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The Viability of Extraordinary Methods to Mitigate Compromised SFP Cooling

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Abstract

Spent Fuel Pool (SFP) cooling and water replenishment is a concern during some nuclear power plant emergencies. In the presence of intermittent or failed temperature monitoring, as occurred at Fukushima Nuclear Power Plant (NPP), Hugo et al. [1, 2] recently proposed a novel approach to estimating temperatures of bodies of water experiencing evaporative cooling under forced airflow over their surface. Estimation of SFP water evaporation aids emergency management and response planning in the presence of disaster-related, failed SFP monitoring systems. Extending observations from Fukushima NPP, we detail some worst-case SFP water loss scenarios below. Further, we compare these worst-case water loss rates to the published water throughput volumes of several alternative water replenishment response methods useful in these hypothetical disaster, response, and mitigation scenarios. Follow-on future modeling and simulation research is proposed.

Keywords

nuclear spent fuel cooling , nuclear accident management, station blackout, SBO, accident analysis

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1.0 Introduction

Since Chernobyl and Fukushima the specter of an unforeseen nuclear disaster at one of the over 500 nuclear power plants currently operating around the world motivates disaster response and mitigation planning. Modeling and simulation of various disaster scenarios enables identification of equipment designs and employment techniques that may contain or otherwise mitigate any potential disaster.

With potential loss of primary and backup power as seen at Fukushima NPP, research often focuses on the potential of passive safety systems to enhance the overall safety of Nuclear Power Plant reactors and spent fuel cooling pools during a long term station black out [3-6]. During loss of coolant accidents (LOCAs) that often accompany station black outs (SBO), older reactor designs often require external means to replenish cooling water reservoirs while some newer reactor designs like the AP1000 include gravity feed cooling systems and passive heat transfer techniques to enable safe shut down and reactor cooling [7, 8]. J.H. Song et al. [5], R.V.

Gencheva et al. [9], J. Kim et al. [10], and S.Y. Park et al. [11] explore changes to and new methods for developing mitigation and response strategies when external events occur that are beyond design basis.

Despite these extensive efforts, few models address the effects of long-term SBO on Spent Fuel Pool (SFP) evaporation. P. Groudev et al. [12] investigates SFP dryout, but only in a very specific set of conditions and limit the time horizon of their analysis to ~17 hours. E.D. Throm [13] conducted an extensive analysis of SFP behavior during beyond design basis events including cost benefit analysis of several prevention and mitigation strategies. His analysis at the time concluded the probability of occurrence was very low and the available response strategies exhibited relatively high cost / low benefit ratios. Thus he recommended no preventative measures be undertaken since the relatively low decay heat of spent fuel offered a large window of response before uncovery and source term radiation release.

20 years later, the Fukushima NPP defied odds, presented operators with SFP problems beyond design specification, and precipitated a situation that necessitated ad hoc measures to resolve. Lack of planning and available data about SFP evaporative loss rates led disaster management to several unsatisfactory mitigation strategies being employed and time lost before settling on a long-term approach for supplying water to replenish SFPs [14]. To better plan for future beyond design or low probability events, mathematical modeling and simulation of worst-case SFP behavior during long-term SBO is essential for appropriate and timely advice to disaster management teams. Obvious concerns include, how rapidly might SFP water evaporate? How long before fuel uncovery occurs?

B.R. Hugo et al. [1], B.R. Hugo et al. [2], B.R. Hugo [15] propose a novel approach to computing evaporative loss of SFP water at high water temperatures. Their model accounts for evaporative loss from mass transfer (diffusion) processes in contrast to prior models that based their predictions on empirical data or heat transfer [1, 2, 15]. The Hugo et al. model differs from [16], which only accounted for coolant loss through heat transfer evaporation until fuel uncovery and cladding failure. Further, the Hugo et al. model includes velocity of air over the water surface, as occurred after destruction of the containment structure at Fukushima NPP. As shown by Hugo et al. and below, velocity of air over water is a key factor in more accurately predicting observed evaporative loss and SFP temperatures than other methods [17, 18].

