Its R&D Mission Completed, EGADS Evolves

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Fifteen years ago, theorist John Beacom and I first proposed introducing 100 tons of a water-soluble gadolinium [Gd] compound, gadolinium chloride, $GdCl_3$, or the less reactive though also less soluble gadolinium sulfate, $Gd_2(SO_4)_3$, into the Super-Kamiokande (Super-K, SK) detector. Called GADZOOKS! (Gadolinium Antineutrino Detector Zealously Outperforming Old Kamiokande, Super!), the basics of this load-SK-with-Gd idea have been detailed in a *Physical Review Letters* article [1], as well as in this very publication [2].

In a nutshell: neutron capture on gadolinium produces an energetic gamma cascade, so the inverse beta decay (IBD) reaction, $\overline{\nu}_e + p \rightarrow e^+ + n$, in such a Gd-enriched Super-K will yield coincident positron and neutron capture signals. Looking for these coincidences (or the lack thereof) will allow a large reduction in backgrounds and greatly enhance the detector's response to both supernova neutrinos (galactic and diffuse) and reactor antineutrinos. It will also improve the detector's sensitivity to proton decays by cutting backgrounds; genuine nucleon decay events should usually not have free neutrons in the final state. In addition, solar neutrino studies

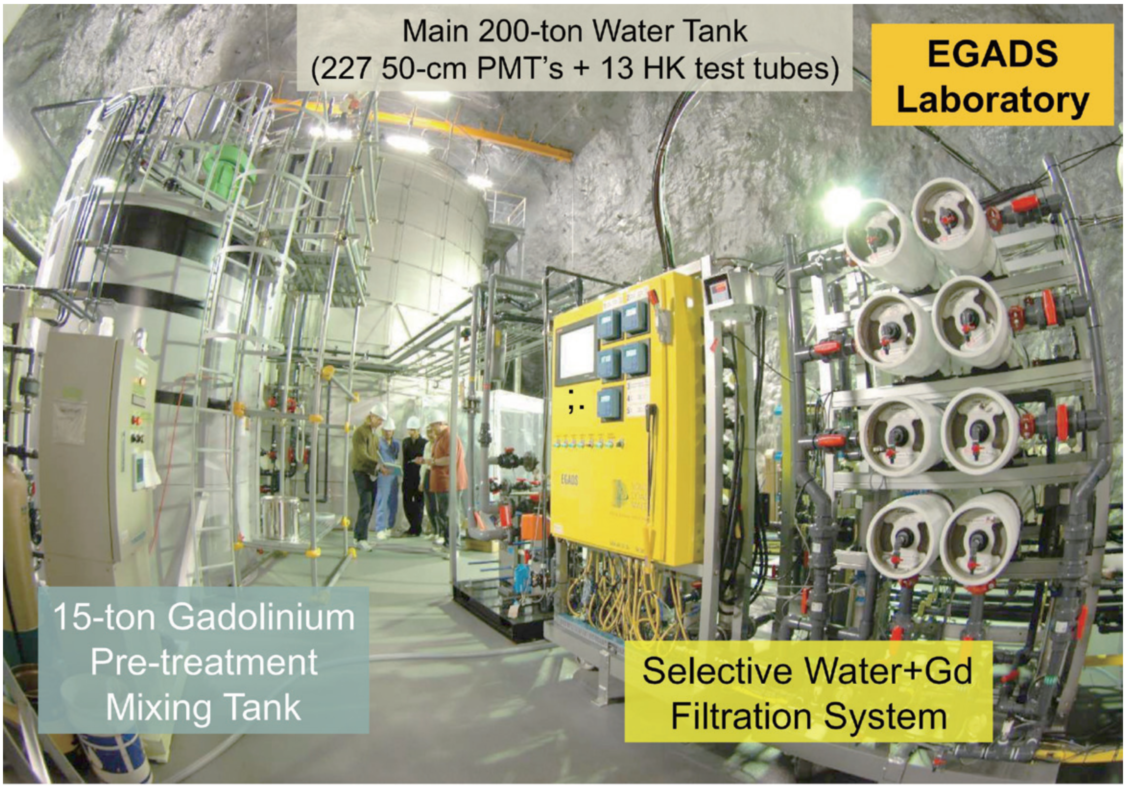


Figure 1: EGADS, the large-scale gadolinium test facility in the Kamioka mine.

