Developing the 20-inch semispherical photomultiplier tubes

The Nobel Prize winning achievement seen from a company R&D perspective

1. Introduction

On October 8, 2002, Masatoshi Koshiba, professor emeritus of the University of Tokyo, was awarded the Nobel Prize in Physics for his work in pioneering a new branch of astronomy that seeks to solve the mysteries of the universe by measuring neutrino particles. The Kamiokande Neutrino Observatory responsible for making these neutrino measurements relies on a large number of 20-inch (about 50 cm) diameter semispherical photomultiplier tubes developed by Hamamatsu Photonics. The granting of this award was a real source of satisfaction to those of here who took part in its development and brought back memories of that work some 23 years ago. Here we describe the course of its development with a sincere feeling of gratitude.

On March 9, 1987, the newspaper evening editions were abuzz with big news. At 4:35 on the afternoon of February 23, 1987, the Kamiokande Observatory announced the detection of neutrinos traveling far from a supernova (1987A) that emerged out of a corner of the Large Magellanic Cloud some 170000 light years from the earth. These supernova explosions are said to occur only once in every several hundred years. In fact, the last time such an event could be seen by the naked eye was in 1604, so Kamiokande did well to capture this extremely rare event. Indeed this was the first time neutrinos from a supernova could be observed and this event marked the beginning of so-called "neutrino astronomy" using elementary particles to probe the universe.

On November 1, 1979, Toshikazu Hakamata of our sales department visited the office of Professor Masatoshi Koshiba (currently professor emeritus of the University of Tokyo) at the Faculty of Science, University of Tokyo. In July 1978, we had supplied Professor Koshiba with 3000 photomultiplier tubes for high energy physics experiments at the German Electron Synchrotron (DESY) laboratory. Each photomultiplier tube was 3 inches in diameter (about 76 mm) and had operated without trouble throughout the experiments.

This time Professor Koshiba was planning new “proton decay measurement” experiments and, based on the good results at DESY, he was thinking to ask us at Hamamatsu TV Co., Ltd. (currently Hamamatsu Photonics K. K.) to develop a new photomultiplier tube. Hakamata described a photomultiplier tube with a 5 inch (about 130 mm) diameter semispherical photocathode using data he had brought along to the meeting. However, Professor Koshiba’s planning was a truly vast scale that called for developing an even larger 20-inch diameter photomultiplier tube and, moreover, he wanted 1200 of these photomultiplier tubes by the fall of 1981 to install them in the “13 meter by 13 meter by 13 meter” water tank to be built at the Kamioka mine in Gifu Prefecture.

On the afternoon of November 16, Professor Koshiba dropped by our main factory and again asked "Could you make me 20-inch diameter photomultiplier tubes?" The company president Teruo Hiruma and 7 others listened to the professor's request. When Hiruma asked, "Will using neutrinos help us understand the earth's structure?" Professor Koshiba then described about neutrinos and the high energy physics experiments at DESY.

In describing proton decay the professor said that "on the atomic level, strong interactions, weak interactions, and electromagnetic interactions likely express different sides of the same phenomenon and verifying that requires observation of proton decay." He went on to add that decay causes the proton (P) to split into one positron (e^+) and one pion (π^0). The pion decays into two gamma rays. The proton has a life span of about 10^{32} years, while the universe itself has a life span of about 2×10^{10} years, so the life span of the proton is on a much longer scale. There are approximately 3×10^{32} protons in 1000 tons of water so that observing the decay of 3 protons per year should be possible. The professor also stated that, "This is an extremely difficult experiment in which I want to embed three thousand 20-inch diameter photomultiplier tubes into the walls of the water tank. Photomultiplier tubes having a large diameter are essential. Anyway I need you to do the best you can." This meeting lasted over two hours.

At that time, proton decay had been predicted in the Grand Unified Theory but still had not been proven experimentally. The Grand Unified Theory, which unifies the weak, strong, and electromagnetic interactions, was an influential theory where the proton making up the atomic nucleus once thought perpetually stable actually had a certain life span.

In that period, American scientists were also proceeding with plans for proton decay observation experiments to verify the Grand Unified Theory. These plans called for the use of three thousand 5-inch diameter photomultiplier tubes in 7000 tons of water in a water tank whose scale was more than double that of the Japanese experiment. When Professor Koshiba heard of the American plans, he believed he had to do something to compensate for the smaller scale Japanese plan and achieve faster results. He therefore proposed the use of large diameter photomultiplier tubes. A larger diameter photomultiplier tube means that more of the "Cherenkov radiation" serving as proof of the proton decay process can be trapped. Though the Japanese plan had fewer photomultiplier tubes, each tube had a larger photosensitive area which would also minimize the number of required signal processing circuits. This project was called the "KAMIOKANDE: KAMIOKA Nucleon Decay Experiment" and its concept envisioned the embedding of more than one thousand 20-inch diameter photomultiplier tubes on approximately a 20% area of the inner walls of a cylindrical water tank that was 16 meters in height and 15.6 meters in diameter and filled with 3000 tons of pure water.

