National Aeronautics and Space Administration

SYSTEM FAILURE CASE STUDIES

MAY 2010 VOLUME 4 ISSUE 5

Head-On Collision

The Large Hadron Collider (LHC) located in Geneva, Switzerland is a particle accelerator made up of a 17-mile ring of electromagnets. After sixteen years and billions of dollars of development, the LHC suffered a serious failure stemming from a simple engineering error during final testing. On March 27, 2007, structural supports in one of the magnets burst during a crucial pressure test. Repairs to the support structures required over six months of additional work, delaying the original project start date and incurring millions of dollars in additional cost.

BACKGROUND

What is the LHC?

The large Hadron Collider (LHC) is the world's most powerful particle accelerator. Approved for construction in 1995 in an international collaborative effort managed by the European Organization for Nuclear Research (CERN), over $10 billion went into LHC design and construction. The ring consists of 9,300 superconducting electromagnets laid end to end. The electromagnets weigh 35 tons each, and are built from coils of special cable that become electrical superconductors when cooled to almost Absolute Zero, around -455° F. Superconductivity has allowed particle acceleration to 99.9999991% of the speed of light to date with manageable power requirements.

The accelerator fires two beams of high-energy particles, called hadrons, in opposite directions. The term "hadron" for LHC use refers to composite subatomic particles made up of protons or lead ions. Traveling near the speed of light, the hadrons gain energy with each lap around the ring until guided into collision with each other, up to 30 million times per second. Scientists believe these collisions mimic the conditions immediately following the Big Bang, and new data from high-energy LHC experiments will likely advance our understanding of physics.

At four points along the 17-mile ring are large electromagnetic detectors, one of which is seen in Figure 1. Built to measure the different particles and analyze how they behave, these detectors collect, store, and process the vast amount of data produced by the colliding particles. The detectors themselves range in size and weight, from seven thousand to twelve thousand tons. (For reference, the Eiffel Tower weighs seven thousand tons.)

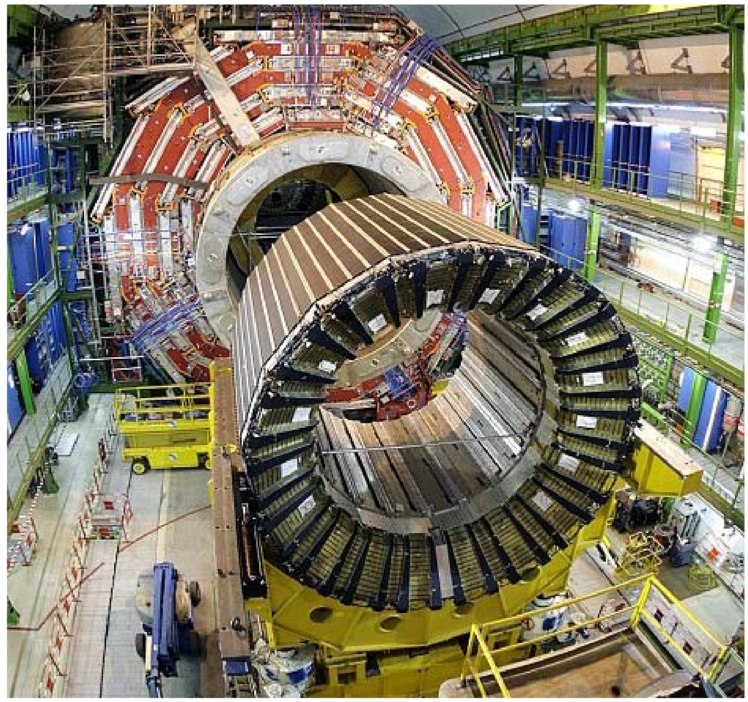

Figure 1: One of the four immense electromagnetic detectors pictured during LHC construction.

WHAT HAPPENED?

