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PWR FUEL INSPECTION AND REPAIR TECHNOLOGY DEVELOPMENT IN THE REPUBLIC OF KOREA

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Abstract

As of September 1997, 10 PWRs and 2 PHWRs generate 10,320MW electricity in Korea. And another 8 PWRs and 2 PHWRs will be constructed by 2006. These will need about 400 MTU of PWR fuels and 400 MTU of PHWR fuels. To improve average burnup, thermal power, fuel usability and plant safety, better poolside fuel service technologies are strongly recommended as well as the fuel design and fabrication technology improvements.

During the last twenty years of nuclear power plant operation in Korea, more than 4,000 fuel assemblies has been used. At the site, continuous coolant activity measurement, pool-side visual inspection and ultrasonic tests have been performed. Some of the fuels are damaged or failed for various reasons. Some of the defected fuels were examined in hot cell to investigate the cause of failure. Even though 30 PWR fuel assemblies were repaired by foreign engineers, fuel inspection and repair technologies are not established yet. Various kind of design for the fuel make the inspection, repair and reconstitution equipments more complex. As a result, recently, a plan to obtain overall technology for poolside fuel inspection, failed fuel repair and reconstitution through R&D activities are set forth.

1. INTRODUCTION

1.1. Status of Nuclear Energy in Korea

Since 1978, nuclear energy has been one of the major sources of energy along with hydraulic, coal and oil, considering availability, long-term supply, economics and technology (Table 1). 10 PWRs and 2 PHWRs are now operating with total capacity of 10,316 MWe and supply 43.2£¥ of the national electricity requirement. Additionally, 14 PWRs and 2 PHWRs with total capacity of 16,600MWe are planned to be built and one PWR is planned to be decommissioned by 2010. By the time, total capacity of nuclear power plants will be 26,330MWe.

TABLE I. NATIONAL ENERGY PROSPECTS
[UNIT: MWH (%)]

Year	Nuclear	LNG	Oil	Coal	Hydraulic	Total
1993	7,616 (28.0)	6,198 (22,9)	5,574 (20.5)	5,260 (19.4)	2,498 (10.4)	27,153
1995	8,620 (26.8)	6,740 (20.9)	5,920 (18.4)	7,820 (24.3)	3,090 (9.6)	32,180
2000	13,720 (26.0)	14,200 (26.9)	5,140 (9.8)	15,830 (30.0)	3,880 (7.3)	52,760
2005	18,720 (27.5)	16,210 (23.9)	5,500 (8.1)	22,030 (32.4)	5,480 (8.1)	67,930
2010	26,330 (33.1)	22,010 (27.7)	3,530 (4.4)	21,700 (27.3)	5,980 (7.5)	79,550

Various types of nuclear reactors are generating electricity in Korea (Table 2). Westinghouse designed Ko-Ri units 1&2 of two loop reactors, Ko-Ri units 3&4 and Young- Gwang units 1&2 of three-loop reactors. Ul-Jin units 1&2 of three-loop reactors are designed by Framatome which are slightly different from those of Westinghouse. Young-Gwang units 3,4,5&6 and Ul-Jin unit 3,4,5&6 are designed based on ABB C-E System 80 design concept. Furthermore, two CANDU reactors are being operated and another two are under construction. Considering the scale of nuclear power production capacity in Korea, these variety of plant design makes it complicate to conduct construction, licensing, maintenance, improvement and repairs of the plants as well as fuel design, fabrication and service.

1.2. Status of Nuclear Fuel Cycle in Korea

Figure 1 shows a block diagram of fuel cycle in Korea. Conversion, reconversion, fabrication process of CANDU and PWR are established. Nuclear fuel design technology, materials and components development, increase of fissile resource usability, fuel services such as fuel inspection, examination and repair and waste disposal are tasks on a waiting list.

