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Make No Little Plans – The PCCS Solution

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1. Introduction

"Make no little plans; they have no magic to stir men's blood and probably themselves will not be realized. Make big plans; aim high in hope and work, remembering that a noble, logical diagram recorded will never die, but long after we are gone be a living thing, asserting itself with ever-growing insistency. Remember that our sons and our grandsons are going to do things that would stagger us. Let your watchword be order and your beacon beauty." These are the words of famed Chicago city planner and architect Daniel Burnham ringing out from more than 100 years ago, a siren song which so aptly applies to the current politics surrounding the Korea nuclear power industry.

The miracle on the Han River was not built with little plans, and yet today the Korea nuclear power industry is facing an existential challenge with muted response. In contrast to the announced intent of the current government [1], the approach outlined here is a grand bargain which will: (i) significantly improve nuclear safety, (ii) maintain the low cost electricity to which the Korean industrial export economy is vitally entwined, (iii) restore the Korea nuclear program plan to sustainable levels, and (iv) minimize greenhouse gas emissions.

2. Method and Approach

Proposed here is a massive, passive Primary Containment Capture System (PCCS) designed to protect containment integrity and to mitigate severe accidents. Assuming implementation, it will be illustrated that the probability of radiological release from such scenarios can be substantially reduced improving public safety for <u>any</u> combination of operating nuclear units.

The cost of such a system is substantial but the benefits are similarly considerable in terms of: (i) public acceptance, (ii) public safety, and (iii) improved energy sector economics.

Outlined below is: (i) the basic concept of the PCCS, (ii) a set of scenarios for future nuclear unit additions and retirements, and (iii) an illustration of the relative outcomes for Core Damage Frequency (CDF), Large Early Release Frequency (LERF), and greenhouse gas emissions for each of the scenarios.

2.1 PCCS

The PCCS concept as previously introduced [2] is a massive, passive secondary containment which serves as pressure relief for the primary containment in the event that containment depressurization systems fail under a severe accident sequence (e.g., Fukushima Daichi Units 1, 2, and 3). The PCCS is essentially an external ASME-designed pressure vessel linked to the containment atmosphere for all units located on a given site. The PCCS concept is uniquely suited to Korea since the nuclear program is currently centered on just four sites (Kori / Shin Kori, Wolsung / Shin Wolsung, Hanbit, and Hanul / Shin Hanul). Correspondingly, just four (4) PCCS installations are proposed to serve up to thirty-two (32) nuclear units.

The configuration of the PCCS is illustrated in the simplified diagram per Fig. 1 below.

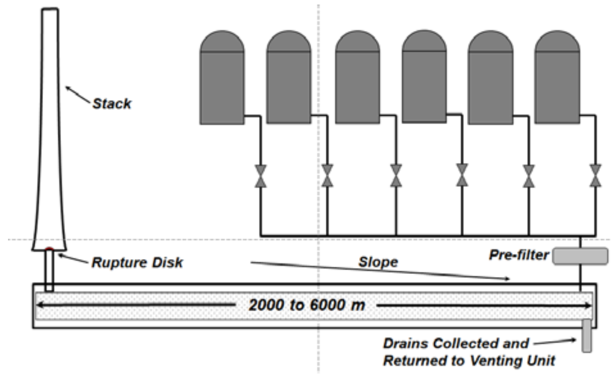

Fig. 1. PCCS configuration (simplified)

In the event of a severe accident for any of the connected containments experiencing containment pressurization, the containment, on approaching design pressure, would then be vented to a Code compliant underground pressure vessel with a volume of two to four times the containment volume. Heat and radionuclide absorbing material (i.e., gravel) would then collect vented non-condensables, condense the released steam, and affix radionuclides such as iodine, cesium, strontium, and tellurium before returning condensate to the affected containment.

The flow paths for a containment under severe accident venting conditions are depicted schematically in Fig. 2 below.

