Status of Fuel Irradiation Tests in HANARO

Hark Rho Kim+, Choong Sung Lee+, Kye Hong Lee+, Byung Jin Jun+, and Ji Bok Lee+*
HANARO Operation Team, HANARO Utilization Research, Korea Atomic Energy Research Institute

ABSTRACT

Since 1996 after finishing the long-term operational test, HANARO (High-Flux Advanced Neutron Application Reactor) has been extensively used for material irradiation tests, beam application research, radioisotope production and neutron activation analysis. This paper presents the fuel irradiation test activities which are now conducted or have been finished in HANARO.

KAERI developed LEU fuel using an atomization method for the research reactors. Using this LEU, we have set up and conducted three irradiation programs: (1) medium power irradiation test using a short-length mini-assembly made of 3.15 gU/cc U_3Si, (2) high power irradiation tests using full-length test assemblies made of 3.15 gU/cc U_3Si, and (3) irradiation test using a short-length mini-plate made of 4.8 gU/cc U_3Si_2.

DUPIC (Direct Use of spent PWR fuels in CANDU Reactors) simulation fuel pellets, of which compositions are very similar to DUPIC pellets to keep the similarity in the thermo-mechanical property, were developed. Three mini-elements including 5 pellets each were installed in a capsule. This capsule has been irradiated for 2 months and unloaded from the HANARO core at the end of September 1999.

Another very important test is the HANARO fuel qualification program at high power, which is required to resolve the licensing issue. This test is imposed on the HANARO operation license due to insufficient test data under high power environment. To resolve this licensing issue, we have been carrying out the required irradiation tests and PIE (Post-irradiation Examination) tests. Through this program, it is believed that the resolution of the licensing issue is achieved.

In addition to these programs, several fuel test plans are under way. Through these vigorous activities of fuel irradiation test programs, HANARO is sure to significantly contribute to the national nuclear R&D programs.

1. INTRODUCTION

HANARO (High-Flux Advanced Neutron Application Reactor) is an upward flowing, light water cooled and heavy water reflected research reactor of $30MW_{th}$ with an open-chimney-in-pool

* Presenting Author, e-mail: hrkim@nanum.kaeri.re.kr, Tel:82-42-868-2285, Fax:82-42-868-8341
+ 150 Dukjin-dong Yusung-ku, Taejon, Rep. of Korea 305-353
HANARO Operation Team, HANARO Utilization Research, Korea Atomic Energy Research Institute

arrangement [1]. The core is composed of inner and outer cores. The inner core, 0.5m in effective diameter and 1.2m in height, has 23 hexagonal and 8 circular flow channels separated by the flow tubes. Each hexagonal flow tube accepts 36-element fuel bundle. The circular flow tube accommodates an 18-element fuel bundle inside and has space for the absorber shroud to move up and down. Fig. 1 shows the plan view of the HANARO core and reflector. Three holes (CT, IR1 and IR2) are provided in the central part of the core for tests needing high thermal fluxes, while four holes (OR3 ~ OR6) at the outer core are reserved for experiments using epi-thermal neutrons. A total of 25 vertical irradiation holes with different sizes are distributed in the reflector region. Seven tangential beam tubes are deployed horizontally.

