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A BRIEF OPINION ON THE

INCIDENTS, DEVELOPING SITUATION AND POSSIBLE EVENTUAL OUTCOME AT THE FUKUSHIMA DAI-ICHI NUCLEAR POWER PLANTS

INTERIM REPORT

CLIENT: GREENPEACE GERMANY

REPORT REF N° R3196-A1 Final 8 April 2011

JOHN H LARGE

LARGE & ASSOCIATES
CONSULTING ENGINEERS
LONDON

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1st ISSUE	REVISION N°	APPROVED		CURRENT ISSUE DATE
31 MARCH 2011	196-A1 *FINAL 8 PRIL 2011*-R6			10 APRIL 2011

INCIDENTS, DEVELOPING SITUATION AND POSSIBLE EVENTUAL OUTCOME AT THE FUKUSHIMA DAI-ICHI NUCLEAR POWER PLANTS

SUMMARY

This review considers recent events at the Fukushima Dai-ichi nuclear site where three nuclear reactor power plants (NPPs) have undergone quite violent explosions and, separately, the spent fuel pond of another reactor block has been severely damaged by a similarly devastating explosion.

Following the *Tohoku-Taiheiyou-Oki* earthquake-tsunami, when the Fukushima Dai-ichi site lost all off- and on-site power and went into electrical *blackout*, it is believed that the loss of cooling to the reactors of Units 1, 2 and 3 resulted in each nuclear fuel core being exposed, overheating that led to explosion. For Units 1 and 3 the secondary containment structure was devastated by hydrogen accumulating in the charge hall. What fuelled the explosion within Unit 2 remains unclear but, in any case, it was of sufficient force to blow out a sizeable outer panel of the containment building, suggesting that it may have breached both primary and secondary containments of the reactor building.

Prior to the earthquake, the Unit 4 reactor had been shut down and completely defueled with the nuclear fuel transferred to the water filled spent fuel pond located at the higher level of the reactor block. Again, because of the station *blackout* no cooling was available to the fuel pond water, as it boiled away there was no replenishment or make-up water delivered to the pond. This situation also resulted in overheating of the nuclear fuel in the pond, some of which had only recently been transferred from the reactor, leading to violent explosion within and devastation of the charge hall secondary containment.

The reasons for the each of these violent events are not absolutely clear: For the Unit 1, 2 and 3 reactors, it seems that of the two emergency core cooling systems that should have automatically intervened only the reactor core isolation cooling systems engaged, leaving the high pressure core injection systems disengaged. At that stage the plant operator, TEPCO, jury rigged water injection directly into the reactor pressure vessels (RPVs) and prepared to vent or relieve the pressure build-up in the primary containment. However, this TEPCO intervention was not effective and each of Units 1, 2 and 3 sustained a violent explosion:

DATE	JST	EVENT
11 March	15:41	Tsunami Deluges Site
12 March	15:36	Unit 1 Explosion
14 March	11:01	Unit 3 Explosion
15 March	06:10	Unit 4 Spent Fuel Pond Explosion
15 March	06:20	Unit 2 Internal Explosion

In the aftermath of the explosions, TEPCO continued with direct water injection into the RPVs of Units 1, 2 and 3, and introduced overhead water spraying over the areas of the spent fuel ponds of Units 1, 3 and 4.

Fukushima Dai-ichi Plant Condition: The detailed conditions of the Unit 1, 2 and 3 reactors and the associated spent fuel ponds are unknown, but it is reasonable to assume that all RPV fuel cores of Units 1, 2 and 3 have wholly or partially melted and slumped within the RPV and, as a result of this, it is likely that injection cooling is now seriously impeded. Similarly, there is little detailed information about the condition of the Unit 4 fuel pond, whether it remains watertight and, indeed, of the whereabouts of all its 256 tonne fuel contents, some of which seemed to have been ejected from the pond and the Unit 4 building by the force of the explosion.

The condition of each of the Fukushima Dai-ichi Units can be pieced together from a number of official sources of information:

Unit 1: The reactor charge hall was largely demolished by the explosion and the charge floor, including the spent fuel pond, is covered by debris with the charge floor roof that seems to have collapsed downwards into the rubble. The conditions of the spent fuel pond, water levels and ~51 tonnes of fuel contained therein are unknown.

The Unit 1 RPV internal pressure, after a peak event at ~0.5^{+}MPa on 23 March, reduced but is now on the rise again after a coolant flow reversal on 24 March, with the present (4 April) pressure being ~0.5MPa (in normal operation the RPV operates at ~7MPa and the dry and wet well containments at 0.1MPa compared to post accident conditions). Water and steam

conditions within the RPV are consistence with saturation at the RPV pressure and temperature. Only the pressure of the dry and wet well compartments of the primary containment are known, with each closely following the reactor pressure. Although data is extremely limited, there may have occurred a wet well suppression event during 23 March.

Unit 2: There is little outward sign of damage to the reactor and charge hall and the spent fuel pond although, that said, the reactor block has been steadily emitting a steam plume since its explosion on 15 March.

Pressures within the RPV and dry well have collapsed – there are no pressure readings available for the wet well.

The Unit 2 reactor primary containment is believed to have ruptured (or at least the containment is being bypassed by failure of services penetration seals or, perhaps the containment closure head) and this, as acknowledged by TEPCO, is the main source of the heavily contaminated water accumulating in the bund trench and service tunnels of the Unit 2 turbine hall.

Unit 3: Like Unit 1 but more severely damaged, the reactor charge hall was demolished by the explosion. The charge floor, including the spent fuel pond, is covered with debris. The conditions of the spent fuel pond, water levels and the ~89 tonnes of fuel contained therein are unknown, although water spraying of the pond area from an overhead jib continues (3 April).

The Unit 3 RPV pressure, peaked at ~0.3MPa on 20 March and again at 0.4MPa on 24 March, and has now collapsed. The dry well closely followed the 20 March peak and this may indicate a suppression event at that time, although no wet well pressure is available for this period.

The fuelling of Unit 3 is of particular concern because the fuel core includes a trial batch of mixed oxide fuel (MOX) containing about 230kg of plutonium-239. Sampling around the Fukushima Dai-ichi site has found 5 localities contaminated with Pu-239, two of which have been positively identified to derive from the Unit 3 MOX fuel.

Unit 4: Recent remotely taken video footage shows the fuel pond area of the charge floor to be in utter shambles: the pond appears to be completely devoid of water, fuel racks that were previously clamped into position have been overturned and are strewn about the pond area, and the overhead gantry crane seems to have collapsed into the pond void and straddles directly on the fuel racking.