1.2.1. Status of PWR Fuel

From 1989, home-made nuclear fuels have been supplied to all the power plants. A new fabrication plant with capacity of 350MTU/y of PWR fuels and 700MTU/y of CANDU fuels is ready to supply fuels to the existing nuclear power plants as well as new ones to be constructed. These nuclear power plants are using several type of foreign or home-made fuels(Table 2). 14X14, 16X16 and 17X17 rod arrays of 'Standard Fuel Assembly(STD)', 'Optimized Fuel Assembly(OFA)', 'Advanced Fuel Assembly(AFA)', 'KWU Optimized Fuel Assembly(KOFA)', 'Korea Advanced Fuel Assembly(KAFA)' and 'Vantage 5H' for Westinghouse type PWRs, ABB C-E type 16X16 fuel (Figure 2) for ABB C-E type PWRs and 37 fuel rod cluster type fuel (Figure 3) for CANDU type PHWRs has been used. Such a variety of fuel type lead Korea Nuclear Co. Ltd.(KNFC) to be rich in technical experiences as well as problems. Based on their experience and international cooperation, KNFC is now trying to have his own design, fabrication and related technologies.

1.2.2. PWR Fuel Irradiation Performance

Since Ko-Ri PWR Nuclear Power Plant unit 1 starts its operation in 1978, numerous fuel assemblies have been burned (Table 3), but some of them are damaged due to flow induced vibration, debris, handling mistakes and unknown reasons(Table 4).

1.2.3. CANDU Fuel

Since 1983, numerous CANDU fuels, 100 MTU(¡-5,000 fuel clusters)/year, were supplied by KAERI and Canadian GE. The new fabrication plant of KNFC will supply fuels to the four CANDU reactors. No elaborate efforts are paid to examine the fuel integrity because any safety problem due to the fuel has not been issued yet and price of the fuel is relatively cheap(less than $1,500/fuel cluster).

2. FUEL INSPECTION, TEST AND EXAMINATION

2.1. Current Status of Pool-Side Inspection for Refueling

Considering that so many power plants are being operated, constructed and scheduled to be constructed in Korea, it seems to be urgent to establish technologies to supply more reliable engineering services; i.e., pool side fuel inspection, repair and integrity examination, in time.

