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Technical, Regulatory, and Policy Feasibility Assessments of Rod Consolidation in Spent Nuclear Fuel Disposal

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2 Nuclear Fuel Disposal

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27 **Abstract**

28 Various approaches have been proposed to address the challenges associated with storage and  
29 disposal of spent nuclear fuel. Rod consolidation, which involves extracting only the fuel rods  
30 from fuel assemblies and combining them for storage with reduced spacing, gained attention  
31 until the 1990s for its benefits in storage efficiency. In this case study, experts from diverse  
32 backgrounds evaluate the technical and political feasibility of rod consolidation for enhancing  
33 disposal practices. This study conducts a technical and regulatory analysis of rod consolidation  
34 under disposal conditions and evaluates its feasibility from a disposal perspective. From a  
35 technical viewpoint of 2:1 and 1.5:1 rod consolidations, the rod consolidation methods  
36 demonstrate positive effects on nuclear criticality compared to the reference, non-rod  
37 consolidation case. For the advanced repository design with elevated temperature conditions  
38 of 150 °C or higher, the applicability of rod consolidation becomes more convincing, thereby  
39 achieving a reduction in the number of required disposal canisters. In addition, regulatory  
40 considerations primarily focus on the requirements for applying rod consolidation technology  
41 under the Korea Nuclear Act. Moreover, this research conducts environmental, economic, and  
42 acceptance analyses to ascertain the viability of rod consolidation. The findings provide  
43 compelling evidence supporting the feasibility of rod consolidation technology for disposal  
44 purposes, highlighting its technical, regulatory, economic, environmental, and societal  
45 acceptance advantages. However, challenges remain, particularly concerning its applicability  
46 to high-burnup nuclear fuel and unresolved regulatory and technical issues.

47 **Keywords:** Rod Consolidation, Spent Nuclear Fuels, Geological Repository, Nuclear  
48 Criticality, Thermal Analysis, High Burnup, LEU+

49

## 50        1. Introduction

51        Due to the rapidly increasing usage of nuclear energy, supplying 14% of total electricity of  
52        global demand to date, a considerable volume of spent nuclear fuels (SNF) have been generated  
53        [1]. By 2017, the quantity of SNF in interim storage reached 400,000 metric tons of U, with  
54        this amount of SNF continuing to rise [2,3]. Consequently, the permanent disposal of SNF has  
55        garnered worldwide attention, especially in countries lacking reprocessing plans.

56        Despite the growing focus on permanent disposal, several countries have faced major  
57        challenges such as public opposition, notably the Not-In-My-Backyard (NIMBY) phenomenon,  
58        which complicates securing disposal sites. Additionally, economic considerations and technical  
59        challenges related to the storage, transportation, and disposal of SNF have come to the forefront  
60        [4]. As a result, various efforts have been made over the years to enhance storage efficiency  
61        and minimize disposal areas to address these issues effectively.

62        Since the 1980s, rod consolidation technology, which involves reassembling fuel rods into an  
63        assembly with narrower spacing by extracting only the fuel rods from fuel assemblies, has  
64        gained attention due to its beneficial characteristics for the storage and disposal of SNF  
65        worldwide. Rod consolidation technology was the subject of numerous studies in the United  
66        States (US), Germany, Sweden, and Korea since the late 1980s to the early 1990s, aiming to  
67        enhance storage efficiency in wet pools [4,5]. For instance, in the early 1990s in the US, long-  
68        term storage became a primary issue due to a moratorium on fuel reprocessing. Therefore, the  
69        US analyzed various high efficiency storage options such as high-density racking, dry storage,  
70        and rod consolidation [6]. Among these options, rod consolidation including rod removal,  
71        fabrication of consolidated rods, and NFBC compaction were demonstrated. Additionally,  
72        economic studies such as cost impact analysis were also conducted during the same period  
73        [7,8]. However, further studies were not conducted due to its lower competitiveness from  
74        technical and practical viewpoints, such as thermal management, radiation issues, and change  
75        of nuclear waste policy, compared to those of high-density racking and dry storage technologies.  
76        In the meantime, Germany considered rod consolidation technology to enhance disposal  
77        efficiency and reduce costs and accumulated various techniques including interim storage  
78        before disposal, transportation, disposal safety; however, after the pilot test, the research did  
79        not continue [4]. Korea also had considered the technology in the storage and disposal  
80        viewpoints.

81 This technology offers advantages: (i) high storage efficiency due to dense management with  
82 an ideal consolidation factor of 2, (ii) relatively easy non-proliferation as it can be achieved  
83 through only mechanical processes rather than chemical processes, and (iii) enhanced public  
84 acceptance based on the reduced disposal area and environmental impact. However, rod  
85 consolidation has not been implemented due to competition with high-density racking and  
86 expanding of dry storage, which were selected for their short-term economic feasibility and  
87 practicality. With increasing interest in optimizing waste management and improving storage  
88 efficiency, rod consolidation is now gaining renewed attention. To fully realize its potential, it  
89 is essential to investigate not only its application for storage but also its feasibility for disposal  
90 as its application for disposal has not yet been thoroughly studied [4].

91 In order to apply this technology to the disposal aspect, several technical and regulatory  
92 challenges must be addressed. Nuclear criticality and thermal-hydraulics behavior within Deep  
93 Geological Repository (DGR) are primary technical concerns for the disposal of consolidated  
94 SNF. Rod consolidation, with 1.5 or 2 times more spent nuclear fuel assemblies per canister,  
95 leads to the increase in fissile material density and higher decay heat density. From a regulation  
96 perspective, rod consolidation can provoke issues with domestic nuclear-related legislation.  
97 This includes how rod consolidation technology is interpreted as the narrow or broad  
98 perspective of nuclear materials. A broader interpretation may require more complex licensing  
99 and regulatory scrutiny, while a narrower view might simplify the process. This also includes  
100 considerations related to international concerns such as non-proliferation. Additionally, various  
101 other concerns, such as waste management and economic viability, public acceptance, and  
102 technical difficulties must be addressed in the implementation of this technology.

103 In this paper, the disposal feasibility of rod-consolidated SNF has been studied. In terms of a  
104 technical perspective, nuclear criticality and thermal-hydraulic behavior analysis were  
105 conducted using the MCNP (Monte Carlo N-Particle) and HADES (High-level rAdiowaste  
106 Disposal Evaluation Simulator) codes, respectively [9,10]. In addition, an analysis to determine  
107 the required number of canisters, considering thermal criteria of 100 °C and over 150 °C,  
108 respectively, was performed. Regulatory requirements for the rod consolidation were also  
109 assessed based on the Nuclear Safety Act of Korea. Moreover, the economic viability, waste  
110 impact public acceptance, and potential technical difficulties were also addressed, taking into  
111 account the current situation in Korea.

112

## 113        2. Rod Consolidation Technology

114        This technology involves extracting only the fuel rods from fuel assembly structure, as depicted  
115        in Figure 1, and combining them for storage with compact spacing compared to the original  
116        fuel assemblies. The rod consolidation process comprises five primary stages as depicted in  
117        Figure 1 [11]:

118        End fitting removal: Removal of upper nozzles from the used nuclear fuel assemblies.

119        i.        End fitting removal: Removal of upper nozzles from the used nuclear fuel  
120        assemblies.

121        ii.       Fuel rod removal: Extraction of fuel rods from the assembly skeleton structure.

122        iii.      Fuel rod array reconfiguration: Reconfiguration of fuel rod array for densification.

123        iv.      Consolidated rod packaging: Packaging of densified fuel rods.

124        v.       Off-normal rod handling: Handling of off-normal fuel rods.

125        Subsequently, the remaining assemblies such as Non-Fuel Bearing Components (NFBC) are  
126        transferred to the metal waste treatment process followed by transformation into metal waste  
127        solid forms. Finally, the volume of NFBC can be squeezed into maximum 10% of the original  
128        waste volume [7].

