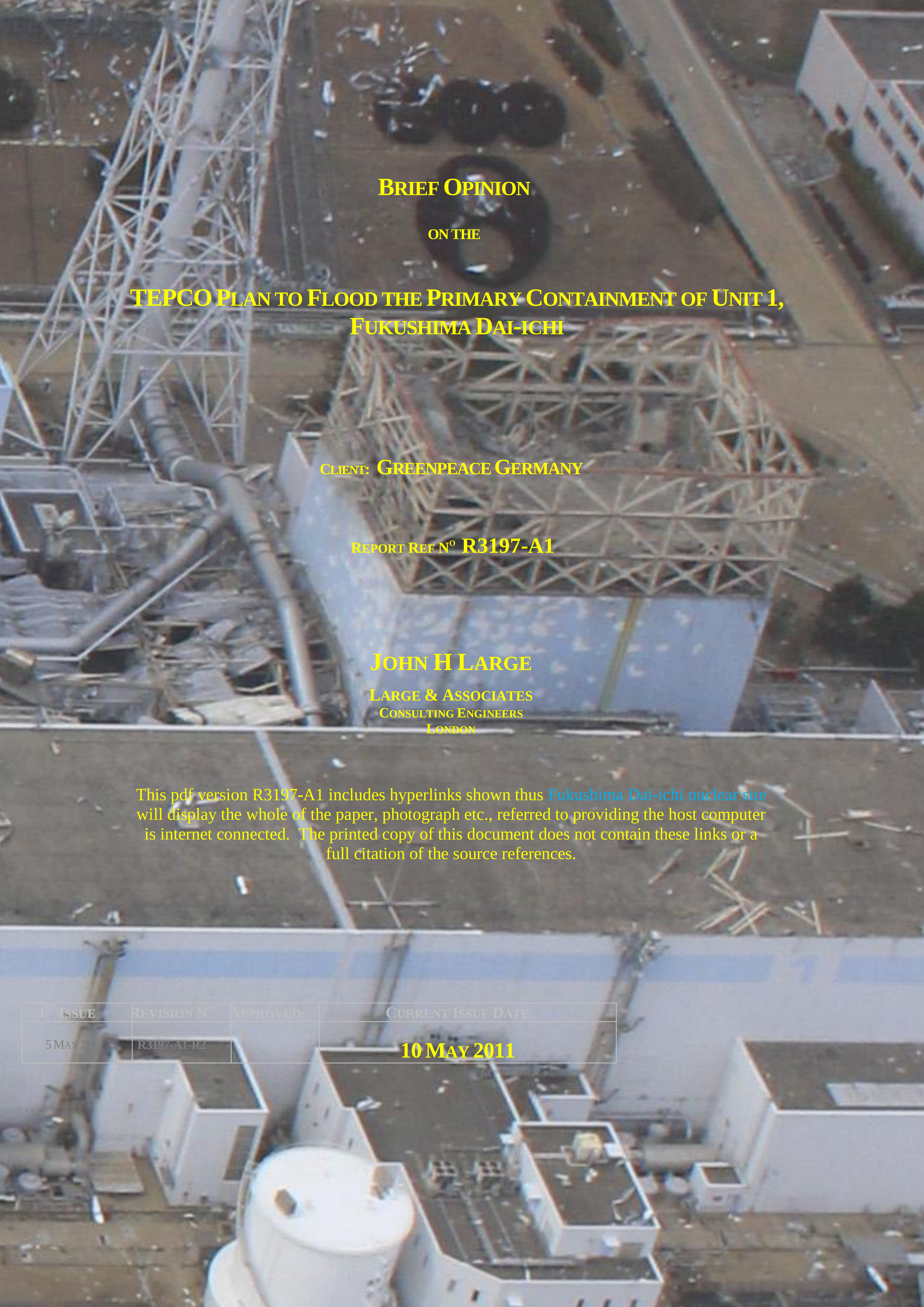

BRIEF OPINION

ON THE

TEPCO PLAN TO FLOOD THE PRIMARY CONTAINMENT OF UNIT 1, FUKUSHIMA DAI-ICHI

CLIENT: **GREENPEACE GERMANY**

REPORT REF N^{o} **R3197-A1**

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TEPCO PLAN TO FLOOD THE PRIMARY CONTAINMENT OF UNIT 1, FUKUSHIMA DAI-ICHI

SUMMARY

This brief review considers the TEPCO plan to flood the primary containment of the Fukushima Dai-ichi Unit 1 reactor block – TEPCO announced this scheme on 5 May 2011 presenting a summary report (4pp) it claimed justified the scheme that had full approval of NISA, although no further detailed information on the justification and nuclear safety case, if indeed undertaken, has been made available from either party.

To date and particularly with its somewhat flimsy summary report that attempts to justify the flooding, it is not at all clear that TEPCO's assessment has fully accounted for all of the potential risks and shortfalls of the scheme. These areas of uncertainty relate to the actual state of the fuel in the reactor pressure vessel (RPV), the condition of the RPV and, strikingly absent, the structural surety of the primary containment, particularly in fulfilling its enclosure and structural roles when subject to aftershocks and, quite probably, future seismic events.

