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# Fukushima Dai-Ichi Unit 1: The First 30 Minutes

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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 1 stops before the arrival of the tsunami, and well before the point at which fuel in the reactor core was damaged by overheating. Much of the available information ends at 3:17 pm local time, about 30 minutes after the earthquake occurred at 2:46 pm. This available information for the first 30 minutes following the earthquake shows:

1. Sensors detecting ground motion caused by the earthquake triggered an automatic shut down of the reactor at 2:46 pm local time. All of the control rods fully inserted into the reactor core.

2. When the operators manually tripped the turbine/generator per procedure 50 seconds after the reactor shut down, normal power supplies to in-plant equipment were lost.

3. Both emergency diesel generators on Unit 1 automatically started and connected to their in-plant electrical buses within 6 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. Both isolation condensers were placed in service about 5 minutes after the reactor shut down to control a rising pressure trend inside the reactor vessel.

6. It appears that both isolation condensers were removed from service after approximately 11 minutes due to an excessive cool down of the water inside the reactor vessel.

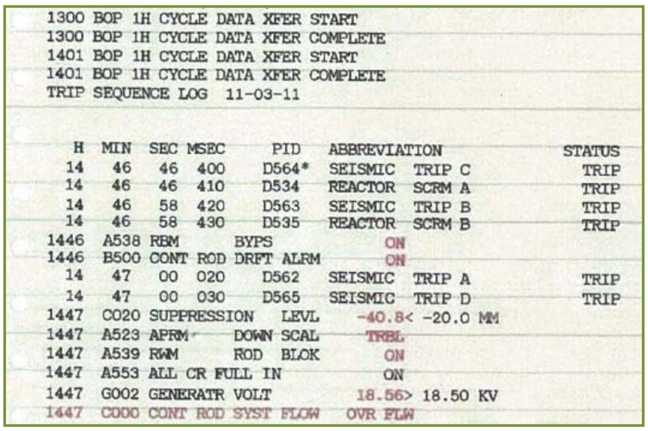
7. Around the time the isolation condensers were removed from service, there was an unexpectedly large downward step change in the indicated water level inside the reactor vessel.

8. After the isolation condensers were removed from service, there was an excessive heatup of the water inside the reactor vessel.

Key aspects from the first 30 minutes on Unit 1 are detailed below.

The earthquake triggered an automatic shut down of the reactor at 2:46 pm local time.

There are four sensors monitoring ground motion caused by an earthquake. These four sensors are arranged in the common one-out-of-two taken twice logic scheme for automatic reactor shut downs. This logic scheme allows for periodic testing that does not shut down the reactor and works even when a sensor fails. In this case, two seismic sensors exist in each trip channel. Either sensor detecting ground motion from an earthquake causes that channel to trip (one-out-of-two). A single failed sensor cannot prevent the channel from tripping. Both channels must trip in order for the reactor to be automatically shut down (taken twice). Workers periodically increase the output from each seismic sensor to verify by test that the channel trips when the specified ground motion level, or setpoint, is reached. By removing the sensor stimulus and resetting the tripped channel before moving to the second channel, workers can conduct the testing while the reactor is operating without causing it to automatically shut down.



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1300 BOP 1H CYCLE DATA XFER START
1300 BOP 1H CYCLE DATA XFER COMPLETE
1401 BOP 1H CYCLE DATA XFER START
1401 BOP 1H CYCLE DATA XFER COMPLETE
TRIP SEQUENCE LOG  11-03-11

