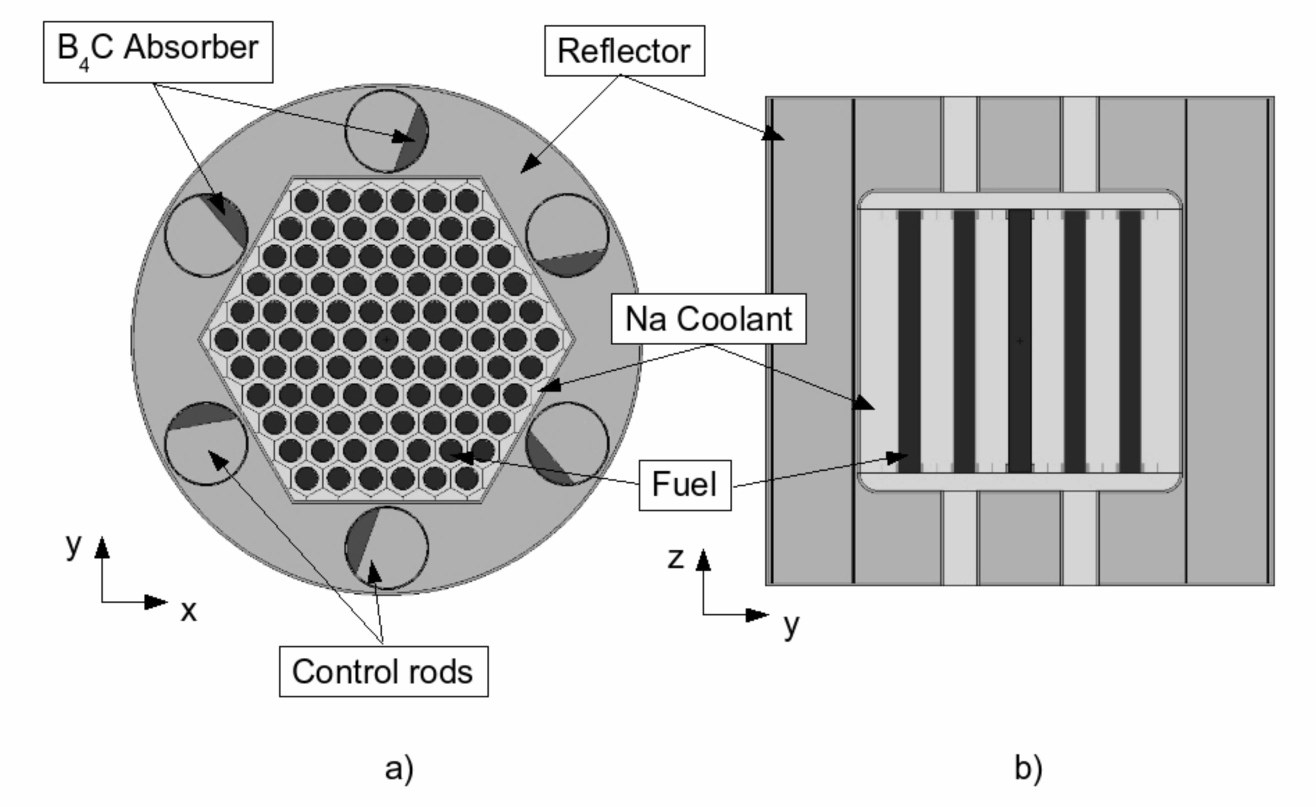
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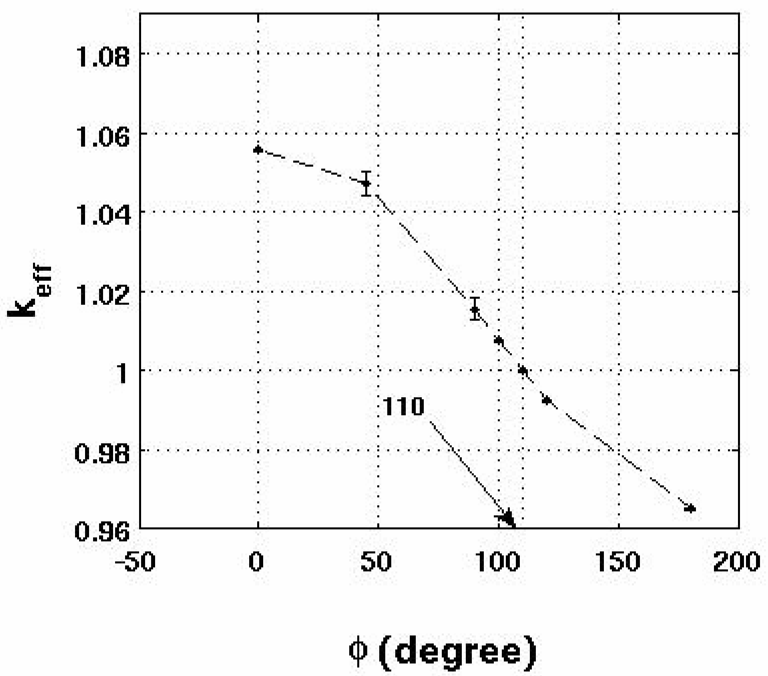
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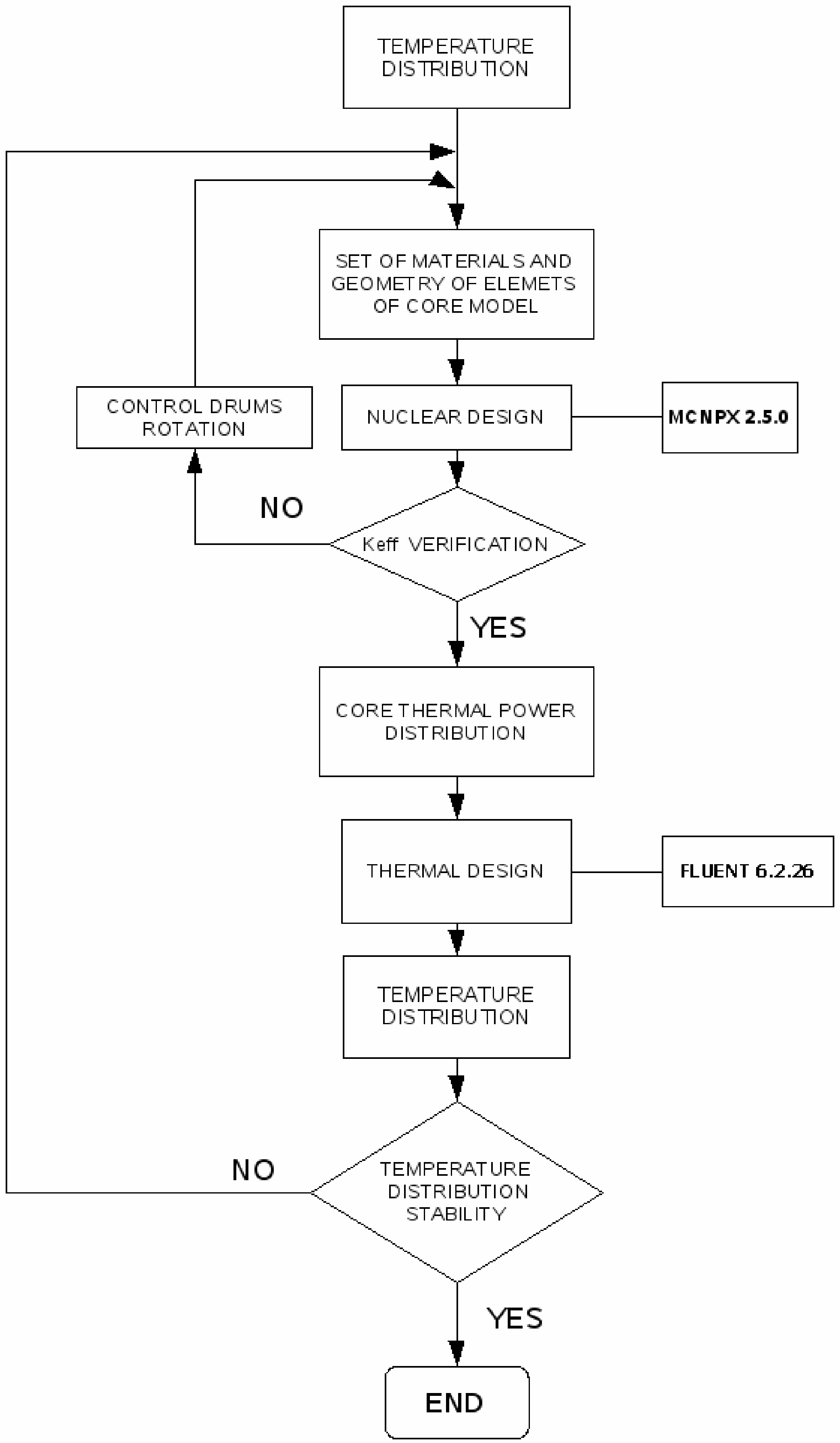
TEMPERATURE DISTRIBUTION
SET OF MATERIALS AND GEOMETRY OF ELEMETS OF CORE MODEL
CONTROL DRUMS ROTATION
NUCLEAR DESIGN
MCNPX 2.5.0
NO
Keff VERIFICATION
YES
CORE THERMAL POWER DISTRIBUTION
THERMAL DESIGN
FLUENT 6.2.26
TEMPERATURE DISTRIBUTION
NO
TEMPERATURE DISTRIBUTION STABILITY
YES
END

Table I Reactivity at different temperatures.

N.	**Description**	**Temperature (K)**	**Sodium density (g/cm^3)**	**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

Table II Temperature effect on reactivity.

	Temperatures	**Δk (pcm)**	**Δk/ΔT (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

Table III Beryllium S(α,β) effect on reactivity

Description	**k_{eff}**	**k_{eff} (no Be S(α,β))**	**Δk_{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

Table IV Doppler broadening effect on reactivity.

Temperature jump	Sodium coolant density (g/cm^3)	Maximum Reflection Δk_{eff} (pcm)	Maximum Absorption Δk_{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

Table V Sodium density effect on reactivity.

Sodium density jumps (g/cm3)	T (K)	Maximum Reflection Δk_{eff} (pcm)	Maximum Absorption Δk_{eff} (pcm)
ρ (T=50 K) -> (T=300 K)	50	160±36	166±34
	300	1353±36	1447±33
ρ (T=50 K) -> (T=1300 K)	50	1314±36	1434±33
	1300	1311±36	1410±33
ρ (T=300 K) -> (T=1300 K)	300	1129±37	1268±34
	1300	1158±37	1262±34