Of particular concern is that the post-haste approach has, or so it seems from the limited information publicly available, skirted around the development and validation of a nuclear safety case. If it is inevitable that the primary containment will have to be flooded to salve a worsening situation in Unit 1, it should nevertheless be rigorously justified on nuclear safety and environmental impact grounds.

This is because fully flooding the primary containment is an entirely unique application that does not seem to have been considered at the design stage of this BWR NPP some 40 to 50 years past. The fact that the built structure of the primary containment has been in service for forty years (some might opine a period well beyond its design service life), over which it has been subject to inevitable age-related degradation, and that it has sustained the severe seismic event of 11 March, followed by a violent explosion of 12 March all, surely, make it even more imperative that the adequacy to perform this new (and *beyond-design-basis*) task be openly and thoroughly demonstrated.

Because of the high radiation levels persisting in and around the Unit 1 reactor block, TEPCO has been denied access to painstakingly inspect the built structures. Although it acknowledges there to be leaks through the containment, TEPCO has been unable to, first, identify the locations of these leaks and, second, to relate how these leakage paths (that must be structural discontinuities) could impair or degrade the structural containment role of Unit 1.

In this respect, TEPCO's justification for proceeding with the flooding, as presented in the publicly available summary report,[13] is scant and lacking the rational and disciplined approach that such a project merits.

Certainly, TEPCO's approach in presenting the flooding scheme is not sufficiently comprehensive, omitting as it does any consideration of the period over which the Unit 1 primary containment will have to act as a *'water sarcophagus'* – it gives little cognisance to the radiological consequences should the containment fail in the near or longer terms – there is no consideration of how the surety of this adaptation of the containment and building hulk of Unit 1 might be maintained in future years nor, indeed, how it might be practicably dismantled and decommissioned at some unspecified time in future.

In short, TEPCO's scheme for the flooding of Unit 1 seems to be poorly-thought through and, although now in the process of practicable implementation, a demonstrable nuclear safety case has not been presented. Moreover, it is empirical and hastily prepared scheme for which, should it fail, there is and cannot be a contingency plan.

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TEPCO PLAN TO FLOOD THE PRIMARY CONTAINMENT OF UNIT 1, FUKUSHIMA DAI-ICHI

The Tokyo Electric Power Company (TEPCO) has announced[1] that it is to bring the Fukushima Dai-ichi Unit 1 reactor to cold shutdown.

Cold Shutdown: Essentially, cold shutdown (sometimes referred to as *thermal rollover*) is the sub-critical and stable state present in a nuclear reactor when the coolant system is at atmospheric pressure and a temperature below 95°C. This temperature is low enough that the water cooling the fuel in a light water reactor, such as a boiling water reactor (BWR), does not boil even when the reactor coolant system is completely de-pressurised. Since cold shutdown has to be achieved and preserved for refuelling and reactor pressure vessel (RPV) primary circuit maintenance and repair work, any heat extraction (ie cooling) has to be predominantly by natural circulation and convective means, although the low pressure residual heat recovery (LPRHRS) may be used to supplement natural heat dissipation. Because the fuel core of the Unit 1 reactor at Fukushima Dai-ichi is acknowledged to be damaged,[2] the other parameters determining the shut down state cannot be assumed to be in place.[3]

Application to Unit N° 1 Fukushima Dai-ichi: The Unit 1 reactor was the first nuclear power plant (NPP) constructed and commissioned on the Fukushima Dai-ichi complex.

TABLE 1 FUKUSHIMA DAI-ICHI NPP DETAILS

NPP	TYPE	IAEA CODE	THERM/NET ELECT MW	CORE FUEL	REACTOR SUPPLIER	1st COMMERCIAL GENERATION
FUKUSHIMA 1 - 1	BWR-3	JP-5	1380/439	LEU	General Electric	1971

The Unit 1 reactor is contained within the so-called in the Mark I *light bulb-and-doughnut* containment system, comprising a steel-lined drywell (the *light bulb*) and the interconnected torus shaped wetwell (*doughnut*) – see FIGURE 1, APPENDIX A.

In normal operation, the reinforced concrete structure forming drywell supports the RPV and acts as an enclosing biological shield. The wetwell has no specific function during normal, incident–free operation of the reactor.

In abnormal operation, for example under conditions of a loss of coolant accident (LOCA), the high pressure steam escaping from the RPV expands into the drywell cavity. The increased pressure in the drywell cavity channels the steam through vents into the wetwell where it is bubbled through numerous tubes submersed in the half water filled torus chamber, being quenched and condensed by this suppression process.[4] FIGURE 2A

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[1] TEPCO Press Release 5 May 2011 - http://www.tepco.co.jp/en/press/corp-com/release/11050503-e.html - TEPCO is the company responsible for all six NPPs at the Fukushima Dai-ichi nuclear complex.

[2] TEPCO assessment of Core Damage and CAMS data of Units 1, 2 and 3, includes corrections of previous assessment.

[3] The definition of *'cold shutdown'* is usually applied to a reactor with an undamaged fuel core also includes the parameters relating the subcriticality and reactivity of the fuel core, in terms of the shut-down margin usually expressed as delta-k/k_{eff} and also in the control rod worth less the core excess – the US Nuclear Regulatory Commission (NRC) provides the normally accepted and basic definition of cold shutdown.

