Union of Concerned Scientists
Citizens and Scientists for Environmental Solutions

Fukushima Dai-Ichi Unit 3: The First 80 Minutes

David Lochbaum
Director, Nuclear Safety Project

In the middle of May 2011, the Tokyo Electric Power Company (TEPCO) posted information such as scans from paper recorders in the control rooms, computer alarm printouts, parameters plotted from high-speed data recorders (the nuclear equivalent to aircraft black boxes), and operator log books online at http://www.tepco.co.jp/nu/fukushima-np/index10-j.html.

I reviewed the information for Units 1, 2, and 3. While working as a shift technical advisor in the early 1980s at the Browns Ferry nuclear plant in Alabama (with three boiling water reactors (BWRs) having Mark I containment designs like those at Fukushima Dai-Ichi Units 1-3), I authored several reports for unplanned reactor shut downs. To prepare those reports, I reviewed many of the same materials. More recently while working as a BWR technology instructor for the U.S. Nuclear Regulatory Commission, I taught during the two-week R504B course. During that course, we covered transients both in classroom and control room simulator settings. In the classroom sessions, we would provide students with control room chart recorder plots of seven key parameters (average power range monitor power level, reactor vessel pressure, reactor steam flow, turbine steam flow, feedwater flow, reactor vessel narrow range water level, and total core flow) and ask them to determine what transient explained all the squiggles on the charts. Later in the control room simulator, we'd demonstrate the transients for the students.

The available information for Unit 3 does not extend long after the arrival of the tsunami, and does not extend to the point at which fuel in the reactor core was damaged by overheating. Much of the available information ends at 4:05 pm local time, about 80 minutes after the earthquake occurred at 2:46 pm. The available information for the first 80 minutes following the earthquake shows:

1. The reactor shut down around 2:46 pm local time and remained shut down.

2. Normal power supplies to in-plant equipment were lost about a minute later. It is assumed that this occurred when the operators manually tripped the turbine/generator per procedure.

3. Both emergency diesel generators on Unit 3 automatically started and connected to their in-plant electrical buses within seconds of the power loss, restoring power to essential plant equipment.

4. The power interruption caused the main steam isolation valves to automatically close, disconnecting the reactor core from its normal heat sink and disabling the normal source of makeup water to the reactor vessel.

5. A safety relief valve (SRV) automatically opened around 2:52 pm to control rising pressure inside the reactor vessel. This SRV automatically re-closed when reactor pressure dropped. This SRV followed by two other SRVs cycled opened/closed periodically over the next 73 minutes to control pressure inside the reactor vessel.

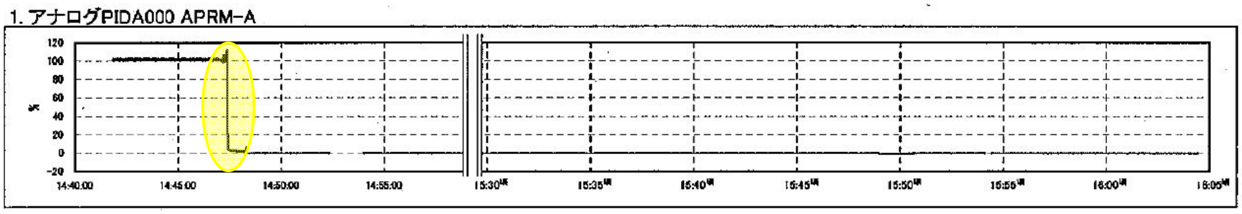
6. The water level inside the reactor vessel steadily declined as cooling water was discharged through the open SRVs into the torus. By 4:00 pm, the water level had dropped below the bottom end of the level monitoring scale. There's no compelling evidence that any system was used to provide makeup flow to the reactor vessel from the time that the MSIVs closed around 2:48 pm until 4:00 pm.

7. Around 3:38 pm, one of the emergency diesel generators stopped running. About a minute later, the other emergency diesel generator stopped running. It is assumed that the tsunami caused these failures.

8. Around 4:02 pm, the RCIC system appears to have been placed in service. The data ends shortly

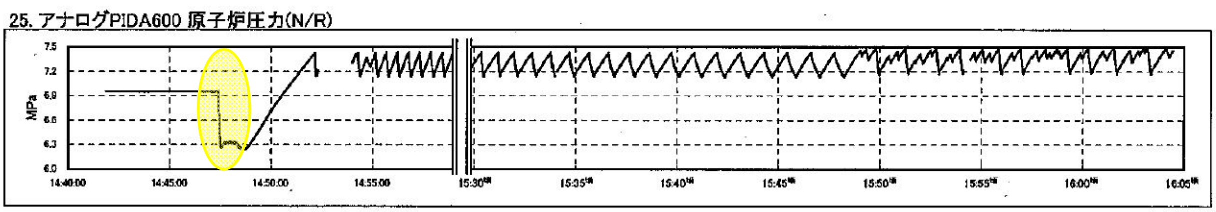
afterwards at 4:05 pm.

Key aspects from the first 80 minutes on Unit 3 are detailed below.

