Application of Solar Chimney Concept to Solve Potential Safety Issues of Nuclear Power Plants

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1. Introduction

Following the Fukushima Daiichi nuclear power plant accident, more concerns were raised for nuclear reactors safety and its environmental impact. Severe accidents and its causes got more attention due to its complexity and its direct potential hazards on people and environment, therefore, more research and analysis should be conducted to provide solutions and countermeasures for such events. In this paper two main events and their causes have been investigated and a potential alternative supporting system will be provided.

The first event to be addressed is the Station Blackout (SBO) caused by the inherent unreliability of the Emergency Diesel Generators (EDGs) and Alternative AC (AAC) power sources. Different parameters affect The EDG unreliability; for instance, mechanical, operational, maintenance and surveillance. Those parameters will be analyzed and linked to plant safety and Core Damage Frequency (CDF). Also the AACs, the SBO diesel generators, will be studied and their operational requirements similarity with the EDGs will be discussed.

The second event to be addressed is the Loss of Ultimate Heat Sink (LUHS) caused by the degradation of heat exchange effectiveness, that is, the poor heat transfer to the Ultimate Heat Sink (UHS). Different causes to such case were observed; intake lines blockages due to ice and foreign biological matters formation and oil spill near the heat sink causing the oil leakage to the heat exchangers tubes. The later cause, oil spill, has been given a special attention here due its potential effects for different nuclear power plants (NPPs) around the world; for example, Finland and the United Arab Emirates (UAE).

For the Finnish case, the Finnish nuclear regulator (STUK) took already countermeasures for such scenario by introducing alternative heat sink, cooling towers, for the primary used heat sink, sea water, for one of its nuclear power plants [1]. However, for the UAE case, as recommended in the 2012 fifth semi-annual report of the UAE International Advisory Board (IAB), more assessment of the potential hazard due to large oil spills resulting from tanker accidents should be performed [2].

The abundance of the solar irradiation in the UAE region provides a perfect condition for the implementation of solar power applications. Utilizing this unique characteristic of that region may provide promising alternative and diverse options for solving potential safety related issues of their NPPs. The Solar Chimney Power Plant (SCPP) could be employed to serve as a supporting system to provide emergency power, in the case of SBO, and emergency cooling, in the case of LUHS. In addition to its dual functionality; it provides a complete independent and diverse means of safety functions supporting, a free carbon oxide power production source and allow following the world's trend toward the usage of renewable energy sources.

2. Potential Safety Issues

2.1 Station Blackout

Station blackout (SBO) means the complete loss of alternating current (ac) electric power to the essential and nonessential switchgear buses in nuclear power plant; that is the loss of offsite electric power system and the unavailability of the onsite emergency ac power system. The loss of the ac power system may result in the failure of rector trip and the emergency power system (EPS) failure causing an Anticipated Transient Without Scram (ATWS) event if the plant at critical condition, and if the plant in shutdown condition; it may fail to operate the residual heat removal system. For instance; for the U.S. commercial power plants, the total CDF is 1.7E-5/ry, the SBO contributes 3.0E-6/ry; that is 18% of the CDF is due to SBO event. More specifically for the PWR the contribution of the SBO in the total CDF is 18% on average, while for the BWR is 15%, showing the SBO event high risk on the plant safety [3].

EDGs are used as the primary emergency ac power source. Its reliability based on two elements, or two phases of operation, the start reliability and the load-run reliability. Thus the EDG reliability is the product of those two reliabilities [4], i.e.

