MARVEL Shock and Vibration Test Plan

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MRP Microreactor Program

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SUMMARY

The shock and vibration test plan for the MARVEL microreactor establishes the procedures, functional objectives, and laboratory testing methodology for transportation shock and vibration qualification, building directly upon the functions and requirements developed in the MARVEL Reactor Shock and Vibration Functions and Requirements Document (FRD).[a] The test plan is intended to serve not only the immediate testing needs of the MARVEL reactor program, but also to establish a technical framework that informs shock and vibration testing for future deployable microreactor systems. All procedures and test methods are developed in accordance with applicable defense and national standards, including the *Department of Defense Test Method Standard: Environmental Engineering Considerations and Laboratory Tests: MIL-STD-810H and Calibration Laboratories and Measuring and Test Equipment, General Requirements: ANSI/NCSL Z540.1.1994 (R2002)*.

This document is organized into two parts, each addressing a distinct phase of the testing program.

Section 1 characterizes the MARVEL reactor subsystems and components that are subject to shock and vibration environments during transportation, identifying the specific environmental conditions each element may encounter across applicable transportation modes. This section recognizes that microreactor qualification requires a comprehensive, multidisciplinary approach, integrating engineering and technical inputs across structural, nuclear safety, and systems engineering disciplines. The environmental design and test process is implemented through a well-defined but flexible methodology, informed by the MARVEL reactor engineering team, to ensure program-specific design considerations are fully captured and reflected in the test approach.

Section 2 applies the general recommended guidelines for laboratory transportation testing to the MARVEL reactor and its specific components. For each applicable test method, this section identifies the preferred laboratory procedure, recommended test equipment, and associated testing methodology, providing a practical technical reference for design engineers and test facility personnel. Planning guidance is structured to realistically capture environmental stress data and relevant performance information that can be used to inform, bound, and validate the testing phase. Applied in sequence, the test methods defined in Section 2 collectively establish the holistic qualification basis necessary to demonstrate transportation survivability across the full range of applicable shock and vibration environments.

Together, the two parts of this document ensure that MARVEL reactor subsystems and components meet the environmental and operational durability requirements necessary to survive the transportation environments associated with each applicable mode of transport in accordance with applicable defense and national standards. All supporting tasks spanning design, analysis, instrumentation, test execution, and data reduction are integral to the success of the qualification program and are not independent of one another.

[a] PNNL report, "Functions and Requirements for MARVEL Reactor Shock and Vibration Study" (2026), establishes the associated functions and requirements for developing this Shock and Vibration Test Plan.

Ultimately, this test plan supports MARVEL FRD by defining a transportation shock and vibration qualification basis derived from established defense industry standards and safe transportation practices. Successful execution of this plan will provide validated test data and a documented qualification record that supports analyses for the MARVEL reactor and establishes precedents for future deployable microreactor systems. The relationship between this test plan and its supporting documents is illustrated in Figure 1.

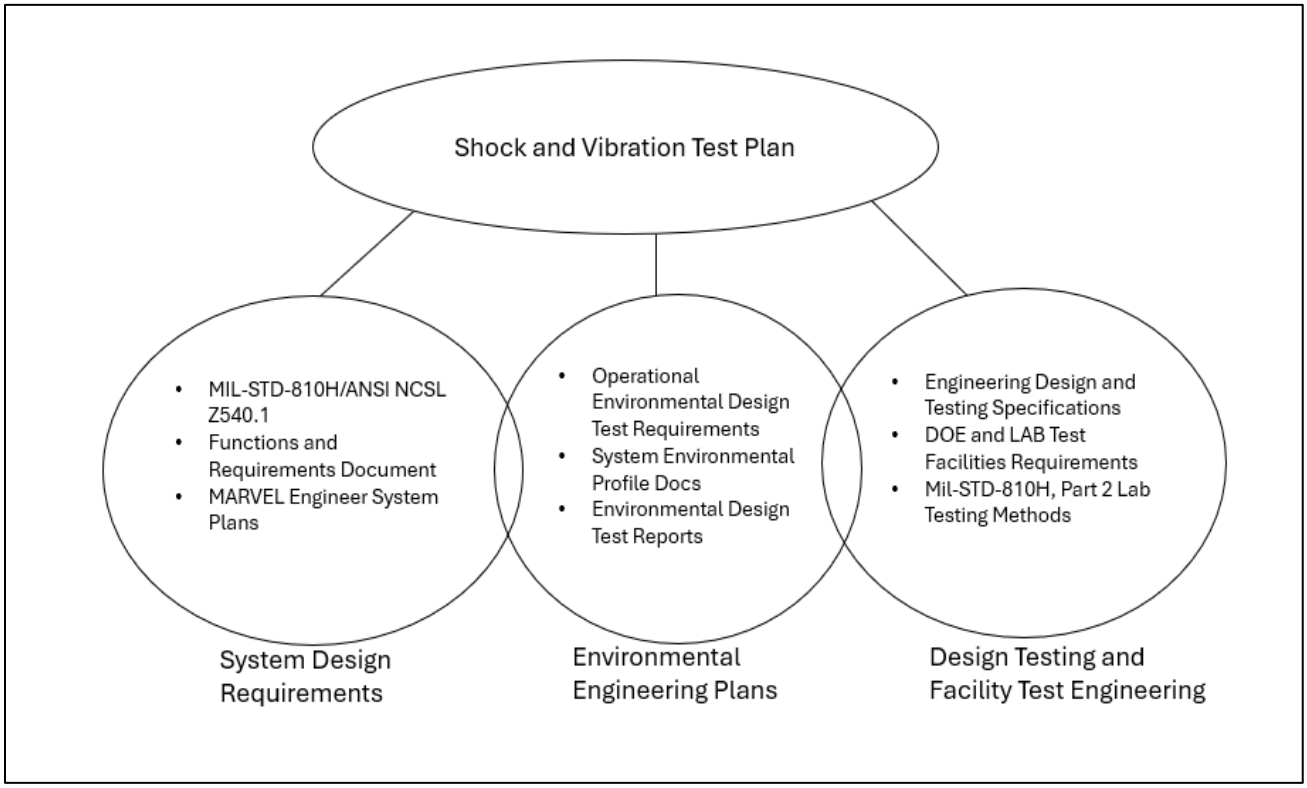


Figure 1. Shock and Vibration Test Plan and supporting documents in the Environmental Design and Testing Process.

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ACRONYMS

APU	Auxiliary Power Unit
ATR	Advanced Test Reactor
BeO	Beryllium Oxide
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
DOE-ID	U.S. Department of Energy-Idaho Operations Office
FRD	Functions and Requirements Document
ft	Feet
Hz	Hertz
I&C	Instrumentation and Control
IHX	Intermediate Heat Exchanger
INL	Idaho National Laboratory
kg	Kilogram
kWth	Kilowatt Thermal
lbm	Pounds Metric
MARVEL	Microreactor Applications Research Validation and Evaluation
MEMS	Micro-Electro-Mechanical Systems
MFC	Material Fuels Complex
MIL-STD	Military Standard
MW	Megawatt
MFC	Materials and Fuels Complex
MRP	Micro Reactor Program
NOAK	Nth-of-a-Kind
NRC	U.S. Nuclear Regulatory Commission
NRIC	National Reactor Innovation Center
PCS	Primary Cooling System
PSD	Power Spectral Density
QCT	Quality Conditions of Transport
R&D	Research and Development
RMS	Root Mean Square
SSC	Structures Systems & Components
TRAMS	Transportation Recording and Monitoring System
TREAT	Transient Reactor Test Facility

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MARVEL Shock and Vibration

1. INTRODUCTION

Microreactors have the potential to deliver scalable power to a location in need. They can be designed to be a smaller size, factory-assembled, energy solution that can be operated in locations where traditional nuclear power plants are impractical for use. In theory, they could be transported by various modes including via rail, vessel, truck, or airplane. The flexibility of transport and mobility of microreactors are advantageous and could minimize the "tyranny of distance" that have traditionally limited the delivery of remote power operations to areas such as the Arctic or the Pacific Islands. Standard microreactor designs generally produce between 1 to 20 megawatts of electrical power (MWe) and transportation design features are integrated into the microreactor design.

