FEASIBILITY STUDY ON SMALL LONG-LIFE PB-BI COOLED REACTOR WITH CAPABILITY OF LOAD FOLLOWING BY FLOW RATE ADJUSTMENT

Toshinsky Vladimir and Hayashi Hideyuki
Fuel and Core System Engineering Group
System Engineering Technology Division
O-arai Engineering Center
JAPAN NUCLEAR CYCLE DEVELOPMENT INSTITUTE
4002 Narita-cho, O-arai-machi, Higashi-Ibaraki-gun, Ibaraki-ken, 311-1393 JAPAN
vtoshins@oec.jnc.go.jp ; hayashi@oec.jnc.go.jp

ABSTRACT

The feasibility of designing small long-life lead bismuth eutectic (LBE) cooled fast reactor, which capable to follow the daily load by coolant flow rate control, is investigated. Since such reactors usually possess small negative power reactivity coefficient, as compared to thermal reactors, the decrease of power level with the purpose to meet the lowest power daily demand (~ 50 % of nominal) by only feedbacks (i.e., without use of control rods) causes significant increase in temperature of core components. In the case of LBE cooled reactors, the most severe constraint that limits load-following capability is the cladding hot-spot temperature of fuel elements, which should be kept under 650 ^{o}C during reduction of power demand. This limit comes from cladding corrosion phenomenon in LBE. Thus, the primary goal of our study is to examine whether it is possible or not to enhance feedbacks to the extent, which allows satisfying the above constraint.

1. INTRODUCTION

One of options for future nuclear power is development with small size long-life reactors and, among overall reactor concepts, the design of **L**BE-Cooled **L**ong-**L**ife **S**afe **S**imple **S**mall **P**ortable **P**roliferation-**R**esistant **R**eactor (LSPR)[1] is considered as one of promising candidates. Such reactor especially suits for developing countries from viewpoints of energy demand, infrastructure development, non-proliferation issues, and availability of professional technicians. To make the reactor operation simpler and safer, a possibility of the reactor daily load following by flow rate control (i.e., using temperature reactivity feedbacks) is investigated. It would allow excluding daily manipulations with control rods and make their utilization necessary only for startup, compensation of burnup reactivity swing, and for the reactor shutdown.

For satisfying typical daily load requirements, the reactor should have ability to reduce power from 100% to about 50%, work at reduced power level for about 4-5 hours, and then return to full-power operation. The typical duration of the power transient lies within 0.5 – 2 hours. In case that the power reduction is provided by negative temperature reactivity feedbacks, the temperature of reactor core components increases during this transient.

To define required temperature feedback reactivity characteristics for successful load following capabilities, the survey computations is performed, which, however, reveals that even significant enhancing of negative Doppler and reduction of positive coolant density coefficients does not provide the cladding hot-spot temperature be under 650 ^{o}C at reduced (~50%) power level for LSPR design.

For strengthening negative feedback, a heat source (in the form of short fuel pins) at the bottom of radial lead-bismuth reflector has been introduced. Implementation of the heat source results in increase of reflector temperature during flow rate reduction that enlarges neutron leakage and provides additional negative reactivity. Such an approach makes the idea of reactor load following by flow rate adjustment feasible.

In this research, **S**implified **P**lant **A**nalysis **K**inetic **S**imulator (SPAKS) is used for transient computations, which is similar to one described in [2]. The code has ability to simulate kinetic behavior of primary circuit (core, hot/cool pools, SG), while imposing boundary conditions to SG secondary loop.

2. CALCULATION DATA

2.1 LSPR SPECIFICATIONS

Figure 1 and Table I give schematic view of LSPR and major plant specifications, respectively [1]. An integral type design, where steam generators are installed within reactor vessel is employed, since severe reaction between LBE reactor coolant and steam generator water coolant is not anticipated.