In water, the speed of light slows so that a phenomenon occurs in which the speed of elementary particles, such as positrons that fly outward when a proton decays, exceeds the speed of the light. As in the case of sonic shock waves that generate when an airplane flies faster than the speed of sound, shock waves generate when elementary particles possessing high electrical energy exceed the speed of light. This emits a weak bluish-white light called Cherenkov radiation at a wavelength of 350 to 400 nanometers. Photomultiplier tubes are used to measure the intensity and time of this light. The light is emitted only in the direction of elementary particle movement, so measuring the pattern and time of this light will reveal the directions that these particles move. In the case of proton decay, two Cherenkov light rays are simultaneously emitted in opposite directions from the point that the proton decays. If the sum of the energy from both Cherenkov light rays matches the mass of the proton, then this proves that proton decay has occurred.

At that time, UK-based Thorn EMI (now Electron Tubes, Ltd.) was already developing an 8-inch (about 20 cm) diameter photomultiplier tube. In spring of that year, Hamamatsu TV Co., Ltd. had just started work on prototype photomultiplier tubes with 5-inch and 8-inch diameter semispherical photocathode envelopes. However, the 20-inch diameter tubes that Professor Koshiba wanted were in a whole different ballpark and President Hiruma "intended to refuse" their development work at the time that he and Tatsuro Hayashi of our engineering department visited Professor Koshiba's engineering lab. However, impressed by Professor Koshiba's zeal, Hiruma relented and agreed to develop the tubes. One memorable episode at that time Hiruma mentioned to the newspapers is seeing an El Greco religious painting when visiting Koshiba's lab and feeling the same fervor and emotion as Professor Koshiba in his pursuit of absolute truth through science.

Hiruma said, "Well anyhow we will give it a try" and that was the start of development work. On December 13, 1979, Haruji Ohtsuka (currently vice president) who was coordinating photomultiplier tube work ordered me to develop a 20-inch diameter photomultiplier tube. The development period was about one year. I was 31 years old at the time and was in charge of photomultiplier tube development in the manufacturing division and remember feeling, "this is going to be a really tough job."

2. Designing the 20-inch diameter photomultiplier tube

The photomultiplier tube is a photoelectric tube for detecting and amplifying the weak Cherenkov light by 10 million times and extracting it as electrical signals. It has a photoelectric surface (photocathode) deposited as a thin film such as alkali metal onto the inner side of a 20-inch diameter semispherical glass window (see K in Fig. 1). The Cherenkov light entering the glass window excites electrons within the photocathode, which are emitted as "photoelectrons" into the vacuum in the tube. These photoelectrons are collected by a focusing electrode (G in Fig. 1) inside the photomultiplier tube into the secondary electron multiplier. The secondary electron multiplier is made up of more than 10 stages of electrodes called "dynodes." When a photoelectron strike the first dynode (Dy-1 in Fig. 1), multiple secondary electrons are released. These electrons then strike the next-stage dynode to produce more secondary electrons. This process is repeated so that the electrons are amplified in a cascade up to approximately 10 million times and are finally obtained at the "anode" (A in Fig. 1) as an electrical signal.

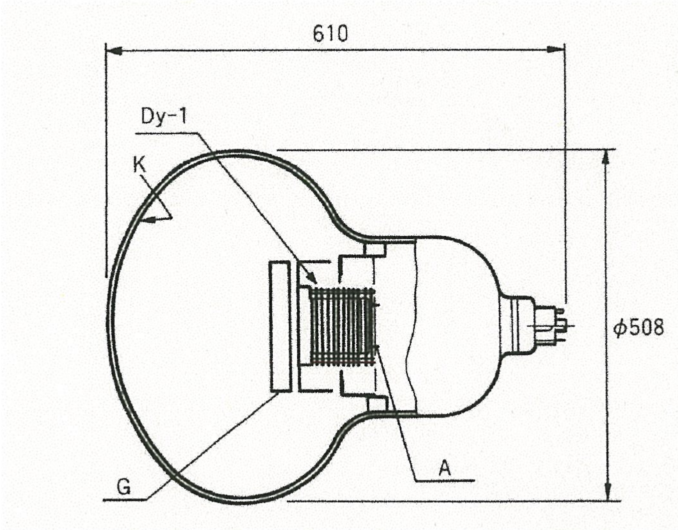

Fig. 1 Cross sectional view of 20-inch diameter photomultiplier tube

The 20-inch diameter photomultiplier tubes mounted in the inner wall of the water tank had to be capable of capturing the Cherenkov light that comes in from every angle. They also had to exhibit accurate time response from wherever the light arrives, have a high photoelectron collection efficiency, and maintain good resistance to water pressure. The shape of the glass window had a slightly flattened hemispherical surface with a cross-section resembling a rugby ball in order to maintain the photoelectron transit trajectories to as nearly the same distance as possible. Even still, the large tube diameter and the high-speed response are a mutual tradeoff. The condition required by Professor Koshiba was a response time difference within 2 nanoseconds (2 billionths of a second) from light input to light measurement, which was an extremely strict condition.

This large size photomultiplier tube not only had to have an unprecedented diameter of 20 inches but also required fabricating a vacuum tube that met harsh conditions such as being installed within 3000 tons of water and all these conditions represented work in yet unexplored territory.

