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AN ALTERNATIVE METHOD TO MITIGATE THE HYDROGEN CHALLENGE IN SEVERE ACCIDENTS AT A NUCLEAR POWER PLANT

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Mitigation of hydrogen challenge is one of the basic goals of severe accident management at a NPP. The main measures for hydrogen control are inertization of the atmosphere and removal of hydrogen. Most of the commonly used strategies for hydrogen removal is based on the use of Passive Autocatalytic Recombiners (PAR) of hydrogen. The analysis of PAR operation specificity reveals that in some scenarios PARs can turn out to be not efficient and reliable enough. The efficiency of the hydrogen removal system will depend on the strategies used, the accident scenario and many different factors. A conclusion is made that the hydrogen mitigation strategy should consist of a combination of different strategies (e.g., PARs with venting) to be more flexible in hydrogen challenge management, and efficient and reliable in a broad scope of accident scenarios. The authors of the paper propose a new alternative method for coping with the hydrogen challenge. The concept and advantages of the method (strategy) are presented. The strategy is more applicable, but not limited for the PWR power plants having big dry containments. The proposed strategy, besides mitigation of hydrogen challenge, also ensures the removal of aerosols from the containment atmosphere, as well as heat removal from the containment as opposed to the operation of PARs, which is in line with the main goals of the severe accident management.

Keywords: nuclear power plant, severe accident, hydrogen challenge, hydrogen mitigation strategy, passive autocatalytic recombiner, spray system, aerosol removal.

Introduction. Nuclear power plants are designed to withstand challenging transients such as one related to the loss of the coolant from the reactor or the loss of the ultimate heat sink. The plant design philosophy is based on using reactor systems and containments that can cope with a broad range of accident conditions, including most of the sequences that could lead to the core damage.

Worldwide experience of operation of NPPs gained over the past decades has shown that accident conditions can occur which threaten the essential function of adequate cooling of the reactor core or fuel in the spent fuel pool, and that severe and extremely unlikely events can occur and lead to challenges to plant systems, resulting in nuclear fuel damage. The occurrence of such conditions is related to so-called severe accidents.

For conditions leading to a severe-accident state, most or all of the systems considered in the emergency operating procedures would be lost for a sufficient time to uncover the core and result in the overheating of the fuel and cladding sufficient to cause extensive cladding oxidation. After the fuel damage has taken place, the accident management is focused on protecting the fission product retention barriers through coping with or mitigating the challenges to these barriers. Very likely, the containment structure will be the only barrier that could have kept its functions during the progression of the accident till the severe phase, and the containment boundary becomes the only barrier against the release of fission products to the environment. The protection of the containment structures will be a high priority task and one of the basic goals of the severe accident management.

The combustion of hydrogen produced primarily as a result of overheated zirconium metal (as well as reactor internal steel components) reacting with steam, can create short term pressure forces that may exceed the strength of the containment structure and lead to the containment failure. Thus, mitigation measures of hydrogen challenge must be considered as one of the essential parts of the plant accident management programme.

Hydrogen challenge mitigation strategies' analysis results. The main measures for hydrogen control are inertization of the atmosphere and removal of hydrogen by burning or recombination, or by venting of the containment. By saying inertization we understand attaining and maintaining such the content of the atmosphere components at which the burning is impossible. This can be reached by limiting the concentration of hydrogen and/or oxygen or either maintaining high concentration of non-combustible or combustion-inhibiting gases (steam, nitrogen, carbon dioxide, etc).

It must be understood that inertization is a temporary solution of hydrogen challenge, and hydrogen must be removed from the containment in a reasonable timeframe during which it is realistic to maintain an inert condition of the atmosphere. The most common strategies for hydrogen removal are the use of Passive Autocatalytic hydrogen Recombiners (PAR) or venting of the containment. In both cases, inertization of atmosphere must be ensured to avoid any possible inflammation of the gas mixture which can result in unacceptable dynamic loads on the containment structures. Burnable mixture formation can be allowed only if anticipated burning mode excludes any flame acceleration.