[4] The heat is removed from the steam by bubbling (cooling) it in the wetwell with the objective to reduce the pressure in the drywell maintaining it below the maximum design pressure of the containment. To be effective, pressure suppression must take place concurrent with the flow of steam but this suppression capacity can be exhausted if the release of steam into the drywell containment is prolonged, thereby resulting in an undesirable increase in the dry and wetwell pressures and, eventually, overpressurisation and damage of the primary containment structures – the design pressure is about 4 to 5 bar

schematically illustrates the emergency core cooling and coolant make up systems typically available in a Mk I BWR NPP.

As well as catering for a LOCA, the primary containment will, in the event of overpressurisation of the RPV, provide for the vessel pressure to be relieved by automatic or manual venting from the RPV head into the wetwell via a separate bubbling manifold.

In the 1980s, all BWR Mark I containments systems operating in the United States (and it is believed all 32 MK I BWRs then operating worldwide) were retrofitted with a second venting system to relieve the build-up of pressure in the drywell during a LOCA. This venting route provides a direct 'hardened tube'[5] to the discharge pylons through which potentially explosive hydrogen-air gas mixes can be released to atmosphere.

The containment venting system is one of several services, instrumentation, feedwater and steam penetrations that pass through the primary containment structure. These services penetrations, together with the sealing of the containment cap into the head of the drywell cavity, are generally considered to be weaknesses in the Mk 1 BWR containment design, provide potential radioactive leakage paths during and in the aftermath of a LOCA-type event.[6,7]

Extant Condition of Unit 1 Reactor and Primary Containment: At this time freshwater is being injected directly into the RPV via one of the available entry routes (probably the feedwater inlet – see FIGURES 2C and 3) at a quantity and rate believed sufficient to maintain the RPV fuel temperature within tolerable limits, although the higher sections of the fuel bundles remain exposed.[8] If the RPV feedwater inlet is in use for water injection, then cooling water is first channelled into the feedwater inlet annulus and not directly to circulate within the fuel core itself, possibly giving rise to a high differential between the monitored temperatures of the RPV outer casing and the inferred fuel temperatures within the RPV.

- Because the RPV residual heat removal plants were either disconnected or irrevocably damaged during the post-tsunami events, the monitored RPV casing temperatures begins to ramp upwards once water injection is stopped, thus indicating that the fuel mass-coolant geometry has yet to reach 'cold shutdown' condition.

(0.4 – 0.5MPa) at the incident temperature which is generally taken to be around 140°C on the basis that any fuel melt corium does not melt through the RPV and pour into the primary containment. For a core melt through scenario, primary containment (drywell) temperatures are forecast to reach 1,480°C- Hyman, C R, *Multicell CONTAIN Analysis of BWR MK I Drywell Response to Time-Dependent Vessel Release of Core Debris*, presented at *Severe Fuel Damage, Containment Loads, and Source Term Research Program Review Meeting*, Silver Spring, Maryland, October 19-23, 1987.

[5] It is not clear if the Fukushima Mk I containments were retrofitted with such a *'hardened'* vent route.

[6] Yue D D, *BWR Containment Failure Analysis During Degraded-Core Accidents*, Oak Ridge National Laboratory, ANS Annual Meeting 1982.

[7] Perkins K R, Vang J W, Greene G A, Pratt W T, Hofmayer C, *Containment Performance for Core Melt Accidents in BWRs with Mark I and Mark II Containments*, BNL-NUREG-37676 Dept Nuclear Energy Brookhaven National Laboratory, 1986.

[8] Even so, it has not been possible to inject sufficient water into the RPV to cover the exposed higher sections of the fuel bundles thus giving rise to, possibly, continuing formation of hydrogen via zirconium-steam reaction, and the need to vent the RPV into the wetwell and, hence, continuing the nitrogen purge of the drywell to suppress hydrogen explosion.

TEPCO estimate fuel damage to range 55% to 70% of the fuel core,[2] most of which has probably slumped to the RPV bottom head region. The slumped core or corium mass is probably starved of cooling from the injected water stream and the RPV peripheral core nozzles may be salted up and ineffective because of what seems now to have been the earlier and injudicious deployment of seawater for injection cooling.[9]

- Hydro-thermal conditions within the RPV are subject of much speculation: fuel temperatures can only be arrived at by inference and, similarly, the extent and nature of the fuel damage has been cobbled together by similarly indirect means referenced to the drywell gamma rates.[2]
- Other than the nuclide inventory of the radioactivity being released from the Unit 1, which is not sufficiently exclusive and/or comprehensive, there is no reliable gauge of the condition and reliability of RPV boundary, particularly if its containment is at or near catastrophic failure.

Radiation levels inside the turbine building/reactor block, but beyond the primary containment, peak at >90mSv/h and range more generally between 20 to 50mSv/h – one report gives a radiation dose rate at one normally accessible locality of 1,100mSv/h. Following installation of ventilation equipment there resulted a marked reduction in the radiological environment within Unit 1.[10]

Remote dosimetry inside the primary dry- and wetwell containments yield levels of 25 to 50Sv/h.

- The higher than expected radiation rates within the drywell endorse the general acceptance that the fuel core in the RPV has partially melted and slumped into the bottom region of the RPV.

TEPCO Flooding Plan: To progress towards cold shutdown of the Unit 1 reactor, TEPCO is to flood the cavity formed between the reactor pressure vessel (RPV) and the primary containment enclosure.

