HYBRID POWER EXTRACTION REACTOR (HYPER) PROJECT

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Abstract

The KAERI ADS system is known as the *HY*brid *P*ower *E*xtraction *R*eactor (HYPER) project. Research on this project began as a 10-year nuclear research programme in 1997. The conceptual design of the HYPER core is almost complete. HYPER is designed to transmute TRU and some fission products such as ^{129}I and ^{99}Tc. HYPER is a 1 000 MW$_{th}$ system and its k_{eff} is 0.98. The required current is 10.6 mA at BOC and 16.4 mA at EOC. The inventory of TRU is 6 510 kg at BOC, and 282 kg of TRU is transmuted per year. In the case of fission products, ^{129}I and ^{99}Tc are transmuted at the rates of 7 and 27 kg/yr, respectively. Pb-Bi is used as the coolant and target material. The average outlet temperature is 490°C when the inlet temperature of coolant is 340°C. The maximum cladding temperature turned out to be 570°C. It was found that a 2.5-mm thick beam window is needed to sustain the mechanical load. When the inlet velocity of Pb-Bi is 0.95 m/s, the maximum allowable current is 24.1 mA, which is greater than the required current of HYPER. U surrogate fuel was fabricated and tested. KAERI joined the MEGAPIE project in 2001 for Pb-Bi research. KAERI also installed the static Pb-Bi corrosion test device in 2003 and began experiments. KAERI will complete the construction of a Pb-Bi corrosion loop in 2004.

Introduction

KAERI has been working on ADS since 1997. The KAERI ADS system is known as the *HY*brid *P*ower *E*xtraction *R*eactor (HYPER) project. Research on this project began as a 10-year nuclear research programme funded by the government. The ADS research of KAERI consists of three stages. A basic concept of HYPER was established in the first stage (1997-2000) of development. The basic technology related to HYPER was investigated in the second stage (2001-2003) while upgrading the design. The third stage of research began in March 2004. The conceptual design of the HYPER core will be completed during this third stage (2004-2006). The investigation of key technologies will be continued in the third stage.

The conceptual design of the HYPER core was almost finished during the second stage. The upgrade of core design and transient study will be done in the third stage. Regarding experimental research, fuel and Pb-Bi study were performed during the second stage. U surrogate fuel was fabricated and tested. KAERI joined MEGAPIE project in 2001 for Pb-Bi research. KAERI also installed the static Pb-Bi corrosion test device in 2003 and started experiments. KAERI will complete the construction of a Pb-Bi corrosion loop in 2004. The I-NERI programmr, related to lead-alloy experiments, will be launched in 2004. For the fuel/FP target study, KAERI plans to perform fission product irradiation test using KAERI's research reactor HANARO.

In this paper, the results obtained through the research of the first and second stages and plans for the third stage will be described. The results and plans for further research are also discussed, and fall into two categories, one being design and analysis, the other experimental.