129

130        **Figure 1. Schematic design of rod consolidation (left), and flow diagram of rod**  
131        **consolidation technology (right).**

132

### 3. Modeling Scenarios of Spent Nuclear Fuel Rod Consolidation

As illustrated in Figure 2, along with the global increase in nuclear energy generation, the uranium (U) enrichment and burn-up level of Pressurized Water Reactor (PWR) SNF have risen from approximately 3 weight percent (wt%) initial enrichment and 30 Giga Watt Days per Metric Ton Uranium (GWD/MTU) to levels of around 5 wt% initial enrichment and 60 GWD/MTU of SNF [12,13]. Moreover, even in a single country, various PWR SNF with different U enrichment and burn-up levels are utilized over individual nuclear power plants at the same period. The annual amount of SNF assemblies in Korea has increased, reaching about 20,000 assemblies by the year 2018.

**Figure 2. The global trend in U enrichment and burn-up of SNF (left), and annual and cumulative amount of SNF assemblies of Korean (right) [12,13].**

A case study matrix was constructed as shown in Table 1 to evaluate the feasibility of rod consolidation technology for discharged SNF from a technical perspective. The considered U enrichment for SNF are 3, 4, 5, and 6 wt%, and burn-up levels are 30, 40, 50, and 60 GWD/MTU. The concentrations of fission products and the decay heat from SNF at each U enrichment and burn-up level were computed using the ORIGEN code of SCALE 6.2. In addition, the considered rod consolidation ratios are 2:1 and 1.5:1, after 40 years of cooling time within wet storage of SNF.

**Table 1. Case study information of rod consolidation.**

The variation of decay heat with each U enrichment and burn-up is presented in equations in the supplementary file section A, and corresponding decay heat evolutions are provided in Figure 3. The decay heat over time is calculated using equation (1), with cooling in a spent fuel pool for 40 years:

$$\text{Decay heat} = 2 \times A \times (t + 40)^{-b} \quad (1)$$

In this equation, A is a constant related to the initial decay heat at the time 0, and b is a decay

161 constant that characterizes the rate at which the heat decreases over time. Note that relevant  
162 coefficients used for decay heat calculation are presented in supplementary file Section A. The  
163 equation was derived to maintain a correlation coefficient of at least 0.97 of  $R^2$  value [14].  
164 Additionally, Figure 3 shows decay heat and the evolutions of primary fission isotopes, with  
165 60 GWD/MTU and 3 wt% of U concentration. The concentration of U-238 was approximately  
166 82.353 wt% and remained nearly constant over time. These two calculations impact the  
167 Thermal-Hydraulic (TH) analysis and criticality analysis, respectively.

168

169 **Figure 3. Decay heat (left) and fission isotopes (right) evolutions with time.**

170

#### 171 **4. Nuclear Criticality Analysis**

172 The application of rod consolidation technology results in a denser arrangement of nuclear fuel  
173 rods, with 1.5 or 2 times more rods in the same space compared to the conventional assemblies,  
174 raising concerns about criticality attainment. Furthermore, it is crucial to examine whether the  
175 system could reach criticality in scenarios where the integrity of the canister containing SNF  
176 is compromised, potentially allowing groundwater ingress into the assembly. Groundwater  
177 could act as a neutron moderator, significantly influencing the criticality of the system. Thus,  
178 the application of rod consolidation was investigated under two scenarios: one with the  
179 canister's internal space filled with He (representing normal conditions) and the other with  
180 water ingress (indicating canister failure), to determine if the system maintains subcriticality,  
181 with the criterion of  $k_{eff} < 0.95$  [15].

182 For criticality analysis, MCNP6.2 was used. MCNP (Monte Carlo N-Particle) is a general-  
183 purpose Monte Carlo radiation transport code widely used for simulating neutron, photon,  
184 electron, and coupled transport. It has been applied in various fields, including radiation  
185 shielding and criticality safety. For instance, MCNP can simulate neutron and gamma-ray  
186 transport to evaluate shielding designs for spaces handling radiation, such as treatment rooms,  
187 laboratories, and irradiation chambers [9]. It is also used to assess criticality in reprocessing  
188 equipment or to calculate the critical mass of specific materials [16,17]. In this study, the  
189 KCODE card, an MCNP command for criticality analysis, was used.

190 The composition of the SNF materials was obtained using the ORIGEN code in SCALE. The

191 following specific actinides were chosen for the criticality calculation, with the fission products  
 192 excluded from the analysis to facilitate calculations and ensure a conservative approach.[18].

193 The actinides included are as follows:

195  $^{234}\text{U}$ ,  $^{235}\text{U}$ ,  $^{236}\text{U}$ ,  $^{237}\text{U}$ ,  $^{238}\text{U}$ ,  $^{238}\text{Pu}$ ,  $^{239}\text{Pu}$ ,  $^{240}\text{Pu}$ ,  $^{241}\text{Pu}$ ,  $^{242}\text{Pu}$ ,

194  $^{241}\text{Am}$ ,  $^{243}\text{Am}$ ,  $^{244}\text{Cm}$ ,  $^{245}\text{Cm}$ ,  $^{246}\text{Cm}$ ,  $^{237}\text{Np}$ ,  $^{239}\text{Np}$ .

196

#### 197 **4.1. Input parameters and methods**

198 Figure 4 shows cross-sections of the reference and rod-consolidated assemblies. A standard  
 199 Westinghouse 17×17 assembly was used, placed inside a steel pipe and cast iron insert, and  
 200 encased in a copper overpack canister [14,15,19]. Additionally, there was a steel lid and a  
 201 bottom of the canister. Surrounding the canister is a thick layer of bentonite, beyond which lies  
 202 the host rock made of granite. A reflective boundary condition was applied at the outer  
 203 boundary of the host rock. The detailed geometry specifications are summarized in Tables 2  
 204 and 3 with the main parameters of the fuel assembly and disposal canister, respectively. The  
 205 specifications for the composition of SNF were provided in the supplementary file section B.

206

207 **Figure 4. Cross sections of deep geological repository system.**

208

209 **Figure 5. (a) 1:1 rod consolidation applied assembly (reference case), (b) 1.5:1 rod**  
 210 **consolidation applied assembly, and (c) 2:1 rod consolidation applied assembly. The**  
 211 **reference assembly contains 264 fuel rods, while the 1.5:1 and 2:1 rod consolidated**  
 212 **assemblies contain 409 and 537 fuel rods, respectively.**

213

214 **Table 2. Main parameters of the fuel assembly [18,20,21].**

215

216 **Table 3. Main parameters of the disposal canister [14,15,18,19].**

217

#### 218 **4.2. Criticality calculation results**

219 The reference case represents the 1:1 rod consolidation scenario. The criticality analysis was  
220 performed for cases where the assembly is filled with either He or water, applying consolidation  
221 ratios of 1:1, 1.5:1, and 2:1. The results for the cases with He are shown in Figure 6. It is  
222 observed that criticality decreases as burn-up increases, while enrichment tends to increase  
223 criticality. As shown in the figure, rod consolidation increases criticality in all cases due to the  
224 densification of the fuel rods, with 2:1 rod consolidation having a greater impact than 1.5:1  
225 ratio. However, even in the most conservative assumption case of 6 wt% enrichment and 30  
226 GWD/MTU burn-up, criticality remains below 0.35 for both cases, much lower than the  
227 criticality criterion of  $k_{eff}$  0.95.

228

229 **Figure 6. Nuclear criticality over burn-up and U concentration of 1:1 rod consolidation**  
230 **(reference case) and 1.5:1 rod consolidation (left), and 1:1 rod consolidation and 2:1 rod**  
231 **consolidation (right) when assemblies are filled with He.**

232

233 Figure 7 illustrates the evolution of criticality over time from 40 years to 1 million years from  
234 the discharging point for 5 wt% enrichment and 50 GWD/MTU burn-up. Criticality tends to  
235 decrease over time, ultimately decreasing from 0.219 to 0.210 after 1 million years in the case  
236 of 1.5:1 rod consolidation, and from 0.261 to 0.251 after 1 million years in the case the of 2:1  
237 rod consolidation.

