Report on the Super-Kamiokande Accident

(As of November 22, 2001)

Translated
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1 Introduction

At 11:00, November 12, 2001, about 60% of the 50cm photomultipliers (PMTs) used for the Super-Kamiokande detector were destroyed in a few seconds. This accident forced us to halt temporarily a series of experiments with the detector for some time.

This report describes, what happened in time, the status of the damages, the analysis results of the observed data, assessment of possible causes of the accident and so forth. It was written to be submitted to the committee set up to investigate the cause of the accident and to other organizations in order to provide information available as of November 22, 2001. The content will be updated as new information become available.

2 Event Sequence Toward Accident

Super-Kamiokande (SK) underwent upgrade work to replace PMTs that began in mid-July, 2001 and ended in mid-September. It had been filled with water since September 18. On the morning of November 12, the purified water filled the tank to the level 31.7 m above the bottom (about 3/4 of the tank). On that day before the accident SK was taking data without any problem. A physicist on shift entered the mine at 8:00 to monitor the data-taking process. Furthermore two technicians (hereafter referred to as technician A and B) entered the mine at 9:00 and cleaned the top of the water tank and the entrance area of SK.

At 11:01:30 the physicist and technician A felt violent shaking accompanied by roaring sound. At this moment the physicist was in the control room while technician A was at a location one or two meters from the edge of the top of the water tank. Technician B was on his way from the mine entrance to the SK site carrying lunch boxes. (See Reference "Map of the mine".) It seemed that the roaring sound lasted about 5 to 10 seconds. According to technician A, at the beginning the sound was small but it gradually became bigger. He also felt some wind pressure when the sound became big and he saw the transparent plastic sheets that separate the clean room containing the entrance to the tank from the rest of the space expanded outward. (See Reference "Technician A's account".) Later it was found that a seismological recorder of the Laboratory of Disaster Prevention located at 8.8 km from the SK site recorded seismological vibration. (See Reference "Chart of seismological recorder".) From the chart record, the vibration caused by this accident lasted about 5 seconds.

3 Actions Taken Right After Accident

Right after the roaring sound was heard, the SK event rate went up extremely high. The rate rose over 1 MHz while normally it is about 10 Hz. (See Reference "Trigger rate".) The physicist went to electronics huts to turn off the high voltage supplies to the PMTs. The technician A checked to see if there was any abnormality around the tank and the entrance to SK and found none. When the technician B arrived, the physicist asked him to check carefully any water leak from the SK tank along an inclined tunnel around the tank. The technician B found nothing unusual and reported to the physicist.

At about 11:40 the physicist and the technician A removed a black plastic sheet that covered the entrance to inside of the tank and take a look into inside of the tank to find that the water was not as transparent as it should have been and that there was abnormality with side PMTs. They descended inside the tank by a gondola and discovered that glass envelops of side PMTs were broken and parts were exposed in and below the 6th layer from the water level. (See Reference "Photos 1 and 2".)

The physicist, as the director of the Kamioka Laboratory was out of Japan on a business trip, phoned the director of Research. At about noon, he stopped the operation of the water purification system that was providing purified water to the tank. He also told other staff members at the Kamioka Laboratory to come to the mine to investigate damages. At about 13:00 the physicist lowered a water-proof camera into the inner detector part of the tank to assess damages made to PMTs on the side and bottom. At about 14:00 a device to measure the water level was installed in the tank and the measurement of water level started. At about 15:00, he went down to the outer detector part of the tank by a gondola and checked the status of damage there. At about 16:00, the water-proof camera was lowered into the outer detector part and an investigation on PMT damage was done for the outer detector. At about 19:00, he again lowered the camera into the inner detector and counted the number of visually undamaged PMTs in the inner detector.

	Dead	Installed
Bottom	1,748	1,748
Side	4,917	7,650
Top	0	1,748
Total	6,665	11,146

Table 1: The numbers of dead and installed PMTs.

4 Status of Damage and Methods of Investigation

4.1 Inner detector

4.1.1 PMTs

Right after the accident through a hole near the inner detector wall a camera was inserted, the status of the damage was examined on a TV monitor, and a rough number of visually undamaged PMTs was counted. At the depth of 5 m and below glass envelops of the most of the inner PMTs were completely smashed and metal parts inside came out hanging and sticking out from the wall. In the following we describe how we investigated the number of damaged PMTs in three steps. For the information of the PMTs see References "R3600-5 50 cm PMT data sheets".