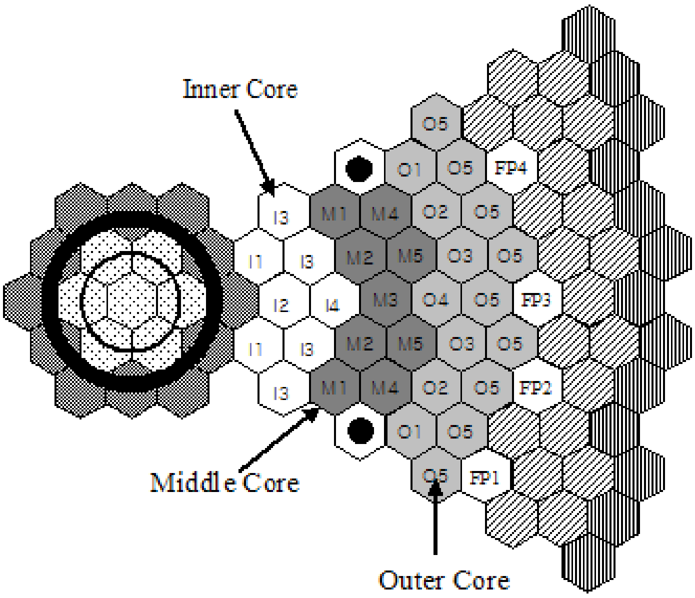
Design and analysis

Core

HYPER is designed to transmute TRU and some fission products such as ^{129}I and ^{99}Tc. HYPER is a 1 000 MW$_{th}$ system and its k$_{eff}$ is 0.98. Figure 1 shows a schematic configuration of the HYPER core with 186 ductless hexagonal fuel assemblies. As shown in the figure, the fuel blanket is divided into three TRU enrichment zones to flatten the radial power distribution. In HYPER, a beam of 1-GeV protons is delivered to the central region of the core to generate the spallation neutrons. To simplify the core design, the LBE coolant is used as a spallation target as well. In addition to the ultimate shutdown system (USS), six safety assemblies are placed in the HYPER core in case of an emergency. The safety rods are also used conditionally to control the reactivity of the core. For a balanced transmutation of both TRUs and LLFPs (^{99}Tc and ^{129}I), ^{99}Tc and ^{129}I are incinerated in moderated LLFP assemblies loaded in the reflector zone.

It is well known that the LBE coolant speed is limited (usually <2 m/sec) due to its erosive and corrosive behaviour. Therefore, the lattice structure of the fuel rods should be fairly sparse. In fast reactors, a pancake-type core has been typically preferred mainly to reduce the coolant pressure drop. Unfortunately, it has been found that the multiplication of the external source is quite inefficient in a pancake-type ADS because of the relatively large source neutron leakage. It was shown that the maximum source multiplication can be achieved when the core height is about 2 m [1]. Taking into account the source multiplication and the coolant speed, the core height of HYPER was compromised at 150 cm, and the power density was determined such that the average coolant speed could be about 1.65 m/sec. To reduce the core size and improve the neutron economy, a ductless fuel assembly is adopted in the HYPER system. An advantage of the ductless fuel assembly is that the flow blockage of a subassembly is basically impossible and the production of the activation products in the duct can be avoided.

Figure 1. Schematic diagram of the HYPER core



Concerning a TRU-loaded ADS using a fixed cycle length, one of the challenging problems is a very large reactivity swing, leading to a large change of the accelerator power over a depletion period. Even in an ADS loaded with a minor actinide (MA) fuel, the burn-up reactivity swing is found to be fairly noticeable, although it is relatively smaller than that of a TRU-loaded core. The large burn-up reactivity swing results in several unfavourable safety features as well as deleterious impacts on the economics of the system. In the HYPER core, the ^{10}B was also used as a burnable absorber (BA) in a unique way to reduce the reactivity swing and control the core power distribution [2].

The required current is 10.6 mA at BOC and 16.4 mA at EOC. The inventory of TRU is 6 510 kg at BOC and 282 kg of TRU is transmuted per year. In the case of fission products, ^{129}I and ^{99}Tc are transmuted with the rates of 7 and 27 kg/yr, respectively. The fuel cycle is 180 days. HYPER adopts a scattered fuel reloading system.