Below we use the Hugo et al. model and worst-case environmental conditions to predict SFP evaporative loss rates for the remote but possible scenario under which power and control systems outage exist during a long-term SBO and SFP backup passive safety, cooling, and water replenishment systems are exhausted. We evaluate several extraordinary methods as possible mitigation options based on each method’s ability to counteract the SPF water evaporation rates suggested by Hugo et al. model. Further, we discuss potential applications of Hugo et al. model in simulation analyses for evaluating the viability of these extraordinary methods to mitigate compromised SFP cooling and water replenishment systems. Predictions and recommended follow-on modeling and simulation research may advise future disaster management teams on appropriate mitigation strategies and behaviors.

2.0 Use Case and Assumptions

Empirical data from the exposed Fukushima Daiichi unit 4 SFP with a substantial decay heat load is the representative case for this research. The Fukushima use case has the added advantage of substantial containment structure damage thus exposing the SFP to wind induced airflow over its surface. We assume the Hugo et al. model below and use their assumptions for air flow restriction [1, 2] to compute evaporation rates and total water loss from the pool under environmental conditions during the period from 12 April 2011 to 7 May 2011. We also assume 24-hour values for each day of weather data [19] from the Fukushima airport, though inland from the Fukushima NPP, over the same time period. Any variance in environmental conditions at the airport and the power plant, especially wind velocity, is accounted for by a wind speed reduction ratio applied to account for remaining building structure and water levels below the refueling deck. Additionally, predicted SFP water temperature data reported by [2] with a velocity reduction ratio of ~20% fits the observed Fukushima NPP SFP temperature data. Additional assumptions are mean daily relative humidity (ϕ in the model) and mean daily ambient and saturation pressures (P, $P_{sat,a}$, and $P_{sat,w}$) to compute a mean 24-hour evaporation rate. Since the Hugo et al. model requires water vapor pressures for various temperatures, this data was collected as a look-up table from the NIST Standard Reference Database 69: *NIST Chemistry WebBook* [20]. Finally, we assume the Fukushima NPP Unit 4 SFP has a water surface area of 120 m^2 and that 1 kg of SFP water has a volume of 1 L.

3.0 Model and Results

For the Fukushima NPP Unit 4 SFP disaster, we apply observed daily environmental input data into this model from [2]:

$$E = 9.24(1 + 2v^{1.35})^{0.67} \frac{T}{273K} \ln \frac{P - \phi P_{sat,a}}{P - \phi P_{sat,w}} \quad (1)$$

where,

$E =$ mass flux, $kg/m^2 sec$

$v =$ velocity, m/sec

$T =$ temperature, K

$P =$ atmospheric pressure, Pa

$P_{sat,a} =$ saturation pressure of water at the ambient air temperature, Pa

$P_{sat,w} =$ saturation pressure of water at the pool water temperature, Pa

$\phi =$ relative humidity, dimensionless

The model outputs an evaporation volume per hour per m^2 estimate for each given date. While [1] proposed the model and [2] verified the accuracy of the model, we use it to predict daily volumetric loss from the SFP.

Table 1 reports the resulting daily data. For each date, the following six Table 1 columns are inputs to Equation (1). Evaporation Rate (*E*) is the output of the equation. Table 1 Water Surface Level loss rate column reports the computed estimate of drop in the Unit 4 SFP water surface level for each given date. Table 1 SFP Water Volume loss rate column computes total SFP Water Volume loss rate in liters per hour for the given date. Note the mean wind speed in Table 1 is the Fukushima airport value and Equation (1) uses 20% of this value per [2]. [19] provides additional daily mean relative humidity, barometric pressure, and wind speed data. The National Institute of Standards and Technology Chemistry WebBook [20] provides saturation pressures for these reported SFP water and mean ambient air temperatures.

