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# Abnormal Hydrogen Generation in Fukushuma BWR Units Accidents

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**Abstract:** ***A simulation of loss of AC power in a 720 MWe BWR with Mark II containment has been made to compare with the sequence of events that occurred at Fukushima Daiichi BWRs in March, 2011. In this study, all AC power was considered lost after the tsunami swept through Fukushima Daiichi units following an earthquake with intensity of around 0.5g. The affected Fukushima units were BWR-1, with Mark I containment, Unit 1 rated at 439 MWe, and other three units rated at 784 MWe each. The simulation corresponds to BWR unit 2 and unit 3, which experienced hydrogen fire/explosion following excessive Zr-water reaction and radiolysis. In the simulation, actions and failures of all emergency coolant injection and recirculation systems, and containment vapour suppression systems of typical BWRs were simulated. The simulation also computed the extent of metal-water reaction in the reactor vessel. Even with severe starting assumptions, the hydrogen yield is grossly under predicted. The amounts of hydrogen that got generated during these accidents were greatly in excess of the design limits. The amounts of hydrogen and oxygen that got generated in units 1, 2 and 4 were enough to create massive fires in these units. In unit 3, these gases were enough to support a hydrogen explosion. A hypothesis is proposed which could explain the causes of excessive Hydrogen generations in reactor environments are presented. However, it is necessary to perform experiments to prove or disprove this hypothesis. Pending such verification, interim measures are necessary to minimise risks in the short term of repeat of Fukushima type events. Interim suggestions for controlling metal-water reactions in nuclear power plants and for mitigating their effects under accident conditions are presented.***

**Keywords:** station black out; severe accidents; Zr-water reaction; hydrogen combustion; hydrogen explosion

## 1. Simulation of Loss of Power Accident on BWR 720 MWe for End of Cycle condition

A simulation of loss of AC power in a 720 MWe BWR with Mark II containment has been made to compare with the sequence of events that occurred at Fukushima Daiichi BWRs in March, 2011. In this study, AC power was considered lost when the site experienced an earthquake (E/Q) that led to the tsunami. This E/Q had a peak ground intensity of around 0.5 g *[1]*.

The flood caused by this tsunami submerged several equipment, such as the DGs and related switchgear of all 4 units, DC batteries of units 1, 2 and 4 *[2]*. From published reports, it appeared that the DC power supply was lost for motive power in units 1, 2 and 4, but enough DC power may have remained for control purposes. On unit 3, DC power was available for some time *[2]*.

The affected Fukushima units were BWR-1, with Mark I containment, Unit 1 rated at 439 MWe, and other three units rated at 784 MWe each. The simulated BWR, rated at 720 MWe corresponds to BWR unit2 and unit 3.

A comparison of Mark 1 containment parameters of Fukushima 1,2 and 3 with those of another Japanese 1100MWe BWR containment of Mark II type is shown in the table A-1 below:

**Table A-1**

| Containment Parameter | BWR-460 MWe Mark I | BWR-784 MWe Mark I | BWR-1100 MWe Mark II |
|---|---|---|---|
| Containment volume | 7780 cubic meters | 10380 cubic meters | 13280 cubic meters |
| Water volume in WW | 1865 cubic meters | 2980 cubic meters | 3400 cubic meters |
| Design pressure | 5.4 bars | 4.9 bars | 4.2 bars |

The simulated BWR, rated at 720 MWe, with Mark II containment, had larger pro-rata drywell (DW) and wetwell (WW) volumes as compared to those of units 2 or 3. This can be inferred from the table A-1 above. However, the other assumptions, namely, EOC condition, SBO at the moment of E/Q should make the computed results more severe than actual. In the simulation, actions and failures of Automatic Depressurizing Systems (ADS), Reactor Core Isolation Cooling systems (RCIC), High Pressure Coolant Injection system (HPCI), Low Pressure Coolant Injection system (LPCI), Residual Heat Removal Systems (RHR), and secondary (SC) containment vapour suppression systems could be simulated. The simulation could also compute the extent of metal-water reaction in the reactor vessel, its accumulation in the drywell (DW), and wetwell (WW). Even with severe starting assumptions, the hydrogen yield seems to be grossly under-predicted by the current Baker-Just co-relationships.

