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The Issues of Primary Causes for Severe Accidents Fukushima-Daiichi

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Abstract. The review of the primary causes for severe accidents on NPP Fukushima-Daiichi using well-known data from nuclear safety regulatory state organizations of Great Britain, USA and Japan including data from operator TEPCO (Tokyo Electric Power Company) are presented.

It is shown that the main causes of severe accidents and the devastating explosions were fundamental drawbacks of early BWR projects in overcoming consequences of of extreme natural events, as well as the lack of trained personnel to manage accidents which has relatively low probability.

Keywords: nuclear safety; severe accidents; Fukushima-Daiichi

1 Introduction

Right after the accident at the Fukushima-Daiichi nuclear power plant in March 2011, the authors of this article conducted a preliminary analysis of the main reasons that led to severe accidents with damage of nuclear fuel. The relevant additional measures to improve the safety of nuclear energy in Ukraine was developed and approved [1].

More than two years after the accident, during which the world nuclear community is actively engaged in research on causes, consequences and lessons of the big accident at Fukushima-Daiichi. Most experts agree that the main cause of the accident was beyond design basis earthquake and tsunami which led to the flooding of the industrial site, a complete loss of long-term electricity and all design systems to ensure effective management of the accident.

2 Analysis of Primary Causes for Severe Accidents

The report of the operating organization TEPCO [2] on the analysis of a large accident at the Fukushima-Daiichi nuclear power plant indicates that the main direct cause of the accident was a beyond design basis flooding of industrial site, which led to a loss of the necessary security features to ensure residual heat removal after emergency shut-down of reactors. Also, according to TEPCO, established the following:

1. Seismic effects of beyond design basis earthquake (including possible damage to systems and equipment) were not the direct cause of the accident (except for the loss of remote power supply).
2. The main reason for beyond design basis accident was the flooding of NPP site by tsunami wave, which led to the deterioration of the conditions of the emergency measures. Debris from the tsunami has prevented the movement of vehicles, radiation situation on the site has increased, the cables and hoses of water supply has damage, emergency personnel got injuries, etc. Tsunami flooding of NPP site was the main cause of "simultaneous overall loss of AC and DC current for a prolonged period of time" and "loss of heat removal emergency systems using a sea water for a long period of time".
3. Using of alternative supply of fresh water and sea water to cool the nuclear fuel in the blocks number 1 - 3 through the line of fire protection was not effective. There is no confirmation that cooling medium was supplied precisely into reactor pressure vessel.
4. As a result, preventive action on ventilation air containment Unit 1 and 3 confirmed the pressure drop in these containment. However, it was not possible to avoid a hydrogen explosion that destroyed the upper structure of the building blocks of the reactor compartments Unit 1 and 3. The main reasons for the explosion of hydrogen at Units 1 and 3 are associated with inadequate ventilation of buildings for the removal of hydrogen. Presumably hydrogen has entered to the building through the ventilation system of containment. Also is assumed that a hydrogen explosion within the containment of Unit 1 and 3 were not realized, as the system nitrogen purge containment was active. The absence of a hydrogen explosion at Unit 2 is due to the opening of the access panel on the top floor of a building block (due to an explosion on Unit 1), that provided the necessary ventilation of the building.

The reduction of pressure on the unit number 2 as a result of preventive action on ventilation containment was not confirmed, but a hydrogen explosion in this unit was not.

1. The cooling functions for the storage pool of spent nuclear fuel (SFP) on Unit 4 was successfully restored by emergency actions. The required levels of coolant were supported before and after the explosions on Unit 4. The devastating explosions in SFP of Unit 4 were caused by hydrogen which was transported during ventilation of Unit 3 (via pipeline of the reserve system of gases processing).

The earthquake and tsunami, that has occurred, disproved "... all assumptions that have been made previously about accident management at the nuclear power plant ...". TEPCO acknowledges that the preliminary training and provision of personnel to manage such accident were inadequate [2].