238

239 **Figure 7. Nuclear criticality evolution of 5%, 50 GWD/MTU over time if assemblies are**  
240 **filled with He.**

241

242 If failure of the copper canister occurs, groundwater infiltrates into the canister, filling the  
243 assemblies and displacing the He. The results for the cases with water with 1:1, 1.5:1, and 2:1  
244 rod consolidation are shown in Figure 8. Similar to the He-filled cases, criticality tends to  
245 decrease with higher burn-up and lower enrichment. The most significant difference from He  
246 cases is that criticality decreases across all burn-up and enrichment pairs with rod consolidation  
247 is applied. While criticality exceeds the criterion at the highest critical point of 6 wt%, 30  
248 GWD/MTU, reaching 0.995, with a 1.5:1 rod consolidation, it decreases below the criterion to

249 0.921 when 2:1 rod consolidation is applied. For 1.5:1 rod consolidation, the decrease in  
 250 criticality compared to 1:1 rod consolidation is less significant than with 2:1, but a greater  
 251 reduction in criticality is observed as the enrichment increases.

252

253 **Figure 8. Nuclear criticality over burn-up and U concentration of 1:1 rod consolidation**  
 254 **(reference case) and 1.5:1 rod consolidation (left), and 1:1 rod consolidation and 2:1 rod**  
 255 **consolidation (right) when assemblies are filled with water.**

256

257 Figure 9 illustrates the variation of criticality over time from 40 years to 1 million years. Unlike  
 258 the case where He is present, in this case, criticality tends to increase over time. In the case of  
 259 the reference assembly, the value begins at 0.831 and ultimately increases to 0.837. For 2:1 rod  
 260 consolidation, it starts at 0.698 and escalates to 0.766 after one million years, which remains  
 261 under the critical criterion while it increases from 0.799 to 0.851 for 1.5:1 rod consolidation.

262

263 **Figure 9. Nuclear criticality evolution of 5%, 50 GWD/MTU over time if assemblies are**  
 264 **filled with water.**

265

266 Unlike in He cases, the reduction in criticality due to rod consolidation in water-filled cases is  
 267 closely associated with the ratio of fuel to void space between fuel rods. The Hydrogen to  
 268 Heavy Metal ratio (H/HM ratio), used to understand and analyze the physical and chemical  
 269 phenomena occurring within the reactor core, represents the relative quantities of H and U [22].  
 270 The H/HM ratio for cases with and without the application of 2:1 and 1.5:1 rod consolidation  
 271 is calculated as follows:

$$\frac{H}{HM} = \frac{N_{Hydrogen} \times (Coolant\ volume\ fraction)}{N_{Uranium} \times (Fuel\ volume\ fraction)} \quad (2)$$

$$\frac{\frac{H}{HM_{2:1\ rod\ con}}}{\frac{H}{HM_{ref}}} = \frac{1.0724}{3.4453} = 0.31126 \quad (3)$$

$$\frac{\frac{H}{HM_{1.5:1 \text{ rod con}}}}{\frac{H}{HM_{ref}}} = \frac{1.8056}{3.4453} = 0.52408 \quad (4)$$

272 This implies that rod consolidation reduces the amount of water surrounding the fuel. In other  
 273 words, the decreased neutron moderation and reflection due to decreased H/HM ratio lowers  
 274 criticality. On the other hand, the criticality under normal conditions increases regardless of the  
 275 H/HM ratio, since the influence of neutron moderation and reflection by He is less significant  
 276 compared to that of water.

277

278 **Figure 10. Neutron flux spectrums over neutron energy of 1:1 rod consolidation**  
 279 **(reference case), 1.5:1 and 2:1 rod consolidated cases filled with water, 5 wt% and 50**  
 280 **GWD/MTU.**

281

282 Figure 10 depicts the neutron flux graph as a function of neutron energy for the reference case,  
 283 2:1, and 1.5:1 rod consolidated cases when water fills the assemblies. As evident from the  
 284 figure, the neutron flux in the thermal neutron energy range decreases by more than 2.5 times  
 285 for 2:1 rod consolidation, and the 1.5:1 rod consolidation also results in a significant decrease.  
 286 This reduction in neutron flux is attributed to the decreased volume of water due to rod  
 287 consolidation, resulting in reduced neutron moderation and reflection. Consequently, with  
 288 fewer neutrons in the thermal region, fission occurrences diminish, leading to a lower criticality.  
 289 The extent of the reduction in neutron flux can explain why the 2:1 rod consolidation decreases  
 290 criticality more than the 1.5:1 rod consolidation.

291

## 292 **5. Thermal-Hydraulics Analysis**

293 Due to the dense storage, rod consolidated fuel assemblies release 1.5 to 2 times more decay  
 294 heat compared to normal fuel assemblies. Therefore, thermal-hydraulic analysis is required to  
 295 evaluate the effect on disposing of SNF in the Deep Geological Repository (DGR). In this study,  
 296 the decay heat from rod consolidated SNF is considered 1.5 or 2 times higher than reference  
 297 case assuming a linear increase of decay heat transitioning from a 1:1 to 1.5:1 to 2:1 rod  
 298 consolidation scenario.

299 First of all, the thermal criteria of repository were set at 100°C as the reference temperature, at  
300 the interface between the copper canister and the bentonite buffer. Additionally, since new  
301 thermal criteria of up to 130 °C, 150 °C and 200 °C are currently being considered to decrease  
302 the disposal area, the thermal-hydraulic behaviors based on these advanced thermal criteria are  
303 also estimated here [23,24].

304 The code used for thermal-hydraulic behavior analysis is the HADES code developed by the  
305 authors, which is a safety assessment code for high-level radioactive waste disposal facilities  
306 [10,25]. HADES was developed based on the open-source software framework Multiphysics  
307 Object-Oriented Simulation Environment (MOOSE), developed by Idaho National Laboratory  
308 (INL) [26]. The numerical analysis technique employed in HADES is the Finite Element  
309 Method (FEM), and it utilizes a Newton-Raphson solver for solution convergence.

310

### 311 **5.1. Numerical input parameters**

312 For the thermal-hydraulic (TH) behavior analysis of SNF with rod consolidation in DGR, the  
313 concept of KAERI Reference disposal System (KRS, Figure 11), located 500 m below  
314 underground was modelled. The distances between boreholes and tunnels are 7.5 m and 40 m,  
315 respectively. The copper canister has a diameter of 1.03 m and a height of 4.78 m, and the  
316 bentonite buffer has a diameter of 2.02 m and a height of 7.78 m, respectively. Additionally,  
317 since the borehole are arranged asymmetrically, a quarter geometry was utilized.

318 The bentonite buffer and host rock are KJ-II bentonite and crystalline rock, respectively, and  
319 the backfilled material has been assumed to be a 30:70 bentonite-sand mixture as presented in  
320 Table 4 [11, 21–24].

321 The initial temperature of Natural Barrier System (NBS), or host rock, has 30 °C/km thermal  
322 gradient with 10 °C of ground temperature, and initial degree of saturation is 0.999. The initial  
323 temperature and saturation of Engineered Barrier System (EBS), including bentonite buffer and  
324 backfilled material are considered 25 °C and 0.6, respectively. As thermal boundary conditions,  
325 the decay heats from SNF with the different initial U enrichments and burn-ups are applied to  
326 the canister surface with similar formation of equation (1), and the adiabatic condition is  
327 applied on the side surface due to asymmetric geometry. For hydraulic boundary conditions,  
328 an impermeable condition is adopted on the canister surface and side surface of geometry due  
329 to the same reason of thermal conditions. Additionally, the top and bottom surfaces of geometry

330 have constant hydrostatic pressures as shown in Figure 11 [6, 11].