1.1. Background

Idaho National Laboratory (INL) is developing an advanced nuclear reactor known as the Microreactor Applications Research Validation and Evaluation (MARVEL). Underneath the authority of the United States (U.S.). Department of Energy (DOE), MARVEL is expected to be one of the first operating advanced microreactors in the U.S. that will be dedicated to research and testing. Through collaboration with multiple agencies, it will provide a solid platform for industry, academia, and additional federal agencies to conduct testing of a microreactor transportation environment under real operating conditions. MARVEL will meet the research and development (R&D) needs identified by DOE and the Microreactor Program community. While MARVEL will be a testbed rather than a standard operating commercial reactor, this will help inform new operational and regulatory frameworks which can inform decisions about lifecycle management principles.

This effort will help industry to better understand the regulatory and technical risks for Nth-of-a Kind (N-O-A-K) microreactor designs

Through collaboration between the DOE Microreactor Program and the National Reactor Innovation Center (NRIC), development of the MARVEL test bed provides an opportunity to establish and exercise key NRIC capabilities to support future reactor demonstrations. Some of the core NRIC capabilities are to work with industry and national laboratories to bridge the gap between concept, demonstration, and commercialization of advanced nuclear technology. They also work to build new or enhance current existing U.S Department of Energy infrastructure to support testing components and systems that are key to successful deployment of advanced nuclear technology. The goal of the MARVEL reactor test bed is to establish a small microreactor test system to test requirements that will support the energy consumer. Additionally, it can offer a platform to test next generation microreactor technology. Microreactor system testing will help to shape requirements for future systems to meet deployment specific use cases.

The MARVEL reactor will be installed and operated at INL's Transient Reactor Test (TREAT) facility (see Figure 2). The plan to test, demonstrate, and address operational issues will also be considered. Transportation of the system components and key operating systems in the fueled reactor are not currently being considered for the program. This test plan addresses the transportation activities of the MARVEL system for the purposes of transporting those subsystem components from the requisite fabricator facilities to the TREAT facility by road, located within the INL site boundary and co-located within the Materials and Fuels Complex (MFC). The additional test plan considerations will examine offsite road routes specifically for shock and vibration testing purposes.



Figure 2. Concept of MARVEL reactor at the INL TREAT Facility.

1.2. Scope and Objective

Safely transporting a microreactor requires deliberate planning and well-defined requirements to move the associated systems from origin to destination. Vendors and/or operators must define standards of operation and quality for the various components of the microreactor. These will be useful to examine the microreactor post-transport to ensure no significant damage occurred to critical systems. Instrumentation prior to transport is also necessary as it can help investigate potential impacts of transportation on key components of the reactor which can later be mitigated through engineering and design. Industry, national laboratories, and government agencies are actively evaluating how to safely transport microreactors to known deployment sites based on unique mission requirements. Consequently, many microreactor designs are assumed to be factory built and transportable, so transportation is an essential characteristic of the design features and the overall deployment strategy for this technology to be successful.

Microreactor deployments are being considered to meet various industry requirements. Advanced nuclear reactors include energy systems like Generation III+ reactors, that are small modular reactors, microreactors, and mobile reactors that have the potential to deliver resilient, secure, and reliable power to critical defense facilities and other mission capable resources (Section 4, Presidential Executive Order 14299, “Deploying Advanced Nuclear Reactor Technologies for National Security”, 2025). Deployment options might consider shipping the unirradiated fuel separately and inserting the fuel in the microreactor at the deployment site or shipping the fuel inside the reactor core while maintaining a subcritical state until assembly and startup. Both fueled and unfueled microreactors will face shock and vibration during transit which could introduce vulnerabilities or damage on the materials and subsystems of the microreactor. Establishing the overall impact of transportation on a microreactor is key to mitigating any significant damage which could create future safety risks.

This test plan establishes the procedures, test conditions, instrumentation, and acceptance criteria for shock and vibration qualification testing of the MARVEL microreactor that should be considered during road transport. This study could lead to a follow-on study for rail transportation that could be conducted on the INL site using many of the same planning fundamentals. The objective of this test plan is to demonstrate structural integrity of the MARVEL reactor systems, subsystems, and components under transportation-induced shock and vibration environments. This plan will also identify natural frequencies, defense test standards, and additional test evaluation criteria for the MARVEL test article. The

transportation data and environments considered for road transport are referenced from (DoD 2019). A comprehensive test plan typically considers the following areas:

a. **Verify structural integrity** – Confirms the MARVEL reactor, subsystems, support structures and ancillary equipment can withstand induced shocks and vibrations without permanent deformation or damage.

b. **Protect safety-significant structures, systems, and components (SSCs)** – Demonstrate that SSCs important to nuclear safety remain functional and within design limits after transport.

c. **Validate transportation design** – Confirms that the reactor transportation frame, tie-down system, isolation mounts, and packaging can adequately protect the MARVEL reactor during highway transport.

d. **Characterize transportation environment** – Measures or simulates the dynamic environments expected during transportation (handling, loading, unloading during normal conditions of transport and in transportation-related events). These could also identify other issues such as road irregularities, crane lifts, and handling operations.

e. **Support regulatory compliance** – Supports objective evidence that transportation requirements are satisfied under applicable regulations and standards, according to authority set by DOE, the U.S. Department of Transportation (DOT), and the U.S. Nuclear Regulatory Commission (NRC).

f. **Reduce transportation risks** – Minimize the likelihood of microreactor equipment damage, costly repairs, or associated safety issues by validating the transport configuration before deployment.

g. **Provide data for engineering evaluation** – Provide measured acceleration, frequency, displacement, and response data (utilizing MARVEL subsystems transport opportunities or shaker tables). These testing opportunities will confirm design assumptions used in the microreactor's transportation and structural analysis.

2. REQUIREMENTS

Functions and requirements for this test plan are defined in the Pacific Northwest National Laboratory (PNNL) document, *Functions and Requirements for MARVEL Reactor Shock and Vibration Study* (Stewart et al. 2026). The Functions and Requirements document (F&RD) defines what the system must do and its functions, which directly drive what this test plan must demonstrate. For a transportable microreactor, functions such as how systems should be loaded and secured or where shock and vibration data should be obtained for road transport are the basis for this test plan's objectives. Shock and vibration requirements 1–21 in Table 2 of the F&RD (Stewart et al. 2026) provide a sound basis for the supporting analyses in subsequent sections of this document.

3. TRANSPORTATION ENVIRONMENT

The MARVEL reactor project provides opportunities to evaluate procedures, protocols and the regulatory framework to transport microreactors to deployment sites. Deployment strategies should include planning and stakeholder engagement. A deployment strategy could encompass a variety of deployment modes (rail, road, sea, and air) however, the deployment strategy must be realistic based on planning assumptions and real-world constraints such as limited resources, time, route constraints, weather, and competing transportation commerce demands. Extensive route planning is required to support the road transport mode, and critical components would need to be packaged/crated for efficiency and safe shipment.

System components and subsystems requiring shipment should be tested for boundaries that describe how those items will be secured, restrained, and tied down to the transport conveyances (e.g., chains, binders, cargo straps, bolt patterns, isolation mounts). Pre-test inspection requirements should also be defined to conduct visual, dimensional, and functional checks on the tested system components prior to the testing. These could include, but are not limited to, visual inspections such as documenting the pre-existing condition of the system components for defects to establish a baseline before testing. Dimensional inspections will measure and record key dimensions such as size, and structural components to ensure accurate interface points for lifting and tie-down. Functional inspections will verify instrumentation checks (e.g., sensors, accelerometers, and data acquisition systems) to ensure they can be installed correctly on the test articles.