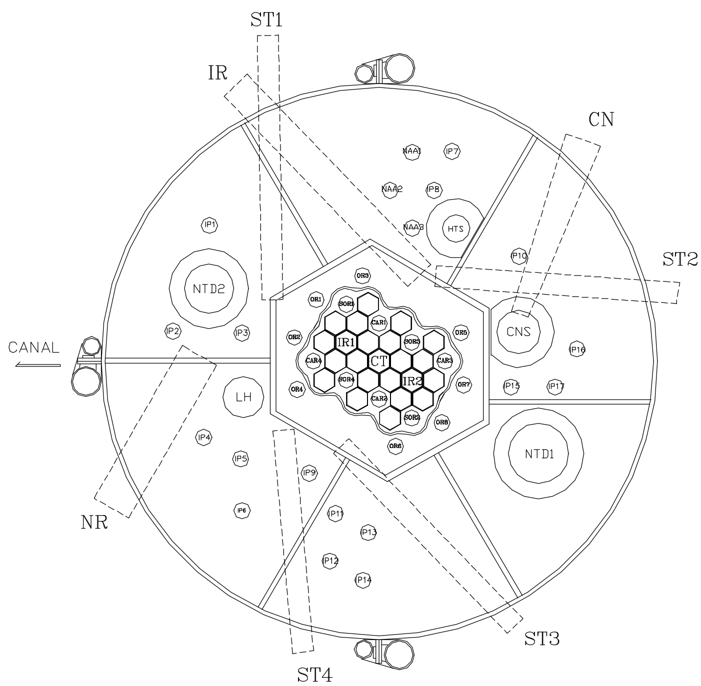


Fig. 1 Plan View of HANARO Core and Reflector

The major driver fuel of HANARO is a 36-element fuel bundle of which the fuel element is arranged in a hexagonal array. The standard core fuel element is seated in two inner rings of a hexagon while the reduced core fuel element in an outer ring, in order to have uniform power distribution in a bundle. Another driver fuel is an 18-element fuel bundle whose six and twelve elements are located in two concentric rings with an equal angular distance. There is furnished, a central tie rod made of Zircaloy in the center of each bundle. Fuel elements and central tie rod are clustered into a bundle and gripped by three spacer plates to enhance bundle stiffness.

Four CARs (Control Absorber Rods) are driven by a stepping motor and kept in the similar axial position to avoid the power tilt in normal operation. However, a CAR might be frozen to have a tilted flux distribution for experimental purposes. The other four SORs (Shut-off Rods) are always fully withdrawn from the core during operation and sustained by a hydraulic system.

For the fuel and material tests, the safety requirements are defined in the HANARO Technical Specification. The reactivity of a target is limited to 12.5mk so as to accept as many targets as possible. The locking device should be provided to prevent an inadvertent removal during power operation when a target has larger reactivity than 1.5 mk. Also the reactivity insertion rate is controlled below 0.125 mk/sec for the target that needs movements during power operation.

Therefore, an irradiation target designer should take into account these general requirements. Also the designer should ensure to safely remove the heating induced by fission events or gamma heating during tests. This introduces users to use a small size target at the beginning and then increase the test specimen afterwards, especially in the case of fuel. This paper presents the fuel irradiation test activities in HANARO to support the national nuclear R & D program in Korea.

2. SAFETY ASSESSMENT SYSTEM FOR IRRADIATION TESTS

To assess the safety of an irradiation target, HANARO uses its own fuel management system, HANAFMS (HANARO Fuel Management System) [2] as well as MCNP4B [3] with ENDF/B-V library. HANAFMS basically consists of WIMS/D-4 and Bold VENTURE but some parts of them were modified for our own purposes. They were validated with the HANARO commissioning data. Using WIMS/D-4 with the KAERI-developed 69-group nuclear data library [4], 5-group macroscopic cross sections for all the regions comprising the reactor core, reflector and pool are generated. The upper limits of 5 energy groups are 10 MeV, 0.821 MeV, 9.118 keV, 4.0 eV, 0.625 eV. At present, the computational model in HANAFMS uses a total of 954 structural materials and 9 fuel materials including a target. The reactor is described in H-Z grid structure and radially divided into 253 x 253 hexagons which enables a fuel element to be modeled in a node. In the axial direction, the fuel part is divided into 14 segments and the total number of axial mesh is 34.

