Outline:

• Description of a NUMI target

• Operational history

• Latest target failure (NT-04) - do we understand how?
  - It started with an internal water leak ... And then a pressure spike

• Do we have a way to prevent Target NT-05 failing in similar fashion?
  - Cranking helium pressure back up to 23 PSIG should do this.

• Next spare (NT-06) ready in spring 2011.

• (If have time) some details/pictures of previous target failures
NUMI MINOS target

2 int. length long; narrow so pions get out sides without re-interacting

Graphite Fin Core
6.4 mm wide

Water cooling tube

Fits within the horn without touching.

Every pulse, center heats to 330 C in 10 micro-seconds, cools to 58 C in 2 seconds
NUMI was designed before $\Delta m^2_{\text{atm}}$ was well known.

Target can move over 2.5 m range, changing neutrino spectrum, allows match to oscillation L/E

Oscillation maximum is actually 2 GeV, so almost all running has been ~ LE.

Running with other locations has been useful for studies of systematics
MINOS Target carrier

- Work cell
- Target module in beam-line
- 1st target being removed
NT-04 residual radiation
Tip would give weekly dose limit in 4 seconds

NUMI Target Beam Right
Doserate @ 1 foot

<table>
<thead>
<tr>
<th>Point</th>
<th>(mR/hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4000</td>
</tr>
<tr>
<td>2</td>
<td>10000</td>
</tr>
<tr>
<td>3*</td>
<td>40000</td>
</tr>
<tr>
<td>4</td>
<td>15000</td>
</tr>
</tbody>
</table>

* note: point #3 was taken on contact with the target tip, with the target in the LE 100 position
Experience with MINOS targets before NT-04 failure

1st Target took beam for over a year. Two problems:
- water leak soon after turn-on; back-pressured with Helium to keep water out
- target motion drive froze up after year of operation - stuck in High Energy focus

2nd Target ran 3 years, replaced when neutrino spectrum changed ~ 10%

3rd Target ran 1 year, failure at target tube support ceramic

4th Target ran 3 weeks, failure at target water line and helium vessel

<table>
<thead>
<tr>
<th>Target Design specification</th>
<th>Max. Proton/pulse</th>
<th>Max. Beam Power</th>
<th>Integrated Protons on Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target Design specification</td>
<td>4.0e13 p.p.p.</td>
<td>400 kW</td>
<td>3.7 e20 p.o.t. or 1yr minimum lifetime</td>
</tr>
<tr>
<td>1st target</td>
<td>3.0e13 p.p.p.</td>
<td>270 kW</td>
<td>1.6 e20 p.o.t.</td>
</tr>
<tr>
<td>4th target</td>
<td></td>
<td></td>
<td>0.2 e20 p.o.t.</td>
</tr>
</tbody>
</table>
down-time due to NuMI target

Target failures cost:
39 days during commissioning and
22 days of 1428 otherwise “beam available” days
(5/1/2005 -> summer shutdown)
So 2%- 4% downtime (count commissioning or not)

This NT-04 failure will add ~ 44 days of down-time.
A target change-out takes about 2 weeks.
Rest of down-time because don’t have spare ready yet.
(construction of a spare ~ 1 year)

Uptime: NuMI was taking beam 73% of days 5/1/2005 - 8/21/2010
accumulating 1.07e21 P.O.T. at 120 GeV
→ 0.65 MW-yr of beam power
Target

Water inlet line
Vacuum/Helium port
Water outlet line
Ceramic electrical insulator
See water drip, corrosion looks like left by water.
Other tests: See tiny hole in top during smoke-test.
See evidence of tiny water holes on Be window.
NT-04, Where Upstream Beryllium window should be

What upstream “window” looks like:

Most of Beryllium is on floor of target pile, although Beryllium window shard resting on upstream baffle:

What it should look like
Target developed a small internal water leak to helium volume.
Amount of water was small enough to not be obvious during beam scans

Sept 9 21:40 pressure spike, knocking out upstream window,
and producing holes in downstream target tube - helium leak.
beam permit stops beam because of helium leak.

How big a pressure spike? ~ 100 psi to break window loose,
(about me stepping on window with my heel).
Note the 30 psi rupture disk at top of target pile did not rupture.

