

# Gadolinium-loading in Water Cherenkov Detectors

Mark R. Vagins

Kavli Institute for the Physics and Mathematics of the Universe (WPI), The University of Tokyo Institutes of Advanced Study, University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba, 277-8583, JAPAN

E-mail: [mark.vagins@ipmu.jp](mailto:mark.vagins@ipmu.jp)

**Abstract.** Water Cherenkov detectors have been used for many years to study neutrino interactions and search for nucleon decays. Super-Kamiokande [Super-K, SK], at 50 kilotonnes the largest such underground detector in the world, has itself enjoyed close to two decades of interesting and important physics results. Looking to the future, for the last thirteen years extensive R&D on a potential upgrade to the detector known as GADZOOKS! has been underway and is now nearly complete; the project was formally approved in June of 2015. The progress being made towards enriching Super-K with 100,000 kilograms of a water-soluble gadolinium [Gd] compound – thereby enabling it to detect thermal neutrons arising from inverse beta decay, making it the world’s largest antineutrino detector – will be discussed.

## 1. Dream a Little Dream

More than a decade ago, theorist John Beacom and I first proposed [1] introducing a water-soluble gadolinium [Gd] compound, gadolinium chloride,  $\text{GdCl}_3$ , or the less reactive though also somewhat less soluble gadolinium sulfate,  $\text{Gd}_2(\text{SO}_4)_3$ , into the Super-Kamiokande detector. As neutron capture on gadolinium produces an 8.0 MeV gamma cascade, the inverse beta decay reaction,

$$\bar{\nu}_e + p \rightarrow e^+ + n \quad (1)$$

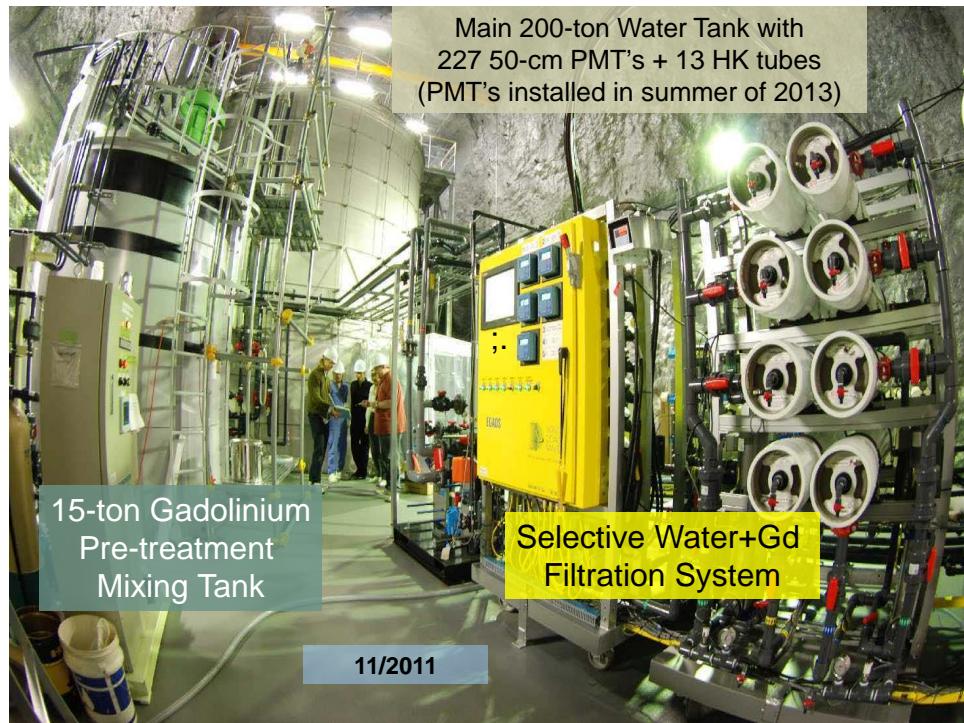
in such a Gd-enriched Super-K will yield coincident positron and neutron capture signals. This would allow a large reduction in backgrounds and greatly enhance the detector’s response to both supernova neutrinos (galactic and relic) and reactor antineutrinos. After dissolving 100 tons of gadolinium compound we would have 0.1% Gd by mass in the SK tank, and just over 90% of the inverse beta neutrons would be visibly caught by the gadolinium, with the remaining 10% being captured near-invisibly on hydrogen nuclei in the water. In effect, adding gadolinium to Super-K could turn it into the world’s largest antineutrino detector, with the antineutrinos individually tagged by neutron captures. We proposed calling this new project “GADZOOKS!” In addition to being an exclamation of surprise, here’s what it stood for:

Gadolinium Antineutrino Detector Zealously Qutperforming Old Kamiokande, Super!

This dream caught the attention of the community, in addition to that of the Super-Kamiokande Collaboration itself: our *Physical Review Letters* article has averaged one citation every sixteen days for the last twelve years... not too shabby for a proposed upgrade.