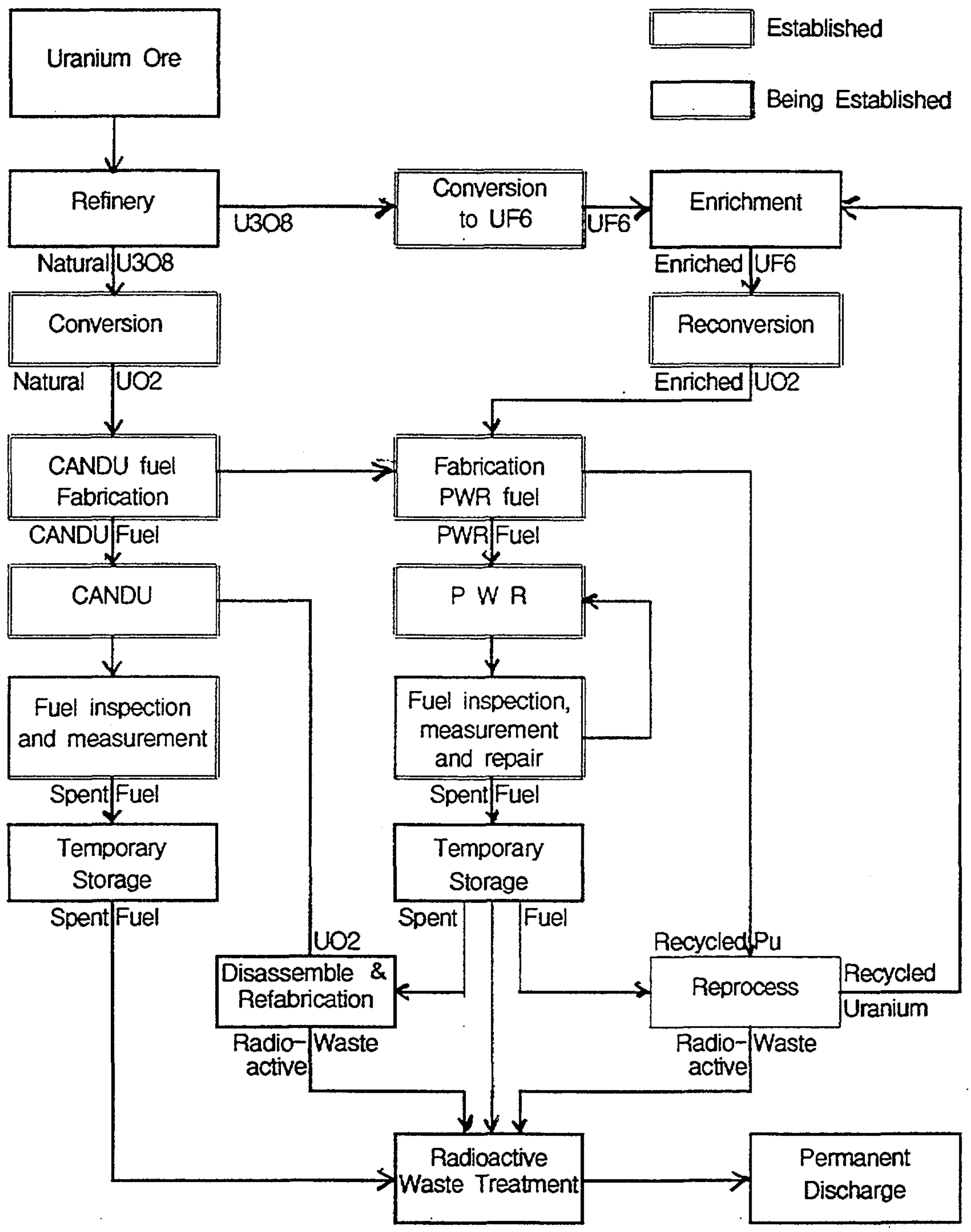


FIG. 1. Fuel cycle in Korea

TABLE II. STATUS OF NUCLEAR POWER PLANTS AND FUELS IN KOREA

Nuclear Plant	unit #	Fuel Type	Fas in Core	Output (MWe)	Commerc. Start-up	Cycle (Month)	Enrich-ment(%)	Batch Burnup (MWD/MTU)
Ko-Ri	1	14x14, W	121	587	'78. 4	15	3.8	35,000
	2	16x16, W	121	650	'83. 7	15	3.8	33,000
	3	17x17, W	157	950	'85. 9	18	4.2	40,000
	4	17x17, W	157	950	'86. 9	18	4.2	40,000
Young-Gwang	1	17x17, W	157	950	'86. 8	18	4.2	40,000
	2	17x17, W	157	950	'87. 6	18	4.2	40,000
	3	16x16, CE	177	1000	'95. 3	12	3.1/3.6/4.1	43,000
	4	16x16, CE	177	1000	'96. 1	12	3.1/3.6/4.1	43,000
	5	16x16, CE	177	1000	'01. 6	12	3.1/3.6/4.1	43,000
	6	16x16, CE	177	1000	'02. 6	12	3.1/3.6/4.1	43,000
Ul- Jin	1	17x17, W	157	950	'88. 9	18	4.2	40,000
	2	17x17, W	157	950	'89. 9	18	4.2	40,000
	3	16x16, CE	177	1000	'98. 6	12	3.1/3.6/4.1	43,000
	4	16x16, CE	177	1000	'99. 6	12	3.1/3.6/4.1	43,000
	5	16x16, CE	177	1000	'03. 6	12	3.1/3.6/4.1	43,000
	6	16x16, CE	177	1000	'04. 6	12	3.1/3.6/4.1	43,000
Wol-Sung	1	37rod cluster	4560	679	'84. 4	12	natural	8,000
	2	37rod cluster	4560	700	'97. 6	12	natural	8,000
	3	37rod cluster	4560	700	'98. 6	12	natural	8,000
	4	37rod cluster	4560	700	'99. 6	12	natural	8,000

- additionally, eight PWRs will be constructed until 2010.