The analyzed reactor events begin with station black-out (SBO) at the moment of scram under E/Q sensing (actually, the reactors scrammed on E/Q sensing, SBO occurred about one hour after).

The analyzed reactor sequence assumes that the Auto-Depressurizing System gets actuated soon after scram. Actually, the reactor cooling systems RCIC would have operated to cool Units 2 & 3 for about 40 hours, until the tsunami wave swamped the plant site and possibly affected the suction line from the condensate storage tank to the RCIC system. Even after SBO, the ADS could come in after 23 minutes on low level in RPV of unit 1.

The Table A-2 shows results of the simulation, following E/Q and SBO simultaneously for EOC condition.

**Table A-2:** Parameters Important To This Study – BWR-720 MWe SIMULATION

| Time Past SBO<br>Parameter | 0 min. | 23 min.<br>ADS on | 25 min. | 42 min. | 60 min. | 68 min. | 78 min. | 90 min. |
|---|---|---|---|---|---|---|---|---|
| RPV pr, bars | 70.6 | 67.4 | 67.8 | 1.44 | 1.44 | 1.59 | 1.76 | 1.96 |
| DW pr. Bars | 1.0 | 1.02 | 1.05 | 1.44 | 1.44 | 1.59 | 1.75 | 1.96 |
| WW pr. Bars. | 1.0 | 1.06 | 1.08 | 1.47 | 1.47 | 1.62 | 1.78 | 1.99 |
| CORE WATER LEVEL, m. | 14.8 TAF+3.9 | 11.9 TAF+.5 | 8.92 BAF+1.2 | 6.80 | 4.41 | 3.78 | 3.38 | 2.82 |
| WATER IN CORE tons | 240 | 200 | 170 | 130 | 100 | 90 | 80 | 66 |
| PEAK FUEL TEMP. $^0$C | 667 | 324 | 251 | 1660 | 2225 | 2225 | 2225 | 2225 |
| PEAK CLAD TEMP. $^0$C | 290 | 292 | 249 | 880 | 1650 | 1651 | NA | NA |
| $H_2$ formed. Kg. | 0 | 0 | 0 | 0 | 77 | 114 | 152 | 220 |
| $H_2$ in % | 0 | 0 | 0 | 0 | 10 % | 14 % | 18 % | 22.4 % |

TAF stands for Top of Active Fuel, BAF for Bottom of Active Fuel Length. Active Fuel Length was 3.7 m.

The design limit on pressure for DW and WW for Mark II containment was 4.2 bars. The extent of Zr reacted is 220 kgs. or about 0.43 % of the cladding.

When compared to actual events and figures for units 2 and 3, it will be seen that these limits were grossly exceeded during the accident sequence. After analyzing the data of units 1, 2 and 3, **it is hypothesized that yields of hydrogen from Zr-water reaction in steaming irradiated cores had greatly exceeded the estimated yields as per current relationships such as Baker-Just relationship.**
**Likewise, It is hypothesized that radiolysis of steam in irradiated cores had been under-estimated by current co-relationships**

It should be noted that the amount of water in the RPV (240 tons) at start of the sequence comes down to around 150 tons, when the RPV water level hits BAF, i.e. around 60 % of initial amount. The data on units 1, 2 and 3 in succeeding tables show the sensed/indicated water levels. These reactors did not go below BAF, and stabilized at around BAF plus 1.8 meters, i.e., around 50 to 60 % of active fuel height.

