The Station Blackout Incident of the Maanshan NPP unit 1

Atomic Energy Council

Taiwan, R.O.C.

April 18, 2001

1. INTRODUCTION

At 00:46 March 18, 2001 a seasonal sea smog, containing salt deposit, caused the malfunction of all four 345 KV power transmission lines in Fengkang and Hengchun region in southern Taiwan, resulting in the loss of offsite power event at the Maanshan nuclear power plant (NPP). As both the safety-related A/C power systems of unit 1 went out of service and both the emergency diesel generators (EDG) failed to operate, the consequence was a complete loss of power of the two 4.16 KV essential buses at unit. A "3A" rating of site emergency event on domestic scale was announced subsequently. With the endeavor of plant staff, the essential power was established at 02:54 by connecting a swing diesel generator to service and the emergency event was thus called off. Neither radioactive release nor environmental impact was observed throughout the whole duration of the incident.

Although the unit 1 reactor was not adversely affected throughout this incident, both trains of the safety system did experience a loss of function for as long as two hours and eight minutes. This incident was viewed as the most notable event over the 22-year history of nuclear electricity generation in Taiwan. Soon after the incident, the Atomic Energy Council (AEC) dispatched both a staff investigation team and independent investigation team to investigate the incident and its impacts. This report summarizes the combined observations from both investigation teams.

2. SEQUENCE OF EVENTS

The incident leading to the loss of essential AC power (station blackout) at Maanshan NPP unit 1 in Taiwan on March 18, 2001 proceeded as follows:

(1) 03:23, March 17

Unit 1 of the plant lost its 345 KV offsite power and was shut down automatically. Reactor was placed in hot standby condition since then. Although the 345 KV power was restored later on, it remained at an unstable condition.

(2) 00:41, March 18

The plant lost all 4 trains of 345 KV offsite power. The 4.16 KV essential bus A breaker #17 opened and breaker #15 closed automatically, transferring supply from the 161 KV offsite power.

(3) 00:43, March 18

The Dar-Peng 345 KV power was restored while breaker #17 remained open.

(4) 00:45, March 18

At 00:45:06, switchyard staff closed oil-cooled breaker (OCB) 3620, getting ready to switch the offsite power from 161 KV to 345 KV manually.

(5) 00:45, March 18

At 00:45:07, a ground fault at the essential bus A of unit 1 occurred, causing breaker 3510 trip. At 00:45:09, breaker 1670 tripped as well. These malfunctions caused the plant lost essential power from offsite sources completely. Two emergency diesel generators (EDG) of unit 1 were unable to provide AC power to both essential buses. The plant entered an alert condition.

(6) 00:49, March 18

The plant staff acknowledged that the control building CO_2 fire extinguisher activated automatically. There was also a report from on-site staff that heavy smoke was coming out from the control building at floor location 46 feet below the control room, where the essential buses were located.

(7) 00:51, March 18

Operator attempted to reconnect 161 KV power to essential bus via breaker 1670, but failed.

(8) 00:56, March 18

The plant on-site firemen rushed to site but lacked of adequate lighting and ventilation equipment. Operator attempted to close breaker 3510 but failed again.

(9) 00:57, March 18

The plant operator connected EDG A to the essential bus A manually. In the meantime, the auxiliary feedwater system was successfully activated by properly operating the turbine-driven pump. The EDG A only provided power for 40 seconds and tripped because of signal failure at the train A essential bus.

(10) 00:58, March 18

According to the Plant Emergency Procedure 570.20, operator started to conduct required procedure to handle the situation of station blackout.

(11) 01:06, March 18

The plant staff attempted to restore the EDG B, but the building was full of smoke and lighting was not sufficient, the plant personnel were not able to get into the switchgear room.

(12) 01:41, March 18

The plant called the Hengchun local fire department, requesting for additional lighting and ventilation equipment to assist expelling the smoke.

(13) 02:15, March 18

Plant staff decided to connect the swing EDG to the unit 1 4.16 KV essential bus B, and the preparation was ready at 02:50. It was activated manually in EDG control room, but was not successful at the first attempt because of low lube oil pressure. Plant staff judged that the reason was power loss of the constant-temperature oil pump and not equipment failure. A second attempt was then made and was successful.

(14) 02:54, March 18

The swing EDG was connected to train B of the essential bus successfully. The AC power was restored and the emergency condition at unit 1 was then called off.

(15) 12:50, March 18

To verify the root cause of the earlier excitation failure of EDG B, plant staff restarted EDG B. This time it started successfully and worked normally.

(16) 22:12, March 18

Plant staff separated two essential buses of unit 1. Essential bus B of unit 1 was powered via 161 KV through the unit 2 transformer and the swing EDG was then disconnected. The offsite power of the unit 1 was restored at this time.

3. ESSENTIAL BUSES FAILURE INVESTIGATION

The electric power distribution system of the Maanshan NPP is shown in Figure 1. The incident was initiated due to failure of the 4.16 KV essential buses at unit 1. The essential buses are consisted of two separate, redundant and independent power sources. In an event if one of the buses failed, the other bus could still provide the required AC power to ensure the plant safety. From the perspective of nuclear safety, the most important issue for the incident occurred is that why both essential buses lost offsite AC power at the same time, while the offsite 161 KV power source remained functionally available.

The # 15 and #17 breakers on the 4.16 KV essential bus A were seriously damaged (as shown in photo 1 through photo 3). From the readings of the breakers' voltage before the incident (between 00:41 and 00:45), the 161 KV bus remained available (as shown in Figure 2). It was first determined that breaker #15 cannot be the first fault. This is further evidenced by the fact that breaker 3620 closed at 00:45:06, and consequently breaker 3510 tripped to open at 00:45:07. As a result, breaker #17 must be where the initial fault occurred.

Looking through the switchgear room of the 4.16 KV bus A, the bus end of breaker #17 was visibly undamaged after the incident. In addition, conditions of the power side connection end revealed that breaker #17 was damaged by over-voltage instead of over-current. This result reasonably matches the event sequence that breaker #17 was at open position before the incidence, and then incident occurred when breaker 3620 closed.