When considering the strategies for mitigation of hydrogen challenge using PARs it must be taken into account that:

– PAR capacities (hydrogen depletion rates) are very limited and may not cope with high hydrogen production rates in some scenarios so that at certain periods of accident progression, a certain mass of hydrogen can be accumulated in the containment or its separate part and, thus, flammability limits can be reached or exceeded (so-called hydrogen pockets can be created) [1].

– PARs are passive systems without any possibility of control over their operation – in case the PAR operation is related with a certain risk (e.g., ignition) in current conditions of containment atmosphere, it is impossible to mitigate this risk.

– Depletion rates of PARs, besides the current concentration of hydrogen, will depend on several other factors, such as oxygen concentration, pressure and temperature of the atmosphere, etc. Only in case of large - scale convection zones of the containment, an approximately uniform steam-air-hydrogen distribution will be observed. In stagnation zones separated by partitions or stratification phenomena, different compositions can develop [1]. Thus, the real depletion rates of PARs can be very different, sometimes significantly lower than the rated ones (assessed for specific conditions). Optimal positioning of PARs in the containment can be different for different scenarios, thus, any considered variant of positioning cannot be optimal for a broad scope of scenarios.

– In case of non-inert atmosphere and certain content of hydrogen and oxygen, PARs can act as a source of ignition (due to significant overheating of catalytic surfaces).

– The removal of hydrogen by PARs is possible only in case of availability of oxygen - if in any area of containment the oxygen is exhausted due to the operation of PARs, hydrogen can accumulate in this area and create a risk of further formation of burnable mixture (e.g., due to further intensive mixing of atmosphere of different parts of containment related with some accident management actions).

– The operation of PARs results in more intensive circulation of atmosphere and, thus, decreases the natural deposition of aerosols (in scenarios without availability of spray system natural deposition could be the preponderant way of aerosol removal from containment atmosphere).

The removal of hydrogen by venting the containment is related to the removal of the significant volume of gas atmosphere from the containment and need of filtering of high amount of gas to minimize the radioactive releases, thus the capacity of the filtered venting system may not be sufficient to cope with high rates of hydrogen generation. The existing filtered venting systems are designed for preventing, in case of SA, the overpressure failure of the containment and keeping the containment pressure to acceptable levels (by discharging steam, air and incondensable gases to the atmosphere) while mitigating the radioactivity releases. They are designed mainly for limited flow rates and cannot be used as a means for hydrogen removal to cope with the hydrogen challenge.

The efficiency of the hydrogen removal system will depend on the strategies used, the accident scenario and many different factors. It is clear that in different scenarios different systems can be more or less efficient and the implementation only of PARs or of a venting system cannot be assessed as a reliable strategy for mitigation of the hydrogen challenge. The conclusion is that the hydrogen mitigation strategy should consist of a combination of different strategies (e.g., PARs with venting) to be more flexible in hydrogen challenge management, and efficient and reliable in a broad scope of accident scenarios.

Besides that, it must be considered that severe accident management actions may have not only a positive influence on accident conditions but also some negative impacts - coping with or mitigating any challenge during the severe phase of the accident can create another challenge. Some simple examples are as follows:

– Inertization of the atmosphere of the containment is mainly performed through increasing the content of steam, thus, results in the increase of pressure. The increased pressure is related to the potential of releases of radioactive materials from the containment.

– Limitation of the radioactive releases during a severe accident can be achieved through the minimization of the mass of radioactive aerosols in the containment atmosphere. The most efficient way of removal of aerosols is the operation of the containment spray system. However, spraying in the containment will condense part of the steam and result in the decrease of the steam concentration and the increase in the hydrogen and oxygen concentrations with a risk of losing the atmosphere inertness.

– High pressure in the primary of a PWR plant during a severe accident is related to the risk of failure of steam generators' tubes (i.e., of the containment bypass) by the mechanism of high temperature creep rupture, as well as the risk of high pressure melt ejection phenomenon in case of the reactor pressure vessel bottom head failure. The most effective way of depressurizing the primary is the relief of media from the primary. This is related to the possible fast release of hydrogen accumulated in the primary volume to the containment.

