131.ND.02.08 TPC Module Assembly & Testing: Overview

Mike Mooney, L3 TPC Module Assembly & Testing Lead

ND-LAr Preliminary Design Review

29 June 2022

Schweizerische Eidgenossenschaft
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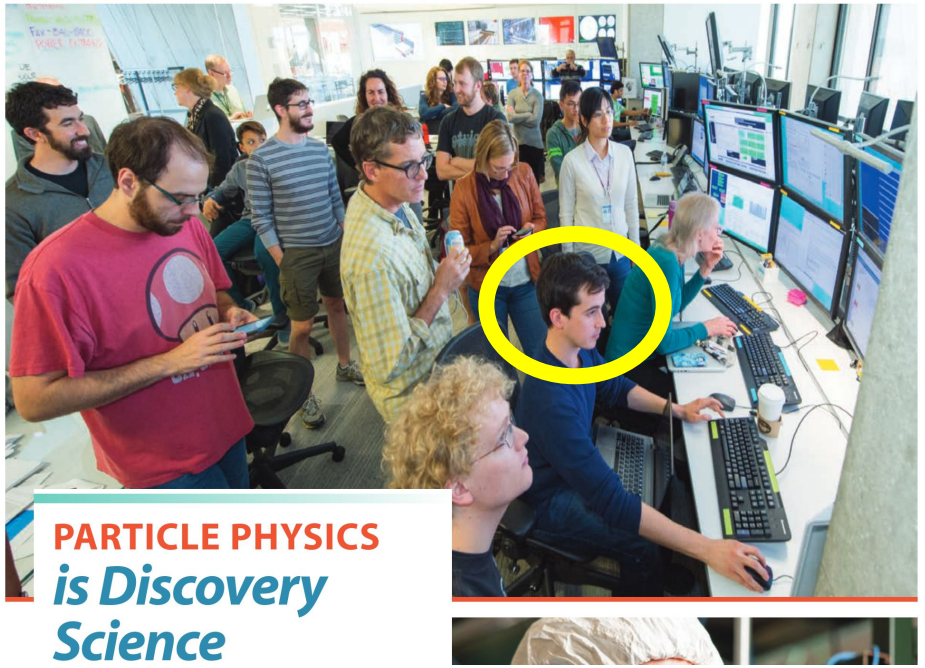
U.S. DEPARTMENT OF ENERGY | Office of Science

Who am I

- Mike Mooney
  - Assistant Professor at Colorado State University (CSU) since August 2017
    - Postdoc @ BNL (2014-2017) – work on MicroBooNE, SBN Program, and DUNE
    - PhD studies @ Princeton University (2008-2014) – Higgs boson search w/ CMS detector (PhD advisor: Jim Olsen)
    - Undergraduate studies @ MIT (2004-2008)
  - Expertise in LArTPC detector operations and detector physics (e.g. space charge effects)
    - Functional cubic foot LArTPC detector ("SingleCube") in Mooney Lab @ CSU
  - First MicroBooNE Run Coordinator (2015-2016), including initial operations w/ beam
  - DOE HEP Early Career Research Program awardee (2020)

Brochure from www.usparticlephysics.org

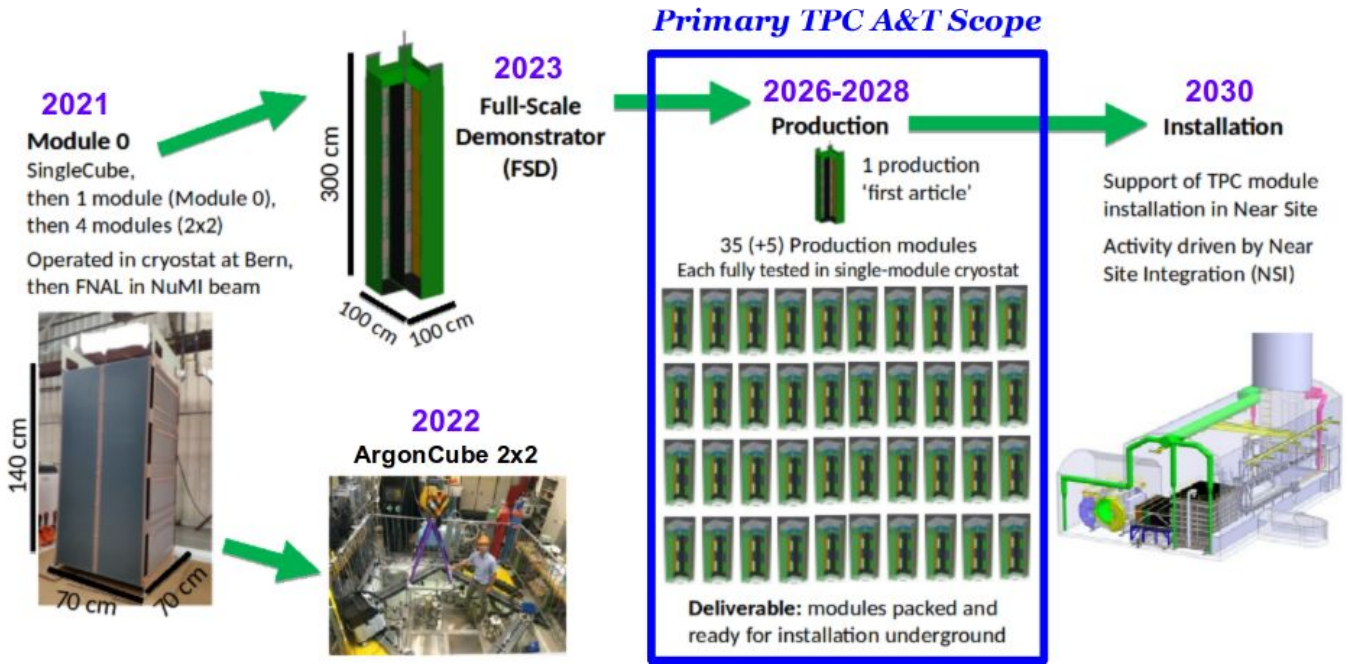
First beam neutrinos at MicroBooNE (Oct. 2015)

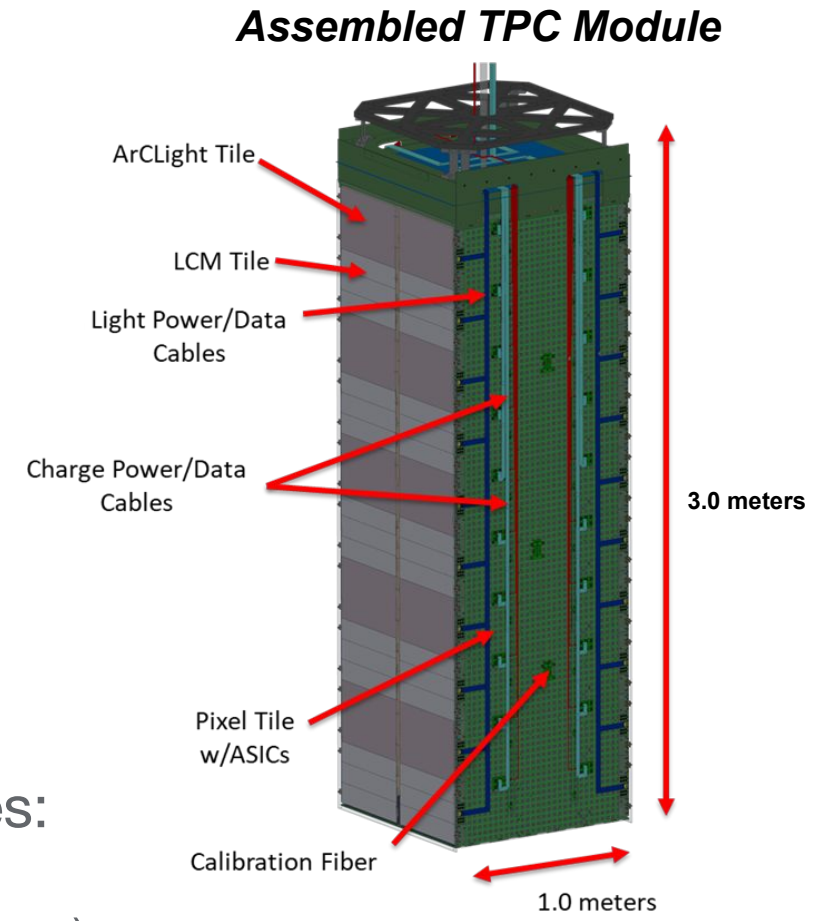


Outline

- Overview
- Scope
- Requirements
- Interfaces
- QA/QC and Prototyping
- Testing Plan
- Risks
- Recommendations from Previous Reviews
- Cost and Schedule
- Summary

