

FESHM 10210: TECHNICAL APPENDIX

Revision History

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TABLE OF CONTENTS

1.0	INTRODUCTION AND SCOPE	3
1.1	Common Terms/Glossary.....	3
1.2	Review and updating.....	3
2.0	ENGINEERING MANUAL APPLIED TO EQUIPMENT TRANSPORT	5
2.1	Documentation Management	6
2.2	Transportation Specification and Review	6
2.2.1	Transportation Specification (Shock and Vibration)	7
2.2.2	Specification Review, Versioning, and Updating.....	8
2.3	Risk Assessment – FMEA and Prevention through Design.....	8
2.3.1	Templates, Revision, and Updating.....	9
2.4	System Design and Design Review.....	9
2.4.1	Transport Device Design	10
2.4.2	Transportation Frame Design	10
2.4.3	Transport Design Documentation and Review	11
2.5	Procurement.....	11
2.5.1	Transport of Procured Devices	12
2.6	Planning and Implementation.....	12
2.7	Testing and Validation	13
2.7.1	Acceptance Testing.....	14
2.8	Release to Operation/Final Documentation	14
3.0	DETAILED TRANSPORT EXAMPLES	14
3.1	PIP-II Cryomodule Shipment.....	15
3.1.1	Documentation.....	15
3.1.2	Transport Overview	15
3.1.3	Transport Contacts	16
4.0	TECHNICAL GUIDANCE	16
4.1	Transportation System Design	17
4.1.1	Shock/Vibration Inputs during Transport	17
4.1.2	Relevant Lifting Fixture Codes and Handling Consideration.....	17
4.1.3	Finite Element Analysis for Transport System Design – Modal Analysis	18
4.1.4	Wire-Rope Isolator usage for Transport System Design	19
4.1.5	Interfaces.....	19
4.1.6	Other Design Considerations	20
4.2	Transportation Environmental Design.....	20
4.3	On-Site Transport Consideration	21
4.3.1	Load Bearing Rating for Roads and Berms	21
4.4	Transportation Instrumentation.....	22
4.4.1	Vibration/Shock Monitoring.....	22
4.4.2	Power Storage for Transports	24
4.5	Fasteners	24
4.6	Special Considerations for Pressure & Vacuum Equipment	24

1.0 INTRODUCTION AND SCOPE

FESHM 10210 and the MSS Equipment Transportation Subpanel have two explicit missions:

1. Serve as an oversight mechanism for high-risk equipment transportation for FNAL activities
2. Collect, organize, and maintain the transportation expertise of the lab as an ongoing resource of technical, logistical, and organization knowledge.

This document is the central informational repository for the second mission, serving as technical appendices to supplement the oversight process laid out in FESHM 10210.

This document contains information that may be pertinent to all equipment transports, not just those deemed Critical Transports and thus falling within the formal oversight of the Panel. All aspects of transport should be captured here, not simply limited to engineering calculations. The contents are updated by the Panel as new content becomes available.

Section 2 of this document ([Engineering Manual applied to equipment Transport](#)) takes the engineering procedures and process required by the FNAL Engineering Manual and puts them in the context of equipment transport, including guidance on documentation, organization, testing, and reviews. Each major section of the engineering manual is reflected in a subsection of Section 2.

Section 3 of this document ([Detailed Transport Examples](#)) provides, in the context of the processes in Section 2, worked examples of documentation sets for major transportation projects with links to the described documentation.

Section 4 of this document ([Technical Guidance](#)) details best practices and state of the art techniques for transportation as may be applicable to all transports, including instrumentation, handling, packing, reviews of applicable codes, including technical references as available.

1.1 COMMON TERMS/GLOSSARY

- Transported Device: The critical deliverable that is being relocated.
- Transport Frame: Generic term for a protective fixture, crating, and/or isolation system specifically designed to interface with the Transported Device for all/part of the transportation process.
- Transport System: Integrated object to be transported including the Transported Device, Transport Frame, padding or other isolation/damping systems, temporary shipping supports, temporary lifting/handling devices, instrumentation, signage, or any other protective barriers.
- Transport Panel: MSS Equipment Transport Subpanel responsible for maintaining FESHM 10210 as well as the oversight processes laid out within.

1.2 REVIEW AND UPDATING

As the Engineering Manual is updated, Section 2 will be updated by the Transport Panel to reflect the new or changed requirements. This review and update is expected to be triggered by the release of the

updated EM. At each major revision cycle of the other sections of this Technical Appendix, Section 2 will also be revisited to identify any procedural updates required.

Worked examples of documentation packages will often be added as references after completion of major milestones for transports within the oversight of the Transport Panel. The goal of this section is to provide complete, worked, reviewed, released, and successful documentation packages for transport engineering efforts as examples for future projects. When such a milestone is achieved, the Transportation Panel will determine, on a case-by-case basis, if the transport in question is a valuable addition to Section 3.0 of this Technical Appendix.

As part of the Transport Panel's regular business, interesting or potentially useful technical information or examples will be collected for later review. On a semiannual basis, these collected items will be rolled into this document, reviewed, and released as part of Technical Appendix Section 4.0.

2.0 ENGINEERING MANUAL APPLIED TO EQUIPMENT TRANSPORT

SUMMARY OF ENGINEERING PROCESS

- Specifications
 - Must be approved by requester (Word file, email, or verbal)
 - Written down and controlled
- Engineering Risk Analysis
 - Must be approved by department head or designee or lead engineer's supervisor
- Specifications Review (from Chapter 1)
 - Reviews conducted at the department level with the requester.
 - Reviews can be formal or informal
 - **Results of the review must be recorded**
- System Design
 - Should include drawings, calculations, component specifications, software overview, etc.
- Engineering Design Review
 - Reviews conducted at department, division/section or Project
 - Reviews can be formal or informal based on the Graded Approach
 - If requested, reviews may also be conducted for the Division/Section or the Project Manager by larger independent panels.
- Procurement
 - Document technical specifications needed for procured materials, parts and/or purchase requisitions
 - **Document all vendor communications**
- Implementation
 - Production schedules, delivery dates, progress reports, and QA tests of, parts and subcomponents **must** be documented
- Testing and Validation
 - Testing plans and results **must** be documented using the graded approach.
 - Testing answers the question "Does the product meet the specifications?"
- Release to Operations
 - Documentation necessary before using the product
 - Any maintenance procedures **must** be documented and available
- Final Documentation
 - Collect all documentation from previous chapters
 - Create the final report
 - Include any possible lessons learned, safety reports, publications or other extra information