The Unit 4 fuel pond contained 256 tonnes of LEU spent fuel, 95 tonnes of which had been recently discharged from the full fuel core of the Unit 4 reactor. Thermal images suggest that fragments of spent fuel assemblies may have been ejected from the pond during the explosion, this is further endorsed by the detection of neutron emitters (fuel) up to 2km distance from the Unit and the expedient measure of bulldozing and burying some radioactive emitting items in the area between Units 3 and 4.

A constant spray of water is being directed into the spent pool area from an overhead jib, although the effectiveness of this cooling and the condition of the remaining fuel remains unknown.

Units 5 & 6 Both Units 5 and 6 were in a cold-shutdown state at the time of the incident, electrical power supplies have be re-established, although Unit 5 spent fuel pond temperatures remain elevated above ambient.

Contaminated Water Discharges: The emergency measures implemented on the Fukushima Dai-ichi site have included, in the main, arranging for water injection, first seawater and now freshwater, into the reactor primary circuits and by overhead spraying of the exposed parts of the wrecked charge floors (Units 1, 3 and 4), and some spray cooling has been undertaken on the separate Central Fuel Storage Pond. For water injection and spraying, adaptation of existing equipment and plant was required, particularly to receive the surplus and residual waters – the plants so commandeered and adapted to receive this water, include the condenser vacuum tanks, condensate reservoirs and the suppression pool surge tanks, etc.. Even with these large reserves of storage space for residual water, the bund trenches, tunnels and basement areas of the Unit 1, 2, 3 and 4 turbine halls have become so inundated with contaminated water that access to certain areas of the site and buildings have been rendered radiologically challenging – surface dose rates for the water accumulated in Trench 2 and its interconnected services tunnels have been reported to be 1,000mSv/h with the Iodine-131 level at 5,400,000 Bq/cm^3 (compared to the statutory notification limit of 0.04 Bq/cm^3) in the locality of the condenser water intake screen to Unit 2 on 2 April 2011.

TEPCO has already discharged about 12,000t of what it claims to be low contaminated water from the Central Radioactive Waste Disposal facility and the sub drain pits of Units 5 and 6 in order to free-up storage capacity for the levels of contaminated water that is accumulating about the Fukushima Dai-ichi site. Various estimates reckon that up to 60,000t of contaminated water may have accumulated on the site and that this will require treatment and decontamination before discharge, although there is serious doubt that the existing radioactive abatement plants on the site have the rate or storage capacity to process this water.

Station Blackout and Fuel Meltdown: The water contamination data is not particularly consistent, nevertheless, the information available strongly indicates that the water accumulating around the Fukushima Dai-ichi site has been in direct contact with exposed (declad) nuclear fuel. The higher levels of the water surface dose rate, and the radio-iodine and caesium contents in the locality of Unit 2 suggest that the fuel core of this reactor has, at least, been exposed and is undergoing, or has undergone, a fuel melt. For this reason, this Review examines the most likely outcome following the station electrical *'blackout'* of the Fukushima Dai-ichi complex, the progression towards a melt down of the fuel core and how the resulting molten corium could have broken through the RPV and subsequently failed the BWR dry and wet wells of the primary containment – a situation that might have already run its full course for the Unit 2 reactor containment and which might be potentially an ongoing threat for Units 1 and 3. There is also a similar threat to the effectively uncontained 256 tonnes of fuel in or about the Unit 4 spent fuel pond (and also similarly for the spent fuel ponds of Units 1 and 3) for which there is little information available.

Within or Beyond the Design Basis: In assessing the safe operation of the Fukushima Dai-ichi nuclear plants, it must have been that both TEPCO and the Japanese nuclear safety regulator NISA considered the challenge that a combination of earthquake and tsunami posed to the nuclear complex. Generally, this would have been assessed in terms of the composite of *acceptable risk and tolerable consequences* and have concluded, since the Fukushima Dai-ichi plants were permitted to operate substantially unmodified since commissioning in the 1970s, that the risk of occurrence of such a devastating combination of seismic magnitude and tsunami wave height was so infrequent to be considered an *incredible*, beyond design basis event. So much so, it would have been argued by TEPCO and accepted by the nuclear regulator NISA, that since such a severe challenge was in all probability never likely to occur, the measures required to safeguard against it could be entirely disregarded.

However, the station *blackout* (SBO) that followed was not a corollary unique to the *incredible* earthquake-tsunami event of 11 March 2011 in that, irrespective of the initiating cause, an SBO is a credible event. This is because the general expectation is that such SBO events will occur at credible (within the design basis) frequencies, so much so that in the United States there are clear regulatory rules that require US NPPs be capable of withstanding a SBO for a specific period and of maintaining the RPV fuel core cooling during that period.

So, how well prepared was TEPCO for the SBO at Fukushima Dai-ichi?

This Review explores and identifies how a BWR NPP responds under SBO when fuel core cooling is lost and, within this, the ways and times over which the formation of corium, its melt through the RPV and interaction with the dry well containment could lead to several modes of failure of the primary and secondary containments. Very certainly, TEPCO would be well aware of the ways and times over which an unattended and uncooled reactor core would run its inevitable course to a fuel melt and, thus, pose a threat to surety of the primary and secondary containments. It follows that TEPCO would also have been aware and would have had, surely, plans and procedures, including spare equipment, with which the fuel melt could have been managed within the known timeframes to stability and a safe resolution.

Moreover, there is an established predictability of the course of events that an uncooled reactor fuel core will follow when under SBO conditions: fuel melt to corium, burn through of the RPV, slumping down to the base-mat and interaction with the liner and concrete of the drywell, and so on. These events, various degrees of outcomes, their probabilities and time scales are well understood, so it is very surprising that TEPCO has been unable to manage a situation for which it should have prepared plans and procedures, spare equipment, and so on.

Clearly, with each of the three operating reactors running down what seems to be an identical cascade of malfunction leading to a violent explosion, whatever plans TEPCO had in place, if it had any at all, have failed. In fact, certain of TEPCO's actions in the aftermath of the explosions have been confused and, some might opine, lacking discipline of purpose to the extent that expedient decisions have been made without proper forethought and judiciousness to avoid knock-on consequences: for example, the injection of seawater may have resulted in salt deposits sufficient to foul cooling flows in the lower regions of the RPV; the liberation of hydrogen from seawater is more rampant than from freshwater and radiolysis of oxygen from the cooling water could provide stoichiometric conditions and ignition with hydrogen in the absence of air in the containments; and the latest and most recent announcement to deploy a nitrogen purge to the Unit 1 reactor seems yet another ill-explained and unjustified desperate measure.

The situation relating to the violent destruction of the Unit 4 spent fuel pond is even more surprising. This is because it is a relatively straightforward calculation to predict the *boil-down* time to when the fuel is uncovered (several days) at which the risk of hydrogen generation and deflagration occurs, so just why the simple and obvious expedient of providing cooling water via a temporary pump (ie a fire tender) was not implemented by TEPCO in a timely manner is baffling.