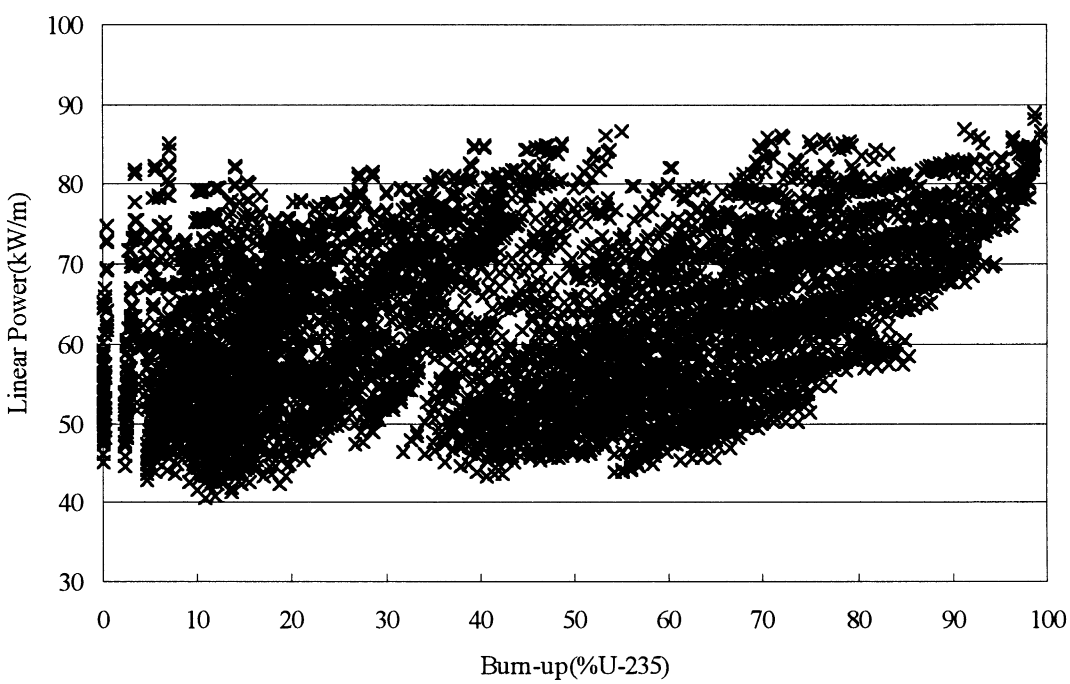
Prior to the detail design of target, MCNP is first applied to obtain the power distribution for the reference core and the reactivity effect since the reactor and target can be explicitly described using MCNP with the continuous energy library. This is compared with the result of HANAFMS and the discrepancy for the same model is interpreted. Based on this preliminary design analysis for the selected target loading site, the detail design is proceeded so as to successfully provide the test condition as well as to have an allowable margin for the reactor safety. For the detail design of the target, the burnup state of the operating core should be taken into account by using HANAFMS. By considering the discrepancy between MCNP and HANAFMS results, the predicted power information of the target is transferred to the thermal-hydraulic analysis in order to ensure the cooling capability of the target during transient states as well as normal operation. For the thermal hydraulic analysis, we established a subchannel analysis system of MATRA_h, KAERI version of COBRA-IV-I and the accident analysis system, RELAP5/MOD3.2 with HANARO correlations. Based on the detail safety assessment such as fuel centerline temperature, margin to onset of nucleate boiling and minimum critical heat flux, the decision on the target loading is eventually made.

3. FUEL IRRADIATION TEST PROGRAM

3.1 Atomized LEU Qualification Tests

3.1.1 Mini-Assembly Test [5]

Different from the current LEU production process, KAERI developed the atomization process. In 1996, the first LEU U_3Si product of 3.15 g/cc was fabricated into a mini-assembly. The test bundle is similar to the HANARO 18-element fuel bundle but it has only 6 fuel elements in the outer ring. The fuel meat is only 20 cm long in the axially middle part of the fuel element and the other axial part is made of aluminum to fabricate the fuel element of 70 cm in length. This test bundle was loaded into the OR4 hole and resided in the core for 220 days. Using HANAFMS, the average and peak discharge burnups are expected to be 85%U-235 and 99%U-235, respectively. This bundle was tested under the medium power level and Fig. 2 shows the irradiation behavior of the test bundle in the core. The best-estimated peak linear power was 88.9 kW/m at 98.7%U-235. Since the fuel meat is axially located at the beltline of the reactor, the CAR movement gives strong influence on the power distribution. Except the beginning of the test, the peak power occurred when the CAR moved up to 500 mm. This test bundle is being cooled prior to the PIE (Post-irradiation Examination) test to check the basic material properties, which include dimensional change, microscopic structure observation, and oxide layer thickness, blistering test and bending test.