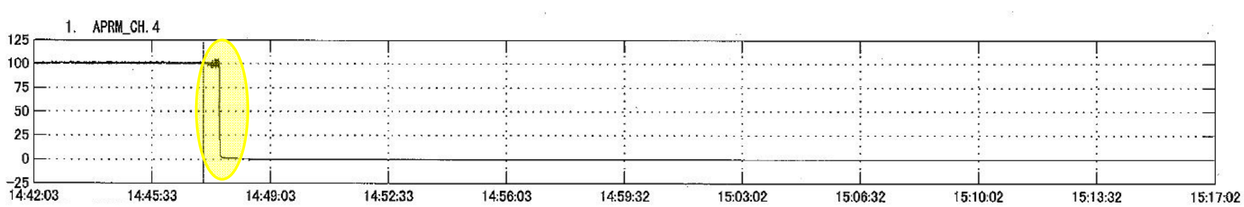
  H  MIN  SEC MSEC      PID   ABBREVIATION              STATUS
 14   46   46  400    D564*   SEISMIC  TRIP C             TRIP
 14   46   46  410    D534    REACTOR  SCRM A             TRIP
 14   46   58  420    D563    SEISMIC  TRIP B             TRIP
 14   46   58  430    D535    REACTOR  SCRM B             TRIP
1446  A538 RBM        BYPS         ON
1446  B500 CONT ROD DRFT ALRM      ON
 14   47   00  020    D562    SEISMIC  TRIP A             TRIP
 14   47   00  030    D565    SEISMIC  TRIP D             TRIP
1447  C020 SUPPRESSION   LEVL   -40.8< -20.0 MM
1447  A523 APRM       DOWN SCAL   TRBL
1447  A539 RWM        ROD  BLOK    ON
1447  A553 ALL CR FULL IN          ON
1447  G002 GENERATR VOLT        18.56> 18.50 KV
1447  C000 CONT ROD SYST FLOW  OVR FLW
```

At 46 seconds past 2:46 pm, Seismic Sensor C detected ground motion above its setpoint and tripped. It in turn caused Reactor Scram Channel A to trip 10 milliseconds later. One half of the one-out-of-two taken twice logic was tripped.

At 58 seconds past 2:46 pm, Seismic Sensor B tripped. It caused Reactor Scram Channel B to trip 10 milliseconds later. The second half of the one-out-of-two taken twice logic was tripped, producing a full signal to shut down the reactor.

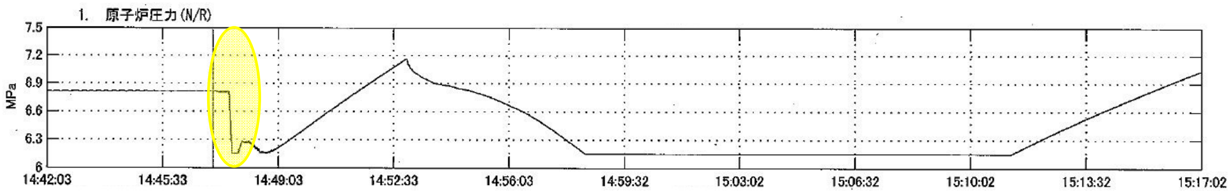
All 97 control rods rapidly inserted into the reactor core within seconds to shut down the nuclear chain reaction. At 2:47 pm, the alarm typer printed “ALL CR FULL IN” – all control rods were fully inserted.

At 2:47 pm, Seismic Sensors A and D tripped. These were the remaining two sensors in the one-out-of-two taken twice logic scheme. Had the other two sensors malfunctioned or been out of service at the time for calibration, these channel trips would have triggered the automatic shut down of the reactor.



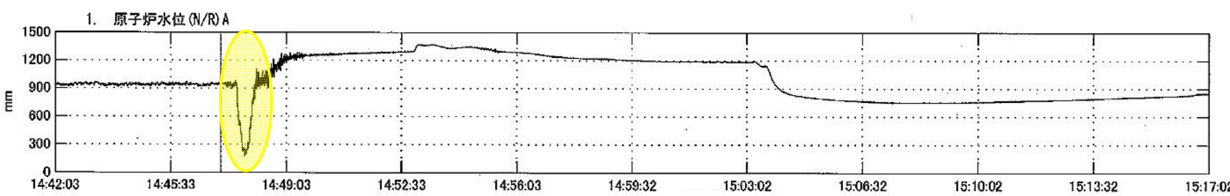

Unit 1 had 88 neutron detectors of the local power range monitoring (LPRM) system installed within the reactor core. There were 22 strings of LPRM detectors at different core locations. Each LPRM string contained 4 LPRM detectors spaced from core bottom to core top. 14 or 15 of the LPRM detector signals 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 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 it 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.

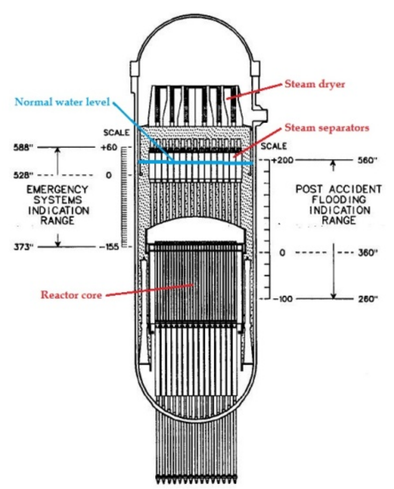



Power, pressure, and water level are the three key parameters to monitor for the reactor core and the reactor vessel. The power level went to zero as control rods rapidly entered the reactor core. The chart above shows the pressure inside the reactor vessel. The pressure had been steady at 6.817 megapascals (MPa, corresponding to 988.7 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 6.075 MPa (881.1 psig).

The chart above plots the narrow-range reactor vessel pressure that only monitors pressure down to around 6.15 MPa. The chart of wide-range reactor vessel pressure, which tracks pressure down to 0 MPa, showed the extent of the reactor vessel pressure drop resulting from the reactor shut down.




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 1,500 millimeters (mm). The water level had been steady at 949 mm (37.4 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 separators. 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. It’s similar to the response of a vigorously boiling pot of water suddenly lifted off the stove – the water continues to boil, but the froth level drops as the boiling becomes less vigorous. As the chart above shows, the water level inside the reactor vessel responded to the shut down by dropping from 949 mm (37.3 inches) to around 200 mm (7.9 inches). The water level then “bounces,” rapidly rising towards the original water level point as the steam-driven feedwater pumps providing makeup flow to the reactor vessel increase their output to restore the desired water level. This is entirely normal for what is called a “vanilla scram” – a shut down caused by rapid control rod insertion with no other complications.

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But complications are on their way.

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1447  C057 RX WTR LVL (F/R) A      2750 MM    NORMAL RETURN
  14    47    48  230      D629   TURB MANUAL TRIP            TRIP
1447  G001 GENERATR GROS VARS     205.8 MVAR NORMAL RETURN
  14    47    48  380      D691   GEN POWER LOSS B              ON
1447  G002 GENERATR VOLT          18.21 KV   NORMAL RETURN
  14    47    48  390      D690   GEN POWER LOSS A              ON
1447  E004 SWCHGEAR BUS   1A       7102 V    NORMAL RETURN
  14    47    48  390      D693   GEN POWER LOSS D              ON
1447  T001 CONDENSR PRES B         3.94<  4.30 KPAA
  14    47    48  390      D692   GEN POWER LOSS C              ON
1447  A512 WTR LEVL ROD BLOK         ON
  14    47    48  490      D591   TURSTOP  VALV               CLSD
1447  C020 SUPPRESSION   LEVL      26.8>  20.0 MM
  14    47    48  490      D539   TURBSTOP VALV D             CLSD
1447  S211 CONDENSR PRES           3.50<  4.30 KPAA
  14    47    48  490      D538   TURBSTOP VALV C             CLSD
1447  C004 REACTOR  WATR LEVL       833 MM   NORMAL RETURN
  14    47    48  490      D536   TURBSTOP VALV A             CLSD
1447  C055 RX WTR LVL (W/R) A       853 MM   NORMAL RETURN
  14    47    48  500      D537   TURBSTOP VALV B             CLSD
```