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**Figure 1.** The EGADS experimental hall in the Kamioka mine.

## 2. Working In the Coal Zinc Mine

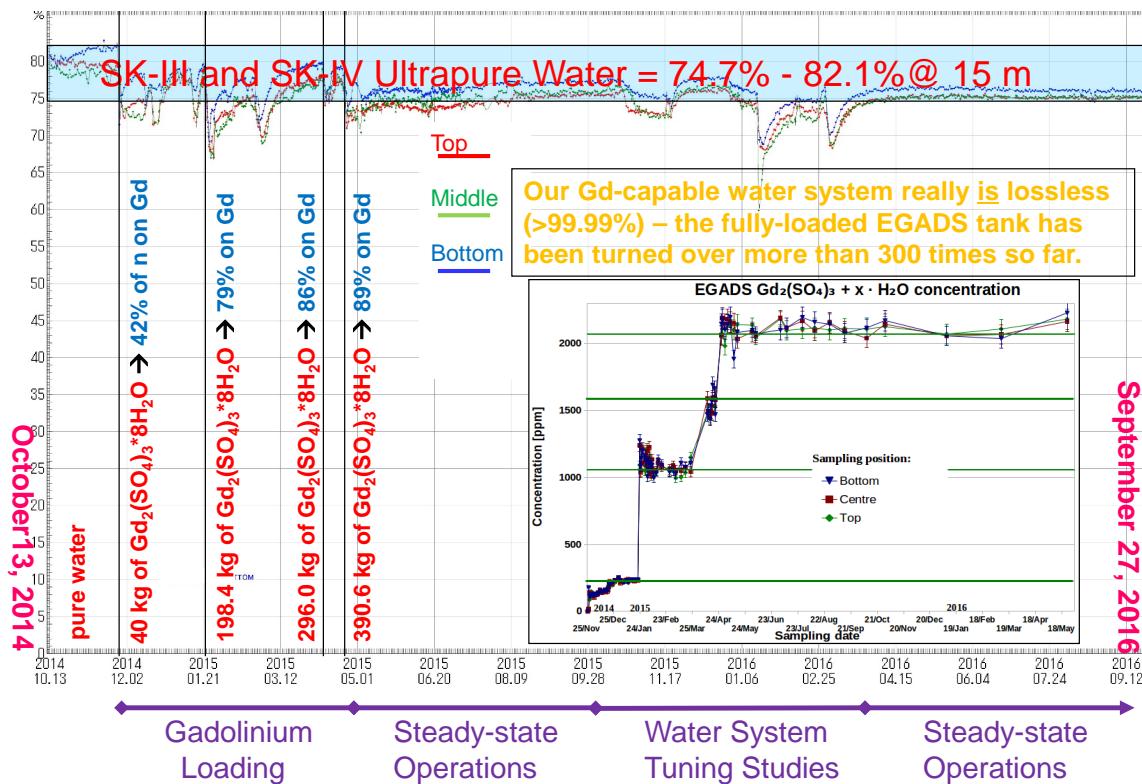
But John and I didn't want to merely dream about a magnificent new future for Super-K; we wanted to make it a reality. To accomplish this, many studies were required, including:

- compatibility of gadolinium compounds with SK detector materials
- how to load gadolinium into the water
- clarity of the resulting Gd-loaded water
- how to clean and recirculate Gd-loaded water without removing Gd
- radio-purity of gadolinium powder
- how to remove the gadolinium if/when required
- impact on existing physics program
- benefits for existing physics programs and newly enabled physics programs

Indeed, over the course of the last ten years the equivalent of over ten million US dollars have been spent in Japan and the US investigating these and other issues. The ultimate series of tests – to make absolutely sure that the introduction of Gd would not adversely interact with the detector materials and to certify the viability of the Gd-loading technique on a large scale – necessitated the creation of a brand-new experimental hall in the Kamioka mine. There we built a 200-ton scale model of SK, complete with its own custom-designed water filtration and measuring systems, as depicted in Figure 1, and containing 240 SK-like PMTs read out by SK-style electronics. This facility is known as EGADS (Evaluating Gadolinium's Action on Detector Systems),

Construction began in September of 2009, and within nine months we had gone from solid rock to an excavated hall with a total volume of about 2.5 kilotons ready for physics occupancy,

## Light @ 15 meters in the 200-ton EGADS tank



**Figure 2.** Water transparency and gadolinium sulfate concentration in the 200-ton EGADS detector over the past two years; fifteen meters is the characteristic light travel distance in Super-K. Inset plot shows the concentration of  $\text{Gd}_2(\text{SO}_4)_3$  at each loading step as measured by an atomic absorption spectrometer. Line colors indicate water sampling positions in the tank.

complete with a 200-ton stainless steel tank. The various water systems were ready in 2011, and all the PMTs and DAQ systems were in place by 2013. After running with pure water for a while to establish a baseline, in November of 2014 we started loading  $\text{Gd}_2(\text{SO}_4)_3$  into the detector. By April 2015 we had achieved full (0.2%) Gd-loading, and the detector has operated filled with this same batch of gadolinium for about two years now.