Instructions for management of beyond design basis and severe accidents have been developed mainly for personnel actions on ensure of the cooling water supply to the reactor under the condition of having of secure power supply sources which have been completely lost as a result of flooding. Therefore, the results of management and mitigation of this major accident largely were dependent on courage, flexibility, creativity and insight of personnel.

It is necessary to make a comments to the conclusions of the operating organization TEPCO about the causes and consequences of accidents at Fukushima-Daiichi NPP.

1. The report TEPCO confirms that measures to maintain the necessary level of coolant in the SFP Unit 4 were made only after a devastating explosion on March 15 (using of mobile pump and helicopters to spray through the damaged roof of the building Unit 4). The availability of the required level in the SFP Unit 4 was based on the results of visual observation on March 16 as well as measurements of radiation effects in the aftermath of the explosion on March 15. The possibility of dangerous decrease of water level in the SFP Unit 4 been predicted TEPCO at the end of March.

At the same time, the preliminary assessment of the SFP Unit 4 [1] indirectly pointed to the reduction of the coolant before the explosion on March 15 (probably due to integrity loss of pool during seismic action). Specialists from Nuclear Regulatory Japan (NISA), USA (NRC), and French company nuclear technology AREVA expressed doubts that the necessary level of coolant in the pool was maintained before and after the explosion on March 15 [1].

1. TEPCO conclusions that the cause of all the explosions were the processes of deflagration / detonation of hydrogen, are based on the fact that the temperature of combustible materials (for example, turbine oil) was insufficient for their explosion, and the pressure in the containment on the quasi-static level was controlled. Relatively small devastating effects is also not typical for steam explosions.

However, these findings do not appear to be sufficiently substantiated for the following reasons:

- the monitoring for steam explosion conditions on the Unit 1-3 in fact was absent;
- before the explosions on Units 2 and 3 the periodic sharp pressure increases in the containment were recorded (in particular, in the morning on March 14) [1];
- the explosion (and possibly a sequence of explosions) on Unit 2 was occurred within the containment filled by recombiners (nitrogen, inert gases) to prevent detonation/deflagration of hydrogen, as evidenced by a sharp pressure decreases (more than three times) in the bubbler after the explosion (possibly as a result of its injury);
- the pressure behavior in the containment of Unit 3 before and after a powerful explosion (March 14, at 11:01), "mushroom" shape of the cloud of explosion, continuous steam torches from containment after the explosion and dramatically larger destruction of the building than on Unit 1 - all this facts not exclude the possibility of the steam explosion on Unit 3 (including the subsequent initiation of the hydrogen explosions in the building [1]).

One of the reasons of increased power and larger devastating effects of the vapor-gas explosion than at Unit 2 may have been the partial use on Unit 3 plutonium-MOX fuel having a relatively low melting point compared with uranium fuel. Furthermore, according to the chronology of events on March 13 (before the explosion) on Unit 3 the cooling was organized using system of coolant injection into the reactor. Up to date, uniquely not determined influence of the cooling by water if MOX fuel is already damaged. According to some data (see, for example [1]) the water cooling of damaged MOX fuel in some cases can lead to neutron-physical processes contributing to the further increase of damaged fuel temperature and intensive steam generation.

Therefore, the causes and mechanisms of explosions that occurred at the Fukushima-Daiichi nuclear power plant require further in-depth analysis.

Thus, summing up the results of TEPCO report on developments in the nuclear power plant Fukushima-Daiichi, it should be noted that the *main reason beyond design basis accident* at Fukushima-Daiichi nuclear power plant was flooding of industrial area caused by the earthquake, tsunami, which led to a complete loss of long-term sources of supply. The immediate impact of the earthquake on the occurrence of conditions beyond design basis accident is uncertain, as there is no necessary and sufficient information about the status of the protective safety barriers, systems and equipment before the start of the stage of severe accidents.

The main causes of severe accidents related to construction-technical deficiencies and a limited capacity of Units 1–4 to overcome the design basis accidents with a complete loss of power supply, as well as an unreasonable and inefficient system of accident management, that used to a relatively low probability events (such as accidents on NPP

Fukushima-Daiichi [1]).