**Likely Sequence of Events on Unit 1, Unit 2 and Unit 3**

Likely Sequence Of Events On Unit 1

1) On unit 1, the isolation condenser (IC) came on after E/Q and scram. It led to rapid cooling @ 55$^0$ C per hour. As this was considered excessive, the operators shut off the IC. After that the tsunami struck, knocking out all AC power sources, leaving the IC blocked shut *[2]*. DC power was lost in a few minutes after the tsunami struck, but was restored from an external source about 3:30 hrs. after E/Q *[4]*. The core cooling would have been minimal in absence of ADS.
2) As stated in Table B-2, at 2:44 hours, water injection into the core was attempted, using external DG power. This injection would have been limited to the capacity of the Control Drive Feed Pump, which runs on class I or class II power. It did not seem to make much difference as the RPV remained at 69 bars at 6:14 hours, while water level dropped to 0.5 m. above TAF, i.e., initiation level for ADS.
3) After SBO, the pressure in the RPV started rising. This rise was controlled initially by SVs and RVs, and later by ADS which got activated to due decreased water level in the RPV.
4) At 6:33 hrs. water level in the RPV fell below initiation level of ADS, leading to blow-down to the suppression pool. During this blow-down, as can be seen from Table 2 the RPV started depressurizing, and water level in core fell to TAF+ .2m. around 6:33 hours after E/Q. The RPV depressurized in about another 5 hours to 8.5 bars and the DW and WW were also at the same pressure by 11:44 hours.
5) The WW pressure had reached 6 bars at 10:03 hours, it must have been due to relieved steam via ADS from the RPV into the WW. It contributed to loss of water level in the RPV. WW got pressurized beyond its design limit of 5.4 bars, indicating that some gas other than steam had been generated in the RPV and released into the WW. Considering that the RPV water level was above TAF, **it is hypothesized that this gas could have been largely hydrogen formed as a result of Zr-steam reaction in radio-active environment of the core.**
6) It can be seen from Table B-1 that after 11 hours 44 minutes, the containment pressure reached 8.4 bars, or > 150 % its design pressure due hydrogen, nitrogen and steam **This pressure grossly exceeded the design limits for DW and WW.** It can be seen from Table 2 that water level in core reached the TAF around 17:09, indicating that enough water and steam were present in the RPV to sustain the hypothesized chemical reaction.
7) At 12:30 hours, diesel driven fire pumps were used to push water into the RPV, since its pressure had dropped to around 8 bars. This pumped in water led to recovery of water level in the RPV and reduction of its pressure to 7.7 bars by 14:23 hours. WW was at 7.7 bars. Since the WW and RPV were at the same pressure, it indicated that steam relief via ADS was still functioning.
8) From 17 hours to 21 hours, the water remained at or above TAF. It came down to 1.6 m. below TAF at around 22 hours, or about 2:40 hours prior to the fire in the reactor building.
9) The operators, alarmed by this excessive pressure rise in the DW and WW, attempted to vent the containment (DW) through emergency vent line at 18 hrs. 29 mins. as can be seen from Table 2. In BWR ventilation systems, ventilation lines from containment (WW and DW), under normal conditions, join with ventilation lines of reactor building service floor, before release through the stack.
10) Since the SBO had disabled the ventilation valves, the exit through the stack would have been severely limited if not blocked and the hydrogen rich air from the containment would have filled the operating floor of the reactor building. After 24 hrs 50 mins. past tsunami, or 6 hours after venting was started, the reactor operating

floor burst into flames. As per Japanese reports, the operators tried to open the containment vent valves using a portable air-compressor since these vent valves were air-to-open, spring-to-shut, and the system compressed air supply would not have been available. After venting for about 2 hours, the reactor building service floor got gutted due to the conflagration. This mode of venting was discontinued, so the containment did not depressurize further, and held its pressure for further three weeks. The foregoing events can be seen in Table 2.

11) The relief of DW by operator action from 18:29 to 20:00 hours possibly caused the RPV water level to drop to 1.6 m. below TAF. The active fuel length was half covered in water 22 hours after E/Q, as the water level was sustained by pumping water by external fire fighting pumps. Hence, around 43 % of the active fuel length stayed from 22 hours onwards, in contact with dry steam. Refer to Table 2 for timings and events.

12) As per BWR ventilation systems, the vents from WW and DW normally merge with the ventilation line from the reactor building. In addition, the emergency ventilation lines from DW and WW lead to the stack after going through filters and fans. Under SBO, the fans would be stopped, and hence release of emergency vents to the stack would be impeded or blocked by the stalled fans and filters. Under emergencies, vent lines from DW and WW goes to the stack, after traversing several isolation valves and a rupture disc. This rupture disc remained intact all along.