The transportation environment in which the MARVEL reactor will be tested should include the following minimum standards before data is considered suitable for use as baseline values in laboratory test procedures. This includes the following supporting analysis:

- A description of the subsystems and critical component materials and the transport platform. (See Section 4.2 for additional information on MARVEL's critical and major components).
- The geographical location of the material or transport platform to which test measurements will be made.
- Identify transportation-specific information (e.g., likely routes, handling, lifting, infrastructure facilities).
- Limits the material will be required to withstand (e.g., g-loads, temperature, humidity, vibration levels, shock, extreme terrain).
- Consider and develop devices that will protect material during testing, if required (e.g., dunnage, foam protectant material, space dampening devices, sheltered containers).

A summary of potential environments the MARVEL microreactor could likely encounter during the road deployment transport phase is identified in Table 1, referenced from (DoD 2019).

Table 1. Summary of potential road transport environments. (DoD 2019)

Summary of Potential Environments During Road Transport
Shocks due to road surface contact with transport vehicle
Vibration due to road surface and engine
Inclement weather (e.g., rain, lightning, snow, wind, hail)
Immersion or water ingress due to flooding or unlikely accident (e.g., vehicle roll-over)
Temperature changes (high/low) dry, humid, freezing
Sand and dust
Electrostatic discharge (handling)
Freefall drop

4. TEST ARTICLE DESCRIPTION AND MAJOR COMPONENTS

4.1. MARVEL Configuration

Figure 3 provides an illustration of the MARVEL core systems and structures. Table 2 describes the core characteristics for the MARVEL design and primary structural material.

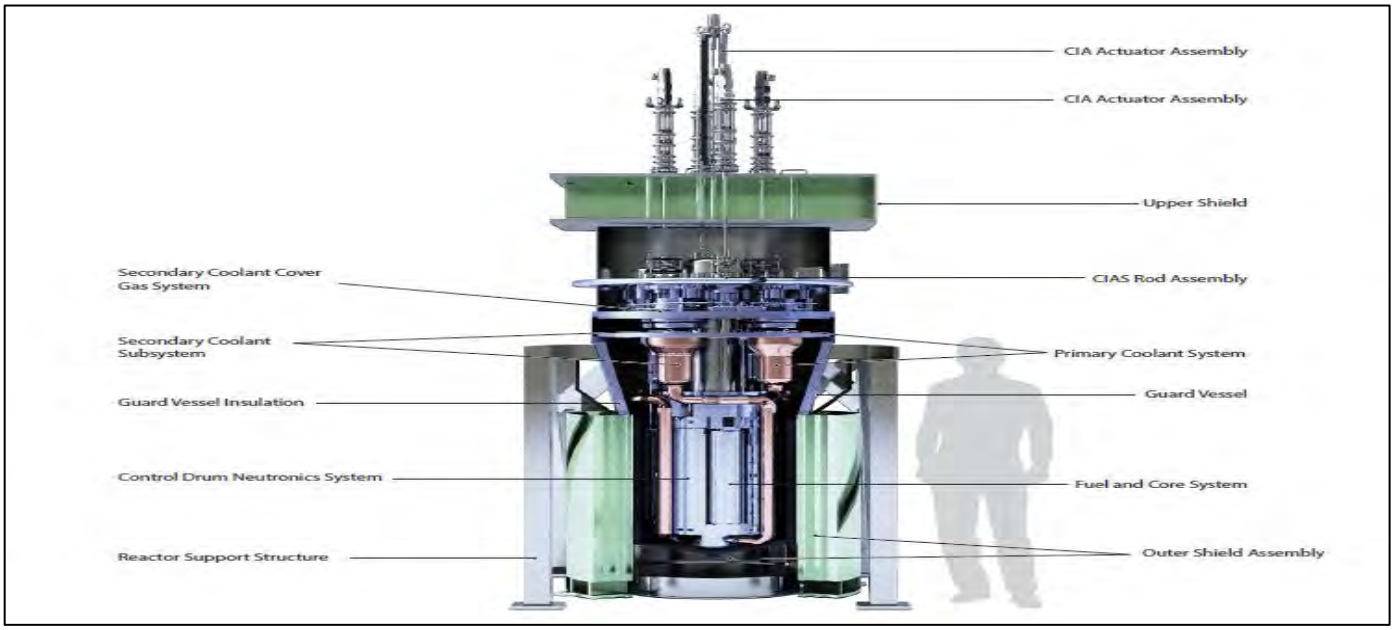


Figure 3. MARVEL Cutaway Tech Callouts.

Table 2. MARVEL Core Characteristics.

Parameter	Value
Reactor Designation	MARVEL REACTOR
Fueling State	Post-fueled after assembly
Core Configuration	Beryllium- and graphite-reflected, hydrogen-moderated, solid fuel, loop-type reactor. 100 kilowatt-thermal (kWth). Holds 36 fuel rods containing 30 weight-percent (wt%) uranium enriched to 19.75% U-235. TRIGA fuel. Primary coolant system (PCS), is a four-loop hydraulic circuit transporting heat from nuclear fuel to four intermediate heat exchangers (IHX). Reactivity control and shutdown provided by active and passive components, four control drums made of BeO, which act as neutron reflectors.
Overall Dimensions (L × W × H)	8-ft long × 12-ft wide × 10-ft high
Total Test Article Mass	kg or lbm
Transport Package Included	No

Primary Structural Material	Reactivity Control System (RCS) – 316 Stainless Steel / BeO Side Reflectors / BeO CD Cylinders / Boron Carbide, Neutron absorber

4.2. Critical Components

Critical components that should be considered in the MARVEL design were defined in the F&RD (Stewart et al. 2026). These components are directly associated with safe operation of the reactor. Associated failures with these components during microreactor operation could lead to a loss-of-cooling functions or release of radioactive material. A suggested list of critical components to consider is identified in Table 3. The list of subassemblies, critical components, and structures should be prioritized and considered for shock and vibration measurements, and/or crating, packaging material prior to shipment.

Table 3. Critical components and assemblies.

Critical Components and Assemblies	Safety Function Category
Fuel elements	Confinement
Reactor Vessel & Primary Coolant Boundary (PCB)	Confinement / radionuclide barrier
Guard Vessel System (GVS)	Decay heat removal / confinement
Reactor Shielding System (SHLD)	Radiation protection
Core Structures Subsystem (CSS)	Structural integrity / decay heat removal support
Control Drums (CDs)	Reactivity control / shutdown
Central Insurance Absorber (CIA) rod	Reactivity control / shutdown
Reactivity Control System (RCS) / Reactor Protection System (RPS) / Interlock cabinet	Reactivity control
Reflector Support Subsystem (RSS)	Structural integrity / reactivity control support
Primary Coolant System (PCS)	Decay heat removal
Secondary Coolant System (SCS)	Decay heat removal

Major components were also defined. They are considered essential components for the reactor system to perform its required functions, but they are not associated with reactor safety (e.g., the power conversion system). The major components to be considered in the MARVEL reactor are listed in Table 4. These systems would be prioritized and most likely have a lower priority for shock and vibration capacities during transport. That said, failure of major components due to shipping damage could still be costly and cause the system to be inoperable during deployment operations.

Table 4. Major components and assemblies.

Major components and assemblies
Power convertor modules
Qnergy Engine Controller (QEC)

Qnergy Heat Rejection Units (HRU)
Electrical Production System (EPS)
Engine Cooling System (ECS)
Reactor vessel internals (baffles, guides, and structural supports) not credited for safety
NaK Handling and Purification System
SCS Fill/Drain and Purification System

5. TEST REQUIREMENTS AND METHODS

5.1. Testing Methodology

There is currently no plan to transport the MARVEL reactor as a fully assembled system. Shock and vibration transport considerations in this test plan consider shipment of components and parts from fabricator facilities to INL utilizing road transportation. In addition, this test plan evaluates hypothetical deployment scenarios for microreactors in context, based on requirements that future microreactor systems could be deployed to a set location.