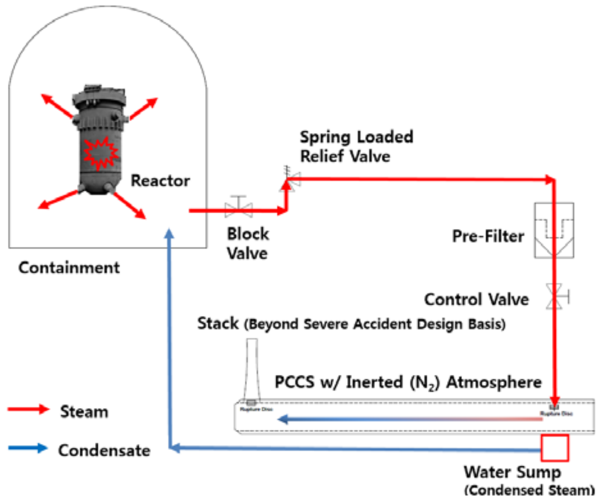

Fig. 2. Containment vent path to PCCS (with contaminated water return) (simplified)

The PCCS 'pipe tunnel' is designed to enclose a very large volume but also to contain gravel as a porous medium representing a massive surface area for radionuclide absorption and a massive heat capacitance for controlling pressure by condensing steam. The PCCS is sized to confine all release and permit a coping time of fourteen (14) days with no venting to atmosphere. The cross-section and sizing of the PCCS underground tunnel and ASME pressure vessel is illustrated below.

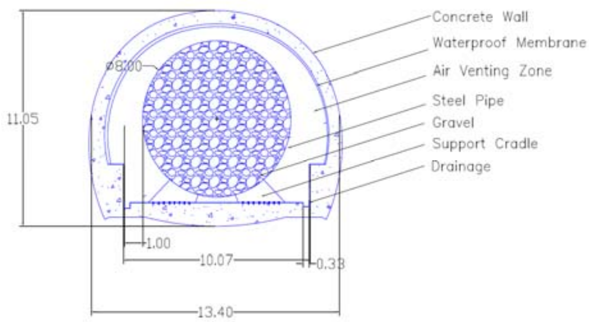

Fig. 3. PCCS cross-Section (dimensions in meters)

From current understanding of post-Fukushima actions, KHNP has committed to add a 'European style' Containment Filter Vent System (CFVS) to each of the operating units in Korea. Relative to the PCCS design, the units installed on European reactor plants are considered to be very small and to provide substantially less margin than proposed for the PCCS. It is suggested here that the twenty-seven (27) CFVS as proposed be replaced by just four (4) PCCS installations, one per site.

2.2 Nuclear Fleet Scenarios

To evaluate the expected benefits of the proposed PCCS, four nuclear fleet scenarios are considered as follows:

Table I: KHNP nuclear fleet scenarios

Scenario	Operating Units	Future Units	Life[1]	PCCS
1 (Base)	24	3	40 / 60	NO
1a	24	3	40 / 60	YES
2	24	3	60	YES
3	24	7	60	YES

1) '40/60' indicates current license without life extension, '60' indicates all units receive life extension to 60 years.

Scenario 1 is intended to parallel the proposed approach as publically stated [1]. Scenarios 1a, 2, and 3 assume installation of four PCCS (completed between 2024 and 2027). Scenario 2 assumes the same fleet as Scenario 1 but includes life extension to 60 years for all reactors. Scenario 3 reflects Scenario 2 but includes the addition of four reactors per the current five year energy plan (2014) (i.e., Shin Kori Units 5, 6 and Shin Hanul Units 3, 4).

Life extension to sixty (60) years for the reactor fleet in Korea is consistent with trends in the USA, Finland, Japan, India, and elsewhere, where, for example, detailed safety reviews for more than ninety (90) reactor plants have found no significant impediments to a 60 year license.