Based on the aforementioned judgments, the possible incidence sequence should be: breaker #17 on the 4.16 KV bus A had a grounded fault at the power side, inducing electric arc and burning out the breaker #15（close to breaker #17）, and subsequently causing grounding of breaker #15 at the power side. Then the 4.16 KV bus A failed due to bus grounding. This led to both breaker 3510 and breaker 1670 to trip and both the 345 KV and 161 KV offsite sources could not supply electric power to the 4.16 KV essential bus B.

Based on the finding that the incident occurred when breaker #17 was at open position and that the site situation was possibly caused by over-voltage, the root cause of the incident is judged to be insulation degradation of breaker #17. Because it is found that the B-phase electric connection end at the power side of breaker #17 is the most damaged location, it is reasonably to assume that the B-phase connection end insulation was degraded before the incident. At 00:41 March 18, it is possible that an electric arc took place locally at breaker #17 during the over-voltage shock resulted from the loss of offsite 345 KV power. The local electric arc made the ambient air ionized. The ionized air was contained inside the cubicle. At 00:45 (4 minutes later), the recovery of the offsite 345 KV power made breaker 3620 to close. The transient voltage from the 345 KV system finally burned out breaker #17. Because the buses were seriously damaged, it is not easy to collect all evidence. The possibility of mechanical fault of breaker #17, on the other hand, may not be completely ruled out.

One possible reason for causing insulation degradation of breaker #17 is the instability of the offsite 345 KV power system (see Figure 3). According to certain analyses, when transient by the 345 KV transmission system occurred, the voltage shock to the connection end of breaker #17 can happen. This voltage can be in the range between 7 KV and 9 KV. The accumulated effect by voltage shock probably causes the insulation degradation.

Another possible reason for causing insulation degradation may be the resonance of transmission lines (Ferro-Resonance). At 20:38 March 17, the offsite 345 KV power system tripped (Figure 4) but the corresponding breakers (breaker 3520 and breaker 3530) did not trip to open. Because the transmission line of 345 KV system to Maanshan NPP is quite long, the interaction between the equivalent capacitor, equivalent conductor, and equivalent impendence of Maanshan NPP startup transformer made the resonance phenomena to happen. Since both units of Maanshan were at shut down condition while the 345 KV system tripped at 20:38 March 17, the 345 KV system should be at off power. However, the switchyard transient recorder at Maanshan NPP indicated that the 345 KV system still had voltage reading for 2 seconds at that time, and the reading was beyond the recorder scale.

The flywheels motion of the Reactor Coolant Pumps (RCPs) of Maanshan NPP was another possible cause for transmission line resonance. At 20:38 March 17, Maanshan NPP lost its offsite 345 KV power while the flywheels of all three RCPs were still rotating due to residual momentum. The driving motors reversibly turned into electric generators and produced reverse power to the 13.8 KV bus, resulted in voltage increase at the 345 KV system through the startup transformer. Consequently, this high-voltage impulse caused severe degradation to the insulation of breaker #17.

It is also found from this incident, that a single essential bus A fault could also lead to bus B failure in receiving both the 345 KV and 161 KV offsite power. Therefore, the design and protection coordination of the electric power distribution system of Maanshan NPP must be re-verified. Besides, when essential bus A fails, power supplies from EDG or through breaker 3510 may further damage the bus. The EDG itself may also be affected. The operating procedures need to be verified in this regard.

4. INVESTIGATION OF EDGs' FAILURE

The emergency diesel generators (EDGs) in Maanshan NPP were provided by the DELAVAL Company of America. The rated power output is 7000KW for each generator. In order to maintain their reliability, Maanshan NPP operates a periodical maintenance program for these generators during each refueling outage. The maintenance program defines step-by-step maintenance procedures, record keeping requirements, and testing verifications to be surveillanced by quality control staff. Shortly after the incident, AEC inspectors went to the plant and checked the maintenance records of unit 1 EDG A & B during EOC-12 outage (the most recently refueling outage). Those records show that maintenance and testing were performed in a satisfactory manner.

The EDGs are safety-related equipment, thus the technical specification clearly lists every required surveillance test. The AEC inspectors also checked the surveillance test records of the 4 EDGs for both unit 1 and 2 reactors over the last three years. There were only two records of test failure, including: unit 1 EDG B on October 19,1998 and unit 1 EDG A on April 22, 2000. Both startup test failures were caused by oil pipe leaks. All other tests were successful.

When the incident happened on March 18, the 4.16 KV essential bus B lost all offsite power supply. The EDG B automatically started up as designed, but cannot establish excitation to generate voltage (Figure 5). The EDG B did start up but fail to supply AC power. After the incident, plant staff restarted the EDG B at 12:50 March 18, it started up successfully and the excitation also functioned properly.

After the incident, Maanshan NPP staff repeatedly tested R1 and K1 relay control circuits of the EDG B. Among those tests, the safety signal from both train A and B are isolated and tested separately. The test results show that when train A was tested alone, the electric magnet valve 141-2A had little air leakage. When train B was tested alone, the electric magnet valve 142-2B did not work (Figure 6). But when both train A and B were tested simultaneously as designed, the EDG got proper excitation and functioned normally.

According to the procedure, the electric magnet valve 141-2A and 142-2B shall be replaced for every three refueling outage (about five years). The most recent replacement was on May 2, 2000 and both valves were tested and verified to be functional conditions. During this incident, EDG B could not excite. The reason was judged to be the sluggish actuation of the electric magnet valve 141-2A and 142-2B, while stochastic failure of R1 relay may not be ruled out.

5. REACTOR SAFETY AND HUMAN PERFORMANCE

When the incident happened, both reactors have already been shutdown for 21 hours. They were in hot shutdown conditions with reactor pressure at 157 kg/cm^2 and temperature at 291^{o}C. During the event the turbine driving auxiliary feedwater pump functioned normally as designed, and with the proper operation of SG's PORV, the core temperature and pressure continued to reduce throughout the event (as shown in Figure 7). According to the level variation of coolant drain tank and containment floor sump, there was no sign of RCP seal leakage.

With respect to operator's response during the event, when challenged by the situation of losing all AC power and heavy smoke, the operators were successful in maintaining the reactor at safe condition with comparably limited means. The swing EDG was successfully started and put into service manually within 2 hour & 8 minutes. The overall responses of the operations and maintenance personnel were thus judged to be appropriate. However, there are much room for improvement in areas such as: the adequacy of fire protection and distinguish equipment, the proper function of public address (PA) system, and the timing for starting the auxiliary feedwater pumps, etc.