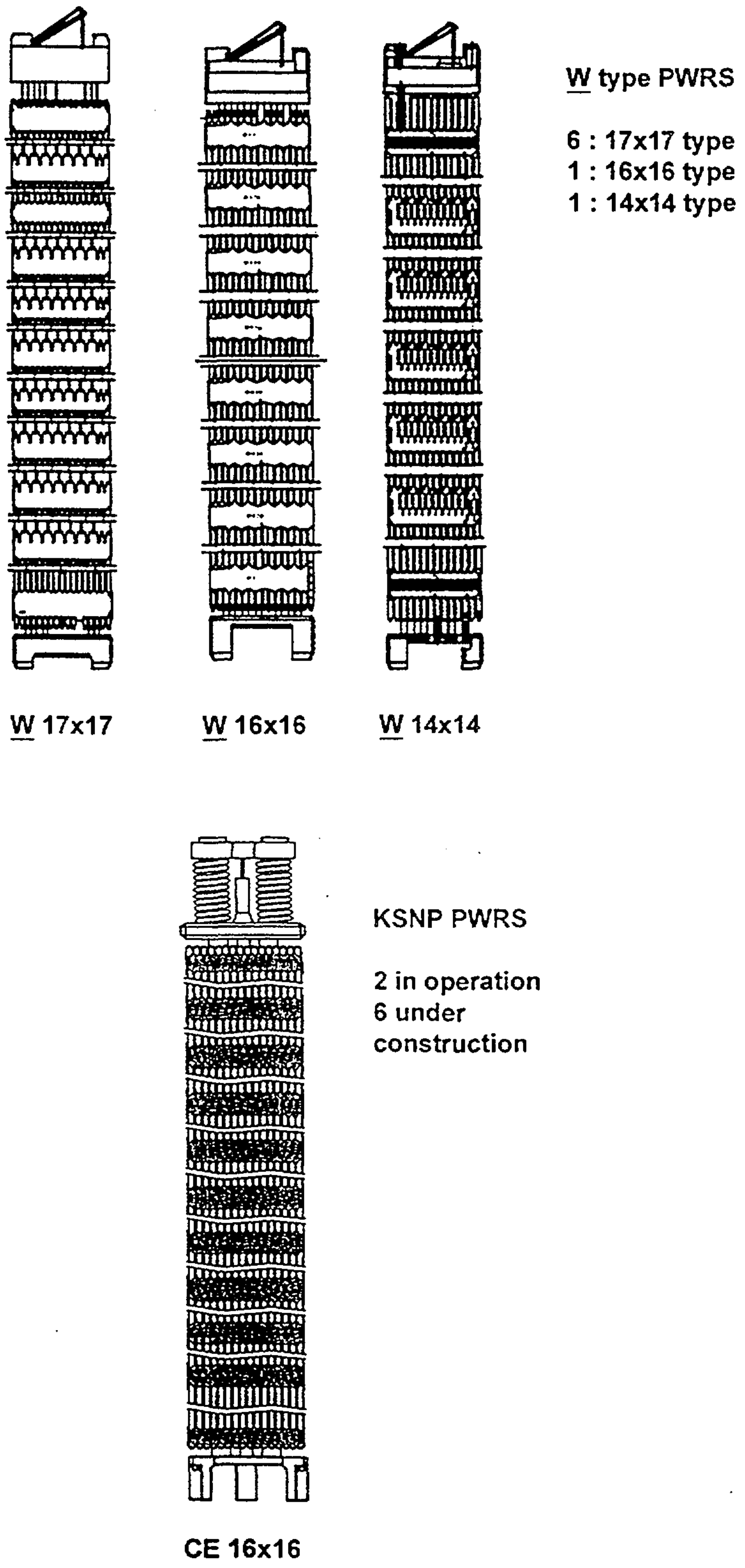
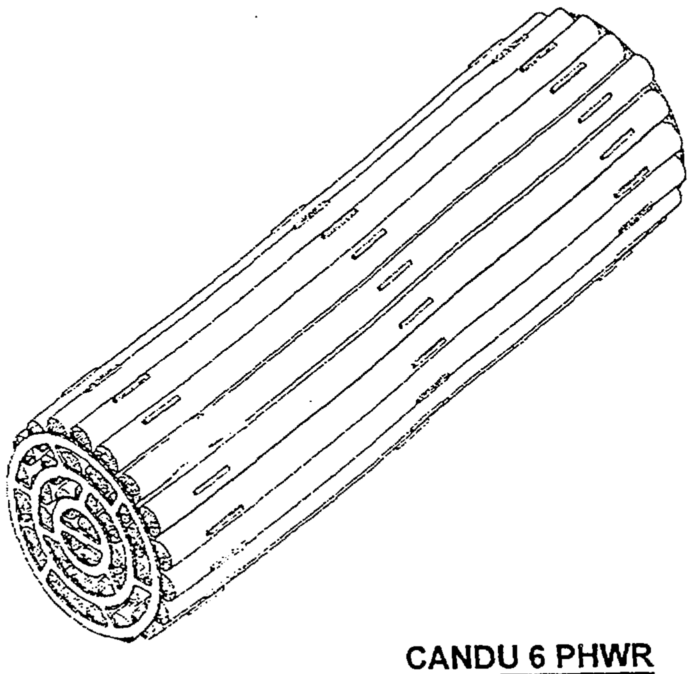