3.1.2 Full-length Bundle Tests [6]

In order to conduct the test for KAERI-developed U_3Si of 3.15 g/cc under high power condition, a full-length test bundle was fabricated in KAERI. This bundle looks like a HANARO 36-element bundle but only 6 elements are standard fuel elements and the others are aluminum elements. The fuel meat length is the same as that of the fuel element. This bundle is being irradiated in the core. The analysis results show that the peak linear power occurred at 0% U-235 as in Fig. 3 and the average burnup is expected to be 13% U-235 as of 16 September, 1999. This bundle is planned to be withdrawn at average burnup of 60%U-235 and then will be cooled enough for PIE testing.

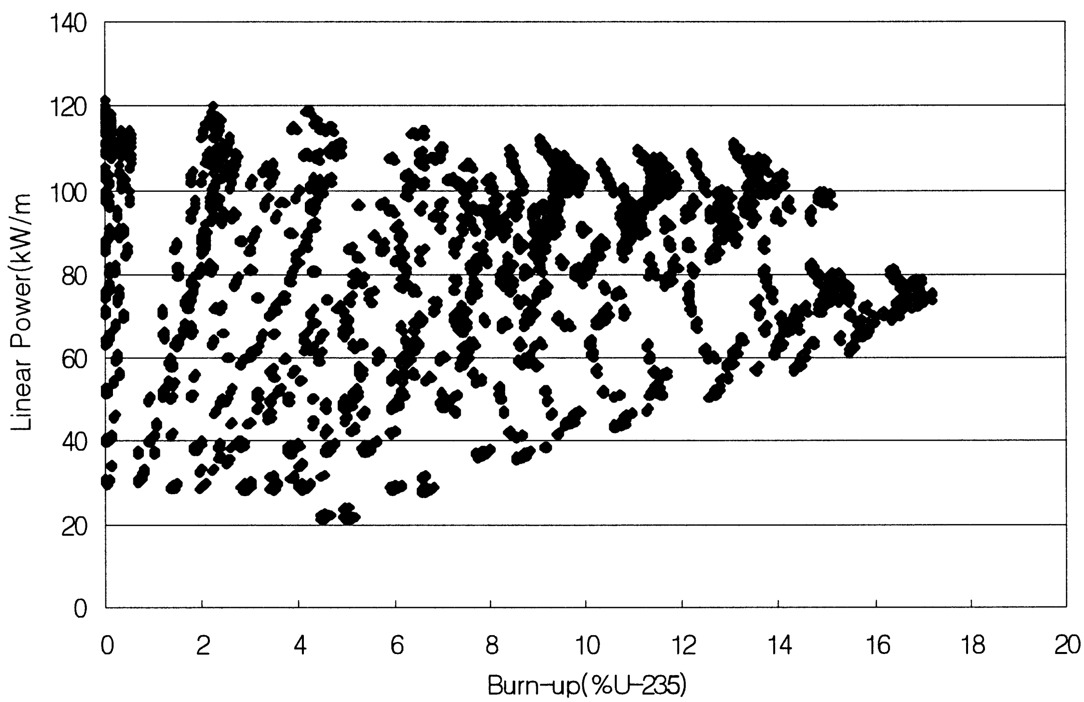


Fig. 3 Linear Power History of Full-length U_3Si Test Bundle in HANARO

3.1.3 High-density U_3Si_2 Mini-plate Test [7]

KAERI also developed U_3Si_2 fuel of 4.8 g/cc and provided some powder to INEEL in U.S.A. who tested this fuel in ATR as a micro-plate form. At present, the INEEL test results show its superiority to the current pulverized LEU. Meanwhile, KAERI set up the test program as a mini-plate, which is encapsulated into a test rig and loaded in OR6. This rig will reside in the core until the average burnup reaches 85%U-235. Fig. 4 illustrates the linear power behavior of this mini-plate to present.