(1) Method:

On November 14 we circled around along the inner wall on a boat and visually examined the status of the damage. Most of broken PMTs lost the glass envelops that were smashed. A few PMTs that still had the glass envelops had transparent glasses that are characteristic of vacuum loss. These PMTs were counted as damaged. Since the water transparency was bad, a visual examination of status of PMTs at the depth of about 15 m or below was difficult. However, it was believed that almost all the PMTs below this depth were broken and that the counting error was about a few counts. Table 1 shows the summary.

(2) Check by base resistance (See Table 2):

	Normal appearance	Abnormal appearance	White glass
Normal resistance	4,449	2*	0
Abnormal resistance	15	6,651	12

Table 2: Base resistance and appearance of PMTs. * One of the two was mistakenly classified as abnormal appearance and the other was possible mistake as well.

	Normal appearance	Abnormal appearance
Normal signal	4,340	2
Abnormal signal	114*	0
Others	25**	0

Table 3: Existence of signal and appearance of PMTs. * 87 flashers, 10 high noise rate. **PMTs at the entrance and others for which the existence of signal cannot be checked but they have normal appearance.

(3) Check by seeing a signal (See Table 3):

(4) Summary (See Table 4):

See Reference "Status of the damage done to the inner side PMTs". References "Current status of PMTs" show the current status of PMTs. These are a hit map of the detector for a cosmic ray muon event and a corresponding event display. calibrations with a Xe lamp is in progress.

	Number of PMTs
Damaged PMTs	6,779
Undamaged PMTs	4,367
Total	11,146

Table 4: Assessment of damaged PMTs

4.1.2 Cables

Under investigation. However, it is believed that the majority of cables attached to the damaged PMTs are unusable.

4.1.3 Tank and support structure

(1) Tank and surrounding rocks

- Method:
  Right after the accident the inclined tunnel along the tank and an area around a manhole at the bottom were visually inspected and no damage was found. However, right after the accident, a sliding safety net at the entrance to the outer detector developed a difficulty of opening, which suggests the accident caused some kind of distortion. On November 14, fringe area of the top floor of the tank was visually inspected and no damage was found. On November 18, the nearby side wall and the bottom surface were visually inspected by a camera near the PMT 10810 (the PMT that is suspected to have imploded first). No damage, water flow, nor existence of rocks were found.
- Summary:
  No major abnormality was found except for some water leak that is described later. However inspection is needed at the time of water draining.

(2) Tank support structure

- Method:
  Right after the accident the bottom and side support structure were visually inspected for possible damages by the camera.
- Summary:
  Most of black sheets attached to the surface of the inner detector wall were stripped off. At least 50 % of Tyvek sheets attached to the surface of the outer detector wall were more or less in place, although some of them are loose now. Many metal bands holding PMTs were deformed and some of them were stripped off. There

Date and Time	Reading	Integrated change	Change per hour
11/13 09:09	39 mm	0 mm	
11/13 10:54	35 mm	4 mm	
11/14 08:20	-17 mm	56 mm	2.4 mm/h
11/15 14:09	-100 mm	139 mm	2.8 mm/h
11/16 15:20	-178 mm	217 mm	3.1 mm/h
11/17 15:15	-257 mm	296 mm	3.3 mm/h
11/18 14:25	-340 mm	379 mm	3.6 mm/h
11/19 17:45	-426 mm	465 mm	3.2 mm/h
11/15 14:09	-518 mm	557 mm	3.8 mm/h

Table 5: Water level and leak speed

are no stripped off sub-frames to which the metal bands were attached to hold 3 PMTs in super-modules. But in some places distortion was observed. Side and bottom support structure show no damage or distortion.

(3) Water level

- Method:
  Since the day after the accident the water level has been measured continuously using a scale from a boat. See Table 5.
- Summary (See Reference "History of water level"):
  The rate of the water level change is 3.1 mm/h, which corresponds to a loss of 3.7 tons/h. This suggests that there is some damage to the tank linings. Although no water leak inspection was done before the accident, it is believed that there was no leak judging from the water level records.