On December 24, 1979, I made several drawings as external views of the 20-inch diameter photomultiplier tube on letter size graph paper. These were design drawings for starting the detailed design work. It was decided that the outer contour of the photocathode side would have roughly a rugby ball shape, but the shape of the stem was left undecided until a detailed design of the electrode structure was made. The external contours at the stem underwent big changes after ordering the glass bulb. The glass material was an important issue and since it would be used in water for long periods, we decided to use "super-hard borosilicate glass" in view of its excellent durability in water.

The photomultiplier tube operates due to the motion of electrons within a vacuum. The electron motion is referred to as the "electron trajectory" yet this is impossible for the human eye to track. We therefore made simulations to visualize the electron trajectories in order to design an ideal electron structure that satisfied the required characteristics. This work is called "electron trajectory design."

Electron trajectories are now currently all calculated by computer when designing the electrode structure. At that time, however, computers were not simple to obtain and use, so we placed a model having the same cross section as the photocathode in a shallow tank of about 1 by 2 meters in size filled with water to a depth of 10 cm in order to simulate the trajectories of photoelectrons entering an electrode model of the secondary electron multiplier. We placed a model of the focusing electrode between the photocathode surface and the electron multiplier section and applied a relatively small voltage to the photocathode. We then dropped probes in the water to follow the tracks of electrons being released from the photocathode provided with the specified initial speed conditions and moving toward the electron multiplier section. The simulated electron trajectories were then recorded on a plotter that was interlocked with the probes. We repeated the tests hundreds of times while changing the relative electrode placement position, the applied voltage, and conditions applied to the photoelectrons until we obtained data that satisfied the required specifications.

The really tough problem in the tube design was the demand from the University of Tokyo that the response time difference be within 2 nanoseconds. This response time characteristic was determined to separate Cherenkov light caused by "proton decay" from the unwanted background caused by "muon(μ)" and set the measurement accuracy of the light emission point and direction. This characteristic signifies the transit time jitter of single photoelectron pulses when the entire photocathode is illuminated. Even the 8-inch diameter photomultiplier tubes used at the time had a time response of 4 nanoseconds, so for 20-inch diameter photomultiplier tubes having a long electron transit time (distance), this condition of 2 nanoseconds was an extremely harsh specification. However, results from repeated testing allowed us to design the time jitter difference from the photocathode to the first dynode entrance to about 2 nanoseconds. This still could not be called sufficient, but the response time difference including the estimated time jitter for all dynodes became 4 to 7 nanoseconds. It was a breakthrough because we had initially predicted that even getting a figure within 10 nanoseconds would be very difficult.

Design of the electron trajectories was the responsibility of Masuyasu Ito in our engineering department who summarized the electrode design into two different focusing electrode drawings. One was a "time jitter" priority design while the other was an "anode signal uniformity versus light incident position" priority design. Work then started on fabricating the prototype tube based on the time jitter priority design. Based on electron trajectory design data, drafting of detailed structural component drawings such as the glass bulb and electrodes then began for fabricating the prototype tube.

A recommendation to use super-hard borosilicate glass was made to the University of Tokyo. However, the University of Tokyo answered that they did not have enough budgets and proposed using a less expensive glass. So we discussed to use JIS Class II borosilicate glass and soft glass such as soda-lime glass. After evaluating and considering the characteristics of those glass materials and the fabrication of large size glass bulb, the choice was made to return to super-hard borosilicate glass. This evaluation process took 5 months and delayed the development schedule by 3 months.

As the super-hard borosilicate glass, we selected a glass brand called "Hario 32" having very high resistance to heat and temperature and widely used in heat-resistant cookware as well as lab flask and beakers. Large quantities of glass were required for making the 20-inch diameter photomultiplier tubes. Blowing the glass was a difficult task initially requiring 3 or 4 veteran workers. Naturally, this involved a large rise in costs. Moreover, the thermal expansion coefficient "32" of this glass was small compared to the "46" of hard borosilicate glass (Kovar glass) usually used in most photomultiplier tubes. This glass could not directly be sealed to the glass stem where the lead wires (made of Kovar metal) were embedded, so a "graded seal" was required that used glasses with gradually different thermal expansion coefficients.

These 20-inch diameter photomultiplier tubes had to be able to withstand 10 or more atmospheres of pressure, so the glass bulb shape and thickness were important factors. Also the cylindrical sealing section was designed to be a large diameter of 10 inches (about 25 cm) due to the diameter of the focusing electrode. This required changing the design of the "graded seal" position to the small diameter stem side. The glass thickness on the 20-inch photocathode side was set to 6 to 8 mm and the 10-inch cylindrical sealing section was set between 5 and 7 mm.

A "bialkali photocathode" having spectral response characteristics close to the Cherenkov light spectrum was used for the photocathode. The dynode electrode utilized a "venetian blind" type structure where narrow strips of metal plates were arrayed in a combination resembling that of the blinds used on room windows. There were other dynode shapes such as linear-focused types and box-and-grid types, but they did not have the ability to collect photoelectrons from a large area photocathode such as the 20-inch diameter photomultiplier tubes. However, there were few manufacturers capable of accurately forming electrodes having this type of large venetian blind shape, and Tomoaki Ikuma of our purchasing department had a tough time selecting where to order this component.