TPC Module A&T Overview





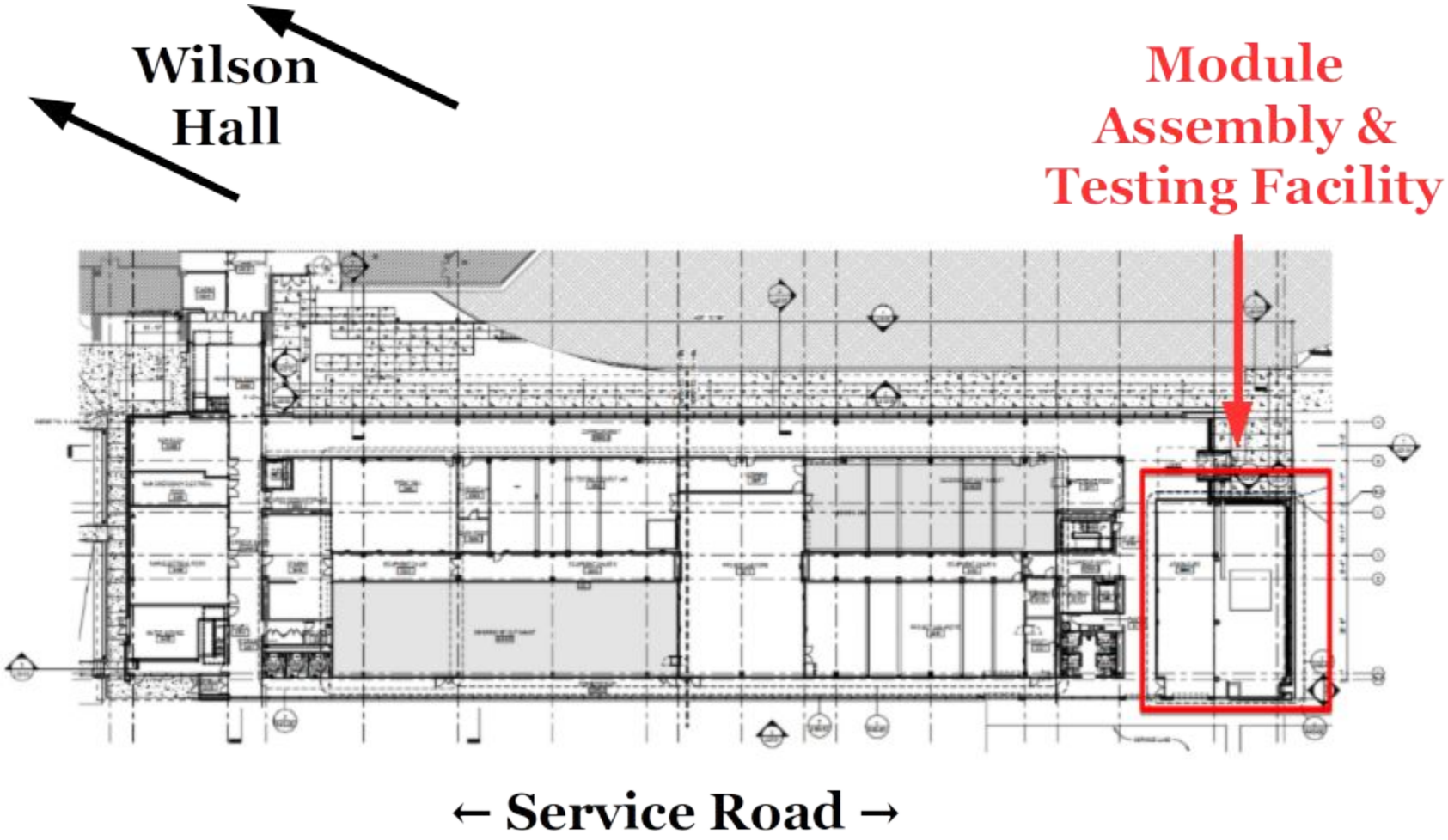
- ND-LAr TPC Module Assembly and Testing ("A&T") involves:
  - Assembly of 35 ND-LAr TPC modules (+ spares)
  - Full-module QC in LN2 for 35 ND-LAr TPC modules (+ spares)
  - QA for above activities in preceding prototypes (e.g. FSD)
- TPC A&T will occur at MATF (Module Assembly and Testing Facility) at Fermilab IERC (Integrated Engineering Research Center) between 2026 and 2028

FNAL IERC

See L. Suter's talk for more details

MATF @ FNAL IERC

See L. Suter's talk for more details



Roles and Responsibilities

- TPC Assembly & Testing L3 Manager – Mike Mooney (CSU)
- TPC Assembly & Testing Engineering Lead – Jay Jablonski (CSU)
- Module Assembly and Test Facility L3 Manager – Louise Suter (FNAL)
- IERC Point of Contact and Interface Coordination – Leo Bellantoni (FNAL)
- Engineering Management – Andrew Lambert (LBNL)
- Principal Cryogenic Engineer – Michael Geynisman (FNAL)
- Secondary Cryogenic Engineer – Michael Zuckerbrot (FNAL)
- Integrated CAD Model/Drawings – Tom Rathmann (LBNL), Jay Jablonski (CSU)
- Engineering Analysis – Zach Rautio (CSU)
- Electrical/Grounding Oversight & FNAL Approval – Linda Bagby (FNAL)

TPC Module A&T Scope

https://edms.cern.ch/document/2619610/1

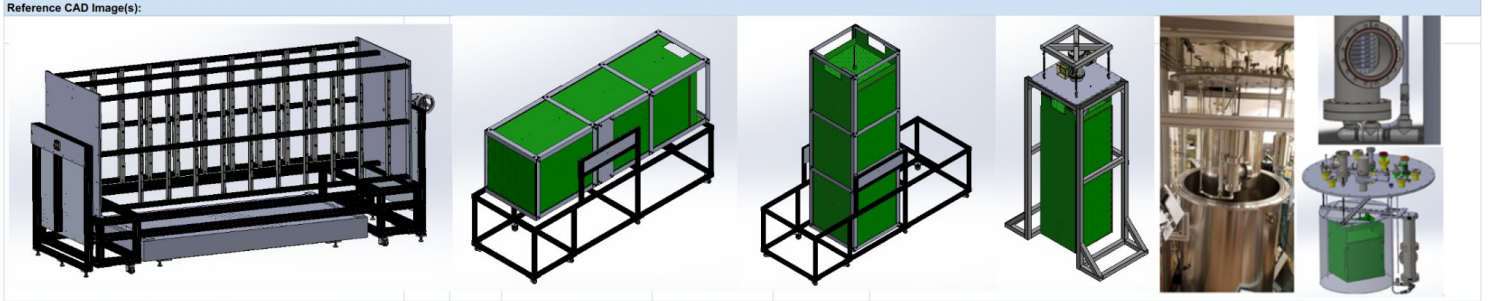
- Detailed subsystem scope for A&T WBS dictionary
- Main responsibilities include assembly fixtures (design, prototyping, production), assembly procedures, technical labor for TPC module assembly, and testing procedures for full-module QC in LN2 at MATF
- A&T serves as “glue” labor (technical/scientific); labor from the various subsystem experts (students/postdocs) will flesh out full team for assembly and testing tasks

131.ND.02.08: TPC Assembly & Testing

WBS Dictionary (Concise):

Assembly & testing program for the TPC Modules of the ND LArTPC detector
Includes:
- Assembly & testing of SingleCube TPCs
- Assembly & testing of 2x2 TPC modules (including Module 0)
- Assembly & testing of Full-scale Demonstrator TPC Module
- Assembly & testing of Production ND TPC Modules
- Assembly & testing procedures
- Assembly & testing result reports
- Assembly, lifting fixtures, and other integration hardware
- Design of cryostat and lid for Full-scale ND module testing at FSDTF

Reference CAD Image(s):