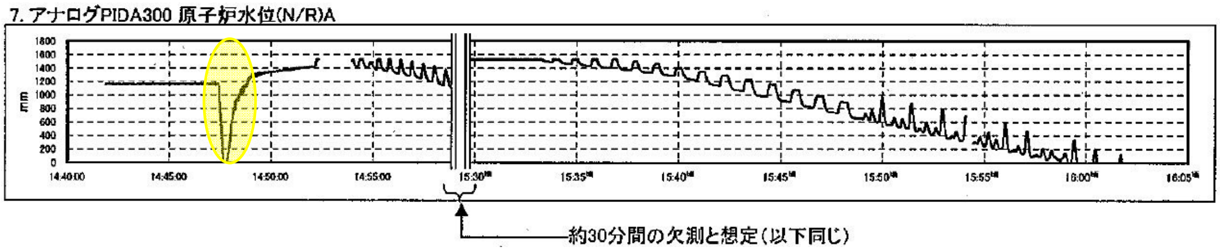


Unit 2 had 124 neutron detectors of the local power range monitoring (LPRM) system installed within the reactor core. There were 31 strings of LPRM detectors at different core locations. Each LPRM string contained 4 LPRM detectors spaced from core bottom to core top. 20 or 21 of the LPRM detector signals from diverse radial and axial core locations were sent to six average power range monitor (APRM) channels. This allowed each APRM channel to monitor overall core power level. Each APRM channel was periodically adjusted to match the percent of rated core thermal power as determined by a mass and energy balance calculation performed by the plant's computer. The APRMs provided real-time, continuous monitoring of the reactor power level and would trigger an automatic shut down if power rose too high.

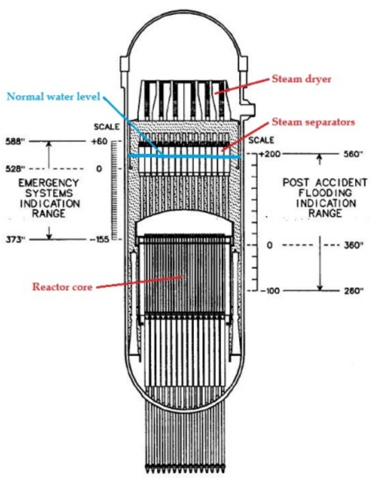
The chart above provides the output from APRM Channel A. The traces for APRM Channels B through F are similar. In response to the rapid insertion of the control rods, the core power level quickly drops from 100 percent to 0 and remained at 0. The reactor core was shut down shortly after the earthquake struck.



Power, pressure, and water level are the three key parameters to monitor for the reactor core and the reactor vessel. The power level went to zero as control rods rapidly entered the reactor core. The chart above shows the pressure inside the reactor vessel. The pressure had been steady at 6.95 mega pascals (MPa, corresponding to 1,008 pounds per square inch gauge, psig) prior to the event. When the control rods rapidly inserted, the ensuing reactor power reduction caused the reactor pressure to decrease to around 6.3 MPa (913.7 psig).



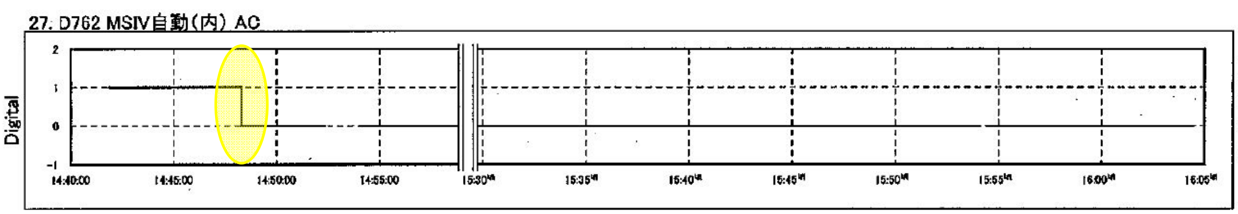
The water level inside the reactor vessel is the third key parameter. The chart above plots the water level over the narrow range of 0 to 1,800 millimeters (mm). The water level had been steady at 1,185 mm (46.7 inches) prior to the earthquake.



For this instrument, 0 mm corresponds to the bottom of the steam separators while 1,500 mm corresponds to the top of the steam separator. This is comparable to the 0 to 60 inch instrument shown in the schematic to the left. **Zero on this scale is 3,940 mm (155 inches or nearly 13 feet) above the top of the reactor core.**

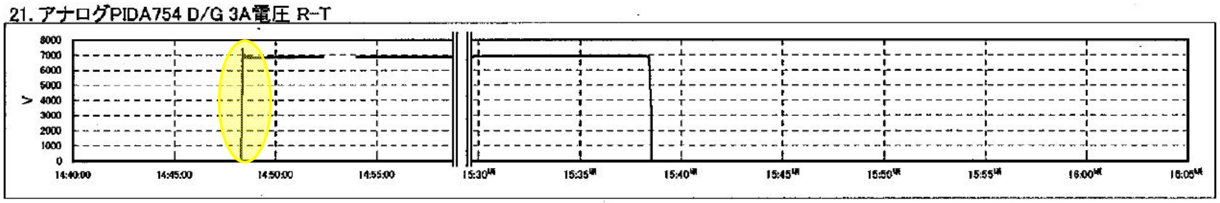
The steam separators and steam dryer are located above the reactor core. Water passing upward through the reactor core is heated to boiling. The steam exiting from the top of the reactor core carries water droplets along with it. The steam separators have curved metal vanes inside hollow metal tubes. The vanes spin the upward flow, causing the heavier water droplets to be flung against the tube walls where tubes drain the water back to the lower region of the reactor vessel. The flow leaving the steam separators enters the steam dryer. The steam dryer further removes water droplets from the flow. The steam leaving the reactor vessel is dry, high quality steam.