On March 27, 2007, scientists put the LHC through the final stages of pressure testing. During one of the stress tests, as the magnet moved longitudinally within its outer jacket cryostat vessel (Figure 3), a support structure holding the cold mass inside this outer jacket tore loose. The structure collapse lifted the 35-ton magnet from its base. Helium gas began leaking into the underground tunnel, severely damaging the LHC components.

Components failed during crucial tests in final stages of LHC development.

Proximate Cause:

- Poor procedures led to magnets' structural support collapsing during final testing stages.

Underlying Issues:

- Failure to Follow Processes
- Failure to Follow Best Practices
- Flaws in General Procedures

Figure 2: The LHC is located under the French-Swiss border, with its central operating offices above ground at CERN in Geneva, Switzerland.

Because the team followed proper procedures during tests, no one was hurt as the magnet structure collapsed. Engineers from Fermilab, the company that manufactured the magnets, shut down the system to evaluate why it failed. Subsequent tests showed that a simple engineering miscalculation caused the failure. During normal operations, longitudinal movement of the magnets is to be expected due to the intense forces they withstand from accelerating particles. However, the Fermilab team failed to account for this movement, and created an insufficient support structure that could not withstand this pressure.

Analysis showed that the Fermilab team only tested the magnets individually during system development, and failed to account for the real operating conditions in which the magnets would function when laid end-to-end. In other words, the design process did not account for the fact that the force on the magnets could be stronger in one direction than the other.

Though the LHC was set to start in 2006 and the team was already behind schedule, Fermilab needed time to rebuild, test, and implement the structural fixes across the entire system. This added six months to the project completion process and drew negative press for the LHC.

Proximate Cause

During the final testing stages of the Large Hadron Collider, the structural systems inside the electromagnets experienced a serious malfunction during a run-through of normal operations. Within the outer cryostat vacuum vessel, the support structure holding the magnet cold mass in place collapsed as the magnets moved longitudinally. This collapse ruptured the cold mass vessel and caused large amounts of helium gas to escape into the LHC tunnel.

Underlying Issues

Failure to Follow Processes

One of the biggest procedure flaws was Fermilab's lack of a standard design process, which resulted in different engineers using differing approaches during development. Documentation of design efforts also varied by individuals, and engineers kept notes and ledgers according to preference. On a summary level, there was also no central design documentation to serve as a central reference. This fragmentation allowed both widely differing methods and varying assumptions to proceed. Without a central procedure, these varying assumptions – one of which included forces exerted on the structural systems – went through to the final testing phases without review or question.

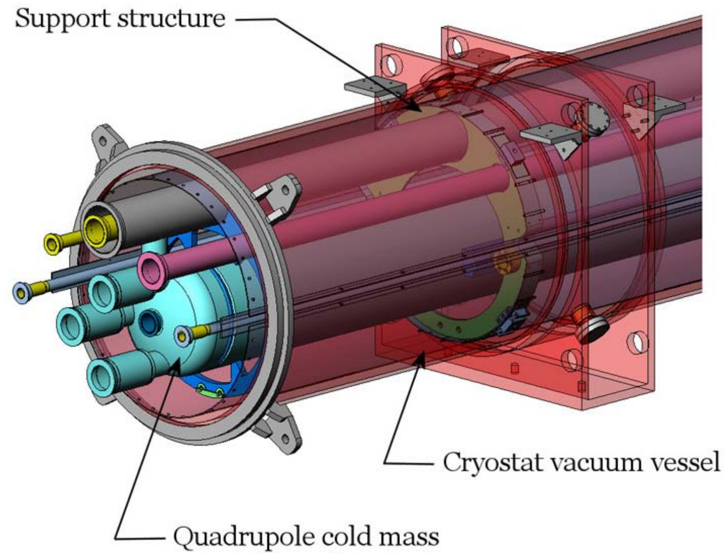

Figure 3: The components of a magnet include the inner quadrupole cold mass holding the liquid helium, the outer cryostat jacket, and the support structure in green.