At the same time, there is every reason to believe that in the case of the implementation of preventive organizational and technical measures to improve the reliability and efficiency of management at such unlikely accidents could have not only to mitigate the consequences of beyond design basis accidents, but also to prevent severe accidents and cause devastating explosions with catastrophic consequences. These activities are - in whole or in substantial duplication of functions of active safety systems by passive systems (as is done, for example, with VVER reactors of the new generation of security), providing isolation of buildings from flooding and the mutual influence of power supply, the introduction of sufficiently solid instructions/guidelines on the management of beyond design basis and severe accident at a blackout, providing effective hydrogen controls to support explosion safety in units buildings and other.

In an official report, a summary of events in the Fukushima-Daiichi nuclear power plant of an independent commission to investigate the National Diet of Japan (CNDJ) indicates that the root cause of the accident was the lack of current organizational and regulatory security system by the operator (TEPCO), regulatory authorities (NISA, NSC) and government support for nuclear power in Japan (METI). The immediate cause of the accident was predictable before March 11, 2011. Fukushima-Daiichi nuclear power plant was not able to withstand the earthquake and tsunami that occurred on this day. The operating organization, the regulatory authorities and public bodies to promote nuclear power could not properly developed the basic safety requirements, such as the assessment of the likelihood of damage and develop a plan of evacuation in the event of a major radioactive release. TEPCO and NISA were aware of the need to strengthen structures according to modern guidelines. The Commission found that none of the necessary measures for strengthening has not been implemented on Units 1–3 at the time of the accident. This was the result of "silent agreement" NISA in respect of a substantial delay of the operating organization to the implementation of activities.

An independent commission of the Japanese parliament also came to the conclusion that the immediate cause of the accident could be beyond the design basis earthquake resulting in damage of equipment/systems. CNDJ believes that the main causes of accidents due to damage of the equipment/systems from the direct effects of the earthquake was: the relative brevity of a powerful explosion on the Unit 1 after an emergency shutdown of the reactor; concern of operators during the accident at the possible water leaks; JNES assessment on the possibility of small LOCA (loss of coolant accident reactor) at the design basis earthquake and others.

Thus, according to CNDJ conclusions the main causes of the accident was associated with impaired organization of operation and safety regulation, and the lack of efficiency of the control system improbable accidents. However, we believe it necessary to make a few comments on the main provisions of the commission's report CNDJ.

1. Insufficiently analysed flaws of "old" BWR projects, operated on Fukushima-Daiichi NPP, associated with the possibility of overcoming the transition beyond design basis accidents to an severe accident. It is these restrictions have been one of the root causes of accidents. Possible damage to the individual equipment/systems from the design basis external extreme impacts are inevitable, but constructive solutions should provide mitigation of the consequences and prevention of severe accidents.
2. In our opinion, harsh accusations addressed to operating and regulatory organizations too categorical and not quite fair because responsible for the accident should be equally carry a design organizations NPP Fukushima-Daiichi, which did not provide the required level of safety in extreme external events. Insufficient attention to the relatively unlikely initiating event is defined internationally accepted approach. From the 90s IAEA cultivated ideology of US regulatory body (NRC) on probabilistic ranking accidents and only after Fukushima-Daiichi accident has come it necessary to review this position [4].

In a report [3], the UK Office for Nuclear Regulation (ONR) analyzes the impact of the consequences of the continued existence and development of the nuclear industry. Regarding the root causes of the accident, the report ONR only indicates that they were beyond design basis earthquake and tsunami; and reference is made to the mission and the IAEA report on the weakness of the NPP Fukushima-Daiichi in overcoming such a tsunami. The main conclusions of the final report of ONR, for the integration of lessons and the consequences of accidents on nuclear power plants Fukushima-Daiichi, the continued existence and development of the UK nuclear industry, lies in the fact that there is no need a fundamental change the UK regulatory system of nuclear and radiation safety, and reducing nuclear power and change the strategy of building new nuclear power plants. Further improvement of the system of licensing of NPP should be aimed at increasing the independence and competence of the regulatory body. Industrial sites with risk of flooding may require profound changes in NPP projects for flood protection.