The rapid insertion of the control rods quickly reduced the reactor power level which in turn reduced the number and size of steam bubbles being produced in water flowing through the reactor core.

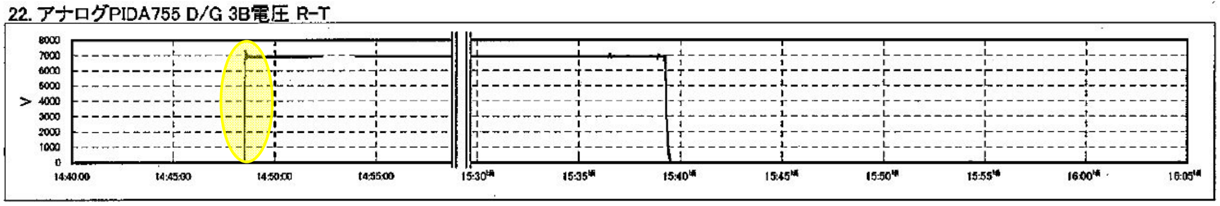


About a minute after the reactor shut down, the main steam isolation valves (MSIVs) closed. The chart above shows the logic signal for the MSIVs – a “1” indicates the MSIVs are open while “0” indicates the valves are closed. The alarm printouts are not available for Unit 2 as they were for Unit 1. It is assumed that the MSIVs closed on Unit 2 for the same reason they closed on Unit 1 – loss of normal power supplies when the turbine tripped.