The decay heat from the shut down reactor core continued boiling water and steam continued flowing to the turbine. The turbine continued spinning the generator making electricity for in-plant power needs. But at 48 seconds past 2:47 pm, 50 seconds after the reactor shut down signal, the operators manually tripped the turbine per procedures. The decay heat was not producing sufficient steam to sustain generator operation, so the operators shut down the turbine.

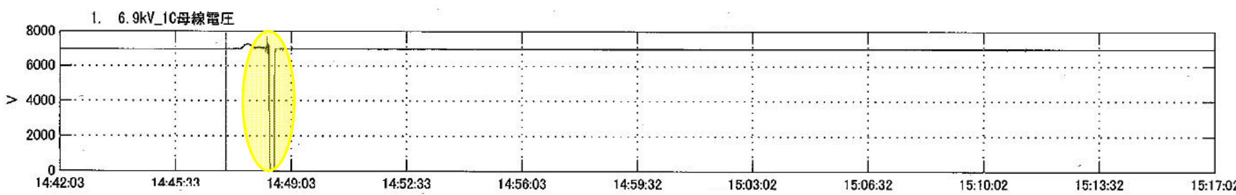
Unit 1 stopped powering its internal power needs when the turbine was manually tripped. The normal response is for in-plant electrical circuits (called buses) to automatically change to being supplied from the offsite electrical grid. But the electrical grid was unavailable due to the earthquake. Both of the normal power supplies to the 6.9 kilovolt electrical buses were unavailable.

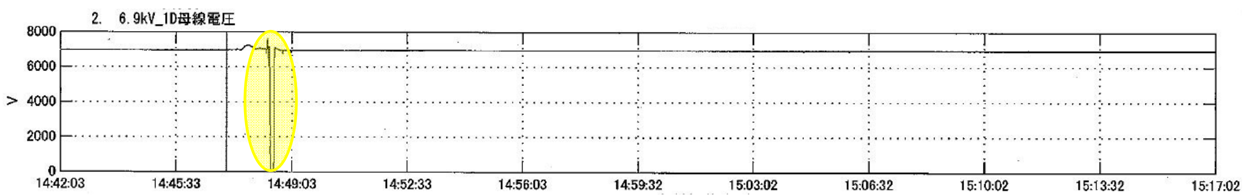
```
  14    47    51   940     D681   6.9KV BUS VLT 1D LOS         ON
1447  A572 #1 MSIV  C   OPN             OFF
  14    47    51   990     D588   AUX POWR LOSS 1S           NORM
1447  A570 #1 MSIV  A   OPN             OFF
  14    47    52   080     D680   6.9KV BUS VLT 1C LOS         ON
1447  A581 #2 MSIV  D   OPN             OFF
  14    47    52   090     D588   AUX POWR LOSS 1S           TRIP

1447  A570 #1 MSIV  A   OPN             OFF
  14    47    52   080     D680   6.9KV BUS VLT 1C LOS         ON
1447  A581 #2 MSIV  D   OPN             OFF
  14    47    52   090     D588   AUX POWR LOSS 1            TRIP
1447  A571 #1 MSIV  B   OPN             OFF
  14    47    52   120     D651   CWP B TRIP                   ON
1447  A573 #1 MSIV  D   OPN             OFF
  14    47    52   130     D657   RFP C TRIP                   ON
1447  A579 #2 MSIV  B   OPN             OFF
  14    47    52   140     D654   CP C TRIP                    ON
1447  A580 #2 MSIV  C   OPN             OFF
  14    47    52   250     D653   CP B TRIP                    ON
1447  B031 CAMS   H2 MONI D/W     LOW RSN
  14    47    52   250     D650   CWP A TRIP                   ON
1447  B032 CAMS   O2 MONI D/W     LOW RSN
  14    47    52   270     D655   RFP A TRIP                   ON
1447  B033 CAMS   H2 MONI S/C     LOW RSN
  14    47    57   070     D590   DIES GEN  CB  1D-1           ON
1447  B034 CAMS   O2 MONI S/C     LOW RSN
  14    47    57   140     D681   6.9KV BUS VLT 1D LOS        OFF
1447  G000 GENERATR GROS LOAD     383.0 MW   NORMAL RETURN
  14    47    58   920     D589   DIES GEN  CB  1C-1           ON
```

