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Conceptual Design for Accelerator-Driven Sodium-Cooled Sub-critical Transmutation Reactors using Scale Laws and Integrated Code System

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ABSTRACT

The feasibility study on conceptual design methodology for accelerator-driven sodium-cooled sub-critical transmutation reactors has been conducted to optimize the design parameters from the scale laws and validates the reactor performance with the integrated code system. A 1000 MWth sodium-cooled sub-critical transmutation reactor has been scaled and verified through the methodology in this paper, which is referred to Advanced Liquid Metal Reactor (ALMR). A Pb-Bi target material and a partitioned fuel are the liquid phases, and they are cooled by the circulation of secondary Pb-Bi coolant and by primary sodium coolant, respectively. Overall key design parameters are generated from the scale laws and they are improved and validated by the integrated code system. Integrated Code System (ICS) consists of LAHET, HMCNP, ORIGEN2, and COMMIX codes and some files. Through ICS the target region, the core region, and thermal-hydraulic related regions are analyzed once-through. Results of conceptual design are attached in this paper.

I. INTRODUCTION

The objective on transmutation reactors is to incinerate transuranics and actinides and transmute the long-lived fission products(LLFP) in nuclear wastes into the less hazardous material before the permanent repository. In addition, to extend the use of transmutation reactors there are needed extremely high level of inherent safety, minimal production of LLFP and elimination of the need of geologic repositories, and high resistance to diversion. Therefore, to accomplish the criteria the accelerator driven sodium-cooled transmutation reactors should enhance the safety, resistance to diversion, and high transmutation capability.

Main concerns in the most of accelerator-driven sub-critical transmutation reactors are target material, coolant, neutron spectrum, fuel material and geometry, and thermal-hydraulic system. Hence these concerns should be preferred in some candidates and reference reactors. Figure 1 is the overall procedure for conceptual design optimization.

A reactor is classified to Minor Actinide (MA) burner and LLFP transmutation burner according to waste concern, which is for MA incineration or LLFP transmutation. MA can be incinerated by high-energy fission and its high fission-to-capture ratio. LLFP can be transmuted by the neutron capture in the low energy level. Therefore, Reactor objectives have the neutron spectrum be adopted by these reasons. Target materials should generate low deposition energy by spallation and many neutrons per incident proton. Coolant should have excellent heat transfer capability, high boiling point, and good chemical property. In this paper it is assumed that accelerator specification and desired thermal power are previously supplied by user. Using these specifications effective multiplication factor and re-circulation power ratio should be calculated. Then conceptual design parameters and their related neutronic parameters are verified through scale laws and integrated code system (ICS).

II. Preliminary Reactor Design

Before applying the accelerator-driven sodium-cooled sub-critical transmutation reactors with scale laws and integrated code system, the reference reactor should be chosen to develop the preliminary reactor type. The preliminary reactor type can be developed by the overall design procedure in Figure 1, in which the neutron spectrum, coolant, target material, and overall reactor system should be studied in the many respects of feasibility to have the reasonable relationship with one parameters and another parameters.

In this paper the transmutation reactor is developed to incinerate the MA. The feasibility on transmutation of LLFP will be also studied in addition. Therefore the fast neutron spectrum is adopted and ALMR is adopted as the reference reactor system, which is reference reactor of Energy Amplifier (EA-F). The coolant is Sodium (Na) which has high thermal conductivity and more much information on its properties. Target material is the liquid Pb-Bi, which has high neutron yields, high thermal conductivity for heat removal, low melting point, and characteristics of low energy deposition and easy purification. Specification of the accelerator is in power level of 1GeV, 20mA with the efficiency of 60%. For the flat power distribution in fuel region, the liquid fuel is applied, which can supply the makeup fuel and constant re-purification. Fuel is the partitioned particles in eutectic Pb-Bi contained in interconnected plenum system, and Tc/CsI are contained in separate channels in somewhat distance with the fuel region. Overall reactor system is referred in ALMR reactor system and especially KALIMER.