Per industry standards, Fermilab had a Quality Assurance Manual, which held design tasks, reviews, and interface requirements. However, the procedures in this document were not mandatory for the design phase. Design engineers were aware of the QA Manual's existence, but the wide belief was that it applied only to the fabrication stage, not to design. In reality, the QA manual held valuable information on cross-checking design basis calculations and integration, which, if followed, may have prevented the subsequent failure.

Failure to Follow Best Practices

In addition to the procedural flaws, Fermilab's best practices were also lacking along the way. First, Fermilab's training programs were unfocused, encompassing broad topics such as General Employee Training, Safety, and Orientation. Training did not provide information on proper design procedures, standards, or techniques such as team-based reviews or project controls within the design process.

Project managers at Fermilab also received inadequate training for their roles. Instead of certified project managers coming from a focused project management background, PMs were usually personnel who had developed a new concept or pushed for new experiments and initiatives. As a result, these project managers performed double duty; leading LHC project component development while also focusing on their own areas of expertise and research. Here we see a failure to adhere to stringent project management procedures, as project managers provided general guidance and direction but typically did not oversee day-to-day operations.

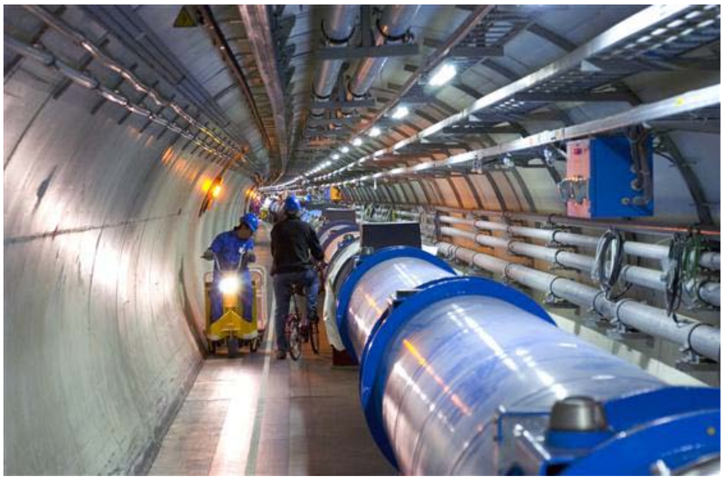

Figure 4: The LHC ring consists of 9,300 electromagnets laid end to end. To inspect the magnets, scientists move around the ring on carts, bicycles, and scooters.

Flaws in General Procedures

Finally, Fermilab's processes were defective from the start. Not only were the operational and performance specifications not defined until late into the design and even construction phases, these specifications were not finalized until late in the project life cycle. Even worse, the final specifications did not take the linear assembly and performance of the magnets into account. Because of the late finalization, the specifications were not prepared in time for independent reviews, allowing design flaws such as this one to go unnoticed.

In addition to the incomplete specifications, Fermilab's independent review processes were also poorly conducted. The process was not well documented, and the reviews did not cover as much ground as they should have, restricting themselves to vague and broad topics. Furthermore, Fermilab does not require that design basis calculations be reviewed during the research and development process. In the few cases where reviews were performed, they were conducted based on the judgment of individual scientists and engineers instead of relying on a system-wide set of qualifications.

Finally, the programmed independent reviews that were required had been planned and carried out with a focus on critical components, paying very little attention to system assembly. These reviews were also usually PowerPoint presentations addressing broad issues in design or performance. By failing to address the specific assumptions, specification validation, or detailed design basis reviews, these review processes failed to catch smaller issues like the calculation error that ultimately resulted in the malfunction.

Aftermath

After the structural failure, Fermilab faced strong scrutiny from the scientific world. Because the LHC was a high-profile project and because of the immense resources pouring into it, Fermilab's simple error was seen in an especially poor light. The LHC was already over budget and behind schedule.