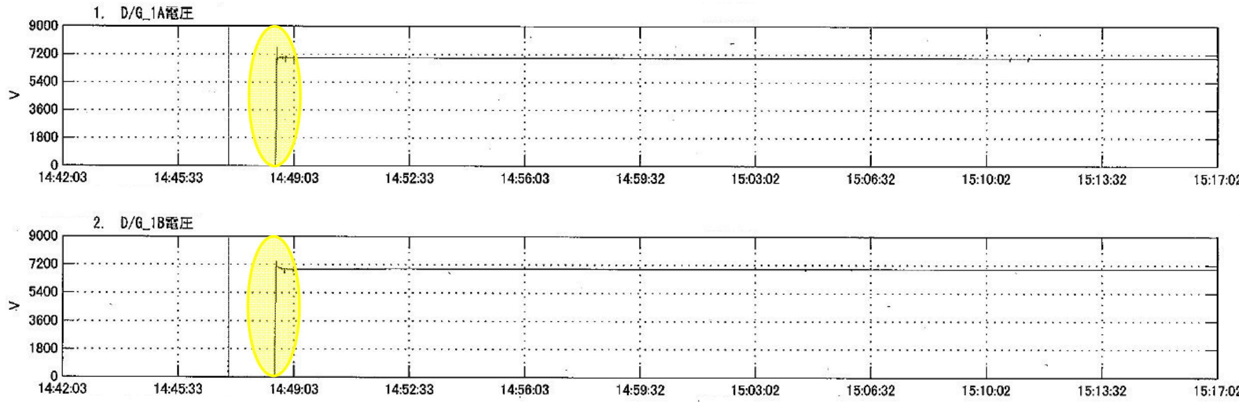
At 51 seconds past 2:47 pm, 6.9 kilovolt bus 1D alarmed on low voltage. A second later, 6.9 kilovolt bus 1C alarmed on low voltage. The normal supplies of power to plant equipment – the output from the Unit 1 generator and the electrical grid – had been lost.

As designed, the backup supply of power from the onsite emergency diesel generators became available. At 57 and 58 seconds past 2:47 pm, the circuit breakers (CB) for emergency diesel generators 1D and 1C respectively indicated they had closed to restore power to the 6.9 kilovolt buses.