The objectives of flooding the drywell include:

a) by flooding the primary containment, the greater mass of water (~7,400 tonnes) in the containment cavity provides a larger heat sink thereby delaying fuel temperature rise if the cold water injection (or top-up) becomes, for whatever reason, unavailable;

b) if the flooded containment level can be maintained high enough, then the exposed higher sections of the RPV fuel bundles will be immersed in water;

c) the longer delay time between bouts of water injection for fuel cooling will, possibly, enable TEPCO operatives to install (ie jury rig) a heat removal system that will reduce the amount of injected water that is being dumped from the RPV circuit; and mainly as a side benefits

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[9] Even if it is serviceable, the RPV peripheral core spray may not being deployed because of the risk of hydrogen deflagration in the RPV should the spray be effective in condensing the steam space.

[10] See TEPCO Impact Assessment Results of 7 May 2011.

d) if the exposed RPV fuel is covered, then the radioactive aerosol release from the fuel surfaces (via any venting into the wetwell) will be reduced and further 'washed out' in the water filled primary containment; and

e) flooding the primary containment will provide an additional shielding barrier, thereby reducing dose and increasing permissible exposure times in the locality of the Unit 1 reactor building.

Progress Towards Implementation: Preparation to flood the containment comprises several distinct stages:[11]

1) TEPCO has to install air filtration equipment and ducting within and generally decontaminate the reactor services area of the Unit 1 reactor block – these high radiation exposure tasks are likely to be undertaken by teams of individuals in order to limit the individual dose uptake;[12]
2) air filtration, decontamination and the pumping out of any accumulated waters in the basement of the reactor block and adjacent turbine hall, will permit longer time access to the services, particularly the residual heat removal system which might be recommissioned into service to cool the RPV and flooded primary containment cavity; and
3) the lowering of the radiological environment within Unit 1 and the turbine hall will enable operatives access to the services of Unit 1, thereby giving TEPCO greater opportunity to gauge the validity of its current assessment[13] of the impact and risk of flooding the containment.

Flooding of the primary containment, both dry and interconnected wetwells, to virtually the full depth is not a previously recognised design function for which there is a developed and approved nuclear safety case.[14] General and specific issues raised by flooding of the primary containment include:

i) Generally, additional superimposed loading on the primary containment structures by the (hydrostatic) head of water arising from flooding – the overall height of the dry-wetwell containment up to the top of the RPV fuel bundle is about 30m, with this head of water producing a maximum hydrostatic pressure at the lowest point of the wetwell of about 3 bar (0.3MPa).

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[11] At 5 May 2011, the water level in the Unit 1 primary containment vessel had reached ~6m deep from the bottom plateau of the drywell. To cover the core fuel the water level will have to be 18m deep – at an increase water injection rate of 14 tonnes/h the complete flooding operation will take about 22 days – other information sources give injection rates for Unit 1 to be between 8 and 10 tonnes/h.

[12] Although team sharing may limit the individual dose and, hence, individual risk, the collective dose (man Sv) remains high so, it follows, the same health detriment will apply across the group as a whole – see TEPCO statement of 5 May 2011.

[13] TEPCO, *Report Regarding the Implementation of a Measure to Flood Primary Containment Vessel to the Upper Area of Fuel Range in Unit 1 of Fukushima Daiichi Nuclear Power Station (Summary)*, 5 May 2011

[14] To the author's knowledge the General Electric containment design for Unit 1 does not include for deliberate flooding of the cavity to the full height, although specific plants (LOVIISA VVER-440) in Finland have been licensed to include for partial flooding of the primary containment – see Bal Raj Sehgal, Hyun Sun Park, *PRE-DELI-MELT, Pre-Project (PRE) on Development & Validation (DELI) of Melt Behavior (MELT) in Severe Accidents*, NKS R 2002 02, June 2004. However, the NRC refers to a procedure *SAMG- I, Primary Containment Flooding, Leg RC/F-4*, although this seems not to be a publicly available document.

ii) The mass of the water filling the containment cavity will have a significant impact on the seismic response of the containment structure, particularly with the water mass magnifying the seismic inertia action resulting in additional tensile stress loading of the structural couplings of both dry and wetwell containment shells. In detail:

- This a complex area of analysis requires accurate input data in order to reliably model the response of the water-filled structure to seismic loading generated by aftershocks – the liquid-structure-soil dynamics have to be considered for the primary containment modelled as a three-dimensionally excited system.
- Sensitive aspects of the containment structure are the services penetrations (steam, feedwater, etc), failure of which could result in release of the water fill, and the stability of the internal structures with the additional seismic inertia introduced by the water fill, placing relatively slender components at risk of failure (such as the pedestal support for the RPV in the lower drywell area).
- Account has to be taken of degradation of the built structures, from ageing and previous seismic loading,[15] and from changes brought about therefrom (ie the collapsed charge hall roof). Because of the high levels of radiation within the Unit 1 reactor building and turbine hall, access the building structures seems to have been very limited.[16,17,18]

iii) Although not detailed in the TEPCO summary report,[13] it is assumed once that the primary containment cavity is water filled, that any necessary venting of the RPV will be via the wetwell torus route. The vented steam will condense in the flooded wet- and drywell cavities and the non-condensable gases, particularly any hydrogen generated by continuing steam-zircaloy reaction, will accumulate in some pocket or pockets about the containment or, and most likely, percolate up to the ullage space formed at the top of the containment cavity under the closure cap. In detail:

- It is not clear what facility, if any, is available to safely vent this higher ullage space of accumulating hydrogen via a *'hardened'* route.