6. INVESTIGATION OF EMERGENCY RESPONSE

According to the existing rule, TPC's emergency plan executive committee (EPEC) should immediately report the plant condition to AEC for an incident of category 2 or higher. As for the classification of the incident, EPEC must access plant operation data, confirm the classification, form an evaluation team, and inform AEC via telephone within an hour.

At 02:19 March 18, AEC received the emergency call from TPC 's EPEC that unit 1 of Maanshan NPP had a 2A (alert) incident as defined in the emergency plan. AEC set up an emergency control center within 1 hour and evaluated the event immediately. There were 17 AEC staffs called from their home and some were dispatched to the plant right away. Even after receiving call from EPEC that the 4.16 KV essential bus B has regained power, AEC was in continuous monitoring of the unit until all safety concerns were clarified in the following morning. Special meetings to clarify the event were held right away, along with site investigation by a few senior AEC inspectors. The result was open to the public in an almost real-time basis.

Just before the incident on June 6, 2000, AEC has called a meeting asking TPC's EPEC and NPP staff to evaluate the reporting and activation system of the emergency plan. AEC made a request to enhance the training of emergency personnel to ensure that the plan can be activated smoothly and accurately. Investigation of this incident on emergency preparedness, two misconduct are found:

1. NO IMMEDIATE REPORT

   According to the existing rule, Maanshan plant should report to TPC's emergency plan executive committee (EPEC) immediately after the incident, and then EPEC should report the plant condition to AEC. The incident started at 00:45 March 18, TPC emergency plan executive committee received report from Maanshan NPP. But AEC didn't receive reporting of the 2A incident until at 02:19 March 18.

2. WRONG CLASSIFICATION OF THE EVENT

   According to AEC's accident classification rule, when loss of all offsite and onsite AC power for more than 15 minutes, the plant is classified as site area emergency (3A) condition. But at 02:19 March 18 (the Maanshan plant has lost all offsite and onsite AC power for 1 hour and 34 minutes), TPC still reported the event to AEC as a 2A incident.

7. RADIATION SAFETY INSIDE AND OFFSITE PLANT

There are 5 environment high-pressure ionization chambers (HPIC) at the Maanshan NPP site boundary. These detectors are part of the emergency response facility (ERF). During the incident these detectors functioned normally and transmitted data to the control station. According to the records, the radiation values varied within the range from 0.05 to 0.07 μSv/hr, which is around the background level. It's confirmed that no radiation was released throughout the incident.

Radiation Monitoring Center (RMC), a subsidiary of AEC, also has many HPIC gamma-ray detectors located on nearby local population center surrounding the Maanshan NPP. Those detectors can continuously record the environment radiation level. According to the data detected during March 17 to March 18, all radiation readings varied around background level (as shown in Figure 8).

To access the possible environment impact of gas and liquid release, RMC dispatched staff to the plant and collected some air and water samples at some critical spots surrounding the Maanshan NPP right after the incident. After thorough analysis of these samples, all data varied around background level.

8. SUMMARY

Based on the investigation reports by staff and independent review teams, the combined results are summarized as the follows.

(1). INVESTIGATION RESULTS

1. MAIN CAUSE

   Breaker #17 fault on the 4.16 KV essential bus A is the main cause of this incident. One possible cause of breaker #17 fault is determined to be insulation degradation of B-phase electric connection end before the incident. The other possible reason is the instability of the offsite 345 KV power distribution lines, causing harmful effect to breaker #17 insulation. Among other possible causes, the high-voltage impulse by transmission line resonance due to offsite 345 KV tripped at 20:38 March 17 may also play an important role for accelerating the breaker insulation degradation.

2. REACTOR SAFETY AND ENVIRONMENTAL IMPACT

After thorough examination of the operating parameters, it is ensured that reactor was at safe condition, and no radiation was released throughout the incident. According to the data collected by RMC surrounding the plant, no noticeable variation before and after the incident was observed. All detected readings are within the range around background level.

3. EMERGENCY RESPONSE

The incident started at 00:45 March 18. TPC emergency plan executive committee received report from Maanshan Plant at 01:33. But AEC didn’t receive any report about the 2A incident until at 02:19 March 18. That is a practice against the established emergency informing procedure.

4. VIOLATION CLASSIFICATION

According to “Guideline for Handling the Violation of the Nuclear Power Plant” by AEC, this incident is rated as a level 2 violation. TPC is obliged to investigate its administrative responsibility on personnel misconducts.

(2). CORRECTIVE ACTIONS

1. SALT DEPOSIT PROBLEM

   TPC must thoroughly resolve the salt deposit problem onto transmission lines connecting to the Maanshan plant.

2. ESSENTIAL BUS AND ELECTRICITY EQUIPMENT

   (1). Maanshan plant must improve the power supply scheme to essential buses to ensure system independency and redundancy.

   (2). TPC must review and improve the surveillance program for the breakers of all essential buses.

   (3). Maanshan plant must review and improve the design adequacy of their electrical protection system.

3. EMERGENCY RESCUE EQUIPMENT AND REPORTING

   (1). TPC must overview the function of NPP's fire protection systems and equipment, such as: smoke ventilation systems, illumination systems, to sustain function ability during incident or accident condition.

   (2). TPC must improve communication systems at NPP’s, especially during emergency conditions.

   (3). TPC must improve the efficiency of information and reporting system during emergency conditions.