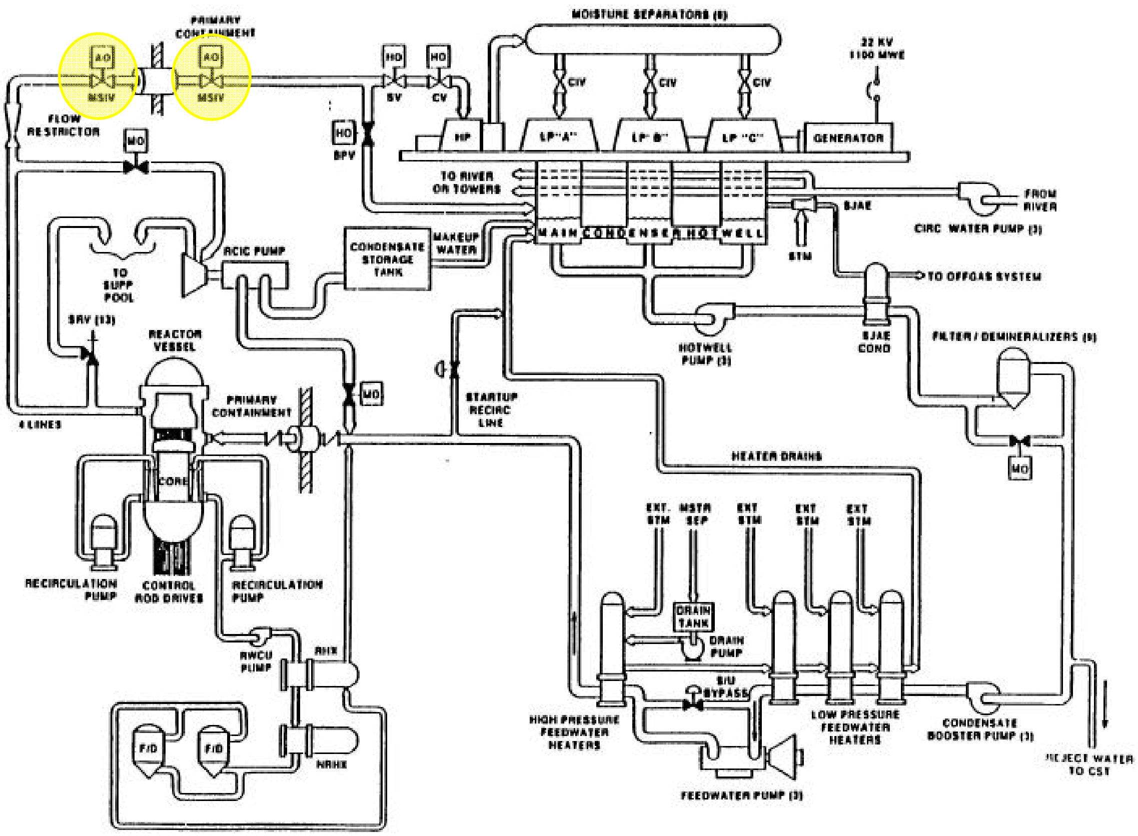
21. アナログPIDA754 D/G 3A電圧 R-T



22. アナログPIDA755 D/G 3B電圧 R-T



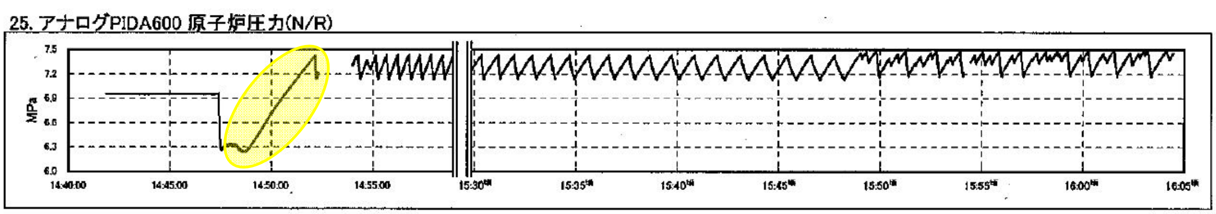
The charts above show the electricity output by emergency diesel generators 3A (top) and 3B (bottom). When the normal supplies of in-plant electricity from the Unit 3 generator and from the electrical grid were lost, both emergency diesel generators automatically started and provided power to essential plant equipment within seconds.



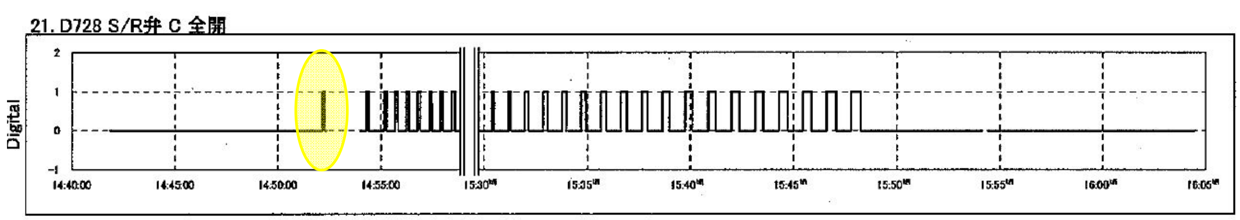
Simplified BWR Primary and Auxiliary Systems

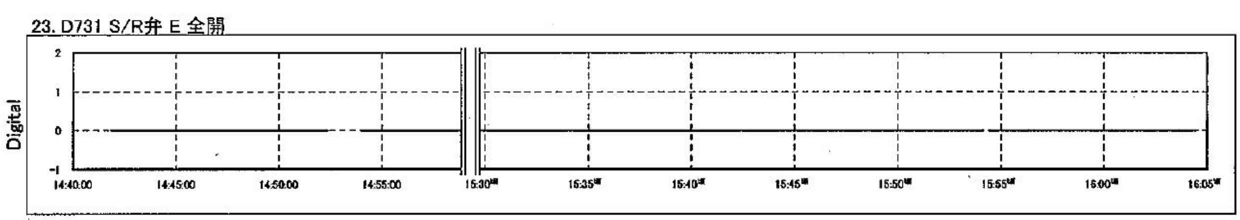
The momentary loss of power closed the main steam isolation valves (MSIVs). As shown in the diagram above, there are two MSIVs in each of the four pipes carrying steam from the reactor vessel to the turbine. The fail-safe position of the MSIVs is closed. When power was lost, the MSIVs closed. Steam being produced by the reactor core's decay heat had been traveling through the steam lines to the turbine. When the MSIVs closed, that steam could no longer travel this path. In addition, the normal supply of makeup water to the reactor vessel to compensate for water leaving as steam is via the feedwater system. The feedwater system features steam-driven pumps. The source of steam for the feedwater pump turbines is taken from the steam lines downstream of the MSIVs. Thus, closure of the MSIVs made the feedwater pumps unavailable.

The successful start of both emergency diesel generators restored power to essential plant equipment. The operators would have been able to re-open the MSIVs. But that step, if taken, would not have been long-lasting. The emergency diesel generators do not provide power to the equipment handling the steam collecting in the main condenser. Normally, the pressure inside the condenser is maintained as close to perfect vacuum conditions as can be obtained. The near-vacuum conditions help pull steam through the turbine. As condenser vacuum is lost, sources of steam to it are automatically isolated. Thus, if re-opened, the MSIVs would have soon automatically re-closed.



The closure of the MSIVs changed the trend of pressure inside the reactor vessel. Pressure had been trending downward as the amount of steam produced by the reactor core's decay heat was transported through the steam pipes to the turbine. When the MSIVs closed, the steam had no place to go. Bottled up inside the reactor vessel, the continued production of steam caused the reactor vessel pressure to steadily increase for the next five minutes.





Unit 1 had isolation condensers to control reactor pressure and reactor vessel inventory when the MSIVs closed. Unit 3 did not have isolation condensers. Safety relief valves (SRVs) were used on Unit 3 to control pressure inside the reactor vessel. As shown on the diagram on the preceding page, the SRVs were attached to the main steam pipes between the reactor vessel and the MSIVs. As the chart for SRV C shows (top strip on preceding page), when the pressure inside the reactor vessel rose to about 7.35 MPa (1,066 psig), this SRV automatically opened to send steam through a pipe to the suppression chamber, also called the torus. The pipe discharged the steam below the surface of the water inside the torus. The water cooled the steam, turning it back into water.