Transportation environments create a fundamentally different and often more severe dynamic shock and vibration profile than stationary or operational conditions for a few key reasons. First, during transport, the unit is subjected to continuous, near-constant dynamic excitation for the entire duration of the journey, potentially hours or days. Secondly, every event is a sequence of different dynamic conditions each with its own frequency content and severity. The MARVEL transportation testing methodology follows a low-to-high sequencing philosophy that characterizes the test article at low levels before applying damage to a high-level environment. The idea is to protect associated microreactor subsystems and components while validating instrumentation and defining a baseline to compare against after testing.

5.2. Associated Transportation Testing Scenarios

Table 5 highlights the applicable test considerations, specific modes, deployment conditions, and the governing regulatory standard used in this test plan. The Table 5 section that is highlighted in orange shows MARVEL testing requirements for the current program. The Table 5 sections highlighted in green show additional areas that could be considered for microreactor deployments.

Table 5. Transportation testing scenarios by mode, route conditions, and governing standard.

Mode	Test /Considerations/Condition	Governing Standard
Ground — Highway Truck	Test to CONUS road transport environment, paved and unpaved	MIL-STD-810H Method 514.8, Category 4
Ground — Rail	Test to rail impact testing standard for freight rail	MIL-STD-810H Method 514.8, Category 7
Air — Fixed Wing Aircraft	Test to g-load requirements for cargo aircraft, if unirradiated and shipped with no fuel.	MIL-STD-810H Method 514.8, Category 15
Sea — Ship	Test to simulated sea state for acceleration, shock and vibration	MIL-STD-810H Method 514.8, Category 12

Key testing selection factors for this MARVEL test plan include:

- Mass loading — Mass loading effects must be accounted for in laboratory test models, since the microreactor's components are lightweight and thin-walled, making them more susceptible to shifts in dynamic response caused by added sensor or fixture mass.
- Mounting and securing test sensors— Testing near the most optimal shock and vibration points during shipment, charge-output accelerometers with remote preamps to last for transit duration.
- Frequency range — Ensure sensors cover at least 10× the highest frequency of interest.

5.3. Mounting and Torque Requirements

Mounting is one of the most critical, but often underspecified areas of a shock and vibration test plan. Poor mounting can lead to excessive movement and create more noise or inaccurate results when capturing shock and vibration data. Using accelerometers at the fixture drive point will maintain the specified input environment throughout testing. Response accelerometers at critical component locations (pressure vessel, control rod drives, instrumentation and control [I&C] electronics, skid structure) capture how loads (dynamic mechanical forces from vibration and shock) transmit through the assembly. There are tradeoffs to continuous data recording versus threshold-initiated data recording. Given that this document discusses both laboratory testing (controlled, likely shorter duration, higher instrumentation density) and transportation mapping/real-world deployment characterization (potentially longer duration, field conditions), the trade-off often plays out differently depending on the phase. Section 6.1 provides additional details regarding accelerometer mounting and placement during road transport.

5.4. Laboratory Testing for Shock

Shock environments can be particularly severe on equipment, and the probability of material surviving without structural damage or operational failure is low without prior qualification testing. Shock is defined as a sudden change in acceleration that imparts transient mechanical energy into a structure, typically exciting one or more of its natural frequencies. Unlike sustained vibration, shock events are short in duration but can generate peak loads that far exceed those produced by random or sinusoidal vibration environments. Shock tests on transportation material are performed under three basic scenarios:

- Packaged — The test article is evaluated within its transportation packaging or container, assessing the combined system’s ability to attenuate and survive shock inputs.
- Unpackaged — The test article is evaluated in its bare or operational configuration, without protective packaging, to characterize its inherent structural and functional shock tolerance.
- Non-operational — The test articles are evaluated in a non-powered or inert state representative of a stowed or transit configuration, where functional performance during the event is not required, but structural integrity must be maintained.

In accordance with *MIL-STD-810H, Method 516.8* — “Shock. In Environmental Engineering Considerations and Laboratory Tests”, 2019, shock testing of transportable microreactor material is conducted for the following purposes:

1. **Transportation and Handling Survivability.** It is necessary to provide a degree of assurance that microreactor material can physically withstand the shock environments without significant damage (defined by standards of operation or previous tests) encountered during handling, transportation, and service. This includes an assessment of overall system integrity for nuclear safety purposes under any applicable transportation, handling, or operational conditions. For microreactors in a non-fueled (unirradiated) or fueled (unirradiated) subcritical configuration, maintaining geometric and structural

integrity of the reactor core, shielding, and reactivity control elements is a primary safety consideration.

2. **Fragility Level Determination.** It is important to establish the material's fragility level — the threshold of acceleration at which physical or functional damage occurs — so that packaging, stowage, lifting provisions, and mounting configurations may be designed to protect the materiel's integrity throughout its transportation deployment life cycle. For multi-deployment microreactor concepts, this information is essential for repeated transport qualification and cumulative damage assessment.

3. **Crash Hazard and Restraint Verification.** It is critical to test the structural adequacy of the transport platforms under crash-level loading conditions. This includes confirming that the material does not present a secondary safety hazard — i.e. components, subassemblies, or fastened items are not damaged, disabled, or ejected during a crash event in a manner that could compromise personnel safety, vehicle control, or nuclear material containment.

When testing for shock, the general methodology for physical and functional performance of material to be exposed is generally limited to a frequency range not to exceed 10,000 Hz, and a duration of not more than 1.0 second. In most cases, it shouldn't exceed 4,000 Hz and the duration of material response will not exceed 0.1 second (MIL-STD-810H, Method 516.8 — "Shock. In Environmental Engineering Considerations and Laboratory Tests", 2019).

5.4.1. Shock Test Procedures

Transportation shock test procedures on the MARVEL systems should be representative of the repetitive low-amplitude shock loads that occur during road transportation. The two optional testing configurations based on the scenario should be a packaged or unpackaged test item(s) in standard shipment configurations for truck and large-assembly transport (e.g., large assemblies, shelters vans, and trailer units). The testing procedure should be applied to evaluate the influence of shock loading on a cargo restraint system or operational loaded test system. A terminal peak Sawtooth shock test sequence is defined in Table 6 and highlighted in orange to identify the testing requirement that most closely resembles the MARVEL microreactor transport scenario. In addition, the shock waveform applied can be tailored with measured data and implemented with shock replication techniques under Time Waveform replication. Transportation shocks can be frequently completed following the vibration test using electrodynamic or servo-hydraulic test systems, and the same test setup configuration.

Table 6. From MIL-STD 810H, Table 616.8-VII Procedure II: "Example of Transportation Shock Test Sequence" (Method 516.8 — "Shock. In Environmental Engineering Considerations and Laboratory Tests", 2019).

On Road (5000 km)[4] **Terminal Peak Sawtooth** **Pulse Duration: 11 ms**			**Off Road (1000 km)[4]** **Terminal Peak Sawtooth** **Pulse Duration: 5 ms**	
Amplitude (G-PK)	**Number of Shocks**		**Amplitude (G-Pk)**	**Number of Shocks**
5.1	42		10.2	42
6.4	21		12.8	21
7.6	3		15.2	3

Note 1: *The shocks set out in Table 516.8-VII must always be carried out together with ground transportation vibration testing as specified in Method 514.8, Category 4 and/or Category 20.*

Note 2: *The above tabulated values may be considered for both restrained cargo and installed material on wheeled and tracked vehicles. Transportation shock associated with two-wheeled trailers may exceed off-road levels as defined.*

Note 3: *The shock test schedule set out in Table 516.VII can be undertaken using either terminal peak Sawtooth pulses applied in each sense of each orthogonal axis, or a synthesis based on the corresponding SRS that encompasses both senses of each axis.*

Note 4: *The above number of shocks is equivalent to the following distances: a) On-road vehicles: 5000 km; b) Off-road vehicles: 1000 km. If greater distances are required, more shocks must be applied in multiples of the figures above.*

5.4.2. Shock Testing Steps

The steps below define the shock testing and procedural steps that should be followed to accurately represent system requirements for set test conditions.