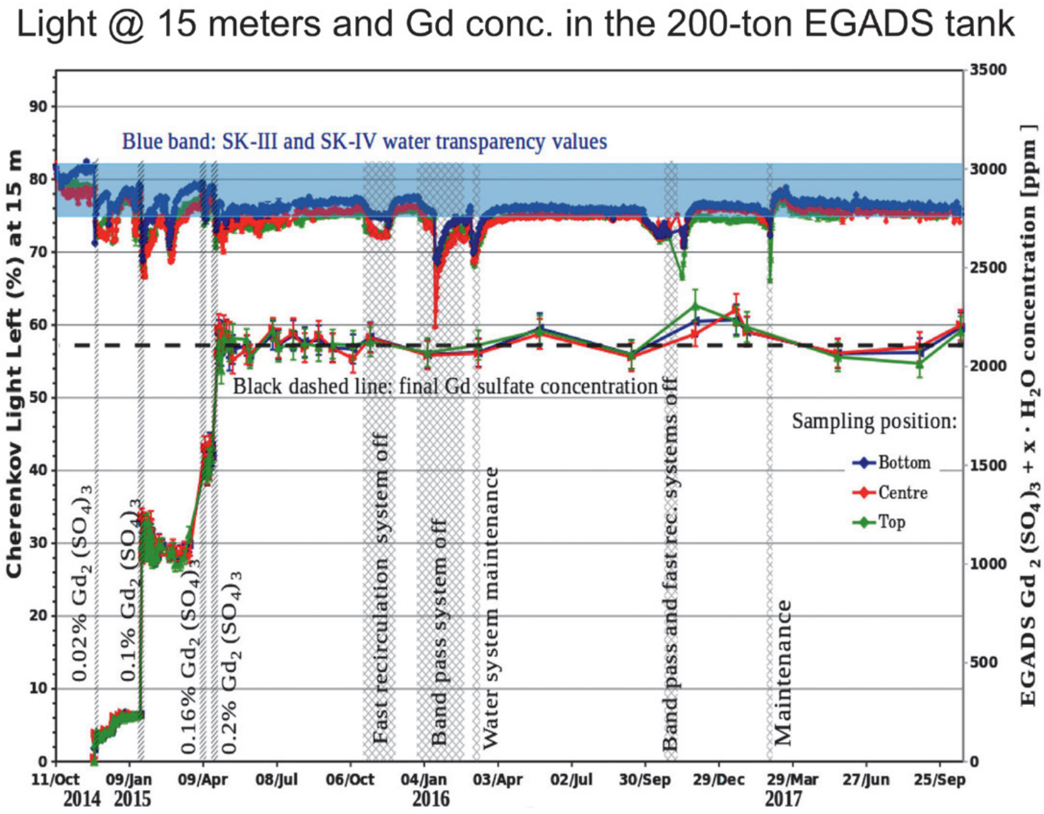


Figure 2: Primary EGADS results.

will benefit from reduced spallation backgrounds.

While the physics potential of the GADZOOKS! concept was readily apparent, there were technical issues to address if it were to become a reality. Naturally, the compatibility of gadolinium with detector materials needed to be demonstrated, but the primary challenge was that in detectors such as Super-Kamiokande the long mean free path of light (~100 meters) is maintained by constant recirculation of the water through a water purification system. The existing SK purification system would rapidly eliminate any added gadolinium along with all of the unwanted contaminants that are removed to maintain optical clarity.

To solve this crucial problem, I developed a fundamentally new type of filtration system: my "Molecular Band-pass Filter" was designed to selectively extract $Gd_2(SO_4)_3$ from the water and return it to the tank, while simultaneously allowing all other impurities to be removed.

Starting in September of 2009 a new experimental chamber was excavated in the Kamioka mine, located close to Super-Kamiokande. There, a dedicated, large-scale gadolinium test facility and water Cherenkov detector (essentially a 200-ton scale model of Super-K, along with a few prototype Hyper-K phototubes) was built [3] as depicted in Figure 1. Known as EGADS (Evaluating Gadolinium's Action on Detector Systems), it was designed to make absolutely sure that the introduction of Gd would not interact adversely with the detector materials and to certify the viability of the Gd-loading technique on a large scale, closely matched to the final Super-K requirements. Those studies have now been completed.

Figure 2 shows the main EGADS results: water transparency – characterized as the light remaining after 15 meters of travel through the water, the average distance traversed by light in Super-K – and the amount of gadolinium sulfate in the 200-ton tank are plotted as a function of time. They are both measured at three points in the tank: the bottom, the middle, and the top. Transparency (percentage of light remaining, left hand scale) is indicated by the upper set of three lines, and concentration (parts per million, right hand scale) by the lower set of lines. The transparency range of the ultrapure water in Super-K, the most transparent large volume of water ever made, is shown as a blue band near the top of the figure.