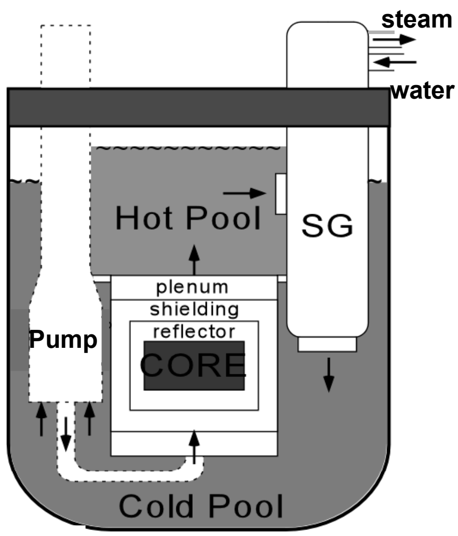


Figure1. Schematic view of LSPR.

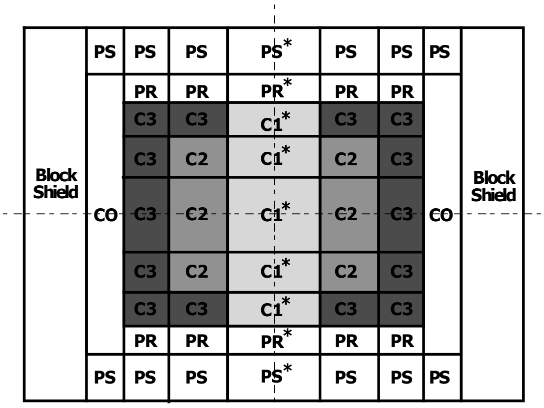
Table I. Major plant specifications.

Item	Unit	
Reactor Thermal Output	MWt	150
Reactor Electric Output	MWe	53
Reactor Outlet Temperature	℃	490
Reacot Inlet Temperature	℃	340
Reactor Vessel Diameter	m	5.2
Reacor Vessel Height	m	15.2
Core Barrel Diameter	m	3.4
Type of Steam Generator		Serpentine Tube
No. of Steam Generators	unit	2
Type of Pump		Centrifuge Pump
No. of Circulating Pump	unit	2
Total Pressure Drop	kg/cm2	0.7
Pb-Bi Coolant Flow Rate	ton/hr	12300
Pb-Bi Coolant Core Velocity	m/s	0.9
Feed Water Temperature	℃	210
Feed Water Flow Rate	ton/hr	2940
SG Outlet Steam Temperature	℃	280
SG Outlet Steam Pressure	MPa	6.47

Figure 2, and Table II shows LSPR core structure and core specifications [3]. Nitride fuel is used because of its good adaptability with LBE coolant. Natural uranium or depleted uranium fuel assemblies are placed at the center of the core as an inner blanket, whereas plutonium fuel assemblies are settled outside of the inner blanket. In this core composition, the burnup of fuels will progress from the outer core into the inner blanket region, which is beneficial for sustaining the reactivity for long-term burnup with small reactivity swing.

Table II. LSPR core specifications.

Item	Unit	Value
Thermal Power	MWt	150
Life-time	Years	12
Core diameter	cm	165.2
Core height	cm	108.0
Number of fuel elements		26700
Fuel/Bonding/		(Pu U)N_{15}/ Pb-Bi/
Cladding/Coolant		HT9/ Pb-Bi
Average power density	W/cc	64.8
Average linear power density	KW/m	5.19
Enrichment (middle/outer core)	%	12.5/ 15.5
Fuel pellet diameter	mm	10
Cladding thickness	mm	0.8
Pitch-to-diameter ratio:		
(inner/outer region)		1.11/1.18



C1: core1 (UN : natural uranium)
C2: core2 ((UPuN) : low enrichment)
C3: core2 ((UPuN): high enrichment)
PR: pin reflector (HT-9 replaces fuel pellets)
PS: pin shield (B4C replaces fuel pellets)
CO: Pb-Bi reflector
(*): inner region

Figure2. Overview of LSPR core.

2.2 KINETIC PARAMETRS AND REACTIVITY COEFFICIENTS

For transient calculations, the kinetic parameters, given by Table III, are computed by PIJ-CITATION module of SRAC code. The coolant temperature and Doppler coefficients reactivity maps (See Tables IV and V, respectively) are computed by SLAROM-JOINT-CITATION-PERKY computation system.