(4) Electronics

- Method:
  Pedestals of ATM channels were measured using ATMs' self-calibration system.

- Summary:
  Only two out of 11,232 channels had abnormality but there was no problem with electronics.

(5) High voltage supply

- Method:
  All the high voltage supply cables were removed and the high voltage supplies were checked stand-alone by measuring the outputs at a standard voltage.
- Summary:
  Two channels failed to provide the standard high voltage but they had this problem even before the accident. Therefore out of 11,129 channels there was no damage by the accident.

(6) Water quality

- Method (See Reference "Locations where the water samples were taken"):
  21 hours after the accident six samples of water were taken. One sample was taken right below the water surface at the center of the tank, two right below the water surface near the side wall, one at 9m above the bottom at the center of the tank and two at 2m above the bottom at the center of the tank. (See "Map of the sampling points".) These samples were tested at Center for Environmental Industry of Shizuoka Prefecture (A), Kamioka Smelting and Mining Company (B), and Kamioka Health Company (C).
- Results (See Reference "Results of water quality test):
  As an example, the test result from the laboratory (A) is summarized below:
  Cr^{+6}: All six samples contain less than the sensitivity of .005ppm
  All Cr: All six samples contain less than the sensitivity of .01ppm
  Mn : All six samples contain less than the sensitivity of .01ppm
  Sb : At depth 0 m all less than 0.003 ppm
  At depth -30 m 0.010 ppm
  At depth -37 m 0.015 ppm

At depth -37 m 0.015 ppm second sample

For comparison, a table of maximum allowed levels is attached. (See Reference “Maximum allowed levels of chemicals in water”.)

4.2 Outer detector (US responsibility)

4.2.1 PMTs

(1) Damage check by appearance

- Method:
  Status of damage was inspected visually by a camera.
- Summary:
  As in the case of the inner PMTs, almost all PMTs were destroyed at the depth of 5 m or below the water level. Number count has not been conducted yet.

(2) Check by applying a voltage

- Method:
  Output current was measured with applied voltage of 100 V. If the output current was not normal (0 or above the maximum), a PMT was classified as damaged.
- Summary:
  881 PMTs were damaged by the accident out of 1885 PMTs. There were 56 bad PMTs prior to the accident.

(3) Check by existence of signal
In addition to 881 + 56 dead PMTs, 136 more PMTs were found dead. This makes the total number of damaged PMTs due to the accident 1017. (See Reference “Map of damage done to the outer PMTs”.)

(4) Cables
Under investigation.

(5) Tank and support structure

- Method:
  Visual inspection of side PMTs was done by lowering a camera from the entrance to the outer detector.
- Summary:
  Some wavelength shifter plates were smashed. Some of Tyvek sheets attached to the outer detector side surface were ripped off but most of them seemed undamaged. Tyvek sheets on the tank wall were intact. There was no problem with the support structure.

(6) Electronics
Under investigation.

(7) high voltage supply
7 out of 160 HV cards were found broken.

5 Analysis of Data Collected at Time of Implosion

5.1 First PMT event displays as a function of time

Data had been taken continuously since the end of September when purified water started to fill the tank until just before the accident. Right after the accident, the trigger rate went up over 1 MHz while the normal trigger rate is about 10 Hz. See Reference "Trigger rate". Because of this extremely high rate, normal data-taking became impossible and the data-taking system ceased to function. About 6 hours after the accident, we attempted to recover the data collected by a computer in a 30 msec period right after the accident. And we were partially successful to reconstruct events that seemed related with the accident. The following is a summary of this analysis.

5.1.1 Change of event rate in time

Reference "Trigger rate" shows four plots of different rates as a function of time recorded by scalers and printed just before and after the accident, although theses records were not kept. The first two plots are the trigger rates with low and high energy thresholds, the third the trigger rate from the outer detector. At least 24 hours prior to the accident the rates were normal and stable. At 11:01, November 12, all the rates shot up as seen in the plots. A few minutes after the accident when the physicist turned off the high voltage supplies, the rates went down to a few Hz.