331

332 **Figure 11. Schematic design of a PWR-type disposal unit (left) and unit is mm, and**  
333 **initial and boundary conditions (right).**

334

335 **Table 4. Thermo-Hydro material properties of bentonite, backfilled material,**  
336 **and host rock initial and boundary conditions.**

337

## 338 **5.2. Thermal-Hydraulics results**

339 The TH behavior analysis of rod consolidated SNF was conducted for two scenarios: 2:1 rod  
340 consolidation and 1.5:1 rod consolidation. Firstly, the results for the 2:1 rod consolidation are  
341 depicted in Figure 12. It is observed that the estimated DGR temperature increases with  
342 increasing burn-up, while higher U enrichment tends to lower the DGR temperature relatively.  
343 Among these variables, burn-up has a major effect on the DGR temperature, while U  
344 enrichment has a relatively minor effect.

345 From the perspective of the existing temperature criteria at 100 °C, when applying a 2:1 rod  
346 consolidation, the calculated maximum temperatures all exceed 100 °C, meaning that a 2:1 rod  
347 consolidation is not allowed under the current conceptual design, as shown in Figure 12. If the  
348 peak temperature is set at 150 °C, the 2:1 rod consolidation can be applied to SNFs with a burn-  
349 up of up to 35 GWD/MTU, regardless of initial U enrichment. Additionally, if the peak  
350 temperature is considered to be 200 °C, SNFs with 45 GWD/MTU can be consolidated.

351

352 **Figure 12. Temperature evolutions (left) and maximum temperature distributions**  
353 **(right) of 2:1 rod consolidation with varying uranium enrichment and burnup level. The**  
354 **B-C interface means bentonite-canister interface.**

355

356 However, a 1.5:1 rod consolidation shows feasibility within the current thermal criteria. The  
357 calculated peak temperature for every SNF with a burn-up of 30 GWD/MTU remains under  
358 100 °C, as shown in Figure 13. In addition, if the peak temperature is set at 150 °C, the 1.5:1

359 rod consolidation can be utilized for SNFs with a burn-up of up to 45 GWD/MTU, regardless  
360 of initial U enrichment. If the peak temperature is considered to be 200 °C, all SNFs considered  
361 here can be consolidated without any limitations.

362

363 **Figure 13. Temperature evolutions (left) and maximum temperature distributions**  
364 **(right) of 1.5:1 rod consolidation with varying uranium enrichment and burnup level.**

365 **The B-C interface means bentonite-canister interface.**

366

367 Table 5 shows the feasible rod consolidation options for three different thermal criteria.  
368 According to the Table 5, a 1.5:1 rod consolidation can be utilized for SNFs with a burn-up of  
369 up to 30 GWD/MTU under the original criterion of 100 °C. However, with the advanced  
370 criterion of 150 °C, up to 35 GWD/MTU with 2:1 rod consolidation and 45 GWD/MTU with  
371 1.5:1 rod consolidation can be applied. Additionally, under the enhanced advanced criterion of  
372 200 °C, SNFs with a burn-up of up to 45 GWD/MTU and 60 GWD/MTU can be consolidated  
373 using 2:1 and 1.5:1 rod consolidation, respectively.

374

375 **Table 5. Feasible types of SNF for each temperature criterion**

376

## 377 **6. Discussions**

### 378 **6.1. Regulatory compliance**

379 For regulatory analysis of rod consolidation, judgments should be made based on the nuclear-  
380 related legislation in each country. The applicability of rod consolidation was examined,  
381 focusing on the case of the Republic of Korea (ROK). In ROK, nuclear material must be  
382 defined according to Article 2, 3, and 35 of the Nuclear Safety Act [28]. If nuclear material is  
383 interpreted narrowly to mean nuclear fuel pellets, the rod consolidation process facility falls  
384 under nuclear facility classification. If it is interpreted broadly to encompass fuel rod structure  
385 including fuel cladding, it is classified as a SNF treatment facility.

386 If nuclear material is interpreted narrowly to mean nuclear fuel pellets, in other words, if  
387 nuclear material is not separated from nuclear fuel rod structure, the facility for rod

388 consolidation can be pursued as part of nuclear facility operations. In such cases, no licensing  
389 process is required, and implementation can proceed through operational modification permits.  
390 In addition, it is anticipated that this process would require Radiological Environmental  
391 Reports (RER) and Safety Analysis Reports (SAR). However, if nuclear material is interpreted  
392 broadly to include fuel cladding and fuel assemblies, the facility would necessitate licensing as  
393 a SNF treatment facility. In this case, only the RER would be required. Additionally, during  
394 this process, it is also necessary to assess whether construction is feasible within the existing  
395 nuclear power plant site. Such evaluations would likely require various additional analyses,  
396 including radiation dose assessments.

397 The U.S.A attempted to license rod consolidation technology for the Maine Yankee Nuclear  
398 Power Plant (NPP) in the 1980s, not for the general use. The U.S NRC opposed the use of rod  
399 consolidation due to following reasons: (i) safety of the facility, (ii) safety of the fuel, (iii)  
400 consolidation procedure [31]. The facility safety addresses thermal and mechanical issues, such  
401 as coolant evaporation caused by decay heat from the consolidated fuel, and the structural  
402 capability of the storage pool to handle the consolidated fuel weight. The second concern,  
403 safety of the fuel, deals with nuclear criticality. The final concern, regarding the consolidation  
404 procedure, focuses on ensuring a homogeneous arrangement of nuclear fuel in the consolidated  
405 assemblies.

406

## 407 **6.2. Waste management and economic viability**

408 From a waste management perspective, rod consolidation technology faces several issues  
409 related to environmental and economic factors. In terms of environmental aspects, the primary  
410 byproducts, known as NFBC, and secondary wastes, gaseous fission products, are generated in  
411 several processes: (i) fuel rod removal, (ii) off-normal rod handling, and (iii) NFBC handling.  
412 In terms of solid wastes, although the volume of waste occupies significant volumes, they can  
413 be classified as Intermediate-Level Waste (ILW) or Low-Level Waste (LLW). In addition, the  
414 gaseous products captured by filtration system because both processes are conducted in wet  
415 (storage pool) or dry (hot cell) facilities. The gaseous products are solidified in filter. Therefore,  
416 these byproducts are relatively easy to manage and pose fewer environmental concerns due to  
417 their solid forms, which results in lower heat release and dose rate compared to the original  
418 fuel, fortunately.

419 From an economic perspective, the advantages of rod consolidation include the reduced  
420 quantities of copper canisters and bentonite needed for disposal, as well as the significant  
421 reduction in disposal area, which is the primary advantage. According to the thermal analysis,  
422 rod consolidation technique, such as 2:1 and 1.5:1 consolidation, can be applied to all SNF,  
423 having 45 GWD/MTU, discharged to date, with a maximum temperature limit of 200 °C. When  
424 applied to the distribution of SNF quantities in ROK up to 2018 based on U enrichment and  
425 burn-up with 40 years of cooling time, the use of reference, 2:1, and 1.5:1 rod consolidation  
426 results in reductions in the number of disposal canisters used to around 5,000, 3,333, and 2,500,  
427 respectively, as illustrated in Figure 14.

428 It is predicted that approximately \$200,000 or \$190,000 are required to fabricate or cast a  
429 canister, including labor and copper costs, in ROK based on the manufacturing cost estimation  
430 of copper canisters in 2007, respectively [29]. Considering the current amount of SNFs with a  
431 burn-up of 45 GWD/MTU, the total costs of canisters using the original disposal method, 1.5:1  
432 rod consolidation, and 2:1 rod consolidation technique are approximately \$948.6, \$668.3, and  
433 \$501.3 million, respectively. Additionally, although the cost is estimated from the 1990s,  
434 according to cost estimations for 2:1 rod consolidation from the Civilian Radioactive Waste  
435 Management System (CRWMS), rod consolidation prior to transportation and at the repository  
436 could save approximately \$500 and \$400 million in net costs, including transportation and  
437 packaging [7].