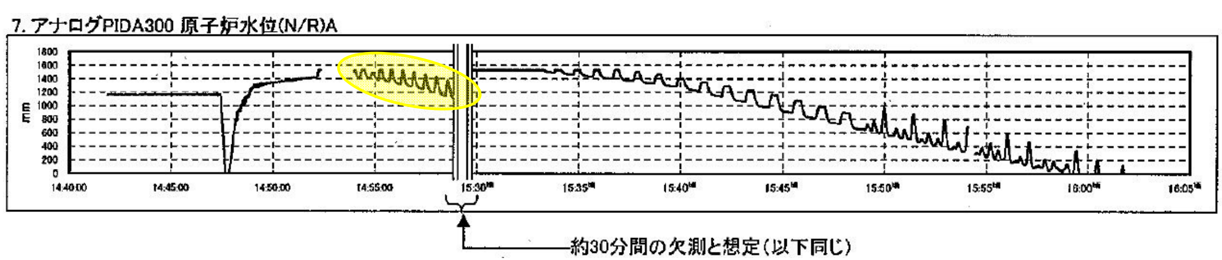
When the open SRV lowered pressure inside the reactor vessel to about 7.1 MPa (1.030 psig), the SRV automatically re-closed. The charts for pressure and SRV C show this sequence repeated, leaving the classis “sawtooth” pattern on the pressure chart as the SRV cycled to control pressure. As the decay heat level of the reactor core decreased over time, the frequency of SRV openings decreased.

The chart for SRV E (bottom strip on preceding page) shows that it did not open during this period. The strip charts for the other SRVs also indicate they did not open during this period. This response is per design. If all the SRVs had opened, the pressure inside the reactor vessel would have dropped farther and faster than necessary. SRV C opening periodically adequately controlled the reactor vessel pressure. Other SRVs would also have opened if necessary to prevent excessive pressure.

The emergency procedures for U.S. boiling water reactors would generate similar plots with one significant difference. Rather than permit one SRV to repeatedly cycle open and closed automatically, the operators at U.S. boiling water reactors would manually operate all the SRVs one at a time in a rotating sequence to control reactor pressure between a range of something like 5.5 MPa (800 psig) and 6.9 MPa (1,000 psig) for two primary reasons.

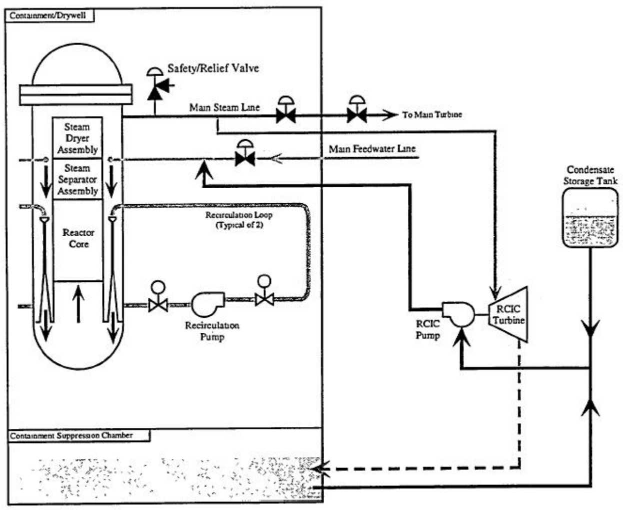
First, SRVs have a history of sticking in the open position after repeated use. A stuck-open relief valve contributed to the partial meltdown of the Unit 2 reactor at Three Mile Island. A stuck-open relief valve depressurizes the reactor vessel with loss of cooling water inventory along the way. Utilizing all the SRVs minimizes the number of operations by individual SRVs, lessening the odds of experiencing a stuck-open SRV.

Second, the SRVs discharge steam into the torus. Utilizing all the SRVs more uniformly distributes the steam releases, and associated heat inputs, throughout the entire torus. This practice prevents local hot spots and reduces thermal stresses on the torus structure.



The use of SRV openings to control reactor pressure comes at the cost of losing cooling water inventory from the reactor vessel. Each time an SRV opens, water from the reactor vessel flows to the torus in the form of steam. As the chart above shows, the effect is to lower the water level inside the reactor vessel.

The “bumps” in the water level plot correspond to the SRV openings. After shaking up a bottle containing a carbonated beverage (e.g., a soda bottle), unscrewing the cap a little will cause the liquid to shoot towards the top. Similarly, opening an SRV lowers the pressure inside the reactor allowing steam bubbles to grow larger, raising the indicated water level. Closing the SRV has the opposite effect.

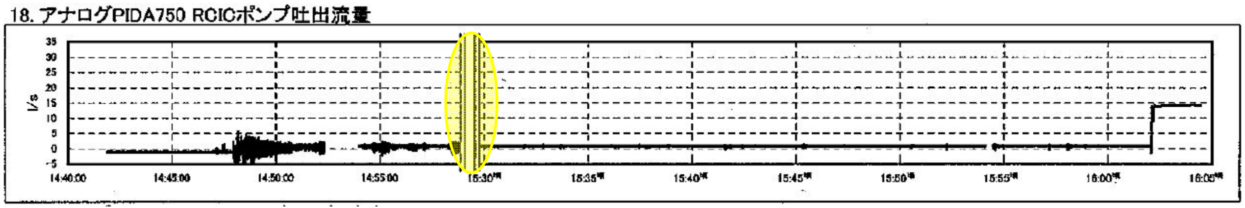


Unit 3 had a reactor core isolation cooling (RCIC) system to handle the water inventory loss associated using SRV openings to control reactor pressure. The RCIC system uses a steam-driven turbine connected to a pump to supply makeup water to the reactor vessel.