Figure 1 - FNAL Engineering Manual Summary

Broadly, the Engineering Manual covers the following phases, which will be addressed in order:

- Specification Documentation and Review ([Transportation Specification and Review](#))
- Engineering Risk Assessment ([Risk Assessment – FMEA and Prevention through Design](#))
- System Design and Design Review ([System Design and Design Review](#))
- Procurement ([Procurement](#))
- Planning and Implementation ([Planning and Implementation](#))
- Testing and Validation ([Testing and Validation](#))
- Release to Operation/Final Documentation ([Release to Operation/Final Documentation](#))

2.1 DOCUMENTATION MANAGEMENT

In all cases where documentation is to be provided to the Transport Panel as part of oversight, the documents must be released in Teamcenter with reasonable and traceable review and versioning/updating practices. This is to ensure uniformity of availability and robustness of traceability for long-term record keeping, both for auditing and instructive purposes.

In cases where this technical appendix is being used as a guide for non-Panel oversight transports, it is strongly recommended to follow the same review and versioning best practices, including long-term storage with strong backup and naming functionality. At Fermilab, many groups use docdb-based file management which provides much of this functionality but may have restricted access. In these cases, it is recommended that critical documents (design summaries, major presentations, engineering notes) instead be released in Teamcenter where they are generally accessible.

The standard that is recommended in these cases is organizing all documentation such that it will be findable and useable in case the Transported Device needs to be moved again in the future.

2.2 TRANSPORTATION SPECIFICATION AND REVIEW

One of the core documents for transportation planning is a detailed specification document that logically lays out the requirements for all aspects of the Transport System in all configurations. The specification and design of Transported Systems is complicated by the interplay of various vibration inputs, shocks, and configurations that a Transported System will potentially experience during its full lifecycle. Specification documents must reflect this complexity clearly.

It is critical to define all configurations and stages of transport, then break up the specification/design process for transport into manageable pieces. While the details of each transport will vary based on technology and requirements, the following sections will detail a process that should be generalizable to all transports.

Each activity in a transport is defined by a set of three distinct factors that, combined, determine a safe or unsafe transport:

Transported Device Vulnerabilities: Vulnerabilities of the device being transported to shocks (high peak accelerators for short periods) and ongoing vibrational energy (potentially large mechanical

response to many-periods long environmental driving terms causing fatigue and failure), environmental factors, tipping angles, etc.

Expected Transportation Environment: Typical/expected input vibration and shock loads from the system being used to transport the system (e.g., vibration and shocks typical of an over the road transport via air ride trailer), potential handling/environmental factors or events, including all transport methods and major events (handoffs, transfers, hold points, etc.)

Transport Packaging Performance: The properties of the Transport System for the Transported Device, which may include an isolation/damping system used to reduce or otherwise isolate the Expected Transport Environment from the Transported Device, and protection from ingress or environmental conditions.

2.2.1 Transportation Specification (Shock and Vibration)

Transportation performance cannot be assessed without a clear understanding of all three factors; however, it is possible that the design of the Transport Frame and Transport System may be done separately from the design of the Transported Device itself. Early in the design process, a unifying specification should be written that clearly defines:

1. The transportation methods (rail, road, air, sea, etc.) to be used, and the codes and standards used to determine the expected input shocks and vibration levels from these transportation methods.
2. The maximum allowable shocks and vibration levels the Transported Device may experience during transport in all three directions. This, compared to the inputs, drives the design of the Transport Frame and Transport System.
3. The required maximum shocks and vibration levels the device itself is designed to experience with no expected failures or damage. While this can be the same as the previous item, a design margin is typically applied to the load and/or material properties. This requirement drives the transportation analysis of the device. **In general, determining the transported device's vulnerabilities and requirements is quite challenging and must be entirely within the scope of its design team. Other design teams (either FNAL-internal, or external Partners/vendors) cannot be expected to have any insight into the transported device besides the written specifications.**

Other topics that should be covered in a transport specification:

- Physical Interfaces
- Environmental Factors
- Transportation Instrumentation
- Handling/Lifting Requirements

2.2.2 Specification Review, Versioning, and Updating

During specification review and feedback, three groups should be considered in addition to the review by the Transport Panel:

1. Team internal review: Major stakeholders from the Transported Device's design team should first review the specifications. Analyzing the Transported Device's vulnerabilities and designing sufficient fixturing/tooling or configurational changes is generally the most challenging part of transport and should be considered first.
2. Transport stakeholder review: All other major design/device stakeholder teams should have a chance to review and comment on the integrated Transport System specification. This is especially critical in cases where the transport system is not designed by the same team as the Transported Device. The Transport System design team will be expected to design mating systems based only on these transport specifications (e.g., when this design is done by a transport vendor or partner laboratory).
3. External expert review: In cases of very significant transport challenges, it may be beneficial to bring in external transportation experts to review the transport specification (perhaps as part of a more general transport planning review). This can range from FNAL-internal but Project-external document review to a procured consulting contract with a major delicate transportation vendor (Emmert, the vendor that moved the g-2 ring, would be an example).

It is recommended to review and approve/release this specification prior to the initiation of the detailed design of the Transported Device so that any changes can be incorporated into the final design. The transport specification should be updated as major changes are made to the Transported Device design and at major milestones in the transportation system design as issues are inevitably identified. Each revision/update, the relevant stakeholders should be involved in the review and approval process.

2.3 RISK ASSESSMENT – FMEA AND PREVENTION THROUGH DESIGN

The Engineering Manual includes a high-level assessment of a broad array of risks, including transportation. Completion of this risk assessment is a basic requirement of all projects at the lab, regardless of scope, and it helps drive the level of documentation, review, and planning required. This EM Risk Assessment table can be found here: (<https://ad.fnal.gov/EPG/index.html>).