13) It is very likely that the vented gases from DW and WW, composed of hydrogen, relatively small amount of radiolytic oxygen, nitrogen and steam would have entered the large air-filled space of the reactor building operating floor. This combustible gas mixture led to fire on that floor.

**14)** There was **<u>no second</u> <u>deflagration after the first fire event</u>**, even as the RPV stayed at 5.2 bars pressure and the DW and WW stayed at 2.7 bars for as long as 27 days after the tsunami. The RPV temperature was reported to be 143 $^0$C, i.e. close to saturation temperature of water at that level. The temperature of RPV was at 225$^o$C. The RPV water level was reported as 1.6 m above BAF *[3]*. These data would suggest that the hydrogen generation could have been continuing at low temperatures even after the fire event. The containment did not experience fire as it did not have enough oxygen to support combustion of the generated hydrogen

**Table B-1:** Times and Events Significant in this study in Unit 1 *[4]*

| Time Past E/Q and SCRAM | Events and Actions |
|---|---|
| 6 minutes | IC starts on high RPV pressure |
| 17 minutes | IC manually shut down on high cooling rate |
| 21 to 24 minutes | Suppression chamber (WW) spray starts |
| 49 minutes | Massive tsunami wave hits the site |
| 51 minutes | Loss of AC and DC power and of UHS |
| 2 hours 44 minutes | DC powered water injection into core attempted |
| 5 hrs. 40 minutes | WW at 6.9 bars, RPV at 70 bars |
| 6:14 to 6:33 hrs. | RPV at 69 bars, RPV water level at .5 m above TAF, starts ADS |
| 9:00 to 10:03 hrs. | WW pressure at 6 bars |
| 11:44 hrs. | RPV pressure at 8.4 bars, RPV water level at TAF + 0.9m. |
| 12:30 hours | Diesel Driven Fire Pump used to pump water into core |
| 14:23 hrs. | RPV and WW at 7.7 bars |
| 17:09 hours | Core water level at TAF |
| 18:29 to 20:09 hrs. | Operators opened DW vent valves, using portable air pump |
| 21:19 hours | Core water level at .2 m. above TAF |
| 22:09 hours | WW pr. at 7.5 bars, Core water level at 1.6 m. below TAF |
| 24:05 hours | WW pressure at 5.8 bars |
| 24:50 hours | Fire wrecks service floor of reactor building |

**Likely Sequence of Events On Unit 2**

1) On unit 2, the E/Q triggered the scram. As unit 2 had no IC, its steam RVs and SVs would have acted to relieve steam pressure in the initial minutes. After several minutes (estimated at 20 minutes), the steam-driven RCIC system would have cooled the reactors for about 1 hour, until the tsunami struck. The E/Q affected the motive DC power supply in Unit 2.
2) Once the tsunami had disabled the DGs, the only power supply seems to have been DC power supply for control purposes. This DC power supply enabled RCIC to function intermittently from 52 minutes to 9:43 hours, as can be seen from Table B-2. In this period of time, the fuel was submerged by around 3 to 4 meters above TAF.
3) On Unit 2, the RCIC worked, drawing water from the condensate storage tank for the initial period upto 9:43 hours past E/Q. The water level had built up in the WW pool. Hence its suction was switched to the WW pool at 13:33 hours (Table B-2).
4) From 26:43 hours to 69:13 hours, **<u>the WW pressure rose from 2 bars to 4.8 bars. Here again, design limit on WW pressure limit was approached , presumably due to generation of hydrogen and oxygen,</u>** while the RPV water level was 2.9 meters above TAF ) (Table B-2).
5) The RCIC which was fed from WW at 13:33 hours would have continued to bleed steam to the WW and feed water to the RPV from the WW upto 69:13 hours or beyond. (Table B-2)
6) The core water level fell from TAF at 74:30 hours to BAF at 75:36 hours (refer Table B-2).

