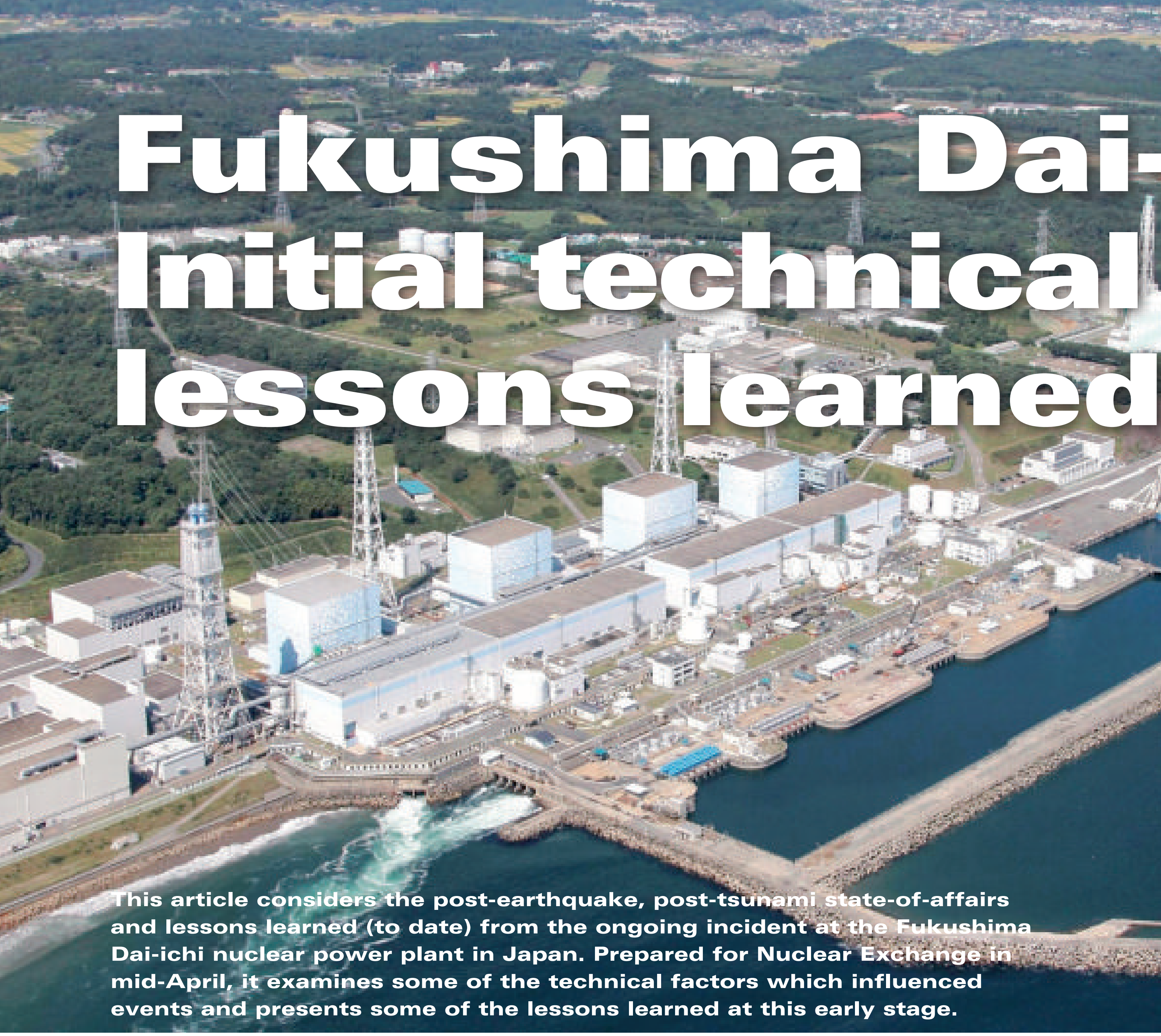

Fukushima Dai- Initial technical lessons learned

This article considers the post-earthquake, post-tsunami state-of-affairs and lessons learned (to date) from the ongoing incident at the Fukushima Dai-ichi nuclear power plant in Japan. Prepared for Nuclear Exchange in mid-April, it examines some of the technical factors which influenced events and presents some of the lessons learned at this early stage.