In other words, the station blackout that occurred at Fukushima Dai-ichi was a prescribed event for which TEPCO should have had in place procedures and countermeasures - obviously, adequate plans and countermeasures were not in place so, in this respect, the nuclear safety culture at Fukushima Dai-ichi was fundamentally flawed.

If it is the case that, at Fukushima Dai-ichi, TEPCO failed then, it follows that the Japanese nuclear safety regulator NISA also failed because it permitted TEPCO to operate a hazardous nuclear complex in an unsafe way and without adequate emergency plans with which to counter the inevitable. If this is correct, then the Japanese nuclear safety culture is fundamentally flawed which means, because the same nuclear safety rules, limits and conditions are almost universally adopted internationally, that the demonstration and regulation of nuclear safety worldwide is equally and, perhaps, irrevocably flawed.

In short, little progress is being made at Fukushima Dai-ichi and, indeed, it is difficult to envisage what further preventative action can be taken to curtail nuclear events developing further, with more degradation of the fuel and breaching of the containments occurring. At best, the present level of emergency intervention response may be necessary for weeks, if not months throughout which the threat of a significant radiological event and consequences to both the marine environment and general population of the area, the region, if not the greater geographical area will persist.

JOHN H LARGE
LARGE & ASSOCIATES
Consulting Engineers, London

INCIDENTS, DEVELOPING SITUATION AND POSSIBLE EVENTUAL OUTCOME AT THE FUKUSHIMA DAI-ICHI NUCLEAR POWER PLANTS

1 QUALIFICATIONS AND EXPERIENCE

2 I am John H Large of the Gatehouse, 1 Repository Road, Ha Ha Road, London SE18 4BQ.

3 I am a Consulting Engineer, Chartered Engineer, Fellow of the Institution of Mechanical Engineers, Member of the Nuclear Institute, Graduate Member of the Institution Civil Engineers, and a Fellow of the Royal Society of Arts.

4 I am qualified and experienced in nuclear matters. I consider myself to be sufficiently qualified, experienced and practised in the topics relating to the incidents at the Fukushima Dai-ichi nuclear plant to provide an interim opinion.

5 INSTRUCTIONS:

6 On 30 March 2011, Shaun Burnie acting on behalf of Greenpeace Germany asked that I prepare and submit an opinion on the causes, potential development and radiological and environmental consequences arising from the ongoing incident at the Fukushima Dai-ichi nuclear plant.

7 My instructions are to provide explanation and opinion on the causes of the nuclear incidents that have occurred at Fukushima Dai-ichi nuclear plant, how these have developed into radiologically significant events to the environment, and if and how the situations at Fukushima Dai-ichi might develop over the near and interim future.

8 INCIDENTS AT FUKUSHIMA DAI-ICHI NUCLEAR COMPLEX

9 The *Fukushima Dai-ichi*[1] nuclear power complex is located nearby the town of Okuma in the Futaba District of Fukushima Prefecture, on the east coast of central Japan.

10 The complex includes six boiling water reactors (BWR) nuclear power plants (NPPs) of combined electrical output capacity of about 4.5GWe operated by the Tokyo Electric Power Company (TEPCO).

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[1] There is another nuclear plant in the Fukushima Prefecture, *Fukushima Daini* (No 2) located about 13km south of the Dai-ichi NPPs. The four BWR NPPs of, commissioned during the early to mid-1980s, are not subject of this Review.

11 The 6 NPPs were commissioned into electricity generation during the 1970s.

12 TABLE 1 FUKUSHIMA DAI-ICHI NPP DETAILS

NPP	TYPE	IAEA CODE	THERM/NET ELECT MW	CORE FUEL[2]	REACTOR SUPPLIER	1ST COMMERCIAL GENERATION
FUKUSHIMA 1 - 1	BWR-3	JP-5	1380/439	LEU	General Electric	1971
FUKUSHIMA 1 - 2	BWR-4	JP-9	2381/760	LEU	General Electric	1974
FUKUSHIMA 1 - 3	BWR-4	JP-10	2381/760	LEU + MOX	Toshiba	1976
FUKUSHIMA 1 - 4	BWR-4	JP-16	2381/760	LEU	Hitachi	1978
FUKUSHIMA 1 - 5	BWR-4	JP-17	2381/760	LEU	Toshiba	1978
FUKUSHIMA 1 - 6	BWR-5	JP-18	3293/1067	LEU	General Electric	1979

13 Further details of the operating history of the Fukushima Dai-ichi NPPs are given by the International Atomic Energy Agency (IAEA).

14 **Boiling Water Reactor NPP:** Essentially, a BWR reactor plant comprises a reactor pressure vessel (RPV) in which steam is raised. The steam is transferred via a closed loop reactor primary circuit to expand through high and low pressure steam turbines linked to an electricity generator, thence the exhausted, low pressure steam passes to a seawater cooled condenser, condensed to water then pumped back into the RPV to be heated by the nuclear fission process.

15 Units 2, 3, 4 and 5 the Fukushima Dai-ichi NPP RPVs comprise a thick walled upright, steel cylinder of about 7m diameter and 21m height, each containing about 95 tonnes (t) of nuclear fuel. Unit 1 is smaller with about 70t fuel core and Unit 6 larger with a 132t fuel core.

16 The reactor fuel core provides the basis of the nuclear fission in which nuclear chain reaction is maintained by fissioning (splitting or fragmenting) the fissile uranium-235 atom, with each fission liberating heat that is used to raise the cooling water temperature and steam. The fuel is made up of assemblies, comprising a square lattice of fuel pins each containing a stack of fuel oxide ceramic pellets clad and restrained by zirconium alloy (Zircaloy) sheathing and bracing.

17 Under fissioning, the radioactive fission product fragments are contained within the fuel matrix of the pellet and within the annular gap between pellet and the Zircaloy sheathing. These radioactive fragments accumulate over time rendering the fuel assemblies and reactor core progressively more radioactive as the fuel is irradiated or ‘burnt-up’.