Task/Item: ND-LAr TPC A&T Equipment, Procedures, and Labor	Qty	Spares	Institutions	Funding Source	Funding Status	Detailed description
Equipment						
Module Assembly Fixture	2	1	Colorado State University	DUNE US Project	Allocated	Fixture to aid in assembly of TPC modules
Module Rotation Fixture	2	1	Colorado State University	DUNE US Project	Allocated	Fixture to aid in the rotation between horizontal/vertical orientations
Module Lid Support Fixture	2	1	Colorado State University	DUNE US Project	Allocated	Fixture to hold assembled TPC module
Module Lifting Fixtures	2	1	Colorado State University	DUNE US Project	Allocated	Fixture to lift TPC module
Procedures						
Module Assembly Procedure	1	0	Colorado State University	DUNE US Project	Allocated	Procedure to use assembly fixture, per site ESH
Module Rotation Procedure	1	0	Colorado State University	DUNE US Project	Allocated	Procedure to use rotation fixture, per site ESH
Module Lifting Procedure	1	0	Colorado State University	DUNE US Project	Allocated	Procedure to lift TPC module, likely critical lift, per site ESH
Module Travelers	35	2	Colorado State University	DUNE US Project	Allocated	Travelers to record the as-built condition of the TPC modules
Component QC/Verification Plan	6	0	Colorado State University	DUNE US Project	Allocated	Component QC plan to cover each ND-LAr subsystem
Module QC/Acceptance Testing Plan	1	NA	Colorado State University	DUNE US Project	Allocated	Module QC and Acceptance Plan that covers requirements verification of assembled modules
Module to Cryostat Insertion/Extraction Critical Lift Procedure	1	NA	Colorado State University	DUNE US Project	Allocated	Procedure to install/extract the TPC from cryostat, likely critical life, per site ESH
Module to Module Crate Critical Lift Procedure	1	NA	Colorado State University	DUNE US Project	Allocated	Procedure in insert module to crate, likely critical lift, per site ESH
Acceptance Test Report	35	2	Colorado State University	DUNE US Project	Allocated	Report detailing TPC module performance with respect to requirements
Labor						
Technical and Scientific Labor to Design, Prototype, Procure, Assemble, Test, and Ship all Equipment	NA	NA	Colorado State University	DUNE US Project	Allocated	Engineering design, management, and support for A&T activities
QA/QC and characterization						
Reception Testing on Received Module Structure Components			Colorado State University	DUNE US Project	Allocated	Quality control at receipt of all components received from identified subsytem during Assembly & Test activities
Reception Testing on Received High Voltage Components			Colorado State University	DUNE US Project	Allocated	Quality control at receipt of all components received from identified subsytem during Assembly & Test activities
Reception Testing on Received Field Structure Components			Colorado State University	DUNE US Project	Allocated	Quality control at receipt of all components received from identified subsytem during Assembly & Test activities
Reception Testing on Received Charge Readout Components			Colorado State University	DUNE US Project	Allocated	Quality control at receipt of all components received from identified subsytem during Assembly & Test activities
Reception Testing on Received Light Readout Components			Colorado State University	DUNE US Project	Allocated	Quality control at receipt of all components received from identified subsytem during Assembly & Test activities
Reception Testing on Received Calibration Components			Colorado State University	DUNE US Project	Allocated	Quality control at receipt of all components received from identified subsytem during Assembly & Test activities
Reception Testing on all assembly fixtures			Colorado State University	DUNE US Project	Allocated	Quality control at receipt of all components received from identified subsytem during Assembly & Test activities
Prototypes for 2x2						
2x2 Module Assembly Fixture	1	1	Colorado State University	In-Kind	Allocated	
Cathode Bracket Sets	4	0	Colorado State University	In-Kind	Allocated	
Quality Control on 2x2 Modules	4	0	Colorado State University	In-Kind	Allocated	
Prototypes for FSD						
Module Assembly Fixture	2	1	Colorado State University	DUNE US Project	Allocated	Fixture to aid in assembly of TPC modules
Module Rotation Fixture	2	1	Colorado State University	DUNE US Project	Allocated	Fixture to aid in the rotation between horizontal/vertical orientations
Module Lid Support Fixture	2	1	Colorado State University	DUNE US Project	Allocated	Fixture to hold assembled TPC module
Module Lifting Fixtures	2	1	Colorado State University	DUNE US Project	Allocated	Fixture to lift TPC module

TPC Module A&T Requirements

https://edms.cern.ch/document/2589287

- Key requirements in **red**; focus is on ensuring success of TPC module assembly and full-module quality control

ID	Name	Primary Text	Value	Rationale	Parent Req/Spec ID(s)
INT-001	**Module Assembly**	TPC A&T shall assemble and integrate the stated number of full-scale LArTPC modules	35	Integrates all sub-system deliverables into 35 modules and 5 spare modules	SYS-002
INT-002	**Module Acceptance Testing**	TPC A&T shall test and verify performance requirements for the state number of assembled LArTPC modules	35	Must verify that all modules destined for the Near Site meet performance requirements	SYS-002
INT-003	**Module Packaging/Shipping**	TPC A&T shall package the stated number of acceptance tested LArTPC modules for storage and handoff to TPC I&I	35	Scope includes integration, testing, transportation and storage	SYS-002
INT-012	**Assembly Fixtures**	TPC A&T fixture design shall comply with site ESH requirements	N/A	Ensure that fixtures do not violate site safety requirements	SYS-031
INT-007	**Lifting Fixture per host ESH**	ND-LAr Module Lifting Fixtures shall be designed, fabricated and tested to meet host ESH plans	NA	Ensure that fixtures do not violate site safety requirements	SYS-031
INT-022	**Lift Plan per host ESH**	ND-LAr Module Lifting Plans shall be written, reviewed and released per the guidelines established in host ESH plans	NA	Lift plans need to be written according to institutional requirements, otherwise lift plans cannot be executed	SYS-031
INT-016	**Component Receipt Testing**	TPC A&T shall perform reception testing on received components and verify post-shipment function	N/A	Ensure no change in component/subsystem performance post-shipment to the assembly and testing site	INT-001
INT-023	**TPC Assembly Space Size**	The TPC assembly space shall meet the specified dimensions	12' x 18' x 8' TBC	Requried space to safely assemble TPC components and perform system checks	INT-001
INT-024	**TPC Assembly Space Cleanliness**	The TPC assembly space for the ND-LAr modules shall have cleanliness specification that meets or exceeds the specified ISO designation	ISO 8	2x2 module construction at Bern has occured in an assembly space with a cleanliness not exceeding ISO 8	INT-001
INT-025	**Number of TPC Assembly Spaces**	In order to facilitate assembly of the TPC modules, the stated number of assembly spaces are planned	2 TBC	Paralellize the assembly process of multiple modules	INT-001
INT-020	**Assembly and Test Procedures**	TPC A&T procedures shall adhere to site ESH requirements	N/A	Ensure that fixture procedures do not violate site safety requirements	INT-001, INT-002
INT-021	**TPC Module Quality Assurance / Quality Control Plan**	TPC A&T quality assurance / quality control plan shall adhere to DUNE project QAQC requirements	N/A	Ensure that quality control activities meet LBNF/DUNE requirements	INT-002
INT-015	**Pre-Assembly Component Storage Space**	Amount of storage space needed for TPC module components prior to assembly at both FSD and MATF	L x W x H	Space is needed to receive and prepare components for assembly	INT-001
INT-017	**Post-Assembly Module Storage Space (short-term)**	Amount of storage space at the MIF for fully-assembled TPC modules after testing	~12' x 18' x 4' (~5 modules, horizontal)	Space is needed to store acceptance tested modules (short-term)	INT-002, INT-003
INT-018	**Post-Assembly Module Storage Space (long-term)**	Amount of storage space at the MIF for tested TPC modules prior to shipping to ND storage site, including modules that need to be retested	L x W x H	Space is needed to store acceptance tested modules (long-term)	INT-002, INT-003

TPC Module A&T Interfaces

- Primary interfaces with FSD (left), MATF (right) – only showing first few interface items below (see EDMS for full lists)
- Also interface with subsystems for component receipt at FSD/MATF

https://edms.cern.ch/document/2610898/1

This section represents interfaces between the following two entities:	
WBS 131.ND.02.07	WBS 131.ND.02.11
TPC Assembly & Testing	FSDTF
Mike Mooney	Tom Markiewicz
131.ND.02.07 Manager	131.ND.02.11 Manager

The interface table below details interfaces between the TPC Assembly and Testing (A&T) subsystem and the Full-Scale Demonstrator. TPC A&T coordinates the delivery of subsystem components to the FSDTF.