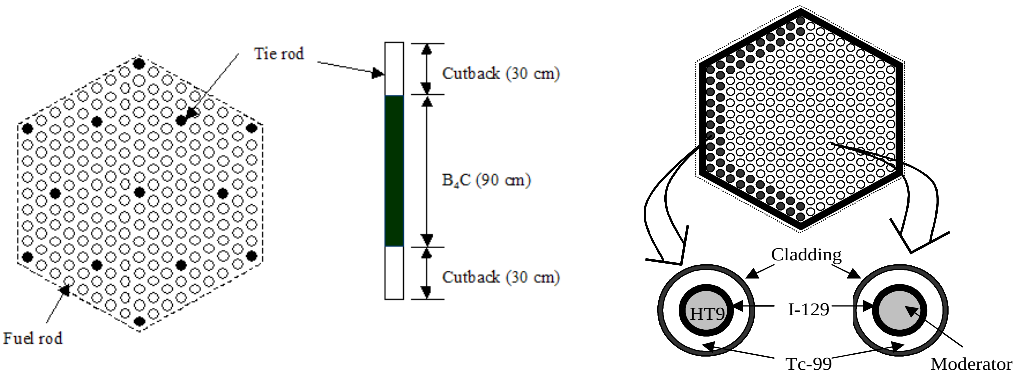
MC-CARD, REBUS-3 and DIF3D are used for the core analysis. The LAHET code system is used for the target neutronic calculations. KAERI is also developing a kinetics code called Design Evaluation and Simulation of Nuclear Reactor (DESINUR).

Fuel and fission products

In general, a non-uranium alloy fuel is utilised in a TRU transmuter to maximise the TRU consumption rate. Previously, a Zr-based dispersion fuel was used as the HYPER fuel since it was expected that a very high fuel burn-up could be achieved. However, we have found that the dispersion fuel transforms to a metallic alloy during the high-temperature operation. Therefore, in the current design, a metallic alloy of U-TRU-Zr is utilised as the HYPER fuel, in which pure lead is used as the bonding material. As a result, a large gas plenum is placed above the active core.

Each fuel assembly has 204 fuel rods, which are aligned in a triangular pattern with 13 tie rods. A fairly open lattice with a pitch-to-diameter (P/D) ratio of 1.49 is adopted in HYPER. In Figure 2, a schematic configuration of the ductless fuel assembly is shown. The ^{10}B burnable absorber is loaded

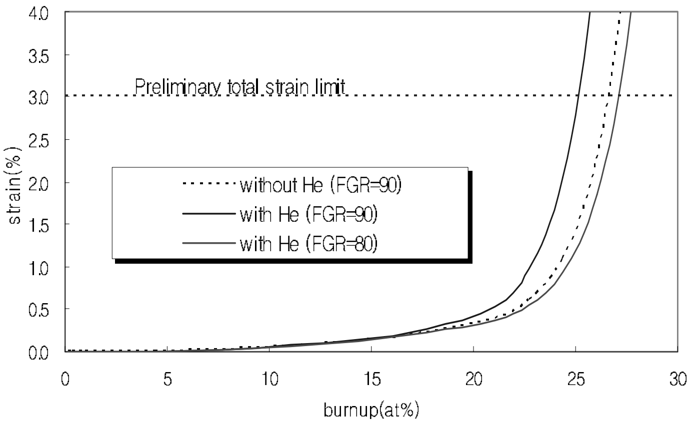
Figure 2. Fuel and fission product assemblies



into the tie rods with top and bottom cutbacks in order to enhance the ^{10}B depletion rate and also to flatten the axial power distribution of the core. The BA concept with the cutbacks can effectively mitigate the peak fast neutron fluence of the assembly. The peak fast neutron fluence is a limiting design criterion in LBE-cooled fast reactors.

MACSIS-H (for an alloy fuel) and DIMAC (for a disperison fuel) are being developed as the steady-state performance analysis codes. The main structures of each code consist of the temperature profile calculation routine, the swelling/FGR calculation routine and the deformation calculation routine. The He production rates calculated by the other code are inserted into the swelling/FGR routine of each code. Figure 3 is an example of MACSIS-H calculation. The strain was calculated as a function of burn-up of HYPER fuel. The calculation was performed with and without He generation varying the fission gas rate. The result shows that the maximum strain is lower than the limit at a HYPER average discharge burn-up of 17 at.%.