FIG. 2. *PWR fuels used in Korea*



CANDU 6 PHWR
2 in operation
2 under construction

❑ Component
- 37 Fuel Pin
- 2 Zry End Plate
- Spacer & Bearing Pad

FIG. 3. CANDU fuel bundle

TABLE III. DISCHARGED FUEL ASSEMBLIES AND FAILED FUEL ASSEMBLIES

Year	'78-'81	'82-'84	'85-'87	'88-'90	'91-'93	'94-'96	total
Discharged FA	80	161	420	1,000	1,209	1,137	4,007
Failed FA	5	12	6	5	31	3	62

TABLE IV. ROOT CAUSE OF FUEL FAILURES

Root Fault	Events	Failed Fuels	Comment
Baffle Jet Injection	5	17	Coolant Flow Path Design
Assembly Vibration	2	29	Fuel Design
Debris	6	11	
Manufacturing	2	2	
Fuel Handling	1	1	
Unknown	2	2	
Total	18	62	

2.1.1. *Visual Inspection*

The first step to examine integrity of irradiated PWR fuels is visual inspection using an under water TV camera. Even though this technology is well used, it is needed to be improved to have image analysis.

2.1.2. *Sipping Test*

To identify failed fuel assembly(ies) with leaking fuel rod(s), sipping test was performed, but, is no more applied now because failed fuel rod could not be identified with it.

2.1.3. *Failed Fuel Rod Detection System (FFRDS)*

FFRDS using ultrasonic test technology is used to identify leaking fuel rods. Even its performance is satisfactory, more reliable and convenient inspection system are anticipated.

2.2. Post irradiation examination at hot cell

2.2.1. PIE facility for fuel irradiation performance

Korea Atomic Energy Research Institute(KAERI) has a PIE facility which is composed of a pool, hot cells and radiochemical laboratory. Major jobs are as follow;

- Pool Side Examination : visual inspection, dimensional measurements, eddy current test and sampling of crud on the fuel rod cladding;
- NDT of Fuel Rod : visual inspection, dimensional measurement, axial gamma-scanning, X-ray radiography and eddy current test;
- DT of Fuel Rods : fission gas sampling, rod ovality and length variation, residual gap measurement, micro/macro ¥ã\och-scanning, burnup measurement and metalography, density measurement and chemical analysis of the pellet fragment;
- Radiochemical Laboratories : radiochemical analysis of the radioactive materials, such as crud, fission fragments, cladding materials etc.

2.2.2. R£¦D in the hot cell

2.2.2.1. PWR Fuel Post Irradiation Examination

Since 1986, seven irradiated PWR fuel assemblies and two fuel rods, which are burned for 1,2,3 or 4 cycles, have been examined in hot-cell to evaluate their irradiation performance.