5.1.2 Kamiokande data at time of accident and interpretation

Description of event sequence

In the following we describe events that we managed to reconstruct. Because of high trigger rate, the data-taking system could not catch up with influx of events and lost a part or sometimes most of PMT information. Furthermore while the system tried to transfer the data, it could not take in new data. Because of this limitation during this 30 msec period the system only managed to record the data in periods, 0-1 msec, 3-16 msec, 26-27 msec and 29-30 msec after the the sudden rise of the event rate. See Reference “Trigger rate”.

The first event after the event rate rise (Event 11211-921342) was recorded at 11:01:29. The event prior this was recorded 77 msec before the event 11211-921342 and was a normal cosmic muon event. The first event 921342 is shown in Reference “Event displays”. In this event a hit cluster is seen at the bottom near the edge. The PMT that had the largest light was PMT 10810. The next event display in this Reference is an exploded view of the same event with focus on the PMTs in the cluster. Judging from our past experience with flashing PMTs and the signals from these PMTs, it is very likely that PMT 10810 or a nearby PMT started to flash.

After this event a few events with a similar cluster were recorded in a time interval of a few μsec. See event displays for Event 921343 and 921345 in Reference “Event displays”. These events were followed by noise events with few hits for 0.4 msec and then the data taking system stopped temporarily. 3.8 msec after the rise of the event rate, the data taking system resumed to function and recorded increased number of events with most of PMTs fired. In Event 11211-921483, 5.27 msec after the event rate rise, from PMT 10810 or a nearby PMT intense light from arc or flash emitted upward was observed. See event displays for Event 921483 in Reference “Event displays”. This event pattern resembles characteristics of events caused by flashing PMTs (flashers) which have been extensively studied for analyses of atmospheric neutrinos.

Therefore, we believe that these signals detected by PMTs were generated by light and at that moment PMTs were working normally.

Conclusion 1: Location of implosion

From the data taken during a a few msec period after the rise of event rate, there were many characteristic events that involved PMT 10810 and/or 8 adjacent PMTs around PMT 10810. Judging from these events it is most likely that the accident was caused by an implosion of one of PMTs 10810 or adjacent ones.

Conclusion 2: Global view of shock wave

The time scale from an implosion of a PMT to a collapse of the PMT is about 10 msec. It means that it takes 10 msec for an implosion of a PMT triggers another at an adjacent PMT. It is, therefore, believed that up until 10 msec after the rise of the event rate only one PMT and/or another adjacent PMT had been smashed. This suggests that in the event 5.26 msec after the rate rise (Event 921483) we see the early stage of the accident and all the PMTs except for the first imploded one were still functioning to see light. (See an event display of Event 921483 in Reference "Event display".) This means that in the recorded data we cannot see the entire sequence of events that have lead to the partial destruction of SK.

5.1.3 Singles rates of 9 suspected PMTs

With an assumption that PMT 10810 or its adjacent 8 PMTs imploded, Reference shows singles rate of these PMTs. None of PMTs show any unusual behavior as far as this rate is concerned. See Reference "Singles rate".

5.1.4 History of imploded PMT

The locations of the 9 suspected PMTs at the bottom are shown in References " Map of the inner bottom PMT locations" and "Map of the inner bottom PMT locations around PMT 10810". Among these PMTs only one (PMT 10850) was replaced during the upgrade. Table 6 show information about these 9 PMTs.

PMT number	Serial number	Location	History
10767	CD7089	1BP6P3C-W	
10768	AB7389	1BP7P3C-U	
10769	CD7048	1BP7P3C-V	
10809	AB5293	1BP6P3D-W	*
10810	GJ4324	1BP7P3D-U	*
10811	GJ4067	1BP7P3D-V	
10850	AB7979	1BP6P4A-W	05/30/01,6/2,6/12 measurement done Replaced 08/30/01
10851	GJ4198	1BP7P4A-U	*
10852	KM4188	1BP7P4A-V	

Table 6: PMT history. * Worker put extra weight during upgrade work.

5.2 Others

6 Possible Cause of Implosion

6.1 External factor

6.1.1 Blasting in mine

There was no blasting in the mine on November 12.