For transportation of complex and sensitive Transported Devices it is strongly recommended that the detailed failure modes be systematically identified and mitigated. A Failure Mode and Effect (FMEA) tool has been developed by the Transportation Panel to assist in this process, including assessment of:

- Process risks (Human Factors): Mistakes of procedure or execution, including misconfiguration of the transport system, improper handling, etc.
- Design risks: Critical design feature that are vulnerable to transport activities or the shocks/vibrations of transport itself (ceramics cracking, thin bellows fatiguing, etc.). This process is critical for ensuring that transport fixturing, and tooling is sufficient to mitigate the risks of transport

- External factors: Logistical or technical factors that are generally outside of the control of the transport company or FNAL that may have significant impacts on shipment (delays, inclement weather conditions, etc.).

The FMEA tool also uses a graded approach for assessing and prioritizing these risks, including assessing the severity, likelihood, and probability of detection of each risk.

Personnel safety is a primary concern for all work at Fermilab. Various processes at the lab include safety assessments of varying detail, ranging from verbal/mental Hazard Assessments to full Transport Panel oversight. *Transport poses an enhanced set of risks because it is, in almost every case, off-normal work performed a small number of times and in an equipment configuration that is generally not the designed use case (i.e., normal operating conditions after Transport Device is fully installed in final location).*

Because of the unusual effort and diversity of safety risks involved in transport, a dedicated, written safety assessment, Prevention through Design, is recommended for all transports. The PtD Table requires identifying all major stages of the transport lifecycle and the safety risks at each stage. A graded assessment of the safety risk without any mitigation is then compared to a post-mitigation assessment, allowing prioritizing of safety risks at all stages.

2.3.1 Templates, Revision, and Updating

The current templates for the Prevention through Design Table and Transportation Failure Mode and Effects Analysis, including training materials, can be found at ED0012422. *Completed FMEA and PtD Table in these formats are required documentation for transports within the oversight of the Transport Panel.*

Both FMEA and PtD table are meant to be living documents, drafted and reviewed early in the design process and updated on a regular basis as the design evolves and mitigations are incorporated into the design. It is strongly encouraged to have a broad variety of inputs and feedback to the list of failure modes and their mitigations, including relevant representation of the design and implementation teams, especially technicians.

2.4 SYSTEM DESIGN AND DESIGN REVIEW

Clear definition of the breakdown of design scope and requirements in the transport specification are essential to providing actionable design criteria during system design. The details of the design activities will vary greatly based on the technology and scale of equipment to be transported, but the following are general guidelines for transport design:

- All designed items should be documented including, where applicable, drawings, 3D models, schematics, stay-clear envelopes, physical interfaces, and physically vulnerable items
- All major transport design calculations should be documented and reviewed to a level commensurate with the system complexity, including FEA, modal analysis, alignment assessments, etc. where relevant. Calculations should be reproducible.

Transportation should be considered at all stages of the fabrication and installation to the extent possible. Examples include:

- Transportation of sub-assemblies/incomplete components between fabrication locations on-site at FNAL
- Loading and unloading into transportation systems (crane, fork-truck, etc.) or between transport systems (e.g., handoff at an airport from truck to plane)
- Transport using different modes of transport (train, plane, trailer over road, etc.).

Each transportation stage must be identified and defined clearly. Each stage must then be analyzed separately because the Factors discussed above will be different and may require separate solutions. Identification of potentially vulnerable components/features early in design reduces the risk and cost of modifications. If needed, the transport specification can be modified to put more stringent isolation/damping requirements on the crating/transport fixturing, or the transport methods can be changed to avoid the most serious shock/vibration sources.

When design is complete, the transport design should be documented, demonstrating that the design meets the specified shock/vibration environment with the specified design margins.

2.4.1 Transport Device Design

The Transported Device Vulnerabilities are a product of the system's design decisions and technology choices. Given this extreme potential diversity, the designers of the Transported Device are expected to be the experts in the technologies of the Transported Device. Relying on outside vendors to assess Transported Device internal vulnerabilities is not recommended.

Design for transport to a given specification should include:

- Identification of vulnerable components
- Design of transport fixturing and tooling to support/restrain specific items
- Choice of suitable transport configurations, including potential partial shipments and disassembly/reassembly after transport.

Example factors that should be considered during transport design:

- Changes in alignment
- Fatigue-sensitive components (either high-cycle number or large displacement)
- Low frequency mechanical resonances
- Damage to brittle components.

2.4.2 Transportation Frame Design

In more complex transports, dedicated Transport Frame design may be considered its own design effort. The Transportation Frame design can be quite complex depending on the requirements of the device being shipped. In addition to vibration/shock isolation, the Transportation Frame and Transport System may be required to provide a robust handling

interface, protection from environmental effects, housing for instrumentation, and external signage. All these requirements should be detailed in the Transport Specification.

2.4.3 Transport Design Documentation and Review

Transportation should be integrated into the system design as early as possible and included in design review activities. Dedicated assessment of transport as a design topic, either as part of the system design review, or a stand-alone assessment, is highly recommended because of the diversity of design activities that impact transport. It is strongly recommended that all design or documentation reviews include reviewer(s) that are experienced in general transportation and, optimally, transportation of equivalent/similar technology.

For more complex or critical transports, dedicated transportation design reviews may be called for. These reviews should cover:

- Specification and design factors for the system being transported
- Choice of transportation methods
- Isolation frame design (if used)
- Procedural steps for loading/unloading, shipping configuration/preparation, instrumentation, etc.
- Chosen design validation plan (simulation, impact testing, test shipments, etc.)

All transport calculations and design reports should be held to review standards equivalent to the device design documentation itself including (but not limited to):

- Transportation Specification
- Transported Device Design Report
- Transportation Frame and System Design Report
- Related Design and Interface Drawings
- Required Risk Assessment Documentation (Prevention through Design Table and Transportation Failure Mode and Effect Analysis)

2.5 PROCUREMENT

It is common for equipment transport activities to include vendor effort/expertise. This ranges from using standard shipping services (USPS, FEDEX, etc.) to dedicated critical transport companies that design, fabricate, and validate custom shipping systems and execute/coordinate complex shipping procedures. Regardless of the complexity of the procurement involved, a well-written shipping specification is critical to success. The following factors should be considered while writing this specification:

- Clear scope of vendor activities
- Shipping environment requirements that must be provided (shock/vibration, handling requirements like no rail transport/no fork trucks allowed)
- How these requirements will be verified (vibration monitors, GPS tracking, direct supervision, etc.)