Keywords: nuclear power plant, accident, meltdown, spent fuel pool, loss of off-site power, earthquake, tsunami

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The Japanese Fukushima Dai-ichi (D1) and Dai-ni (D2) nuclear power station with 4 GE-BWRs (4 x Mark I type) units (U1-4) at one site and 2 BWR units (U5-6; 1 each, Mark I, Mark II) respectively co-located side-by-side on the north-central eastern coast of Japan withstood a 9.0 earthquake and a large-scale tsunami on March 11, 2011. All six units were constructed via a GE/Hitachi/Toshiba collaboration from 1967-1979. Two planned GE ABWRs due to begin construction in 2012 have recently been cancelled. In spite of the immediate shut down of all units (D1, U4 was shutdown at the time) based on ground-level acceleration and decay heat cooling for some 30-45 minutes, loss of off site power by ingress of water into the earthquake-proof diesel generators' pit, initiated an event that can be broadly defined as loss-of-heat-sink, classified as a 'beyond design basis accident'. Further, along with decay heat cooling of the reactor core, all units faced additional, unanticipated challenge of decay heat cooling of spent fuel pool (SFP) situated above the reactor core in proximity of both the core and containment building. In fact, for U1-4, the spent fuel pool is situated in a lightly-structured confinement building. During the initial week, March 11-18, there were up to three larger (likely H2 explosion) explosions, vapor/steam jets and fires that further stressed the RPV, the containment and (weather) confinement buildings. One of the later explosions conceivably damaged the primary (coolant) containment and thus, water found in the adjacent basement of the turbine building pointed to high-levels of radiation including fission products. Additional large volumes of contaminated water were found in the U-shaped electrical conduit 'trenches' off of U1-3 and spreading into other areas such as beneath the reactor site. Technical specifications for U1-6, focused on relevant parameters at the time of (accident) initiation, are given in Table1. Note that the Table includes details about the lateral acceleration threshold for shutdown and also the number of fuel assemblies in the SFP that contributed to the accident. The common SFP is also included. Table 2 gives estimates of the reactor core decay heat versus time after shutdown; thermal decay heat determines the cooling needed after shutdown. A little known site map is given in Figure 4, along with 'before' and 'after (March 18)' images in Figures 1 & 2. The site map is particularly handy in conjunction with images by Cryptome (2011). Figures 3 and 5 respectively provide qualitative schematics of the

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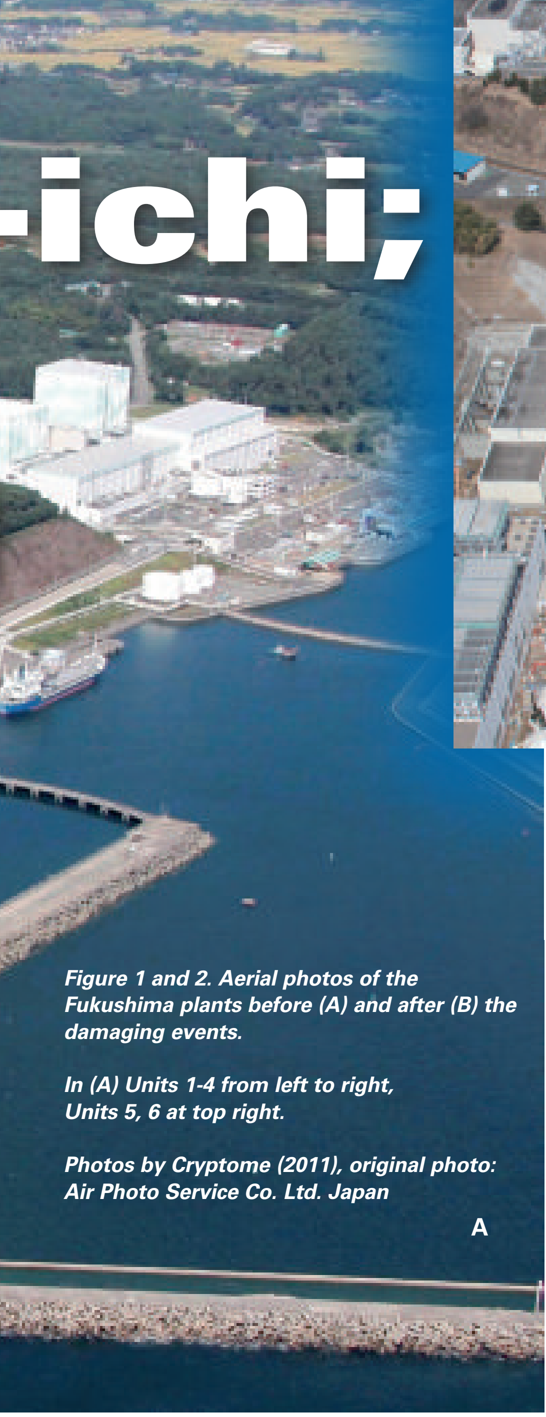

Figure 1 and 2. Aerial photos of the Fukushima plants before (A) and after (B) the damaging events.