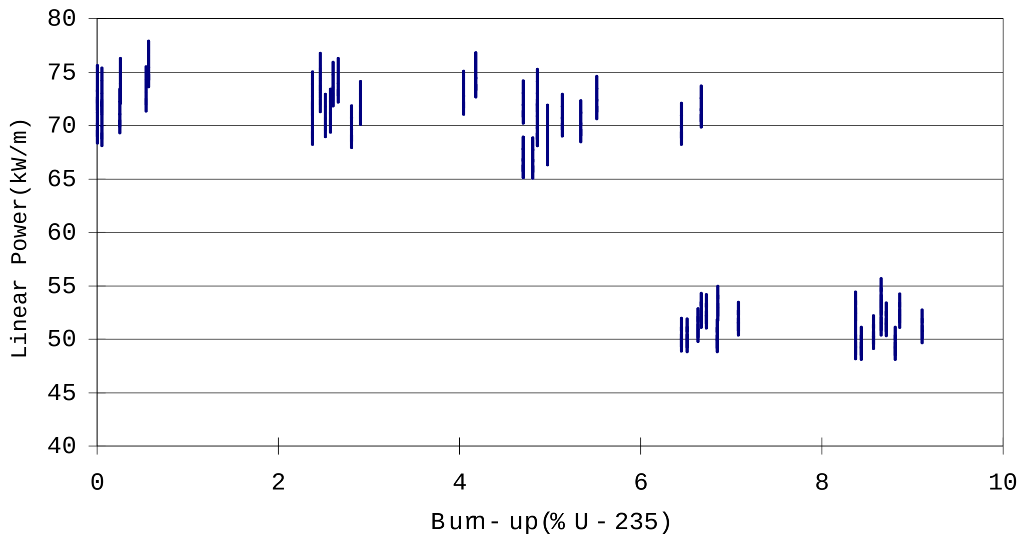


Fig. 4 Linear Power History of High-density U_3Si_2 Mini-plate in HANARO

3.2 DUPIC Fuel Irradiation Tests [8]

The development of DUPIC fuel is an international co-operative research with Canada, U.S.A. and IAEA. The DUPIC fuel irradiation tests comprise the successive tests of pellets, elements, and bundles. There are four stages in the DUPIC pellet irradiation plan. In the first stage, SEU (Slightly Enriched Uranium) and DUPIC simulation fuel (SEU plus fission products) are irradiated in a non-instrumented capsule. The capsule design is verified and the irradiation conditions at HANARO are confirmed in this stage. The in-pile performance assessment and safety analysis report is submitted to the HANARO Operation Committee for the approval of irradiation. The pellet surface roughness and the microstructure of the fuel are examined prior to irradiation. After two months of irradiation from July, 1999, the burnup is measured by gamma scanning and the dimensions are compared; before and after irradiation. Also the fission gas is analyzed, the extent of microstructure change and pellet and cladding interaction is assessed, and the formation and distribution of fission products in the pellet are measured.

In the second stage of pellet irradiation, DUPIC lead pellet will be irradiated in a non-instrumented capsule with the average discharge burnup. The irradiation behavior of DUPIC pellets will be analyzed and the technology for remote assembling and handling will be developed in parallel. In the next two stages of pellet irradiation, the thermal behavior and the fission gas release of DUPIC pellet will be assessed after the irradiation in the Instrumented capsule. The temperature and pressure as well as the flux will be monitored using this capsule.