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[15] Early reports regarding Units 1-3 stated plant operators deployed the safety relief valves to relieve pressure in the RPV by venting into the water filled torus of the wetwell. In addition, when the fuel rods became uncovered, hydrogen formed in the core (due to zirconium/water reaction) was also directed into the wetwell. The combination of steam and hydrogen flowing into the wetwell increased the wetwell temperature and pressure. Since there was no on-site or off-site power available, there was no means to cool the wetwell water so, over time, the pressure in the primary containment rose, exceeding the design pressure. At or about this point the primary containment hydrogen-steam mixture may have leaked (past services penetration seals and, particularly the containment closure head cap – or it may have been deliberately manually vented), into the charge hall wherein the vented hydrogen gas deflagrated, destroying much of he charge hall structure. RPV venting into the wetwell is accompanied by quite severe hydrodynamic loading onto the downcomer pipes connecting the wet and drywell containment structure – see NUREG-06661 July 1980.

[16] NISA required TEPCO to undertake an evaluation of the built structures on 13 April 2011, particularly with respect to the resilience of the structures to seismic aftershocks, although nothing has been published to date

[17] Radiation dose levels inside the drywell cavity have been very high (on average around 40 to 50Sv/h on 2 April 2011 and which be expected to have decayed down to about 20Sv/h to date) thereby rendering human intrusion into the drywell cavity totally unrealistic.

[18] In 2005, ageing damage to the wetwell torus in the form of through-wall fracturing was discovered at the Fitzpatrick Mark I BWR (commissioned 1975) located nearby to New York

- Being of limited volume, gas pressure in the ullage space could increase over a relatively short period and release via the cavity closure cap seals.
- Unless a facility to vent the RPV steam space (ie above the top of the fuel bundle) is maintained then a contained space above the fuel bundle could, if further hydrogen is generated, result in sufficient RPV steam space pressure build-up to uncover the fuel – this is quite contrary to the TEPCO logic that the reduction in free gas (-phase) space is more than offset by the reduction in pressure. (para 4, bullet 3, p3, fn 13)
- The TEPCO statement(para 4, p3, fn 13) that insufficient hydrogen would be generated by a further bout of steam-zircaloy burn is unsubstantiated and inconsistent with TEPCO's assessment[2] that the Unit 1 fuel damage is limited to 55 to 70%. It is also contrary to the fact that TEPCO have been, for the past week or so, pumping nitrogen into the Unit 1 drywell containment cavity, suggesting an ongoing concern that fuel damage (and hence hydrogen generation) is continuing.

Potential Risks During/Following Primary Containment Flooding: There are a number of potential risks and hazards that might arise during or as a result of the primary containment flooding. Briefly, these include:

a) **Ex-Vessel Steam Explosion:** If, as is possible, the corium mass that is likely to be slumped at the bottom head of the RPV is continuing to melt or burn through the RPV casing, then until the rising water level in the drywell cavity immerses the bottom head of the RPV and effects cooling of the corium, there remains risk of an energetic steam explosion as the corium mass jets or drops into the subcooled water under the RPV.

  - Such a molten metal-water explosion could be of sufficient vigour to collapse the pedestal supporting the RPV and/or breach the primary containment.

b) **Corium Melt Coolability:** This is perhaps the most vexing unresolved issue, since it is not clear how to cool and quench a slumped melt pool interacting with a concrete basemat for the drywell should, that is, the corium mass burn through the RPV. The obvious action of flooding the drywell, with water, to quench and retain the melt in the containment has been shown not to achieve complete coolability in all circumstances.[14]

  - Failure to cool a corium mass that has dropped or jetted from the RPV could result in a containment breach, particularly if the inner steel liner of the drywell is burnt through at a services penetration, thereby permitting a release route via the styrene fill void between the steel liner and concrete structure of the containment.[19]

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[19] Large & Associates, *Incidents, Developing Situation and Possible Eventual Outcome at the Fukushima Dai-ichi Nuclear Power Plants*, Interim Report, R3196-A1, 10 April 2011.

c) **Dosing Cavity Water with Boric Acid:** As a form of criticality control it may be considered desirable to dose the injected water entering the RPV with boric acid, thus quenching any possibility of a resumption of criticality. However, when the borated water leaks through gaskets, valves, threaded joints, or cracks in containment boundary parts, the acid can concentrate and cause rapid corrosion of the carbon and low-alloy steels typically used in pressure boundary structures.

- A balance has to be struck on the amount of boric acid added to the injected water, especially in account of the presence of salt (from the residue of the earlier seawater injection) – particular regard should be given to the potential degradation of the steel liner and concrete structures in the interim and longer terms if, as is likely, the containment flooding becomes a permanent feature.

d) **Linkage Between Cavity Water and RPV Fuel:** Obviously, to minimise the efficacy of radioactive release the number of potential pathways to the environment should be minimised. Indeed, throughout the now two month aftermath period since the *Tohoku-Taiheiyou-Oki* earthquake-tsunami struck, TEPCO has gone to considerable lengths to emphasise that the RPVs of the stricken Unit 1, 2 and 3 reactors remained sound.