On the main findings of the report the UK regulatory body should, in our view, to make a number of comments.

1. The report ONR not deep enough analysis of the main reasons for the Fukushima-Daiichi accident, and focuses on the prospects for the further operation of nuclear facilities and activities of the regulatory body the UK. In particular it is not reasonable is the conclusion that only a limited impact MOX (Unit 3) on the consequences of a severe accident. Some well-known experimental and theoretical studies (see, for example, [1]) show that cover with water of damaged MOX fuel can result in a significant impact on the development of uncontrolled processes during severe accidents, respectively, and a significant impact on the environment and human health. One of the main causes of accidents has been insufficient attention to the design, oper-

ating and regulatory organizations in the management beyond design basis accidents which have such a relatively low probability.

2. The lessons from Fukushima-Daiichi accident confirmed the limitations of approach to regulate the safety, which generally accepted in the world (including the UK), with respect to an unlikely accident events which usually not modeled, not analyzed and, accordingly, not developed emergency measures for such cases.

NRC and the nuclear industry in the United States took an active part in the support and assistance of Japan, as well as to analyze the causes and lessons of the Fukushima-Daiichi accident. As the main cause of the accident was determined mismatch design basis for nuclear power plant Fukushima-Daiichi required level of protection from any design basis earthquake and tsunami [6].

NRC initially defended the position that the causes and lessons of the accident at the Fukushima-Daiichi nuclear power plant did not affect the level of safety of American nuclear power plants (including 23 units with BWR similar to Japanese reactors), since the flooding of industrial areas of the United States nuclear power plants like the tsunami is highly unlikely: the station provided with the necessary emergency response system for accidents with blackout and guidelines for severe accident management (SAMG). In addition, after the September 11 attacks in the United States launched a program known as "B.5.b", which has been requested to provide NRC "mitigate" the effects of the fall of the aircraft at the plant. In frequency, the program involves the placement of additional mobile pumps and diesels.

NRC and the nuclear industry in the United States actually determined the flooding of the industrial site of NPP Fukushima-Daiichi beyond design basis tsunami, which led to a complete blackout, and is main cause of accidents. However, these events can be considered as one of the main causes of early stage BDBA. *The main reason of occurrence of severe accidents (with unacceptable damage of nuclear fuel), and the devastating explosions were flaws of BWR projects and the lack of appropriate management of beyond design basis and severe accidents*.

These flaws NRC has identified as a "weakness" identified in Fukushima-Daiichi accident, but not as a cause leading to severe accidents and their consequences. However, if BWR projects of nuclear power plant Fukushima-Daiichi before accident to have been equipped with the necessary leakproofness against flooding of penetrations and compartments, where were located diesel generators, sufficient to cool the reactor containment and passive safety systems that do not require power, independent systems of units ventilation, hydrogen recombination systems outside containment, etc., regardless of the actions of emergency personnel was possible not only to "mitigate" the consequences, but also to prevent the occurrence of severe accidents. An indirect confirmation of the recognition of the flaws of NRC BWR projects and related systems emergency control can be themselves NRC recommendations for their modernization, presented after Fukushima accident. The expediency of the effective implementation of these recommendations is quite obvious, and their timely implementation could prevent the accident.

If we recognize the fundamental flaws of BWR projects in overcoming a long full blackout as one of the main causes leading to the severe accident stage, it is necessary to recognize the vulnerability for such NPPs with BWR which operating not only in Japan and the need to stop them for carry out the necessary modernization.

The first series of inspections to check the readiness and ability of each plant to cope with blackout and severe natural disasters (eg, tsunami, flood, tornado or hurricane) and provide cooling of the reactor cores and the spent fuel pools. These inspections have determined that the existing capacity may be insufficient. For example, some of the equipment, some programs B.5.b, such as mobile diesel pumps and generators were placed in the buildings that are vulnerable to tornadoes and earthquakes, and thus might not be available in the event of an accident caused by severe natural phenomena. In addition, the supply of portable pumps and generators were in many cases not sufficient for the needs of several reactors at the site. In fact, this finding should not be a surprise: the equipment program "B.5.b" was not intended to be used after natural disasters such as earthquakes and floods, and therefore NRC did not require that the equipment be protected from such events. Similarly, the NRC instructions concerning blackout did not require from station owners to assume that, it will cover several reactors or blackout occurs simultaneously with another event (such as earthquakes).