Figure 3. Strain vs. burn-up for HYPER fuel

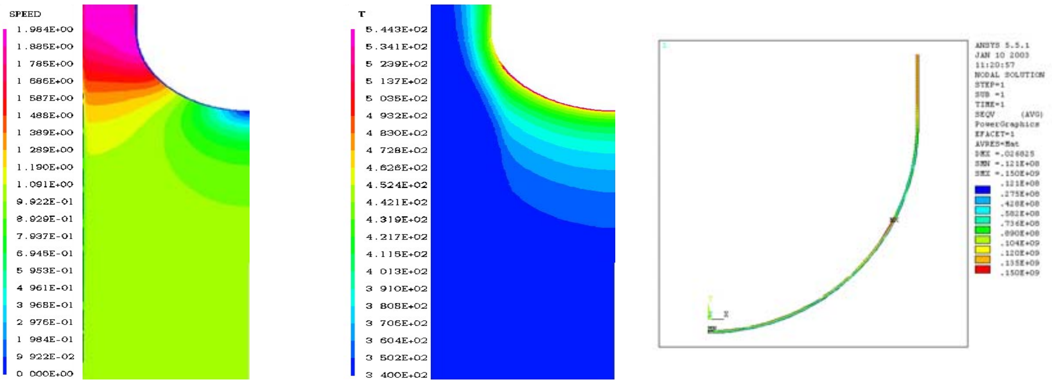


Coolant and target

Pb-Bi is used as the coolant and spallation target material. The coolant is not separated from the target. MATRA and SLTHEN are used for the core thermal-hydraulic calculations. SLTHEN can be used for multi-assembly analysis. Therefore, a 7-assembly and a 45-assembly analysis of HYPER were performed using SLTHEN. MATRA was developed to be used for the ductless assembly with grid spacer, which is the case of HYPER fuel assembly. The sub-channel analysis was performed using MATRA and the result shows that the average outlet temperature is 490°C when the inlet temperature of coolant is 340°C. The maximum cladding temperature turned out to be 570°C

The cylindrical beam tube and the hemispherical beam window were adopted in the basic target design concept with 1-GeV proton energy, and the thermal-hydraulic and structural analyses were performed with the CFX and ANSYS codes. The target window material is 9Cr steel such as T91 and 9Cr-2WVTa. The beam window diameter and thickness were varied to find the optimal parameter set based on the design criteria: maximum lead-bismuth eutectic (LBE) temperature < 500°C, maximum beam window temperature < 600°C, maximum LBE velocity < 2 m/s and the maximum beam window stress < 160 MPa. The results show that a 40-cm wide proton beam with a uniform beam profile should be adopted for HYPER. It was found that a 2.5-mm thick beam window is needed to sustain the mechanical load. When the inlet velocity of Pb-Bi is 0.95 m/s, the maximum allowable current is 24.1 mA, which is greater than the required current of HYPER.

Figure 4. CFX and ANSYS results of HYPER target calculation



Velocity (Max=1.96 m/s)

Temperature (Max=544 °C)

Stress (Max=150 MPa)

Experiment

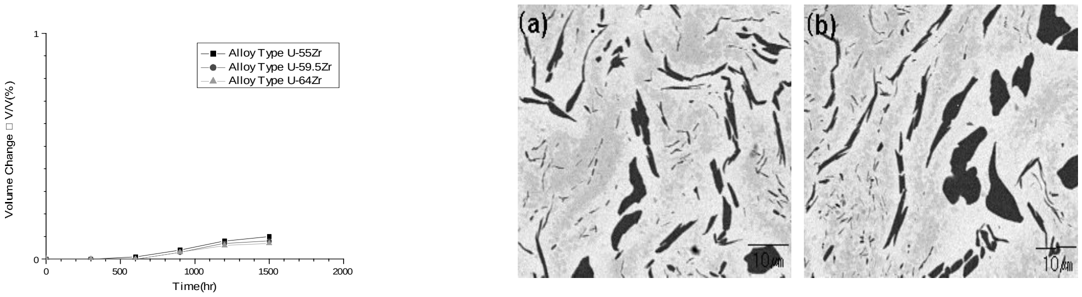
Fuel

Two types of metal fuels were considered for HYPER fuel. One is metal alloy type and the other is dispersion type. Both types of U surrogate fuel samples were fabricated and basic characteristics were investigated. It was found that dispersion fuel was not made with good microstructure and the original structure of dispersion fuel was not kept after annealing. Therefore, we chose the metal alloy fuel for HYPER.