2.2.2.2. Control rod examination

Since 1980, Hafnium rods have been used along with Ag-In-Cd rods as control rods in Korea. Post irradiation examination was performed with several damaged Hafnium rods.

2.3. New hot-cell at KMRR

In 1994, Korea Material Research Reactor(KMRR) with seven concrete hot cells and seventeen lead hot-cells was constructed to be used to produce radio isotopes and examine experimental specimens irradiated in the KMRR.

2.4. Pool-side fuel integrity test and dimensional measurement system development

KAERI developed an inspection system comprising with visual inspection equipment and dimensions, oxidation layer and holddown spring force measuring systems to investigate irradiation performance and root cause of fuel failure. With KAERI and international technical cooperation, an improved pool-side inspection facility is planed to be jointly developed from 1998 to 2002(Table 5). The scope is as follows;

2.4.1. Joint design and fabrication of the equipment

- fuel inspection stand
- fuel assembly inspection system;
  - periscope, underwater TV camera system
  - dimensional measuring devices(FA twist and bowing)
  - oxide thickness measurement device and crud sampling device
  - top nozzle spring force measurement device, etc.
- rod inspection system
  - periscope, underwater TV system
  - dimensional measuring device(ovality, diameter, rod length, profilometry)
  - eddy current test

- oxide film thickness, etc.
- skeleton inspection system
    - grid spring force measurement
    - borescope
    - guide tube dimensional change, twist and bowing
    - equipment for transportation
    - trailer and boxes

TABLE V. MILESTONE OF POOLSIDE INSPECTION EQUIPMENT DEVELOPMENT

year	1998	1999	2000	2001
Hardware	● Conceptional design ● Detailed design	● Parts make or purchase ● Fabrication	● Test ● Inspection ● Modification	● Practical use
Software	● Database buildup ● Training	● Inspection manuals ● Training	● Training	

Equipment will be fabricated in Korea or overseas depends on its convenience.

2.4.2. Training

- staffs need more practical experience through international cooperation

3. SPENT FUEL REPAIR

3.1. Fuel repair in Korea

In Korea, numerous Westinghouse type PWR fuels have been burned as they are scheduled, however, some of the fuels are failed(Table 3). Failed fuels are substituted with fully burned fuels and several fuels located in symmetric positions and are collected and repaired(Table 6) if the fuels can be burned for one or two cycles but slightly damaged. Furthermore, even when the Westinghouse type fuels is failed, the fuel is better to be repaired for use as scheduled in the view of fuel cycle management as well as plant management.

In 1995, two fuels are failed during startup test of the first cycle of Young-Gwang unit 4. When fuels burned in ABB C-E System 80 reactor are happen to be failed, they are better to be repaired to avoid extension of overhaul period as two or three months are needed to design emergency core. 12 ABB-CE engineers came with repair equipment(Figure 4), trained KNFC personnel and repaired the failed fuels. It cost quite a lot because the repair job has to be done in very short time and new fuel repair equipment have to be purchased.

3.2. Plan for fuel repair technology development

Fuel repair equipment is scheduled to be developed from 1998 to 2002 with a fund of about $5,500,000 (Table 7). International and internal cooperation are expected to design and fabricate the equipment, train personnel and participate fuel repair job as follows;