18 At its most radioactive, the spent fuel will dissipate about 6% of its fuel power heat by radioactive decay of the accumulated fission products. In fact, the radioactive decay generates so much heat

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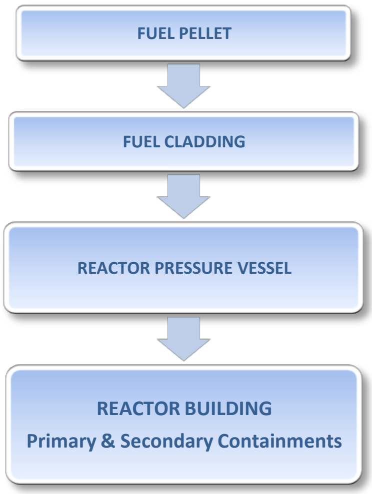
[2] i) LEU – Low Enriched Uranium 3 to 4% ii) MOX – Mixed Oxide Fuel with the fissile content being Plutonium-239.

that the reactor fuel core requires a high level of forced (ie pumped) cooling following close-down and cessation of the nuclear fissioning process. During the first few weeks of post reactor close down, the overall radioactive decay of the fuel is dominated by the short-lived fission products or radionuclides. This early component of radioactive decay is relatively rapid, so much so that after about three months cooling of irradiated or spent fuel, both reactor core and spent fuel storage pond situations, can be achieved by relatively low capacity residual heat removal systems.

19 At Fukushima Dai-ichi, Units 1, 2, 4, 5 and 6 are fuelled with low enriched uranium (LEU). Unit 3 is fuelled with LEU and a plutonium based mixed oxide fuel (MOX) containing, overall, about 230kg of the fissile plutonium-239 (~5%).

20 **BWR Reactor Containment:** The containment of a typical BWR NPP usually embraces the whole nuclear reactor circuit forming a barrier to inhibit release of radioactivity from the reactor primary circuit into the local environment for transportation into the public domain, particularly by atmospheric dispersion and subsequent deposition.



21 This multi-barrier approach is considered to be an integral part of the *Defence in Depth* strategy that is set against a series of prescribed fault/accident conditions or *Design Basis Accidents*.

22 The most important barriers of the Fukushima Dai-ichi NPP containment are arranged with the steel reactor pressure vessel (RPV) contained within the bulb-shaped, steel lined, reinforced concrete containment which is located within the NPP nuclear island building – referred to as the *primary* containment.

23 The primary containment is divided into *Dry* and *Wet Well* compartments, informally referred to as *light-bulb-and-doughnut* containment, that during fault conditions interact providing a pressure suppression role.

24 If, during a fault condition, the RPV breaches the ~300 or so tonnes of primary circuit water coolant flashes into steam as it discharges into the larger volume and lower pressure *dry well*. This steam is directed downwards into the *wet well* via the large diameter vents, to be dispersed by bubbling through numerous, small diameter pipes submerged into the water filled toroid or *suppression pool*. The suppression pool serves to quench and condense the steam by entirely passive means, thereby limiting the ultimate pressure rise within the building containment.

25 At Fukushima Dai-ichi, the NPP reactor buildings are each cube-like structure with the bottom two-thirds being the *primary* containment proper of the reactor in reinforced concrete, and with the highermost third being a relatively lightweight, framed structure housing the refuelling gantry crane and access to the spent fuel pond. The less robust building structure over the charge hall is referred to as the *secondary* containment

26 Periodically, about every eighteen months or so, about one-third or so of the fuel in the RPV is replaced with fresh fuel. The *'spent'* fuel is transferred for interim storage into the open spent fuel pond located at the highermost level of the building.

27 In addition to the reactor dedicated fuel ponds in each reactor building, there is a central fuel store, receiving spent fuel from all six Fukushima Dai-ichi NPPs located at ground level once that it has been in the reactor spent fuel pools for about two years or longer.

28 Approximate quantities of spent fuel in the storage ponds at Fukushima Dai-ichi are:

29 TABLE 2 RPV In-Core Spent Fuel Assemblies in Storage at Fukushima Dai-ichi

	REACTOR CORE		SPENT FUEL POND[ξ]	
UNIT	ASSEMBLIES	~ TONNES U[‡]	ASSEMBLIES	~ TONNES U[‡]
1	400	69.4	292	50.6
2	548	95.0	587	101.8
3	548[§]	95.0	514	89.1
4[†]	0	0.0	1,479	256.5
5	548	95.0	826	143.2
6	764	132.5	1,136	197.0

ξ Pool inventories vary slightly with data source.

† All fuel unloaded from reactor core about 100 days prior to 11 March, probably to facilitate a service inspection of the interior of the RPV – some new fuel assemblies are also held in Unit 4.

‡ Assumes each assembly contains 173kg of uranium oxide.

§ Includes mixed oxide assemblies of about 230kg Pu-239.

30 Irradiated or spent fuel is periodically removed from each reactor core and transferred to a fuel pond incorporated into the higher level of the reactor containment building where it remains for about 18 months before transfer to the Central Spent Fuel store that receives fuel transferred from each of the six reactor local ponds.

31 TABLE 3 Spent Fuel Assemblies in Central Storage Pond at Fukushima Dai-ichi

CENTRAL SPENT FUEL POND†	
ASSEMBLIES	~ TONNES U‡
6,375	1,097

† Data as at September 2010

‡ In addition, about 70tU of spent fuel is stored on site in dry casks.

32 **Incidents following Tohoku-Taiheiyou-Oki:** At the time of the *Tohoku-Taiheiyou-Oki* earthquake-tsunami incident (14:46 Japanese Standard Time (JST) 11 March 2011). Units 1, 2 and 3 were operating; Unit 4 was shut down and had been completely defueled; and Units 5 and 6 had been previously shut down for several weeks or more, and were in a *'cold shutdown'* state.

33 At around 14:46 JST each of the three operating reactors automatically tripped upon receipt of the seismic signal from the earthquake epicentred just of Sendai to the North. At about the same time, a number of other NPPs in North Japan also independently tripped which, it is believed, caused the collapse of the regional electricity grid.

34 Fukushima Dai-ichi, like the other tripped NPPs, drew upon, first, batteries for instrumentation and essential control functions, and then standby diesel generators to provide on-site electrical power to maintain the reactor core cooling pumps and other essential electrical supplies. However, thereafter at about 15:41 JST the site was swamped by a >10m high tsunami wave and, as a result, diesel generation ceased leaving the Fukushima Dai-ichi nuclear complex electrically *blacked-out* without any on- or off-site electrical power resources to draw upon for continued cooling of the reactor units[3,4] and spent fuel ponds.

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[3] The BWR has a number of automatic and/or operator activated emergency core cooling systems that would or could be activated during a station blackout, these are: 1) *Reactor Core Isolation Cooling* (RCIS) provides make up water when the main steam lines are isolated and the normal supply of make up water is lost, being driven by an electrically independent steam turbine pump taking fresh water from the condensate tank. 2) *High and Low Pressure Emergency Core Cooling System* (ECCS) which include automatic opening of selected pressure relief valves, with the HP ECCS being driven by an electrically independent steam turbine pump.

