Some NuMI experience relevant to DUSEL

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- Disclaimer: am pretty free with opinions rather than hard facts in parts of this. Thus it is submitted as an “internal” document. It is written before any serious design (at least on my part) of a beam from FNAL to DUSEL.

- *Should you listen to a man dumb enough to have a ladder fall out from under him? Well, maybe you should use him as an object lesson of what not to do.*

Outline

- Comment on level of risk
- What were the worst problems for NuMI ?
- What went right for NuMI?
- How does DUSEL differ from NuMI?

Note: Will not discuss anything upstream of the target

Comment on level of risk and beam-line design

- NuMI was a lower priority project at lab –-- CDF and D0 were the big guys. So it is a major difference that DUSEL is talked about as being the flagship experiment for the lab in 2020.
- Another major difference is that (I believe) DUSEL will be much more expensive than NuMI, so will be under greater scrutiny.
- The beam-line will also be more demanding than NuMI because of the higher beam-power.

- To me, this implies <u>DUSEL must be a beam-line designed with less risk.</u> Hence we have to have greater concern when installing things we can't repair.

- We likely also want a beam-line with less down-time than NuMI.   Hence <u>we need higher reliability, should plan for faster component change-out, and we should push hard to have spares from the beginning</u>.

- To summarize, we cannot cut as many corners.

Comment on level of risk and beam-line design *(cont.)*

As an example of risk-management, let's discuss the target.

For NuMI, we managed to get through the 1998 baseline review by saying we believed we would be able to design a low-energy target, even though the engineering design was not yet in hand. The target prototype testing at AP0 was only able to demonstrate that there was no significant radiation damage for an equivalent of a few weeks of NuMI running; we used low-energy neutron data to argue it was plausible that a NuMI target should last for at least the one year design specification. I doubt that this level of uncertainty will be acceptable when people get serious about base-lining DUSEL.

<u>We need to do R&D early to prove critical concepts like the target will work.</u> For the target, this could be demonstrating that a target will last a reasonable amount of time, or it could be showing a system that could swap a fairly low-cost target out say once-per-month. (The experience with the NuMI target could be used to support at least a one-month lifetime for a graphite target).

Comment on level of risk and beam-line design *(cont.)*

Some systems at NuMI that are risky in that they have the possibility of not being repairable are

- the decay pipe window,
- the decay pipe wall,
- the decay pipe cooling,
- the absorber cooling
- the water under-drain system beneath the target hall and decay pipe (critical to prevent tritium reaching groundwater).

The complication in most cases is residual radiation. There are possible patches for some failure modes of these systems, but repair/replacement options were not built into the designs for these systems. For example, Sam Childress urged strongly that the decay-pipe have a port where a robot could be inserted to repair any holes that developed in the decay pipe, but this was not implemented. I asked that there be a small pipe connected to the upstream end of the decay pipe, in case we ever had to run with helium instead of vacuum. This was also not implemented. We also made no provision for repair/replacement of the decay pipe window.

<u>DUSEL design must pay close attention to reparability.</u>

What were the three worst problems for NuMI? #1

Tritium. This could have been a show-stopper.

- Although the event that made this a crisis was a surface pond leak, it is also true that the tritium production of NuMI was mis-estimated. Design calculations for the target hall only addressed the tritium produced in the air, not considering that tritium produced in the steel could evaporate to the air. (A first mitigation step was to collect the condensate from the air cooling coil). Further, it was not thought of that tritium from the air would condense to the water drains as air went down the decay-pipe passageway (which air path is needed to provide transit time for short-lived radio-isotopes to decay) before air was exhausted up to the surface. (A second mitigation step was to dehumidify the air before it enters the decay-pipe-passageway).

- The tritium issue is especially worrisome because being below regulatory limits may not be enough to save a project from cancellation-due-to-adverse-public-reaction. (The tritium levels in ponds from NuMI were never very high).