- Design requirements (if any) for the shipping system including interfaces, vibration/shock isolation, physical/environmental protection, required assumptions for device behavior
- Expected schedule of transports and realistic flexibility of schedule so that realities of shipping schedules can be considered
- Handoff requirements (pickup/delivery including effort for loading/unloading)
- Oversight of any 3rd party handling, especially rigging, loading and unloading
- Requirements for customs, including inspections, fees, and access at all stages of transport
- Recommended signage and labeling for the shipment including code compliance and other documentation to be attached to this shipment itself.

It must be restated that, excepting very special cases, shipping vendors cannot and should not be expected to have any insight into the details of the Transported Device beyond the requirements laid out in the specification.

It is recommended to include some form of validation to the written procurement. This may scale from a first-article test shipment to a staged testing of a complex transport system. These milestones, including clearly defined testing responsibilities, methodology, and success criteria should be in the procurement specification.

Once a shipping contract is awarded, ongoing communication is recommended, up to and including design reviews for the vendor design scope. The technical complexities of transport are not trivial, and it is important to ensure that the vendor clearly understand the specification, both during bid evaluation and after the contract is awarded.

Special attention should be paid to customs, Value Added Tax, and pre-clearance for international shipments. For example, an SRF cavity was being shipped to a partner at the University of Pisa in Italy. Italian customs did not recognize the University of Pisa as part of the Ministry of Education Universities and Research complex, which has a declaration for research goods that allow VAT free entry into the country. The shipment was delayed in customs for 30 days while payment of this tax was settled.

2.5.1 Transport of Procured Devices

In the case of procured equipment or equipment from a partner lab, it is strongly recommended to get detailed information/documentation on how transport is accomplished. Deliverables such as crating design, procedures, and inspection criteria can be critical to a later transport of a delivered item.

2.6 PLANNING AND IMPLEMENTATION

Transportation is rarely complex enough to drive the level of scheduling/cost oversight of a project. For all projects, the schedule and costs of transport should be captured to the level of granularity used for other activities. All reporting and statusing should also be commensurate with other project activities.

In general, it is recommended that a realistic assessment be done of transport costs and schedule, including validation activities. It is extremely common for first transports/testing to be delayed vs. expected schedules.

It is recommended that the risk of transport failures be captured, as appropriate, in the project planning (e.g., risk registry, contingency planning).

The exception to this is, potentially, the Equipment Transport Panel oversight requirements. FESHM 10210 outlines the required documentation and reporting for transports that fall under the oversight of the Panel, and these should be satisfied regardless of the scale of the rest of the project.

It is recommended that a Transport Plan be created, and include information such as:

- Description of the equipment to be transported
- Number of devices/transport
- Basic schedule of transport activities
- Responsibility matrix for all transport activities
- Any special facilities needed
- Documentation list of the transport activities
- Plan to identify, assess, and mitigate design vulnerabilities including validation testing and design reviews.

Transports requiring oversight of the Panel are required to have such a Transport Plan, as laid out in FESHM 10210.

2.7 TESTING AND VALIDATION

All requirements for a design must be verifiable, and transport is no exception. This may include verification via calculation/simulation, inspection, testing, or demonstration in use. Verification must be considered for all transport requirements, and a verification plan should include the specific calculations, inspections, testing, etc. that will be done.

Complex activities including assembly, reconfiguration, and major tests should have a written test plan/procedure/traveler with steps and measurements and definitions of success. For more complex transports, a Quality Control plan should be developed early in planning that details the critical activities of transport (inspection, assembly, tests, etc.) and what procedures/travelers that will be written for those activities. This may include adding transport-specific inspections into fabrication/assembly travelers as appropriate.

Independent validation of the transport system, including assembly and performance is recommended if practical. This may be accomplished by replacing the device to be shipped with a dummy mass with realistic interfaces and similar gross physical properties (weight, envelope, moments). This allows for verification of the transport system requirements separately from the device requirements, reducing the risk of damage from underperforming transport tooling.

Validation of the shipping system (with dummy mass or real device) may include staged testing as practical to reduce risk. Examples include test assemblies, short road testing, up to complete transport of dummy mass or prototype device. All of these tests should include as realistic and complete configuration as possible including instrumentation, packing list, and procedure.

2.7.1 Acceptance Testing

It should be noted that transport system validation is separate from device acceptance. It is expected that the Transported Device will undergo an entirely separate validation, outgoing inspection, and incoming inspection process totally driven by the device design itself.

Incoming inspection of a routine transport is likely to include tests such as visual inspection, fastener torque measurement, and analysis of transport documentation (e.g. records from shock loggers/vibration sensors, GPS monitors, and/or temperature sensors). Failure of a transport specification (high shock, extreme temperatures, etc.) should trigger additional scrutiny of the device, but in the vast majority of cases the ultimate acceptance/rejection of the device should be driven by the Transported Device's acceptance criteria, not the transport specification criteria on their own.

2.8 RELEASE TO OPERATION/FINAL DOCUMENTATION

In the case of transport, release to operations is relevant in the transition from validation/first article transport to routine transport.

Once validated, a transport system process should include (where appropriate) approved/released:

- Procedures/travelers including reconfiguration, assembly, inspections, instrumentation, etc.
- Drawing packages/models including transport configuration.

These should be, as much as possible, consistently applied during routine shipping, with standard non-conformance documentation and resolution practices applied. Major revisions to the transport process should not be made lightly, should be well-documented, and all efforts should be made to revalidate the transport system requirements with the updated process.

This philosophy is especially true for vendor/partner delivered items where FNAL does not own the transport design or execution for delivery. Modification to the transport scheme (tooling, procedures, etc.) becomes very challenging when the underlying transport design documentation is not available.