It must also be considered that the implementation of technical means for a severe accident management strategy may become a restraint for the implementation of another strategy to cope with another challenge. Example: installation of PARs may become a serious limitation for the operation of the spray system aimed at the removal of aerosols from the containment, as well as reduction of pressure in the containment –the operation of sprays may result in the loss of the atmosphere inertness and ignition from PARs. In the conceptual design of the hydrogen removal system, the main anticipated actions within the severe accident management must be considered.

A new hydrogen challenge mitigation strategy proposal. The authors of the paper propose an alternative strategy for coping with the hydrogen challenge - a strategy which can be considered as an alternative venting strategy. The proposed strategy can be implemented in parallel with another strategy as an additional strategy to cope with hydrogen challenge, e.g. with installation of PARs. The strategy is more applicable, but not limited for the PWR power plants having big dry containments.

The idea of the strategy is to concentrate (accumulate) the hydrogen locally before venting to minimize the volume of gases to be removed from the containment and to ensure the removal of radioactive aerosols. The strategy implementation scheme is presented in the Figure. A specially designed and implemented spray system covers only a small part of the containment. Due to the operation of sprays in the dedicated area and condensation of steam, a flow of gases from other parts of the containment is anticipated. Due to such a flow and continuous condensation of steam, accumulation of hydrogen and air will take place (increase of concentration) with a parallel decrease in the steam concentration. Venting is performed from this dedicated area through specially implemented lines. The operation of sprays can remove the major part of radioactive aerosols from the atmosphere. Additional aerosol filters can be used to stop the remaining part of aerosols that have not been removed by sprays. Iodine filters can also be installed as it is often done in conventional filtered venting systems.

Venting from this dedicated area and operation of sprays should be done in alteration. When, during the spraying phase, the concentration of hydrogen reaches the defined maximal allowed local concentration, the spraying is stopped and the venting is started. The removal of hydrogen is performed by portions. This alteration is performed several times before reaching non-dangerous conditions in the containment.

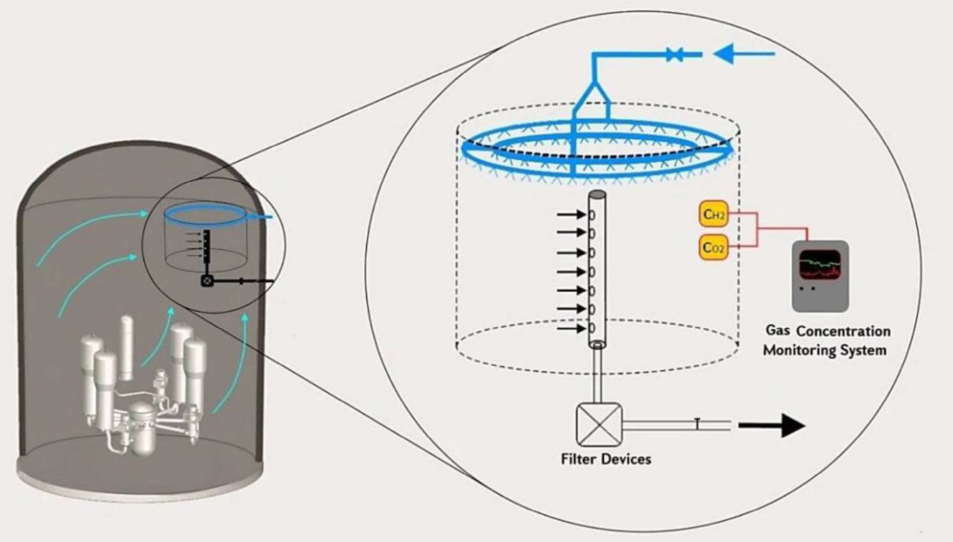

Fig. Schematic concept of the strategy

The advantages of the strategy are as follows:

– The spray system changes the content of the atmosphere only in a relatively small volume - no risk of global burn will exist. Through control of sprays the concentration of hydrogen can be limited within values excluding dangerous modes of burning;

– venting of the containment after “accumulating” the hydrogen in a specific area will significantly reduce the volume of gases to be removed;