Select the test conditions and calibrate the shock apparatus as follows:

1) Identify accelerometers and analysis techniques
    a. If you are planning to perform shock testing and want to integrate acceleration data for velocity or displacement, you must use either a capacitive micro-electro-mechanical system (MEMS) or piezoresistive accelerometer. Piezoelectric (PE) or piezoresistive accelerometers may be used for mechanical shock in scenarios in which levels are known to be within the established (verified through calibration) operating range of the transducer, thereby avoiding non-linear amplification and frequency content.
    b. Accelerometer sensitivity is expected to have some variance over its large amplitude dynamic range.
    c. Vibration and shock amplitude linearity results should agree within 10% over the amplitude range of interest for a given test.
2) Mount the calibration accelerometer to the test equipment load and fixture in a similar configuration to that of the actual test article. The test setup and fixture should prevent distortion of the shock waveform.
    a. Perform calibration shocks until two consecutive shock applications reproduce waveforms that are within the test tolerance specification.
3) Remove the calibration load and install the test item on the test equipment.
4) Subject the test item to the shock test sequence and perform intermediate inspections as required between shock events. Allow sufficient time between shocks for the previous shock event to fully decay.
5) Perform post-test inspection of the test item, and an operational test if required.

5.5. Laboratory Testing for Acceleration

Acceleration tests are performed to ensure material can structurally withstand the steady-state inertial loads induced by acceleration, deceleration, and rapid directional change in a transportation or operational environment, and that the material continues to function without damage following exposure to these

forces. Acceleration in this context is defined as a quasi-static load factor—commonly expressed as a gravitational load factor (g-load) applied gradually and sustained for a sufficient period to allow the full distribution of resulting internal loads throughout the structure. Unlike shock or vibration, acceleration testing does not intentionally actuate the dynamic response of the material; the slow application rate ensures that inertial forces are reacted as essentially static structural loads. This distinction is important: where shock tests assess the material's response to transient impulse loading, acceleration tests assess its ability to sustain prolonged directional inertial loading without structural failure or functional degradation.

Acceleration tests on transportable microreactor systems and components would be performed for the following purposes:

- **Structural Survivability Under Sustained Inertial Loading.** Provides confidence that microreactor material can physically and functionally withstand steady-state inertial loads encountered during transportation, including vehicle acceleration and braking on road and rail loads, and lifting operations. Testing assesses whether the material retains sufficient structural integrity and functional capability after exposure to these loads to continue safe operation or safe transport.
- **Crash Hazard Verification.** Ensures that microreactor material does not become a secondary safety hazard following exposure to crash-level inertial loads. This includes confirming that the material and its subcomponents, including mounting hardware, shielding assemblies, and core structural elements—do not fracture, separate, or become ejected in a manner that could endanger personnel, damage adjacent systems, or compromise nuclear material containment.
- **Nuclear Safety Assurance Under Inertial Loading.** Provides assurance for microreactor systems in an unfueled or pre-fueled subcritical configuration. Sustained inertial loads may affect the geometric relationship between core components, reflector assemblies, and reactivity control elements. Acceleration testing provides assurance that core geometry and subcriticality margins are maintained under the full range of transportation-induced g-loads, consistent with a nuclear safety basis.

High levels of sustained acceleration can produce detrimental effects on microreactor components and systems. Testing is necessary to confirm the material's response to these loads and to identify any of the following failure modes:

- **Structural Failure.** Permanent deformation, cracking, or fracture of primary or secondary structural members that render the material unserviceable or unsafe for continued transport or operation.
- **Mounting Hardware Failure.** Failure of fasteners, brackets, or restraint systems resulting in loose or displaced components within internal cavities or on external surfaces, creating secondary impact or ejection hazards.
- **Electronic and Control System Malfunction.** Deformation or displacement of electronic circuit boards, control panels, wiring harnesses, or connector interfaces resulting in malfunctioning or inoperable control circuits, including I&C systems associated with reactor safety functions.
- **Reactivity Control Mechanism Failure.** Relay switches, solenoid-actuated devices, or control rod drive mechanisms that fail to actuate, seat, or release properly under sustained inertial loading, potentially affecting the ability to insert or withdraw reactivity control elements.
- **Pressure Boundary Leakage.** Degradation or displacement of seals, gaskets, or pressure-retaining joints in the primary coolant system or instrumentation lines resulting in leakage that compromises system integrity or creates a radiological concern.

- **Flow and Pressure Control Degradation.** Pressure regulators, flow control valves, or orifice assemblies that shift set-point or fail to control within design tolerances following inertial loading, affecting coolant flow management during post-transport startup.
- **Rotating Machinery Impairment.** Pumps, blowers, or turbomachinery components that fail to operate within design parameters following sustained acceleration, including turbine assemblies that cannot properly absorb thermal energy from the reactor core or maintain design rotational characteristics.
- **Core Geometry Distortion.** Displacement or misalignment of reflector panels, moderator blocks, or core structural elements due to sustained inertial loading that could affect neutron economy, subcriticality margins, or coolant flow geometry in post-transport configuration.

5.5.1. Acceleration Test Procedures

There are four separate test procedures for acceleration effects on materials: structural, operational, crash hazard, and strength tests. MARVEL subsystems and components shall be tested to meet structural and operational tests. Crash hazard tests should only be performed based on package performance requirements under hypothetical accident conditions, 10 CFR Part 71, Subpart E. Crash hazard load factors are significantly higher than operational or structural test levels and are derived from a transportation crash scenario analysis in 10 CFR Part 71 and MIL-STD-810 H. Strength tests should only be performed when analytical structural margins cannot be established with sufficient confidence by analysis alone.

Structural tests will evaluate the structural integrity of MARVEL reactor components and assemblies when subjected to sustained steady-state acceleration loads representative of transportation environments. The test article is in a non-operational state during this procedure; functional performance during the acceleration event is not required, but the structural integrity of all load-bearing systems, mounting interfaces, and safety-critical elements must be maintained throughout and verified following test completion.

The following test conditions will apply to structural acceleration tests:

- Load application rate: Quasi-static – Applied gradually to avoid exciting dynamic response of the test article. Load shall be increased at a rate not exceeding [0.5 g/minute] unless otherwise specified.
- Load levels: Per the DOT Pipeline and Hazardous Materials Safety Administration (PHMSA) restraint pay load factors, DoD MIL-STD 1366D, and the F&RD (Stewart et al. 2026) requirements. As a minimum, the following load factors in Table 7 shall be applied in each specified direction.

Table 7. Structural test load factors.

Load Direction	Load Factor	Road Transport Scenario
Deceleration (Forward)	0.4 g	Emergency braking highway
Acceleration (Aft)	0.5 g	Vehicle acceleration
Acceleration (Vertical Down)	0.2 g	Gravity + dynamic overshoot
Acceleration (Lateral)	0.25 g	Road curve, rail sway, lane change

- Hold duration**:** Each load level shall be sustained for a minimum of 60 seconds to ensure full internal load distribution throughout the test article structure.

- Number of load applications: One application per axis direction unless fatigue assessment requires multiple cycles.