3.0 DETAILED TRANSPORT EXAMPLES

In this section, specific examples of equipment transport are documented. Each example should include:

1. Documentation List
2. Overview (with references to above)
 - a. Transport Scope
 - b. Brief description of the device transported
 - c. Highlights of transport specification including notable vulnerabilities
 - d. Validation Process and High-Level Lessons Learned
 - e. Relevant contact information (MSS Transport Panel representatives, technical leads)

3.1 PIP-II CRYOMODULE SHIPMENT

3.1.1 Documentation

Table 1 - PIP-II Cryomodule Transportation Documentation

	HB650 Cryomodule	LB650 Cryomodule
Transport Spec	ED0012328	ED0013421
Transport Plan	ED0012594	ED0013424
Transport ISD	ED0012741	ED0013425
Transport FMEA	ED0012325	ED0013422
Transport PtD	ED0012559	ED0013423
Frame Design Report	ED0012560	TBD
pCM Transport Analysis	ED0012420	TBD
On-Site Transport Spec	TBD	TBD
CM Transport Config Drawings	TBD	TBD

3.1.2 Transport Overview

The PIP-II Project is shipping large cryo-assemblies from two different European partners with intentionally aligned strategies. Their designs are highly convergent, but many technical and logistic details are necessarily divergent. Design details are also handed individually by the Partner labs, so their transport documentation was completely separated, although the content of the two sets of documents is highly convergent.

European labs are, as In-Kind Contributions for the PIP-II Project, fabricating, assembling, and delivering cryomodules (CMs) from their labs to FNAL. STFC-UKRI (UK) is producing the HB650 CMs and CEA (France) is producing the LB650 CMs. Transport of these large, delicate devices requires a dedicated shipping frame and use of a specialized transport company. The exact scope ownership of the CM designs, Frame designs, and transport execution is relatively complex and laid out in detail in the Transport Plans for each lab. Despite the complexity of detailed ownership, the labs worked collaboratively to establish a systematic and common approach to transport to minimize extraneous design effort and maximize the benefit of lessons learned.

These CMs are large (~10m) cylindrical vacuum vessels mainly containing SRF cavities and associated hardware (RF Couplers, cryogenic piping, etc.). Their designs are similar to other SRF projects, LCLS-II (HE), XFEL, CEBAF, etc.

Based on experience from these projects, the cryomodule is specified to be able to survive unlimited numbers of shocks up to 1.5 g (transverse), 3g (vertical), and 5g (longitudinal, beam direction). The protective transportation frame is specified to ensure, given input

vibration/shocks derived from the MIL-STD-810H standard for road and air transport, the cryomodule is isolated from shocks greater than 1.5g, 2.5g, and 3.0g (transverse, vertical, longitudinal) to give margin for unexpected shocks during transport.

The cryomodule design includes a specification that individual critical designs must have no mechanical resonances under 30 Hz, and that the assembled module has no major resonances below 20 Hz. The transport frame is specified to provide 90% isolation of all input above 10 Hz. In this way, low resonances can be identified early in CM design at the individual component level and the full assembly can be assessed realistically while providing overall margin for transport. This is critical because of the significant number of fatigue sensitive thin-walled bellows in the vacuum and piping components.

The transport frame is also designed as a self-contained lifting fixture, certified to both US and EU lifting codes. This simplifies handling and protective requirements for the transport frame, ensuring no required access or disassembly during transport and handoffs. Due to the extended duration and loading/offloading concerns, only road and air travel are allowed, no rail or sea transport. Loading/handling activities at the airport will necessarily be done by third party riggers, and the code certified lifting fixture with dedicated shackle/slings greatly reduces the risk of mishandling.

Validation of the transport systems is planned in several stages:

1. Validation of the CM design as possible during production via impact testing
2. Validation of the transport system with a dummy load, verifying isolation and lifting performance via escalating road test, culminating in a full transport from FNAL to STFC-UKRI, realistic in all aspects except the transported load itself. This additionally validates transport service procurement, oversight, and vendor handling. This also provides a training opportunity for the STFC-UKRI staff for loading and unloading activities.
3. Final validation of the integrated transport system is with a validated prototype HB650 CM, first local escalating road tests, then a shipment to STFC-UKRI and back, where it will be re-cold tested and validated.
4. First shipments of a CM from STFC-UKRI and CEA will be carefully monitored for deviations from the demonstrated transport performance.

3.1.3 Transport Contacts

- MSS Transport Panel Representative: Jeremiah Holzbauer
- PIP-II Transport Lead: Jeremiah Holzbauer
- Lead CM Transport Designer: Sergey Cheban, Josh Helsper
- Lead Transport Frame Designer: Mitchell Kane, STFC-UKRI.

4.0 TECHNICAL GUIDANCE

In this section, major categories of technical information are gathered as potential guidance for all transports. Where possible, repetition of existing resources is avoided, and links/references provided.

4.1 TRANSPORTATION SYSTEM DESIGN

The transport system, encompassing the device being transported and any specialized fixturing, is a very broad topic depending on the techniques involved. This section will touch upon points of consideration during the design of this integrated system.

When designing an isolation system with significant flexibility, be sure to assess travel during transport and include the envelope of maximal travel in the interfaces/system design.

4.1.1 Shock/Vibration Inputs during Transport

A universal topic for transport is definition of input loads to be used as the basis of the design. These inputs, captured in the specifications/requirements, drives the transport design.

One type of input that may be relevant is maximum vibrational input spectra, commonly specified in acceleration spectral density. Various sources exist for this data for all types of transport which can be used. For multi-modal transport, various codes can be combined in a ‘worst-case’ envelope of spectra for your design inputs.

- United States Department of Defense, MIL-STD-810H, Department of Defense Test Method Standard for Environmental Engineering Considerations and Laboratory Tests, 2019
- British Standards Institution, BS EN ISO 13355:2016 Packaging - Complete, filled transport packages and unit loads - Vertical random vibration test, 2016.
- ASTM International, ASTM D4169 - 16 Standard Practice for Performance Testing of Shipping Containers and Systems, 2016.

Shock inputs are also challenging to clearly define ahead of time due to the diversity of realistically possible. Critical for analysis is the time structure of any shock applied to the structure. The most detailed procedure for clearly defining these shocks for calculation is done here:

- MIL-STD-810H, Method 516.8 Procedure II.