The reactor has 2 Intermediate Heat Exchanger (IHX) and 4 EM pump in reactor vessel. Secondary loop is in reversed U-type with target system connected to remove the residual heat from energy deposition. Containment system has no slot in reactor vessel and the guard vessel with Ar gas of low density.

Spallation target system was referred in one version of Institute of Physics and Power Engineering (IPPE) in Russia, which is full pumped flow target with diffuser disk in the flow guide. A flow along most of the beam entry window is generated by a reentrant shape of the window which consists of a cone and a small hemisphere. Formation of a stagnation zone at the top of the hemisphere will be prevented by a suitably placed diffuser plate with an optimized distribution of bores and placed at just the right distance from the hemisphere.

In the preliminary design, the effective multiplication factor and the re-circulation factor should be adopted through considering G-value, which is ratio of thermal power to accelerator power.

$$G = \frac{G_o}{1-k_{eff}} \qquad G_o \approx 2.4 \text{ or } 2.5$$

It is assumed that k_{eff} is ranged from 0.95 to 0.98 and re-circulation power ratio is from 5% to 9%. Therefore, the number of accelerators determines the values of k_{eff} and re-circulation power ratio, which can be implemented in parallel.

III. Scale Laws and Criteria

In this paper, scale criteria developed by Ishii and Kataoka is used to obtain the conceptual design parameters under single phase flow condition, which are driven from the fluid balance equations, boundary conditions, and solid energy equations. In the governing equations, fluid properties are assumed to be constant except for the buoyancy by Boussinesq assumption. To develop the scale criteria, the significant dimensionless similarity parameters are verified to meet the geometrical and the physical characteristics. Their similarity is achieved between the process observed in the model and in the prototype and the additional constraints are needed to meet the thermal-dynamic similarity related with the flow field and the fluid properties. Scaling methodology and formula are in detail described in the author's previous work.

In addition, similarity on the heat transfer condition should be modified because the primary coolant is sodium and secondary coolant is Pb-Bi. Difference of heat-transferred coolant has the additional constraint on heat transfer coefficient. This problem can be solved like the followings.

$$\delta_R = \sqrt{l_R / u_R} \qquad d_R = \frac{1}{\rho_R C_R}\sqrt{u_R / l_R}$$

$$Nu = \frac{hd}{k} \qquad h = \frac{Nuk}{d}$$

These are scale criteria related with heat transfer similarity and driven from time-preserving volumetric method. In addition Nusselt number is expressed like the following for liquid metal and the second term is very small in comparison with constant.

$$Nu = 4.82 + 0.0185(RePr)^{0.83}$$

Therefore similarity parameter on heat transfer coefficient is like the following.

$$h_R = \frac{k_R}{d_R} = (Nu)_R = \rho_R C_R \ (Nu)_R$$

$$= \rho_R C_R \ (4.82 + 0.0185(\rho u d/\mu \quad \mu C_P/k)^{0.83})_R$$
$$= \rho_R C_R = 1/d_R$$

Hence heat transfer condition at the heat exchange region of IHX can be scaled by the reciprocal of ratio of hydraulic diameter.

IV. Integrated Code System (ICS)

When incident proton particle interact with the target material, by neutron spallation the target nuclide experiences the high-energy fission, which is different from the thermal fission with uranium in LWRs. As the spallations go on, a spallation neutron does the elastic, inelastic scattering, and absorption reaction, and a proton does the elastic, inelastic scattering.

Because it is to be simulated that neutron, proton, and charged particles with energy much more than 20MeV interact with the target material, A Lahet Code System is needed for high-energy simulation. A code for burnup calculation is necessary to verify the transmutation rates of each nuclide, and ORIGEN2 was used to develop the ICS. Through the ICS the scaled reactor should be also designed in respects of thermal-hydraulics. Therefore COMMIX code was attached in addition. Overall flow chart of ICS is illustrated in Figure 2.