The steam is produced by the reactor core's decay heat. The connection for RCIC's steam supply is on the steam piping between the reactor vessel and the MSIVs. The steam exhausted from the RCIC turbine flows to the torus.

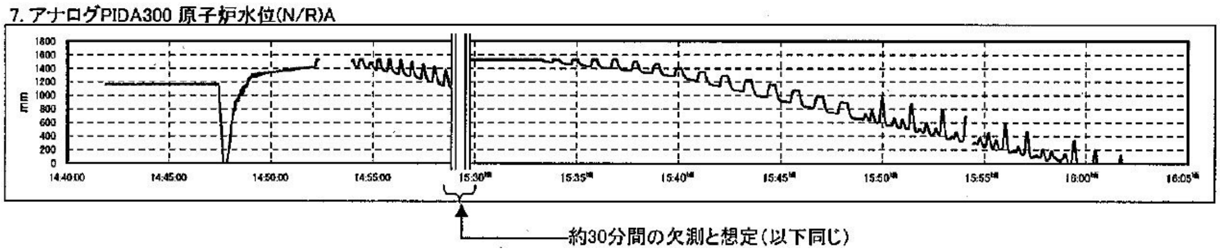
The RCIC system normally draws water from the condensate storage tank but can also take water from the torus.

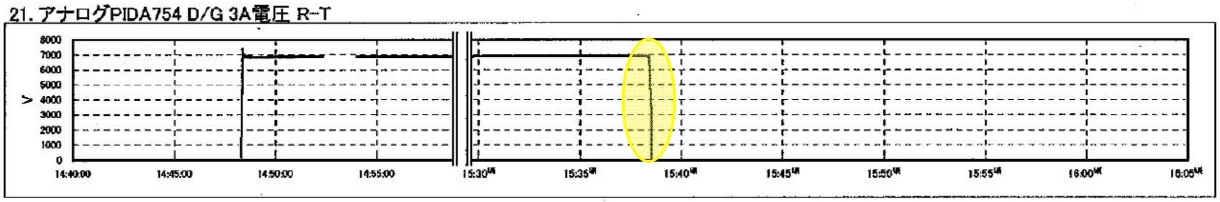
18. アナログPIDA750 RCICポンプ吐出流量

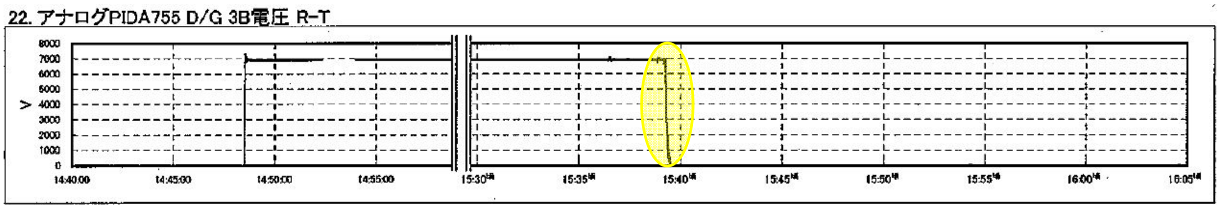


The RCIC system flow rate to the reactor vessel is plotted in the chart above. It does not shows the system operating prior to 4:02 pm. There's a 30 minute gap in the data between 3:00 pm and 3:30 pm. It is possible that the RCIC system operated during this half hour to restore the water level inside the reactor vessel. The following chart shows the water level inside the reactor vessel. Prior to the data gap, the level had dropped to below 1,200 millimeters (47.2 inches). After the data gap, the level was around 1,550 mm (61 inches). If something refilled the reactor vessel, the leading candidate is the RCIC system.