- <u>An obvious lesson-learned is that tritium in target pile shielding and decay pipe shielding must be considered during design.</u>

- <u>Another point is that public relations is critical.</u> (Recall the neutrinos-killed-the-dinosaurs flap and radio programs in Wisconsin wondering about the effect of neutrinos on cows. DUSEL will be sending neutrinos to several new states).

- A deeper question is, how does one protect oneself from issues that one does not know will be issues – the unknown-unknowns?

What were the three worst problems for NuMI? #2

Decay-pipe window as a safety hazard became a very serious issue when corrosion was seen on the decay-pipe window.

- This caused us to switch to helium from vacuum in the decay pipe, and is a lot more work and balancing act than one might imagine; there are several sub-issues involved still being worked on. It entangles very large amounts of dangerous stored-energy (even with helium), ODH, radiation safety, and physics issues for the experiment, complicated by changes in atmospheric pressure and internal heating, beam induced stress on the window, and corrosion by unique environmental conditions. It affects our ability to access the target hall.

- This could have been a show-stopper; it still has the potential to be a very serious operational problem.

- A lesson-learned is that a critical component like the decay-pipe window should be repairable/replaceable.

- Another lesson is that we need to do more upfront R&D on materials in the extreme target-pile environment. As a first step, we should be figuring out what the target-pile air environment is – how much ozone, how much nitric acid, etc. Also, we need to understand how radiation ionization interplays with this in terms of doing damage.

- Likely want a decay-pipe window shutter for DUSEL, to disconnect target hall access from state-of-the-decay-pipe.

What were the three worst problems for NuMI? #3

Lack of early spare target and horn.

- Spares were de-scoped from the original project to save money. (But we did not have the manpower to build the spares anyway. Spares are still a major headache three years into operation).

- We could have used both a spare target and spare horn in the first six months of operation – instead we were scrambling to repair radio-activated components that were not designed for repair, and were lucky that we succeeded.

- We built a horn system that is very efficient at producing neutrinos, and lasts a long time. I sometimes think we should have re-optimized to something that was fast to build.

- For DUSEL, target and first horn should be more optimized for short construction time and fast replacement.

What were other significant problems for NuMI?

Drainage under target pile blocked up after a couple years of operation

- Water then flooded pre-target floor and penetrated target pile upstream block wall, causing high humidity and increased tritium-to-MINOS-sump.
- Have bypassed the drainage system for pre-target water (i.e. we pump water from pre-target past the target hall, into the decay pipe drainage).
- If we did not have the low-humidity outside-the-pile-steel air cooling system, we would have to explain how we were keeping tritium from reaching groundwater with drainage system in an unknown state. In a water-cooled target pile system, could have been a show-stopper.
- <u>The drainage system (civil construction) must be maintainable as it is not just water drainage, it is radiation mitigation.</u> This is similarly true for the decay pipe area – it is not entirely maintainable at NuMI. That must be done better for DUSEL than for NuMI.

What were other significant problems for NuMI?

Design flaw of electrical insulators on water lines to horns.

- A continuous metal water line on a horn would be an electrical short-to-ground. A ceramic insulator is used to provide a break in the water line, as other insulators will not withstand the radiation. Because a metal-to-ceramic transition is tricky, NuMI initially used a commercially available off-the-shelf transition piece.
- The Kovar metal portion of the transition piece was rather thin, and failed repeatedly in NuMI operation.
- Two pieces were autopsied. In one case, erosion of the Kovar apparently led to cracking. The other case was a pin-hole leak, perhaps because of a local defect.
- An FNAL-designed transition piece with much thicker metal is now being used, but it took several extended down-times to replace all the old-style transition pieces.

What were other significant problems for NuMI?

De-scoping of hadron monitor replacement capability.

- We are planning to replace the hadron monitor next April, as it is a rather critical piece of monitoring equipment that is failing (and was expected to fail with radiation damage).
- The replacement is very difficult, because it is in a high radiation area with constricted access, and provisions/planning for replacement were removed from the NuMI project to save a rather small amount of money.

Transition from early off-site engineering to internal engineering, causing a lot of work to be done twice. This cost both money and time.

What were other significant problems for NuMI?