Table III. Kinetic parameters.

Λ [s]			2.218E-07		
β			4.386E-03		
β_i	1	8.100E 05	λ_i	1	1300E-02
	2	8.790E 04		2	3.119E 02
	3	7.746E 04		3	1323E-01
	4	1.634E 03		4	3.466E-01
	5	7.661E 04		5	1.408E+00
	6	2.466E 04		6	3.778E+00

The fuel axial expansion coefficient is estimated as -*1.5200E-06* [dK/KK'/°C] by CITATION code. Negative reactivity effect due to core bowing is not considered in the present analysis to keep conservatism, since this effect may have many uncertainties due to subassembly deformation induced

Table IV. Map of coolant temperature coefficients [dK/KK'/^{o}C].

-9.18933E-08	-9.18933E-08	-9.18933E-08	
-6.99182E-09	-1.80792E-07	-1.80792E-07	(-4.16000E-06) 0.00000E+00
-1.99767E-08	-6.49244E-08	-1.54821E-07	
-3.49592E-08	2..91650E-07	-6.99182E-09	
-4.09522E-08	4.79416E-07	1.10869E-07	
-3.99534E-08	4.80415E-07	1.08871E-07	
-3.49592E-08	2.87655E-07	-6.99182E-09	
-2.19743E-08	-6.79210E-08	-1.55820E-07	
-6.99182E-09	-1.84787E-07	-1.84787E-07	
-6.59233E-08	-6.59233E-08	-6.59233E-08	

Table V. Map of Doppler coefficients [dK/KK'/^{o}C].

0.00000E-00	0.00000E-00	0.00000E-00	
0.00000E-00	0.00000E-00	0.00000E-00	0.00000E-00
-4.39487E-08	-2.14753E-07	-1.53822E-07	
-1.30849E-07	-7.29200E-07	-5.03436E-07	
-1.72801E-07	-9.94935E-07	-6.95235E-07	
-1.73800E-07	-1.044890E-06	-7.30199E-07	
-1.35843E-07	-8.46081E-07	-5.81353E-07	
-4.59464E-08	-2.67694E-07	-1.86785E-07	
0.00000E-00	0.00000E-00	0.00000E-00	
0.00000E-00	0.00000E-00	0.00000E-00	

from irradiation. The reactivity caused by coolant dilatation in radial reflector region is not taken into account at preliminary analysis as shown on Table IV. All the above data corresponds to the fuel composition at the beginning of equilibrium cycle (BOEC) of LSPR.

3. DESCRIPTION OF COMPUTATION TOOL AND SAMPLE PROBLEM CALCUALTION

3.1 SIMULATION BY SPAKS CODE

Simplified **P**lant **A**nalysis **K**inetic **S**imulator (SPAKS) is capable to simulate kinetic behavior of primary circuit: core (R-Z geometry), hot/cool pools by solving time-dependent equations for mass, momentum, and energy conservation. For primary and secondary sides of SG, the steady-state equations for mass, momentum, and energy conservation are repeated at each time-step during transient (quasistatic approach). The calculation model is schematically shown on Figure 3, and Figure 4 represents the computation flow diagram.

For power computation, the point kinetic approximation is used. Multi-channel core model is applied for reactivity computations. During power maneuverings, the pressure in the secondary loop assumed to be constant and the following boundary condition is imposed to SG secondary loop: constant water specific enthalpy at SG inlet, constant specific enthalpy at SG outlet, while secondary flow rate varies during power maneuverings (See Figure 3). In the present analysis, the secondary flow rate is assumed to be proportional to load. The notations T, P, H and G on Figure 3 correspond to temperature, pressure, height and flow rate, respectively.