7. アナログPIDA300 原子炉水位(N/R)A

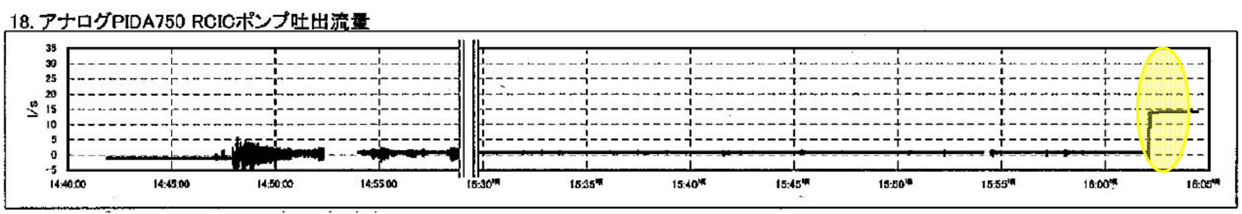


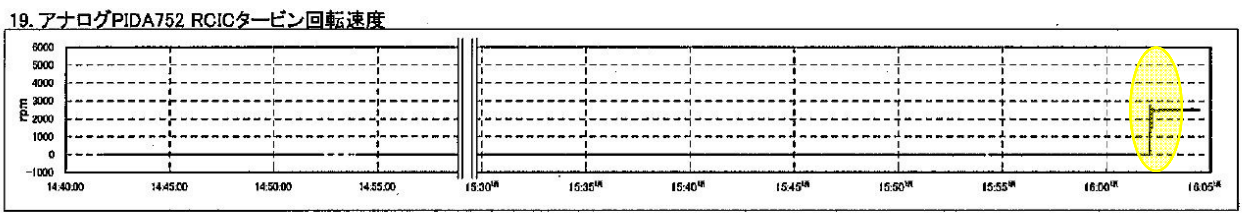




The charts above show the electrical output being supplied by emergency diesel generators 3A (top) and 3B (bottom) between 2:40 pm and 4:05 pm. At around 3:38 pm, emergency diesel generator 3A stopped running. Within a minute, emergency diesel generator 3B stopped running. This left Unit 3 without any power except that coming from batteries.

The RCIC system's turbine controls and valves are battery powered. So it can operate when only battery power is available. The SRVs were being operated mechanically. The SRVs are kept closed by spring pressure, similar to how a spring coil keeps a mousetrap closed. When pressure inside the steam lines rose high enough to overcome the spring force, the pressure would open the SRV against its springs. After the open SRV lowered pressure sufficiently, the spring force would re-close it. Thus, the SRV pressure control function did not require power from the emergency diesel generators or batteries.

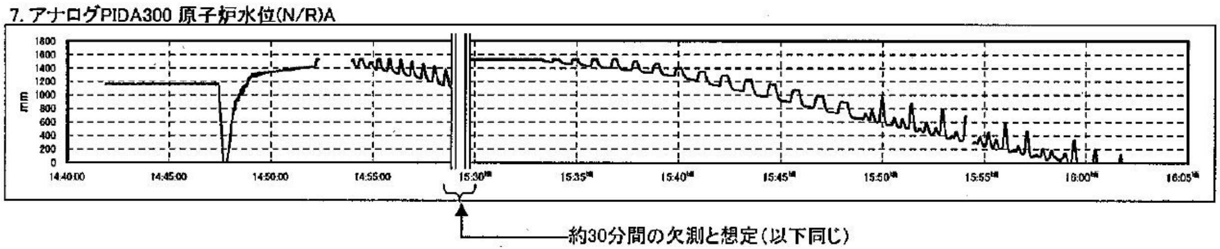




The two charts above show the RCIC system flow rate in liters per second (top) and the RCIC turbine speed in revolutions per minute (bottom).

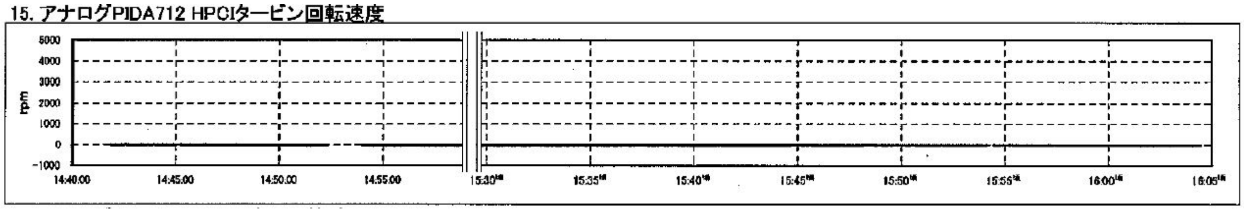
It appears that the RCIC system went in service around 4:02 pm. As shown in the following chart, the water level inside the reactor vessel had already dropped below zero (with zero being the elevation of the instrumentation tap, well above the top of the reactor core) before 4:00 pm.

7. アナログPIDA300 原子炉水位(N/R)A

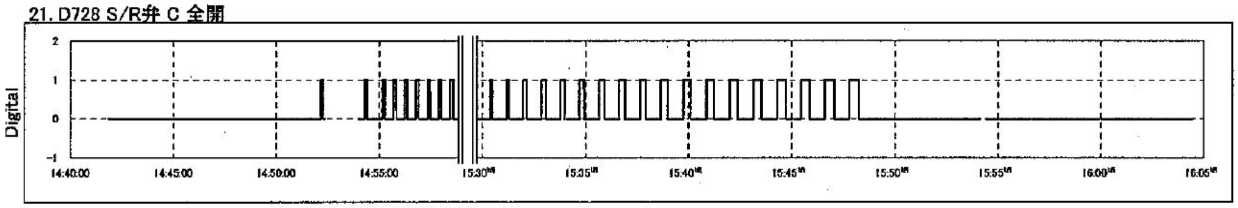


The available information does not explain why the water level in Unit 3 dropped below zero by 4:00 pm. The RCIC system appeared to be operable, yet was apparently not operated – except for perhaps during the 30-minute data gap beginning at 3:00 pm. As the following chart shows, the high pressure coolaint injection (HPCI) system apparently did not operate either. The HPCI system is basically a larger verison of the RCIC system with about 10 times the makeup capacity.