438

439 **Figure 14. Evolutions of amount of canister released from NPP.**

440

### 441 **6.3. Technical difficulties**

442 Although the rod consolidation technology has various advantages in waste management, it  
443 faces technical issues. The primary issue is the thermal criteria. According to the thermal-  
444 hydraulic calculation in section 5, only SNFs with a burn-up of 30 GWD/MTU, assuming 40  
445 years of cooling, can be consolidated without exceeding the reference temperature in the  
446 conceptual design. In addition, rod consolidation cannot be utilized for the fuel with a burn-up  
447 over 60 GWD/MTU. Therefore, in order to address this problem, it is suggested to mix SNFs  
448 with low burn-up together with high burn-up fuels.

449 There are also a technical concern during the fuel rod removal and insertion processes [4]. The  
450 rod consolidation technique cannot be applied to damaged fuel, which is mainly abundant in  
451 high burn-up fuel. Since high burn-up fuel usually suffers from various failure modes such as  
452 corrosion and dimensional change, additional fuel damage is anticipated during the removal  
453 process [33].

454

## 455 **7. Conclusion**

456 In this study, the feasibility of rod consolidation was assessed in a geological disposal, in terms  
457 of regulatory, economic, and technical aspects. According to these studies, rod consolidation  
458 offers significant advantages in SNF disposal aspects, as shown in Table 6. From a technical  
459 viewpoint, rod consolidation reduces nuclear criticality even under water infiltration accident  
460 scenarios. However, its thermal-hydraulic behavior exhibits limitations, as rod consolidation  
461 techniques can only be used when employing new thermal criteria (150 °C and 200 °C). To  
462 address this limitation, several methods, such as mixing fuel having different burn-ups and  
463 cooling times, can be suggested for disposal optimization.

464 Regulatory compliance in the Republic of Korea depends on the interpretation of nuclear  
465 material. If interpreted narrowly as fuel pellets, rod consolidation could proceed with fewer  
466 regulatory hurdles. A broader interpretation, including fuel cladding, would require more  
467 extensive licensing as an SNF treatment facility. From environmental perspective, the  
468 technique can reduce the amount of HLW by up to one-tenth compared to the original HLW,  
469 although the remaining wastes are considered as ILW or LLW. Despite the increase in the  
470 amount of waste, ILW and LLW are easier to manage due to their lower levels of radiation and  
471 heat. In addition, from an economic perspective, the costs of manufacturing copper canisters  
472 and facility operation are compatible. Nevertheless, rod consolidation can save a maximum of  
473 \$1 billion, in canister manufacturing, facility operation, transportation, and packaging costs.

474 Rod consolidation technology faces notable technical challenges, primarily related to thermal  
475 management. The current techniques can only be applied with new reference temperatures  
476 (150 °C and 200 °C), limiting their use for high burn-up fuels. Additionally, issues such as  
477 CRUD (Chalk River Unidentified Deposit) deposition and fuel degradation complicate the  
478 removal and processing of high burn-up fuels, necessitating careful handling to avoid further  
479 damage.

480

481 **Table 6. Feasibility analysis of rod consolidation depending on technical, regulation, and**  
482 **other perspectives.**

483

484

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491

492

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- 588

**Table 1. Case study information of rod consolidation.**

Fuel information	Fuel library: Westinghouse 17×17 Fuel weight: 1.844 MTU/canister Operation condition: 3cycle with 500 days per cycle and 50 days for refueling
Uranium enrichment	3, 4, 5, and 6 wt%
Considering burnup	30, 40, 50, and 60 GWD/MTU
Rod consolidation ratio	2:1 and 1.5:1
Cooling time	40 years

**Table 2. Main parameters of the fuel assembly [13,15,16].**

Fuel rod diameter [mm]	8.898
Fuel pellet diameter [mm]	7.840
Fuel material	$UO_2$
Fuel density [ $g/cm^3$ ]	10.5216
Gap thickness [mm]	0.081
Gap material	He, light water <sup>a</sup>
Gap density [ $g/cm^3$ ]	0.000167, 0.9880 <sup>a</sup>
Cladding thickness [mm]	0.448
Cladding material	Zircaloy-4
Cladding density [ $g/cm^3$ ]	6.56
Fuel rod length [mm]	3657.6
Assembly pitch [mm]	380

<sup>a</sup> Abnormal case of water intrusion due to copper failure

**Table 3. Main parameters of the disposal canister [11–14].**

Canister diameter[mm]	1020
Channel inner size[mm]	239.4
Distance between channels[mm]	380
Insert material	Cast iron
Insert density[ $g/cm^3$ ]	7.15
Insert diameter[mm]	920
Pipe material	Steel
Pipe density[ $g/cm^3$ ]	7.82
Pipe thickness[mm]	10
Overpack material	Copper
Overpack density[ $g/cm^3$ ]	8.96
Overpack thickness[mm]	50
Bottom and lid material	Steel
Bottom and lid density[ $g/cm^3$ ]	7.82
Bottom and lid thickness[mm]	50
Bottom and lid diameter[mm]	920
Length of channel[mm]	4370
Length of canister[mm]	4830
Hostrock material	granite

**Table 4. Thermo-Hydro material properties of bentonite, backfilled material, and host rock initial and boundary conditions.**

Parameter	Symbol	Bentonite	Backfilled material	Host rock
Dry Density [kg/m <sup>3</sup> ]	$\rho$	1600 <sup>a</sup>	1600 <sup>*</sup>	2650 <sup>*</sup>
Porosity	$\phi$	0.41 <sup>b</sup>	0.4 <sup>*</sup>	0.0116 <sup>d</sup>
Thermal conductivity (Dry) [W/(mK)]	$\lambda_{dry}$	0.6611 <sup>a</sup>	1.00 <sup>*</sup>	3.05 <sup>d</sup>
Thermal conductivity (Wet) [W/(mK)]	$\lambda_{wet}$	1.2243 <sup>a</sup>	2.00 <sup>*</sup>	3.31 <sup>d</sup>
Specific heat (Dry) [J/(kg K)]	$C_{p,dry}$	894 <sup>c</sup>	980 <sup>*</sup>	820 <sup>d</sup>
Specific heat (Wet) [J/(kg K)]	$C_{p,wet}$	1337 <sup>c</sup>	980 <sup>*</sup>	820 <sup>d</sup>
Intrinsic permeability of liquid [m <sup>2</sup> ]	$K$	2.56E-20 <sup>b</sup>	1.6E-19 <sup>*</sup>	1.0E-18 <sup>e</sup>
Relative permeability of liquid	$K_{Rel}$	$S_l^{3.0*}$	$S_l^{1.9*}$	$S_l^3*$
Van Genuchten (alpha) [Pa <sup>-1</sup> ]	$\alpha$	2.6E-7 <sup>d</sup>	3.3E-7 <sup>*</sup>	5E-7 <sup>*</sup>
Van Genuchten (lambda)	$\lambda$	0.2941 <sup>d</sup>	0.5 <sup>*</sup>	0.6 <sup>*</sup>
Residual saturation	$S_r$	0.01 <sup>*</sup>	0.01 <sup>*</sup>	0.01 <sup>*</sup>

<sup>a</sup> [22] Yoon et al: <https://doi.org/10.3390/en11092269>

<sup>b</sup> [23] Yoon et al: <https://doi.org/10.1016/j.heliyon.2023.e18447>

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<sup>e</sup> [25] Ko et al: <https://doi.org/10.7733/jnfcwt.2019.17.S.15>

\*: Assumed value

**Table 5. Feasible types of SNF for each temperature criterion**

Temperature criteria	Feasible types of SNF
100 °C	30 GWD/MTU of 1.5:1 rod consolidation
150 °C	35 GWD/MTU of 2:1 rod consolidation 45 GWD/MTU of 1.5:1 rod consolidation
200 °C	45 GWD/MTU of 2:1 rod consolidation 60 GWD/MTU of 1.5:1 rod consolidation