Table 1: Weather and SFP data and their predicted evaporative impact

Date	**(ϕ)** Mean RH (%)[a]	**(P)** Mean Sea Level Pres (Pa)[a]	**(v)** Mean Wind Speed (m/s)[a]	**($P_{sat,a}$)** Saturated VP [air] (Pa)[c]	**(T)** Water Temperature (C)[b]	**($P_{sat,w}$)** Saturated VP [water] (Pa)[c]	**(E)** Evaporation Rate (kg/(m^2*hr))	Water Surface Level loss rate (cm/day)[d]	SFP Water Volume loss rate (L/hr)[d]
4/22/11	93	101800	1.39	1313	90.6	71796	18.24	43.79	2189.39
4/23/11	97	100700	5.83	1498	82.6	52632	20.05	48.13	2406.54
4/24/11	62	100500	5.83	1313	85.3	58551	24.12	57.90	2894.98
4/25/11	72	100700	3.89	1228	80.0	47414	13.57	32.58	1628.88
4/26/11	52	101100	3.06	1313	84.4	56519	15.78	37.87	1893.44
4/27/11	64	100400	4.44	2065	80.9	49169	15.39	36.94	1847.09
4/28/11	72	99900	5.83	1403	69.4	30400	9.39	22.54	1127.23
4/29/11	55	101200	3.89	1228	91.6	74556	29.66	71.18	3559.24
4/30/11	67	101500	3.61	1403	91.6	74556	28.31	67.93	3396.62
5/1/11	69	100400	5.28	1819	91.6	74556	35.80	85.92	4296.07
5/2/11	55	100800	5.00	1403	91.6	74556	34.47	82.73	4136.57
5/3/11	66	101200	2.78	1599	91.6	74556	25.16	60.38	3019.02
5/4/11	54	101100	3.06	1599	90.1	70449	23.39	56.14	2806.88
5/5/11	67	101800	3.61	1313	92.6	77403	30.60	73.44	3671.99
5/6/11	71	102100	2.78	1403	87.9	64767	18.74	44.97	2248.59
5/7/11	87	101300	5.28	1599	85.6	59242	22.66	54.38	2719.09

[a]: Raw values taken from Weather Underground; [b]: Values taken from [2]; [c]: Derived from NIST Chemistry Webbook; [d]: Derived as noted above from Equation (1) results and Unit 4 SFP specifications

Relatively small changes in water temperature (T) over time have very little effect on the variability of the evaporation rate (*E*). Specifically, since the denominator of the natural logarithm term in Equation (1) is related to basically constant water temperature, the denominator changes very little from day to day. The constancy of water temperature may be seen if one ignores the temperature variance caused by “intensive water injection from April 22 to April 27" [14] and notices that water temperatures are constant for 5 days after and then vary only slightly until more injections began again on 5, 6, and 7 May [18] resulting in somewhat larger variations from day to day. Essentially, all significant change in measured pool temp is a result of water injection. Additionally, the numerator of the natural logarithm term changes very little since the saturation pressure is relatively small at low temperatures compared to the ambient pressure the saturation pressure is being subtracted from. This leaves the air velocity term in Equation (1) as the dominant variable in changing evaporation rates from one day to the next.

Disaster management may be most concerned with worst cases for evaporative loss rates. While evaporative loss during SBO's has been investigated [13, 21], worst cases for evaporation were often concluded to be too remote to be of concern due to the long response times available. These analyses used a water level approximately 100 cm above the top of the fuel racks as the point beyond which recovery was unlikely due to the "significant radiation field in and around the SFP at lowered water levels" [21]. But are long response times really available? Despite over 2000 tons of water being added to the Fukushima NPP Unit 4 SFP between 20 March and 23 April, the water level in the pool was measure to be only 150 cm above the top of the fuel racks on 23 April [14, 18]. At the loss rates predicted in Table 1, Unit 4's SFP was ~24 hours from the critical point and about 3 days from fuel exposure.

Further highlighting the potential SFP disaster that could have been, extremely concerned if not desperate disaster management teams had to inject large amounts of seawater into the SFP to avoid disaster for several days beginning on 22 April [14]. This happened to coincide with some of the windiest days in April and the three windiest within our period of interest. The three highest reported hourly wind speeds on the windiest days, 23, 24, and 28 April, were 9.25, 7.19, and 10.28 meters per second (hourly wind speeds not shown in the Table 1 wind speeds) respectively. Using the data for each of these dates from Table 1 and replacing the mean wind speed with these maximum observed hourly winds, "worst-case" evaporative loss rates are shown in Table 2.