3. Creating the world's largest photomultiplier tube

Main processes in the photomultiplier tube production include cleaning of materials, depositing of antinomy onto the dynodes, assembling and wiring of the electrodes, sealing of the glass bulb and stem, evacuation to a vacuum, photocathode activation, inspection, and assembly-finishing. Fabricating a 20-inch diameter photomultiplier tube involves the same processes as a conventional photomultiplier tube, but there were many unknown areas in making a large-size tube and so a staff of leading experts in each field and able to handle problems in any particular area were assembled as the development team.

The decision of which glass material should be used came late, so the order to the glass manufacturer (Shibata Hario Glass Co., Ltd.) was made on June 1980, and the prototype glass bulb arrived at the end of July. Actual study of the glass welding/sealing, which was thought to be difficult from the start of this project, was delayed even further. Numerous evaluation issues still remained such as the type of combustion gas and burner for use, glass distortion countermeasures, preventing oxidation on the metal electrodes, and glass bulb durability testing. Evaluation of the sealing method was the job of Koichi Ohki who was our leading expert in glass processing and is even now my constant partner in development work. The bulb and stem sealing using the super-hard borosilicate glass called "Hario 32" was an extremely difficult task. Results from the glass melting tests showed that large diameter and moreover hard glass of 5 to 9 mm in thickness did not melt in conventional gas burners. Ohki raised the heating effect by changing over to hydrogen gas. He also installed a 20-nozzle hydrogen gas burner tool in a large-size glass lathe. The amount of heat generated from the 20-inch tube sealing operation was larger than imagined and oxidized the electrodes of the secondary multiplier section installed in the bulb. Shortening the sealing operation time in order to prevent oxidation caused "distortion" to remain in the glass and cracks occurred. A large size conventional gas burner was jointly used for "annealing" and efforts made to find a balance between glass distortion and electrode oxidation. Even still, cracks occurred in the test tubes. Ring-shaped cracks appeared on both side of 10-inch diameter sealed section at about the 5 cm point and distortion still remained. At that point it was decided to change the thickness specification for the sealed glass section to thinner dimensions of 3 to 5 mm from the original 5 to 7 mm. Ohki then discovered annealing conditions to match the shorter glass fusion time, and the problem of glass distortion and electrode oxidation finally started moving toward a solution.

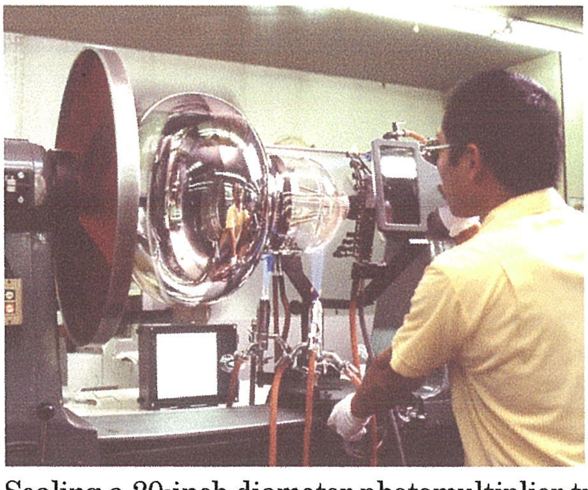

Fig. 2 Sealing a 20-inch diameter photomultiplier tube

To perform the water pressure resistance test, a steel tank was custom-ordered to allow completely immersing a 20-inch diameter photomultiplier tube. In this test, the 20-inch diameter photomultiplier tube now having a thinner glass thickness was placed in the tank, the water pressure then raised, and the photomultiplier tube was confirmed to withstand a pressure up to 8 atmospheres. The outer contours of the photomultiplier tube were decided by this test.

One factor in successfully developing the 20-inch tube was the choice of the Hario 32 glass that was resistant to heat and crack, and also easily withstood slight distortion and rough handling.

In the second week of October 1980, about one year after Professor Koshiba's development request, serious work started on prototype tube fabrication using all of the custom-made special order facilities at our main factory.

The assembly process was carried out differently than in previous work. Rather than electron tube assembly, the term blacksmithing was more appropriate. Burrs were removed from the electrodes with a lathe. Sometimes quick trips were made to the hardware store for large sheet metal scissors and other items when the available tools couldn't handle the job. The secondary electron amplification ratio (gain) of the venetian blind type dynode was greatly dependent on the tilt angle of electrode strips and their positions relative to each other. The electrodes tended to easily warp during the heat treatment process and constant care was used during their handling. It was also found that the incident photoelectrons might entirely miss that electrode surface depending on the tilt angle of the first dynode strip electrode. This had bad effects on the two-dimensional uniformity of the gain. So a review was made of the electron trajectory data and the first dynode profile was modified to a symmetrical shape extending from the center to the left and right to improve the spatial uniformity of the gain. These electrode modifications requiring constant care and efforts continued while getting blisters on the hands until a glance at the clock showed it was now midnight. However, the team handling this job (Toshihiro Suzuki, Keiju Ikuma, Hiroshi Kondo) had worked well together up to that point in development work and looking back on that experience they commented that "every day was fulfilling work without really feeling it was a painful struggle."