6.1.2 Change of rock bed condition

There is a possibility that a change of surrounding rock bed condition caused external force that lead to the implosion of a PMT. There are no data on movement of rock beds for the period around the accident. However, in the week of November 19 a measurement on rock bed movement was made, although the result is yet to come. According to the data on temporal change of bed rocks, no sudden distortion in bed rocks nor destruction was observed in the period between the time of excavation of the SK cavity and March, 2001.

According to a study by the Kamioka Smelting and Mining Company there is no change in rock bed condition around SK. This study also found no abnormality in the SK cavity, surrounding tunnels, the inclined tunnel around the SK tank, the access tunnel from the mine entrance to the SK site and other nearby tunnels.

A measurement of underground water level at a water level observation well shows no large change. See Reference "Water level". In the south-eastern Mozumi development area in the mine the underground water level is unchanged at about -503 m and the amount of gushed water shows no change. In the east No. 4 excavation area, because it was a dry season, at -500 m there is no gushed water and the underground water level is stable.

(Comment)

From the data presented above, change of bed rock condition is an unlikely cause of the implosion.

6.1.3 Sudden distortion of structure by movement of rocks

It is possible that a sudden movement of rocks broke through the stainless steel wall plates. If this is the case, there should be pieces of rocks scattered around at the bottom of the tank. But there is no sign of rock pieces or of abnormality near PMT 10810.

(Comment)

This sudden movement of rock occurs when stress is released. It is not feasible that this happened while the tank was being filled with water (existence of water pressure to rocks).

6.1.4 Impact due to breakdown of an anchor bolt on bottom stainless steel plate

During the upgrade the tank water was completely drained on August 25. That time there was water pressure from remaining water under the bottom stainless steel plates and some water gushed out at a few locations as shown in a photo in Reference "A photo of the water leak point at bottom". For the location see References "Location of the water leak point at bottom". On the morning of August 28, this leak was stopped by putting filling material. A few hours after this temporary repair at this location the welding of an anchor bolt with the stainless steel plate gave in and a part of the plate came out a few cm. Since this anchor bolt was put into concrete as a temporary measure until stainless steel plates were welded, it is not meant to be something that supports the tank structure. However, there is a possibility that when the plate came out an impact was created and put a stress on the imploded PMT.

- (Comment)
  Immediately after this incident in August, visual investigation was conducted and nothing unusual was found in the structure. There was no damaged observed with PMTs.

6.1.5 Fallen tool

- Comment:
  The upgrade was finished in mid-September and all tools were cleared. As we were taking data at the time of accident, this possibility is very unlikely.

6.2 Cause related with PMT

6.2.1 Case where first imploded PMT was not replaced one

- Upgrade work:
  For upgrade work at the bottom of the tank, Styrofoam boards were put on top of PMTs and workers walked around on the boards. There is a possibility that during this work some stress was imposed to the PMT. See Reference "Locations of Styrofoam boards used during upgrade work". When workers replaced PMTs, they used a Styrofoam board with a hole at the center and it was placed on a PMT. The PMT to be replaced was then put on this board and taken away from the location. After replacement work, all the PMTs new and old were cleaned. For that, Styrofoam boards were placed so that workers could walk around. See Reference "Locations of Styrofoam boards used for cleaning during upgrade work".

  (Comment)
  As it was anticipated that some extra weight would be placed on bottom PMTs during the upgrade work, several tests were conducted to make sure that PMTs would be safe. See Reference "Procedure and result of PMT strength tests for upgrade work at bottom".

- Stress due to draining of water

- Aging of PMT glass in water

- Aging of PMT glass under pressure

6.2.2 Case where first imploded PMT was replaced one(10850)

- Upgrade work:
  Same as the previous case above.

- Water pressure:
  Some of PMTs were tested under 6 atm and found safe. However, there is a possibility that this PMT happened to be faulty against high pressure.

  (Comment)
  One out of every 95 PMTs, a total of 151 PMTs, were pressure tested (under 6.5 atm for 24 hours). One PMT developed a crack at its neck. However, as it turned out that the pressure applied was 7 atm, it was concluded that the specification that PMTs were safe under 6 atm was satisfied.