The second series of inspections to investigate the "guidelines for the management of severe accidents" – emergency procedures and training of operators who will carry out the liquidation of a severe accident, such as at Fukushima, after the beginning of core damage. These inspections have shown that the accident management procedures to be used by operators on the American reactors, often are outdated and operators rarely (if ever) are trained to use them. In some areas, these procedures were not even readily available to operators in the control room.

The main causes of severe accidents and destructive explosions - flaws and limited capacity of the NPP Fukushima-Daiichi (including American reactor plants with BWR) to overcome the transition of these design basis accidents in the stage of severe accidents and the devastating explosions, as well as lack of training and instructional personnel security accident management with complete loss of long-term power supply in case of flooding of the NPP site with multiple units.

The main lesson of the big accident at the Fukushima-Daiichi nuclear power plant, we believe, is the need for a fundamental change in the relationship to the relatively unlikely emergency events, which, in particular, summarizes many of the "technical" lessons formulated by IAEA experts mission May 24 - June 2, 2011 [4].

Previously used the *conventional approach to prioritize consideration of accidents* according to their contribution to the integrated probabilistic safety indicators *should be revised*. It is because of this approach the accidents like had occurred on Fukushima-Daiichi NPP, almost not analyzed during the development of emergency response measures.

Formulated in this work the main causes of the accident at the Fukushima-Daiichi nuclear power plant are closely "resonated" with the main causes of the Chernobyl disaster, which formulated as early as 1996 at the International Conference of the IAEA in Vienna, "Ten years after the Chernobyl disaster - the results of the consequences of the accident": "... the main causes of the Chernobyl accident was the combination of serious flaws in the design of the reactor and its shutdown with violation of the rules of operation".

In Ukraine, the operating organization (NAEC "Energoatom") and the regulator (ГИЯРУ) developed and adopted a plan to implement additional measures to further improve the security of nuclear power units based on the lessons of accident at Fukushima-Daiichi. As a first step in the implementation of this plan were performed stress tests of the state of security, the main purpose of which is associated with the justification of specific additional measures for the integrated (combined) program of improving the safety of Ukrainian NPPs (КсППБУ-2010) taking into account the lessons of the accident Fukushima-Daiichi nuclear power plant [5].

3 Conclusion

The main causes and lessons of the accident at Fukushima-Daiichi are relevant for the global nuclear energy that determines the need to review and improvement of nuclear reactor projects, as well as studies of their safety and checking the effectiveness of accident management procedures.

Bibliography

[1] В.И. Скалозубов, А.А. Ключников, В.Н. Ващенко, С.С. Яровой: Анализ причин и последствий аварии на АЭС Fukushima как фактор предотвращения тяжелых аварий в корпусных реакторах. – Чернобыль: ИПБ АЭС НАНУ, 2012. – 280 с.

[2] Fukushima Nuclear Accident Analysis Report //TEPCO, Inc. – 20.06.2012.

[3] Japanese earthquake and tsunami: implications for the UK nuclear industry. Find Report / HM Chief inspector of Nuclear installations. ONR of HSE – September, 2011.

[4] IAEA: International Fact Finding Expert Mission Of The Fukushima Dai-Ichi NPP Accident Following the Great East Japan Earthquake and Tsunami: IAEA Mission Report. – IAEA, 2011. – 160 p.

[5] Про результати виконання цільової позачергової оцінки стану безпеки діючих енергоблоків АЕС з урахуванням подій на АЕС Фукусіма / Колегія Держатомрегулювання, № 13 від 24-25.11.11 р.

[6] NRC Recommendations for enhancing reactor safety.- 12.07.2011.