In (A) Units 1-4 from left to right, Units 5, 6 at top right.

Photos by Cryptome (2011), original photo: Air Photo Service Co. Ltd. Japan

Mark I plant with unique toroidal suppression pool and location of the SFP, and a sectional view, with several overall relevant dimensions. Notable in Figure 5 is the realization that there are flow paths of contaminated water from the containment into the basement of the turbine building and further into channels (trenches) beyond where it can leak into the hydrosphere (ocean or water source). These are presented here to facilitate your own assessment of the timelines and news releases since March 11, 2011. Regularly issued press releases include the following: MEXT, JAIF, IAEA, NRC, TEPCO, Kyodo News Wire, The Japan Times, Wikipedia and Der Spiegel (all since March 11, 2011). The most viewed Internet-based news included (all Japanese): NHK-BS2, Fuji News Network, Tokyo Broadcasting System, Nikkei and Asahi News Network.
Since event initiation the above news sources have reported a number of (likely) hydrogen explosions, venting of radioactive steam plumes, and fires. Interestingly enough, the reported events leading to global radiation fears may have substantiated the author's work (Tokuhiro); that is, that mass-media dissemination of 'nuclear' and 'radiation' events accentuates perception of risk by a factor of at least 1000-times.
Under emergency response and (technical) crisis management, the world has witnessed helicopter drops of water, pumping of seawater into the containment building, spray injection cooling of the SFP using a ~15m(50 foot) 'arm' affixed to a large truck and recent pumping of 'clean' water brought to the site via a large barge-based tank. Global mass-media has reported the events non-stop, week after week. As a result of the recovery effort, large volumes of contaminated (radioactivity-laden) water have collected in various channels and basins and in early April were released into the ocean. Detectable concentrations of radioactivity have been measured in farm and sea products, such as green vegetables, beef and fish, within the 20km and 30km evacuation zones. Potable water was also contaminated to varying degrees. Through all this, TEPCO, NISA and the Japanese government have been the 'face' of the daily reporting of the situation. It is evident that, as the situation persists, the public perception of risk and benefit of nuclear energy is shifting toward the former.

Lessons learned

From a technical perspective, up to the end of the first week of April 2011, I believe that the global community of nuclear energy professionals may acknowledge the provisional list of lessons learned. At this point, it is clear that full technical assessment of the extent of in-core, in-vessel, in-containment damage will not be forthcoming for at least 5-years. Post-TMI images of the partially melted core became available in 1985, 6 years after the accident (Wikipedia). Cleanup was completed in 1990. So, with multiple units with partial core and/or SFP damage, we can only project that assessment may be in 2016 (5-years) and cleanup sometime between years, 2017-2027. As for the potential impact on the global nuclear energy renaissance, it seems self-evident that there will be a 1-3 year 'slowdown'; however, anything beyond this is highly speculative. Permit me to instead, list some of the lessons learned to date. These are classified broadly into two general categories, "Design" and "Operational", with second classifier that is more specific as noted. So, the lessons are:

1 **Design/R&D.** Nuclear R&D institutions must consider alternatives to zirconium-based and zircaloy cladding so that the chemical reaction that generates hydrogen is prevented. We (as an industry) need to accelerate development and deployment of non-hydrogen producing cladding materials; that is, assuming that the coolant/moderator/reflector remains (light) water. For GCR, water ingress may initiate a reaction with graphite to generate CO_2 and H_2.
2 **Design/R&D.** Nuclear R&D institutions must consider degradation dynamics of cladded fuel and fuel assemblies in-core and in spent fuel pools. We need a better understanding of the potential fuel 'reconfiguration' under, zircaloy-water chemical reaction such that the cladding is lost and further, the fuel begins to melt. Unless the reconfigured core or SFP is known, one cannot adequately know the availability of coolant flow paths other than the fact that the entire spent fuel mass is submerged in coolant. Our predictive capability of partially (5% to 95%) melted or degraded core (or SFP) configuration is inadequate.
3 **Design.** It is clear that the spent fuel pool (SFP) cannot be in proximity of the reactor core, reactor pressure vessel or containment itself. The SFP, in its current form, is essentially an open volume subcritical assembly that is not subject to design requirements generally defining a reactor core. Yet, unless thermohydraulic cooling is maintained, it is subject to similar consequences as a reactor core without adequate cooling. Therefore, we need new pas-