[4] At this point in time it is only possible to speculate on the course of events that occurred in the operating reactors of Units 1, 2 and 3 although the following might have applied:

1) At the seismic trip signal the reactors would have automatically isolated from the turbine hall and other non-essential services using emergency battery power whilst the diesel generators start to provide on-site power.
2) Diesels continue to operate until tsunami swamps site, station enters complete *blackout* except for emergency batteries which initiate remaining emergency system the reactor core isolation RCIS.

35 Some time thereafter, the operating company TEPCO issued a press release declaring a *Specific Incident and Special Measures of Emergency Preparedness*.

36 In the days following, Units 1 and 3 were subject to violent explosions most probably originating in the lightly enclosed reactor charge hall in which, it is assumed, accumulated hydrogen being drawn from either the reactor pressure vessel (RPV) or the dry well containment. Unit 2 underwent an internal explosion, again it is assumed from the generation of hydrogen from the fuel zirconium alloy cladding,[5,6] and the Unit 4 fuel pond violently exploded (either from a criticality incident, or again, hydrogen deflagration) when the fuel pond water was assumed to have boiled away.

37 TABLE 4 Chronology of Events at Fukushima Dai-ichi[4,7]

DATE	JST	EVENT
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3) Steam from RPV drives RCIS turbine pump uplifting coolant water from suppression wet well at atmospheric pressure – high pressure core injection (HPCI) initiation valve may have been rendered inoperable because the battery was immersed in tsunami water.
4) RCIS stops operating in each Unit at various times – after about 1 hour in Unit 1, longer in Units 2 and 3.
5) Without RCIS cooling, pressure in RPV head rises, steam relief valves either automatically or are manually activated to dump RPV pressure to wet well – reactor water level lowers exposing fuel core.
6) RPV head temperature rises to >1,000°C prompts Zircaloy-steam reaction in fuel core, hydrogen generated, pressure rises in RPV head.
7) Hydrogen vents into charge hall secondary containment, either i) into wet well via RCIS turbine steam line that remains open, then to dry well then via bypass leakage into Charge Hall of secondary containment and/or ii) is deliberately vented into discharge stack routed through Charge Hall.
8) Units 1 and 3 hydrogen deflagration in Charge Hall, breaks out of secondary containment.
9) Unit 2 internal explosive event, water levels in bund trench and Unit 2 turbine hall being to rise, radioactive contamination levels in trench and Unit 2 condenser canal rise to very significant levels.
10) Outcome: Units 1, 2 and 3 fuel cores at least in some stage of fuel melt and corium eutectic formed, Unit 2 corium may have burnt through RPV bottom head and dropped into dry/wet wells, RPV cores now most likely to be flooded, dry/wet well primary containments of Units 1 and 3, and possibly 2 flooded, although Unit 2 is most probably leaking into labyrinth of services tunnels located at basement level.

[5] Oxygen embrittlement of fuel sheathing resulting from high temperature oxidation in steam is the most obvious fuel failure mechanism during a loss of cooling of the FD fuel cores. In high temperature steam, zirconium alloys form an outer layer of zirconium oxide (ZrO2) and an inner layer of oxygen-stabilized α-Zr immediately below. The metal/steam reaction for Zr-2.5Nb in the temperature range 1000 to 1600°C results in a stripping of the oxygen and liberation of hydrogen from the steam. The basic exothermic reaction is Zr + 2 H2O → ZrO2 + 2 H2 applies to the zirconium-tin alloy referred to as Zircaloy.

[6] The cause and fuel for the Unit 2 explosion remain speculation.

[7] Chronology extracted from NISA.

38 The progression of ongoing developments is regularly reported by the operator TEPCO and the various national authorities involved, the Japan Atomic Industrial Forum (JAIF) and the Nuclear and Industrial Safety Agency (NISA).

39 Although lacking in detail and to a certain extent scope, it has to be assumed that TEPCO, JAIF and NISA are reporting factually. That said, there have been a number of contradictions of fact between these parties.

40 For example, as late as 31 March 2011, TEPCO claimed in its Press Release that *"no reactor coolant is (sic) leaked to the reactor containment vessel"*, thus inferring that the RPV containment remained sound and that no primary coolant had transferred to the dry well region of the BWR primary[8] containment building. In stark contradiction to this, JAIF reports that *"It is presumed that radioactive material inside the reactor vessel may [have] leaked outside at Unit 1, 2 and Unit 3, based on radioactive material found outside. NISA announced that the reactor pressure vessel of Unit 2 and 3 may have lost airtightness because of low pressure inside the pressure vessel. NISA told that it is unlikely that these cracks or holes in the reactor pressure vessels [are] at the same location"*.

41 Of course, the reported and verified presence of airborne radioactivity and, particularly, exceptionally high levels of radioactivity in the water accumulating[9] in the tunnels, trenches and open puddling in the turbine halls on the Fukushima Dai-ichi site utterly contradicts the TEPCO assertion that all of the RPVs and primary containments were sound (31 March 2011).

42 DOUBTS OVER THE CONTINUING CONTAINMENT AT FUKUSHIMA DAI-ICHI

43 a) INTERIM EXPLOSIVE STAGE

44 At Fukushima Dai-ichi, two separate abnormal events or fault conditions arose as a result of the cascade of challenges that commenced with the earthquake and finished with the swamping tsunami.

45 The first of these fault conditions led to the explosions, probably through deflagration of hydrogen liberated by the melting nuclear fuel as water cooling progressively failed – the fuel charging floors of Units 1 and 3 were utterly devastated and, for Unit 2 where the explosion seemed to be

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[8] Here *'primary'* containment refers to the envelope around the RPV and both wet and dry wells but which excludes the spent fuel pool and charge hall in the topmost third of the reactor block, whereas this is referred to as the *'secondary'* containment.

[9] It is not clear if some of this accumulated water arose from the swamping of the site by the tsunami or if all of it derives from spillages from the water injection of the reactors and water spraying of the reactor fuel spent ponds.

contained in the primary containment, although the lower wet well levels of the primary containment seem to have ruptured.

46 The second fault condition resulted from the boiling off of the cooling water in the spent fuel pond of Unit 4 to which a full RPV core load had been recently added. The explosion may have been triggered because the overheating fuel assemblies could have corrupted and distorted into a critical[10] situation, and/or the overheating fuel Zircaloy cladding could have violently reacted with the steam to liberate hydrogen and its deflagration. Alternatively, molten fuel dropping into the water residue at the bottom of the pond could have initiated a violent molten metal-steam explosion.

47 Until further investigation and analysis has been undertaken, the causes and circumstances leading to these events are unlikely to be fully understood.

48 However, what is known is that in the aftermath of these abnormal events significant amounts of fission product radioactivity has been, and continues to be released into the atmospheric and, particularly, the marine environments around the Fukushima Dai-ichi site.