The reference blanket fuel pin of HYPER consists of the fuel slug of the TRU-xZr (x = 50-60 wt.%) alloy, and it is immersed in lead for thermal bonding with the cladding. The blanket fuel cladding material is ferritic-martensitic steel HT-9. As a basic study on the HYPER fuel, we fabricated surrogate U-50, 55, 60 wt.% Zr alloy fuel instead of the actual TRU-Zr fuel. The U-Zr metallic fuel was fabricated by mixing, pressing, sintering and extrusion. The sintering temperature and time were 1 500°C and 2 hrs, respectively.

After fabricating the surrogate fuel, thermal properties such as thermal conductivity and thermal expansion coefficient were measured. Thermal stability testing of the surrogate fuel was also performed, so as to investigate volume and microstructure change. The fuel samples were placed in the furnace for 1 500 hrs with temperatures of 630°C and 700°C. Figure 5 shows volume change as a function of time and microstructure change after annealing. Reaction characteristics were also investigated among Pb bonding, cladding material (HT-9) and U surrogate fuel.

Figure 5. Volume and microstructure change of U-Zr sample after annealing



Volume change

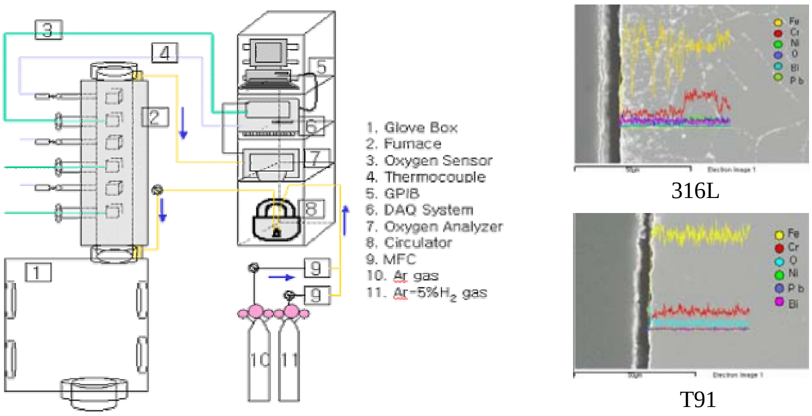
Microscopic structure : (a) Before (b) After

Pb-Bi

KAERI joined the MEGAPIE project in 2001 for the experimental study of Pb-Bi. MEGAPIE is the 1-MW proton beam irradiation test of a Pb-Bi target. PSI, CEA, CNRS, FZK, ENEA, SCK•CEN, KAERI, JAERI and LANL are members of the MEGAPIE project. The Pb-Bi target is currently in the stage of fabrication.

The most significant problem in handling Pb-Bi is corrosion. Therefore static corrosion tests were performed at the FZK's facility COSTA to investigate the dissolution effect. KAERI also installed a static corrosion facility in 2003 and began static corrosion tests. Figure 6 shows the schematic diagram of the static corrosion facility. It is mainly composed of tube furnaces, a gas system and a glove box. The furnace has three independent zone heaters to reduce the temperature difference.