The now assembled electron multiplier was heavy weighing more than 2 kilograms. On an ordinary photomultiplier tube, the electron multiplier section is connected to the stem leads by resistance welding using nickel wire material. However, this wire material could not withstand the heavy 2 kilogram load, so 7 mm wide thick stainless steel plates were used as a substitute. This task always required two workers to complete it. The electron multiplier was now successfully clamped, but the problem of bent leads on the stem side appeared. To reinforce it, a glass ring identical to the stem was mounted during this process. The stem was now a somewhat strange looking two-layer structure.

The electron multiplier assembled onto the stem was placed at the specified position within the tube, and the sealing was performed. Then the tube internally dried by filling it full of nitrogen gas to prevent oxidizing. Compared to the evaluation stage, the task of melting the glass and sealing the tube took a short time, but after allowing an adequate amount of time for preheating and annealing after sealing, this job could require up to an hour.

The first prototype that was made developed cracks extending from the sealed section. The glass welding was inadequate. I told myself, "It might be a good sign if the very first prototype does not go well" remembering the jinx that plagued us up to now. For the second prototype, we tried melting the glass a little bit more. The sealing job was a success and we now moved on to the vacuum evacuation process.

The photocathode activation process was the job of Tatsushi Tominaga who was well experienced in this work. He wore a protective helmet equipped with an anti-explosion mask and protective clothing in case the 20-inch diameter photomultiplier tube cracked and exploded when evacuated to a vacuum. The sealed photomultiplier tube was attached to a large vacuum-pumping system and then heated for two days in an electric furnace. After sufficient degassing, the photocathode was formed on the third day. The photocathode was formed by depositing a thin film of antimony on the inner surface of the glass window and then causing a sequential reaction with vaporized potassium and cesium. This process requires controlling the thin film thickness and the reaction amount of potassium and cesium to obtain an optimal result. If the reaction was not appropriate or lacking in uniformity, then irregularities appeared on the photocathode surface causing poor sensitivity. For ordinary photomultiplier tubes, we use a measuring device to verify each state while proceeding with the photocathode activation process. This process has now been automated, but at the time the activation of the large-size photocathode was done completely by feel. The photocathode color changes with each fabrication process. We judge the state of the photocathode by observing the changes in color and proceed to the next step. Even in the case of this large-diameter photomultiplier tube, we expected the reactions would proceed the same as with an ordinary photomultiplier tube. Tominaga was himself worried about whether the reactions would occur correctly in such a large tube and he was uncertain until completion of the first tube. However, we continued to trust in Tominaga's "eye" or judgment.

Tominaga succeeded in forming the antimony thin film. Then, causing this thin film to react with potassium instantly changed its color to beautiful purple. The development staff gathered around the vacuum pumping system then gave a big cheer. This was truly an "emotional moment" for us. One factor in this success was incorporating a potassium agent inside the tube as proposed by Tominaga. Next, causing a reaction with cesium made a vivid "amber colored photocathode" appear and the needle on the ammeter in front of us gave a big swing. This was proof that the world's largest high-sensitivity photocathode had indeed been achieved.

Simultaneous with forming the photocathode, the vaporized alkali metal also reacted with the antinomy thin film on the dynodes to form "secondary emission surfaces." Oxidation on the electrodes from the sealing operation also affected a reaction with the alkali metal which decreased the gain and its uniformity. Various types of measures were taken to raise the gain, but eventually it was decided to use methods based on conventional techniques.

When first developing a newly designed photomultiplier tube, the conditions needed for the photocathode activation process are unknown and finding the optimal conditions is usually a process of repeated trial and error. In this case, however, the very first 20-inch diameter photomultiplier tube we developed successfully exceeded the goal of 20% quantum efficiency at a wavelength of 400 nanometers. The gain of the second tube we produced exceeded one million. The gain specifications were later changed to 10 million, but this was solved by increasing the number of dynodes from 10 to 13 stages.

Most of the development goals had now been met and work started on developing numerous other photomultiplier tubes, but this type of work was a totally new experience. Hamamatsu Photonics has relied on the "tacit knowledge" and experience, acquired and accumulated through daily manufacturing activities and challenge to solve research problems posed in this unknown field. This has helped us developed our state-of-the art products. For example, the world's first multialkali photocathode side-on photomultiplier tube called the "R928" was born here more than 30 years ago. It has still been used in many analytical laboratory instruments. As with the R928, the 20-inch diameter photomultiplier tube is truly a product developed from this tacit knowledge.

After making 10 tubes, the target goals were changed over from prototype tube manufacture to mass production.

4. Prototype tube evaluation tests

Evaluating the prototype tubes was the job of Hidehiro Kume and Akihiro Sawaki in our engineering department. Due to the size of the large diameter tube, the necessary measurement instruments were placed in the main factory's cafeteria and then moved to one side of room during lunch breaks. There were wide variations in gain in the prototype tubes, which were mainly caused by thermal effects from the sealing operation. The gain that is approaching 10 million also had bad effects on voltage breakdown characteristics, sometimes causing discharge. However, making slight adjustments to the alkali metal during the photocathode activation process remedied the problem. Work on improving the time jitter that had been a cause of concern also reached a maximum figure of 3.3 nanoseconds, and attained an average figure of 7 nanoseconds. These figures again proved the high level of prototype fabrication accuracy and electron trajectory design.