Operational tests will evaluate the ability of the MARVEL reactor's systems and components to function correctly during and after sustained acceleration loading. Unlike structural tests, the microreactor subsystems are in an operational or fully assembled state during this procedure, and functional performance shall be maintained throughout the acceleration event. This procedure verifies that safety-related systems, including I&C electronics, reactivity monitoring, and coolant flow management, will continue to operate within design parameters under transportation-induced inertial loads.

Load levels under operational tests will still be compliant with regulatory standards (e.g., DOT PHMSA, DoD MIL-STD 1366D, and the F&RD requirements). Load levels will be equal to or less than structural test loads. As a minimum, the load factors in Table 8 shall be applied in the specified direction.

Table 8. Operational test load factors.

Load Direction	Load Factor	Road Transport Scenario
Deceleration (Forward)	(=/-) 0.4 g	Normal braking deceleration
Acceleration (Aft)	(=/-) 0.5	Normal vehicle acceleration
Acceleration (Vertical Down)	(=/-) 0.2 g	Road surface vertical loading
Acceleration (Lateral)	(=/-) 0.25 g	Cornering and lane change

5.5.2. Acceleration Testing Steps

The steps below define the acceleration testing and procedural steps that should be followed to accurately represent system requirements for set test conditions.

- Step 1: Select the test method or facility (modeling, test track, road route) and if using testing equipment, ensure they are calibrated. (e.g., accelerometers, shaker tables).
- Step 2: Test and inspect the test items afterwards as specified in Section 5.5.1. according to acceleration loading factors.
- Step 3: Repeat this test procedure for the remaining five tests in all directions based on load factors.

5.6. Laboratory Testing for Vibration

Vibration on materials can be generated during factory fabrication, transport to and from deployment sites, scheduled maintenance, component servicing, and normal reactor operation over its service life. Vibration is defined as oscillating mechanical motion about a position of equilibrium and may occur as a single frequency (sinusoidal), a broad spectrum of simultaneous frequencies (random), or a combination of both. For microreactor systems being transported by road, vibration environments arise from multiple sources across the deployment lifecycle, including road surface irregularities transmitted through vehicle suspension systems and machinery-induced vibration during lifting, loading, unloading, packaging, and onsite assembly operations. In a multi-deployment scenario, these exposures are repeated across the system's operational life, creating potential for cumulative stress fatigue damage that must be assessed in addition to single-event survivability.

Vibration testing of transportable microreactor components is conducted for the following purposes:

Lifecycle Vibration Survivability. To provide a degree of confidence that microreactor material can physically and functionally withstand the vibration environments encountered throughout its entire lifecycle — from initial transport of components and assemblies, through operational use, to final decommissioning transport. This encompasses both structural integrity and the continued operability of

safety-related systems, including I&C electronics, reactivity control mechanisms, and primary coolant boundary components.

Resonance Identification and Structural Characterization. To identify the natural frequencies, mode shapes, and damping characteristics of the microreactor assembly and its subcomponents. Knowledge of resonant frequencies is essential to ensure that transportation-induced vibration spectra do not persistently excite structural resonances, which could result in fatigue damage, mechanical loosening, or misalignment of safety-critical components such as control rod drive mechanisms or core support structures.

Endurance and Fatigue Assessment. To evaluate the material's ability to withstand prolonged or repeated vibration exposure without degradation of structural or functional performance. For microreactors intended for multiple deployments, endurance testing shall envelop the cumulative vibration dose expected over the system's full transportation life cycle, accounting for the number of planned deployments and the duration of each transportation event.

Packaging and Isolation Design Verification. To confirm that vibration isolation systems, transportation packaging, and mounting configurations are effective in attenuating the input vibration environment to levels within the material's demonstrated fragility limits. This is particularly relevant for sensitive components such as reactor instrumentation, electronic control systems, and precision-aligned core internals.

Conducting vibration testing of components using a vibration or “shaker table” shall utilize appropriate vibration exposure spectra for ground transportation over U.S. highways as defined in the F&RD (Stewart et al. 2026), which is informed by MIL-STD 810H through representative field measurements. Figure 4 is a visualization of the Method 514.8 Annex C, Figure 514.8C-2 highway truck profile, with vibration spectra analysis for ground transportation over U.S. highways, and Table 9 is representative of the spectral breakpoint values for curves of common carriers with vibration Hz in the respective regions (U.S. Department of Defense 2019).

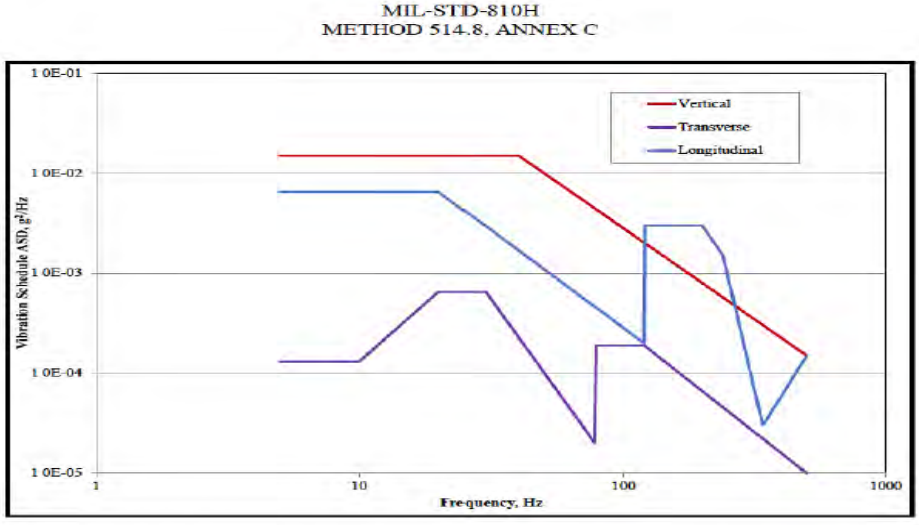


Figure 4. From Figure 514.8C-2 Category 4, “Common Carrier (U.S. highway truck vibration exposure) MIL-STD-810H,” Method 514.8. Annex C.

Table 9. From Table 514.8C-I, Category 4, "Common Carrier (Break points for curves of figure 514.8C-2) MIL-STD 810H," Method 514.8. Annex C.

Vertical		Transverse		Longitudinal	
Frequency, Hz	**ASD, g2/Hz**	**Frequency, Hz**	**ASD, g2/Hz**	**Frequency, Hz**	**ASD, g2/Hz**
5	0.015	5	0.00013	5	0.0065
40	0.015	10	0.00013	20	0.0065
500	0.00015	20	0.00065	120	0.0002
		30	0.00065	121	0.003
		78	0.00002	200	0.003
		79	0.00019	240	0.0015
		120	0.00019	340	0.00003
		500	0.00001	500	0.00015
rms = 0.21		rms = 0.21		rms = 0.76	

5.6.1. Vibration Test Procedures

The procedures for conducting vibration testing are based on determining vibration levels and durations (e.g., frequency range, and magnitude of power spectral density and impact on the systems). Laboratory test methods should replicate interaction between the test platform (shaker tables) and the test article (MARVEL reactor subsystem components). These loads are expressed as inputs at the interface between the test article modeled as a rigid body — and the vibration exciter (shaker table). For large microreactor components, it is important to recognize that the material may be difficult to control in a single flex system such as a laboratory vibration test. A suitable test for such systems would be the "large assembly transport test." Table 1 in F&RD (Stewart et al. 2026), provides a table that highlights the vibration environment for a large assembly transport.

5.6.2. Vibration Testing Steps

- Step 1: Select test surface(s) and vehicle(s) to replicate the transportation environment.
- Step 2: Load test materials on the vehicle, then secure and mount in place.
- Step 3: Attach data collection devices.
- Step 4: Drive the vehicle and components over designated track or highways between given points.