**Table 6. Feasibility analysis of rod consolidation depending on technical, regulation, and other perspectives.**

Perspectives	References	Analysis
Technical aspects	Nuclear criticality	Rod consolidation meets the criticality criteria sufficiently under normal conditions and reduces criticality in accident scenarios.
	Thermal-Hydraulics	When employing 100°C thermal criteria ✓ 30 GWD/MTU of 1.5:1 rod consolidation When employing 150°C thermal criteria, ✓ 35 GWD/MTU of 2:1 rod consolidation ✓ 45 GWD/MTU of 1.5:1 rod consolidation When employing 200°C thermal criteria ✓ 45 GWD/MTU of 2:1 rod consolidation ✓ 60 GWD/MTU of 1.5:1 rod consolidation
Regulation aspects	Act	Narrow interpretation ✓ RER & SAR Wide interpretation ✓ RER & Feasibility assessment of facilities in NPP site
Environmental and Economic viability	Environmental viability	In terms of amount of HLW ✓ Significant reduction up to 1/10 In terms of ILW and LLW ✓ Although total amount of waste is increase, but their management is much easier.
	Economic viability	Canister cost saving ✓ 50% cost saving (approximately, 464 MEUR) Consolidation cost saving ✓ About 400 million dollars net cost saving

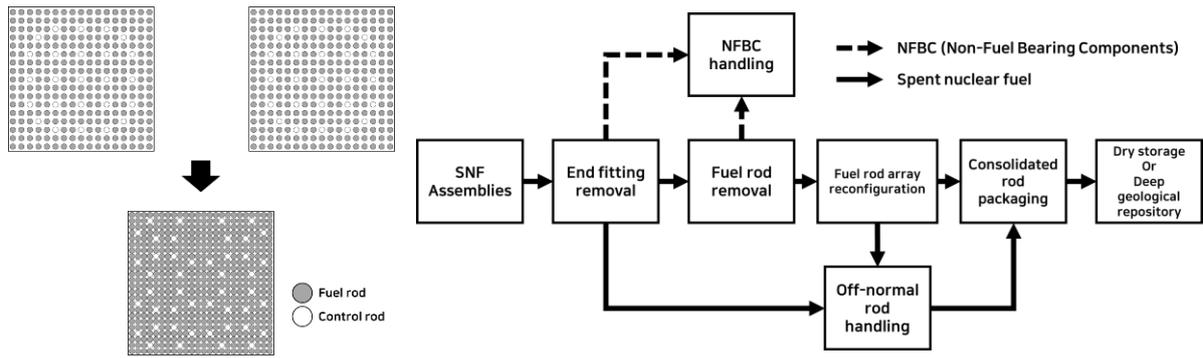


Figure 1. Schematic design of rod consolidation (left), and flow diagram of rod consolidation technology (right).

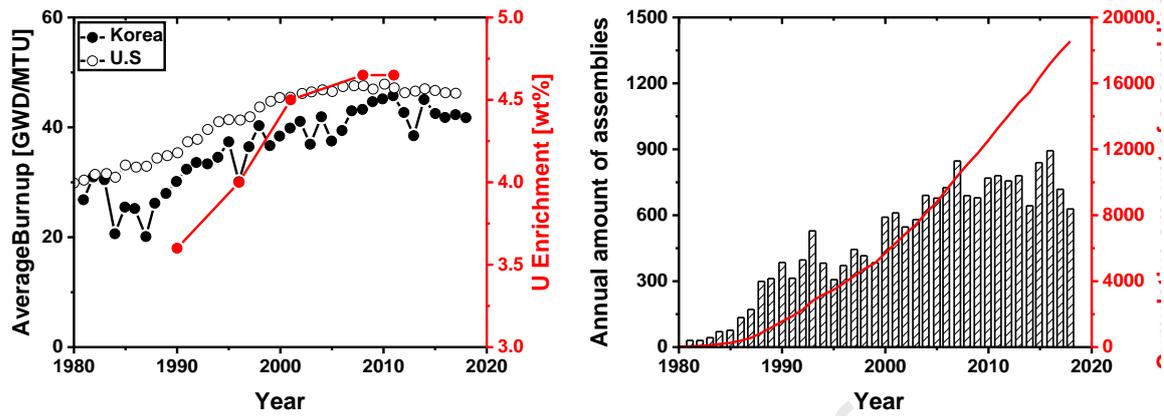


Figure 2. The global trend in U enrichment and burn-up of SNF (left), and annual and cumulative amount of SNF assemblies of Korea (right) [9,10].

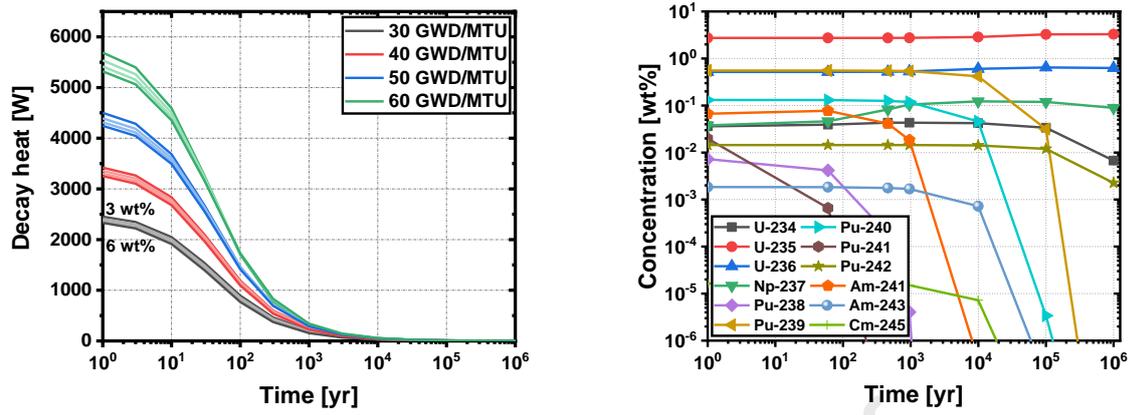
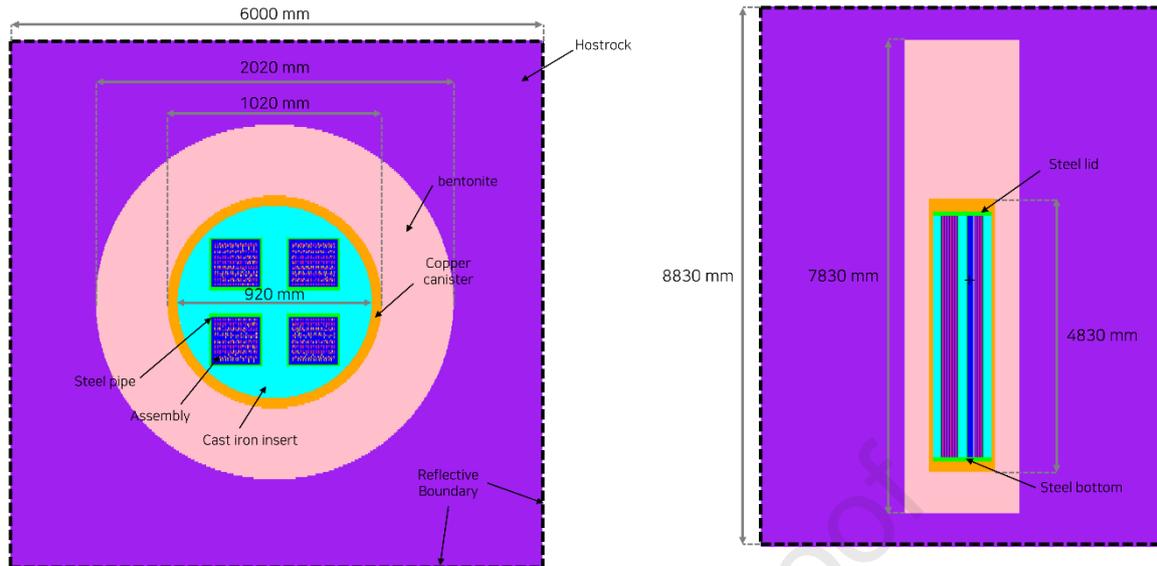
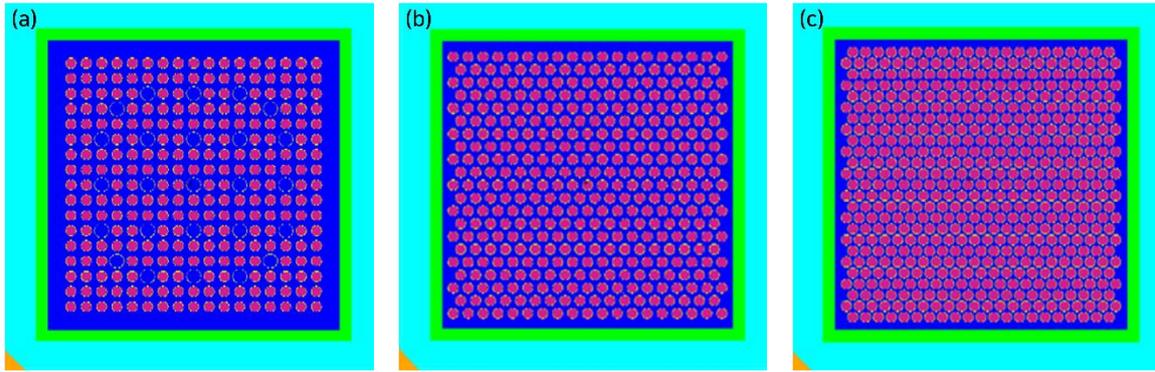