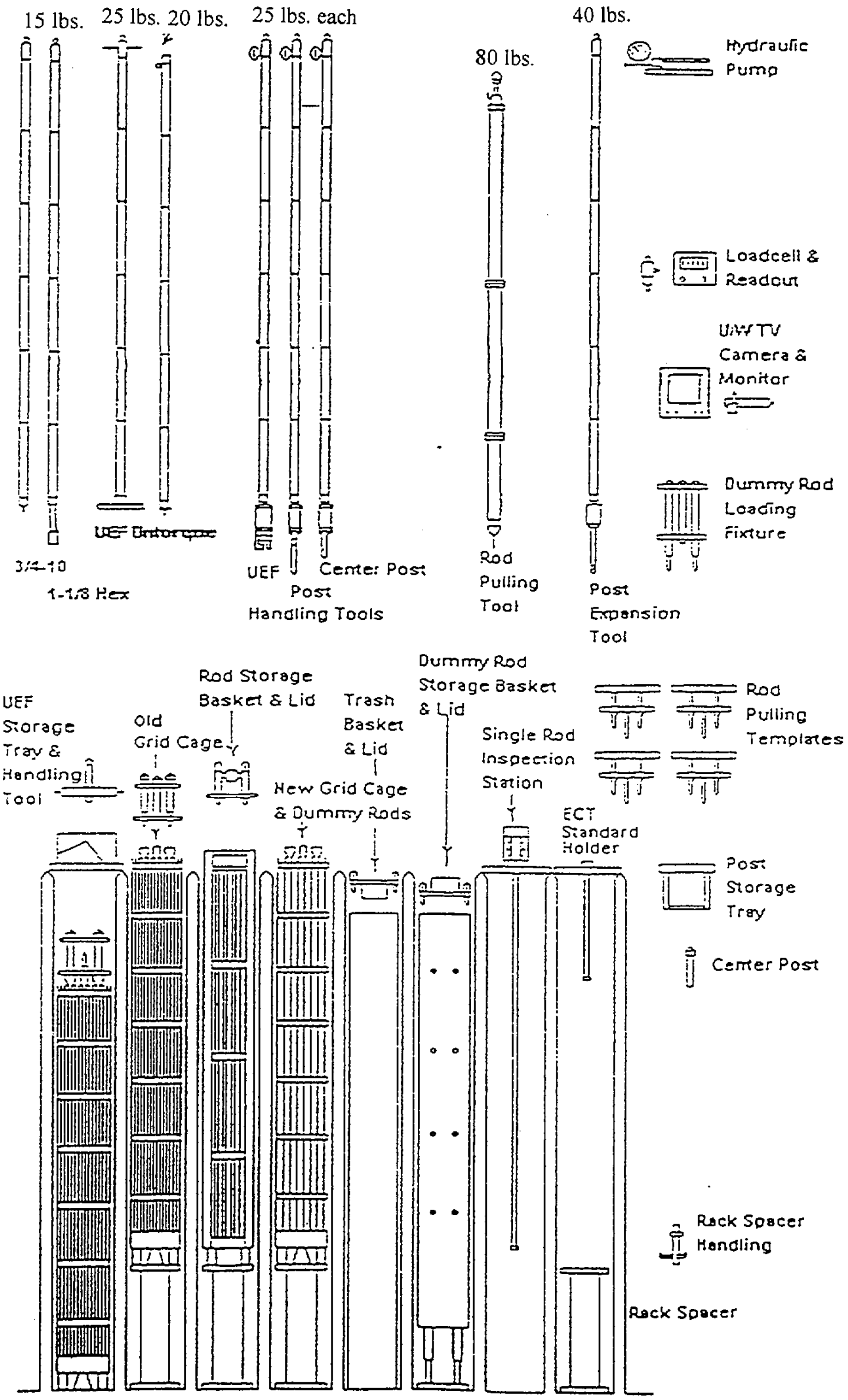


FIG. 4. ABB-CE fuel reconstitution tools

TABLE VI. REPAIRED FUEL ASSEMBLIES

Repaired Year	Design origin	Fuel Type	Repaired FAs	Repaired by
1985	W	14x14	17	Westinghouse
1991	W	14x14, 17x17	11	Westinghouse
1995	ABB-CE	16x16	2	ABB-CE/KNFC
Total	30			

TABLE VII. MILESTONE OF FUEL REPAIR EQUIPMENT DEVELOPMENT

year	1998	1999	2000	2001	2002
Hardware	●Concept design	●Detailed design	●Purchase or make parts ●Fabrication	●Test ●Inspection ●Modification	●Modification ●Repair failed fuel
Software	● Cooperation contract	● Tainting	●Database buildup Training	●Licensing Training	●Repair manuals

- equipment will be fabricated in Korea or overseas country depend on its convenience.