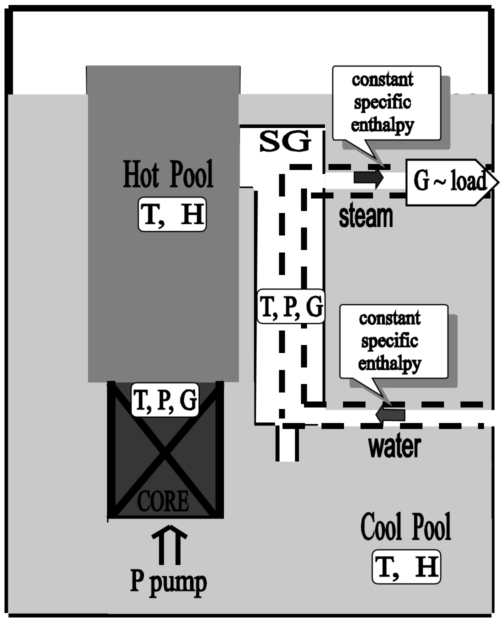


Figure 3.Calculation model.

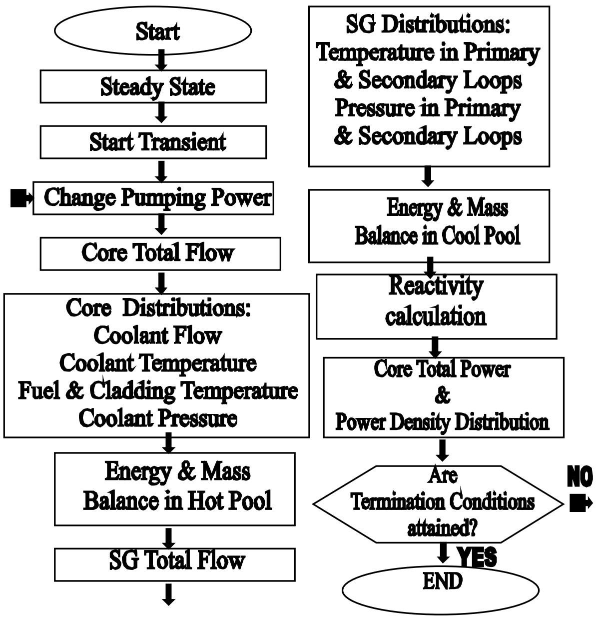


Figure 4. Computation flow.

3.2 RESULTS OF REFERENCE PROBLEM CALCULATION

As reference problem, the following transient is simulated by SPAKS code: the smooth load reduction from 100% to 75% during 30 minutes, and the calculation results are shown on Figures 5a – 5d. The power decrease, which follows the load, is provided by temperature reactivity feedbacks only (control rods are not used) and it is controlled by coolant flow rate. For the hot-spot temperatures calculation, the factor of 1.25 is applied to the nominal hottest temperatures of fuel, cladding and coolant. For the reduction of the hot-spot temperatures, an orificing pattern for coolant flow is implemented, which

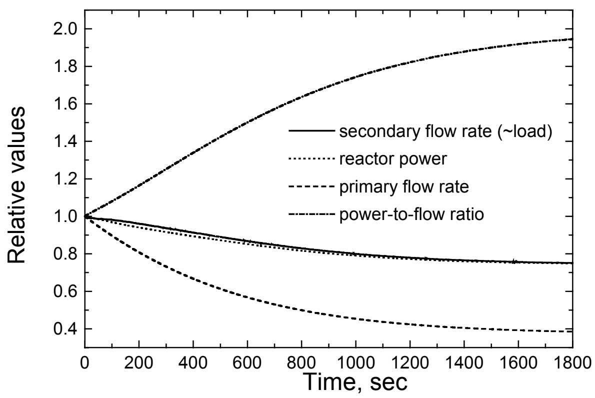


Figure 5a. Load, power, and flow rates.