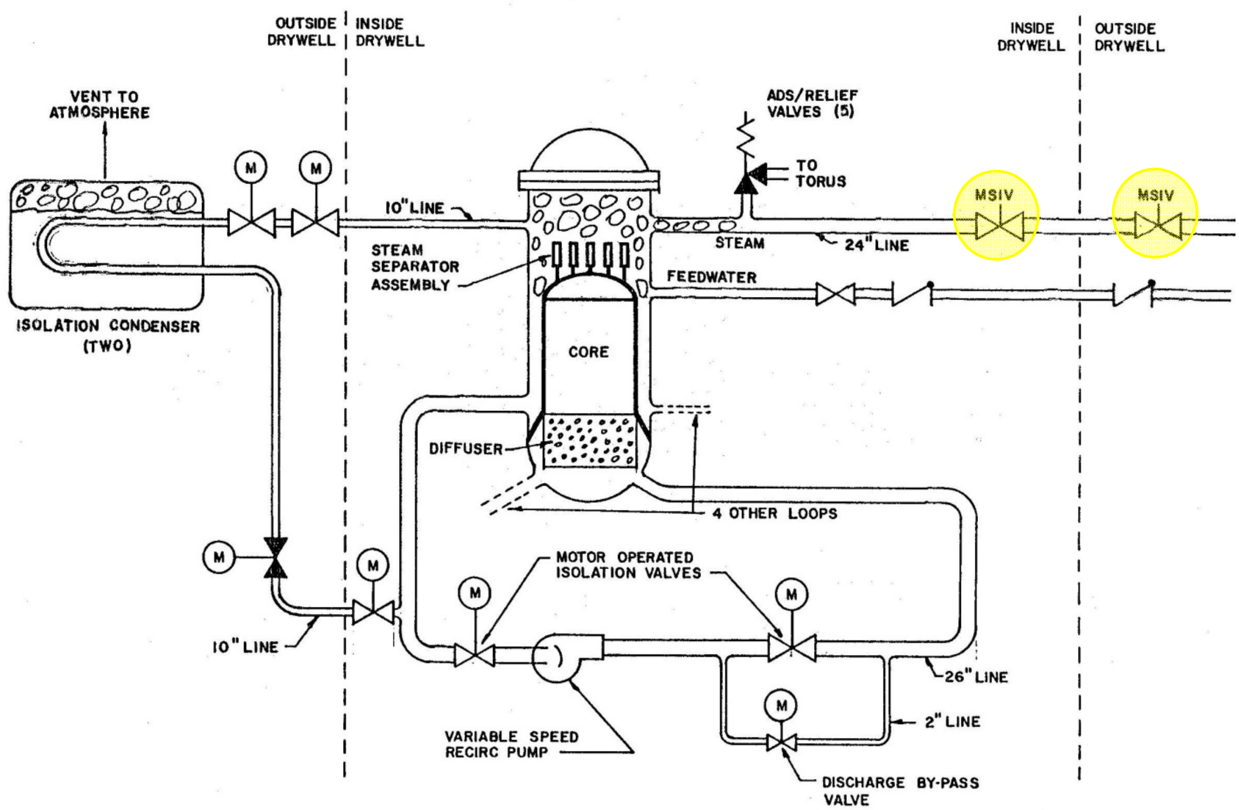



The two charts above show the voltages on 6.9 kilovolt electrical buses 1C and 1D. The plots show the brief power interruptions between the time that the turbine was tripped to stop the supply from the generator's output and the circuit breakers for the emergency diesel generators closed to restore the power supplies.

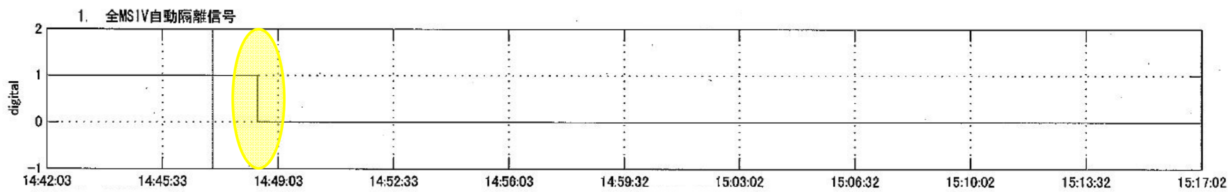



The two charts above show the voltages generated by emergency diesel generators 1A and 1B. These emergency diesel generators automatically started when undervoltage was detected on 6.9 kilovolt buses 1C and 1D and provided backup power when the normal power supplies were lost.

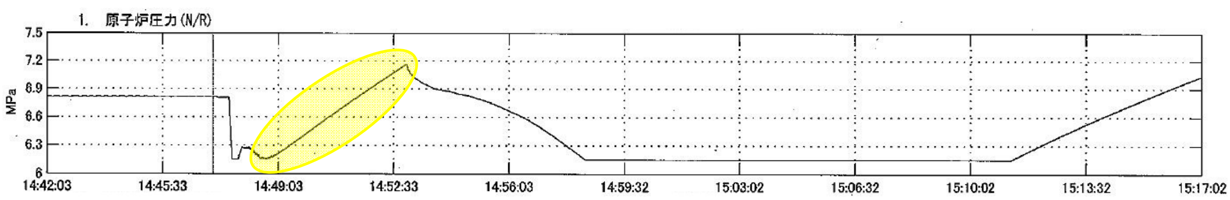



The momentary loss of power closed the main steam isolation valves (MSIVs). As shown in the diagram above, there are two MSIVs in each of the four pipes carrying steam from the reactor vessel to the turbine. The fail-safe position of the MSIVs is closed. When power was lost, the MSIVs closed. Steam being produced by the reactor core's decay heat had been traveling through the steam lines to the turbine.

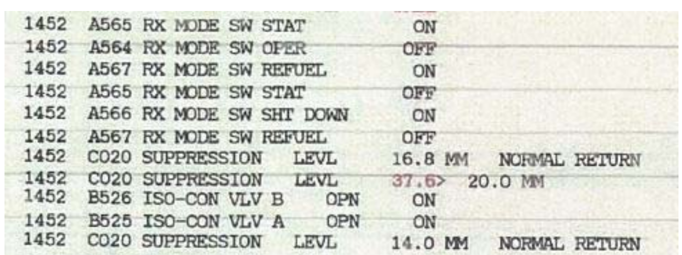
When the MSIVs closed, that steam could no longer travel this path. In addition, the normal supply of makeup water to the reactor vessel to compensate for water leaving as steam is via the feedwater system. The feedwater system features steam-driven pumps. The source of steam for the feedwater pump turbines is taken from the steam lines downstream of the MSIVs. Thus, closure of the MSIVs made the feedwater pumps unavailable.




The chart above shows the digital signal for the MSIVs. A “1” indicates the MSIVs are open while a “0” indicates they are shut. When the power supply was interrupted, the MSIVs automatically closed.