2.3 Core Damage Frequency

A key metric in the evaluation and understanding of nuclear safety is the Core Damage Frequency or 'CDF'. While difficult to quantify with certitude, CDF has found wide acceptance in Probabilistic Safety Analysis (PSA) as a useful tool in evaluating and comparing alternatives for addressing nuclear plant safety. Specifically, quantification of CDF has found a place in nuclear regulation and rulemaking and in assessing the efficacy of proposed safety enhancements.

Here, CDF is computed using a first order approximation for addressing the relative merits of alternatives. The assessment is not intended to represent the comparison with any particular fidelity or within any particular uncertainty. Rather, as an illustration, it identifies the impact of fleet scenarios on accident probability.

For each scenario, and for each year between 2018 and 2090, each operating reactor is assigned a CDF for that calendar year. The assigned CDF is based on the WASH 1400 study [3] with a base value of $5x10^{-5}$/yr in 1975. The assigned value is assumed to decrease by calendar year, with a reduction of 2%/yr (i.e., to the base WASH 1400 rate starting in 1975). This assumption is based on industry wide safety improvements in the areas of licensing, design, fabrication, construction, operation, surveillance, maintenance, and collaboration. For simplicity, the single value of CDF computed for each calendar year is then assigned to each reactor plant. Obviously this simplified approach can be refined by subject matter experts but with considerably more effort.

2.4 Large Early Release Frequency

The other key metric historically used in the evaluation and understanding of nuclear safety is the Large Early Release Frequency, or 'LERF'. LERF provides a measure of safety relative to the general public health and safety and to property damage.

Here, the LERF is assigned a nominal value of 1/10th the CDF for each calendar year (Scenario 1). This is considered to be a reasonable assignment for the purposes of this study.

For scenarios with an operable PCCS, the LERF will see a considerable reduction. Based on past studies [2], it is considered that the PCCS can be designed, constructed, operated, and surveilled in a considerably robust manner. In addition, although not detailed here, ancillary designs incorporated into the PCCS will address many other severe accident safety issues beyond containment pressure integrity, including hydrogen control, and radionuclide transport, deposition, and collection / retention. Finally, the PCCS can be leveraged to make beneficial use of multi-unit sites, so that safety systems can be shared. With the PCCS, multi-unit sites no longer represent a risk and vulnerability, but can be leveraged to be a safety benefit.

With the design as outlined above, the LERF for scenarios in years with an operable PCCS (Scenarios 1a, 2, and 3) is assigned a value of 1/100th (or 0.01 times) the LERF for conditions without the PCCS.

2.5 Electricity Demand and Green Energy in Korea

Estimates of the KHNP nuclear fleet contribution to the national electricity supply are prepared for each scenario. Estimates of national electricity supply are based on per capita electricity usage using population projections from the Korea government [4] with increasing per capita demand of ~0.8% per year through 2030, followed by reductions of per capita demand of ~0.8% per year (to reflect the trends in leading world economies) from 2030 until per capital demand stabilizes at 1 kWe in 2052.

Carbon dioxide emission reductions are based on data from the World Nuclear Association [5] assigning 29 tonnes/GWh to nuclear production and 499 tonnes/GWh to natural gas production. The increased nuclear production for Scenarios 2 and 3 is assumed to replace combined cycle gas turbine unit production.

3. Results

3.1 CDF

CDF is computed for each calendar year based on the operating units for that year and the assumed CDF as described in Section 2.3. The combined annual CDF is then computed and a cumulative value starting in 2018 is plotted per Fig. 4 for the four scenarios.