Item	WBS 131.ND.02.07 TPC A&T Provides	WBS 131.ND.02.11 FSDTF Provides	Interface Point/Drawing
Shipping List / Assembly BOM	TPC A&T provides shipping list and assembly BOM for all components and assemblies delivered to FSDTF	FSDTF provides verification of receipt of all items	EDMS TBD
4-way Cross Assembly / Spool Piece	TPC A&T provides all components in the 4-way Cross Assembly per interface agreements with ND-LAr subsystems	FSDTF provides receipt & check of all items, may require pressure test	EDMS 2610895
Clean Assembly Space (L x W x H)	TPC A&T specifies required space (L x W x H) for TPC Assembly	FSDTF provides clean assembly space of the required size	EDMS TBD

https://edms.cern.ch/document/2741843/1

This section represents interfaces between the following two entities:	
WBS 131.ND.02.07	WBS 131.ND.02.10
TPC Assembly & Testing	MATF
Mike Mooney	Louise Suter
131.ND.02.07 Manager	131.ND.02.10 Manager

The interface table below details interfaces between the TPC Assembly and Testing (A&T) subsystem and the Module Assembly and Testing Facility. TPC A&T coordinates the delivery of subsystem components to the MATF.

Item	WBS 131.ND.02.07 TPC A&T Provides	WBS 131.ND.02.10 MATF Provides	Interface Point/Drawing
Shipping List / Assembly BOM	TPC A&T provides shipping list and assembly BOM for all components and assemblies delivered to MATF	MATF provides verification of shipping schedule and receipt of all items	EDMS TBD
Clean Assembly Space Size and Number (L x W x H)	TPC A&T specifies required space (L x W x H) for TPC Assembly	MATF provides clean assembly space of the required size	Size found in EDMS 2589287 QTY = 2
Clean Assembly Space ISO Designation	TPC A&T specifies ISO cleanliness requirements	MATF provides clean assembly space of specified ISO designation	EDMS 2589287

TPC Module A&T QA/QC and Prototyping

https://edms.cern.ch/document/2459134/1

- Primary Quality Assurance (QA) is training of A&T personnel and functional verification of assembly fixtures at FSD
- Prototyping of assembly fixtures at CSU important initial QA step (see more in J. Jablonski's talk)
- Quality Control (QC) *is* the focus of TPC Module A&T
  - Full-module level QC as opposed to individual component QC carried out first at consortium member institutions
  - Reception tests of components at both FSD and MATF ensure component shipping methods robust

CONTENTS

DEEP UNDERGROUND NEUTRINO EXPERIMENT

ND-LAR MODULE QAQC PLAN

M.MOONEY, J.JABLONSKI

Release Date:

LBNL Document Number: **DU-1002-6389**	Revision: **A.7**
CERN EDMS Document Number: **2459134**	Revision: **v.1**

Document Status: **Working**
Type: **QUALITY ASSURANCE**
LBNL Category Code: **DU2007**

TPC Module A&T Testing Plan

https://edms.cern.ch/document/2459133/1

- Testing Plan covers LN2 testing procedure, including operations workflow, timelines, and performance metrics (see below)
- Testing timescale is roughly two weeks per TPC module
- Dual cryostat operations allows for simultaneous testing of two TPC modules, saving time and operations costs
  - Yields roughly factor of two buffer in timeline to account for problems encountered while testing, which may lead to multiple tests of same TPC module

DEEP UNDERGROUND NEUTRINO EXPERIMENT

ND-LAR MODULE TESTING PLAN

M.MOONEY, J.JABLONSKI
Release Date:

LBNL Document Number: **DU-1002-6390**	Revision: **A.9**
CERN EDMS Document Number: **2459133**	Revision: **v.1**

Document Status: **Working**
Type: **QUALITY ASSURANCE**
LBNL Category Code: **DU2007**

6. PERFORMANCE METRICS

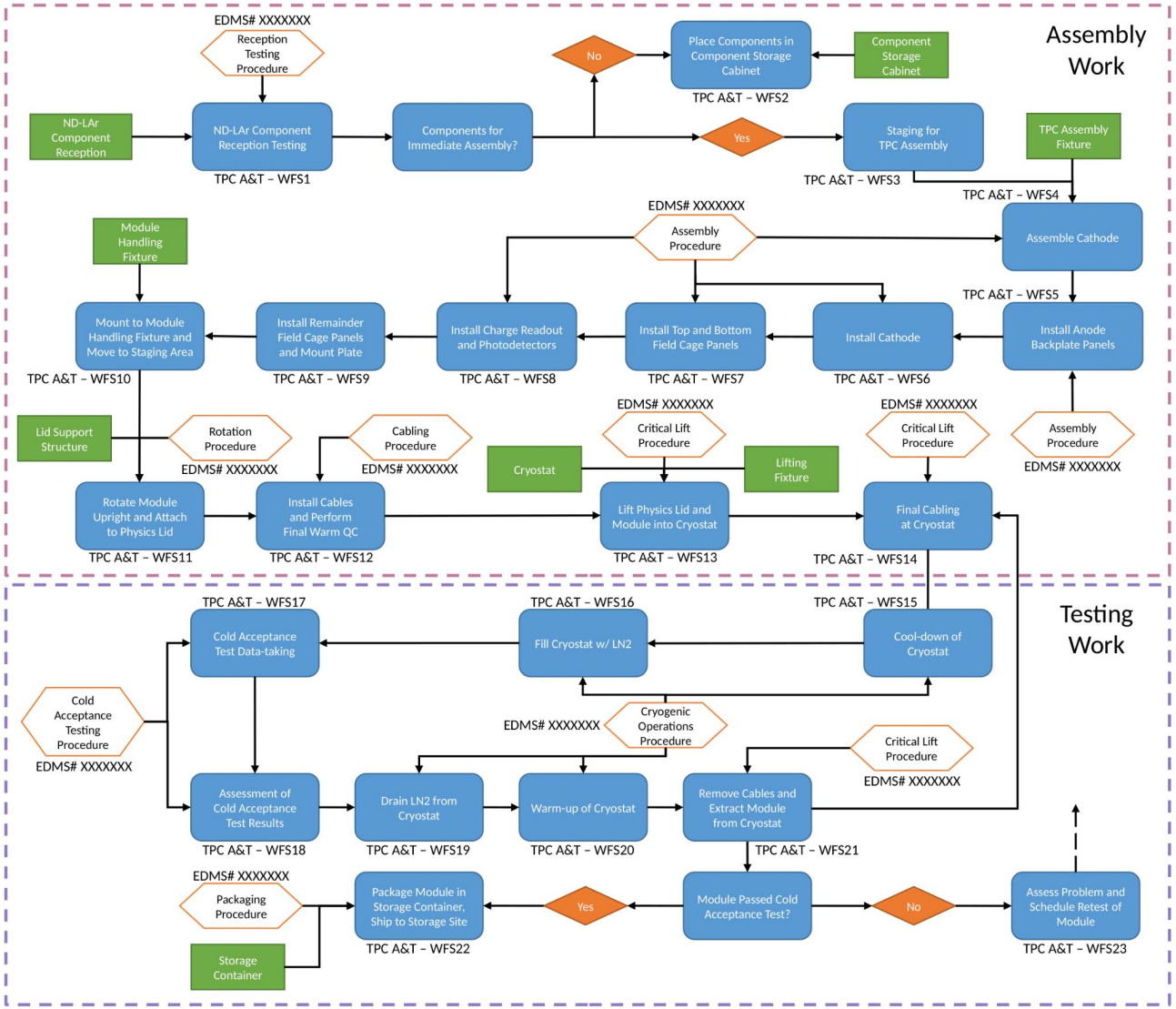
A number of performance metrics will be checked for each ND-LAr during cryogenic testing at the MATF. These metrics include:

- number of dead/inactive channels in the pixel planes and light detectors;
- noise levels in the pixel plane and light detector channels;
- amount of cross-talk between the pixel planes and light detectors;
- stability of electronics gain and other operational parameters; and
- mechanical integrity of the TPC module after exposure to cryogen, assessed by visual inspection.