49 There is clear, indeed irrefutable, evidence that a significant radioactive release has occurred from each of the troubled Units 1, 2, 3 and 4 at Fukushima Dai-ichi – the local and regional monitoring of the atmospheric radiation dose rates demonstrate a direct correlation between each of the events of TABLE 4 and a corresponding increase or peaking in airborne (radio)activity as shown in FIGURE 1.

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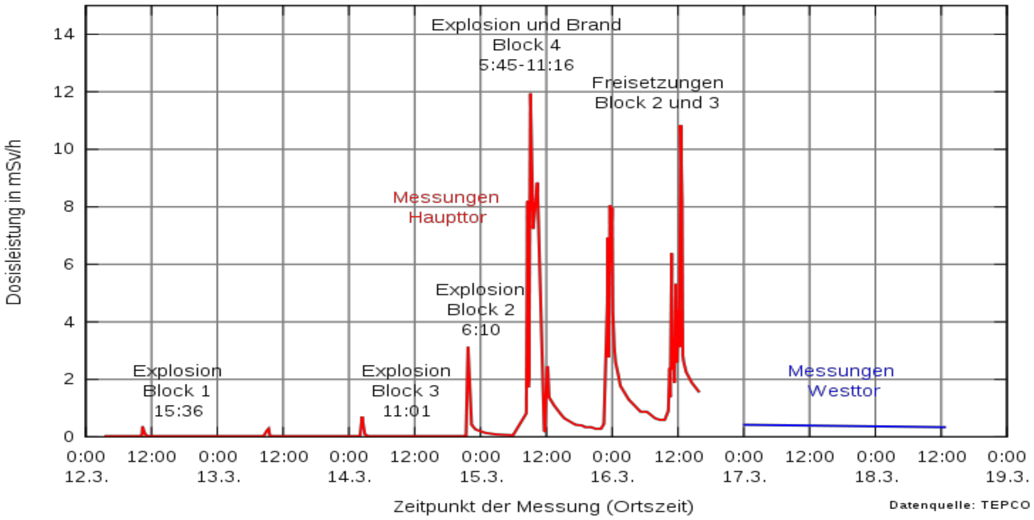
[10] Following the Unit 4 explosion, TEPCO refer to the risk of *'recriticality'* of the fuel contents of the pond, although it is more likely that the Unit 4 pond event was dominated by hydrogen deflagration initiated by the fuel being exposed to a high temperature steam environment as the water boiled away and the level dropped.

50 FIGURE 1 Atmospheric Radiation Dose Rates in Fukushima Dai-ichi Locality[11]



Datenquelle: TEPCO

51 However, setting aside the radiological significance of the atmospheric radioactive releases and the interim and longer term consequences to the exposed population, it is the increasing levels of radioactively contaminated water on the site that gives rise to cause for concern of a continuing and developing radiological situation on the Fukushima Dai-ichi site.

52 Reported with a surface dose rate in excess of 1,000mSv/h, the accumulating water in the bund trench running along the seaward side of the turbine hall of Units 2/3 and its connected services tunnels under the turbine hall suggest that the primary containment of Unit 2 has catastrophically failed.[12] This implies that the first phases of radioactive release from Unit 2 were via leakage bypassing the seal at the head of the dry well containment space (that is the charge floor access aperture deployed for refuelling), but that the same or thereafter another energetic event ruptured the lower levels of the containment.

53 If so, the ruptured primary containment at a lower level is providing a direct pathway for radioactive release directly into the flooded services tunnels linked to the bund trenches – if the fuel core has slumped and burnt through the RPV, into the drywell and possibly into the wet well toroid, then the fuel corium may be immersed in and releasing directly to the uncontained water.

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[11] A more comprehensive monitoring set covering the Fukushima Prefecture is available as a daily update from Greenpeace International.

[12] Other than the surface dose rates very little other information about the quality and volume of this uncontained water is available – the bund trenches and connected tunnels might be expected to hold several thousand tonnes of contaminated water and the proposal by TEPCO to dump upwards of 11,500 tonnes directly into the local marine environment suggests that the need for cooling water outweighs, at least in the minds of TEPCO and NISA, the need to protect the marine environment - Seawater (but not on site Trench) samples taken from about 330m offshore (26 March) give increasing concentrations of I-131 at 74,000 Bq/l, Cs-137 and Cs-134 at 12,000 Bq/l each (which may be another monitoring reporting mistake because this unity 1:1 activity ratio would not produce the expected 134/137 mass ratio after 15 days following fission suspension).

54 However, the mechanism leading to failure for all three Units 1, 2 and 3 that commenced at the loss of on-site power may not have completed. This is because it could be that the explosions are an interim stage of an overall degradation process now advancing into a second phase that could result in further and very significant radioactive release.

55 b) CORIUM MELT STAGE

56 In Units 1, 2 and 3, the explosions arose from the lack of cooling of the reactor in-core fuel to the extent that the water level in the RPV dropped, leaving the higher one-third of the fuel core exposed with the continuing failure and absence of all core cooling arising from a site blackout.[13]

57 This event has similarities to the Three Mile Island accident of 1979 that involved the prolonged loss of RPV core cooling of a PWR NPP and, since that time, the scenario has attracted much study[14,15] for both PWR and BWR variants of the light water moderated reactor.

58 In one study[14] the core melt down sequence for a BWR is initiated by the rising pressure-temperature transient, combined with failure of the high pressure coolant injection, RPV core isolation coolant, and loss of the low pressure emergency core coolant systems – these losses of core cooling are very similar to the conditions arising at operating Units 1, 2 and 3 at Fukushima Dai-ichi immediately following the station blackout.

59 The analysis goes on to examine the possibility of containment failure by both overpressure and overtemperature modes, particularly with regard to early failure of the electrical services penetrations to the drywell containment, see TABLE 5:

60 TABLE 5 CONTAINMENT FAILURE TIMES[14]

	CONTAINMENT FAILURE TIME - MINUTES		
BWR SEQUENCE	OVERPRESSURE	OVERTEMPERATURE DRYWELL†	WETWELL RUPTURE‡
BLACKOUT	288	193	130

† Containment failure assumed to be via electrical services penetrations.

‡ Pressure failure due to loss of condensation effectiveness as the wet pool temperature rises within the first 130 minutes into the sequence at which time failure is by violent oscillations in temperature and pressure of the steam bubbles generated in the toroid sparger or the *'Wurgaassen effect'* and failure at a overpressure load of 1.22MPa .

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[13] The reactor conditions, pressure, water fill, etc., are given in regular NISA updates in is in tabulated and diagrammatic formats.

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

[15] 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.