- According to the TEPCO flooding scheme,[13] a link between the coolant in the RPV and the primary circuit is to be established – the coolant water injected into the RPV via the open feedwater line is to flow through and around the damaged fuel in the RPV, and then into the wetwell and drywell cavities.
- This arrangement means that a greater volume of water will be at risk of fission product contamination and release to the environment should the containment fail; and also
- the linking and flow arrangement removes the first containment barrier (the RPV) of what is presently a two-barrier containment system, that is reducing the enclosure to the single barrier of primary containment, which it has not been possible to inspect to determine its resilience against further seismic loading.

Findings and Recommendations: First, it has to be acknowledged that flooding of the primary containment of Unit 1 may be the only practicable option available to TEPCO to maintain stability and some essence of control over the very serious radiological situation that persists at the Fukushima Dai-ichi nuclear complex.

To date and particularly with its somewhat flimsy summary report that attempts to justify the flooding scheme,[13] it is not at all clear that TEPCO's assessment has fully accounted for the potential risks of the scheme. These areas of uncertainty relate to the actual state of the fuel, the condition of the RPV and, strikingly absent, the structural surety of the primary containment, particularly in fulfilling its containment and structural roles when subject to aftershocks and, quite probably, future seismic events.

Of particular concern is the unjustified post-haste approach that has, or so it seems from the limited information publicly available, skirted around the development and validation of a nuclear safety case. If it is inevitable that the primary containment will have to be flooded to salve a worsening situation in Unit 1, it should nevertheless be justified on nuclear safety grounds.

This is because fully flooding the primary containment is an entirely unique application that does not seem to have been considered at the design stage of this BWR NPP some 40 to 50 years past. The fact that the built structure of the primary containment has been in service for forty years (some might opine a period well beyond its design service life) being subject to inevitable age-related degradation; and that it has sustained to a severe seismic event, followed by a violent explosion all, surely, make it even more imperative that the adequacy to perform this new (and *beyond-design-basis*) task be openly and thoroughly demonstrated.

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In short, TEPCO's scheme for the flooding of Unit 1 is poorly-thought through and, although now in the process of practicable implementation, a demonstrable nuclear safety case has not been presented.