Water leak early in operation of first target

- Have several suspects but still don't know cause. (Plan to autopsy the first target sometime in coming year).
- Second target has not leaked, although it has been operated at much higher power and for much longer.
- At this point, only lesson-learned that I can draw is to have spares.

De-scoping of space for crane in absorber hall.

- (For non-aficionados, the non-PC name for the absorber is beam-dump).
- Saved money in the "value engineering" exercise, but probably cost us money instead.
- It made installation of the absorber difficult, and causes headaches with trying to replace the hadron monitor and with any future attempt to repair the absorber.

What were other significant problems for NuMI?

Did not prototype horn ejector-pump system due to lack of resources, (another example of risk we knowingly ran).

- This caused pain during intstallation/commissioning; 1st set of water pumps that fed the ejector pumps were not large enough, and getting larger replacement pumps delayed testing horns in target hall by six months.
- The check-valves at the ejector pumps on the modules then failed in two weeks, and had to be replaced with an alternate design.
- Luckily, horns ran flawlessly in target pile, and ejector pump system did eventually work.

Chiller for target pile air-cooling-system.

- Did not have a hot spare because “screw compressors are very reliable” and chiller was rather expensive.
- Vendor produced a system that had design flaws and was a nightmare to diagnose and repair.
- Have now replaced the chiller with an entirely different system from a different vendor that is much more off-the-shelf, complete with hot-spare compressor.

What were other significant problems for NuMI?

A check-valve was mounted in a non-working orientation on the horn water skid, and allowed de-ionization bottle resin beads to get to the horn and clog all the spray nozzles.

- It took a month of creative efforts to clear the beads from the radio-activated horn, and could easily have kept us off-line for a year or more until a spare horn was ready.
- As a lessons-learned, we mounted filters on both supply and return to de-ionization bottles on all horn and target skids.
- The filters probably prevented a similar incident to the target this year, when a replacement D.I. bottle was connected backwards to the target skid.

A bolt holding a horn foot was not wired or pinned in final location.

- It depended on a tightened nut to hold it in place.
- When it vibrated off, there was a horn-to-ground short that took an access to fix.

What were other significant problems for NuMI?

Nickel flakes.

- Because stainless steel is very expensive in large quantities, radiation shielding around the strip-line to the horn was constructed with normal steel, and nickel coated for corrosion resistance.

- The nickel rapidly flaked off in the target-pile environment, falling on the strip-line and causing shorts to ground.

- This did not cause significant down-time because we managed in each case to use the horn power supply to burn flakes off without access. But the potential was there to cause significant down-time.

- This motivated modifications to the horn modules so that the entire module could be electrically isolated from ground, so that one could continue to run with a strip-line to module short.

- Future shielding blocks are being painted instead of nickel-coated. (Use of paint at DUSEL beam-power still needs to be studied). A stainless-steel liner surrounds the strip-line in the spare strip-line module penetrations.

What were other significant problems for NuMI?

Foam noodle air-seal of the target pile.

- Testing at MAB had indicated we could get a sufficient air-seal by stuffing foam noodles between concrete shielding blocks. (We limit air circulation from target pile to give short-lived radio-nuclides time to decay).
- In operation, have had to caulk the noodles in place after each access (and scrape off old caulk each time). It works, but we should spend the half-million or so $ next time to do a more user-friendly air-seal system. This is becoming an ALARA issue.

Use of high-strength steel.

- The production of nitric acid in the target hall air is thought to cause hydrogen embrittlement of high-strength steel, leading to cracks and failure. (Recall the Mini-Boone absorber problem).
- The under-module target motion drive system for NuMI failed a few months ago when a couple bolts snapped. Although we managed a fairly simple replacement of the bolts, the diagnosis and repair incurred a couple weeks down-time.
- High-strength washers were also used on the horn strip-lines, but this has not caused problems yet.

What were other significant problems for NuMI?

Alignment adjustment system.

