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New Approach to Construction and Management of Underground Nuclear Fusion Power Plants in Korea

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1. Introduction

As three reactors were sited underground in 1958, 1961, and 1964 in a large granite rock mass near the Yenisey River in Central Siberia (Russia), small underground test and research reactors installed in the 1960s in Norway, Sweden, and Switzerland, and a small power plant in France [1]. The first two reactors in Russia were for Pu production, and the 1964 reactor produces electricity and provides hot water and heat for the city of Zheleznogorsk. These reactors were water-cooled U-graphite reactors [2]. Studies of underground reactor siting in the 1970s in the U.S.A., Canada, Japan, and Switzerland confirmed the technical feasibility and revealed many safety, security and other advantages, but concluded that underground construction could have a cost and schedule penalty. Interest in nuclear power, as well as underground siting, waned in the late 1970s and 1980s in the wake of the Three Mile Island and Chernobyl accidents and growing public opposition to nuclear power. The exception appears to have been in Russia where interest in underground siting continued into the 1990s and was viewed as being potentially economical, with advantages in operational safety and physical security [3].

Introduction of the underground nuclear park (UNP) concept expanded the possible approaches to underground reactor siting [4]. The number of reactors to be sited underground was increased from one to as many as 18, and the spent fuel storage facility and waste repository supporting those reactors was collocated underground along with the reactors in an open fuel-cycle configuration. The 2004 UNP concept included high temperature reactors and heat exchangers sited 200 meters deep in a thick, bedded-salt rock host rock. Multi-gigawatt levels of produced electricity were to be supplied to users by a high-capacity transmission system. Arguments were presented indicating that the life-cycle cost of electricity from the UNP would be less than under conventional surface siting and waste management approaches, and the level of public acceptance would be greater. Normal underground hazards such as fire and hazardous gases were recognized as needing analysis, as was a safety analysis to evaluate accident scenarios.

Further studies, completed in 2006 and indicated the UNP approach, would lead to the reduced per-reactor cost for construction, operations, security, and waste management relative to an equivalent number and type of conventional surface-sited reactors [5]. Other advantages included increased margins of operational safety, security against attack, and protection against severe weather effects. Conceptual layout and preliminary excavation cost estimates were given for a hypothetical UNP with 18 reactors and their turbine/generators sited in an array of individual chambers at a depth of 100 to 300 meters in bedded salt. Collocation of waste management facilities underground with the reactors would reduce waste transportation cost, associated health and safety risks, and public concern. Environmental justice would be promoted because by collocating the reactors and waste management facilities at the same location the community that economically benefited from the construction and operation of the reactors would be the same community that accepted the waste from the reactors.

There are no spent fuels in common fusion power plants, compared to common fission power plants, since the gas fuels are mainly consumed in the fusion reaction of fusion power plants. However, it is necessary that the highly activated radio-wastes of surrounded components in the fusion reactors, including the fuel breeding structures, would be produced inevitably by the interaction of high-flux fast neutrons (especially, 2.5 and 14.1 MeV neutrons) produced in the fusion reactions. Based on the background information and review developed internationally for long-term investigation about the underground nuclear power plant siting, a new approach to construction and management of underground nuclear fusion power plants for future fusion power plants, such as K-DEMO, K-CFNS, K-PROTO Hybrid, K-PROTO FPP, K-FPP, etc. in Korea, is suggested and summarized in this presentation.

2. Background Study of Underground Nuclear Power Plants

The features of underground power plant siting are not well understood until this time [6]. Gross physical features such as depth of burial, number and size of excavated galleries, equipment layout, and access or exit shaft tunnels must be specified. Structural design features of the gallery liners, containment structure, foundations, and gallery interconnections must also be identified. Identification of the nuclear, electrical, and support equipment appropriate to underground operation is needed. Operational features must be defined for normal operations, refueling, and construction. Several articles have been published the underground concepts. However, the adequate engineering data are not available to support an evaluation of the underground concept. In this section, some of the background information for underground nuclear (fission) power plants are reviewed and summarized.

2.1 Major Underground Nuclear Reactors

Four small European reactors, excluding three Russian reactors, have been constructed in tunnels bored in rocky media [6, 7]. These are listed in Table 1.