– the strategy also ensures the removal of aerosols from the containment atmosphere, as well as the heat removal from the containment as opposed to the operation of PARs which release significant amounts of thermal energy. The parallel use of such a strategy/system with PARs will compensate the heat load of the containment;

– the required flow rates of the coolant for the system should be significantly lower than for the plant main spray system. With this regard, the system will need less energy supply than the main spray system – mobile diesel pumps can be sufficient or the system can be driven passively by gravity or by pressurized gas;

– the strategy will ensure more or less “directed” flow of atmosphere in the containment, as well as some level of mixing which can minimize the likelihood of hydrogen accumulation in some areas of the containment (e.g., “dead-end” rooms);

– the strategy will also ensure the accumulation and removal of oxygen;

– the strategy will also contribute to the deposition of radioactive aerosols from the atmosphere in the specific area of the containment (where the sprayed water will be drained) but not in its all areas (a very important factor for post-accident long-term recovery actions).

If in the main area of the containment, inert atmosphere is maintained, inflammation of gases in the sprayed area (if non inert) will be very unlikely – low temperatures of atmosphere, no component of the plant systems with high temperature, no electropowered component. To avoid any possible static electricity sparks, the system components in the sprayed area can be earthed.

As the aerosol removal is very important for severe accident management, the proposed spray system must be designed considering the physics of aerosol removal by sprays – important findings are summarized in [2]. Sprays remove particles by:

– sweepout of particles unable to avoid the falling droplet;

– interception of particles as they follow steamlines of flow around the falling droplets; and

– diffusion of aerosol particles to the droplet surface.

Sweepout and interception most efficiently remove larger particles (particle diameter > 1 μm). Diffusion is most efficient for very small particles (particle diameter < 0.1μm). Consequently, very fine and very large aerosol particles are efficiently removed from the containment atmosphere by sprays. There is, however, an intermediate size of particle that is minimally affected by sprays. The decontamination of the atmosphere of these intermediate-sized particles is increased by decreasing the size of the spray droplets, which are typically between 250 and 2000 μm in diameter. Because of the particle size dependence of the spray effectiveness, the spray not only changes the concentration of particles in the atmosphere, but also changes the size distribution of these aerosols. Sprays can be very efficient in particle removal if the system includes different types of nozzles (sprayers) which ensure a large spectrum of the droplet size.

The main challenges in designing and implementing the described system will be as follows:

– the need for installation of special partition elements to ensure the "directed" flow during the venting phase, and to avoid or minimize the possible mixing of media of the main area with the media of the sprayed area;

– the need for hydrogen concentration sensors with an adequate measurement range and accuracy, response time, as well as qualification for environment conditions;

– the need for controlling the system operation by the plant staff or automatics;

– the possible difficulties/constraints for implementing the system components in the existing layout of the plant (availability of free space, possible restraints for maintenance works during outages).

The strategy can turn out to be low effective in cases when the steam concentration in the containment is relatively low – the flows of the atmosphere to the sprayed area may not be enough to effectively accumulate the hydrogen.

In order to have an idea of the mass of hydrogen that can be removed using the proposed strategy, authors made some engineering assessments which are summarized hereafter. The maximum allowed concentration of hydrogen is assumed to be 8,0% - below this limit the combustion is incomplete and the flame acceleration is considered to be very unlikely [1]. Considering the possible measurement error, the concentration in the assessments was taken 7,5*%*. Two values of absolute pressure in the containment were considered – 3 and 5 *bar*. The concentration of hydrogen in the main volume of the containment is assumed to be 5*%*. The assessments are made for a volume of 1000 m^3. In the table below, the content of the mixture (the main components' concentrations and masses) for the limiting condition is presented.

Table

The mixture content for the limiting condition for 1000 m^3 (C_{H2}=7.5 % vol.)