61 In another assessment,[15] the possibility of failure of the seal at the drywell head-fuel charge plug before overpressure failure of the drywell containment or its steel liner melt through is considered. In this approach, again for a BWR NPP blackout[16] following a reactor trip from 100% power, the assessment assumes a threshold pressure at which the containment will fail and suffer a loss of holding capability resulting in a significant release of radioactivity. If the containment pressure loading is below the threshold pressure then the radioactive release and, hence, the offsite radiological consequences are limited.

62 In this sequence, the core eventually becomes uncovered, and the corium melt moves to the RPV bottom head. When the RPV bottom head fails, the corium falls onto the dry concrete floor of the drywell and the corium/concrete reaction begins. Steam and noncondensable gases are released from the concrete, the previously unoxidised zirconium in the corium eutectic is assumed to react with the steam and $C0_2$ released from concrete decomposition and, as a result, the drywell pressure and temperature increase beyond the design pressure values.

63 For this model,[15] 80% of the fuel along with all of the Zircaloy and most of the RPV lower head steel (about 63,000kg in total) falls onto the drywell floor resulting in a corium pool depth of some 850mm. This corium slug burns through the steel drywell liner in 5 to 6 minutes which, for the Mark I containment exposes the polyester foam/fibreglass lining fill in the steel liner-concrete containment structure.

64 For the total station blackout scenario, the mode and timing of containment failure is closely related to the temperature and quantity of corium exiting the primary system. The model analysis[15] examined here, considers a smaller corium fuel and debris mass (~30% less) than available in the larger Units 2 and 3, each with a core fuel mass alone of 95 tonnes uranium.

65 For the corium at high temperature and with the maximum amount temperature and maximum non-condensable gas generation via the decomposing concrete, the containment performance suggests that the drywell head-fuel charge plug will partially fail sufficiently to prevent catastrophic overpressure failure of the drywell containment. If, however, the corium level remains high and contacts the drywell steel liner, then this mode has the potential to cause containment failure prior to reaching the overpressure threshold failure point.

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[16] The Nuclear Regulatory Commission of the United States requires an assurance that the loss of both off- and on-site emergency ac power systems (station blackout SBO) would not adversely affect public health – see *Regulatory Effectiveness of Station Blackout Rule*, NUREG-1776 NRC, August 2005 and NRC Regulatory Guide (RG) 1.155, *Station Blackout*, August 1988.

66 More recently, a study relating specifically to the melt down of a BWR[17] provides a good match to the circumstances that beset Fukushima Dai-ichi Units 1, 2 and 3.

67 TABLE 6 Initial and Water Injection Conditions for Fuel Melt Corium[17]

	LOW PRESSURE CORE MELT SEQUENCE			HIGH PRESSURE CORE MELT SEQUENCE	
	Continuous injection of cooling water	No Continuous injection of cooling water		Continuous injection of cooling water	No Continuous injection of cooling water
		Recovery of CRD cooling water injection	Recovery of alternative water injection		Recovery of CRD cooling water injection
INITIATION TIME OF IVR ANALYSIS	1.5 h after accident			2.7 h after accident	
INITIAL RPV PRESSURE	0.46 MPa			7.1 MPa	
WATER INVENTORY IN LOWER PLENUM	93 t			76 t	
FLOW RATE WATER INJECTION	40 m^3/h		140 m^3/h	22 m^3/h	

68 TABLE 6 fortuitously covers a range of conditions that applied within each of the Unit 1, 2 and 3 RPVs at Fukushima Dai-ichi.

69 At plant electricity blackout immediately following the tsunami, there would have been no continuous injection of cold water, usually automatically sequenced and introduced at shut down via the control rod drive channels (CRD) and the RPV would have been at initially at operating (high) pressure and steadily increasing in pressure.

70 For Unit 1, the TEPCO action to vent the RPV occurs at 10:17 JST lowering the RPV pressure[18] and raising the water level in line with the change of saturation conditions in the RPV. This effectively places the Unit 1 situation (for example) into the *low pressure core melt sequence* of TABLE 6.

71 Then, the continuous injection of cooling water was interrupted (Unit 1 at 01:10 JST), followed by a dwell until 15:36 JST at which time Unit 1 exploded.

72 In effect, the explosions in Units 1, 2 and 3 mark the points in time at which fuel melt temperatures were sufficiently high and conducive to trigger the Zircaloy fuel clad and steam reaction liberating hydrogen (1,100 to 1,200°C) – *Figure 7b*[17] estimates the time

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[17] Makoto AKINAGA, Hirohide OIKAWA, Ryoichi HAMAZAKI, Ken-ichi SATO, Takashi UEMURA, *Probabilistic Evaluation of In-Vessel Retention Capability Applying Phenomenological Event Tree*, CSNI/WGRISK Workshop International Workshop on Level 2 PSA and Severe Accident Management Cologne, Germany 29-31 March 2004.

[18] TEPCO stated quite specifically that the Unit 1 RPV was vented and not, as expected, the dry well containment.

to reach the Zircaloy reactor temperature in the absence of CRD cooling to be, on average, about 45 minutes and, thereafter, on the assumption that the water injection recommenced, for example on Unit 1, shortly following the explosion then fuel melt should follow the times and outcomes of *Table 2*[17] namely that all low pressure with recovery of CRD[19] cooling water injection, for all initial corium slug diameters will penetrate the RPV within about 2 hours of the initiating event - *Figures 4a), b) and c)*.[17]

73 Other applications research[20] indicates the time taken from the initiation event for melt down and melt through of the RPV lower head would be about 220 minutes, although some of the smaller and thinner components would be much faster to burn through. For example, the CRD failure time with water cooling available is about 21 minutes but in the absence of water cooling this reduces to about 13 minutes.

74 The conditional probability of RPV failure for the *low pressure core melt sequence* with recovery of CRD cooling water injection is predicted at $5.3x10^{-1}$ and if an alternative means of water injection can be jury rigged then the probability of RPV failure is $2.9x10^{-1}$, although the high injection water flow rates given in TABLE 6 have not been achieved by TEPCO during the Fukushima Dai-ichi emergency.

75 Of course, the act of the 90 or so tonnes or molten corium dropping from the RPV provides the prospect for further adverse events, including compromising the effectiveness of ex-RPV corium coolability during any corium-concrete interaction, particularly with siliceous concrete.[21,22,23] If it is not possible to quench a large volume and, a particularly deep layer (>40cm) of corium then the containment basemat may be put at risk which, if burnt through, would provide a radiological pathway into the environment that would be difficult to tackle and control in both interim and longer terms.

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[19] It is not suggested here that CRD cooling was recovered at Fukushima Dai-ichi - water injection might have been jury rigged to some other RPV connected circuit.