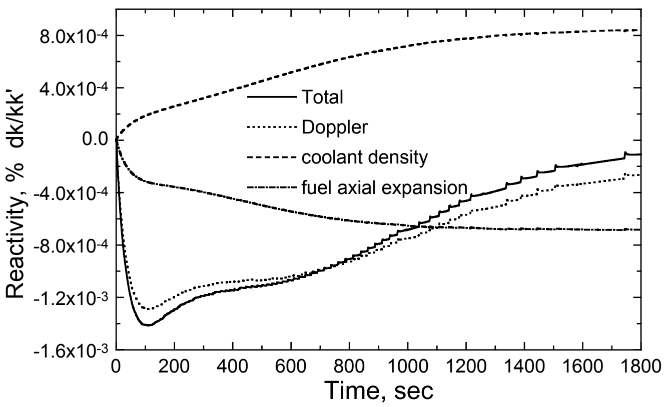


Figure 5b. Reactivity components.

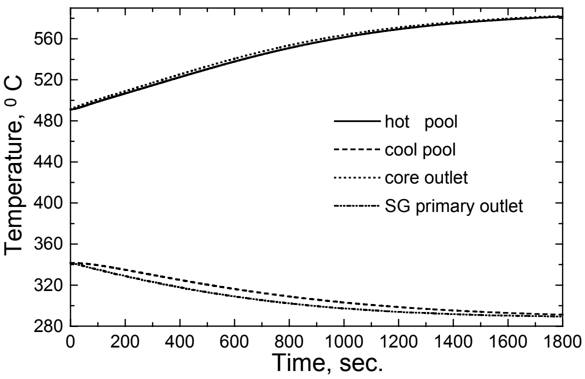


Figure 5c.Temperature behavior.

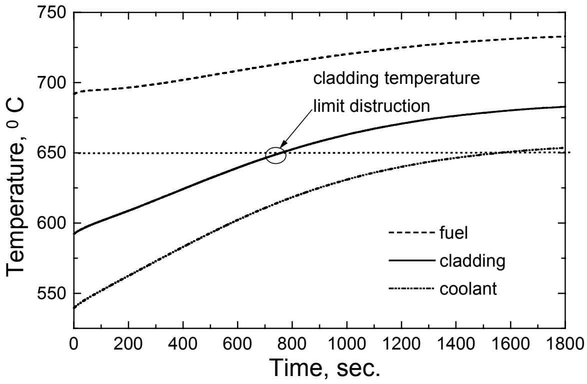


Figure 5d. Hot-spot temperatures.

provides an uniform outlet temperature profile.

To satisfy typical daily load requirements, the reactor should have capability for power reduction from 100% to about 50%, operation at reduced power level for about 4-5 hours, and then returning to full-power operation. As results reveal, even smaller power reduction (from 100% to 75%) leads to the violation of temperature limit for cladding material. The limit is established as 650 ^{0}C for prevention of cladding corrosion in LBE coolant. At power 75%, the cladding hot-spot temperature reaches 680^{0}C (See Figures 5a and 5d), and the target of this research is to find methods for maintaining this temperature below 650 ^{0}C at power level around 50%. Reduction of temperature can be achieved by enhancement of negative temperature reactivity feedbacks. In the next section we will examine sensitivity of power and cladding temperature to variations of different feedback components.

4. ENHANCEMENT OF NEGATIVE TEMPERATURE FEEDBACK REACTIVITY

4.1 SURVEY CALCULATION USING TEMPERATURE FEEDBACK REACTIVITY COMPONENTS AS PARAMETERS

Sensitivity of power and the cladding hot-spot temperature to feedback reactivity components, such as

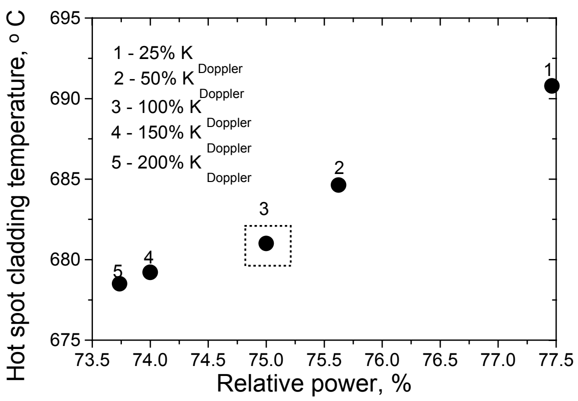


Figure 6a. Doppler coefficient.