In some cases, there is less formal guidance that has been used at FNAL. The specifications for maximum permissible shock & vibration loads given by Fermilab for cryogenic vessels and piping can be found in Section 4.6.

4.1.2 Relevant Lifting Fixture Codes and Handling Consideration

Generally, transport systems (packaging, dedicated transportation fixturing, or simple reconfiguration of the critical device) should be designed considering with all handling methods. This may include, but is not limited to:

- Dedicated fork-truck lifting points including tipping calculations (ANSI B56.1)
- Secure handles with appropriate load rating and ergonomic considerations
- Engineered lift points/attachment interfaces

- Protective masks/caps/covers/fixturing for delicate components (identified in the transport FMEA)

For reference, the 10000-series FESHM chapters cover the oversight of material handling topics at Fermilab and all work at Fermilab must comply with their requirements. This includes crane and rigging (10110, 10110, 10130, 10140, 10180, 10190, 10200), Powered Industrial Trucks (10120), and Onsite Hazardous Material Transport (10150). Considerations of these chapters should be included in all transport system design.

In more specialized transports, especially if rigging/lifting activities will be done by non-Fermilab personnel, it may be useful to have dedicated transport fixturing certified as lifting devices to national safety standards such as:

- ASME B30.20 Below-the-Hook Lifting Devices and ASME BTH-1 Design of Below the Hook Lifting Devices
- BS EN 13155 Cranes – Safety – Non-fixed load lifting attachments.

These code certifications including signage are widely recognized and should help ensure that contracted rigging personnel can be used at handoffs as necessary.

An example of the seriousness of handling and tipping issues during transport is an incident that occurred at ORNL in 2014 (incident ID: 2014-UTB-ORNL-0011). A heavy magnet was being moved on-site at ORNL on a tall, narrow stand with casters. During the move down the ramp from the truck, the magnet tipped, trapping and severely injuring a worker. The investigation revealed that the tipping hazard was known, but not properly communicated. In fact, the magnet had fallen over during a previous transport, damaging the transporting vehicle, but this had not been reported or documented.

4.1.3 Finite Element Analysis for Transport System Design – Modal Analysis

Modal analysis is a tool to identify the natural frequencies of a system. This analysis is broadly useful for transport in two ways: identification of vulnerable mechanical resonances in the critical device, and for analysis of an isolation system. For all calculations, sensitivity assessments should be done reflecting design uncertainty, e.g., total weight, center of mass, isolator stiffness, or other damping material properties.

Analysis of the critical device for mechanical resonances should be done to identify vulnerable components. The resonant frequencies should be compared with the expected input spectra with consideration to factors such as fatigue vulnerability, potential deflection and collision, and brittle components. The specific vulnerabilities of the system will depend strongly on the device being transported and should be driven by the detailed transport FMEA. In all cases, care should be taken while building the model for simulation including boundary conditions, material properties, and other assumptions (e.g., component tensions, fastener behavior, frictional forces, etc.) as these can strongly drive the results of your simulation.

Design of an isolation system should include modal analysis to assess motion of the critical device in all degrees of freedom. Care should be taken to include the realistic isolator

characteristics including damping coefficients, especially if non-linear. The vendor generally supplies this information. For non-linear springs, deflection from gravitational loads should also be considered.

The resonance modes of the isolation system can be used in a vibration response calculation, transforming the acceleration spectral density (ASD) profile selected as input in the specification into the expected ASD input on the critical device after isolation.

4.1.4 Wire-Rope Isolator usage for Transport System Design

Wire-rope isolators are a shock absorber/vibration isolator technology based on loops of stranded metal cables secured between two rigid mounting plates. The main benefit of this technology is that it allows significant travel while maintaining high stiffness with near isotropic stiffness in all three directions. This means that a relatively small number of these isolators can be used to support and isolate a load even when considering large input shock values.

These isolators are produced by a number of vendors, domestic and international, and they will provide guidance on selection of spring model including stiffness curves and sizing calculations. Springs should be selected based on expected maximum specified shocks, not simply static gravity loads. MIL-STD-810H provides design criteria for equivalent drop distances which may be provided as a guidance total compressed spring energy and thus total deflection required during spring selection.

A major complication of using wire-rope isolators is that they are non-linear, providing different response to small excitations compared to large shocks. This non-linearity is challenging to completely assess during design and information from vendors on this topic is limited. It is recommended to design wire-rope isolator systems with conservative performance margins and include realistic isolation system validation into the transport system design process as practical.

4.1.5 Interfaces

Interfaces between the device being transported and crating/transport fixtures often fall in to one of three categories:

1. existing mounting points already on the device for non-transport uses
2. bespoke mounting points for transport
3. use of a clamping or grabbing fixture that directly constricts and holds the device without additional fasteners.

As with all well-engineered systems, the interfaces should be clearly defined early in the design and only modified via a controlled release process, ensuring all stakeholders are informed of any changes.

This includes not only direct physical interfaces, but also envelopes. Released drawings of the expected shipping configuration of the device with explicit space envelopes, stay-clear areas, and vulnerable components identified are essential for crating/transport fixture design.

These stay-clear envelopes should include the maximum extend of motion expected during transport, which can be significant for a spring isolation system. Contact between the isolation system and the load should be avoided in all loading conditions.

4.1.6 Other Design Considerations

A transport system or packaging should include clear and obvious labels in English and language of point of origin indicating:

- Contents of shipment
- Contract number
- Gross weight
- Approximate center of mass when the load is significantly asymmetric, but packaging is not
- Presence of fragile contents
- Presence of shock and vibration monitoring equipment
- Labels warning against tipping the crate from its normal position or stacking any items on top of it.

It is best practice to design the packaging/system for repeated access to the equipment without significant damage occurring to the packaging/system itself.

If a crate/package is designed to be handled via hand-truck/fork-truck/overhead crane, suitable lifting attachments should be included in the packaging design. These features (lift/pick points, tie down locations) should be appropriate and clearly marked exterior features.

4.2 TRANSPORTATION ENVIRONMENTAL DESIGN

A non-trivial factor in transport system design is protection from environmental exposure during transport and storage. This is especially true during long transports via sea or hold overs in customs which are likely when international shipment isn't handled by a specialty vendor to help with preparation of documentation and execution.