3.3 Tests to Resolve Licensing Issue [9]

Another very important test program is the HANARO fuel qualification program carried out at high power that is required to resolve a conditional licensing prerequisite. When HANARO was designed, AECL developed uranium silicide fuel in a rod form. This fuel drew attraction from KAERI. In the course of fuel qualification process, AECL executed lots of fuel pin tests rather than the bundle tests. Using fuel pins, AECL experienced one high power condition, which was a design criterion for HANARO. The Korean regulatory body, KINS did not give credit to this design criterion due to the lack of data. Finally KINS imposed that HANARO shall be operated with a 20% margin to the design criterion until HANARO shows the repeatability of the high power test as well as demonstrates the fuel integrity under the high power condition above 112.8 kW/m.

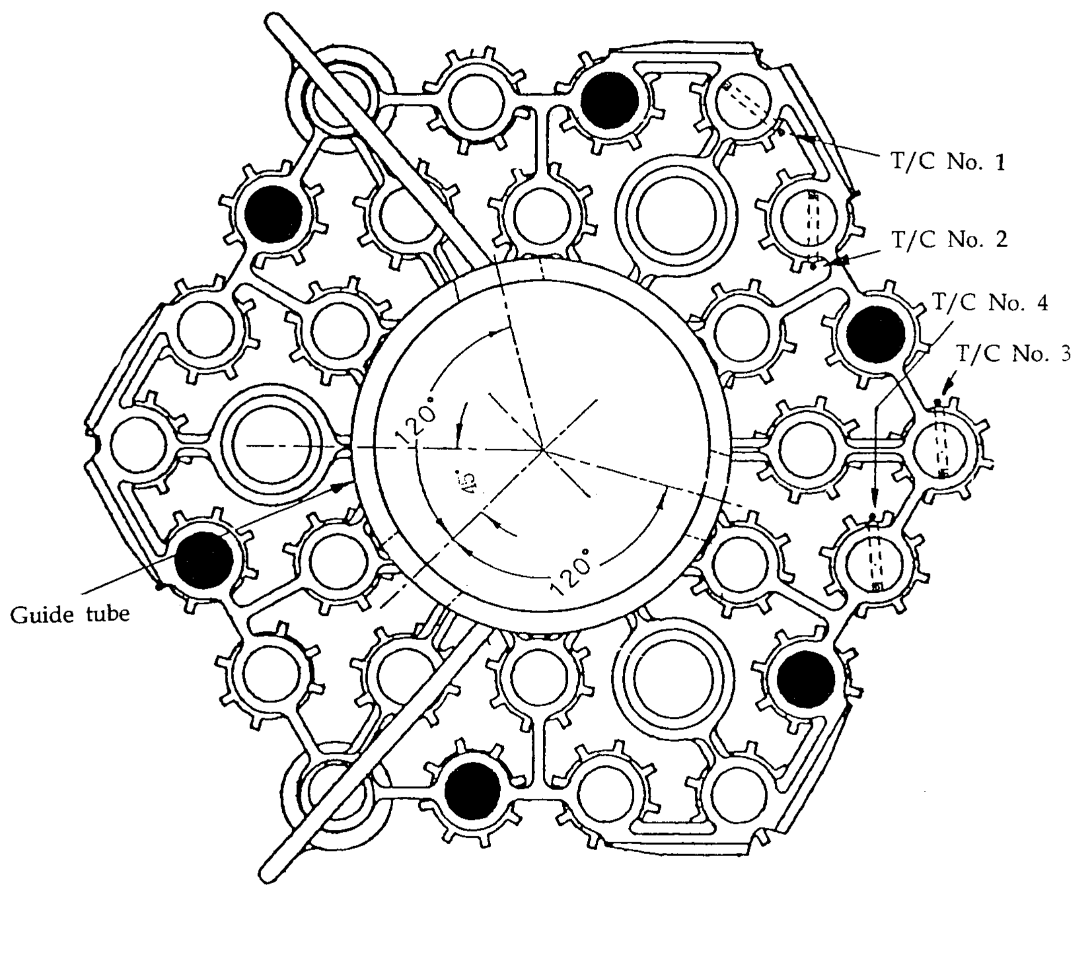


Fig. 5 Plan View of Type A and B Test Bundles

To clarify this issue, KAERI designed two type of special test bundles: two uninstrumented (Type A) and one instrumented (Type B) test bundles. Type A was fabricated by AECL with AECL's fuel elements as shown in Fig. 5. Six fuel elements are located on hexagonal edges. Besides the fuel elements, three hollow tubes are provided, which were used to deploy Au or Ni wires to measure the flux distributions during commissioning tests. Type B was fabricated by KAERI in which AECL's fuel elements and instruments such as Self-Powered Neutron Detector and Thermocouple are installed in the hollow tubes.