Table 1: Underground Nuclear Reactors*

Name and location	Size	Purpose	Configuration/ Location		Status	Reactor Chamber Dimensions [feet]
			Turbine Generator	Reactor		
Halden Norway (BHWR)	25 MWt	Experimental	None	Rock Cavern	Operational (1959-2020)	98' long 85' high 33'wide
Agesta Stockholm, Sweden (PHWR)	80 MWt/ 20 MWe	Heat Production	Above ground at grade level	Rock Cavern	Operated from 1964-1974. Shutdown since 1974.	88' long 66' high 54'wide
Chooz Ardennes, France (PWR)	266 MWe	Power	Above ground	Rock Cavern	Operated from 1967-1991. Shutdown since 1991.	138' long 146' high 69'wide
Lucerne Switzerland	30 MWt/ 8.5 MWe	Test Reactor	Rock Cavern	Rock Cavern	Operated from 1968 to 1969. Shutdown since 1969.	--

*These are besides the three reactors in Russia

2.2 Advantages of Underground Power Plant Siting

(a) Higher resistance against the following [6]:
- Terrorist attack
- Aircraft impacts
- Proliferation
- Sabotage and vandalism
- Conventional warfare effects

(b) Higher levels of protection against severe weather effects
(c) Greater containment capability relative to a surface-sited plant and hence reduced public health impacts from extreme hypothetical accidents
(d) Somewhat, reduced seismic motion
(e) Available usage of grounded surface area over the underground power plants
(f) In smaller countries where adequate surface land is not available and safe distances from population cannot be maintained, the underground siting of nuclear reactors offers a distinct advantage

2.3 Disadvantages of Underground Power Plant Siting

(a) Higher (increased) cost of construction and management
(b) Longer construction time
(c) Reduced accessibility
(d) Problems related with the excavation of caverns with spans larger than 30~35 m
(e) Safety risks common to all underground construction and operations (e.g., fire, rock-fall, and ventilation, etc.) and their impact in the context of underground nuclear reactor operations
(f) Lack of any precedent for the general plant safety design requirements in an underground faculty
(g) Water requirements in case of limited surface and ground water resources

2.4 Description of Underground Nuclear Power Plant

In the 1970s, there were several studies on constructing nuclear power plants underground. Those studies are exemplified by a report published in 1972 under the auspices of the California Institute of Technology (Caltech) [8]. The report identified a number of advantages of underground siting. Those advantages included highly-effective confinement of radioactive material in the event of a core-damage accident, isolation from falling objects such as aircraft, and protection against acts of malice. Based on experience with underground testing of nuclear weapons, the report concluded that an appropriately designed plant would provide essentially complete containment of the radioactive material liberated from a reactor core during a core-damage event.

The Caltech report described a preliminary design study for underground construction of a LWR power plant with a capacity of 1,000 MWe. The minimum depth of the underground cavities containing the plant components would be 45 to 60 meter. The estimated cost penalty for underground siting would be less than 10 percent of the total plant cost. The Caltech report described four underground nuclear reactors that had been constructed and operated in Europe, shown in Table 1. Three of those reactors supplied steam to turbo-generators, above or below ground. The largest of those reactors and its above-ground turbo-generator made up the Chooz plant in France, which had a capacity of 270 MWe.

Since the 1970s, underground siting of nuclear power plants has been considered by various groups. For example, in 2002 a workshop was held under the auspices of the University of Illinois to discuss a proposed US-wide "SuperGrid". The grid would transmit electricity via superconducting DC cables and liquid hydrogen, which would provide cooling to the DC cables and be distributed as fuel. Much of the energy fed to the grid would be supplied by nuclear power plants, which could be constructed underground. Motives for placing those plants underground would include the reduced vulnerability to attack by nature, man or weather and real and perceived reduced public exposure to real or hypothetical accidents.