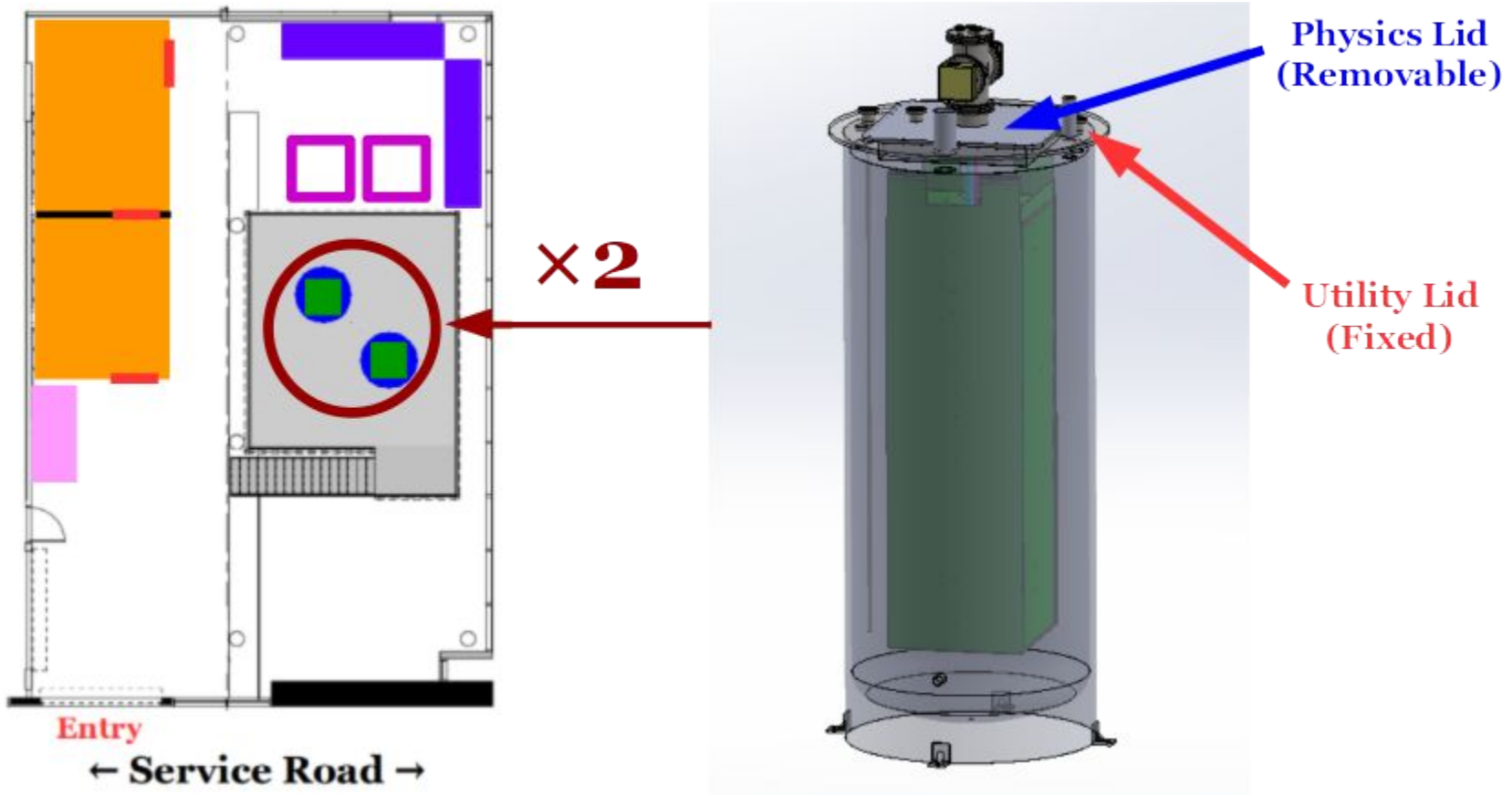
MATF Operations Flow Diagram

https://edms.cern.ch/document/2742799/1

- Presented in Testing Plan
- Gives high-level view of TPC Module A&T operations flow at MATF, including both Assembly Work and Testing Work
- Placeholders for various procedures, currently summarized in single Assembly Procedure document (see J. Jablonski's talk)
- Relevant equipment also included in diagram where appropriate

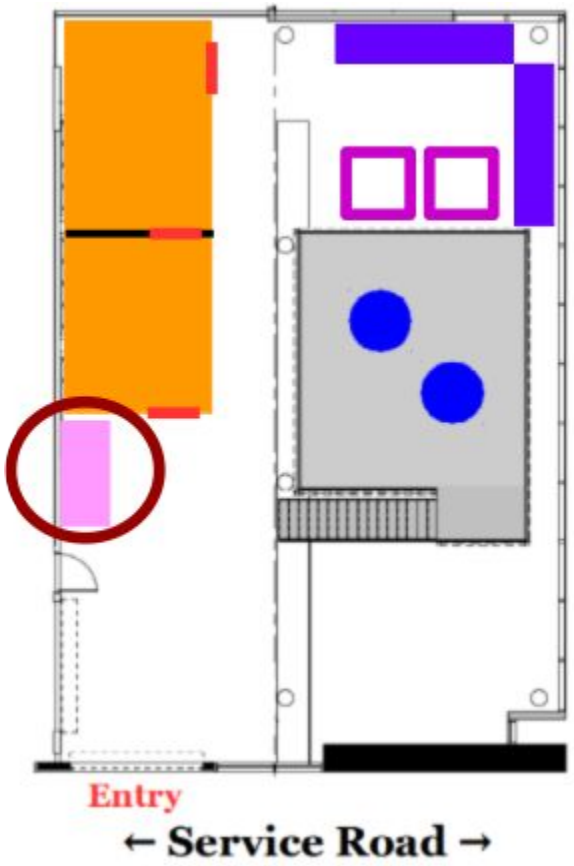


Detailed MATF Operations Workflow



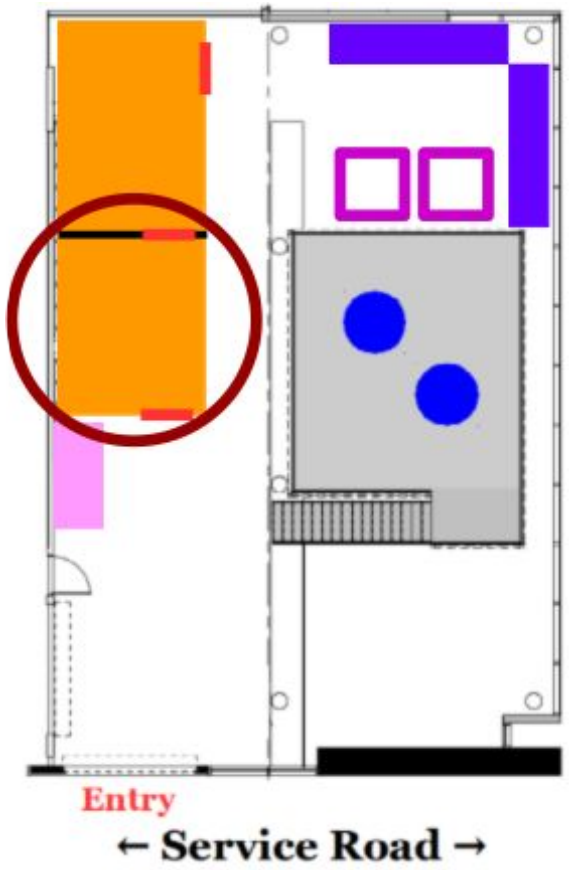
- Detailed overview of operations workflow (assembly + testing) at MATF in next slides
  - Reminder: nominal timeline is to assemble and test two TPC modules in two weeks

Detailed MATF Operations Workflow



- **Step 1:** store components arriving from member institutions in **storage cabinets**

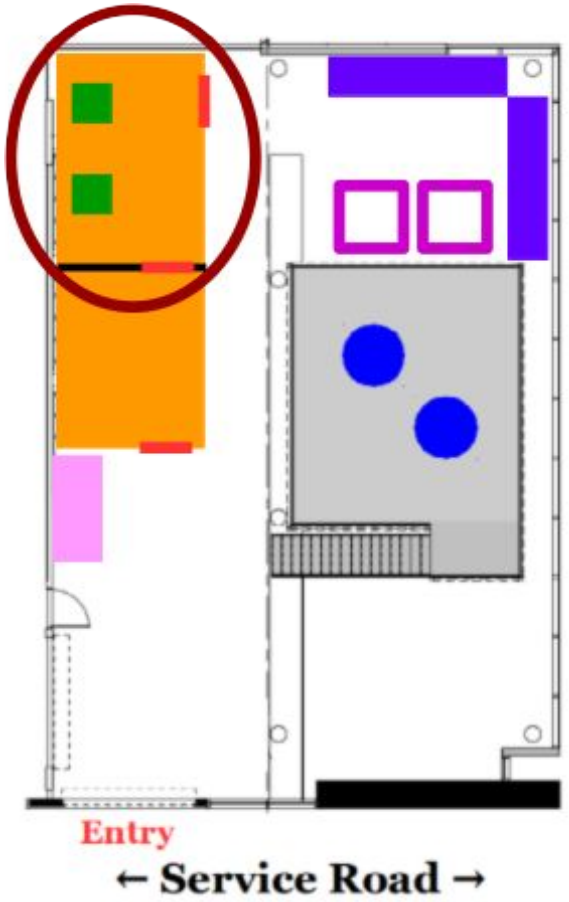
Detailed MATF Operations Workflow



- **Step 2:** carry out component reception tests
  - Use sectioned off part of **clean space** for these tests