A STORY
Beam radiation dissociated water into hydrogen and oxygen,
which had nowhere to go - helium volume was tight to outside air.
Sept 9 21:40 Something ignited the hydrogen,
blowing off the upstream beryllium window and creating holes near target tip,

AN ALTERNATE STORY:
Target filled with water, water heated by beam spill,
pushed off upstream window.
Some extra timeline

Sept 8 stopped beam running to move target from LE100 to LE250

Sept 8 19:00  Beam scan of target looked pretty OK. Not filled with water. (then beam off due to BPM, accelerator problems)

Sept 9 17:00  beam returned, run a few hours

Sept 9 21:40  beam permit stops beam because of helium leak.

Sept 10 4AM beam scan of target looked pretty OK. Not filled with water.

Flow helium, with beam permit set to trip if flow dropped.

Run beam until Sept 17.
Hole in water line is presently small:
Did pressure test, fill with helium to 31.5 psi and capped off.
Dropped to 30 psi in 5+ hours.
(No notable drop in target RAW skid water level week after failure)

Sept 21 Survey in work-cell saw tip 1.5 mm low, with some water visible.
The 1.5 mm droop is possibly from weight of water?
Since target is fin shaped, this vertical mis-alignment is not important for physics signal, but
Think water level is below smoke geyser, but above much of downstream Beryllium window.

Graphite fin still well aligned (beam scans and optical survey)

Bottom line:
Water hammer on delicate welds of water lines likely failure point.
NT01 had similar water leak, but not helium leak. We ran it for a year by over-pressuring the helium (23 PSIG), so helium went into water system, not water into helium volume.

NT02 was also run at 23 PSIG helium pressure.

NT03 was run at 23 PSIG until Dec 2, 2009, then reduced to 12 PSIG. It failed at end of April 2010, (possibly in same way).

NT04 was run with 6 PSIG helium pressure.

Pressure reduction was to bring us more rapidly into compliance with FNAL pressure vessel guidelines, not for technical reasons.

We should run NT05 at 23 PSIG. Mechanical Support Dept. to write hazard analysis, and (on longer time scale) Engineering note. (Dir. Exception?)
Other actions for NT05

Radiograph NT05 before installation, to check internal welds at tip

NUMI-only spills are currently significantly higher intensity than Mixed-mode spills, but not much time spent in NUMI-only.

NuMI-only has been 10% over design intensity - 4.4e13 POT/spill max

Will limit intensity of NUMI-only spills to what we get in Mixed-mode, to eliminate the highest stress pulses.

Cost is ~ 1% of integrated luminosity.

Start autopsies of previous targets next spring.
Finishing a work-cell at C0/RHF to work on horns & targets
Backup slides
On March 23, 2005 water leaked from cooling line into vacuum can, flooding target.

After draining target, we pressurized the can with 23 psig helium (was planning to use helium for high power running anyway)

Helium bubbled through leak to water line, keeping water out of target.
NT-01 Frozen drive shaft
*target replaced because could not move it to LE position*

After month-long test in High Energy position
drive shaft would not rotate to move target
into Low Energy position

Changed to spare target + carrier (NT02)
(drive also became sticky after beam)

NT03 onward, changed to graphite bushing
NT-03 drive moved smoothly at the end
of it's year lifetime.
Target remote drive coupler failure (repaired)

Air + radiation = nitric acid
Nitric acid atmosphere
  → hydrogen embrittlement of high strength steel
  → steel cracks

High strength steel bolts in couplers on target
drive linkage failed, so could not move target
to different position.

Have changed to non-high-strength bolts.
No more failures of this type.
NuMI 2\textsuperscript{nd} target depletion (ZXF-5Q amorphous graphite)

NT-02 replaced when spectrum shift became too large.

Gradual decrease in neutrino rate attributed to target radiation damage

Decrease as expected when decay pipe changed from vacuum to helium fill

No change when horn 1 was replaced

No change when horn 2 was replaced

Spectrum recovered when new target was inserted
Helium leak developed, and target fin moved beam-left. We re-adjusted target so parallel to beam again, and ran another two months. Exam showed leak at ceramic insulator at base of target – presumed cause is failure of braze joint or ceramic causing (X=4 mm, Y=8 mm) displacement of target tip. Exam also showed helium leak/damage at bottom of target tube – presumed collateral damage from horn current with target resting on horn conductor (which limited the vertical displacement to 6 mm). (Since target is fin shaped, vertical mis-alignment is not as important)