- NuMI uses shafts through the modules to do alignment by moving relatively light carriers underneath 27-ton modules.
- Shafts were coated to provide corrosion resistance, but have corroded anyway, causing some headaches with motion.
- This could be avoided by either using stainless steel instead of coated materials or by creating alignment hardware in lower-radiation regions that would move the entire 27 ton module.

Moving parts are problematic in a high-radiation area.

- The target motion system, although very useful for MINOS beam studies, was a continuing operational headache.
- Avoid moving parts inside the pile if at all possible.

What were other significant problems for NuMI?

Water Leaks.

- Avoid water if possible. If use is required, try to design the system so one can keep running in spite of small leaks, or keep running when turning off less-critical parts of the system.
- For NuMI, we put the horn-hanger cooling on a separate circuit than the main horn cooling, and indeed throttled that down when a leak developed, saving the effort of a horn repair.
- Small leaks from the NuMI horns are intercepted by the stainless-steel chase liner, and the water is evaporated by our tritium-containment system; we have indeed used this capability to continue running with small leaks.

Electrical connections to high-radiation area instrumentation.

- The plugs on cabling to thermocouples corroded. (Plug pins cannot be made corrosion resistant, since they must match the material of the thermocouple; plugs are necessary to make remote connection to horn through shielding after installation in a hot area).

What went right for NuMI?

The beam-line worked.

- NuMI target pile and components have functioned at the design beam intensity of 4e13 POT/spill and spec'ed 3.7e20 integrated POT for horn and target.

- Most materials used functioned as specified (the main exceptions being high-strength steel, nickel coatings and dicronite coatings).

- NuMI took data on 70% of the days since 5/1/2005, which is consistent with up-time estimates made in early planning for the beam-line. The main factors that have put integrated POT lower than early estimates are that the Booster only delivered about 4.5e12 protons/batch instead of the predicted 8e12 protons/batch, and that the repetition time was held back to between 2.2 to 3.0 seconds instead of the design 1.87 seconds to improve pbar accumulation for the Tevatron. The horn system took more downtime than expected, but the primary beam magnets compensated by taking less downtime.

Many thousands of design decisions were therefore right, and did not get mentioned.

What went right for NuMI?

Collaboration with IHEP, Protvino.

- The beam group there had experience building and running a neutrino beam. Their experience and ability to do calculations for everything from neutrino yield to beam-heating of materials to stress and radiation resistance helped us tremendously, and was extremely cost effective.

- The openness of the K2K group in sharing their start-up problems also helped us avoid a few pit-falls.

- We need to continue to build relations with the CNGS and JPARC groups so that DUSEL will benefit from their upcoming experience. IHEP is a resource we would do well to continue to utilize.

What went right for NuMI?

Radiation calculations.

- Hot handling environment is within about a factor of two of predicted, so we are able to do the operations we planned.

- Air emissions and prompt radiation are within the envelope.

- Electronics positioned/shielded based on radiation predictions has survived.

What went right for NuMI?

Beam-based alignment scans checked survey for every critical component.

- Must retain this capability for DUSEL.

- Although insisted the systems be installed as a cross-check for experiment systematic-error reasons, re-alignment based on the scans proved necessary

  - Used hadron monitor for primary-beam-centered-on-decay-pipe-and-pointed-to-Soudan alignment.

  - Used hadron monitor and baffle temperature for baffle alignment.

  - Used hadron monitor and target budal monitor for target alignment.

  - Used cross-hairs and specially modified ionization-loss-monitors for horn alignment.

What went right for NuMI?

NuMI had very minimal subsidence; alignment did not wander.

- This was due to solid rock base + careful design of support structure and cooling.
- Since re-doing the beam-scan check on horn alignment requires removal of the target, it is not something one wants to do very often. Stability is a great operational advantage both for running and for diagnosing any deviations from normal running.

NuMI prototype testing of horn

- identified problems in cooling line connections and magnetic field monitor probes that were corrected for first real horn. Also allowed identification and correction of minor problems with horn power supply.

How does DUSEL scale / not-scale from NuMI?

Hot Repairs.