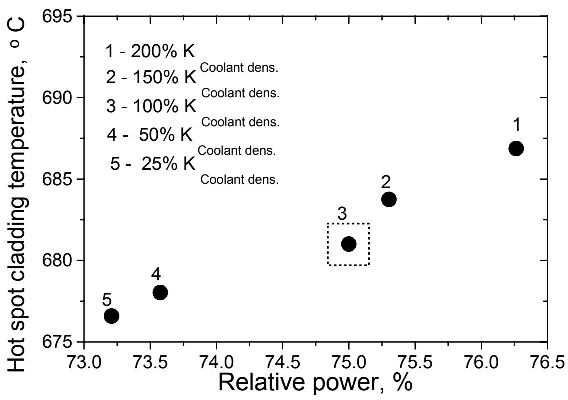


Figure 6b. Coolant temperature coefficient.

Doppler, coolant density, and fuel axial expansion are shown on Figures 6a – 6c. On these graphs the point, which corresponds to reference calculation (Section 3.2), is marked by dotted square.

In general, the results reveal fairly small sensitivity. An enlargement of negative Doppler coefficient twice, which can be achieved, for example, by spectrum-adjustment method with implementation of zirconium hydride in the core region [4], results in rather small decrease of power and the cladding hot-spot temperature - on 1.5% and 3 ^{o}C, respectively. Reduction of coolant temperature coefficient four times, which can be provided by the same method, makes power and temperature smaller on 2% and 5 ^{o}C, respectively. It is also seen that the sensitivity becomes smaller with further enhancing of Doppler and reduction of coolant coefficients and, furthermore, it would lead to significant deterioration of such advanced safety characteristic of LSPR as nearly “zero” burnup reactivity swing [3]. Figure 6c demonstrates that the power and cladding temperature are almost insensitive to fuel axial expansion coefficient. Thus, possible inaccuracies in the coefficient will not notably influence the results. As it was mentioned, in the present analysis we do not consider negative reactivity effect caused by core bowing in order to keep conservatism in our analysis, since uncertainties in its estimation may highly distort the results due to relatively high sensitivity (See Figure 6d). In computations, illustrated on that Figure, the value of core radial expansion coefficient *-8.1200E-06* [dK/KK’/^{o}C] is taken from Reference [3], where it was estimated for similar reactor design.

To summarize the above survey, the results reveal that enhancing of Doppler and reduction of coolant coefficients are not enough measures to ensure load following capabilities of LSPR by flow rate control under limitation on the cladding hot-spot temperature and, thus, some new approaches on enhancing feedback should be searched. One of such methods is described in next Section.

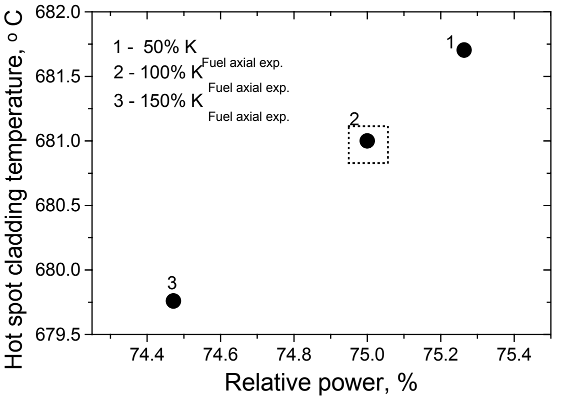


Figure 6c. Fuel axial expansion coefficient.

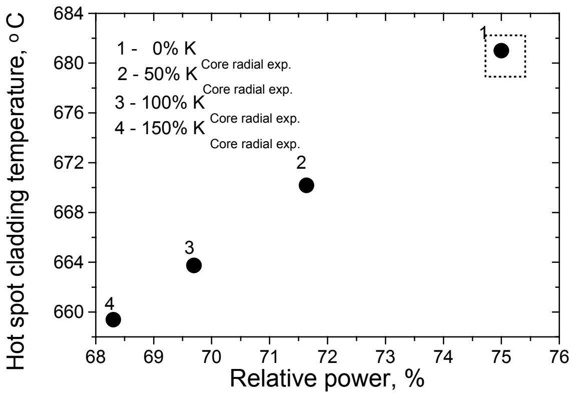


Figure 6d. Core radial expansion coefficient.