Abbreviation

AC	Alternate Current
AEC	Atomic Energy Council
EDG	Emergency Diesel Generator
EOC	End of Cycle
EPEC	Emergency Plan Executive Committee
ERF	Emergency Response Facility
HPIC	High-Pressure Ionization Chamber
NPP	Nuclear Power Plant
OCB	Oil-Cooled Breaker
PORV	Power-Operated Valve
RCP	Reactor Coolant Pump
RMC	Radiation Monitor Center
SG	Steam Generator
TPC	Taipower Company

Appearance of a Normal Breaker

Damaged Breaker #17

Photo 1: normal v.s. damaged breaker

Connector damages of breaker #15

Frame damages of breaker #15

Photo 2 : damage conditions of breaker #15

Appearance of a normal breaker arrangement at a switchgear

Damaged essential 4.16KV bus switchgear

Photo 3 : normal v.s. damaged switchgear

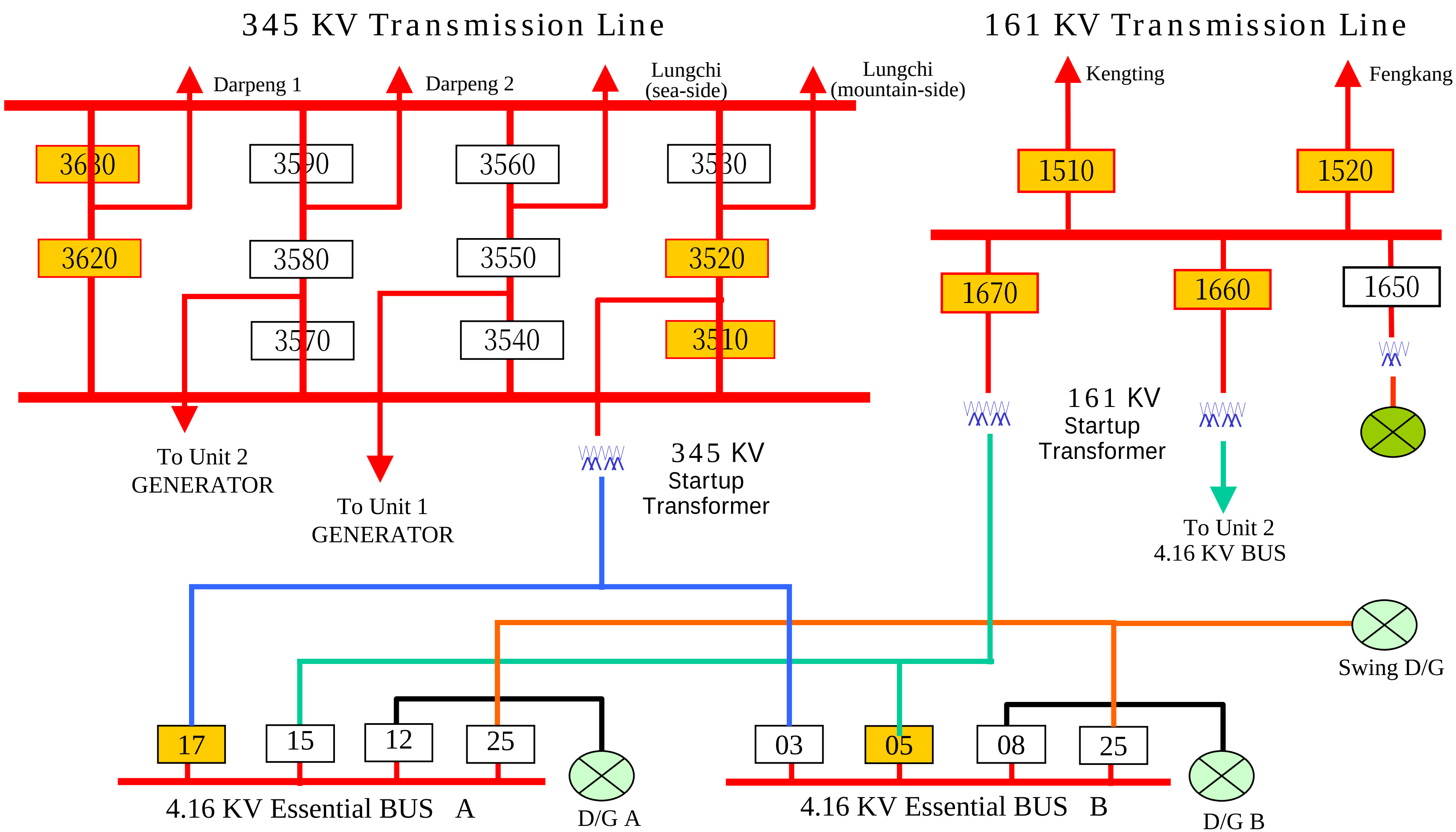

Figure 1: AC power distribution system of Maanshan NPP

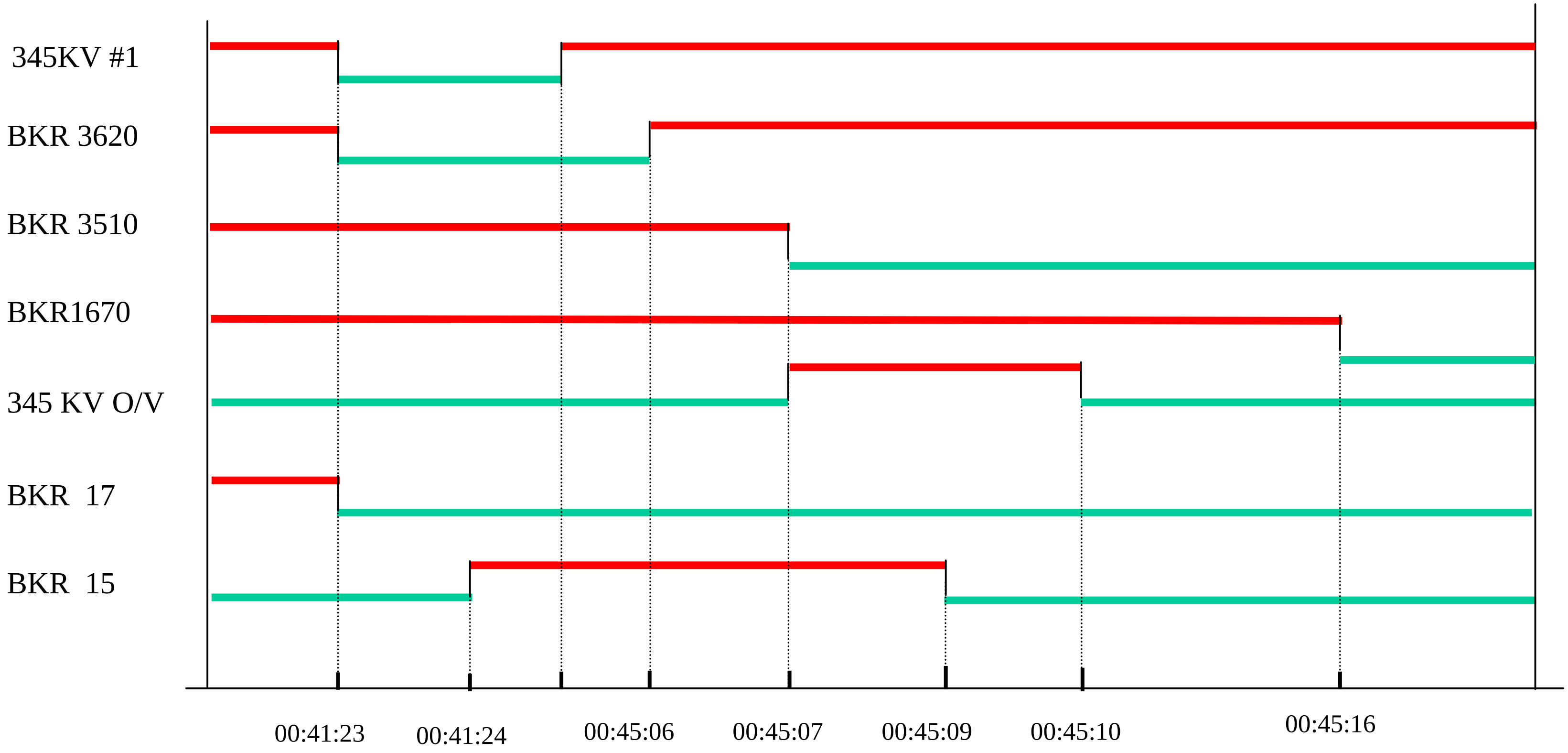

Figure 2: Breaker reactions during the Maanshan incident