- The failed water line connections on the horns were repaired by using a dozen techs with 10 second radiation exposure each. With five times the beam power for DUSEL, we will NOT do a similar fix by using sixty techs for 2 seconds each.
- AD Mechanical Support is developing remote-arm hot-handling capability. Repairs using such systems take longer than the hands-on approach we have used. Engineering of the components is also much more involved in order to allow remote-arm repair.

Tolerances ??

- As a high-statistics disappearance experiment, component tolerances were tight for NuMI compared to other neutrino beams.
- Don’t know what tolerances will be for DUSEL physics; this needs to be studied early in the process as it will affect a lot of engineering design.

How does DUSEL differ from upgrading NuMI?

One of the most significant differences between the Project X study for upgrading NuMI to 2 MW for NOVA and the DUSEL 2 MW beam-line is that for the NOVA off-axis beam the target is upstream of the horn.

Initial studies of the DUSEL beam-line appear to require that the target be inside the first horn. This is potentially a much harder configuration.

For a target upstream of the horn

(i) there is room to use a water-spray cooling system for the target, for which there is a reasonable conceptual design

(ii) there is room for rapid change of target material if radiation-damage lifetime is a problem (for instance a gatling-gun target carrier like CNGS uses or a continuous vertical fin periodically moved by several mm to fresh material).

For the DUSEL beam, a combined-target-short-horn system may be the best option, but needs to be rapidly replaceable, and have a fairly short production cycle (unlike the NuMI horn).

Basic target pile configuration

Neutrino target piles come in a variety of basic configurations.

- NuMI is a top-loaded design, loosely based on AP0, with tightly packed shielding in a pit; components are lowered into place and then covered with shielding.
- WANF at CERN (which CNGS is loosely based on) was a relatively open area with overhead crane; components and shielding were designed to cool off (radiologically) quickly.
- The FNAL neutrino train carried components longitudinally along beam to desired locations, and then used hydraulics to off-load the components.
- Mini-Boone upstream-end-loads the single horn/target combo into the pile.

DUSEL is very likely to be a two-horn system, unsuitable for the Mini-Boone configuration. Given the greater concern at FNAL about activation into surrounding rock, a WANF/CNGS solution is less likely to be cost-effective (although having gravity-drain of water out of the horns is an attractive aspect of their geometry). The train was very useful for a flexible configuration, but DUSEL should not require such flexibility. The top-down AP0/NuMI configuration again looks attractive.

- <u>However, with the higher beam power / residual radiation of DUSEL, it would be prudent to adopt a pull-component-directly-up-into-coffin scheme.</u> One risk with NuMI is that the crane could fail with a hot component hanging from it, making it very difficult to service the crane. The directly-into-coffin scheme would mitigate the risk, but requires a larger capacity crane, and more up-front engineering for the coffin system.
- JPARC uses a helium-filled target pile – is this something we should adopt or not? No opinion yet. Does not appear consistent with 2-day target changeout.

Component change-out → $$

To get to a couple day target change-out, we need to change all the things that slow NuMI change-out down.

- Shield-door to target hall would be motorized.
- Cannot afford the time to put electronics back on the crane, so should have a shielded crane garage.
- Shielding over target would be motorized, to prevent having to un-stack a bunch of blocks.
- Top of module shielding would be marble, to minimize residual radiation for workers.
- Module shielding would be thicker.
- Would not use caulk-between-concrete-shield-blocks as the air seal, but have engineered panels that could be removed-replaced quickly.
- The target module would be as small as possible (e.g. baffle will have a separate module).
- Would have two target modules – change-out would swap entire assembly, and changing target on bottom of module for re-use of module would be done off-line outside the target hall.
- The alignment/survey of the target to the module would be done off-line, outside the target hall; only survey in target hall would be of top-of-module to target hall.
- A quick-transportation system would move the module (with target attached) out of the target hall immediately, rather than using the morgue. (Should shaft go directly to target hall?)
- The work cell would not be in the target hall, but in a surface building (constructed to withstand the impact of a commercial jet airplane).