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APPENDIX A

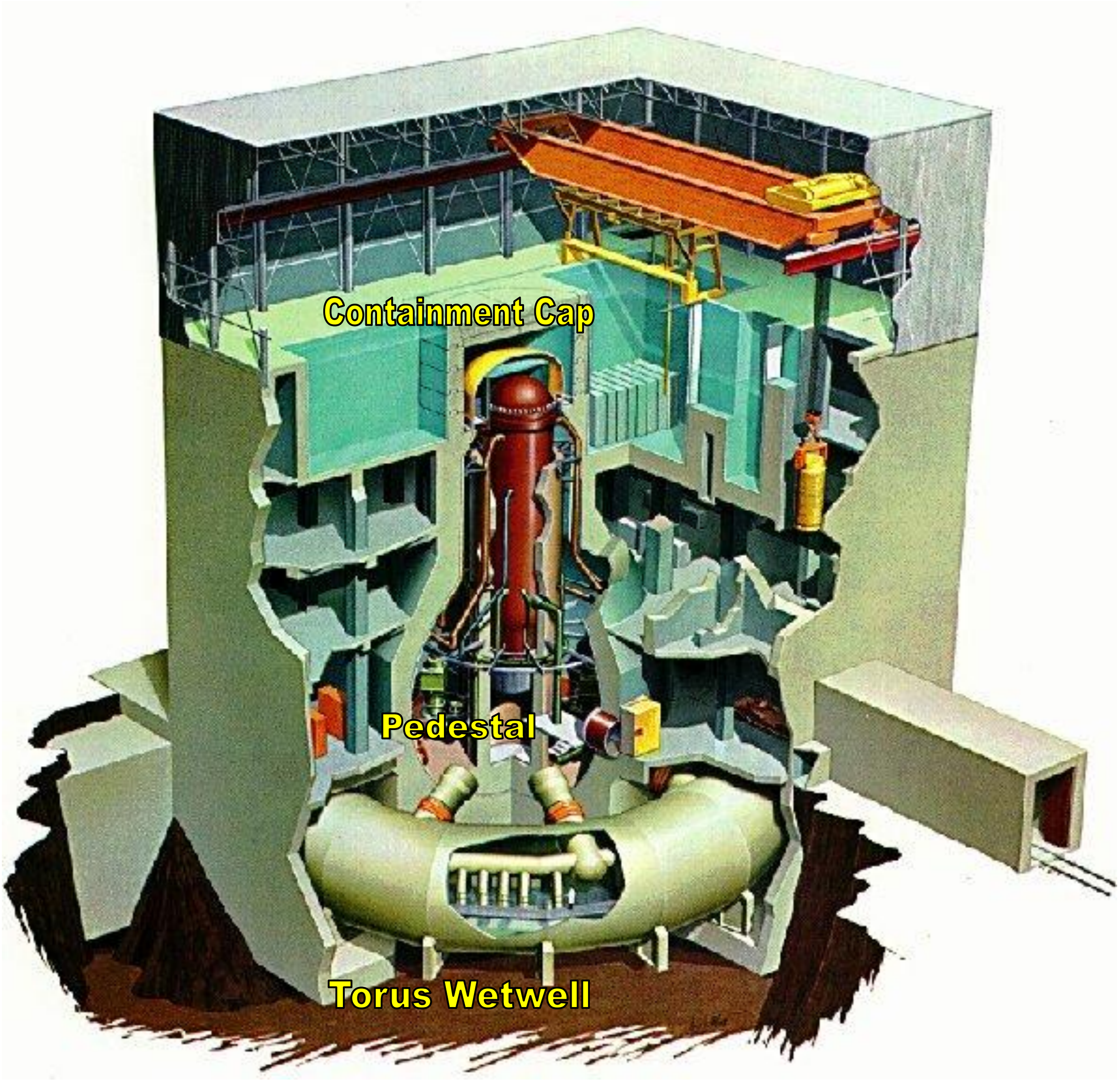


FIGURE 1 CUT AWAY SCHEMATIC OF THE MARK I CONTAINMENT

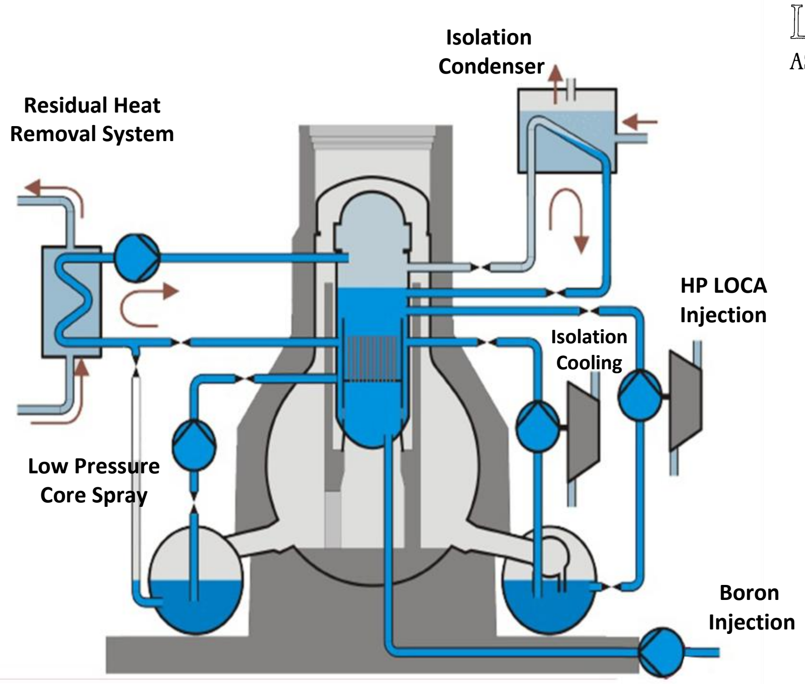


FIGURE 2A EMERGENCY CORE COOLING SYSTEMS (with on/off site power availability)

Source: AREVA

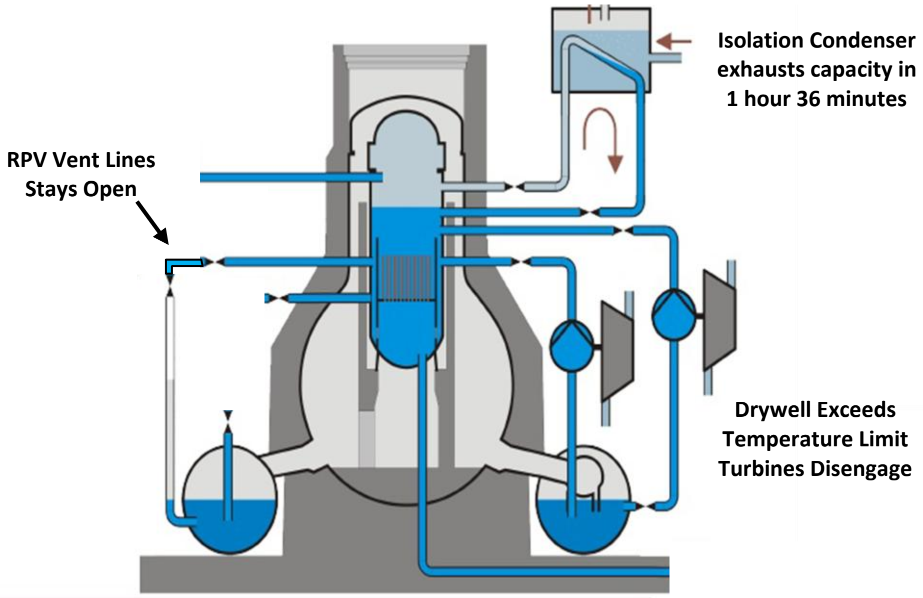


FIGURE 2B EMERGENCY CORE COOLING SYSTEMS (no on/off site power)