On December 22, 1980, Katsushi Arisaka who was then a graduate student of the University of Tokyo (currently a professor at UCLA) visited our company and carried out evaluation tests of the prototype tube along with Hidehiro Kume. Results from two days of measurement evaluations clarified the remaining issues and, though some improvements were needed by January of the following year, it was judged that the prototype work was mostly complete. We repeated the evaluation tests several times along with Arisaka, and proceeded to evaluate product improvements and delivery specifications.

Though evaluation results were good overall, the poor "single photoelectron resolution" (ability to detecting single photons) became a topic for concern. This was not initially a characteristic requested by the University of Tokyo, but a request arrived for changing the method used to discriminate between positive electrons (e^+) and muons (μ^+). This changeover in specifications for the developmental product placed a large load on us. This involved a structural design change from a "time jitter priority design" to a "superior anode signal uniformity design." This modification changed the incident position and angle of photoelectrons onto the first dynode so that the photoelectron collection efficiency of the first dynode was improved and progress made in increasing the single photoelectron resolution. The high dark count rate was another cause of poor resolution. Taking note of the fact that the proton decay observations in the actual experiment was performed in a dark water tank at low temperatures 1000 meters underground, we placed the tube inside a measurement dark box filled with dry ice to cool the tube to approximately 10°C, and then tried making measurements after the tube had been left in the dark box for a while. Lowering the temperature in this way decreases thermal electrons from the photocathode that are one cause of dark current. This improved the single photoelectron resolution yet did not come to a complete solution. Later, the second-generation new 20-inch diameter photomultiplier tube was designed for the "Super-Kamiokande" facility in 1987 by the group of Hiroyuki Hisamisa in our engineering department. It employed newly developed high-performance venetian blind electrodes so that the ability to detect single photoelectrons was significantly improved and also the time jitter was lowered even further to 2.5 nanoseconds. Introduced by an NHK (Japan Broadcasting Corporation) documentary show "Project X", this ability to detect single photons was considered equivalent to the same high sensitivity needed to detect from the earth a flashlight that someone on the moon pointed toward the earth (assuming there were no other lights). Moreover, light moves through water approximately 60 cm in 2.5 nanoseconds, so the position where the light was emitted can be measured with this same level of high accuracy.

5. Delivering the prototype tubes and mass production

On January 28, 1981, we delivered tube "No. 11" as the first prototype tube to the University of Tokyo. Delivery was several months behind schedule but in February most of the development work had ended. The number of prototype tubes was a mere 20, and the period required for their main development was 5 months which was the shortest period so far.

On February 25, 1981, the successful development of 20-inch diameter photomultiplier tubes was announced from the High Energy Accelerator Research Organization (KEK) located in Tsukuba (Ibaraki Prefecture, Japan) as well as the "Proton Decay Measurement" experiment that would be utilizing these photomultiplier tubes.

In April 1984, progress had been made in improving the 20-inch diameter photomultiplier tubes and mass production was just about to start. Evaluation of final specifications and water-proofing methods for the "breeder assembly (voltage-divider circuit assembly)" that operates the photomultiplier tubes had started. However, the testing of photomultiplier tubes which require high voltages and which would be used for years submerged in water at a pressure of approximately 1.7 atmospheres were all unexplored territory in which the testing staff under Seiji Koike had no experience. After viewing results from trial-and-error experiments, we employed the water-proof mold method utilizing urethane resin as proposed by Professor Atsuto Suzuki of KEK (currently professor at Tohoku University).

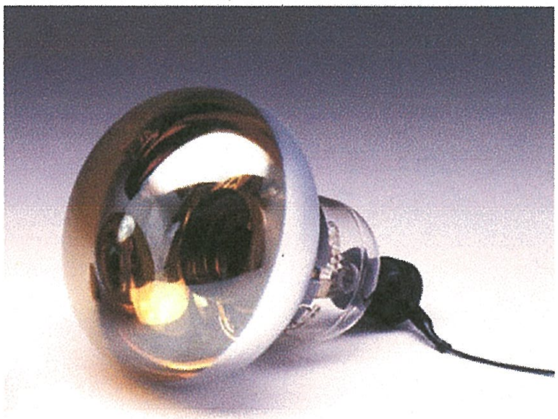

Fig. 3 20-inch photomultiplier tube

On March 1981, Junichi Takeuchi in our production department (currently Electron Tube Division manager) gathered Toshiharu Tozuka and some 30 employees at the Toyooka Factory to start mass production. Since there were not enough workers for the job, he took the special measure of using new employees who had just joined our company in that year. The factory has been modified to allow manufacturing the 20-inch diameter photomultiplier tubes and now overflowed with various types of large materials and equipment including 12 large-size vacuum pumping systems and glass bulbs, etc. Since the workers include many new employees who had little experience, the yield was initially low and Tozuka and his staff spent more time on revising job processes such as sealing and photocathode activation tasks. Tatsuo Asahina who took over the sealing work produced the required number of tubes without saying any complaint as if nothing had happened. Asahina later appeared on one page of our corporate brochure as a typical technical worker. The thickness of the glass tube joining the tube to the vacuum pump was an unheard-of 13 mm thick and so everyone was very careful with the final cutting and sealing off task. Making a mistake here would waste an entire day's labor, so everyone got to work while holding their breath and starting to feel a nervous sweat build up. Many of the tasks required heavy physical labor and the work continued while hands became hard and calloused in assembly wiring, inspections and assembly tasks. These were all completely unfamiliar tasks.