Target pile cooling

- The air-cooling of the NuMI target pile is great, because it does not involve water, and there are no associated water leaks in the target pile.

- Studies done for upgrading NuMI indicate that at 2 MW, the shielding around the horn probably requires water cooling.

Beam windows

Windows on the end of the primary vacuum tube, on the baffle, on the target, and on the decay pipe will all be challenging to design, and should be among the first things studied.

Target

- Several configurations need to be evaluated, such as helium-cooled target, heat-pipe (evaporative) cooled target, graphite directly encapsulated in the horn inner-conductor, etc.
- The target design will be challenging.
- My initial opinion is that a ~1meter-long combined target/horn may make the most sense – so first horn section is swapped with each target.
- In terms of surviving radiation damage, a Project X year is about 7.7 times as many protons as the current NuMI target has accumulated. However, a DUSEL target could spread the protons out over say a factor of two larger area on graphite, so one could to first order guess that four NuMI-like graphite targets per year would likely be sufficient. A projection from low energy neutron data scaled via DPA to high energy proton Monte Carlo indicates a graphite target may survive an entire DUSEL year, but such scaling should be taken with a grain of salt.
- In order to consider half-a-dozen target changes a year, one needs to think about reducing the access time taken for replacement from of-order two weeks to of-order two days.

Horns

- In the existing NuMI LE configuration for MINOS, or the ME configuration for NOVA, the NuMI parabolic horns with modest modifications look quite viable for 2.3 MW both in terms of cooling and radiation damage.
- However, the NuMI configurations do not appear optimal for the desired DUSEL neutrino spectrum, and the DUSEL horns could also end up being quite challenging.
- The horn section near the target will require early R&D as well.

Decay pipe

Just lots of questions:

- Fill: Vacuum? Vacuum-to-Helium? Helium purge? Argon? Nitrogen? Air?
- Active system to have pressure follow atmospheric pressure?
- Re-circulating gas cleaning system?
- Aspect ratio: cylindrical like NuMI? Box like T2K?
- Cooling: Continuous cooling aka NuMI? Spaced ring-intercepts (mini-absorbers)?
- Repair capability for cooling?
- Tritium: to sump pump? Continuous external intercept? Spaced mini-absorbers?
- Repair capability for walls (e.g. port)?
- Replaceable upstream window?
- Window shutter ?

NuMI experience says it will take a lot of work to do decay pipe design well.

Some general comments on process issues

With one-of-a-kind systems, having the original design engineer on-call is very important. There are also complicated interactions between subsystems in NuMI, so that having continuity of knowledgeable people is very important. There should be a big enough core group that continuity can be maintained.

NuMI operations would have benefited by having closer contact with AD operations support groups during design, and clear identification of operational support.

- For instance, water group has made significant modifications to skids after they took over.
- Identifying an internal support group for target hall instrumentation would have made my life a lot easier.
- Upkeep of the target-pile-air-system chiller (designed by PPD) was a dance between PPD, FESS, and AD-mechanical-support.
- Etc.

Some general comments on process issues (cont.)

- NuMI failed to do as-built documentation. This is especially a problem when the designers/builders are not the operators/maintainers. (This is, I believe, far from unique to NuMI at FNAL; in all likelihood, we will fail again with DUSEL).

- Early on, we agreed on a "NuMI hand-book" modeled on the Main Injector handbook, where designs and changes would be filed on a shelf, with threshold for documentation deliberately practically non-existent so it would be easy to keep documentation up-to-date. Eventually, documentation started to be web based, which has advantages. Later in the project, bureaucracy took over, and documentation had to be approved up the management chain, and extensively specified html formats were enforced. Much documentation ceased at that point. Make the threshold for documentation low, or else staff up considerably so that people are not under time pressure and can do the documentation.

- Soon after CD4, the NuMI department dissolved, leaving the "facility" operations transitioning to new support structures, right in the middle of commissioning. Especially the absorber and decay-pipe systems were orphaned.

- During installation, conduit and junction boxes spring up in the most inconvenient places (contrast shielding, where every block is on a drawing you can review).