3.2.1. *Joint design and fabrication of fuel repair equipment*

- work station
- top nozzle disjoint/fixing tools for 14x14, 16x16 and 17x17 of STD, OFA, KOFA, KAFA, V5H and future fuels
- rod removal/insertion equipment for the fuel rods for 14x14, 16x16 and 17x17 of STD, OFA, KOFA, KAFA, V5H and future fuels
- fuel assembly turning(up side down and up) equipment for 14x14, 16x16 and 17x17 fuels
- equipment for transportation ; trailer and metal and wooden boxes
- one set of ABB-CE type fuel repair tools
- baskets for bolt/nut etc.
- fuel inspection equipment; underwater TV camera system, periscope

3.2.2. *Training*

Staff need more practical experience through international cooperation by performing joint repair work in Korea as well as overseas countries.

4. FUEL DESIGN IMPROVEMENT

4.1. Development of advanced nuclear fuel

An advanced fuel having higher thermal margin, burnup and zero-defect is planed to be developed(Table 8). Target goals of the fuel are 5,5000MWD/MTU of batch burnup, 15% of thermal margin, 0.3g of seismic strength and longer cycle length. Hardware development is scheduled from 1998 to 2000 and lead assemblies are scheduled to be irradiated from 2001 to 2004(Table 8). Development of new cladding and grid materials for the fuels is also an important part of the development to get better fuel integrity.

4.2. Fuel design modification for debris resistance

4.2.1. Rod removal/insertion process improvement to prevent scratches

Pushing fuel rods.into or pulling out from a skeleton may induce scratches on the fuel rod surface and also damage grid spring because of friction between the rod and grid spring. To avoid this, a method of rod turning and simultaneously pushing into or pulling out from a skeleton has been developed. The fuel rods might have helical shape scratches, but not deep, on the cladding surface. This helical shaped scratches are considered to be less harmful than the longitudinal one.

4.2.2. Debris resistant bottom nozzle development

One of the major causes of fuel failure is debris induced fretting wear. We are developing a three dimensional helmet shaped tip with a number of smaller size holes to be attached under the bottom nozzle hole. It is assumed that debris which are big enough to induce fretting wear could not pass through the flow holes. Total flow area of the holes on a tip is designed to be bigger than the

TABLE VIII. MILESTONE FOR ADVANCED FA DEVELOPMENT

Phase 1	Phase 2	Phase 3
Development of improved KSNP FA		
• Jointly with a foreign vendor • Use reference design	Verification of In-Reactor Performance	
		Commercial Supply of Improved KSNP Fas
	Conceptual Design of FA Components	
	• Exclusive ownership for all PWRs in Korea	Development of Demo Fas for PWRs

flow area of the original flow hole of the bottom nozzle so that flow disturbance and pressure drop be minimum.

4.2.3. Fuel rod surface hardening by ion implantation

Most of the debris induced fuel failure occurred on surface of a part of fuel rod located just under the lowest grid. One of method to avoid the fuel rod failure is to make the surface of the fuel rod harder and stronger. High energy ion implantation technology is studied to make the fuel rod surface hard. The facility for the ion implantation may be complex but small in size and easy to control.

5. SUMMARY

In Korea, nearly half of national electricity requirement has been fulfilled with nuclear energy. To support these power plants more reliable fuel service technology are needed.

Fuel integrity examination technology is required to inspect spent fuel integrity to use them next cycle, examine fuel performance and investigate fuel failure mechanism. Even efforts had been devoted to build a pool-side spent fuel integrity examination equipment, more improved one is required to be developed to have more accurate and various information about spent fuels.

The fuels burned in Westinghouse type PWRs as well as System 80 reactor had better to be repaired to be used as scheduled. So, multi-purpose fuel repair equipment are required to be developed.

Plans to develop technologies for spent fuel pool-side inspection and repair are going to be set up which are very important part of a long-term national plan for fuel design improvement