Initial inputs, Ma to Pu ratio should be supplied by user and the composition of each isotope of MA and Pu should also supplied from the information on the discharged nuclides from LWRs. These inputs evaluate the effective multiplication factor through KCODE in HMCNP. The analysis on high-energy neutrons from LAHET is conducted to find the neutron yield, deposition energy, and nuclides mass by spallation through HTAPE. Neurons with energy less than 20MeV and photon effect are analyzed in HMNCP to find the neutron flux and one-group cross sections. These files are input into ORIGEN2 to verify the transmutation rates of nuclides in the library. In addition, thermal distribution from HMCNP and deposition energy from HTAPE should be input into COMMIX with geometrical input data previously supplied to verify the temperature distribution and energy balance all over the reactor vessel.

When the radioactivity of target material should be analyzed using the ICS, the decay and generation of nuclides are analyzed through ORIGEN2 on basis of nuclide generation rate from LAHET. These decay data should be included and modified in the decay library of ORIGEN2.

V. Results and Conclusions

In preliminary design, according to overall procedure and reactor objectives the accelerator-driven sodium-cooled sub-critical transmutation reactor was developed like the following Figure 3.

A linear accelerator has a 1GeV, 20mA proton beam, which can generate 1.25e17 protons per second and its G-value is 50. Target system has 6.5e16 n/cm^{2}s neutron flux, 34.48 n/p neutron yields, and 2.1 MWth cumulative thermal power. Overall reactor efficiency is 40% and net electric power is 366.7 Mwe. Diameter and height in the effective fuel region are 298cm and 303cm respectively. Fuel is a MA 14 wt/o – Pu 27 wt/o in Pb-Bi eutectic and has the plenum structure connected with canisters. Liquid fuel uses Ar gas in gas accumulator to circulate the liquid fuel and partitioned particles. Conceptual design parameters for an accelerator-driven sodium0cooled sub-critical transmutation reactor are in detail presented in the following < Table 1 >.

In analysis of neutron reaction in fuel region, one-group cross section data are verified in HMCNP to input into ORIGEN2. In this paper 24 actinide nuclides and 18 LLFP were included and 18 LLFP were

<Table 1. Conceptual Design Parameters from Preliminary Design and Scale Laws>

Proton Beam - energy (GeV) - current (mA) - Proton number (p/s)	1 20 1.25E17	Core - diameter (cm) - length (cm) - LLFP dia. (cm)	298 303 397
Accelerator - efficiency (%) - G-value - recirculation ratio (%)	60 50 8.3	Rx Vessel - diameter(m)/height (m) - # of canister pin - # of assembly	6.4/32 330/372 127
Target System - power (MWth) - flux (10^{14}n/cm^{2} s) - material type - heat removal - n / p	2.1 650 liquid Pb-Bi to 2ndary system 34.48	Primary Cooling System - pumping method - coolant - heat removal - inlet temp. at core (°C) - outlet temp. at core (°C)	4 EM pump sodium 2 IHX 415 550
Power - ther. Power (MWth) - efficiency (%) - net power (Mwe)	1000 40 366.7	Secondary Cooling System - cold /hot leg temp. (°C) - coolant - heat removal	520/340 Pb-Bi S/G and reheater

included and 18 LLFP were included into EMOPUUUC.LIB one-group cross section library. Because the Tc/CsI region have low neutron flux, which is nearly 200 times less than that of effective fuel region. Therefore, transmutation rate of MA is 19.1% but that of LLFP is 0.29%. Neutron energy distributions for fuel region and Tc/CsI region are illustrated in Figure 4-(a) and 4-(b).

In addition it is found that target material, Pb-Bi, generates several long-lived and high toxic daughters. Pb-205, Bi-208, Bi-210m, Pt-193, and Bi-208. Target material can nearly 35 neutrons per proton, most of which are in energy level from 2MeV to 10MeV, which is illustrated in Figure 5 .

Finally, COMMIX code showed that scaled reactors normally generated the 1001.3 MWth all over the reactor and 2.14MWth in target region was removed into the intermediate loop coolant, Pb-Bi.