The 1970s studies concluded there would be an almost certain schedule and cost increase caused by the construction of the underground facilities, and a possible cost increase during operations [2]. The final results were summarized as the following:

(i) Interest in underground siting waned in the west
(ii) Consideration stopped by TMI accident
(iii) Projected rates of demand growth in electricity did not materialize
(iv) Surface sites appeared to be adequate

Table 2: Cost estimation of underground nuclear facility construction

Study Sponsor	Rock Type	Depth (meters)	Construction Cost Penalty
California Energy Commission	Granite	100	50-60%
Ontario Hydro	Granitic Gneiss	450	31-36%
Swiss Federal Institute for Reactor Research	Rock Types in the Swiss Alps	--	11-15%
Japanese Ministry of Trade and Industry	Sedimentary	150	20%

However, salt was apparently not considered in the 1970s studies as a potential rock type for underground siting. The thick and massive deposits of salt have attributes that could be significantly superior to granitic or sedimentary rocks. Salt has remarkable containment qualities, and well-known mechanical, chemical and thermal properties, as demonstrated through decades of successful:

(i) Storage of crude oil, natural gas, and liquefied petroleum gases in salt caverns
(ii) Worldwide salt and potash mining operations
(iii) Drilling through and into salt units during oil and gas exploration and production operations
(iv) Nuclear waste repository studies from the 1950's to present, especially in the U.S. and Germany
(v) Waste Isolation Pilot Plant construction and operating experience

Massive salt deposits are common in many of the world's sedimentary basins. Thick massive salt beds can be 100s of meters thick and cover 1000s of square kilometers. These beds:

(i) have relatively predictable lateral and vertical extent
(ii) are relatively dry, impermeable and lack fracturing
(iii) clearly low-cost to mine

Moreover, we assert, capital and operating costs could actually be lower underground in salt, relative to surface siting, through the cumulative effects of a reduction in:

(i) Decommissioning costs, through in-situ decommissioning and disposal
(ii) Transportation costs, through co-located storage/disposal facilities
(iii) Excavation costs, which are ~$20/$m^3$ in salt vs ~$40 to $80/$m^3$ in granite
(iv) Facility costs, through elimination of the containment structure
(v) Reactor costs, through the use of modular reactor
(vi) Site costs for successive reactors, due to the lack of constraints on lateral expansion in the sub-surface
(vii) Security costs, because of the need for fewer guards and physical protection measures
(viii) Insurance costs, through reduced health and property risks

Underground nuclear power plants are also economical because they do not require expenditures for disassembly, decontamination, and reburial [9]. A spent underground nuclear power plant is simply buried where it is located with minimal work. Spent fuel transportation costs and public concern associated with transportation will be reduced because of the close proximity, underground, of the reactors and the spent fuel storage facility and repository.

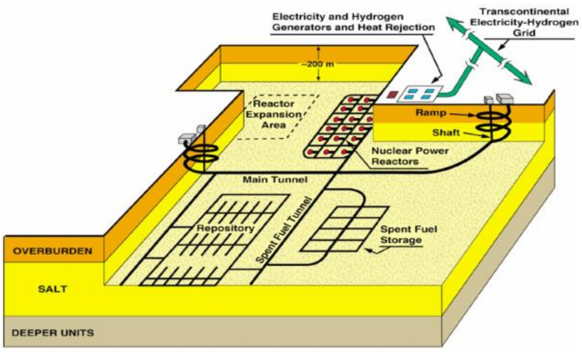

Fig. 1. Concept of an UNP in a shallow and massive salt deposit [2].

The features of the UNP concept are as the following:

(i) Array of high-temperature ($>9000^{o}$C reactors suitable for electricity and/or hydrogen production
(ii) Non-water cooled reactor designs
(iii) Underground, passive air-cooling of spent fuel
(iv) Use of ramps for entry of wheeled vehicles
(v) Use of seals and bulkheads to isolate individual reactors, sectors of the underground nuclear park, and the entire underground nuclear park from the surface

Although, current U.S. policy is for direct disposal of spent fuel, underground chemical processing has been demonstrated in Russia, which raises the interesting prospect of whether reprocessing facilities could become part of an underground nuclear park. However, the change of U.S. policy should be a main concern.