The team poured efforts into analyzing what went wrong and rushed to repair all the structural points that were affected. Fermilab was ultimately able to develop new components and fix the structural problems by September 2007, six months after the magnets failed the stress tests.

The LHC has unfortunately faced several other obstacles in development. An electrical failure in 2008 shut the project down for another two years, and resulted in the weakening of the magnets and cutting their maximum operating power in half.

However, on March 30, 2010, scientists at the LHC celebrated the first successful particle collision experiment in the LHC for the first time. This momentous occasion for the CERN team marks the first data point in their quest for answers to physics' most baffling questions, opening the doors to the mechanics of the universe.

For Future NASA Missions

As other facilities develop the ability to produce, build on, and improve on revolutionizing machines like the LHC, Fermilab may lose its status as the best operator of the most powerful particle accelerator in the world. As the most senior members of the team approach retirement, Fermilab risks losing the knowledge and experience of those senior members, experience which includes the valuable lessons they've learned from malfunctions such as this one. This simple failure, along with the changing landscape in which these projects operate, highlights the importance of thorough processes and procedures not only at Fermilab, but also in knowledge-crucial industries and organizations like NASA.

Public trust and funding of large, high-energy projects demands true systems engineering and attention to quality from the design stage forward. Components may be well-conceived and constructed individually, yet behave after assembly and integration in unanticipated ways. Simulation and testing must account for the whole system operating across and even beyond its design envelope. Diligence to sift through the manuals and handbooks pays off in the confidence to choose the simulations and tests necessary to qualify a system to function in its intended mode for its intended lifespan. Building on the resulting success becomes impossible without the use of a reliable knowledge capture method.

Though the importance of sharing engineering knowledge across groups goes without saying, engineering knowledge is a valuable asset to every organization on a more subtle level. Though not immediately obvious, knowledge is also worth preserving because it drives present as well as future growth, and it keeps the organization alive. As environments change and projects become bigger, better, or faster, an organization's ability to apply its knowledge and keep up with the current pace is essential to its success. On both micro and macro levels, systematic capture and review processes hold a great deal of significance beyond day-to-day operations. The vitality of organizations like CERN, Fermilab, and NASA lay largely in the knowledge of its people and their ability to pass that knowledge forward.

Figure 5: A replacement magnet is lowered into the LHC tunnel during a repair process.

References:

European Center for Nuclear Research. Retrieved from http://public.web.cern.ch/public/en/lhc/lhc-en.html.

Fermilab Today. http://www.fnal.gov/pub/today/.

"Large Hadron Collider Ready to Restart." November 2009. Retrieved from http://www.boston.com/bigpicture/2009/11/large_hadron_collider_ready_to.html

Minkel, J.R. "Particle Collider Magnet Failure Blamed on Faulty Engineering." Scientific American. April 2007.

Overbye, Dennis. "A Giant's Take on Physics' Biggest Questions." New York Times. May 2007. Retrieved from http://tinyurl.com/nytimesLHC11

Questions for Discussion

- What steps do you take to ensure consistent and complete development and testing procedures?
- What knowledge and information capture methods could your organization build on?
- How does your organization facilitate communication to address problems across different groups?
- What are the best practices your organization follows for project management and quality assurance?

Overbye, Dennis. "Large Hadron Collider Finally Smashing Properly." New York Times. March 2010. Retrieved from http://www.nytimes.com/2010/03/31/science/31collider.html?ref=science

Photo retrieved from http://www.vanityfair.com/images/culture/2010/01/hadron-collider-1001-05.jpg

Root Cause Analylsis: Large Hadron Collider Magnet System Failure. Fermilab. September 2007.

SYSTEM FAILURE CASE STUDIES

NASA SAFETY CENTER

Executive Editor: Steve Lilley steve.k.lilley@nasa.gov
Developed by: ARES Corporation