A test was held to assess the extent of damage that might occur from breakage of a 20-inch diameter photomultiplier tube during manufacture or transport. On June 16 in the same year, a drop test was performed with a photomultiplier tube from a height of one meter in an open space on the east side of the Toyooka Factory. Dropping the photomultiplier tube caused a terrific explosion and glass fragments flew out 10 meters in every direction. The staff members who witnessed that explosion were shocked beyond words. The tube inside the cardboard box, however, merely shattered while making a muffled sound. Based on these test results, a metal net was attached to the vacuum pumping system and the tubes conveyed by crane between job processes. After vacuum pumping, the 20-inch diameter photomultiplier tube was placed in a cardboard box when handling and transporting. Looking back on those times, Yousuke Ohashi who was in charge of inspections recalls that, "We all felt proud to be taking part in this great proton decay measurement experiment and that pride helped us through a lot of tough days."

In July in the same year, a fracture test was also carried out at KEK to find what breakage might happen. In the fracture testing in air, a 20-inch diameter photomultiplier tube was placed in the middle of thicket of woods and then hit with small stones from a distance of 30 meters to break the tube. It then exploded with a "bang" and scattered glass fragments everywhere leaving only the electrode remaining.

A fracture test in water was also carried out in a 15 by 15 meter water tank at a depth of about 1.5 meters. Multiple 20-inch diameter photomultiplier tubes were placed in the water at 1-meter intervals and a stone was then dropped from above onto one tube. A "thunk" was heard when the stone dropped and a column of water arose 2 to 3 meters high from the water surface. The water was shallow and there was no consecutive destruction to other tubes.

In September 1981, fifteen 20-inch diameter photomultiplier tubes were delivered to KEK under the product model name "R1449-01." KEK then started experiments using these tubes while placed in the water tank to detect Cherenkov light caused by cosmic rays. They operated with no trouble.

Transport tests were carried out from Hamamatsu City to the inside of Kamioka mine for a period of one week starting from November 16. Drop impact tests were carried out with a photomultiplier tube placed in a shipping carton. However, during setup for the vibration impact test, it was found that the 20-inch diameter photomultiplier tubes were too large to fit them into the test device. Therefore, actual truck shipping tests were repeatedly carried out.

In October 1981, production had just about reached its middle stage. Production, which was at first hard put to attain a 20% level of yield, gradually improved to a continual level of 200 tubes per month. However, at that point in time two serious problems occurred. A first problem was that the budget of the University of Tokyo was too low and they could not come up with funding. This was really bad news for Hakamata who was in charge of sales. Another problem was that construction of the measurement water tank at Kamioka mine was delayed and they were not ready to accept the photomultiplier tubes. This meant that the finished photomultiplier tube products had to be temporarily stored at our factory, but there was no location large enough to store them. During this time, the cafeteria as well as other buildings at the Toyooka Factory soon became full. Later on the rail track space at the Kamioka mine became available for storage and the shipment of photomultiplier tubes then began again.

Production eventually shifted into high gear and finally ended in May 1982 after making 1100 non-defective tubes. By July 28 a total of 1050 tubes had been delivered. Tube development was now complete some two and a half years after first being requested.

6. Kamiokande

In early 1983, the 20-inch diameter photomultiplier tubes were installed inside the large water tank at the Institute for Cosmic Ray Research, University of Tokyo which was a facility located 1000 meters underground at the Kamioka mine in Kamioka-cho, Yoshiki-gun, Gifu Prefecture. The experiment commenced in August with these 1000 large "eyes" quietly gazing into the water tank to capture the moment of proton decay.

Several months after observations had started, Professor Koshiba was able to confirm that data obtained from this equipment was of much higher quality than expected. This was actual proof of the high performance provided by the 20-inch diameter photomultiplier tubes and also indicated that Kamiokande had a potential not only to observe proton decay but also capture neutrinos from the sun because of its high sensitivity enough to detect Cherenkov light. These results prompted Professor Koshiba to proceed with plans to modify the equipment. To shut out natural radiation from the surrounding bedrock as well as background noise from cosmic rays bombarding the earth, water was stored in the areas surrounding the water tank. At the end of 1986, modification work was completed with approximately one hundred 20-inch diameter photomultiplier tubes mounted in the outside water tank to serve as an anti-counter. Starting from January of the following year, measurement of neutrinos emitted due to nuclear reactions occurring within the sun began at Kamiokande in addition to proton decay measurements. In this experiment, the 20-inch diameter photomultiplier tubes capture the weak Cherenkov light that is very rarely emitted when neutrinos flying from the sun pass through the water tank filled with 3000 tons of pure water and collide with electrons in the water. Capturing this extremely rare phenomenon allows investigating the intensity and direction of the light to reveal how the electrons behave and what type of particles collide with them to emit light.