**Table B-2:** Times and Events Significant In This Study In Unit 2 *[4]*

| Time Past E/Q and SCRAM | Events And Actions |
|---|---|
| 03 to 04 minutes | RCIC started up manually, trips I minute later on high water level in RPV |
| 13 to 20 minutes | RCIC system manually started, then tripped. RCIC started manually |
| 44 minutes | RCIC trips on high water level in RPV |
| 49 minutes | All AC power lost, due to massive tsunami wave |
| 52 minutes | RCIC started manually, 3 minutes past tsunami |
| 5:43 hours | RCIC stopped |
| 7:13 hours | Core water level at 3.4 m above TAF |
| 8:38 hours | RPV at 63 bars |
| 9:08 hours | RPV water level at TAF+3.5 m., WW at |

| | |
|---|---|
| | 1.4 bars |
| 9:43 hours | WW at 1.4 bars, RCIC stopped |
| 13:33 hours | RCIC supply switched to WW from condensate storage tank |
| 26:43 hours | WW pressure at 2 bars |
| 36:13 hours | WW at 3.15 bars |
| 41:23 hours | DW vent valve opened to relieve pressure |
| 69:13 hours | WW at 4.8 bars, RPV water level at 3.4 m. above TAF |
| 73:47 hours | RPV relief opened briefly to reduce RPV pressure |
| 75:35 hours | RPV water level at BAF, DW at 6.4 bars |
| 78:16 hours | RPV at 14 bars, WW at 4.2 bars, water level at 1.8 m. below TAF |
| 84:13 hours | DW at 7.5 bars, RPV relief valves opened |
| 87 hours | Deflagration in DW, WW at 7.5 bars, water level at 2.8 m. below TAF |

7) From 26:43 hours to 78:16 hours, the RPV continued to lose pressure from 63 bars to 14 bars, but the **WW pressure rose at 86:13 hours from 2 bars to 7.5 bars**. The core water level fluctuated from 3.4 m. above TAF to BAF and then to 2.8 m below TAF, i.e. the fuel was uncovered at 75:35 hours, but remained about 25 % covered by 87 hours, or the moment of fire. (Table B-2)
8) At around 76 hours, the SRVs were opened manually to lower RPV pressure to allow sea water in via Fire Protection System pumps (FPS). This action caused water level to recover to around 1.2 meters below TAF. (table B-2).
9) **This limited cooling of the fuel inhibited Zr-steam reaction, but it sustained radiolysis of the reactor water and steam (as per hypothesis).** 11. On 27$^{th}$ March, the RPV pressure was reported at 0.83 bars, its temperatures at bottom and FW nozzle areas at 111$^{0}$C and 124$^{0}$C respectively. The PCV pressure was reported 1.1 bars *[3]*. These data would indicate that the RPV and WW had retained their shape and some limited pressure retaining ability even after the hydrogen conflagration.

**Sequence of Events on Unit 3**

1) On unit 3, the E/Q triggered the scram. As unit 3 had no IC, its steam RVs and SVs would have acted to relieve steam pressure in the initial minutes. Some minutes after the E/Q and scram, (estimated at 6 minutes), the steam-driven RCIC system would have cooled the reactors for about 1 hour, until the tsunami struck. The E/Q had not disabled the DC power supply.
2) Once the tsunami had disabled the DGs. The only available power supply seems to have been DC power supply, This DC power supply enabled RCIC to function intermittently from 52 minutes to 21:23 hours, as can be seen from Table B-3. In this period of time, the fuel was submerged by around 3 to 4 meters above TAF but the RPV pressure peaked to 75 bars thereby causing the RVs to open. At 21:48 hours, the RPV pressure had dropped to 56 bars, and HPCI system was invoked. (Table B-3). It could be inferred that the RCIC did not maintain the water level in the RPV. It would also indicate that enough DC power must have been available to power the HPCI.
3) From 21:48 to 35:55 hours, the HPCI functioned to reduce RPV pressure to 6.8 bars. However, the WW was at 5.8 bars, i.e., above design pressure of 4.9 bars. (Table B-3) **This would indicate that with partly submerged fuel, hydrogen generation in excess of prediction had occurred**.
4) At 35:55 hours, sea water was injected into the containment via fire fighting pumps to cool it. The RPV was at 6.8 bars, and WW at 5.3 bars. (Table B-3)
5) From 37:28 hours to 40:58 hours, the fuel started getting exposed to steam, and the RPV pressure rose to 73 bars, while water level in core dropped to BAF, and DW pressure remained high at 4.6 bars. **This increase of pressure would have come from uncontrolled radiolysis of steam in the RPV.**
6) The decrease in water level in RPV from 37:28 hours to 40:58 hours would indicate that blow-down of steam via RCIC and HPCI occurred at expense of water in the RPV and that HPCI and RCIC did not pump in enough condensate water to sustain the water level in the RPV. The fact **that the WW pressure rose from 3.6 to 4.6 bars, and RPV pressure rose to 73 bars would indicate that hydrogen generation increased as more fuel got exposed to steam**. (Table B-3)
7) From 42:38 to 45:33 hours, borated sea water injection into in the RPV started. The RPV pressure came down to 29 bars, RPV water level at 2 m. below TAF, DW at 5.2 bars. (Table B-3)
8) From 61:43 hours onwards, the RPV water level stayed at 3.7 m. below TAF, i.e. at BAF, and the DW and WW pressures stayed at around 5 bars. (Table B-3)
9) The RCIC and emergency sea water injection cooled the fuel for a longer period than in Unit 2. Here again, the extended cooling of the fuel elements inhibited Zr-steam reaction, but sustained radiolysis of the reactor water and steam even more than in Unit 2.
10) The accumulated hydrogen-oxygen steam nitrogen mixture in the DW and WW led to hydrogen detonation inside the containment, leading extensive damage to the reactor building.