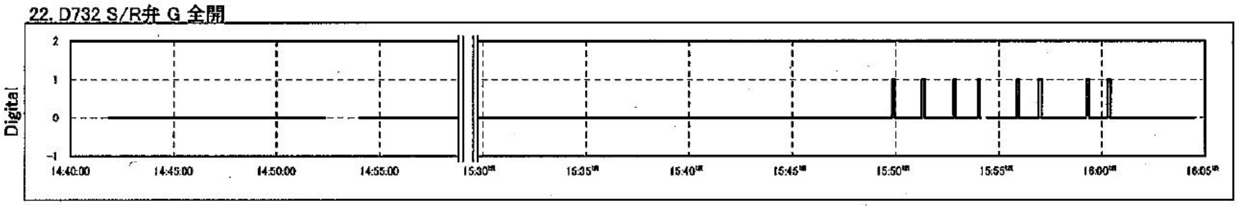
15. アナログPIDA712 HPCIタービン回転速度



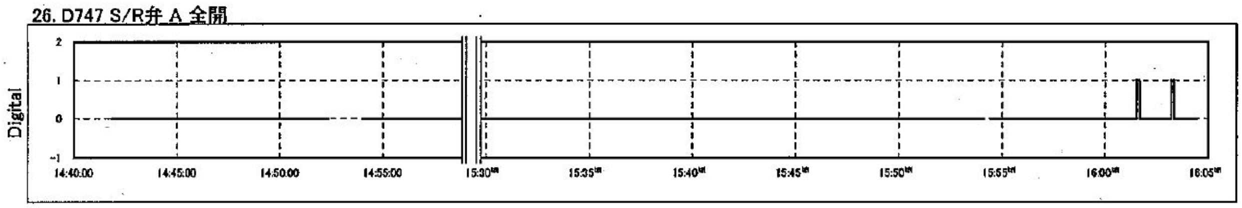
21. D728 S/R弁 C 全開



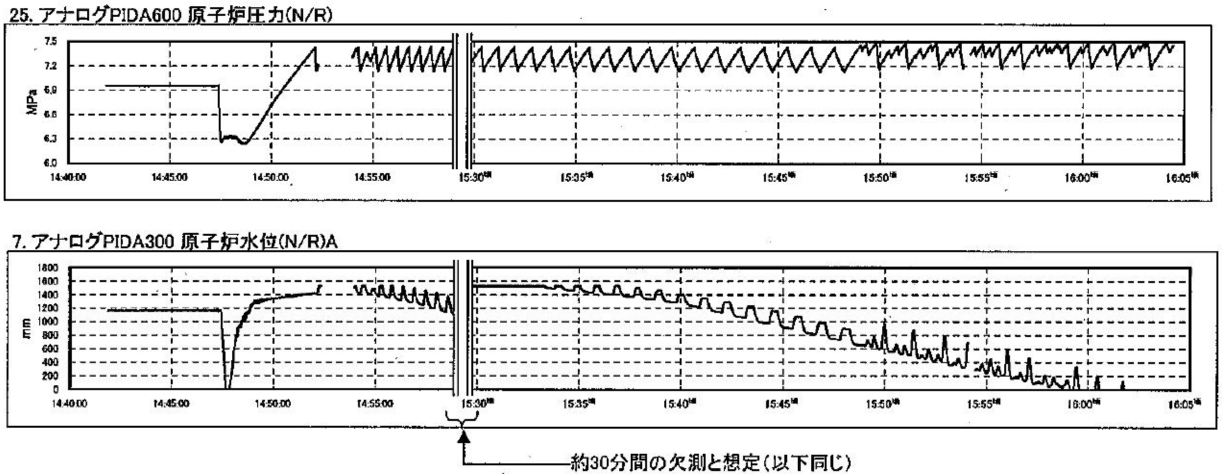
22. D732 S/R弁 G 全開



26. D747 S/R弁 A 全開



The above charts show the logic (1 being open, 0 being closed) for SRVs C (top), G (middle), and A (bottom). SRV C was used to control pressure between 2:52 pm and 3:48 pm. SRV G was used to control pressure between 3:50 pm and 4:01 pm. And SRV A was used to control pressure between 4:02 pm and 4:04 pm. The information does not explain whether the SRVs were being opened manually or automatically. The uniformity of the peaks and valleys in the chart of reactor pressure on the following page suggests that the SRVs opened and closed automatically.



The charts above are pressure (top) and water level (bottom) inside the reactor vessel. Together, they suggest that after the MSIVs closed at 2:48 pm, there was little to no supply of makeup water to the reactor vessel until the data ends at 4:05 pm. The SRVs periodically open and close to relieve pressure. As the decay heat produced by the reactor core gradually declines, the frequency of SRV openings also gradually decreases. And as the SRV openings discharge reactor cooling water to the torus, the water level inside the reactor vessel steadily drops.

The indicated reactor vessel level was about 250 mm higher after the 30-minute data gap than just before it began. But the indicated water level remained constant for the next three minutes or so – highly suspect and totally inconsistent with the expected water level response due to SRV cycling during that interval.

It appears that neither the RCIC nor HPCI systems were used between 2:52 pm and 4:00 pm. It's not clear why they were not used to correct the steadily declining reactor vessel level after 3:35 pm.