Ingress Protection (IP) ratings, defined by the international standard EN 60529, and National Electronic Manufacturers Association (NEMA) ratings are two methods of specifying the design of a system versus access via personnel, tools, or weather. These can specify maximum opening sizes as well as water tightness in various conditions (direct/indirect rain, humidity, etc.). These standards can be useful during the requirements phase of transport system design. Additionally, the situation during transport can be specified during vendor selection, including requirements for:

- Tarping, use of covered vehicles
- Storage in a covered area

- Placement/location in shipping vehicles.

Materials selected for the transport system should be made with potential precipitation (or potential seawater) exposure included to prevent corrosion or other negative impact. This extends to transport equipment, including instrumentation, wiring, and any battery systems used.

Desiccant packages are commercially available and should be considered for humidity sensitive transports that will be transported/stored for long durations.

This consideration should also extend to safety and security of the transported goods. Reasonable measures should be implemented in transport system design and vendor selection to ensure that unintended/malicious access is limited/discouraged, especially when the load is unmonitored.

For international shipments, effort should be taken to ensure the shipping system is ISPM (International Standards for Phytosanitary Measures) 15 compliant. This is a code to limit the spread of pests or insects, and mostly applies to wood used in shipping material. This broadly includes the use of pressure treated wood or plywood.

4.3 ON-SITE TRANSPORT CONSIDERATION

Most material/equipment moves on-site are handled via the Material Move Request (MMR) form on the ServiceDesk. There is a field in the MMR form for ‘additional information’, and it’s encouraged to include any additional transportation oversight procedures or considerations here, potentially including:

- Specific routing requested, including potential pre-surveying of route
- Specific truck/tractor/trailer requirements
- Trail car/observer
- Road closures/security involvement
- Additional speed limitations, driving restrictions such as avoidance of potholes/curbs/berms.

Especially when imposing additional restraints such as the ones listed above, the following best practices are recommended:

- Pre-briefing/toolbox meeting prior to transport to discuss work to be performed including all restrictions and procedural requirements
- Clarification of roles and responsibilities, especially when trail cars/observers are involved
- Use of radio/walkie talkies for the observers to communicate with the drivers if necessary.

4.3.1 Load Bearing Rating for Roads and Berms

The roads on-site at Fermilab in Batavia are built to the same standard as general roads in Illinois ([IL DOT Road Spec](#)). This means that Illinois road legal transport vehicles/loads will generally work well on the roads on-site. One special issue on-site is crossing the main ring berm, which has a limited weight loading and is generally avoided during heavily loaded transports. For heavy item transports that must cross the berm the FESS Engineering Department Head should be consulted to ensure that the berm is not damaged.

4.4 TRANSPORTATION INSTRUMENTATION

It is of paramount importance that requirements for a transport system be verifiable, and shock/vibration monitor systems can provide a powerful tool to verify requirements, monitor ongoing shipments, and assist in post-mortems of transportation incidents. Other potential parameters to monitor will vary by shipment, but may include pressure/vacuum, temperature, and position. A detailed assessment of the system via the transport FMEA should be done to identify potential values for monitoring.

4.4.1 Vibration/Shock Monitoring

There are two major strategies for monitoring of forces during transport: shock and vibration. In reality, these are measurements of the same thing (acceleration at a specific location) but with different implicit time structures.

- Shock measurement: Generally focused on capturing fast ~1-20 ms events and resulting transients (1-10 seconds) where high stress/low-cycle fatigue is a major concern (e.g. cracking of a ceramic). Data capture tends to be triggered by the event instead of continuous with a high data rate (1 kHz or higher) to capture the fine structure of the fast events. Generally this is measured on systems with either lower mass or not protected by a dedicated isolation system (e.g. wooden crate, or the outside of an isolation system to measure the input to the system). The peak acceleration involved can be quite high, meaning that dynamic range of the sensor can become important (realistic shocks on large, crated devices have been seen over 25 g).
- Vibration measurement: Generally focused on repetitive excitation of mechanical resonance, including potential high-cycle fatigue sensitive items. Mechanical resonance tend to be lower in frequency (<100 Hz) and thus require lower sampling/data rate compared to shock measurement. Longer captures have more value, generally limited by the power and data storage capacity available. Especially for delicate systems protected by isolation systems (padding, springs, etc.), the peak acceleration seen tends to be lower, although >10 g events have been occasionally observed in these scenarios.

Low tech shock and tilt monitors are widely available commercially and very straight-forward to use. They generally include visually distinctive ways of indicating if a shock threshold has been reached (numerous shock thresholds are available) or indicating if a tilt about a certain axis has happened and to a rough degree how far they were tilted. One common set of commercial brands is Shockwatch, with Tip-N-Tell and Drop-N-Tell products. Similar products exist for humidity and temperature.

For all accelerometers, the design considerations remain the same:

- Power: How much power does the system draw, and how long can it autonomously run without intervention?
- Data storage: Sampling/Data rate, triggered/continuous, total storage available and thus sensor lifetime without intervention, and data transfer/post-processing effort should be considered when sizing an acceleration monitoring system.

- Complexity of setup and risk of system failure: All measurement systems (homebuilt, commercial packaged sensors, etc.) run the risk of failure and loss of data. This is especially true for transportation where the number of times the system will be used is generally low. Special care should be taken in proceduralizing, testing, and monitoring of a system to ensure high-quality data is captured during the entire transport.
- Sensor positioning: Care must be taken in selecting the locations for acceleration monitoring. Simulations, calculations, or impact testing should drive monitoring to the most critical components, either the most sensitive or locations with high resonant response. These sensors should also be used as feedback, to validate the calculations. This is true for both Transported Device design and isolation system design. Measurement of time-correlated acceleration across an isolation system can be compared with the expected isolation to validate its design.
 - Special care should be used to consider the sensor and wiring's impact on the device being measured, including weight and drag imparted.
 - The sensor should be solidly affixed to the device it is measuring, either by dedicated mounting features or specifically chosen adhesive/double-sided tape. Care should be taken to avoid creating additional resonances or intermittent contact between the accelerometer and the measured device.
- Sensor choice: Broadly speaking two types of accelerometers are widely used: DC-MEMS and Piezoelectric accelerometers. While the exact products available vary widely and are improving with time, broadly, DC-MEMS sensors are DC-coupled, giving a continuous measurement of gravity and very low frequency acceleration, but with a limited high frequency response (>1 kHz). Piezoelectric sensors tend to have a better high-frequency response (>1 kHz) than MEMs sensors, but their low frequency response tends to roll off below 10 Hz.