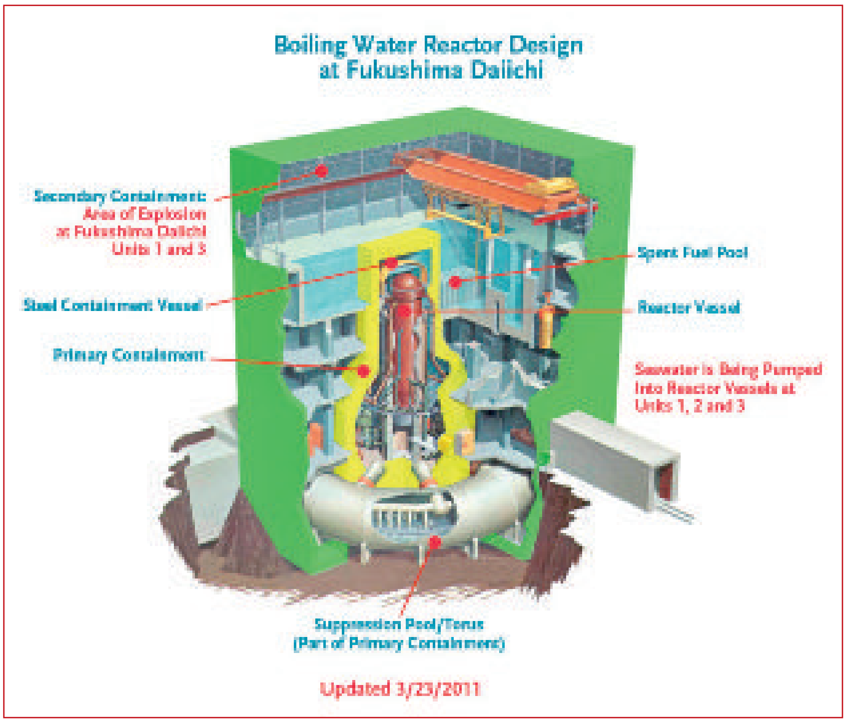

Figure 3. Boiling Water Reactor, Mark-I similar to D1, U1-5. D1, U6 is a Mark-II type. (Cf. www.nei.org)

sive designs of the SFP, away from the actual plant's reactor core.

4 **Design.** (Thus) New standard and design requirements are needed for the SFP. This is especially true for NPPs located in earthquake zones. The SFP should be 'reclassified' as a subcritical assembly with potential for criticality with no active/passive control (rod or soluble 'poison') mechanism. This warrants engineered design of immersed, co-located control rod elements, including DBA and BDBA analyses. In addition, in order to prevent loss-of-coolant, the SFP should have a condensate 'cover' in order to minimize loss-of-coolant due to sloshing of the free surface. Lastly, the SFP should be some distance from the reactor plant.

5 **Design.** In future designs of nuclear reactor systems, we need to reconsider core configurations with low aspect ratio rather than high aspect ratio. Under decay heat natural circulation cooling (single-phase or under boiling), one may need to minimize the coolant volume inventory that is needed to maintain the core submerged in liquid coolant. This further identifies a need to select a coolant that is on-hand; that is, an intended coolant if it is a LWR and a secondary coolant that may suffice for decay heat cooling. This obviously opens up a fundamental question on fluids/materials selection to serve as coolant, moderator and reflector in a nuclear reactor system. The overall maximum vertical height should be limited by the height of emergency responder cooling equipment such as a crane-based firehose or similar. In other words, it is not wise to build a structure so tall that firefighting equipment cannot adequate inject water or similar liquid coolant.

6 **Design/Site Design Basis.** Having multiple (reactor) units at one site needs critical review in terms of post-accident response and management. We must consider the energetic events at one unit exacerbating the situation (safe shutdown) at the other. For nuclear installations, we should review the co-location of facilities with a potential for a criticality accident in one exacerbating access to another during first response. Access is obviously needed for 'cold shutdown' of the intact unit, relative to the damaged unit, in a timely manner.