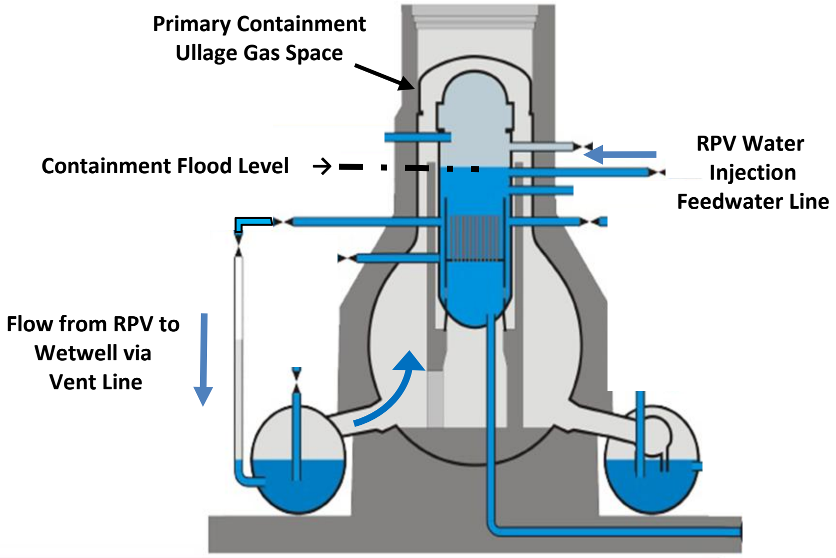
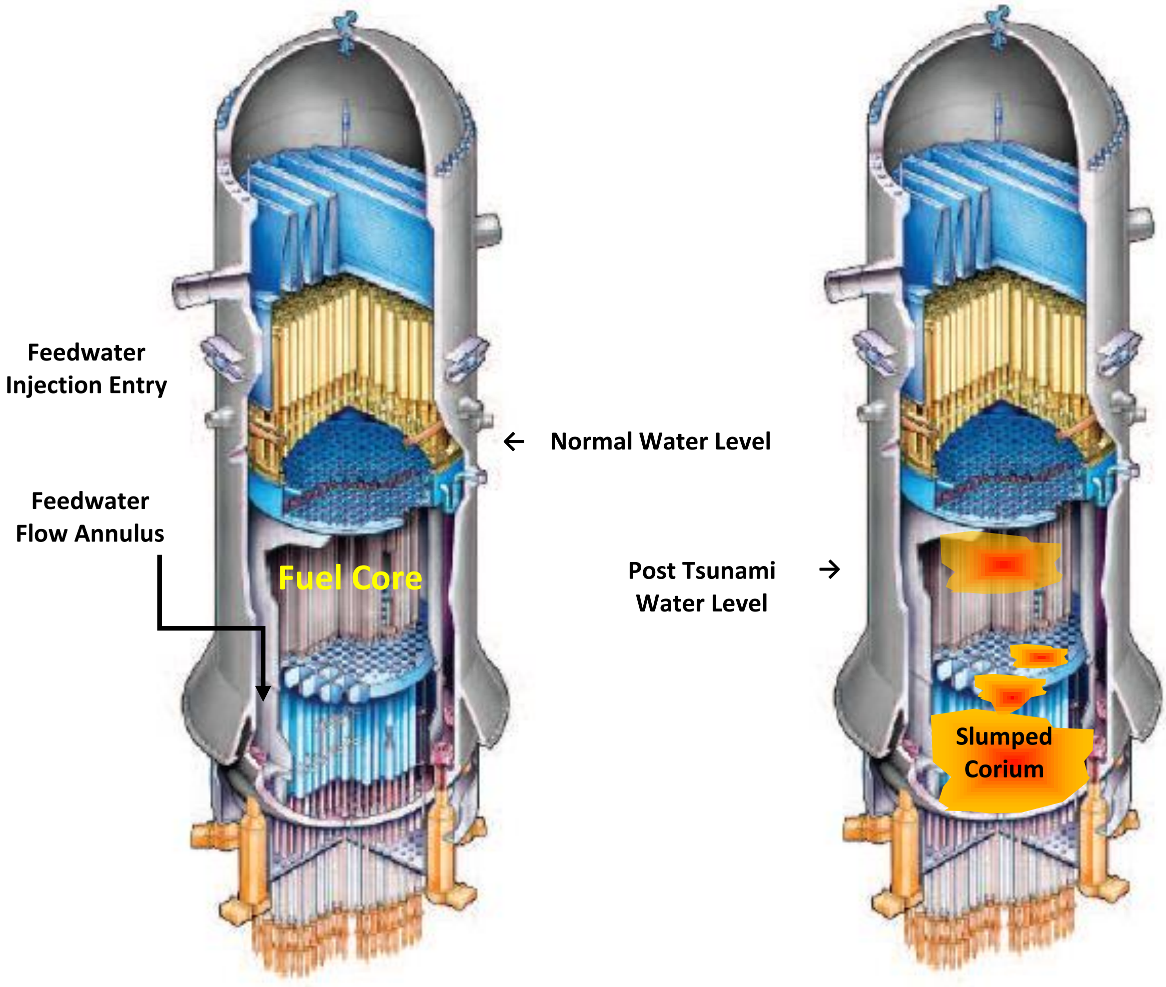


FIGURE 2C CONTAINMENT FLOODING ARRANGEMENTS



Normal Operation

Fuel Melt

Figure 3 BWR Reactor Pressure Vessel