5.7. Testing and Transportation Routes

Route testing chosen for MARVEL should provide as wide and as representative a range of service conditions as possible. Truck routes should be recorded and tracked using time-indexed GPS data. To simulate potential microreactor deployments, measurement runs (see example in Table 10) should be conducted over routes that are representative of the actual transportation environments anticipated for microreactor deployments. In addition, the MARVEL Project should capitalize on transportation testing opportunities through shock and vibration data collection for route analysis as subsystems and components are shipped from fabricator facilities to INL utilizing road transportation.

Route selection should consider the following factors:

- Road surface type—Interstate highway (smooth), U.S. highway (moderate), and secondary roads.

- Speed profile—Highway cruise (55–65 mph), reduced-speed zones, and acceleration and braking.
- Geographic region—Routes representative of anticipated deployment environments (e.g., continental U.S., remote or austere environments).
- Seasonal conditions—If year-round transportation is anticipated, measurements should capture both summer and winter road conditions where practicable (MIL-STD-810H, Annex C, Method 514.8 — "Vibration. In Environmental Engineering Considerations and Laboratory Tests", 2019).

Table 10. Measurement runs route matrix.

Run ID	Route Type	Surface Condition	Speed (mph)	Distance (mi)	Purpose
R-01	Interstate Highway	Smooth / good	60–65	≥ 50	Baseline cruise environment
R-02	U.S. Highway	Moderate / worn	45–55	≥ 25	Secondary road environment
R-03	Construction Zone	Rough / uneven	25–35	≥ 5	Worst-case surface condition
R-04	Highway On/Off Ramp	Smooth curve	25–35	≥ 2	Lateral acceleration characterization
R-05	Emergency Brake Event	Smooth	3–5	≥ 50 ft	Longitudinal deceleration characterization

6. DATA COLLECTION AND HARDWARE

6.1. Sensors

Shock and vibration testing for highway transport confirms the MARVEL reactor and materials can survive mechanical and environmental loads during transport and assurance of Quality Conditions of Transport (QCT) maintenance. QCT refers to the legal frameworks and regulatory guidelines that govern how materials will be transported to ensure safety for the public. The U.S. DOT set guidelines on public roads for QCT, and information is captured in DOT information quality guidelines. Vibration, acoustic, and shock analyses evaluate the structural response for critical components. Completion of these analyses is necessary for mission assurance and should be required before the MARVEL reactor and systems can be certified for transport.

When monitoring and collecting data for highway transport, specific instrumentation and monitoring equipment should be used to capture data. Shock and vibration during transport should be recorded using accelerometer sensors, data loggers, and data acquisition systems. Data acquisition is the process by which data is extracted from a sensor and transformed into electrical signals that are converted into a digital form for processing and analysis by a computer device (Bolton 2015). Standard data collection systems consist of four primary components:

- Sensors: Devices that measure physical attributes and convert the information into electrical signals such as thermocouples for temperature, accelerometers for vibration, and strain or stress gauges to measure stress fatigue on high temperature materials.
- Signal conditioning: Hardware that amplifies weak signals and filters out electrical noise to ensure data is accurate prior to processing information.
- Data acquisition hardware and data loggers: Physical boards or devices that can capture conditioned signals and convert them from an analog signal to digital and structure the data so that the information can be interrupted by a computer. (See Section 6.1.3, Figure 8).

- Computer and software: Computer stations or industrial controllers that can log, visualize and analyze data in real-time.

Accelerometers have the “sensing and signal conditioning” element mentioned above under the primary data acquisition component. The sensing from acceleration or shifts in gravity creates a change between mass and fixed electrodes. These minor changes are amplified and converted into a readable format across an integrated analog-to-digital converter (ADC). Accelerometer hardware requires set specifications to make downloadable information available for analysis. Setting and prioritizing the axes is required to indicate maximum direction of motion while the sensor monitors shock and vibration.

- Single axis measures linear motion in one direction.
- Triaxial (three-axis) measures X, Y, and Z axes simultaneously to show a complete 3-D picture with spatial orientation. Measuring the range can provide precise tilt and slow-motion settings while higher ranges are normally required for impact and shock measurements. The resolution requires settings that ensure the smallest detectable change in acceleration, sometimes ranging from 10-bit to 16-bit, which can be detected on the internal ADC converter. The bandwidth or frequency range for movements allows the sensor to track spectra data between (0.5 Hz to 1,600 Hz).

Noise characterization techniques and data-cleaning analysis should also be considered with instrumentation and monitoring equipment used to capture data.

Noise characterization techniques:

- RMS (Root Mean Square) – Overall energy content of the vibration signal over a time window; useful for comparing overall severity across road types/segments.
- Peak/Crest Factor — Ratio of peak amplitude to RMS; helps distinguish smooth random vibration (low crest factor) from shock-dominated events (high crest factor, e.g., potholes or road damage impacts).
- Kurtosis — Measures "peakedness" of the amplitude distribution; elevated kurtosis indicates non-Gaussian behavior, often associated with impulsive/shock events embedded in otherwise random vibration (common on secondary roads).

Frequency -Domain Descriptors:

- Power Spectral Density (PSD) — The primary tool for characterizing random vibration noise; shows how vibration energy is distributed across frequency and is the standard input format for MIL-STD-810 Method 514.8 test tailoring.
- Grms (RMS acceleration from PSD) — Single-number severity metric derived by integrating PSD over the frequency band of interest.

Data Cleaning Techniques (Pre-Analysis):

- Outlier/glitch removal — Screening for sensor dropouts, electrical spikes, or clipping (saturation) that aren't real physical events; typically done via threshold-based flagging or visual inspection of time histories.
- Detrending — removing DC offset or slow drift (e.g., from thermal effects on sensors) before frequency-domain analysis, since uncorrected drift can distort low-frequency results.
- Filtering:
    - High-pass filtering — Removes very low-frequency drift/noise below the frequency range of interest.

- Low-pass/anti-aliasing filtering — applied before digitization (or verified after the fact) to prevent high-frequency content above the Nyquist frequency from folding back into the data as false low-frequency content.
- Band-pass filtering — isolates a specific frequency range of interest (e.g., isolating rail-joint-induced frequencies from broader road noise).

6.1.1. Accelerometer Placement

To monitor transportation data well, the physical parameters you want to track must first be known. These metrics tell you about vehicle movement, road conditions, and system safety. For example, measuring shock and vibration may require accelerometers to be strategically placed on the transport vehicle to capture shock and vibration data. The MARVEL functions and requirements document identifies the placement location for accelerometers. Where possible, accelerometers should be attached directly to structures (test article, truck/ trailer surface) by some suitable non-marring method, such as clamps with non-marring surfaces of approved contact materials (Stewart et al. 2026). Based on lessons learned and experience in other transportation programs, they can also be placed where most vibration occurs. Sensors attached directly to subsystem components should be minimized whenever possible to alter vibration as little as possible. Figure 5 provides a diagram of accelerometer placement for transport of microreactor systems using a CONEX container as the shipping package. Table 11 shows 10 channels based upon a hypothetical sensor instrumentation plan for a microreactor program.



Figure 5. Accelerometer placement diagram.

Table 11. Channel count dependent upon program-specific sensor instrumentation plan.

Channel Summary			
Ch.	**Location**	**Category**	**Axes**
#1	Tractor Frame (Front)	Reference/Control	X, Y, Z
#2	Fifth Wheel/Kingpin Interface	Reference/Control	X, Y, Z
#3	Trailer Frame (Front)	Structural Response	X, Y, Z
#4	Trailer Frame (Mid-span)	Structural Response	Z only
#5	Trailer Frame (Rear/Over Axles)	Structural Response	X, Y, Z

#6	Microreactor Package (Front—Top)	Payload Response	X, Y, Z
#7	Microreactor Package (Center—Top)	Payload Response	X, Y, Z
#8	Microreactor Package (Rear—Top)	Payload Response	X, Y, Z
#9	Isolation Mount—Output (Package Base)	Isolation System	Z only
#10	Isolation Mount—Input (Trailer Deck)	Isolation System	Z only

6.1.2. Accelerometer Types

Accelerometers used in the transport industry come in different types based on the exact test requirements trying to be achieved. Primary types include PE sensors for high-frequency vibration, capacitive MEMS sensors used for steady tilt/low frequency motion and piezoresistive units for high-impact shock testing. They also include specialized form factors (triaxial units) that measure movement across three simultaneous physical axes (X, Y, and Z) to high-performance accelerometers used in industrial automotive testing. For control accelerometers that are mounted at a fixed point, PE accelerometers are the most widely used for measurement applications and are usually the first choice for most vibration measurements due to their wide frequency response, good sensitivity, and easy installation.