P=3 *bar abs.*				P=5 *bar abs.*			
C_{H2}, *[% vol.]*	7.5	m_{H2}, *[kg]*	13.6	C_{H2}, *[% vol.]*	7.5	m_{H2}, *[kg]*	21.1
C_{O2}, *[% vol.]*	10.5	m_{O2}, *[kg]*	304.8	C_{O2}, *[% vol.]*	6.3	m_{O2}, *[kg]*	283.6
C_{N2}, *[% vol.]*	39.5	m_{N2}, *[kg]*	1003.3	C_{N2}, *[% vol.]*	23.7	m_{N2}, *[kg]*	933.6
C_{H2O}, *[% vol.]*	42.5	m_{H2O}, *[kg]*	692.4	C_{H2O}, *[% vol.]*	62.5	m_{H2O}, *[kg]*	1574.3

It is clear, that the higher is the pressure, the higher is the density of the hydrogen (as well as of the other components), thus, bigger masses of hydrogen can be removed through venting. According to calculations' results, the content of hydrogen in 1000 m^3 at 5 *bar* pressure will be about 21 *kg*. The considered 7.5*%* limiting concentration of hydrogen can be assessed as conservative for many NPPs, as in some countries the safety requirements related to severe accident management allow even the formation of local detonable mixtures. Thus, higher local concentrations (densities) of hydrogen can be acceptable when implementing the described strategy.

For a PWR power plant the containment volume will very likely be within the range of 60.000…100.000 m^3. Some 2.000…4.000 m^3could be dedicated to the separately sprayed area to implement the described strategy. Depending on the volume of the sprayed area, each portion of hydrogen removed through the considered strategy can be about 50…100 kg or even more.

The presented values correspond to the case when the concentration of hydrogen is limited by 7.5%. It must be considered that at a given moment during the accident progression, due to the operation of PARs and venting, the content of oxygen in the atmosphere will be significantly reduced and, thus, even in the sprayed area, the concentration of oxygen can be out of flammability limits (<5*%*) which will allow to continue spraying and "accumulate" hydrogen within the sprayed area up to concentrations higher than the considered 7.5*%* without any risk of inflammation. In such a case, the atmosphere in the sprayed area will mainly consist of nitrogen, steam and hydrogen, and the hydrogen can be removed by bigger portions. To have such a possibility, the system must also be equipped with oxygen sensors.

Considering the combination of the proposed strategy with PARs, an efficient combination can be ensured by the use of PARs in relatively separated areas to exclude the hydrogen accumulation (small rooms of the containment which are subject to possible steam condensation on the walls and accumulation of hydrogen and air, as well as rooms adjacent to the containment into which the hydrogen can penetrate through possible leakages) with a limited number of PARs in the main premises, and the proposed venting strategy will ensure the removal of the major part of hydrogen from the main premises of the containment.

For each type of containment, detailed analysis is needed to assess the effectiveness of the strategy, including the definition of the free volume of the containment that can be devoted to such a system implementation, as well as the risks related with implementation of the strategy.

Conclusions

1. Due to specificities of PARs' operation, they cannot be considered as reliable and efficient means for mitigation of hydrogen challenge for a broad scope of severe accident scenarios at a NPP. The use of combination of strategies will be more efficient, flexible and reliable.
2. An alternative strategy to cope with a hydrogen challenge is proposed and analyzed by the authors. The strategy is more applicable, but not limited, for PWR plants and can be implemented in combination with PARs.
3. The proposed strategy, besides mitigation of a hydrogen challenge, also ensures removal of aerosols from the containment atmosphere, as well as heat removal from the containment as opposed to the operation of PARs, which is in line with the main goals of severe accident management.

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ԱՏՈՄԱՅԻՆ ԷԼԵԿՏՐԱԿԱՅԱՆՈՒՄ ԾԱՆՐ ՎԹԱՐԻ ԴԵՊՔՈՒՄ ՋՐԱԾՆԱՅԻՆ ՎՏԱՆԳԻ ՄԵՂՄՄԱՆ ԱՅԼԸՆՏՐԱՆՔԱՅԻՆ ՄԵԹՈԴ