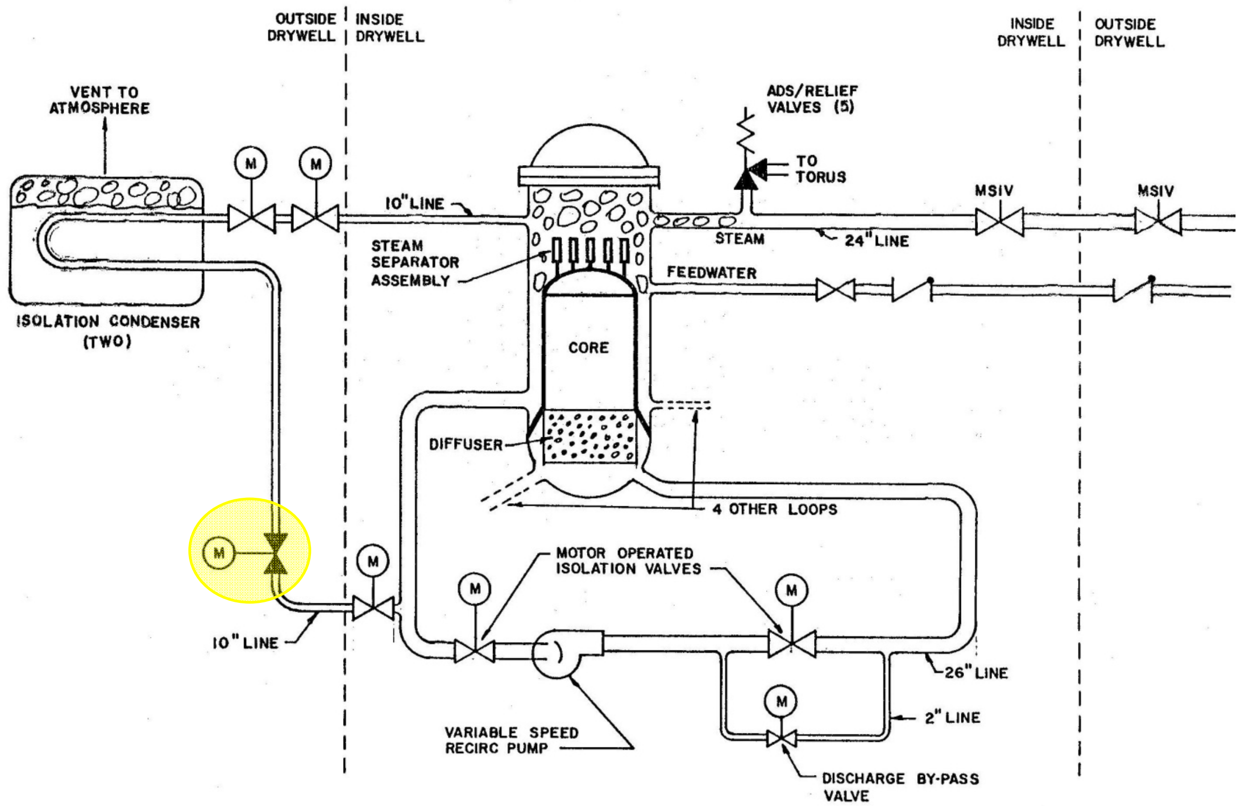



The closure of the MSIVs changed the trend of pressure inside the reactor vessel. Pressure had been trending downward as the amount of steam produced by the reactor core’s decay heat was transported through the steam pipes to the turbine. When the MSIVs closed, the steam had no place to go. Bottled up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

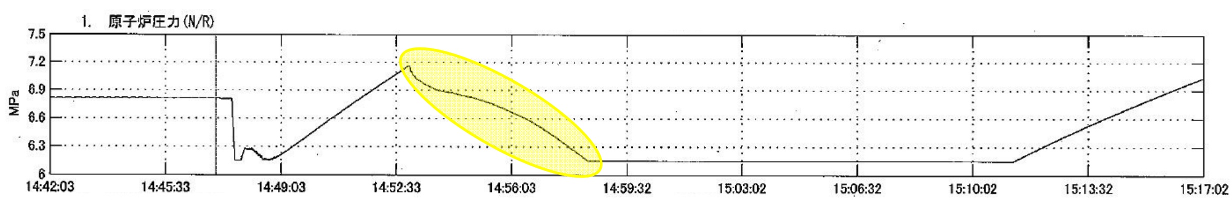


| | | | | | |
|---|---|---|---|---|---|
| 1452 | A565 | RX MODE SW STAT | | ON | |
| 1452 | A564 | RX MODE SW OPER | | OFF | |
| 1452 | A567 | RX MODE SW REFUEL | | ON | |
| 1452 | A565 | RX MODE SW STAT | | OFF | |
| 1452 | A566 | RX MODE SW SHT DOWN | | ON | |
| 1452 | A567 | RX MODE SW REFUEL | | OFF | |
| 1452 | C020 | SUPPRESSION | LEVL | 16.8 MM | NORMAL RETURN |
| 1452 | C020 | SUPPRESSION | LEVL | 37.6> | 20.0 MM |
| 1452 | B526 | ISO-CON VLV B | OPN | ON | |
| 1452 | B525 | ISO-CON VLV A | OPN | ON | |
| 1452 | C020 | SUPPRESSION | LEVL | 14.0 MM | NORMAL RETURN |

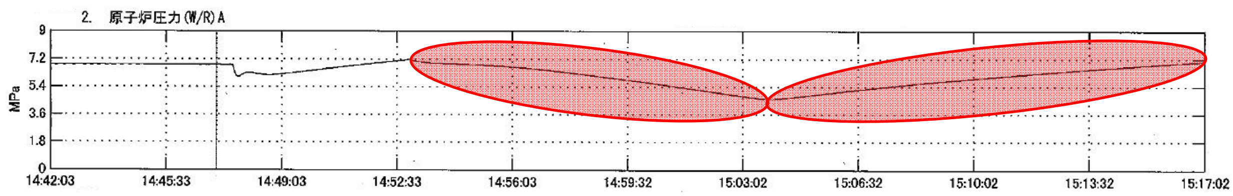
At 2:52 pm, the two valves needed to place both isolation condensers in service opened. It is not clear from the alarm printouts if this action occurred automatically or in response to manual actions by the operators. In any case, the isolation condensers were placed in service.