Detailed MATF Operations Workflow

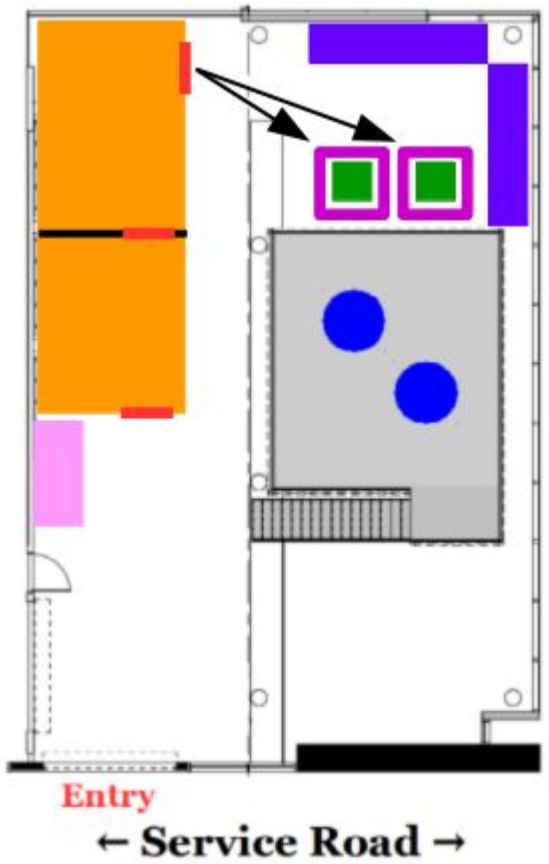
See J. Jablonski's talk for more details



- **Step 3:** assemble full **TPC module**
  - Use other sectioned off part of **clean space** for this assembly

Detailed MATF Operations Workflow

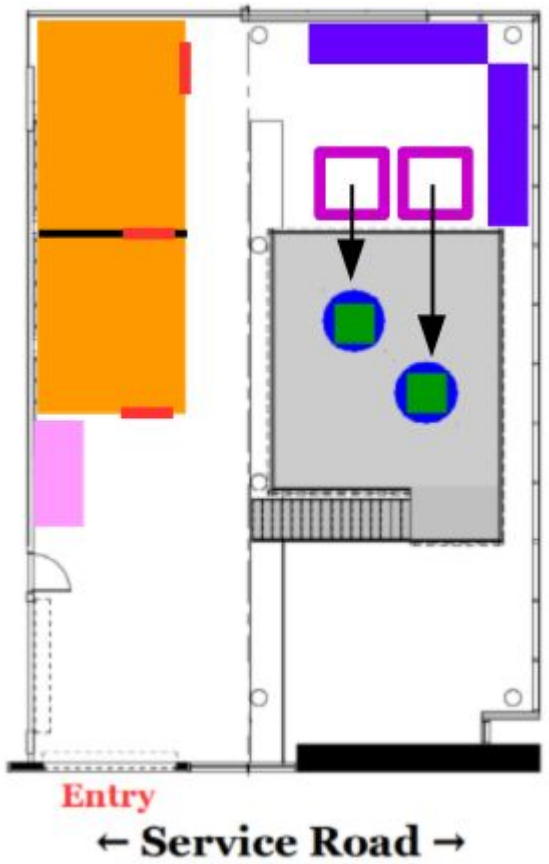
See J. Jablonski's talk for more details



- **Step 4:** move **TPC module** under **lid support structure**
  - Move out of **clean space** using support frame on wheels; attach TPC to physics lid from below

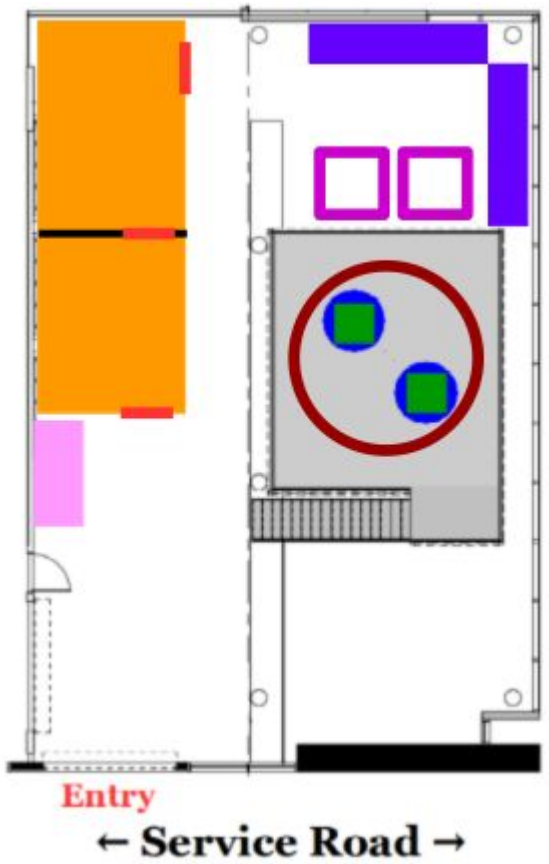
Detailed MATF Operations Workflow

See J. Jablonski's talk for more details



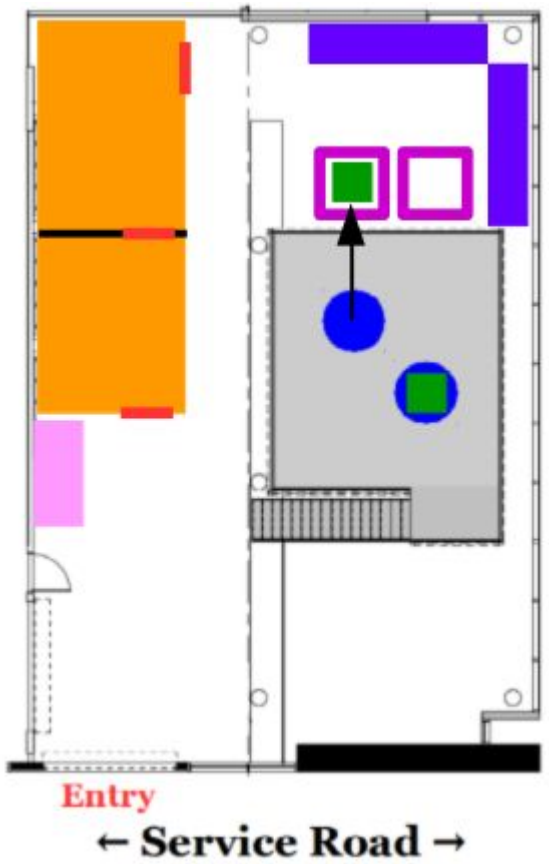
- **Step 5:** attach crane to physics lid at **lid support structure**, move **TPC module** + physics lid into **cryostat** (one TPC module at a time)

Detailed MATF Operations Workflow



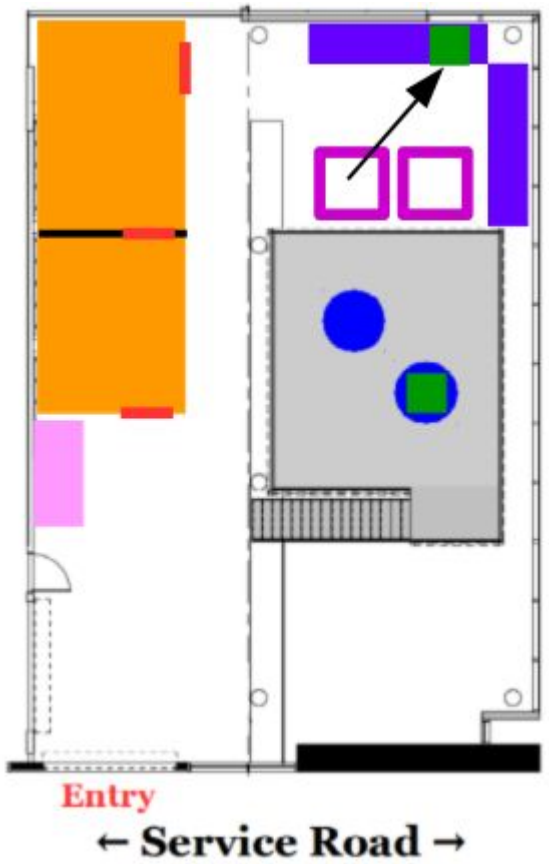
- **Step 6:** perform cold acceptance tests of **TPC modules** in LN2 in **cryostats**