$$R(EDG)=R(start)\times R(load\text{-}run) \quad (1)$$

On the other hand, the EDG unreliability is the contribution of, the failure to start (FTS), the failure to load-run (FTLR), the failure to run (FTR) and the unavailability (UA) due to testing and maintenance [3], as follow,

$$Total\ UR(EDG)=FTS+FTLR+FTR+UA \quad (2)$$

Testing is a very essential data source for evaluating the EDG performance; in fact, data showed that 98% of the EDG starts are accounted from testing, and the other 2% accounted from real demands. However, testing and maintenance UA is a major contributor for the total UR; moreover, the most stress and wear experienced by the EDGs occur as a result of surveillance tests; so that, testing is an unwarranted contributor to the UR. [4]. The FTS the FTR failures are mainly affected by the EDGs' supporting systems, it was noticed that the fuel, electrical and instrumentation and control subsystems accounted for 77% of these failures. The cause of such failures is attributed to hardware malfunctions, related to fuses, relays and contact failures, and to the personal error which mainly take place during maintenance activities [5]. This UR inherently exists in the EDGs design and it cannot be eliminated; furthermore, this UR is showing an increased trend with time [6], as shown in the figure below.

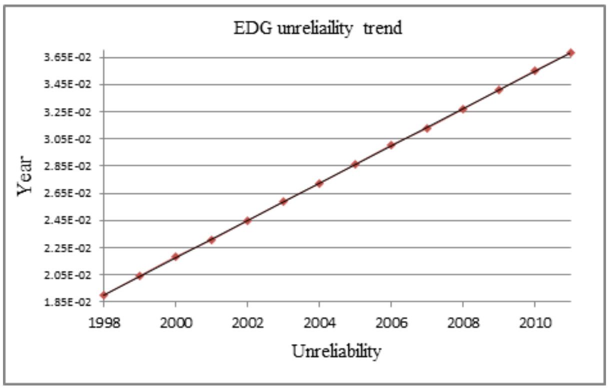

Fig. 1. EDG unreliability trend

Recent reactor designs include an alternative ac (AAC) power sources to cope with SBO event providing a support for the EDGs in case of their failure, usually referred to it as SBO generators. These generators include a similar design and operation failure modes compared with the EDGs. That is, supporting systems like lubrication, instrumentation and control, cooling and other subsystems are included in the generator boundary. These subsystems have the same effect on the failure modes of the SBO generator as well as for the EDG. This could emphasize that a complete redundant and diverse AAC power source should be utilized to minimize the inherent and non-eliminated failure modes of the conventional generator systems.

2.2 Loss of Ultimate Heat Sink

The Ultimate Heat Sink (UHS) is the safety-relevant heat sink to which decay heat of the reactor after shutdown and the heat loss from the safety systems during normal operation and incidents is ultimately transferred. The term Loss of Ultimate Heat Sink (LUHS) is referred to if heat dissipation into the environment is prevented, different potential causes could lead to such event. For example, a blockage of the intake structures by foreign particles in the receiving water and blockage of the intake structure, flooding of the intake or pump structures by internal or external events and impairment of the heat exchange effectiveness due to deterioration of the heat transfer at the heat exchanger surfaces. Emphasis will be given here for the case of the impairment of the heat exchange effectiveness, more specifically to the case caused by oil spill occurrence near the UHS.

The emergency core cooling, residual heat removal, component cooling and the essential service water systems are usually involved in the heat transfer process from the core to the UHS. The essential service water pumps take the service water from the sea and supply it to the component cooling water heat exchanger. Thus, when an incident of crude oil spill occurs near the UHS, the possibility of crude oil to reach the component cooling water heat exchanger through the essential service water pumps should be considered. In 2007 an oil tanker crashed in the Yellow Sea in South Korea dumping 10,500 tons of crude oil, 150 Km away from the incident the Younggwang NPPs staff reported the removal of 83Kg of tar lumps from the service water intake resulting from the oil spill accident [7].
As a response for the Fukushima Daiichi NPP accident, the Finnish nuclear regulator (STUK) reevaluated the risk of LUHS caused by oil spill accident for the Loviisa NPP, which uses the Finnish Gulf as the UHS and where a large oil tankers traffic exist. Based on the study, two cooling towers will be constructed for each unit as an alternative for the primary heat sink. One will remove the decay heat from the reactor and the other will carry the heat from spent fuel pools and provide cooling for other equipment important to nuclear safety [1].