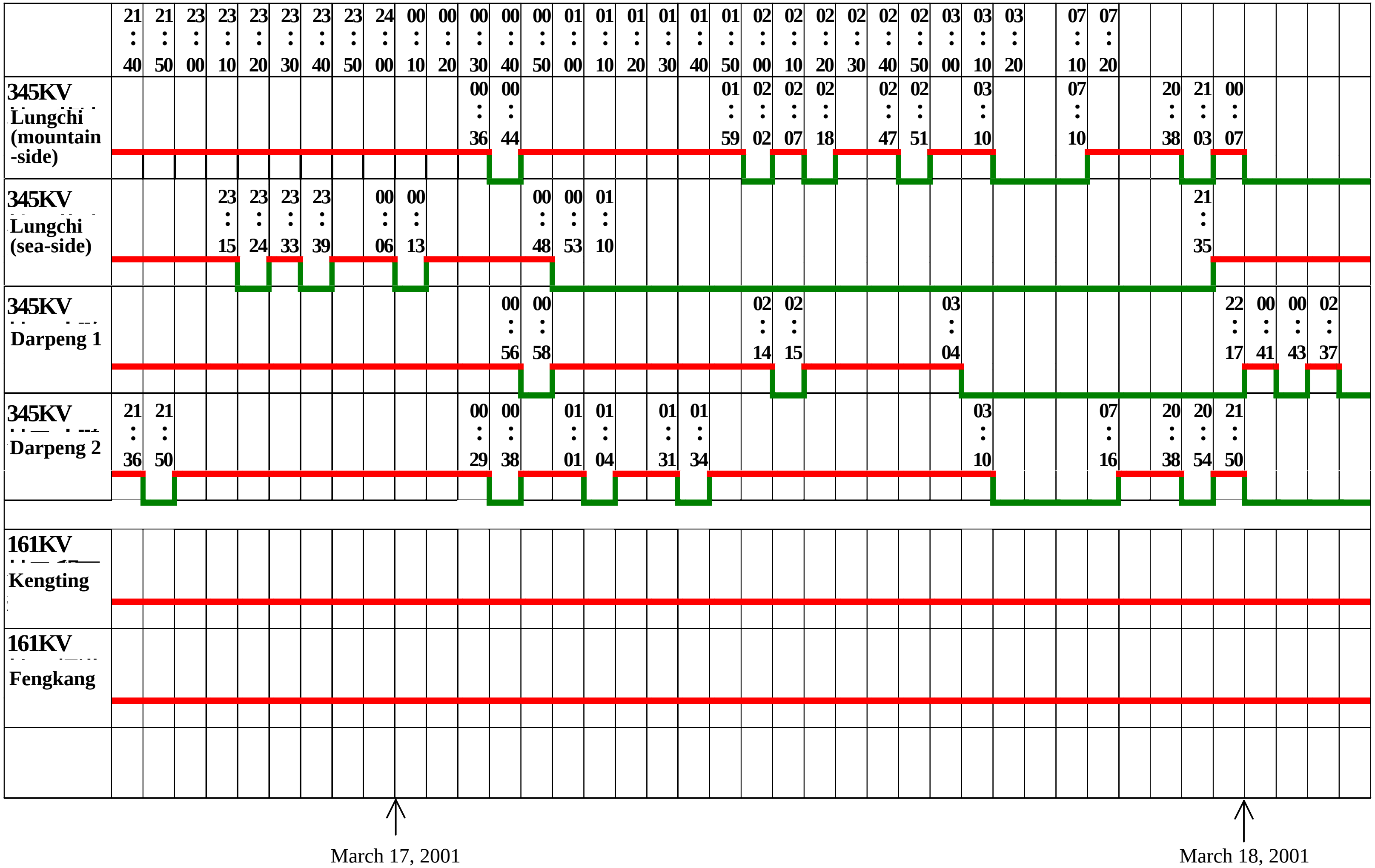

Figure 3: Offsite power situation before the Maanshan incident

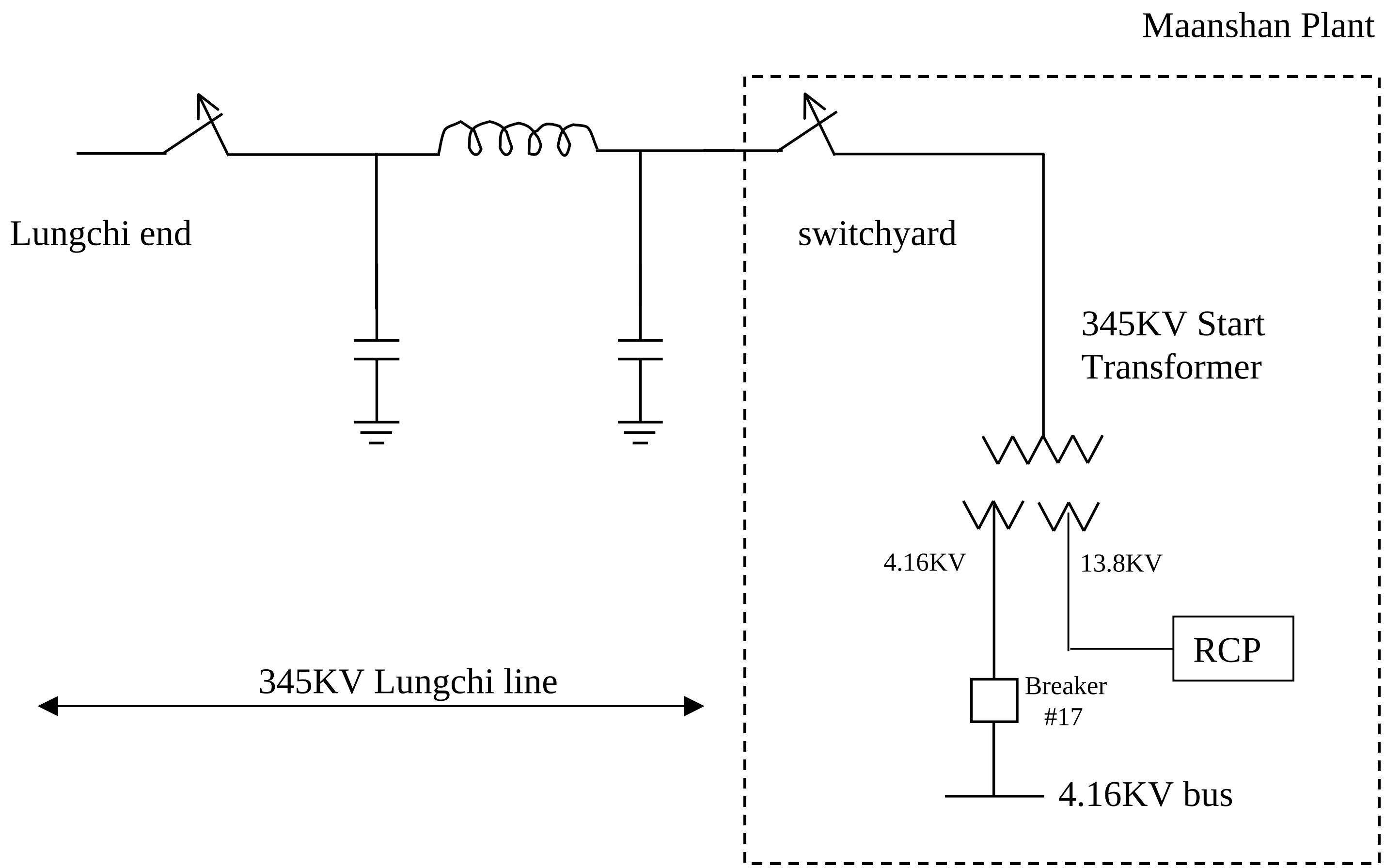

Figure 4: Ferro-Resonance of 345 KV Transmission System

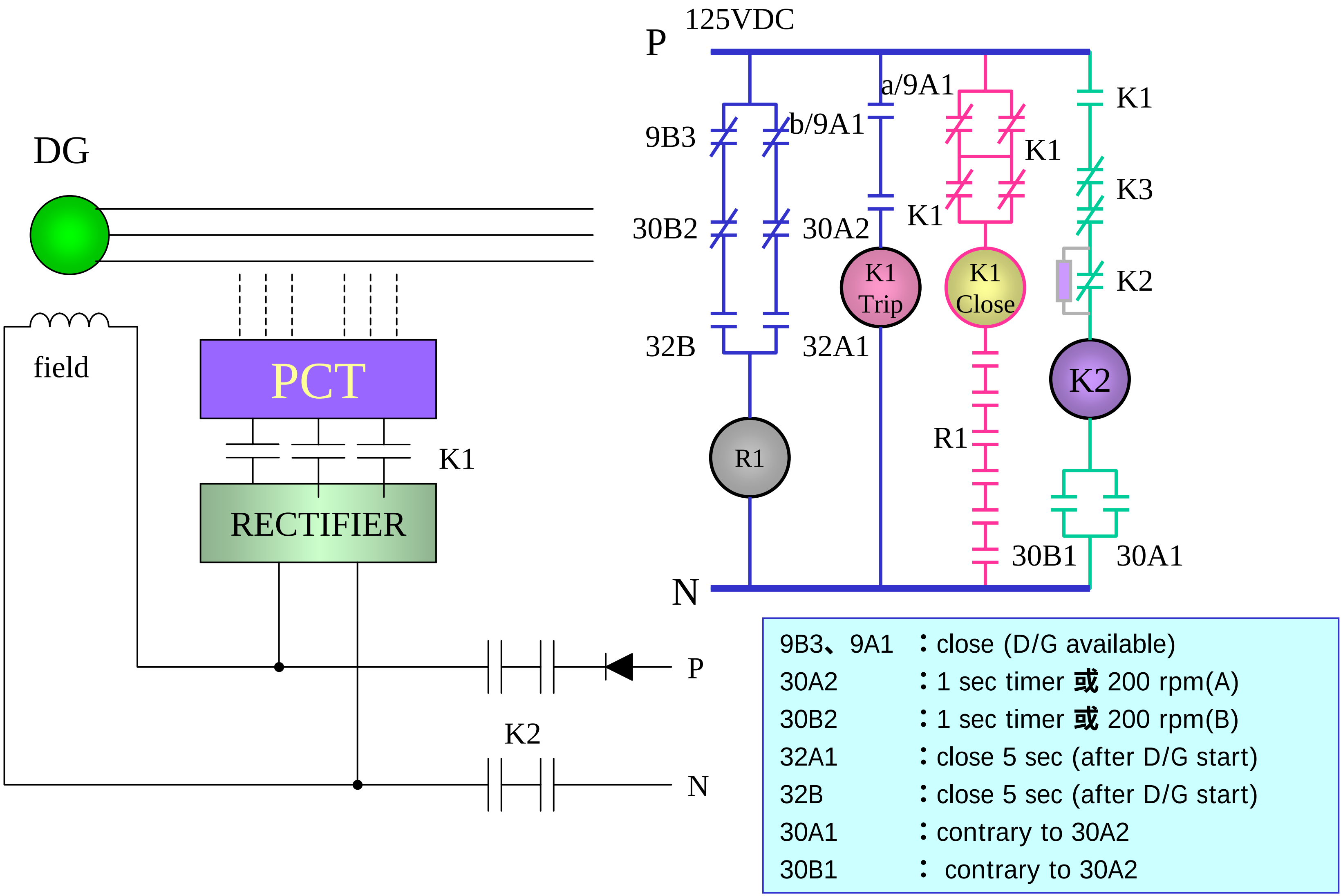

Figure 5 : EDG excitation control circuit