Detailed MATF Operations Workflow



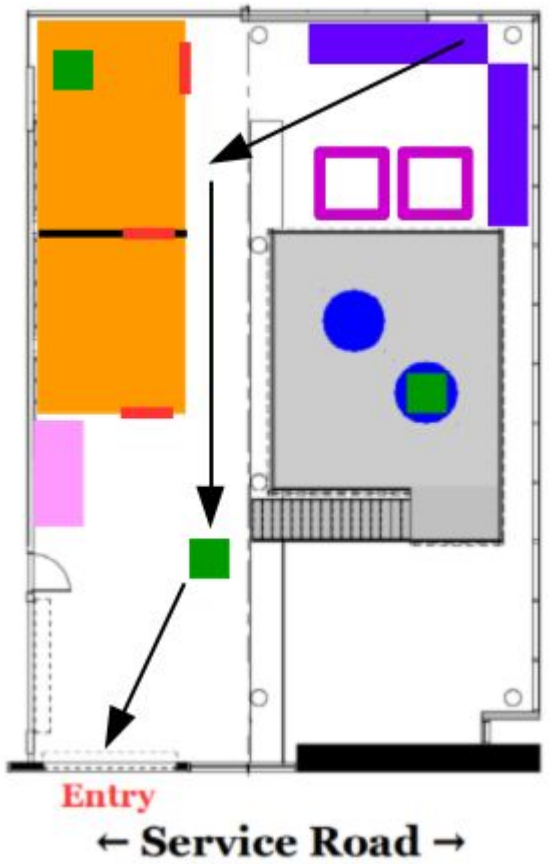
- **Step 7:** remove **TPC module** + physics lid and lower back into **lid support structure**
  - For illustrative purposes, assume one TPC module done w/ testing and second needs more study

Detailed MATF Operations Workflow



- **Step 8:** for successful test, move **TPC module** into **module storage area**; for failed test, move **TPC module** into **clean space** for debugging and/or repair

Detailed MATF Operations Workflow

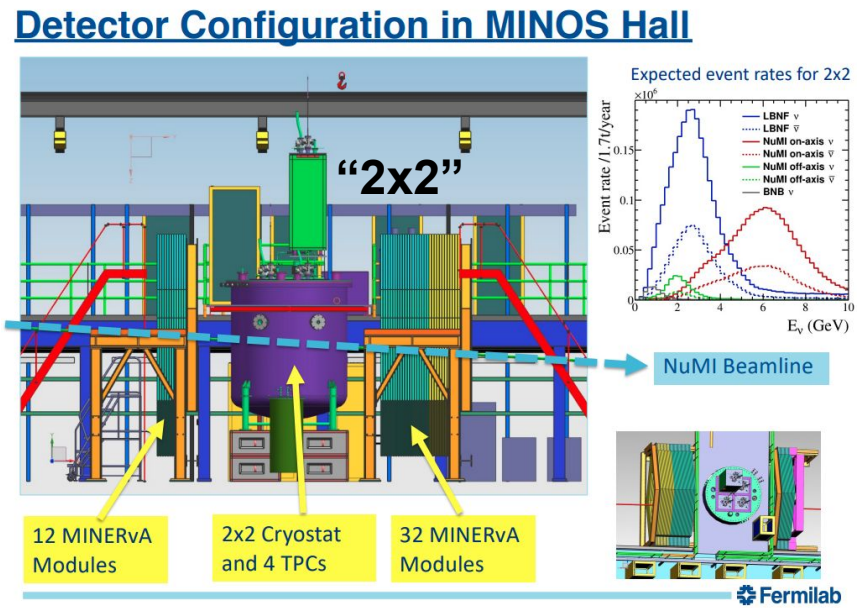


- **Step 9:** pack successfully tested **TPC module** into storage container and ship to ND module storage site; repeat steps 1-9 until 35 modules (+ spares) assembled/tested

Experience from Prototyping

See I. Kreslo's talk for more details

- Previous experience with ND-LAr prototypes has been valuable preparation for A&T activities
  - SingleCube @ Bern, CSU
  - 2x2 Modules 0/1 @ Bern
- Full 2x2 @ FNAL, FSD @ SLAC will further inform assembly and full-module QC @ MATF



Future FSD Test Site @ SLAC

TPC Module A&T Risks

https://edms.cern.ch/document/2589288

- Risks actively tracked through Consortium Risk Registry; most impactful risks highlighted here

Title	Summary	Mitigation	Response	Probability	Schedule Impact (Months)			Cost Impact ($k)			Technical Impact
MATF Cryogenics System Commissioning Delays	If MATF commissioning is delayed due to initial failure of cryogenic system, then would start testing of 35+5 modules at MATF later than initially anticipated	Proposed Mitigation: Commission the cryogenics system for the MATF as early as possible (at least six months prior to operation)	Ask for additional help from local (FNAL) cryogenics experts to debug issues with cryogenics system	20%	1	3	6	50	150	300	0 Negligible
Module Testing Timescale at MATF Longer than Anticipated	If module testing timescale at MATF longer than anticipated, then additional installation labor cost will be incurred and beginning of ND installation/commissioning would be delayed	Prototyping program helps to enforce required tests and testing timescales	Reassess QA/QC criteria to allow for shortening of testing timescale if possible, otherwise incur delay to ND installation schedule	25%	2	3	6	132	198	397	0 Negligible
Module Components Damaged at MATF (US)	If module components damaged during TPC Assembly and Test at the MATF, then minor delays to module tests would be incurred due to waiting for component replacement	Ensure testing procedures are fully developed (both cold and warm testing), ask subsystem experts for input on handling/testing of their subsystem's components, ensure training of operators is complete and consistent Subsystems shall deliver spare components as required by their production yields	Send module components back to responsible institutions for repair/replacement	45%	2	3	4	100	150	200	0 Negligible
Module Components Damaged at MATF (non-US)	If module components damaged during TPC Assembly and Test at the MATF, then minor delays to module tests would be incurred due to waiting for component replacement	testing), ask subsystem experts for input on handling/testing of their subsystem's components, ensure training of operators is complete and consistent Subsystems shall deliver spare	Send module components back to responsible institutions for repair/replacement	45%	2	4	6	100	200	300	0 Negligible
Catastrophic Damage to Module at MATF	If catastrophic damage to module during TPC A&T at MATF occurs, then modest testing delays would result as well as increase in costs	Develop extensive safety plan to be reviewed by Fermilab ESH, ensure training of operators is complete and consistent	Evaluate components to see if they can be recycled, send back to responsible institutions for repair/replacement, reevaluate safety plan with help from Fermilab ESH **If damage is severe, utilize a spare** Fix in operations	10%	0	0	0	0	0	0	1 Somewhat Substandard
Cryogenic System Failure During MATF Operations	If cryogenic system fails during operation of MATF, then significant delays to testing schedule would result	Ensure cryogenics experts are available on-site for quick repair of the system	Ask for additional help from local (FNAL) cryogenics experts to debug issues with cryogenics system	25%	1	2	4	50	100	200	0 Negligible

TPC Module A&T Previous Review Recommendations

https://edms.cern.ch/document/2741842

Review	Comment	Response
ND-LAr Internal Review (May/June 2021)	The MATF team and the installation team should band together to draft detailed testing goals, justifications, procedures, and the pass/fail criteria. The tests during module assembly and detector assembly are likely to be very similar from a QC perspective. This document will be important for justifying the cold test in pure liquid argon of all the modules.	**Closed** - Current baseline is testing in LN2, therefore the comment is not relevant any more.
ND-LAr Internal Review (May/June 2021)	The requirement for a fully redundant cryogenics system for the test facility should be reviewed and justified before the system goes to an external review.	**Closed** - Testing plan has been reassessed to LN2 testing at reduced cost. This was presented at March 2022 US Cost Review.
ND-LAr Internal Review (May/June 2021)	A schedule with basis of estimate will need presented at future reviews.	**Open** – Schedule and detailed cost estimate was presented at the cost review; the BOE will be completed and baselined at CD-2.
US ND Cost Review (March/April 2022)	Consider reuse of equipment and sites for FSD and MATF activities.	**Open** – Reuse of SLAC FSD cryostat or equipment has been discussed.
US ND Cost Review (March/April 2022)	Review A&T and I&I labor estimates.	**Open** – Schedule and detailed cost estimate was presented at the cost review; the BOE will be completed and baselined at CD-2.