Figure 3. Decay heat (left) and fission isotopes (right) evolutions with time.



**Figure 4. Cross sections of deep geological repository system.**



**Figure 5. (a) 1:1 rod consolidation applied assembly (reference case), (b) 1.5:1 rod consolidation applied assembly, and (c) 2:1 rod consolidation applied assembly. The reference assembly contains 264 fuel rods, while the 1.5:1 and 2:1 rod consolidated assemblies contain 409 and 537 fuel rods, respectively.**

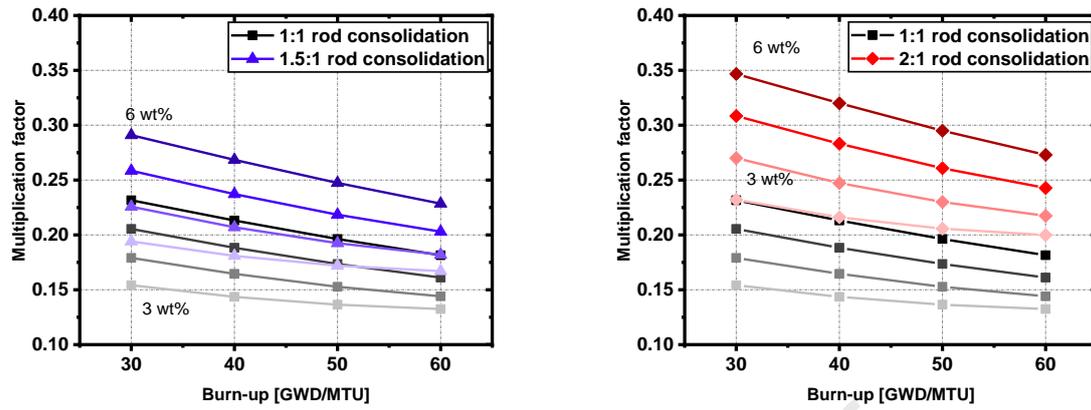
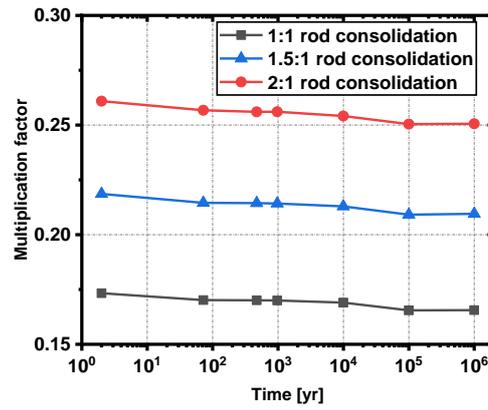
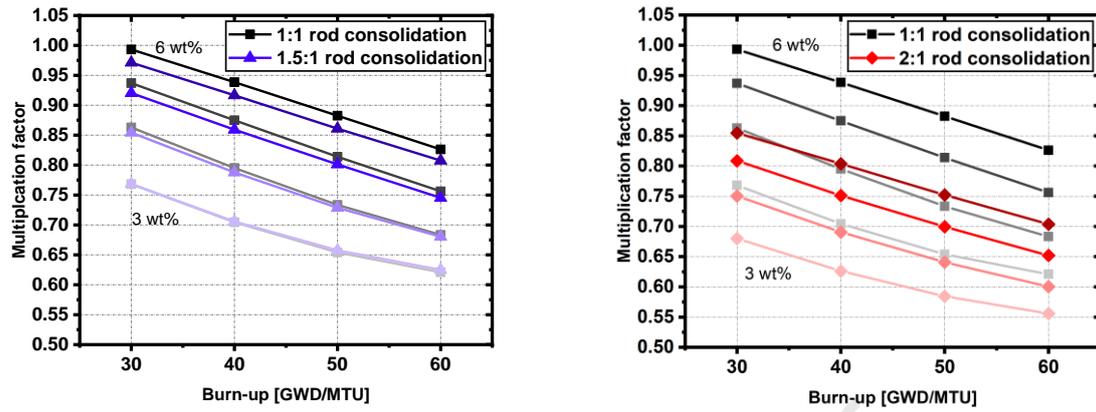


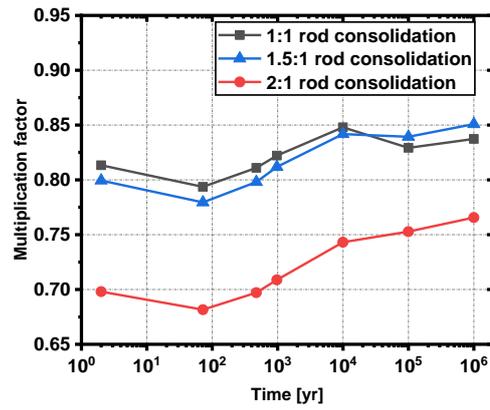
Figure 6. Nuclear criticality over burn-up and U concentration of 1:1 rod consolidation (reference case) and 1.5:1 rod consolidation (left), and 1:1 rod consolidation and 2:1 rod consolidation (right) when assemblies are filled with He.