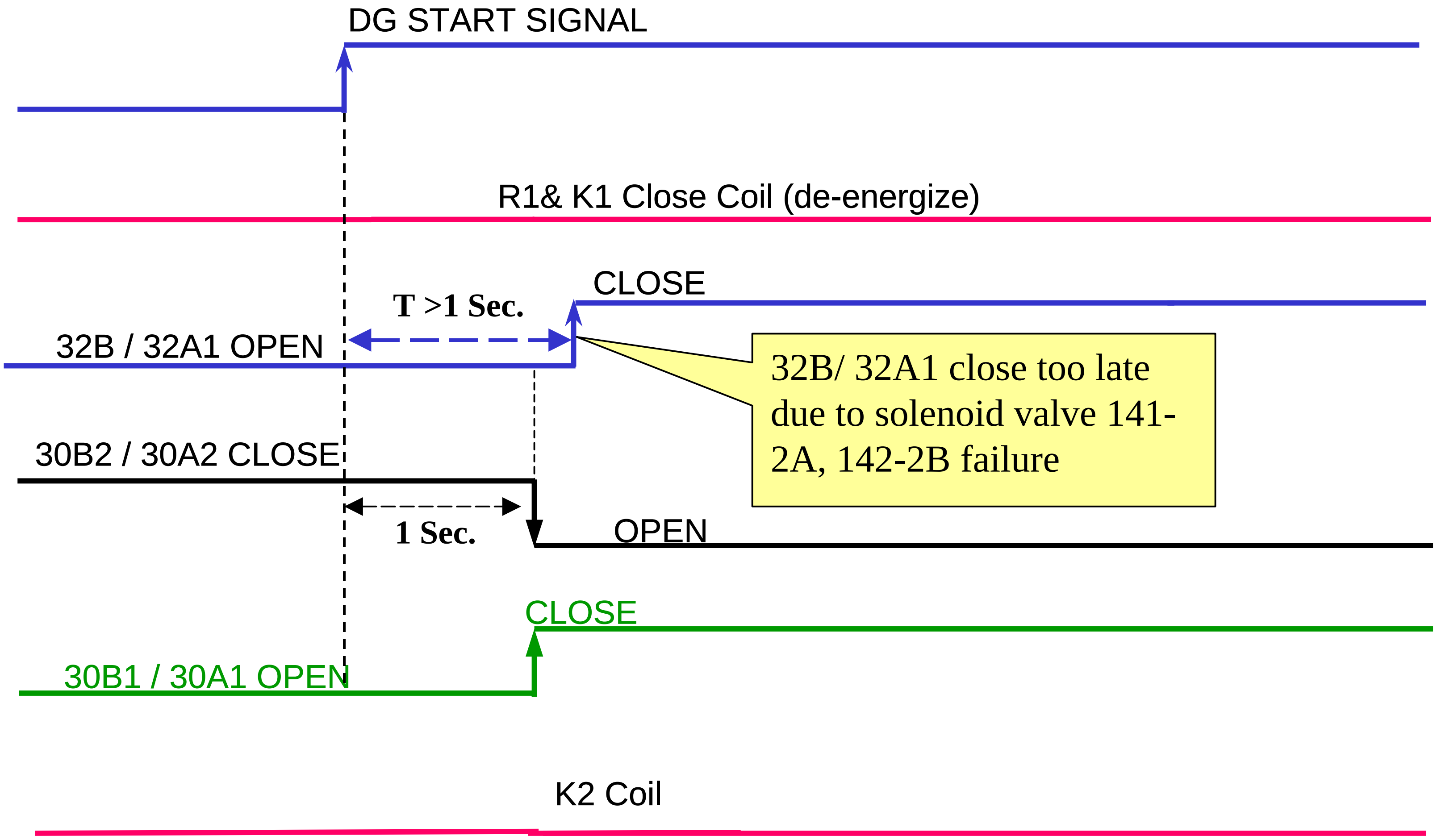

Figure 6: Timing sequence of EDG B excitation failure

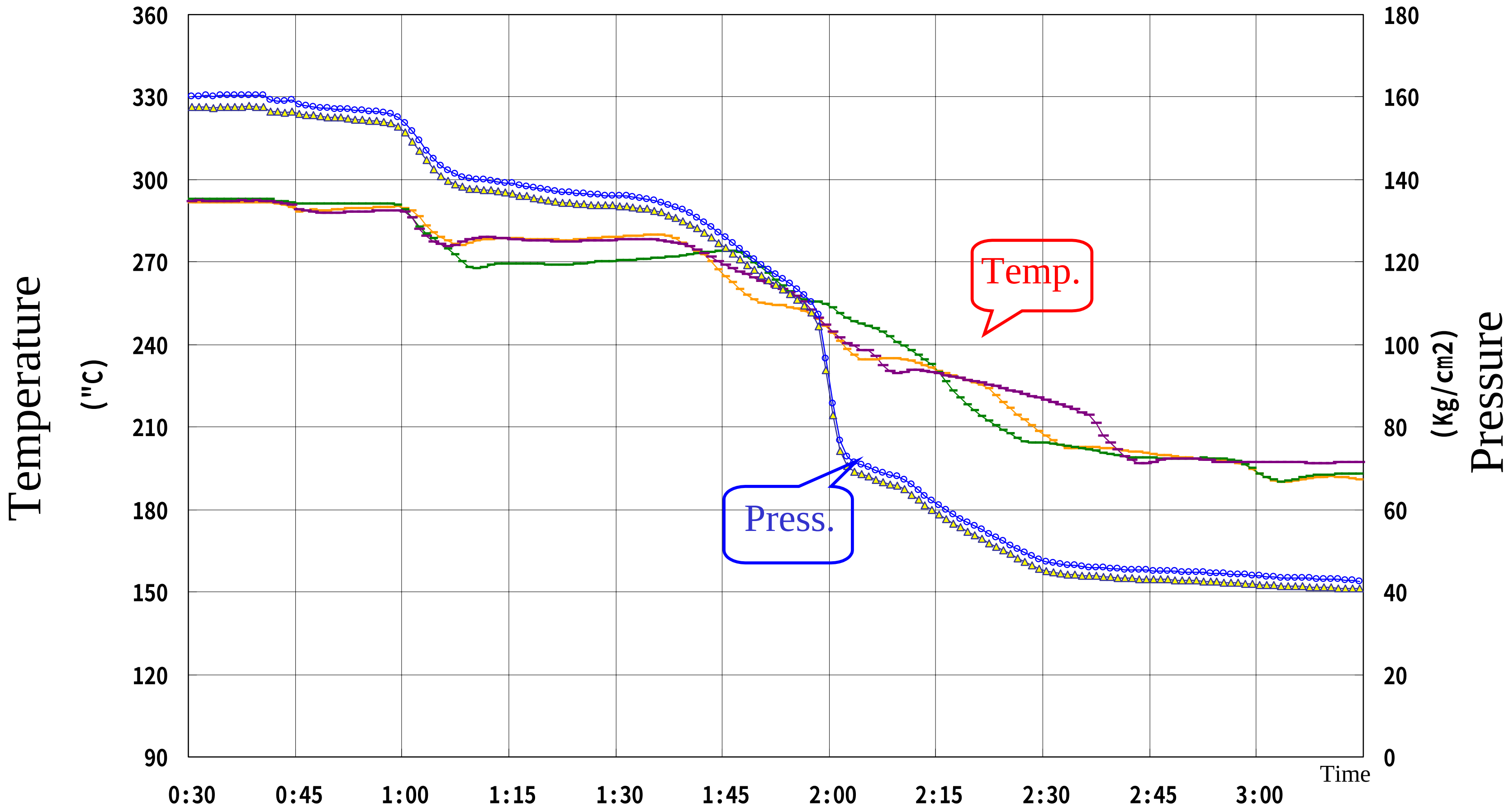

Figure 7: RCS Pressure & Temperature during Maanshan incident

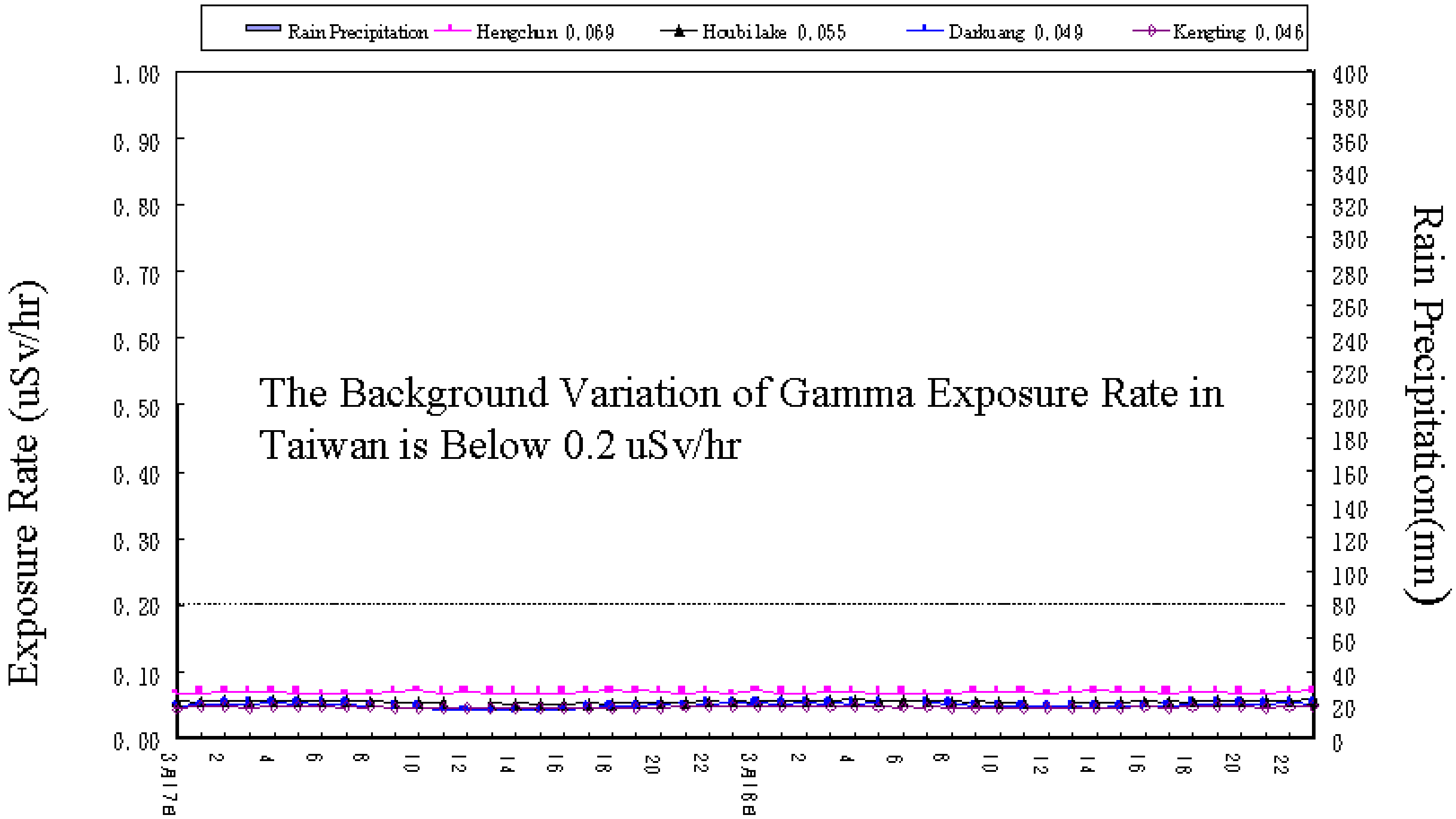

Figure 8 : The Average Gamma Exposure Rate Measured