As can be seen in Figure 2, during steady-state operations, i.e., excluding periods of water system tuning and testing, the transparency of the Gd-loaded water is within the historical range of SK ultrapure water (the blue band). What's more, no gadolinium has been lost after more than 300 complete cycles of the entire water volume through the selective filtration system. Using a brand new technology called “molecular band-pass filtration” (coincidentally invented by the author a decade ago during a coffee break at the AAP2006 meeting), this water system was designed to retain  $\text{Gd}_2(\text{SO}_4)_3$  but remove everything else from the water. Thanks to EGADS we now have the vital proof that it works as expected, and that loading Gd into SK will not destroy the water transparency.

### 3. How You Like Me Now?

Based primarily on these impressive EGADS results, as well as the positive outcomes of many other studies and the wide range of new physics made possible by Gd loading, in June of 2015 the Super-K Collaboration formally approved the proposed upgrade. The official statement was as follows:

On June 27, 2015, the Super-Kamiokande Collaboration approved the SuperK-Gd project which will enhance antineutrino detectability by dissolving gadolinium in the Super-K water.

The actual schedule of the project including refurbishment of the tank and Gd-loading time will be determined soon taking into account the T2K schedule.

Then, in January of 2016, the T2K Collaboration issued the following official statement:

On June 27, 2015, the Super-Kamiokande Collaboration approved the SK-Gd project which will enhance neutrino detectability by dissolving gadolinium in the Super-K water.

T2K and SK will jointly develop a protocol to make the decision about when to trigger the SK-Gd project, taking into account the needs of both experiments, including preparation for the refurbishment of the SK tank and readiness of the SK-Gd project, and the T2K schedule including the J-PARC MR power upgrade. Given the currently anticipated schedules, the expected time of the refurbishment is 2018.

### 4. In the Hall of the Mountain King

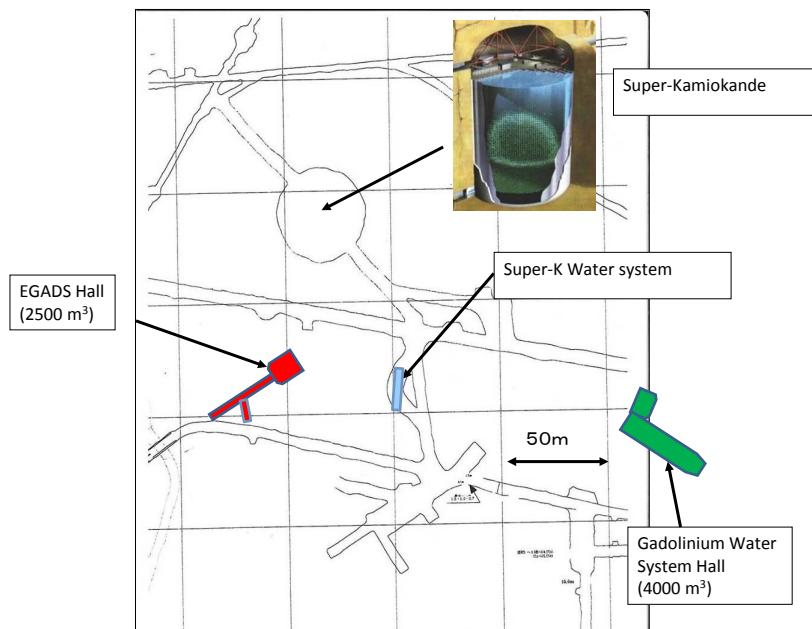
While negotiations on the precise timing are still under way with various interested parties, it now looks very likely that the start of the project will be in mid-2018. In the meantime, preparatory work in the Kamioka mine has already begun.

Since Super-K's existing water system would immediately remove any added  $\text{Gd}_2(\text{SO}_4)_3$ , before we introduce gadolinium we will need to scale up the special selective water systems which keep the EGADS detector with its Gd-enriched water running smoothly and stably. As SK is 250 times the volume of EGADS's 200-ton detector, these new, Gd-capable water systems are going to need a large new underground space. Figure 3 shows the relative locations and sizes of the EGADS hall, Super-K, its present water system, and the new gadolinium water system hall known as "Hall G".

As depicted in Figure 4, Hall G was excavated in 2015 and was ready for occupancy in mid-2016. It is currently being filled with the necessary equipment as we gear up for the upgrade. Adding gadolinium to Super-Kamiokande is no longer just a dream: we are on track for 2018!

### Reference

[1] Beacom, J.F., & Vagins, M.R. 2004, *Phys. Rev. Lett.* **93**, 171101 (*Preprint* hep-ph/0309300)



**Figure 3.** A plan view of the Kamioka mine near Super-Kamiokande.



**Figure 4.** The newly-excavated Hall G. It will house the new water systems required to load Super-K with gadolinium and maintain its water transparency.