In this study, much more decay and cross section data are needed exactly to access the radioactivity of target material but number of those were far less. Therefore it is guessed that overall radioactivity and overall transmutation rates were somewhat low than be in reality. But it is conducted that scaled reactor from preliminary design meets the design requirements and design limitations and has high performance.

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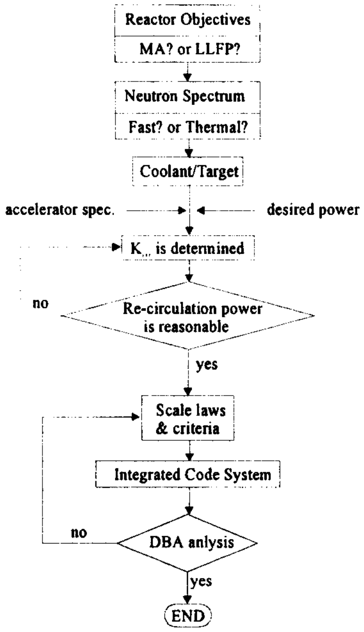
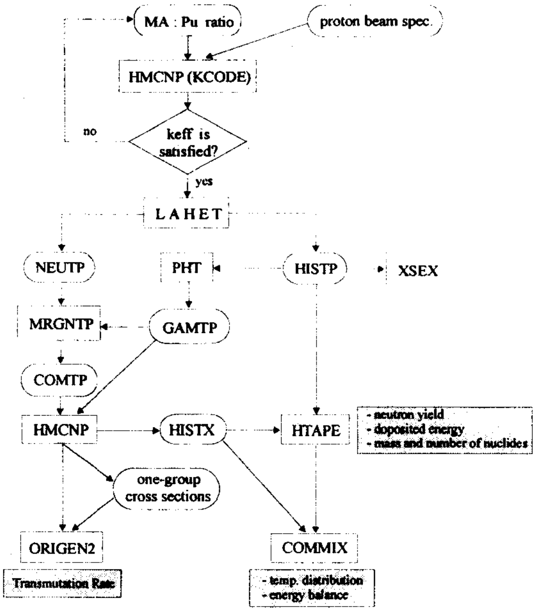
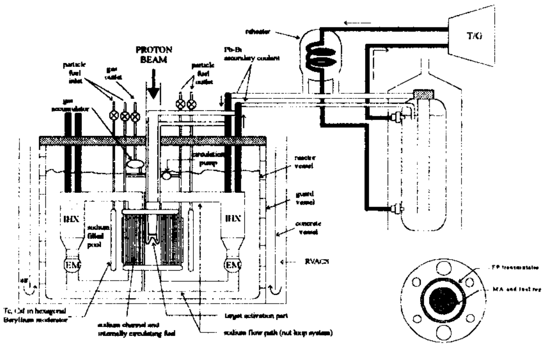


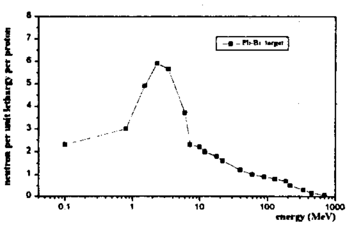
<Figure 1 Overall Design Procedure>



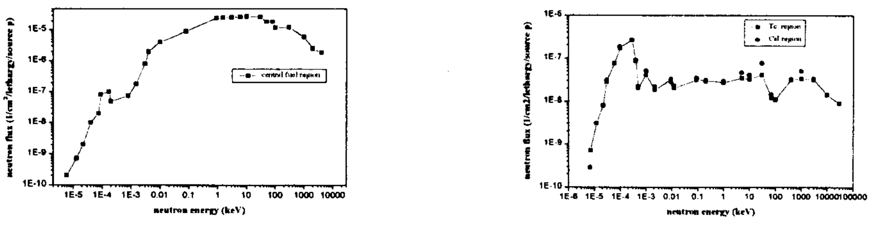
<Figure 2 Flow Chart of Integrated Code System>



<Figure 3 Schematics of Preliminary Reactor>



<Figure 5 neutron yield>



<Figure 4 neutron flux distribution of (a) effective fuel region, and (b) Tc/CsI region>