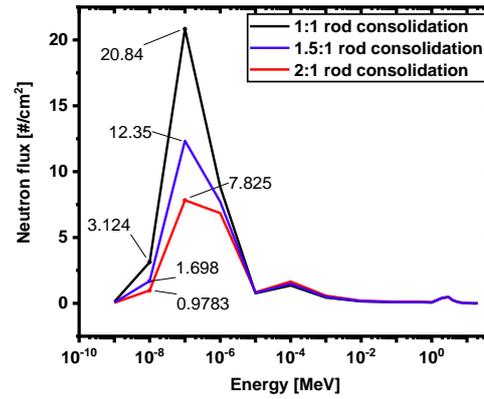
**Figure 7. Nuclear criticality evolution of 5%, 50 GWD/MTU over time if assemblies are filled with He.**



**Figure 8. Nuclear criticality over burn-up and U concentration of 1:1 rod consolidation (reference case) and 1.5:1 rod consolidation (left), and 1:1 rod consolidation and 2:1 rod consolidation (right) when assemblies are filled with water.**



**Figure 9. Nuclear criticality evolution of 5%, 50 GWD/MTU over time if assemblies are filled with water.**



**Figure 10. Neutron flux spectrums over neutron energy of 1:1 rod consolidation (reference case), 1.5:1 and 2:1 rod consolidated cases filled with water, 5 wt% and 50 GWD/MTU.**

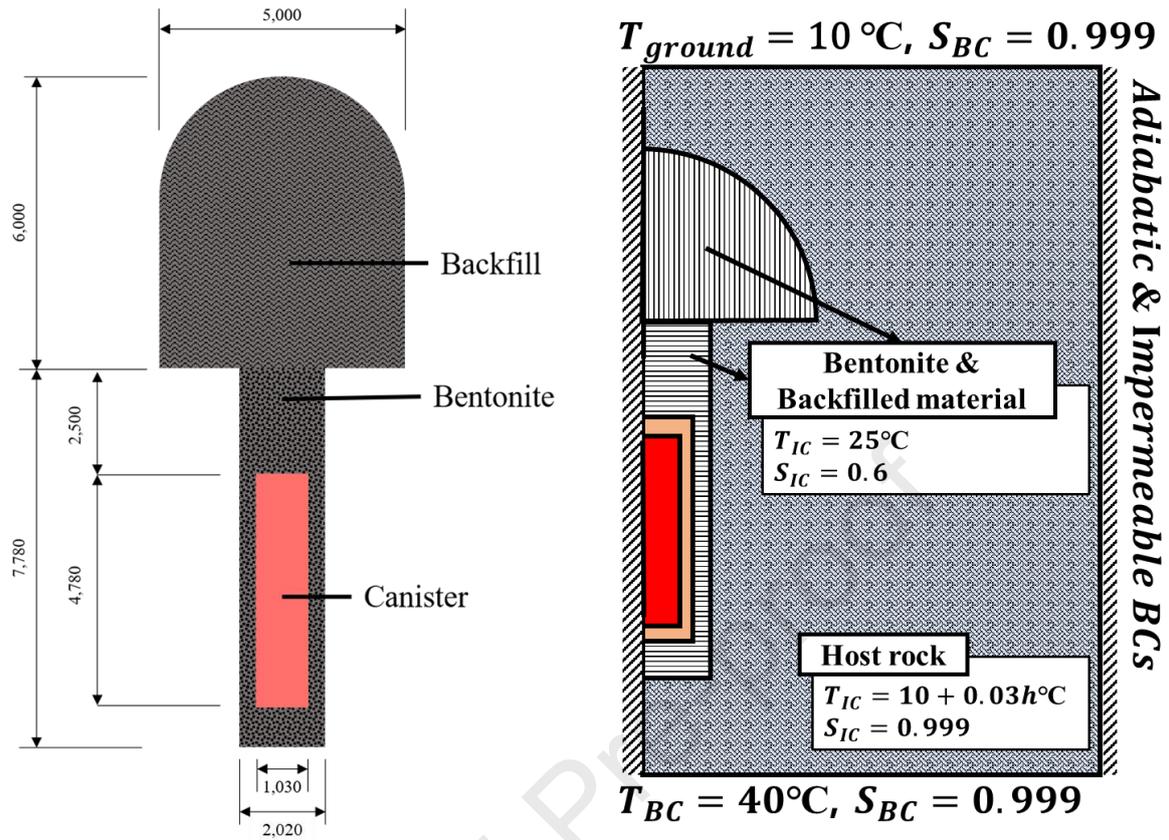


Figure 11. Schematic design of a PWR-type disposal unit (left) and unit is mm, and initial and boundary conditions (right).

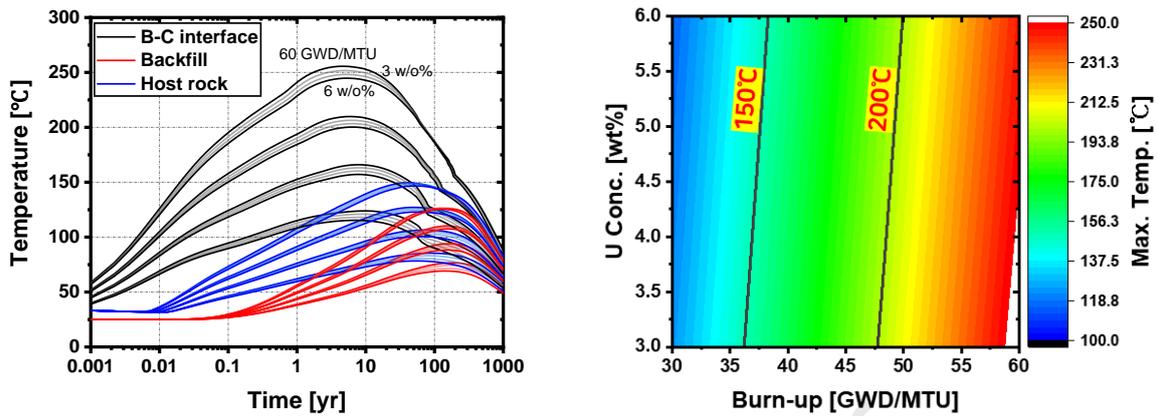
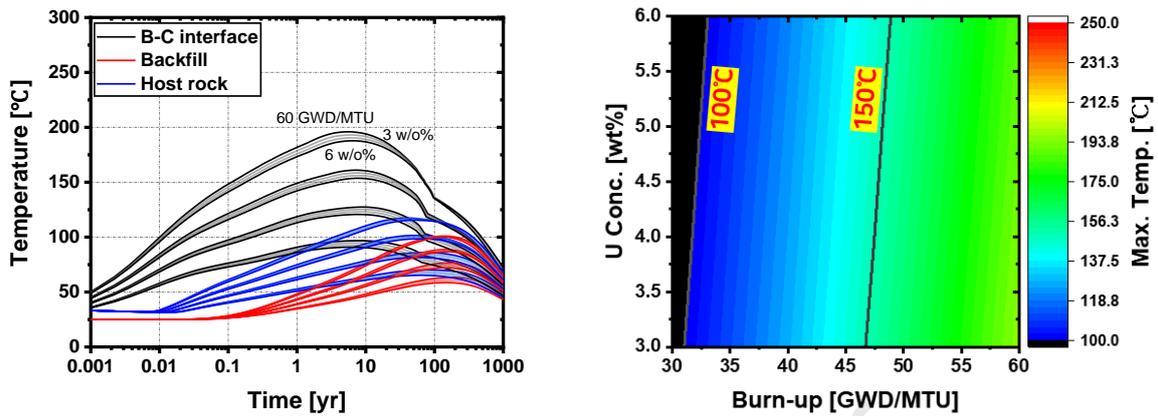


Figure 12. Temperature evolutions (left) and maximum temperature distributions (right) of 2:1 rod consolidation with varying uranium enrichment and burnup level.

The B-C interface means bentonite-canister interface.



**Figure 13. Temperature evolutions (left) and maximum temperature distributions (right) of 1.5:1 rod consolidation with varying uranium enrichment and burnup level.**

**The B-C interface means bentonite-canister interface.**

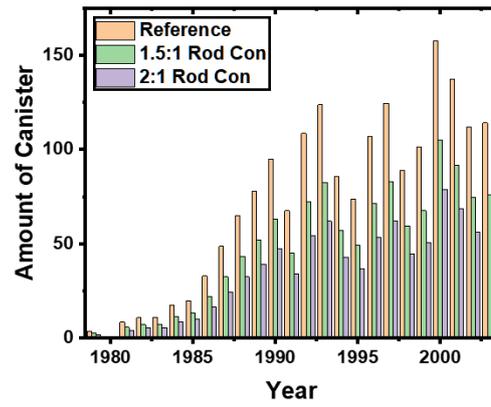


Figure 14. Evolutions of amount of canister released from NPP.

**Declaration of interests**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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