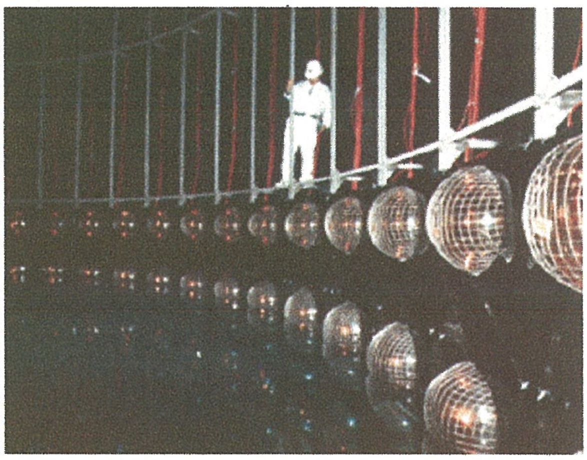

Fig. 4 Photograph of interior of Kamiokande water tank
(courtesy of the Institute for Cosmic Ray Research, University of Tokyo)

Besides neutrinos that are emitted from nuclear fusion occurring within the sun, it is predicted a large number of neutrinos will be emitted from a super large explosion that occurs when a star dies out. This neutrino emission process has been the focus of much attention as a potential key to solving the riddle of how our universe began and evolved. However, these neutrinos have very high penetrating power so that they easily pass straight through the earth, making their observation extremely difficult. However, this strong penetrating power of the neutrinos can be utilized to enable accurate neutrino measurement, because Kamiokande was constructed deep underground to avoid the noise from the various cosmic rays that constantly rain down on the earth so that it could receive only the neutrinos and muons easily penetrating through solid bedrock. Besides Kamiokande there are also other neutrino observation facilities around the world, and those are also all located deep underground in mines or tunnels for the same reasons.

Kamiokande in this way continually awaited the instant of proton decay and was detecting solar neutrinos at the rate of about one every 9 days.

On March 9, 1987, the evening newspapers announced that "at 4:35 in the afternoon on February 23, 1987, Kamiokande had detected neutrinos arriving from a supernova (1987A) emerging out of a corner of the Large Magellanic Cloud near our own galaxy and some 170000 light years from our planet. It is said that supernova explosions only occur once in every several hundred years and the last time one had actually been observed with the naked eye was recorded in 1604 by Johannes Kepler. The current supernova explosion was estimated to rain down some 10 billion neutrinos per square centimeter and an amount of 2×10^{16} neutrinos would fall on the water tank itself. However, among this amount, only 11 neutrinos caused collisions with electrons in the water tank filled with pure water and emitted Cherenkov light. Even so, this was the first time that humanity was able to observe supernova neutrinos and was the birth of "neutrino astrophysics" that opens up a new window to our universe by using elementary particles to observe space.

One thousand of the world's largest photomultiplier tubes built into the Kamiokande water tank continued to operate normally over a period of 4 years while immersed in water, and delivered the expected performance at a superb level that wrote a whole new page in the science of astronomy. This fact is a source of the greatest satisfaction for us. Furthermore, what aroused even deeper feelings among the participants is that Professor Koshiba saw the success of this neutrino observation a mere one month before his scheduled retirement. Professor Koshiba was later awarded the Japanese Order of Culture for this achievement as well as many other honors.

In 1988, the famous Japanese physicist Reona Esaki announced that the "Nobel Prize in Physics" had been narrowed down to 6 candidates, and Professor Koshiba was one of them. On October 18, 1988, newspapers notified our company that there was a high possibility that prize would be awarded to Professor Koshiba. I remember that Hakamata was pressed for a comment in the event the prize was granted and was busy for the preparation. Unfortunately, at some time after 10PM that night, a message arrived that another person had been chosen for the prize. That was the end to a very long day and we had never felt so close to the Nobel Prize.

On the evening of October 8, 2002, the media announced that the "Nobel Prize in Physics" had been awarded to Professor Koshiba. Even though this was awarded some 23 years later, those members involved in that development and production effort still felt a warm bond between them and the joy of winning the Nobel Prize began to sink in as little by little they recalled faded memories of that time. Once again experiencing the emotions of that time both Professor Koshiba and President Hiruma and others are deeply thankful for this wonderful group and their silently shared knowledge.

In August 1990, a plan for "Super-Kamiokande (Large water Cherenkov detector for cosmic particle observation)" was announced by the University of Tokyo. This came about due to the impact of a mainstream in the Grand Unified Theory appearing in recent years which predicts that protons have a life span of 10^{34} years, though it has not yet been observed. To verify this, "Super-Kamiokande" was planned to be a new proton decay and neutrino observation facility that would upgrade the performance some 10 to 100 times that of Kamiokande. It was then constructed at the Kamioka mine about 1000 meters underground at a site 900 meters away from Kamiokande. In January 1996, a total of 11200 of the newly developed, second-generation 20-inch diameter photomultiplier tubes (R3600-05) were installed in the giant water tank at Super-Kamiokande having a size of 39.2 meters in diameter and 41.4 meters in height and filled with 50000 tons of pure water which was 16 times the amount used at Kamiokande. In April 1966, Super-Kamiokande quietly commenced operation. In the old Kamiokande facility site, the Kamioka Liquid-scintillator Anti-neutrino Detector "KamLAND" was constructed and our third-generation 20-inch diameter photomultiplier tubes were installed there. KamLAND started from January 2002.

(Kenji Suzuki, Hamamatsu Photonics K. K.)