As shown on the left side of the diagram above, the isolation condensers are large tanks of water. Tubes pass through the water-filled tanks. When the two valves opened (one isolation condenser and one valve is shown in the diagram – the valve that opened is represented by the black bowtie shaped symbol (highlighted in yellow) in the drain line from the isolation condenser), steam from the reactor vessel flowed through the isolation condensers' tubes. Heat from the steam passed through the thin metal tube walls to be absorbed by the isolation condensers' water. The steam cooled and condensed back into water. This water drained into the recirculation system piping and was returned to the reactor vessel.




The in-service isolation condenser provided some place for the steam being produced by decay heat in the reactor core to go. Consequently, the steadily rising pressure trend following the MSIV closure was stopped and a steadily decreasing pressure trend begun. The decay heat produced by the reactor core was being used to warm the water inside the isolation condenser instead of pressuring the bottled-up volume inside the reactor vessel.



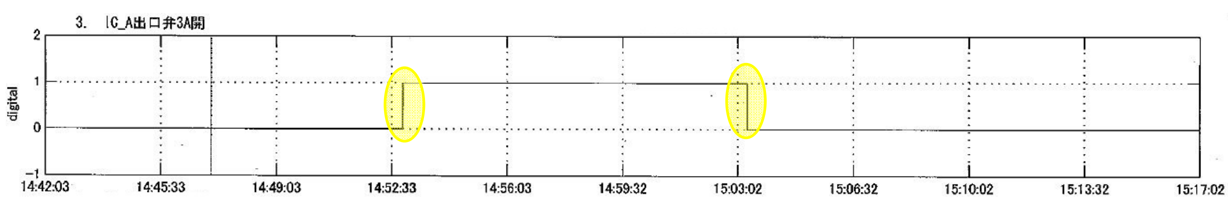

The above chart of pressure inside the reactor vessel over the wider range of 0 to 9 MPa (0 to 1,305 psig) shows that the steadily decreasing pressure trend stopped around 3:04 pm and became a steadily rising pressure trend.

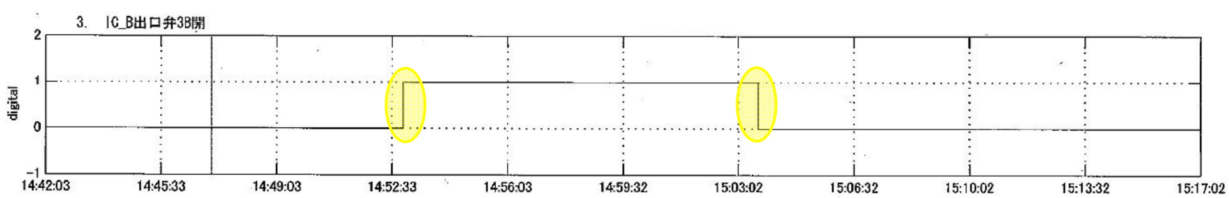
There are reports that the operators took the isolation condenser out of service because the cooldown rate of the reactor was greater than expected or desired. This apparently happened around 3:04 pm.

When the isolation condenser was placed in service around 2:53 pm, the pressure inside the reactor vessel was nearly 7.2 MPa (1,044 psig). This corresponds to a water temperature of nearly 287°C (549°F). When the isolation condenser was removed from service around 3:04 pm, the reactor vessel pressure had dropped to around 4.5 MPa (653 psig). This corresponds to a water temperature of nearly 257°C (494°F). The cooldown rate was approximately 164°C (300°F) per hour (300°F) over those 11 minutes.

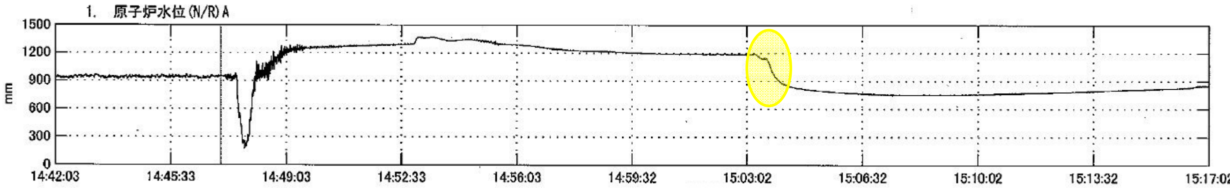
The maximum heatup and cooldown rates are established at 37.8°C (100°F) per hour. The limit on heatup and cooldown rates are intended to prevent the reactor vessel and attached piping from failing due to stresses caused by expansion and contraction of the metal.