4.2 ENHANCING FEEDBACK USING HEAT SOURCE IN RADIAL PB-BI REFLECTOR REGION

For enhancing negative reactivity feedback at flow rate reduction, an innovative idea of introducing the heat source (HS) into radial Pb-Bi reflector region is proposed, as it is schematically demonstrated on Figure 7. Utilization of HS results in increase of Pb-Bi radial reflector temperature during flow rate reduction that enlarges neutron leakage and provides additional negative reactivity.

It is proposed to use short fuel pins as a HS. The characteristics of HS was investigated [5] with an objective to minimize HS fissile inventory and satisfy the following constrains (we considered the same transient as described in Section 3.2):
Cladding hot-spot temperature ≤ 650 ^{o}C;
Maximum coolant velocity at HS region ≤ 2 m/s;
Flow rate fraction through HS ≥ 0.3% rel;
Conversion ratio (CR) of heat source ~1.

The limitation on the cladding hot-spot temperature and maximum coolant velocity were imposed to prevent corrosion and erosion of cladding in LBE. The selection of constraint on flow rate fraction was based on past flow distribution design concerning reflector region. The CR was provided around unity to keep core/HS power ratio constant during reactor lifetime.

As decision variables we considered HS location (S), length (L), power, flow rate fraction through HS, enrichment and fuel pitch. As a result, solution with the following HS characteristics was selected [5]:

Inventory of HS (Pu-fissile) = 26 kg;
S = 22 cm;
L = 2.82 cm;
Power of HS = 0.375 MW;
Flow rate fraction (HS channel) = 3.067E-1 %;
Enrichment of HS (Pu-fissile) = 15%;
Fuel pitch = 13.7 mm (pitch-to-diameter ratio = 1.18);

Coolant temperature coefficient (HS channel) = -3.828E-4 DK/K/ ^{o}C;
Maximum coolant velocity (HS region) = 1.2 cm/s;
Cladding hot-spot temperature (HS region) = 649.7 ^{o}C;
Maximum coolant velocity (core region) = 125 cm/s
Cladding hot-spot temperature (core region) = 649.5 ^{o}C.

For demonstration of benefit from HS implementation, the same transient as considered in Section 3.2 is simulated, and the calculations with/without HS are performed. The results are shown on Figures 8a– 8c.

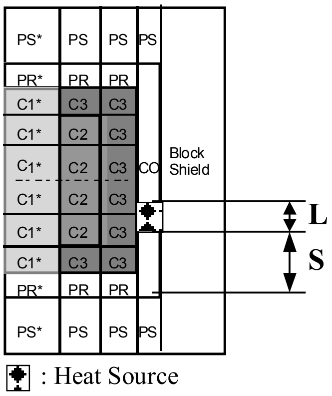


Figure 7. Heat source implementation.

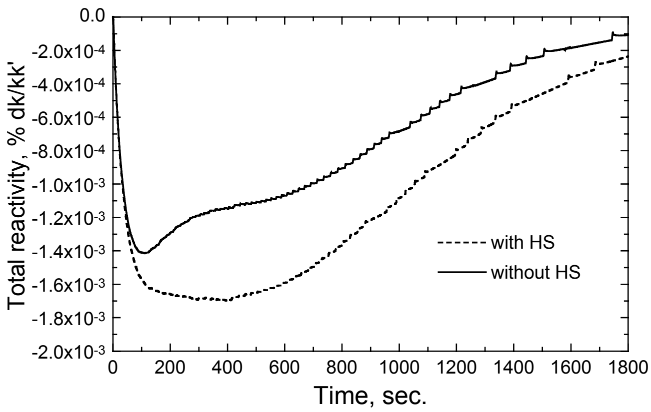


Figure 8a. Reactivity behavior.