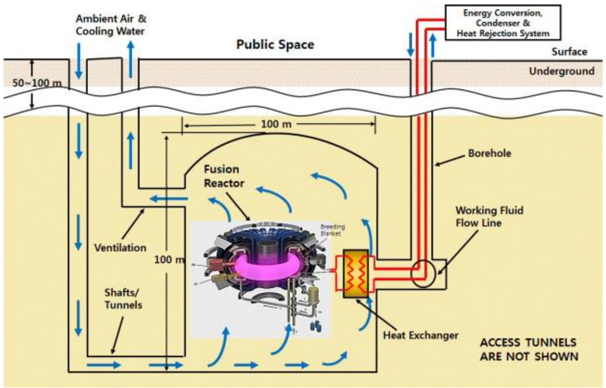

Fig. 2. Schematic of underground nuclear reactor, reactor chamber, ventilation system, and working fluid transfer system.

2.5 Challenges and Issues of Underground Nuclear Power Plant [2]

(a) Plastic Deformation (Creep)
- Control by ground support and ventilation to remove heat

(b) Corrosion
- WIPP and salt mining experience demonstrates that salt is a desiccant (Water removal from air)
- Conclusion: corrosion can be mitigated by control of water ingress and control of salt dust

(c) Abrasion
- Salt is not an abrasive

(d) Optimum Reactor Type and Layout of System Components
- 3D layout is facilitated by underground setting

(e) Safety Issues
- Need for multiple access and egress points
- Need for multiple fluid and ventilation circuits

(f) Regulatory Issue
- USNRC does not have regulatory framework for under-ground reactors

(g) Psychological Issue
- Dark, dirty, dripping, dangerous mine vs clean, dry, safe, modern underground industrial facility.

3. Strategy of Underground Fusion Power Plant Siting

Current researches of the nuclear fusion reactor are mostly devoted to the deuterium-tritium (D-T) fuel cycle. Neutron-induced transmutation of materials in a D-T fusion power plant will give rise to the potential for long-term activation (i.e., neutron-induced radioactivity) in reactor structures [10]. To ensure that the attractive safety and environmental characteristics of fusion power plants are not degraded, careful design choices are necessary. An aim of optimizing fusion power plant design must be to minimize both the level of activation and the total volume of active material that might ultimately be categorized as waste requiring disposal.

Major differences exist between fission and fusion reactors in terms of fuels, reaction products, activated material type, activity levels, half-life, radiotoxicity, etc [11]. The quantity of activated material originating from the fusion power core is larger than that from the fission core (per unit of electricity produced). The main differences between fission and fusion waste are related to their radiotoxicity (much higher in fission for waste originating from the fuel cycle) and waste form for their final disposal. When recycling is conceived, fission has a large share of highly radioactive and radiotoxic liquid secondary waste from spent fuel reprocessing, which has to be solidified by cementation or vitrification. Fusion waste in terms of volume is mostly solid and does not require those processes in extensive way. However, fusion solid waste also requires treatment (decontamination, detritiation, cutting, compacting) and conditioning (stabilizing e.g. by grout, packaging, etc.) which will generate some secondary waste requiring solidification. Most importantly, the fusion generated waste is not intrinsic to the fusion reaction, and therefore is more controllable. Thus, providing prudent and intelligent selection of materials and processes (avoiding noxious impurities), fusion reactors can avoid generating high level and long-lived waste streams. This is probably the most important difference between fusion and fission radioactive waste.

A new concept of underground fusion power plants is considered, at first time in Korea, even though the power density in a fusion reactor is much lower than that of fission reactors, and the main radioactive inventory is generated by neutron activation of plasma surrounding components. All component of fusion power plant is not necessary to locate in the underground site. Highly activated structures including the core fusion reactor component can be located in the underground site, and original components and fresh materials can be located in the suface-air site, as shown in Figure 3.