**Table B-3:** Times and events significant to this study in unit 3 *[4]*

| Time Past E/Q and SCRAM | Events and Actions |
|---|---|
| 18 minutes | RCIC started up manually |
| 38 minutes | RCIC trips on high level in RPV |
| 51 minutes | All AC power lost 3 minutes after big tsunami wave |
| 1:16 hours | RCIC started up manually |
| 5:43 hours | RCIC in operation |
| 8:11 hours | Water level in RPV at 3.5 m. above TAF |
| 21:23 hours | RPV at 75 bars |
| 21:48 hours | RPV water level at 3 m. above TAF, RPV at 56 bars, HPCI started |
| 26:13 hours | RPV pressure at 34 bars |
| 29:28 hours | RPV at 8 bars |
| 35:55 hours | RPV at 6.8 bars, sea water injection started, WW at 5.3 bars |
| 37:28 hours | Water level in RPV at 1.6 m. below TAF |
| 38:13 hours | RPV at 74.6 bars, core water level 2 m. below TAF, WW at 3.6 bars |
| 40:58 hours | RPV at 73 bars, core water level 3 m. below TAF, WW at 4.6 bars |
| 42:38 to 45:33 hours | Injection of borated sea water started into RPV |
| 46:13 hours | RPV at 29 bars, core water level at 2 m. below |

| | |
|---|---|
| | TAF, DW at 5.2 bars |
| 58:23 hours | Injection of sea water stopped. Core water level at 2 m. below TAF |
| 61:43 hours | RPV water level at 3.7 m. below TAF, i.e. at BAF |
| 63:23 to 66:14 hours | DW pressure at 4.9 bars, WW pressure at 5 bars |
| 68:14 hours | Explosion in DW and WW |

## 2. Observations Based on this Study

This study brings out the hazards from hydrogen generation in reactors which can experience bulk boiling under normal and anticipated operational conditions.