Table 2: Calculated loss rates under highest observed wind conditions

Date	**(φ)** Mean RH (%)^a	**(P)** Mean Sea Level Pres (Pa)^a	**(v)** Mean Wind Speed (m/s)^a	**($P_{sat, a}$)** Saturated VP [air] (Pa)^c	**(T)** Water Temperature (C)^b	**($P_{sat,w}$)** Saturated VP [water] (Pa)^c	**(E)** Evaporation Rate (kg/(m^2*hr))	Water Surface Level loss rate (cm/day)^d	SFP Water Volume loss rate (L/hr)^d
4/23/11	97	1007	9.25	1498	82.6	52632	27.64	66.33	3316.63
4/24/11	62	1005	7.19	1313	85.3	58551	27.76	66.61	3330.68
4/28/11	72	999	10.28	1403	69.4	30400	14.01	33.63	1681.58

Clearly, the coincidental actions of the response team with the high winds averted a much larger disaster. Recalling from above that the cold sea water injections had a major effect on SFP temperatures and thus overall evaporation rates, Table 3 provides potentially even worse loss rate predictions for these highest hourly wind observations by replacing the observed water temperatures with the SFP's suspected thermal equilibrium (~90° C) [18]. These potential "worst-case" rates, though not experienced at Fukushima NPP, may have occurred given the fore mentioned environmental conditions. Further explanation of the divergent results of Tables 2 and 3 is given in Section 4.

Table 3: Worst-Case loss rate predictions

Date	(φ) Mean RH (%)[a]	**(P)** Mean Sea Level Pres (Pa)[a]	**(v)** Mean Wind Speed (m/s)[a]	**($P_{sat,a}$)** Saturated VP [air] (Pa)[c]	**(T)** Water Temperature (C)[b]	**($P_{sat,w}$)** Saturated VP [water] (Pa)[c]	**(E)** Evaporation Rate (kg/(m^2*hr))	Water Surface Level loss rate (cm/day)[d]	SFP Water Volume loss rate (L/hr)[d]
4/23/11	97	1007	9.25	1498	90.0	70182	45.89	110.14	5507.18
4/24/11	62	1005	7.19	1313	90.0	70182	38.67	92.80	4640.25
4/28/11	72	999	10.28	1403	90.0	70182	50.64	121.54	6077.23

While remote, these outcomes demonstrate the value of the above methodology for basic “worse case” planning and strategy development. Of note in Table 3 is the water loss rate expressed in cm/day. The model predicts 1+ meter of water loss per day under these conditions, drastically shortening the response window prior to fuel exposure within the pool. The water in SFP 4 was 84 C on 14 March, 3 days after the start of SBO [18]. We can assume negligible evaporation before this due to still rising water temps and lack of air flow since it was before the Unit 4 explosion. Even so, once the explosion exposed the now hot SFP to forced air flow, the 7 meters of water covering the fuel racks lasts only a week. At Fukushima spraying activities did not begin until 20 March. Under worse (windier) weather conditions fuel may have been exposed before replenishment efforts began.

4.0 Discussion and Evaporation Mitigation Alternatives

Interestingly, the loss rates computed in Table 2 are significantly lower than the rate computed in Table 1 for 1 May, the day with the fourth highest reported daily mean wind speed. The fore mentioned massive injection of cold seawater explains differences in the observed lower water temps and correspondingly lower loss rates. Specifically, during the Fukushima disaster “[e]vaporation amount had been above injection amount until around on April 20, and water level had been lowered to the level at +1.5m of the top of fuel rack. After intensive water injection from April 22 to April 27 had made water level recovered to full capacity…” [14].

Naturally, injecting sea water into a SPF is far less than optimal. Could better planning for remote and out of design disasters have afforded emergency managers better options for replenishing SPF water? Certainly, but the existing narrative in the literature is that the probability of occurrence is very low and the available response strategies exhibit relatively high cost / low benefit ratios [13, 21]. The events of Fukushima make clear the need to reevaluate the accuracy of this narrative.