Use of Slamstick-brand accelerometers for transport of superconducting magnet coils for the AUP-HiLumi project identified two potential failure modes/issues with these sensors (summarized in a report at ED0017325):

- The piezoelectric accelerometers (not DC coupled) saw sudden, non-physical, large, full-scale DC shocks that relaxed back to zero with a ~1 second time constant. These piezos have a mechanical resonance near 10 kHz, which was being excited and saturating the associated charge amplifier. The decay period was the electronic decay of the associated circuit. The source of the excitation was not confirmed to be a real vibration.
- The DC-MEMs sensor in the same package experienced sudden bursts of high frequency noise, bin to bin excitation. The vendor claimed this was from a fault in an old version of the built-in anti-alias filter and could be corrected by increasing the sampling rate.

Example of high shocks: During the transport of two 1.3 GHz SRF cavities from a vendor in Europe to FNAL, there was a handling incident that included the wooden crate they were in being stored on its side, triggering the tilt and shock watches on the crate, including a 25 g shock watch. The sensors on the crate were configured for triggered capture, and DC-coupled,

recording large shocks and the box rotation until their battery failed. The shocks recorded by the sensors were limited to their 9 g dynamic range. The full write-up can be found in Teamcenter (ED0017433).

4.4.2 Power Storage for Transports

Transport of hazardous materials is a major consideration for powering instrumentation and monitoring equipment during a transport. Different modes have different requirements, and shipping vendors should be consulted for the details of what materials are restricted or forbidden. Often, materials are allowed with certain constraints but must be declared and labeled. The most restrictive is air freight, where Lithium-Ion and Lead Acid batteries are strongly restricted, along with most signal-generating devices.

4.5 FASTENERS

All interface fasteners should have their fastener calculations checked for expected transportation environments including higher shocks in different directions, quasi-static loading during potential loading and unloading events, and extreme pitch/roll during sea transport.

While torqued fasteners are strongly recommended, some Transported Devices will contain non-torqued fasteners. All fasteners will experience vibrational loads during transport, especially longer distance transports. It is recommended that all fasteners, especially difficult to reach fasteners, be secured by at least one additional method as appropriate including, but not limited to:

- Lock washers (e.g. split ring, serrated tooth)
- Spring washers (e.g. Belleville)
- Nylon insert locknuts
- Threadlocking adhesive or epoxy
- Secured with safety wire/locking wire
- Welded tab nuts.

Galling and thread damage should be prevented through the use of thread lubricants, coatings (e.g. silver plating on austenitic stainless steel bolts) and/or mismatched materials (e.g. austenitic stainless steel bolts with silicon bronze nuts)

Pressure and vacuum flanges that are intended to remain leak tight during transportation should have flange bolts tightened to the target torque values and tightening patterns described in ASME PCC-1 Guidelines for Pressure Boundary Bolted Flange Assembly.

Frictional interfaces like clamps should likewise specify and verify their required clamping force as well and ensuring that device design incompatible with the required forces.

4.6 SPECIAL CONSIDERATIONS FOR PRESSURE & VACUUM EQUIPMENT

All openings shall be sealed against the penetration of moisture, dirt or air. During transport the vessels and piping should be pressurized with dry nitrogen to 5 psig (0.33 bar.g) or their maximum design pressure, whichever is less.

The following specifications for maximum permissible shock & vibration loads have been successfully used by Fermilab for cryogenic vessels and piping:

- The crate shall be designed to undergo a free drop from a height of 6 inches (0.15 m) without transmitting more than the vertical shock limit of 5.0 g's to the equipment.
- The maximum vertical shock acceleration transmitted to the equipment shall not exceed |5.0| g.
- The maximum horizontal shock acceleration transmitted to the equipment shall not exceed |2.0| g.
- The shock and vibration isolation system shall be designed such that a fully loaded crate has a primary (first) mode of oscillation >5 Hz and <10 Hz.

Bellows used on vessels constructed per ASME BPVC VIII and piping constructed per ASME B31 series standards are required to also conform to the Standards of the Expansion Joint Manufacturer's Association (EJMA). Two sections of the EJMA standard that are of special interest to transportation analysis:

- EJMA §4.9 regarding vibration and estimating the natural frequency.
- EJMA §8.2 regarding shipping devices

Lifting, forklifting, and tie down attachments may be welded directly to pressure vessels only by the pressure vessel manufacturer with an official code certification stamp/mark. Lifting, forklifting, and tie down attachments may be welded directly to vacuum vessels, low pressure vessels, and piping by the manufacturer or by Fermilab welders qualified to ASME BPVC IX.

ASME BPVC VIII Div. 1 and Div. 2 both include welded attachments within their scope using the following statement: "where nonpressure parts are welded directly to either the internal or external pressure-retaining surface of a pressure vessel, this scope shall include the design, fabrication, testing, and material requirements established for non-pressure-part attachments by the applicable paragraphs of this Division". ASME B31.3 scope includes pipe supporting elements such as fixtures and structural attachments.

Note that in many cases ASME does not provide rules or equations for designing structural attachments or analyzing shock loads. Finite element analysis may be required for the design of attachments and/or to analyze the shock loads that may occur during transportation. ASME BPVC VIII Div. 2 Part 5 provides the design requirements for design-by-analysis. See also ASME BPVC VIII Div. 1 Mandatory Appendix 46 for rules on designing individual vessel components per Division 2 Part 5. See also ASME B31.3 304.7.2(d) for rules on designing individual piping components per Division 2 Part 5. Similar guidance for performing FEA on EN 13445 pressure vessels and EN 13480 piping systems to analyze structural attachments and shock loads can be found in EN 13445-3 Annex B and Annex C.