1) Even though this study was based on more severe assumptions than the actual conditions, the **hydrogen generations were under-estimated by factors > 2**;
2) **Even this sequence (based on severe assumptions) could not predict pressure of containment to 8 bars, which would require over 3 % of Zr to react.**
3) This study shows that blow-down of reactor water will occur in around 90 minutes. Actually it took around 6 hours to reach TAF on unit 1, around 70 hours on unit 2 due to RCIC cooling, and around 20 hours on unit 3, due to RCIC and HPCI cooling plus sea water injection on unit 3;
4) It can be inferred that neither the RCIC (Units 2 and 3) nor the HPCI system (Unit 3) were effective in restoring the water level in the RPV to levels above their actuation levels. This could indicate that when these systems were functioning, their inlet water supply was impaired.
5) **The slow blow-down rate of units 1, 2 and 3 could be ascribed to creation of back pressure in WW due to excessive hydrogen generation from Zr-water reaction and radiolysis;**
6) Typically, the currently accepted threshold of Zr-water reaction at around 800 $^{o}$ C and start of vigorous Zr-water reaction at around 1100 $^{o}$ C may be an under-estimate;
7) As a case in point, no model could predict the hydrogen fire in unit 4 spent fuel, following a suspected and reported liner leak, leading to partial uncovering of the stored fuel;
8) Hydrogen generations, based on Baker-Just equations may have under-predicted the actual hydrogen yields under reactor environments where fuel experiences high quality steam;
9) **Whereas the fire event in unit 1 could be ascribed, by and large, to hydrogen generation from Zr-water reaction, the generation of hydrogen in units 2 and 3 seems to be largely from radiolysis of steam under gamma rays emanating from the spent nuclear fuel in core.**
10) The fire in unit 2 resulted from contents of the containment alone, without dilution with air from outside. It would appear that enough hydrogen and oxygen had been formed in the reactor during RCIC action without sustained make-up from water storage tanks. It is clear that this hydrogen-oxygen mix formed a combustible mixture.
11) This accumulated hydrogen and oxygen combined in a fire inside unit 2 primary containment. Photographs show the overall reactor building to be externally undamaged except for the area of the blow-out panel.
12) In unit 3, the same sequence appears to have been followed as in unit 2, but radiolysis had occurred over fuel that had been cooled over a prolonged period of time, leading to creation of explosive amounts.
13) Hence, unit 3 suffered a hydrogen explosion and the same is apparent from photographs which show unit 3 to be a bombed out wreck.
14) At the time of unit 3 explosion, unit 4 fuel pool was at **$84^{0}$ C, i.e. it was heating from decay heat emitted by stored spent fuel and lack of active cooling *[5]*.**
15) In unit 4, the E/Q appears to have caused a leak in the spent fuel pool which contained the discharged core and earlier discharged batches of fuel *[3]*. As the water leaked without makeup of water, the spent fuel got partly exposed to air and steam. **This situation, under gamma field appears to have created enough radiolysis to cause a hydrogen fire that wrecked the building about 22 hours after the explosion on unit 3.**

## 3. Recommendations for PWRs, PHWRs and BWRs (actions as prudential measures)

The phenomena of Zr-water reactions and hydrolysis in steaming reactor environments need to be investigated to ensure that such events are prevented. However, pending such investigations, some interim measures are suggested for planned and existing PWRs, PHWRs and BWRs below as prudential actions.

1) In existing or planned water cooled reactors where bulk boiling is expected under normal or anticipated operational occurrences, the predictions of Zr-water reaction and water radiolysis and their control must be validated before these reactors are operated;
2) In existing or planned water cooled reactors where bulk boiling is expected under normal or anticipated operational occurrences, installation of isolation condensers should be assured for the initial period of cool down. Alternately, Passive Heat Removal Systems should be assured.
3) Auto-depressurization systems should be discontinued, and be replaced by Passive Heat Removal Systems (PHRS).
4) In addition, passive high pressure coolant injection systems should be available to cater to small and medium size LOCA accidents.
5) High pressure ECCS should be installed with entry to top and to bottom of fuel assemblies.
6) Where RCIC and HPCI systems are employed, it should be ensured that these systems do not lower the water level in the RPV to the point that hydrogen generation does not go out of control.
7) Where Isolation Condensers are employed, it should be realized that these systems provide residual heat removal upto 8 hours or thereabout; after that period of grace, low pressure injection and cooling must be assured in SBO cases;
8) Where Passive Heat Removal Systems are used, this grace period is extended very considerably, even upto to cooling the primary system down to $>100^{0}$ C;
9) After cool-down to $100^{0}$ C, long term safety support systems not dependent on normal AC power should be

available to cater to post accident conditions until such time that off-site resources are reliably available;

10) There is a crying need to install hydrogen recombiners in the air space over spent fuel storage pools; and these should be both, active and passive recombiners;
11) The air vents from these areas, under DBAs should have provisions for discharge through dryers, absolute filters and recombiners before discharge to environment, even under SBO conditions;
12) Hydrogen generations should be based on Zr in cladding and structurals in core, and in parts of the core experiencing bulk steaming, on radiolysis too.

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