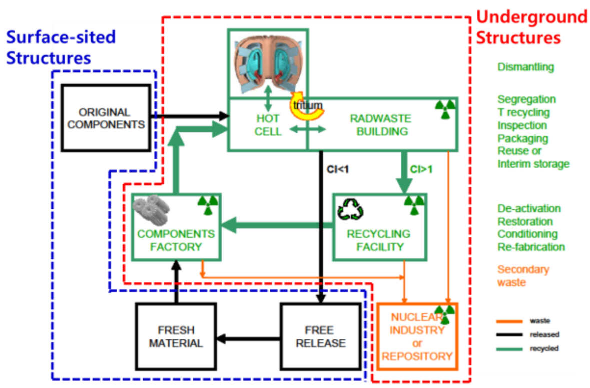

Fig. 3. Diagram of recycling and clearance processes through the closed cycle of fusion power material for fusion reactor structure located in the underground and surface-air sites.

It is also necessary to define the management categories of fusion radioactive materials used for the fusion power plants. Based on these categories, the fusion reactor materials can be supplied and exchanged for the operation of fusion power plants. Management procedures were generically categorized in clearance (unconditional and conditional), recycling in foundries (this applies only to metals) and more complex recycling for which the processes still have to be defined and/or developed, providing the decay heat remains below 2000 W/m^3. Specific levels can be set for these three main categories, but further descriptions are given in the next sections:

(i) For the unconditional clearance, the Clearance Index (CI) must be lower than unity
(ii) For the conditional clearance, this would depend upon local regulations
(iii) For the recycling in foundries, one can for the moment take an activity limit of 1000 Bq/g
(iv) For the other recycling possibilities, the only limit seems to be the decay heat and active cooling needs limit

Table 3: Management categories for fusion radioactive materials (in EU)

<table>
<tr><th>Limit</th><th colspan="2">< 10 μSv/h</th><th colspan="2">< 2 mSv/h</th><th>< 2,000 W/m³ (> 2 mGy/h)</th></tr>
<tr><td>Handling</td><td colspan="2">HOH</td><td colspan="2">SHOH</td><td>RH</td></tr>
<tr><td>Categories</td><td>Clearance</td><td colspan="2">Recycle in Foundries (1)</td><td colspan="2">Processes to Define</td></tr>
<tr><td>Limit</td><td>CI < 1</td><td colspan="2">< 1,000 Bq/g</td><td colspan="2">< 2,000 W/m³ (decay heat)</td></tr>
</table>

CI : Clearance Index
HOH : Hands-On Handling
SHOH : Shielded Hands-On Handling
RH : Remote Handling
(1) For metals

The IAEA developed and published (in 2009) a safety guide containing general scheme for classifying radioactive waste that identifies the conceptual boundaries between different classes of waste and provides guidance on their definition on the basis of long term safety considerations [12]. Under the IAEA safe guide, the radioactive wastes of fusion power plants should be considered clearly for recycling of the materials between in the underground site and in the surface-air site [13].

Table 4: An integrated approach to fusion radioactive materials management

<table>
<tr><th rowspan="2">Regulatory Route</th><th colspan="2">Management Route</th></tr>
<tr><th>Recycling/Reuse</th><th>Disposal</th></tr>
<tr><td>Clearance (unconditional)</td><td>Outside the nuclear industry. All final destinations are feasible [this can be after a certain decay storage time) this can happen within a licensed facility until specific conditions are met to allow clearance (i.e. in melting facilities to produce metal ingots)]</td><td>In a landfill (for urban, special or toxic waste, depending on chemical toxicity of the waste)</td></tr>
<tr><td>Conditional Clearance</td><td>Within the nuclear industry or in general industry for specific applications. Continuous regulatory control. [Examples include: building concrete rubbles for base road construction or as an additive for manufacturing new concrete buildings; or metal used for making shielding blocks and containers]</td><td>In special industrial (and/or toxic) landfill</td></tr>
<tr><td>No-clearance (No-release)</td><td>Within the nuclear industry (it can be direct reuse, or after processing)</td><td>In a licensed repository for radioactive waste (after an interim storage if applicable)</td></tr>
</table>

4. Conclusions

Under the background information and review developed internationally for long-term investigation about the underground nuclear power plant siting, a new approach, at first time in Korea, to construction and management of underground nuclear fusion power plants for future fusion power plants is suggested and summarized based on the categories of neutron-activated radiowaste for the structures and materials.

5. Acknowledgement

The description and opinion expressed in this presentation do not reflect officially those of the Korea Atomic Energy Research Institute (KAERI).

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