Once full Gd-loading was achieved in April of 2015, the key EGADS findings were:

1) Whenever the Gd-capable water systems were allowed to operate normally (i.e., excluding the gray hashed areas), the transparency of the Gd-loaded water became comparable to that of SK's ultrapure water.

and

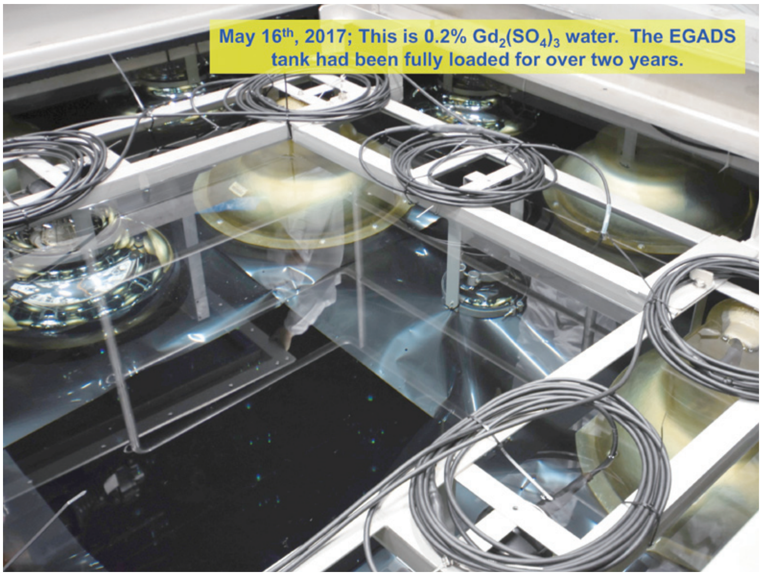
2) During 650 passes of the entire water volume through the Gd-capable water filtration systems there were no detectable losses of gadolinium sulfate whatsoever.

With these results in hand it was time to open the tank and look inside. Figure 3 shows us getting ready to open the big square hatch on the top of the 200-ton EGADS tank. Figure 4 is a view through this hatch at the Gd-loaded water inside, and Figure 5 is an image taken in the bottom wall region looking up the side of the drained tank. Everything was shiny and beautiful: there were no changes after years of exposure to the 0.2% $Gd_2(SO_4)_3$.

The EGADS findings were sufficient for us to receive official approval from both the Super-Kamiokande and T2K Collaborations to move forward with plans to load gadolinium into Super-K.

Meanwhile, with its R&D role finished, EGADS has had its data acquisition hardware and online computing power significantly upgraded and now lives on as the world's most advanced water-based supernova neutrino detector. Refilled and building upon the confidence provided by Gd neutron tagging of IBD events, its ambitious goal is to make a fully automated, standalone announcement of a galactic supernova explosion within one second of the first neutrino's arrival in the detector [4]. This reborn EGADS is now associated with a Japanese network of optical, X-ray, gamma-ray, infrared, and gravitational wave observatories, for true multimessenger astronomy. Even the EGADS acronym has been repurposed: Employing Gadolinium to Autonomously Detect Supernovas.

Figure 3: Getting ready to open the EGADS tank.



May 16th, 2017; This is 0.2% $Gd_2(SO_4)_3$ water. The EGADS tank had been fully loaded for over two years.

Figure 4: Looking down into the full EGADS tank following two years of exposure to Gd.

November 6th, 2017; This view is directed up the side wall from the bottom of the 200-ton tank. Looks great after 2.5 years of exposure to 0.2% $Gd_2(SO_4)_3$ water!

Figure 5: Looking up the side wall of the empty EGADS tank after 2.5 years of soaking in Gd.

References

[1] J. F. Beacom and M. R. Vagins, "GADZOOKS! Antineutrino spectroscopy with large water Cherenkov detectors," *Phys. Rev. Lett.* **93**, 171101 (2004) [hep-ph/0309300].

[2] M. R. Vagins, "Kavli IPMU's Neutrino Forecast: Mostly Sunny, with a Good Chance of Supernovas," *Kavli IPMU News*, No. 19, September 2012, pages 4-9.

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[4] S. M. Adams, C. S. Kochanek, J. F. Beacom, M. R. Vagins, K. Z. Stanek, "Observing the Next Galactic Supernova," *Astrophys.J.* **778** (2013) 164 [arXiv:1306.0559 [astro-ph.HE]].