TPC Module A&T Costs

https://edms.cern.ch/document/2742778

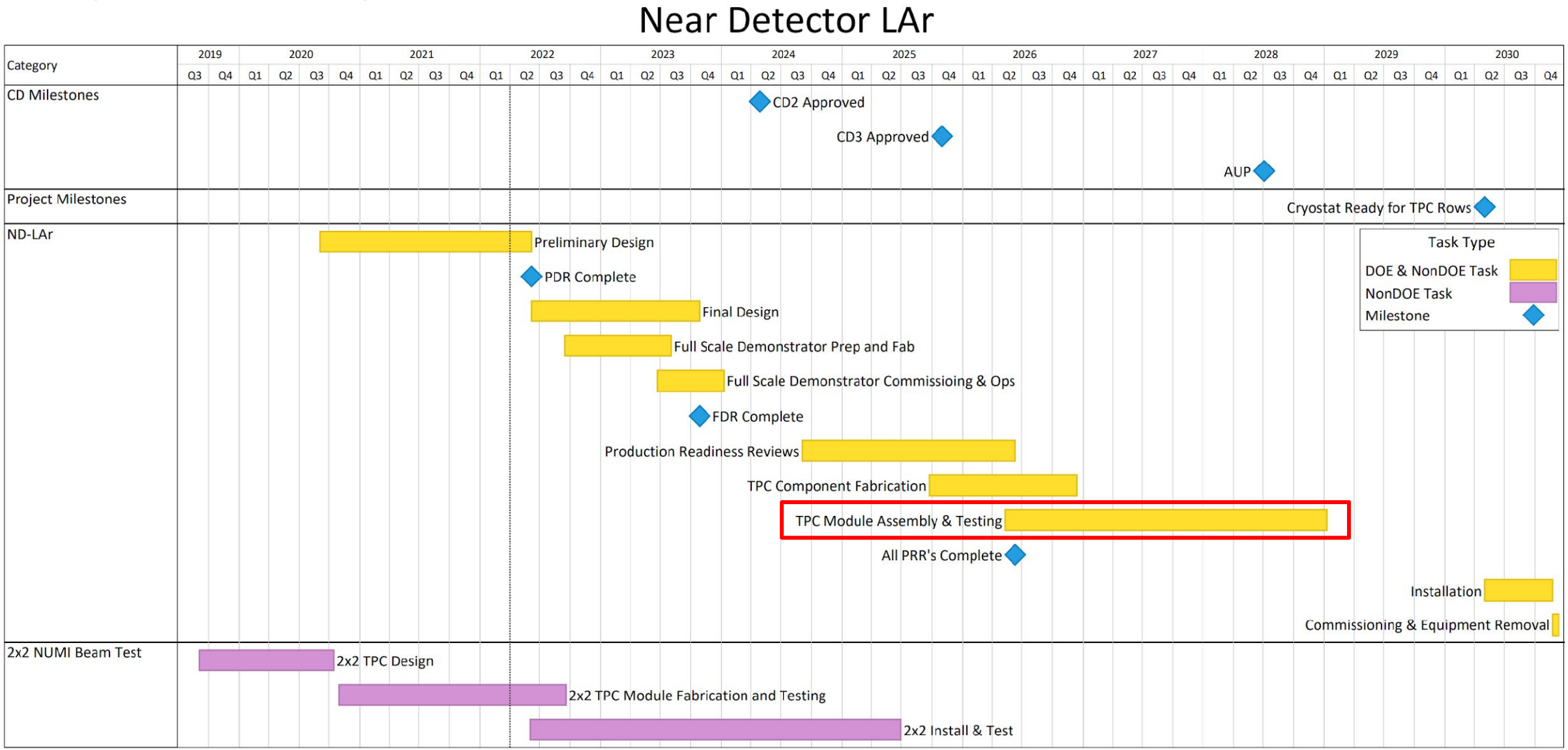
	Design & Prototyping				Production					
	On-Project		Off-Project		On-Project		Off-Project		On-Project	
131.ND.02: ND-LAr	M&S [CY-k$]	Labor [k-hrs]	M&S [CY-k$]	Labor [k-hrs]	M&S [CY-k$]	Labor [k-hrs]	M&S [CY-k$]	Labor [k-hrs]	Total Cost [FBAY-k$]	*Avg. Uncert.*
01 ND LArTPC Management	$401.5	18.3	-	43.9	$412.5	13.8	-	72.5	**$10,114.9**	*10%*
02 Module Structure	-	-	-	14.3	-	-	$2,448.0	22.0	**-**	*-*
03 HV	-	-	-	10.5	-	-	$816.0	14.0	**-**	*-*
04 Field Structure	$159.1	9.4	-	0.6	$3,560.1	4.9	-	6.5	**$7,642.6**	*60%*
05 Charge Readout	$1,331.3	17.7	-	16.6	$3,366.0	5.5	-	20.8	**$10,741.6**	*35%*
06 Light Readout	-	-	-	71.1	-	-	$5,508.0	15.1	**-**	*-*
07 Calibration	$193.7	1.3	-	33.1	-	-	-	20.3	**$414.0**	*50%*
08 TPC Module Assembly and Testing	$368.1	7.1	-	8.6	$103.0	5.7	-	32.0	**$1,865.1**	*41%*
09 TPC Integration and Installation	$584.2	11.4	-	12.4	$426.0	9.6	-	15.0	**$5,384.2**	*50%*
10 Module Assembly & Test Facility	-	5.7	-	-	$1,483.0	10.8	-	27.3	**$4,114.0**	*60%*
11 Full-scale Demonstrator Test Facility	$1,497.5	9.1	-	6.3					**$3,726.2**	*60%*
12 ArgonCube Test Facility	-	-	$1,250.0	20.9					-	*-*
13 2x2 NUMI Test Beam Facility	-	-	$2,300.0	15.0				-	-	*-*
Total:	**$4,535.3**	**79.9**	**$3,550.0**	**253.2**	**$9,350.6**	**50.5**	**$8,772.0**	**245.5**	**$44,002.5**	***43%***

Notes:

1. Extracted from current resource-loaded schedule (P6/Cobra ND-LAr Sandbox, 22 Mar. 2022)
2. Includes all on-project and majority of off-project resource estimates for ND-LAr Consortium.
3. Off-project resources include both international and domestic investments
4. CY-k$: Costs in current-year direct kilo-dollars. FBAY-k$: Costs in fully-burdened at-year (escalated) kilo-dollars.

TPC Module A&T Schedule

https://edms.cern.ch/document/2603073



Summary

- ND-LAr TPC Module Assembly & Testing vital part of overall ND-LAr program
- Detailed plan for assembly and full-module QC established
  - Input from 2x2 program, further QA planned at FSD
  - Interfaces with facilities (FSD and MATF) are well-understood and documented
  - Risks and requirements are in place with established validation methods
- **Demonstrated design maturity at the preliminary design level, ready for FSD & final design phase**

BACKUP SLIDES

TPC Module A&T Costs (Detailed View)

	Design & Prototyping				Production			
	On-Project		Off-Project		On-Project		Off-Project	
131.ND.02.08: TPC Module Assembly & Testing	[CY-k$]	[k-hrs]	[CY-k$]	[k-hrs]	[CY-k$]	[k-hrs]	[CY-k$]	[k-hrs]
02 Design	$110.5	4.4	-	1.8	-	-	-	-
03 Prototyping/Pre-Production	$257.6	3.5	-	9.8	-		-	
04 Production Module Assembly and Testing	-	-	-	-	$93.0	4.6	-	26.6
05 Near Site I&I Support	-	-	-	-	$10.0	0.4	-	2.4
Total:	**$368.1**	**7.9**	-	11.6	**$103.0**	**4.9**	-	29.0

Average Uncertainty = 41%

Notes:

1. Extracted from current resource-loaded schedule (P6/Cobra ND-LAr Sandbox, 22 Mar. 2022)
2. Includes all on-project and majority of off-project resource estimates for ND-LAr Consortium.
3. Off-project resources include both international and domestic investments
4. CY-k$: Costs in current-year direct kilo-dollars. FBAY-k$: Costs in fully-burdened at-year (escalated) kilo-dollars.