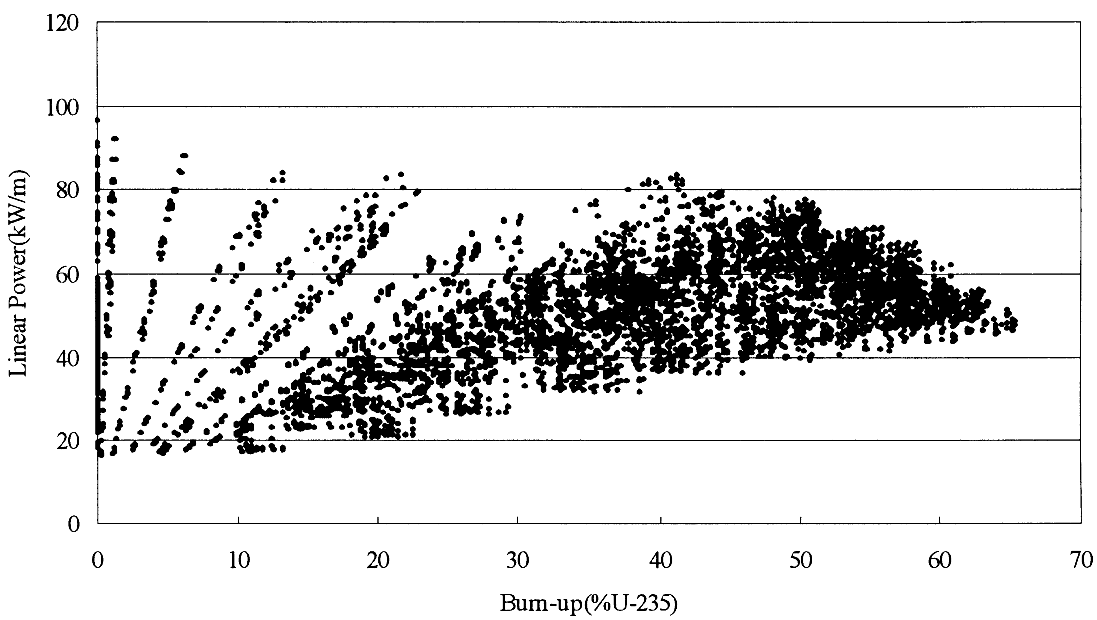


Fig. 6 Linear Power History of Type A Test Bundle-1

Two Type A bundles were irradiated in the HANARO as shown in Fig. 6 and 7. The bundles were withdrawn at average burnup of 52% and 70%U-235, respectively. One of them is under PIE and the other will be subsequently tested. Under 100 kW/m irradiation condition, any physical problems did not occur and thus those bundles are believed to be intact during irradiation. Type B bundle is waiting to be loaded. Loading this bundle was tried but severe FIV (Flow-induced Vibration) was observed at the pool top after loading since a long guide tube is provided at the top of the bundle. To fasten this bundle when loaded, we designed and fabricated a temporary chimney fastener. Using this, the FIV is confirmed to be remarkably diminished. The permanent chimney fastener is now being fabricated and expected to be installed in late October, 1999. Thus, we expected that this Type B test can start at the end of 1999. The predicted power condition is 120 kW/m or more at the beginning and this bundle will be withdrawn at 40%U-235 average burnup.