Figure 6. Schematic diagram of the KAERI static corrosion facility and test results



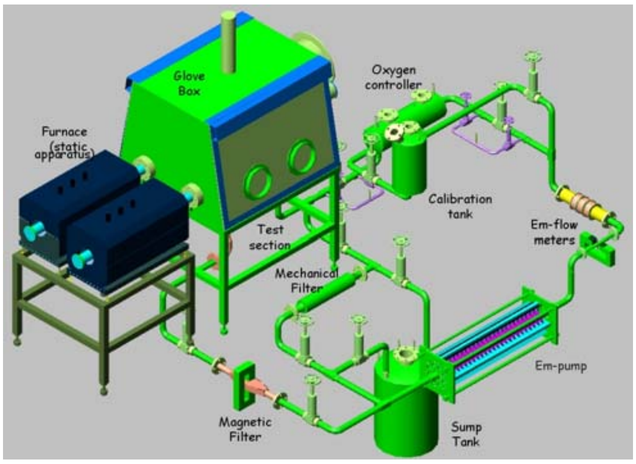
316L

T91

The test materials were 316LN and some ferrite/martensitic steels such as HT-9 and T91. The test was performed under both reduced and oxygen-controlled atmospheres. Part of the test results are shown in Figure 6.

Figure 7 shows the schematic diagram of the dynamic corrosion loop to be installed at KAERI. The LBE loop is an isothermal loop. The flow velocity in the test section was designed to be around 2 m/s in the range of 400~550°C and the charging volume of the LBE is around 0.03 m^3 in the circulation loop.

Figure 7. Three-dimensional schematic diagram of the corrosion loop



The LBE loop is mainly composed of a main test loop, a bypass loop for filtering the LBE and a mixture gas supplying system. The liquid metal in the main test loop circulates in the following order: EM pump – EM flow meter – oxygen controller – test section – magnetic filter – EM pump. From the analysis of the pressure drop, the specification of the piping system was determined as a 1.5-inch pipe to reduce the pressure drop by a high mean fluid velocity. The pressure drop of the main test loop was estimated at around 3 bar with the flow rate of 60 lpm.

The oxygen concentration in the range of 10^{-7} wt.%~10^{-5} wt.% is controlled by the chemical equilibrium between the mixture gas of hydrogen-argon and the water vapour. At present, the oxygen concentration in the LBE and the mixture gas is measured with an oxygen sensor made of yttria-stabilised zirconia as a solid electrolyte cell and Pt/air as a reference system.

Summary

KAERI has been working on ADS since 1997. The KAERI ADS system is known as the *HY*brid *P*ower *E*xtraction *R*eactor (HYPER) project. HYPER research began as a 10-year nuclear research programme. The ADS research of KAERI consists of three stages. The conceptual design of the core was almost completed during the second stage (2000-2003). The core design will be upgraded and modified in the third stage (2004-2006). For example, the dual annular injection tube will be introduced to reduce the flow rate of Pb-Bi in the target channel. The structural analysis of the HYPER fuel assembly will also be performed. The main work related to the design and analysis, however, is the transient case study. Some core transient cases such as LOHS-WS and LOF-WS will be studied. The transient cases related to target, beam window and fuel assembly structure will also be examined.

KAERI fabricated U surrogate metal fuel and performed tests using U fuel samples to investigate basic characteristics during the second stage of research. The HYPER fission product target includes both ^{99}Tc and ^{129}I in the same rod. The fission product rod will be fabricated and subsequently tested using KAERI's 30-MW research reactor HANARO. A fabrication study of the FP target will be performed in 2004 and irradiation will commence in 2005.

KAERI will complete construction of a corrosion loop in 2004. The oxygen control method is considered to test the protection of the steel structure materials against Pb-Bi corrosion. Therefore, an oxygen sensor will be developed. KAERI will launch the I-NERI programme in June 2004. Lead-alloy corrosion will be investigated through the I-NERI programme. The duration of I-NERI is three years and LANL is the US partner.

Acknowledgement

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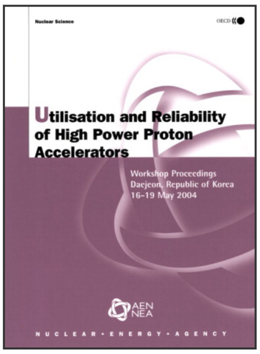

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