7 **Design/Site Design Basis.** There is a need for standby back-up power, via diesel generator and also battery power, at a minimal elevation (100feet/31m) above and remotely located. This is needed to offset loss of off-site power for plants subject to environmental water ingress (foremost tsunami). Spare battery power should also be kept off-site and in a confirmed 'charged' state. There is also a critical need for standby back-up cooling capability (gas or liquid); that is, a liquid-to-air or liquid-to-liquid heat exchanger that can be installed in a timely manner if/when the primary/secondary cooling circuits are unavailable.

8 **Design/Site Design Basis.** For nuclear power plants located in or near earthquake zones, we cannot expect structural volumes and 'channels' to maintain structural integrity. We should also expect the immediate ground underneath these structures to be porous . It may 'liquify' under earthquake and thus become a path for contaminants. Thus design of these volumes and channels should be such that they minimize connections to other (adjacent) volumes from which

Location name, -unit	BWRtype	Start construction/ criticality operations	Power Mwth/ Mwe	Design, peak gnd accel.(g)	Reactor supplier/ A&E/ Construction: GE-General Electric, EB-Ebasoo, KA- Kajima, TO-Toshiba, Hi Hitachi	Reactor Fuel Assemblies, F/As	Spent Fuel Pool, F/As	Fuel type	Fresh Fuel
Fukushima 1-1	BWR-3; Mk-I	7/67;10/70; 3/71	1380/ 460	0.18	GE/EB/KA	400	292	LEU	100
Fukushima 1-2	BWR-4; Mk-I	6/69;5/ 73;7/ 74	2381/784	0.45	GE/EB/KA	548	587	LEU/	28
Fukushima 1-3	BWR-4; Mk-I	12/70;9/ 74;3/ 76	2381/784	0.45	TO/TO/KA	548	514	LEU/ MOX	52
Fukushima 1-4	BWR-4; Mk-I	2/73;1/78;10/78	2381/784	0.45	HI/HI/KA	0	1331	LEU	204
Fukushima 1-5	BWR-4; Mk-I	5/ 72;8/77; 4/ 78	2381/784	0.45	TO/TO/KA	548	946	LEU	48
Fukushima 1-6	BWR-5; Mk-II	10/73; 3/ 79; 10/79	3293/1100	0.45	GE/EB/KA	764	876	LEU	64
Fukushima 1-7	ABWR	Cancelled 04/2011	1380MWe	NA	Cancelled 04/2011	NA	Cancelled 04/2011	LEU	NA
Fukushima 1-8	ABWR	Cancelled 04/2011	1380MWe	NA	Cancelled 04/2011	NA	Cancelled 04/2011	LEU	NA
Central SFP	NA		NA			NA	NA	NA	6375

Table 1. Summary of Fukushima NPP unit selected specifications

contaminated (liquid) effluents can flow.

9 **Design/Site Design Basis.** Place larger structures of hydrodynamic design toward the ocean and smaller installations in the 'wake' region behind these larger structures. That is, in the case of Fukushima, the tsunami always approaches from the ocean. It thus makes imminent sense to hydrodynamically design these larger structures with smaller structures in the wake region of the larger structures. Structures in the wake region will likely have a higher probability of sustaining less damage if place directly on 'ocean-side'.

10 Design/Reactor Design Basis. Loss-of-offsite-power and only partial availability of diesel generator-based and/or battery-based backup power needs to be analyzed as DBA or BDBA.

11 **Design/(Gas-Cooled)** Reactor Design Basis. For loss-of-offsite-power and only partial availability of generator-based and/or battery-based backup power, any depressurization DBA or BDBA may require timely injection of additional coolant (gas), assuming that water is not an option.

12 **Operational.** If an 'in-containment' SFP is maintained, then the fuel transfer crane system must be designed so that it is available to remove the fuel during a post-accident phase or a second means such as a robotic arm needs to be available.

13 **Operational.** We need to identify or review key valves for emergency core cooling and review requirements that they are non-electrically 'functional'. That is, these valves need a secondary means of open and closed status that is remotely located.