If the isolation condenser was intentionally taken out of service around 3:04 pm due to concerns about excessive cooldown rates, that action merely swapped problems. From 3:04 pm until 3:17 pm, the heatup rate was nearly 138°C (254°F) per hour. An excessive heatup rate is as bad as an excessive cooldown rate. Swapping back and forth between excesses is worse than either excess.




The above two charts show the logic for isolation condensers A and B. The charts show that both isolation condensers were placed in service at the same time around 2:53 pm and that isolation condenser A was taken out of service shortly before isolation condenser B at around 3:04 pm. The concurrent initiation times suggests that both isolation condensers automatically responded to the same sensed condition. The staggered termination times suggests manual action consistent with reported events.




Around 3:04 pm, a significant downward step change in the reactor vessel water level occurred as shown in the chart above. The level dropped from 1,200 millimeters (47.2 inches) to around 800 mm (31.5 inches) in less than a minute. Typically, such downward step changes in water level are explained by:

- large, rapid power reductions such as the one occurring when the reactor automatic shut down at 2:46 pm
- large, rapid pressure increases that collapse steam bubbles, causing the indicated water level to drop as the water in the vessel occupies less space
- cold water injections that collapse steam bubbles, causing the indicated water level to drop as the water in the reactor vessel occupies less space
- broken pipes or stuck-open valves that cause water to be drained from the reactor vessel

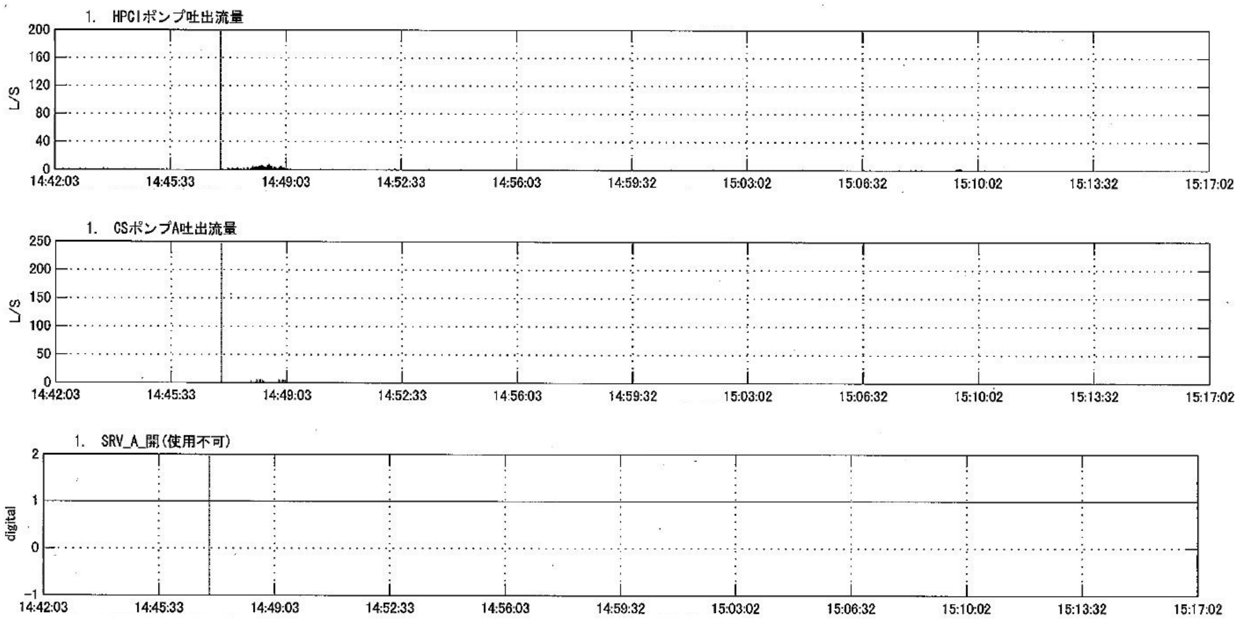
However, none of these appear to explain the step.

The reactor power level had been zero since 2:47 pm, providing no opportunity for another large, rapid reduction.

The reactor vessel pressure plot on page 8 shows a steadily rising pressure trend, not the kind responsible for downward step changes in reactor vessel water level.

There's no data indicating a source of cold water injection around 3:04 pm. The logic, turbine speed, and flow charts for the high pressure coolant injection system indicate it did not operate during this time period. And the reactor pressure was too high for the core spray and residual heat removal systems to supply water to the reactor vessel. Thus, the emergency core cooling system pumps did not inject cold water into the reactor vessel around 3:04 pm. And as previously discussed on page 6, the closed MSIVs prevented normal makeup flow to the reactor vessel via the feedwater system.

Broken pipes, stuck-open valves, and other explanations for the level drop seem to be contradicted by the fairly steady trend between 3:05 pm and 3:17 pm and the increasing pressure trend over that period shown in the prior chart.




The first two charts above show the flow rates for the high pressure coolant injection (HPCI) and core spray (CS) systems respectively. The third chart shows the open/close logic for one of the safety relief valves (SRV). The other SRV logics show the same thing. Neither HPCI nor core spray injected water during this time period, so their operation cannot account for the downward step change in reactor vessel water level around 3:04 pm. Likewise, the SRVs did not open during this time period and cannot have caused the level drop.