Results calculated using the Hugo et al. model and worst-case environmental conditions underscore the significance of timely response during long-term SBO. The injection of relatively cold coolant into the SFP has a non-linear effect on evaporation rate thus water loss rate. Obviously, adding water to the pool directly counters the loss due to evaporation. Additionally, the relatively cold water reduces the overall pool temperature, which slows future evaporation as well. Succinctly, the more cold water added, the less that is needed.

Mitigating evaporation with minimum resource usage is of primary concern when planning and executing emergency response activities. Several mitigation alternatives are briefly evaluated below to provide a rough idea of the magnitude of response required to adequately address SFP evaporative losses.

During the Fukushima disaster, responding management attempted several different methods to mitigate SFP water losses. A truck-mounted fire fighting water canon was the first method attempted but the water canon's limited reach failed to replenish the SFP. Next responding management attempted aerial delivery of water via helicopter borne slung loaded buckets, but quickly abandoned this technique due to high winds and concerns of aircrew radiation exposure severely limiting effectiveness. Finally, concrete pumping trucks delivered from around the globe [22] to the site succeeded in supplying cooling water to the SFPs until the main cooling and circulations systems were brought back online months later [14, 23].

The logistical challenges and environmental factors associated with the Fukushima disaster severely limit the effectiveness of the aforementioned methods making their use difficult or, at times infeasible. For example, Unit 2 at Fukushima NPP did not experience an explosion, so the use of external delivery methods to replenish SFP supply was impossible [23]. In light of these limitations and the potential to meet SFP demand with more cost effective and readily available alternatives, additional methods need consideration. Manual fire suppression equipment and a trained fire brigade are required by NRC regulation [24] at all NPPs in the United States and therefore is an optional method. This equipment includes attack lines capable of supplying 1,892.5 L/min (113,550 L/hr) from a minimum of two separate 1,135,500 L supply tanks per [25]. This makes the option to have a fire brigade team place an attack line in a fixed position feeding into the SFP an effective, but perhaps temporary solution given the limited supply and potential for higher priority demands for that supply especially in a disaster scenario where fires are likely.

Table 4 shows the maximum reported throughput capacity of each of the methods mentioned above. When compared to the worst-case loss rate reported in Table 3 of 6077.23 liters per hour, each of these methods provides re-supply well above the predicted loss volume even with substantial inefficiencies and loss during delivery.

Table 4: Maximum Throughput of Water Delivery Methods

Method	Max Capacity	Source
Concrete Boom Pump	160,000 L/hr	Putzmeister America [26]
Firefighting Water Canon	159,000 L/hr	Elkhart Brass [27]
Slung Loaded Bucket	9,800 L/sortie	SEI Industries [28]
Manual fire-suppression hose	113,550 L/hr	NFPA [25]

While the techniques described here indicate a large buffer in terms of delivery capacity versus evaporative loss, two of the four were quickly abandoned and another was never attempted at Fukushima NPP. As noted above, effectiveness and crew safety are the major factors that impacted the success, failure, or dismissal of each method. Unmanned systems promise additional and potentially affordable alternatives to supplement those mentioned above [29].

5.0 Conclusions and Future Research

We have shown the utility of the Hugo et al. model in computing evaporative loss volumes in the presence of forced airflow and further demonstrated its use as a predictive tool for disaster response planning. Despite the excess capacity apparent when comparing the model's results to the published capabilities of the above mitigation techniques, when examined through the lens of past performance in a real-world situation, the evidence indicates very significant inefficiencies were present during execution at Fukushima NPP and further investigation is warranted.

Recreating such a real-world situation is both dangerous and cost prohibitive. Future research investigating the root causes of particular method failures as well as exploration of the applicability of other methods to the water delivery problem is needed. Further exploration of more efficient techniques for employment of these and other methods of water delivery within the context of response to a nuclear power plant disaster is more readily accomplished within a simulation environment and should be thoroughly explored.

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