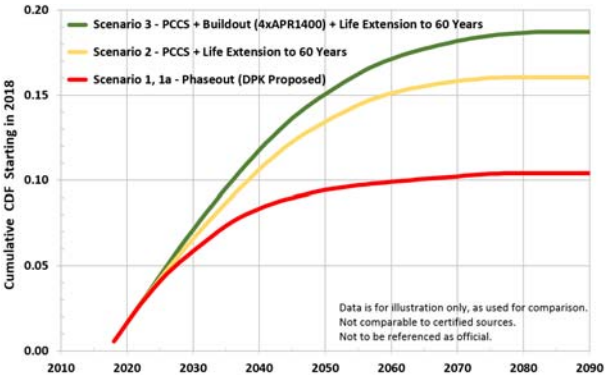

Fig. 4. Cumulative CDF

As indicated above, CDF is a function of the number of operating reactor years and the assumed rate for any given calendar year. More operating years will result in a higher cumulative probability for severe accidents. CDF in not impacted by PCCS implementation.

3.2 LERF

LERF is computed for each calendar year based on the assigned CDF. As discussed in Section 2.4, a multiplier of 0.1 is used for each operating reactor without an operable PCCS, and a factor of 0.001 is applied for each reactor year with an operable PCCS. LERF is then computed and a cumulative value starting in 2018 is plotted per Fig. 5 for the four scenarios.

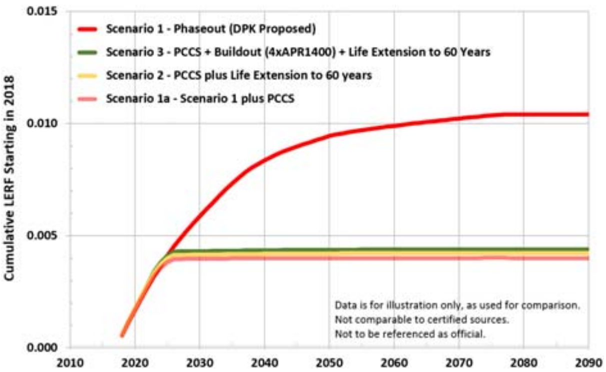

Fig. 5. Cumulative LERF

As illustrated, the PCCS has the potential to greatly improve the protection of public health and safety. For the base scenario, the PCCS would improve long term safety as measured by LERF by more than a factor of two. It is argued here that expenditures for the PCCS can be used to justify continued operation of the nuclear fleet <u>while at the same time significantly improving the protection of the public</u> relative to the anti-nuclear proposals of the current government.

3.3 Fleet Capacity

Fleet generating capacity by calendar year can then be computed for the four scenarios. Similar to computation for CDF, the operating fleet configuration is the same for Scenarios 1 and 1a (the difference being the addition of the PCCS for Scenario 1a). Fleet capacity is illustrated in Fig. 6.

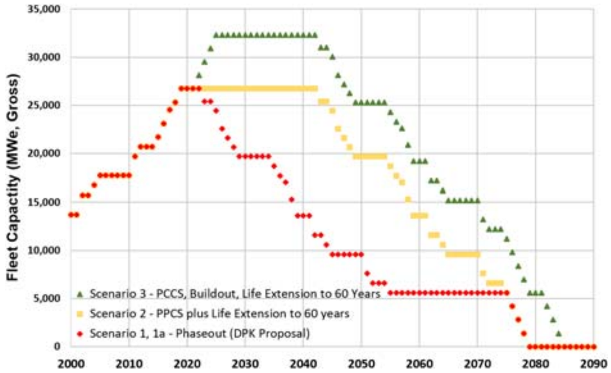

Fig. 6. KHNP nuclear fleet capacity

The proposed PCCS fleet scenario is shown to considerably maximize the benefits of the considerable investment the Korea people have in nuclear power while concurrently improving safety for the general public. The impact on CO_2 emissions is discussed below.

3.4 Electricity Supply and CO_2 Reductions

With increased capacity, the nuclear contribution to national electricity supply will likewise increase. Assuming a combined effect of capacity factor, house load, and transmission losses of 15%, the nuclear output was modeled as 85% of nameplate. Using modeling of electric consumption as outlined in Section 2.5, the contribution of nuclear production to the national consumption is estimated in Fig. 7 below.