2.2.1 The similarity between the Arabian Gulf and the Gulf of Finland.

The Arabian Gulf is a semi-enclosed, marginal sea boarding Iraq, Iran on the northern shore, Kuwait, Saudi Arabia, Bahrain, Qatar, UAE, and Oman on the southern shore. The Arabian Gulf is approximately 990 Km long with a maximum width of 370 Km, occupying a surface area of approximately 239,000 km^2 with an average depth of 36 m. Extensive shallow regions are found along the coast of the UAE with an average depth of less than 20 m, known as Southern Shallows, while deeper regions are found along the northern shore from the Iranian coast and Gulf of Oman side.

By far the most important and biggest industry in the Arabian Gulf region is oil production, with over 76 billion metric tons of recoverable oil and 32.4 trillion cubic meters of reserve gas in the region. Annually 25,000 tankers sail in and out of the Strait of Hormus, the only sea passage from the Arabian Gulf to the open ocean. It transported about 60% of all the oil carried by ships throughout the world. There are about 800 offshore oil and gas platforms and 25 major oil terminals in the region.

The Gulf of Finland forms the 400 Km long easternmost part of the Baltic Sea, its width range from 60-135 km and the average depth is 37 m. The Gulf of Finland considered as an important oil transportation route, moreover, Russia is building more port infrastructure there and it is expected to have more oil transportation traffic with time. In addition to the heavy oil tankers traffic, a very large passenger and cargo transportation experienced there. Almost 14% of its traffic related to oil tankers with more than 6500 oil tankers crossed the entrance of the gulf annually.

Both gulfs have relatively similar conditions, a shallow seabed depth with heavy oil transportation traffic and nuclear power plants using the gulf water as UHS, nevertheless, the probability of oil spill accidents in Arabian Gulf could be higher since more tankers transportation and oil exploration and production facilities exist. Figure 2 shows the oil spill accidents locations happened in the Arabian Gulf region (black circles represent the oil spills locations, the numbered regions are bathymetric provinces) [8]. Thus a potential safety related issues caused by potential oil spills are postulated to the under-construction NPP at Al-Barakah site, using the Arabian Gulf water as UHS, in the UAE. It could be necessary for the UAE nuclear regulator (FANR) to consider the construction of alternative and diverse heat sinks to its NPP. The SCPP is suggested to be used since it provides possible solutions for the cases of the LUHS and the SBO.

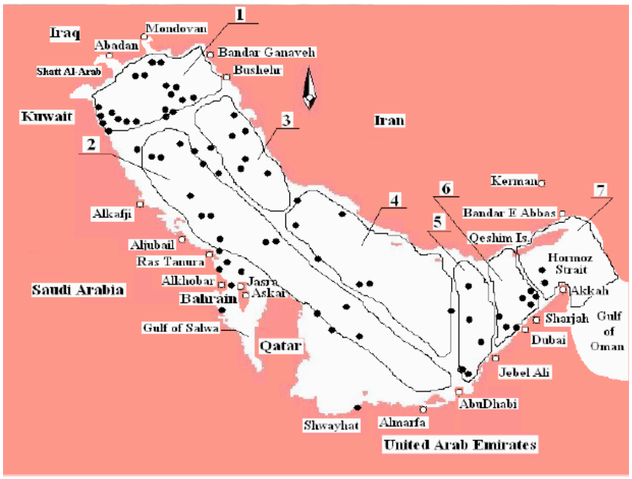

Fig. 2. Arabian Gulf oil spills locations

3. Suggestions to Solve the Potential Safety Issues

The Solar Chimney Power Plant is a completely free carbon emission solar energy based electric power generation plant. Consists of three main parts; the collector area, power conversion unit (turbine and generator system), and the solar chimney. The collector area is a large glass covered area, the solar radiation heats the air beneath the collector area, this air streams toward the center of the collector. At the center, where the power conversion unit placed, the energy in the stream of warm air is partly transformed into electric power. The solar chimney creates a pressure sink at the power conversion unit outlet. The degree of efficiency depends primarily in the size of the collector area, air temperature, and on the height of the solar chimney, the pressure difference. Such power station concepts will only deliver sufficient efficiency in areas with high global solar radiation input of more than 2000 kW h/m^2, as valid in all great deserts up to 30^o latitude north and south of the equator. It is also characterized with intended long design service life of about 80 to 120 years. Figure 3 shows a schematic diagram of the SCPP. [9]