Figure 6, Figure 7, Figure 8, and Figure 9 are industry examples of accelerometer sensors that could be considered when shipping MARVEL reactor subsystems and associated components by highway. These accelerometers were selected based on their recorded use in other microreactor programs to measure shock and vibration during highway transport. They are just a few of the many brand names manufactured across the industry.



Figure 6. Smart Trac UG2 accelerometer sensor.



Figure 7. Triaxial accelerometer sensor.



Figure 8. High-performance accelerometer sensor.



Figure 9. WISE-2410 three-axis accelerometer sensor.

During transport monitoring, accelerometer sensors measure both peak and average acceleration responses. This depends on how they are configured and what type of event they are tracking. They capture continuous vibration data that can be analyzed via averages or root-mean-square values to include transient impact shocks, which are recorded as peak values. Figure 10 displays shock and vibration sample data from a MEMS accelerometer sensor.

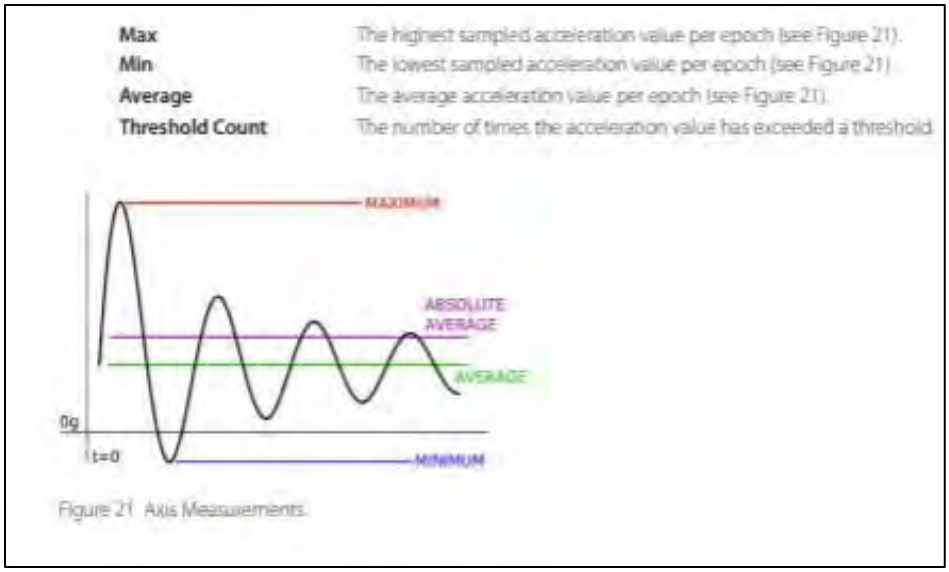


Figure 10. Example of shock and vibration data from MEMS accelerometer.

6.1.3. Data Acquisition System

A data acquisition (DAQ) system called the Transportation Recording and Monitoring System (TRAMS) has been successfully used in other microreactor programs. TRAMS is a computer-based DAQ system that provides information on temperature, shock, vibration, vital truck data, and system health status monitoring for a designated test article, such as reactor components. TRAMS is contained in a 19-inch weatherproof rack that is mounted on a tractor cab. It can be powered by an auxiliary power unit (APU) that is mounted and powered by truck or other transport conveyance, such as a C-17 aircraft. Figure 11 shows a pictorial of the TRAMS DAQ. Figure 12 shows an illustration of the TRAMS mounted on a truck cab.



Figure 11. Transportation Recording and Monitoring System (TRAMS).

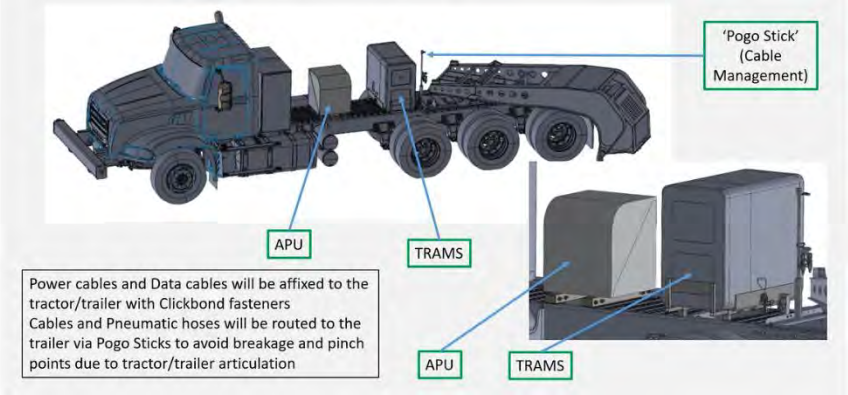


Figure 12. TRAMS mounted on truck cab.

7. TEST EQUIPMENT

Test equipment to support shock and vibration testing is listed below:

- Electrodynamic shakers (shaker tables)—The primary workhorse for large component-type vibration testing and shock spectra analysis. This equipment uses electromagnetic force to generate controlled broadband or sinusoidal motion. An electrodynamic shaker table is suitable for random vibration, sine sweep, and resonance dwell tests.
- Hydraulic (servo-hydraulic shakers)—Uses hydraulic actuators driven by servo valves to generate motion. Preferred for very large, heavy test articles and low-frequency environments where electrodynamic shakers lack stroke or force capacity.
- Shock test machines—Purpose-built machines for generating controlled transient shock pulses per MIL-STD-810H, Method 516.8. Shock-test machines produce half-sine, sawtooth, trapezoidal, and terminal peak sawtooth waveforms across a wide range of peak accelerations and durations.
- Slip tables and head expanders—Auxiliary equipment that extends the shaker's capability to test large or awkwardly-shaped test articles in lateral axes (horizontal X and Y). Slip tables use a hydrostatic oil film to allow frictionless horizontal motion while transferring shaker force.
- Calibration equipment—Equipment used to verify the sensitivity and frequency response of accelerometers before and after testing, ensuring measurement traceability to National Institute of Standards and Technology (NIST) standards. Reference accelerometers require periodic recalibration (typically annual). High-frequency calibration (>5,000 Hz) requires specialized equipment. Field calibration checks cannot replace laboratory primary calibration.

8. CONCLUSION

8.1. Summary

This test plan establishes a comprehensive methodology for the shock and vibration testing of MARVEL microreactor components and subsystems in support of ground transportation. The plan has been developed in accordance with MIL-STD-810H (DoD 2019), the F&RD (Stewart et al. 2026), applicable nuclear transportation regulatory requirements, including additional consideration of requirements that might fall under 10 CFR Part 71, or DOT 49 CFR. It is structured to provide a technically sound, fully traceable testing basis for laboratory testing requirements.

It also considers one section per test discipline (vibration, shock, acceleration), each written to stand alone. This mirrors the structure of the methodology and should provide a structured format to reference specific technical information. This test plan complements the defined requirements and ties back to specific technical areas such as accelerometer placement and torque requirements, closing the loop on the technical rigor of those measured approaches. Together, these three test disciplines envelop the mechanical loading conditions that a microreactor will encounter across its full transportation lifecycle, whether in a single-deployment or multi-deployment operational concept.

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