- Collision among PMTs:
  PMTs were secured in position with a pair of bands made of metal and rubber. These bands squeezed PMTs to hold them and the bands themselves were screwed on support structure. It is possible that faulty screws used to squeeze the imploded PMT created uneven contact between the PMT and the band, the PMT was loosened to float, and it collided with adjacent PMTs.

  (Comment)
  Buoyancy does not depend on the depth of the PMT location. If this is the case, the PMT should have already moved upward when the water level was lower. On September 23, physicists checked all the PMTs under water and they did not find such a problem.

- Stress due to faulty band setting:
  The position where this band was wrapped was close to PMT's connected part. It is possible that the band was put on this weak region and stress had accumulated.

  (Comment)
  The position of the band was about 1 cm below this weak area where the glass surface is flat. Therefore it is unlikely that this is the cause of the implosion.

- Stress or crack during transportation or preparation:
  All the new PMTs to replace old PMTs were calibrated for four days just before the replacement work. In this period somehow by mistake the PMT might have received some stress or developed a crack.

  (Comments)
  Calibration work and cleaning were done by physicists and graduate students very carefully. It is extremely unlikely that a crack was undetected and left alone.

- Aging due to low temperature and high humidity:
  The PMTs to replace old ones had been stored for some years since the SK construction. Some environmental factors such as low temperature and high humidity in the storage area might have caused aging of glass strength.

6.3 Planned future PMT tests

See Reference "List of planned tests of PMTs by Hamamatsu".

7 Assessment of how chain reaction damaged other PMTs

7.1 Shock waves

There is a possibility that the implosion of the first PMT created shock waves which triggered a chain reaction to destroy the other PMTs.

- Comment 1:
  During the construction of Kamiokande, a test with 6 PMTs was conducted to check to see if an implosion of the PMT at center would trigger a chain reaction at the water depth of 1 m. As in this simple test no chain reaction occurred, no preventive measure was taken against a possibility of shock waves for SK. (See Reference "Photos of the impact test of PMT strength conducted in 1981".)

- Comment 2:
  Judging from the successful operation of Kamiokande over 10 years,

when SK was designed, there was no consideration of preventive measure against shock waves.

7.2 Mechanical vibration

Another possibility is that the shock waves vibrated mechanically adjacent PMTs and destroyed them.

7.3 Planned tests on effects of shock waves

(1) Impact test of PMTs under water pressure

(2) Simulation of shock waves
See Reference "Simulation of a PMT implosion". Propagation of a shock wave simulated by a simple model is shown in the Reference above. This model assumed that the PMT volume was 60 liters, its shape was sphere with a radius of 24.3 cm, and inside of the PMT was vacuum. Furthermore the PMT was placed at 30 m below the water surface. In some figures impact pressures at different locations are shown in propagation of a shock wave from the center of the PMT and changes of water fluxes toward the center of the PMT are shown at different locations.

7.4 Others

See Reference "Summary of the procedure for investigation on the cause of the accident".

8 List of References

1. Map of the mine

2. Technician A's account

3. Chart of the seismological wave detector record

4. Trigger rate

5. Photo 1 and 2 (2 pages)

6. R3600-5 50 cm PMT data sheets (4 pages)

7. Status of the damage done to the inner side PMTs (2 pages)

8. Current status of PMTs (2 pages)

9. History of the water level

10. Locations where the water samples were taken

11. Results of water quality test

12. Maximum allowed levels of chemicals in water (2 pages)

13. Map of the damage done to the outer PMTs

14. Event rate

15. Event displays (10 pages)

16. Singles rate

17. Map of the inner bottom PMT locations

18. Map of the inner bottom PMT locations around PMT 10810

19. Underground water level at SK

20. Location of the water leak point at bottom

21. A photo of the water leak point at bottom

22. Photos of the upgrade work at bottom

23. Locations of Styrofoam boards used during upgrade work

24. Locations of Styrofoam boards used for cleaning during upgrade work

25. Procedure and result of PMT strength tests for upgrade work at bottom

26. Photos of the PMT tests (4 pages including a caption)

27. List of planned tests of PMTs by Hamamatsu

28. Photos of the impact test of PMT strength conducted in 1981

29. Simulation of a PMT implosion (4 pages)

30. Summary of procedures for the investigation on the cause of the accident