Վ.Գ. Պետրոսյան, Է.Ա. Եղոյան, Ա.Դ. Գրիգորյան

ԱԷԿ-ում ծանր վթարի կառավարման հիմնական նպատակներից մեկը ջրածնային վտանգի մեղմումն է: Ջրածնի կառավարման հիմնական միջոցառումներն են միջավայրի իներտացումը և ջրածնի հեռացումը: Ամենից հաճախ կիրառվող ռազմավարությունը հիմնված է ջրածնի պասսիվ ավտոկատալիտիկ ռեկոմբինատորների (ՊԱՌ) կիրառման վրա:

ՊԱՌ-ի աշխատանքի վերլուծությունը ցույց է տալիս, որ որոշ սցենարներում ՊԱՌ-ը կարող է լինել ոչ բավարար արդյունավետ և հուսալի: Ջրածնի հեռացման համակարգի արդյունավետությունը կախված կլինի կիրառվող ռազմավարությունից, վթարային սցենարից և մի շարք այլ գործոններից: Եզրակացություն է արվել, որ ջրածնային վտանգի մեղմման ռազմավարությունը պետք է բաղկացած լինի տարբեր ռազմավարությունների համակցությունից (օրինակ, ՊԱՌ և օդափոխում)՝ վթարային սցենարների լայն շրջանակներում արդյունավետ և հուսալի լինելու համար: Հեղինակների կողմից առաջարկվում է ջրածնի վտանգի դեմ պայքարի այլընտրանքային նոր մեթոդ: Ներկայացված են մեթոդի (ռազմավարության) հայեցակարգը և առավելությունները: Ռազմավարությունը առավել կիրառելի է, բայց չի սահմանափակվում PWR էներգաբլոկներում, որոնք տեղակայված են շատ հերմետիկ շինությունում: Առաջարկվող ռազմավարությունը, բացի ջրածնային վտանգի մեղմումից, ապահովում է նաև հերմետիկ գոտու մթնոլորտից ռադիոակտիվ աերոզոլների, ինչպես նաև ջերմության հեռացում, ի տարբերություն ՊԱՌ-ի աշխատանքի, ինչը համապատասխանում է ծանր վթարների կառավարման հիմնական նպատակներին:

Առանցքային բառեր. ատոմային էլեկտրակայան, ծանր վթար, ջրածնի վտանգ, ջրածնի վտանգի մեղմման ռազմավարություն, պասսիվ ավտոկատալիտիկ ռեկոմբինատոր, սպրինկլերային համակարգ, աերոզոլների հեռացում:

АЛЬТЕРНАТИВНЫЙ МЕТОД СМЯГЧЕНИЯ ВОДОРОДНОЙ УГРОЗЫ ПРИ ТЯЖЕЛОЙ АВАРИИ НА АТОМНОЙ ЭЛЕКТРОСТАНЦИИ

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Смягчение водородной угрозы является одной из основных целей управления тяжелой аварией на атомной электростанции. Основными мерами контроля водорода являются инертизация атмосферы и удаление водорода. Используемая в большинстве случаев стратегия базируется на применении пассивных автокаталитических рекомбинаторов (ПАР) водорода. Анализ специфики работы ПАР показывает, что в некоторых сценариях ПАР могут оказаться недостаточно эффективными и надежными. Эффективность системы удаления водорода будет зависеть от используемых стратегий, аварийного сценария и многих различных факторов. Сделан вывод о том, что стратегия смягчения водородной угрозы должна состоять из комбинации различных стратегий (например, ПАР и вентилирование), чтобы быть эффективной и надежной в широком спектре аварийных сценариев. Предлагается новый альтернативный метод борьбы с водородом. Представлены концепция и преимущества метода (стратегии). Стратегия более применима, но не ограничивается для PWR энергоблоков, имеющих большие защитные оболочки. Предлагаемая стратегия, помимо смягчения угрозы водорода, обеспечивает удаление аэрозолей, а также теплоотвод от атмосферы защитной оболочки, в отличие от работы ПАР, что соответствует основным целям управления тяжелыми авариями.

Ключевые слова: атомная электростанция, тяжелая авария, водородная угроза, стратегия смягчения водородной угрозы, пассивный автокаталитический рекомбинатор, спринклерная система, удаление аэрозолей.