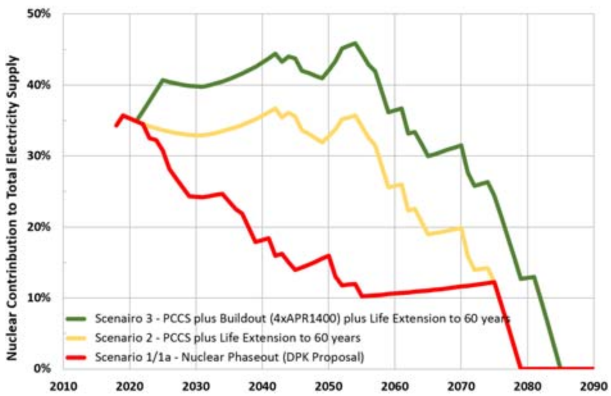

Fig. 7. Nuclear supply versus total consumption

With increased nuclear production comes reduced use of fossil fuel. The cumulative reduction in CO_2 emissions associated with Scenarios 2 and 3 relative to Scenario 1 is plotted in Fig. 8 below (for method, see Section 2.5).

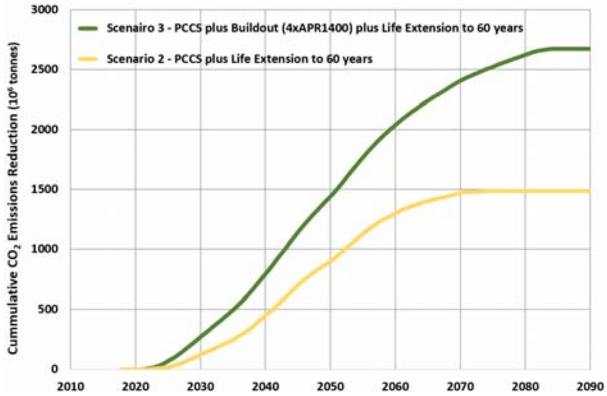

Fig. 8. Reductions to CO_2 emissions with PCCS

4. Conclusions – The 'Grand Bargain'

Proposed here is a 'grand bargain' between the ruling political coalition and the nuclear industry. In exchange for significant capital investment in a unique and robust Korean originated safety system, the PCCS (estimated at ~$10B USD), the government will agree to extend the life of the operating fleet consistent with rigorous licensing constraints as required by the US NRC. Such an agreement will accrue many benefits, including but not limited to:

1) heightened public confidence in the integrity, self-reliance, and responsiveness of the nuclear industry to safety concerns,
2) improved economics for the Korean electricity sector,
3) reduced outflow of hard won foreign exchange to pay for consumables (e.g., natural gas), and
4) substantial reductions in greenhouse gas emissions with Scenario 3 providing more than 100% of the 'high end' Paris accord commitments by 2030, and 1000% of this commitment to the end of the century.

Yes, make no little plans. The Korea nuclear industry includes designers, fabricators, constructors, and operators with proven capability to design and build a robust PCCS fully capable of the promises outlined here. The operative question is one of national will.

REFERENCES

[1] McCurry, J. (2017) 'New South Korean president vows to end use of nuclear power,' *The Guardian*, 19 June [Online]. https://www.theguardian.com/world/2017/jun/19/new-south-korean-president-vows-to-end-use-of-nuclear-power (2017.08.24)

[2] Na, Hyungjooh and R. M. Field, *Conceptual Design for a Primary Containment Capture System*, ANS Winter Meeting, Washington, DC, Nov. 8-12, 2015.

[3] WASH-1400 (NUREG 75-014), *Reactor Safety Study – An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants*, U.S. Nuclear Regulatory Commission, Washington, DC, October 1975.

[4] Statistics Korea. http://kostat.go.kr

[5] WNA Report, *Comparison of Life Cycle Greenhouse Gas Emissions of Various Electricity Generation Sources*, World Nuclear Association, London, UK, July 2011.