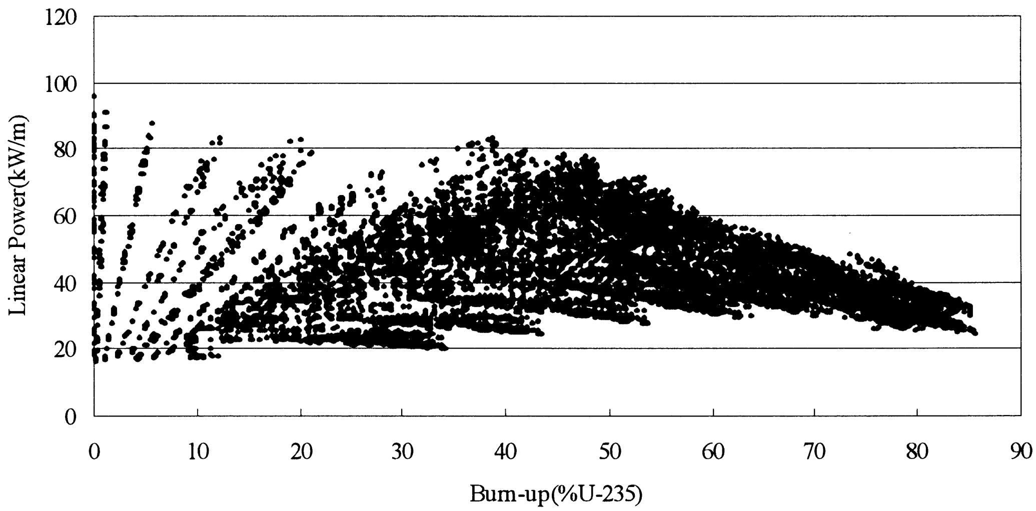


Fig. 7 Linear Power History of Type A Test Bundle-2

4. CLOSING REMARKS

As shown above, HANARO is actively utilized in the field of in-pile test. In the subsequent years, we have test plans for the following:

- Genuine DUPIC fuel element directly fabricated from the spent PWR fuel,
- Fuel for small size reactors for desalination,
- High burnup fuel and fuel containing burnable poisons for LWRs,
- High density fuels for advanced research reactors.

Through these tests and subsequent PIEs, we can justify and confirm the performance of the fuels that KAERI developed. These tests should also meet the requirements in the Technical Specifications to ensure the target safety as well as the reactor safety. From this increasing utilization demand, the contribution of HANARO to the national R & D program surely grows and is expanded.

ACKNOWLEDGEMENT

This paper is a part of the project funded by Ministry of Science and Technology of Korea.

REFERENCES

[1] I.C. Lim, H. Kim, B.W. Rhee, J.B. Lee, "Commissioning experiments for thermal hydraulic design of KMRR," J. of Korean Nuclear Society, Vol. 25, Number 2, 1993.

[2] H.R. Kim, et al., "In-Core Fuel management Practice in HANARO," Nuclear Engineering and Design, 179, 1998.

[3] J.F. Briesmeister, Ed., "MCNP – A General Monte Carlo N-Particle Transport Code, Version 4B," Los Alamos National Laboratory, LA-12625-M, March 1997

[4] J.D. Kim, et al., "Nuclear Data Evaluation and Group Constant Generation for Reactor Analysis," KAERI Internal Report, KAERI/RR-750/88, 1988.

[5] W. Whang, et al., "In-pile Irradiation Test Program and Safety Analysis Report of the KAERI Fuel for HANARO," KAERI Internal Report, KAERI/TR-674/96, 1996.

[6] C.K. Kim, et al., "High Power Irradiation Test Plan," KAERI Internal Report, 1999.

[7] C.K. Kim, et al., "Mini-Plate Irradiation Test Plan," KAERI Internal Report, 1999.

[8] K.K. Bae, et al., "Design and Safety Analysis Report for Irradiation of DUPIC Fuel," KAERI Internal Report, KAERI/TR-1157/98, 1998.

[9] G.Y. Han, et al., "Status of Activities on the Unresolved Licensing Issues for HANARO," pp.101-111, Proceeding of IGORR6, Taejon, Korea, 1998.