Reactor Type		BWR-3		BWR-4
Thermal (MW)		1380(100%FP)		2381(100%FP)
Power After Shutdown				
Time (seconds)	**Time (s,m,h,d,y)**	**MW (thermal)**	**% FP**	**MW (thermal)**
1.00E-01	0.1 s	139.33	10.0961	240.39
1.00E+00	1 s	86.86	6.2943	149.87
1.00E+01	10 s	53.76	3.8956	92.75
1.00E+02	100 s	32.87	2.3820	56.72
1.00E+03	16.7 m	19.69	1.4271	33.98
1.00E+04	2.8 h	11.38	0.8245	19.63
1.00E+05	28 h	6.13	0.4445	10.58
1.00E+06	11.6 d	2.84	0.2057	4.90
1.00E+07	116 d	0.89	0.0641	1.53
1.00E+08	3.2 y	0.12	0.0087	0.21
1.00E+09	31.7 y	0.01	0.0006	0.02

Table 2. Thermal power output of reactor core fuel after shutdown for selected times.

14 **Operational.** Further, there is a definite need for a backup (shielded) reactor plant and/or 'criticality possible installation' control center that is off-site (remote) so that the accidents can be managed with partial to full extent of reactor plant or criticalitypossible installation status (P, T, flowrates, valve status, tank fluid levels, radiation levels). Sensor will need to be 'hard-ened' to withstand energetic events.

15 **Operational.** There needs to be a volumetric guidance analysis for ultimate (decay heat) cooling contingency plans so that not only limitations on volume are understood but also transfer of liquids from one volume to another. Spare tanks and water-filled tanks need to be kept on site as uptake tanks for 'runoff' in case of addition of coolant during accident management phases. Additiional means to produce boric acid need to be available off-site. Earthquake-proof diesel generator housing also needs to be water-proof. Remote diesel generators are also needed with access to equally remote diesel fuel tanks (also see6).

16 **Operational.** Under emergency and crisis management, wider access roads are needed to and from NPPs. The access roads need to be clear of debris and of such width to accommodate large-scale trucks needed as first response and during the recovery phase. A way to access the plant via