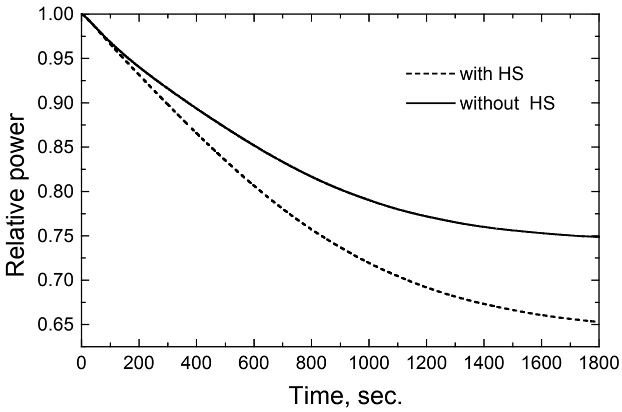


Figure 8b. Power behavior.

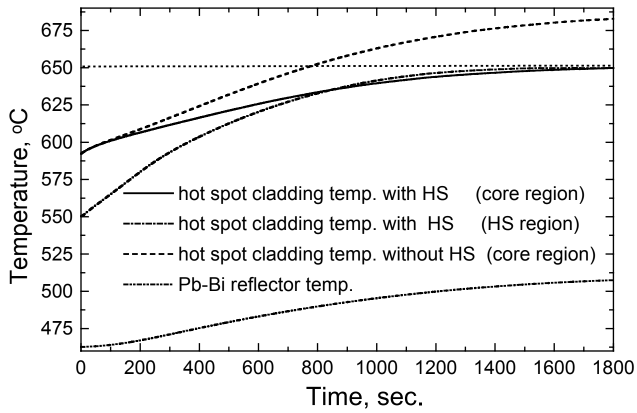


Figure 8c. Temperature behavior.

These results reveal that implementation of HS significantly enhances reactivity feedback that results in more effective reduction of both power (on about 10%) and the cladding hot-spot temperature (on about 30°C), which does not exceed the prescribed limit - 650 °C. The Pu-fissile inventory required for HS is 26 kg that is less than 1% of total fissile inventory. Thus, the increase in LSPR capital cost, resulting from such modification, is negligible.

5. DISCUSSION

It is seen from the Figures 8a-8c that under constrain on the cladding hot-spot temperature - 650 °C, the power can be reduced by feedbacks up to ~65% that is still larger than required level ~50%. Yet, there are some methods, which, as expected, may lead to further improvement of results. They are mainly the followings:

- Adjustment of core height-to-diameter ratio.
- Modification of fuel pin design: placement of upper FP gas plenum right above fuel region (elimination of upper pin reflector (PR) and B_4C pellets, see Figure 2). It will result in enhancing negative coolant temperature reactivity coefficients in upper regions.
- Implementation of He (instead of LBE) bonding together with LBE upper plenum. Such modification results in reduction of Doppler reactivity at some extent, but enhances axial leakage at flow rate reduction.
- So far we did not consider negative reactivity feedback coming from the core bowing, since it might have many uncertainties. If we can perform conservative estimate of this effect and take it into account, it would shift results closer to the target.

CONCLUSIONS

The feasibility study on designing small long-life LBE cooled fast reactor, which capable to follow the daily load by coolant flow rate control (i.e., using temperature reactivity feedbacks only), was carried out. Survey calculations, performed in the course of this research, revealed that even significant enhancing of negative Doppler and reduction of positive coolant temperature coefficients could not provide the cladding hot-spot temperature be below 650 °C at the lowest power level (for daily load variations we assumed it ~50%), that is unacceptable from cladding corrosion prevention viewpoint. To strengthen feedback, the innovative idea was proposed, such as introduction of heat source into radial reflector region. Applying this method, the reactor power could be reduced up to ~65%, while satisfying limit on cladding temperature. In spite that this power level is still higher than required one (~50%), the idea of reactor load following by flow rate control becomes feasible. In the further research it is expected that the results will be improved by some other methods on enhancement of temperature reactivity feedbacks.

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