[20] See Table 2.2-1 of Azodi D, Gruner P, *Numerical Simulation of a BWR Vessel Lower Head with Penetration Subjected to a Postulated Core Damage Accident*, Trans 14th Int Conf Structural Mechanics in Reactor Technology, Lyon France 1997.

[21] Mitchell T. Farmer, D J. Kilsdonk R W. Aeschlimann, *Corium Coolability Under Ex-Vessel Accident Conditions for LWRs*, Nuclear Engineering Division, Argonne National Laboratory, Nuclear Engineering and Technology, Vol 41, No 5 June 2009.

[22] Details of the concrete specification for any of the Fukushima Dai-ichi NPPs are not publicly available.

[23] For an assessment of the effects of a corium melt through on the effectiveness of the suppression chamber of the BWR *light bulb- and-doughnut* suppression containment see Taleyarkhan R P, Podowski M Z, *An Analysis of Molten-Corium-Induced Failure of Drain Pipes in BWR Mark II Containments,* Chem Eng Comm 1995 Vol 134 pp 51-72.

76 Also, the failure to cool the corium spread when at primary containment basement level would be accompanied by generation of non-condensable gases (mostly CO and CO_2). In turn, the high non-condensable gas pressure would subject what is an already weakened primary containment to pressurisation and failure in the interim term, thus resulting in uncontrolled radiological release to the atmospheric environment.

77 A similar but somewhat modified situation might also be expected to arise for the 256 or so tonnes of spent fuel in the Unit 4 spent fuel pond. Obviously severely ruptured and quite incapable of holding any significant quantity of water, formation of a zirconium-uranium eutectic corium in the bottom of the fuel pond must be at significant risk of a Zircaloy-steam reaction with any residual water remaining in the pond. Unlike the in-vessel corium formation, the pond environment might be expected to result in a more porous and fragmented layer that is far from homogeneous, and which may not be particularly conducive to cooling.[24]

78 Formation of corium from the spent fuel in Unit 4 (and quite possibly in the spent fuel ponds of Units 1, 2 and 3) is likely to be underway,[25] if not already developed. If so, in the severely damaged fuel pond it may not be possible to provide any effective means of cooling to the mass of corium, thereby leaving it to remain a potential source (if not already so) of radioactive aerosol release to the atmospheric environment.

79 **In Conclusion:** There is an established predictability of the course of events that an uncooled reactor fuel core will follow: fuel melt to corium, burn through of the RPV, slumping down to the base-mat and interaction with the liner and concrete of the drywell, and so on – these events, various degrees of outcome, their probabilities and time scales are well understood so it is surprising that TEPCO has been unable to manage a situation for which is should have had prepared plans and procedures, spare equipment and so on.

80 If events at Fukushima Dai-ichi continue to progress, and there is little reason to believe that the present efforts on the site are managing to contain and manage the situation,

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[24] T N Dinh, W M Ma, A Karbojian, P Kudinov, C T Tran and C R Hansson, *Ex-Vessel Corium Coolability and Steam Explosion Energetics in Nordic Light Water Reactors*, NKS 160, March 2008. http://news.xinhuanet.com/english2010/world/2011-04/10/13821917_21n.jpg

[25] As noted in ¶18, the short lived radioactive radionuclides dominate the early radioactive decay and, hence, heat generation rates fall off proportionately (at SCRAM about 6%, after 1 day ~1 to 2%, 5 days ~0.5 to 1% etc) so, it follows, generally the more time passed since the SBO then the longer the time for intervention. However, the geometry of the core melt and corium could have significant effect on the meltdown process, particularly if the corium heat transfer surface is limited (ie a deep pool of corium), if a solid crust has formed, effectiveness of the heat transfer film coefficients, and if additional heating is available from interaction with the Zircaloy component of the corium eutectic with steam, etc..

then the RPV burn-through of the corium into the primary containment of Units 1, 2 and 3 could give rise to further and significant bouts of radiological release to, first, the terrestrial environment and, through a linked pathway, to the marine environment. There is also risk of aerosol release to atmosphere should the primary containment seals fail due to over-pressurisation by non-condensable gases formed by any corium-concrete interaction. In Units 1 and 3 release into the wrecked charge halls from the primary containment would be effectively unimpeded and direct to atmosphere.

81 Previous studies of BWR post accident performance involving station blackout[26,27] and loss of all cooling to the reactor core suggest that fuel melt should have by now commenced (if not completed), the corium formed and a partial or complete burn through of the RPV should have happened.

82 As a result of corium formation, these studies suggest a number of possible outcomes ranging from continuing surety of the primary containment; bypassing the primary containment by failure of the service entry seals into the containment; bypassing the primary containment head seals; burn through and failure of the containment steel liner; and, in the extreme, catastrophic failure of the reinforced concrete primary containment itself.

83 It may be that TEPCO's intervention cooling of the reactors and fuel ponds has been successful to a degree but, some might argue, this hurried and poorly thought-through countermeasure has been accompanied by the need to discharge highly radioactive waters directly into the marine environment without cognisance to the high radiological penalty that is likely to arise in the short, interim and longer terms.

84 Similarly, the spent fuel mass of about 256 tonnes originally racked in the Unit 4 fuel pond would, if melted down to a corium, present a very significant source at risk of release directly to atmosphere – an energetic release of this source term could have profound radiological consequences.

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[26] In NRC 10 CFR 50.63, the SBO rule requires that US nuclear power plants be capable of withstanding an SBO for a specified duration and of maintaining core cooling during that period. The specified duration would be determined for each plant by comparing the individual plant design with factors that have been identified in NRC technical studies as the main contributors to the risk of core melt resulting from an SBO. These risk factors are identified in the SBO rule as (1) the redundancy of the onsite emergency ac power sources, (2) the reliability of the onsite emergency ac power sources, (3) the frequency of loss of offsite power (LOOP), and (4) the probable time needed to restore offsite power – see NRC Regulatory Guide *Station Blackout* RG 1.156 August 1988

[27] Plant-specific Station Blackout Core Damage Frequencies (SBO CDF) are given from operating US BWR NPPs in Table B2 of NUREG-1776.

85 What is almost a certainty, is that the reactors of Unit 1, 2 and 3, together with the fuel pond of Unit 4 (and possibly the ponds Units 1 and 2) will require copious quantities of water cooling either injected or sprayed into what remains of the reactors, containment structures and fuel ponds for weeks to come. It follows, that unless capacious holding tanks and effective abatement systems are installed in the interim, a large volume of contaminated water will, once again, accumulate on the Fukushima Dai-ichi site with no option but to, once again, discharge it directly into the marine environment.

JOHN H LARGE
LARGE & ASSOCIATES
Consulting Engineers, London