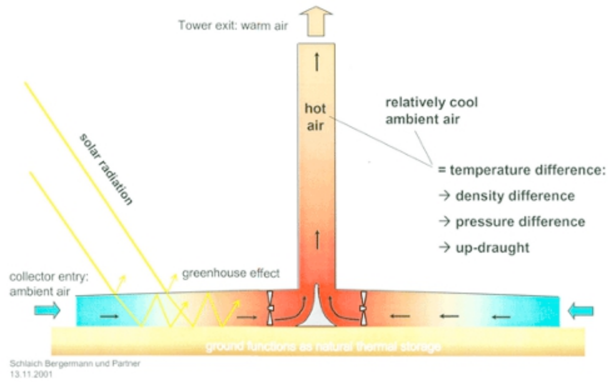

Fig. 3. SCPP schematic diagram

The applications of the SCPP to NPP primary include emergency power backup, to cope with the SBO event, emergency cooling source, in case of the loss of the primary heat sink. It also could provide emergency containment venting function. Its dual functionality to provide both emergency electric power and emergency cooling and long service life nominate it as a potential supporting system for the NPP.

Looking to the solar irradiation map for the UAE in figure 4 [10], it is found it covers the operation requirement for the SCPP, the 2000 kW h/m^2. That is, making it suitable to apply this concept to support the under-construction NPP at Al-Barakah site.

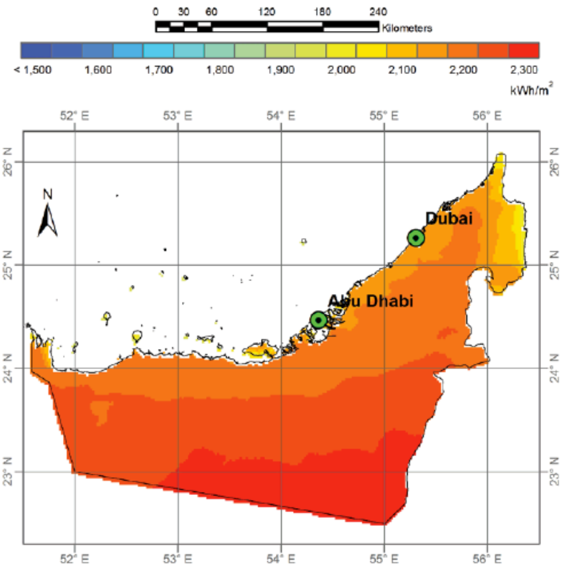

Fig. 4. 2010 solar irradiation for the UAE region

4. Conclusion

The Solar Chimney Power Plant was suggested to be employed as a supporting system for NPPs to provide emergency power, in case of SBO, and emergency cooling, in case of LUHS. It provides a complete independent and diverse means of safety function supporting.

Following the SCPP operation requirements of the availability of high solar irradiation, the UAE region provides a perfect environment for its implementation; furthermore, it can be linked to the under-construction NPPs at Al-Barakah site to deliver alternative emergency power and emergency cooling.

Due to the inherent unreliability of the currently utilized EDGs and the AAC power sources, a postulated SBO event could affect the safety of the NPP in general, and for the specific case of the UAE NPPs, a LUHS caused by oil spill accident in the UHS could be experienced, given the massive oil related activates being performed in the Arabian Gulf. Comparing the similarity between Al-Barakah site and the Loviisa NPP in Finland; looking for solution and alternatives for the enhancement of their reactors safety should be considered by the UAE nuclear regulator.

More analysis of the SCPP working in accordance with NPP to provide its intended function should be performed in the future; that is, analysis for its reliability, availability and survivability. Also analysis should be conducted for the reduction of the daily power variation, between day and night time. Useful information could be obtained by examine the experimental model built in Manzanares, Spain in 1982.

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