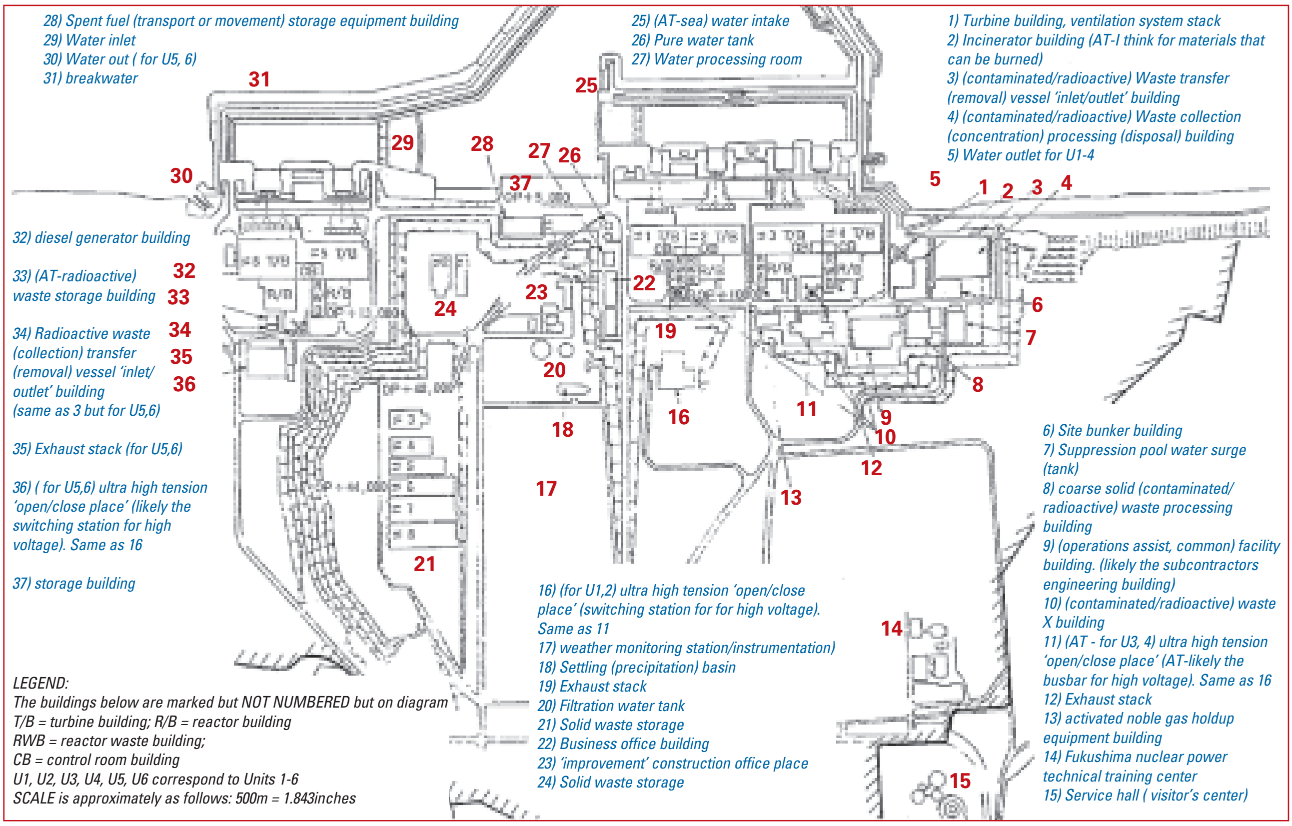

Figure 4. Fukushima nuclear power station site map (original in Japanese)

water calls for infrastructure (boats, water-containing barges, jet-skis etc) and is needed as part of a contingency plan for those plants located near bodies of water.

17 **Operational/Standardization.** Color-coded major components so that in case of an accident such as that at Fukushima NPP station, we will be able to quickly identify the major components from digital images. Nuclear plant site maps, such as Figure 1, should be 'downloadable' or available upon request in order to be used in accident management.

18 **Operational/International.** An international alliance of nuclear reactor accident first responders and beyond first response, a crisis management team are needed. No such international alliance is available at this time. The global nuclear industry cannot wait 3 weeks for international participation.

19 **Operational/International.** We should consider and work toward an international agreement on standards for regulated levels of radiation activity and exposure to the general public and separately, to those workers responding under emergency and extended 'recovery' phases. We should also be consistent in definition and practice of implementing evacuation zoning. We should also strongly encourage acceptance and use of SI units for radiation activity and exposure (consistent use of μSv/hr or mSv/hr)

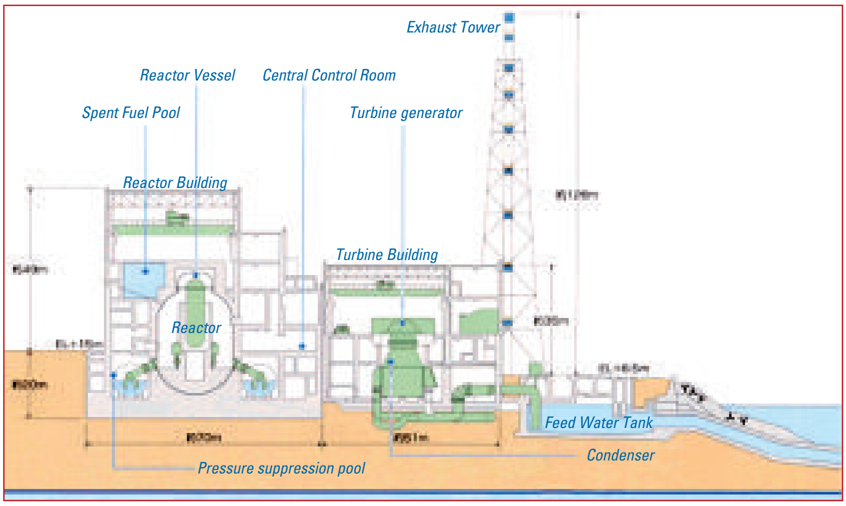

Figure 5. Representative cross-sectional perspective of D1 Unit (not all details are shown)

20 **Operational/International.** In order to promote and actively practice a true "Global Nuclear Energy Partnership (GNEP)", I hereby propose that we designate the Fukushima NPP site and its reactors as an international nuclear post-accident management and decommissioning center (INPMD). The INPMD should be sanctioned by the Japanese government and led by a new Japan-based commission with international lead members (for example, IAEA, U.S., France, Korea, China). The commission should however establish a consortium of member nations. The official language should be English. The level of participation should correspond to commitment of equipment and experts. The lessons learned and data generated in the recovery phases should be open to all. Each consortium member nations should also have risk communication representatives.

References available on request.
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