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Standard Guide for NAPL Mobility and Migration in Sediments—Use of Ebullition Flux Chambers¹

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1. Scope

1.1 This guide addresses the use of flux chambers for quantifying the transport of gas and non-aqueous phase liquids (NAPL)/contaminants from sediment to surface water by ebullition. Degradation of labile organic compounds in the sediment can generate biogenic gas that can migrate through the sediment into the overlying water column. Sediments that contain hydrophobic contaminants (such as NAPL) may adhere to the surface of the gas bubble resulting in ebullition-facilitated transport (EFT) and migration of NAPL/contaminants to the surface water or air–water interface. Ebullition can also result in resuspension of surficial sediment, enhancing contaminant transport to the water column. A detailed summary of biogeochemical and environmental factors that influence biogenic gas production and ebullition rate in sediments is presented in Guide E3300 and Zamanpour et al (1).²

1.2 Ebullition can be quantitatively measured by direct or indirect methods. Indirect measurement methods such as hydroacoustic equipment measure the density of gas bubbles in the water column to estimate ebullition rates. Indirect methods have the advantage of collecting data over large areas and provide better resolution on spatial variability of ebullition fluxes. Direct methods primarily employ a device to capture gas bubbles at the air–water interface, or within the water column.

1.3 In field studies, near-bottom measurements using anchored flux chambers have proven to better represent gas and NAPL/contaminant flux (2, 3, 4, 5) than have surface-based measurements. Although other methods can be utilized to measure ebullition and EFT of NAPL/contaminant fluxes, this guide focuses on the use of cone sampler style flux chambers.

This guide describes the configurations and use of three types of flux chambers used in various environmental settings. However, other flux chamber designs have been successfully used, and the general principles presented in this guide may be applicable to the other designs (for example, 3, 6, 7, 8, 9).

1.4 Flux chambers can be advantageous in understanding sediment site rates for both ebullition and EFT of NAPL/contaminants by monitoring over time. Flux chambers can be deployed for several days or tide cycles to account for temporal variability. Measuring NAPL/contaminant flux near the sediment bed reduces water column impacts on the data. Flux measurements at the air–water interface can be impacted by factors such as wind, waves, and potential sources of contamination within the water column, while near-bottom measurements are less affected by these factors. Use of flux chambers as near-bottom samplers reduces the potential for degradation of NAPL/contaminant mass in the water column or at the water surface (or both) and allows for more precise deployment to a specific location with a defined area for calculating gas or NAPL/contaminant flux (or both). In contrast, sampling devices placed at the water surface may move around during deployment, resulting in flux data that are less representative of a defined area.

1.5 *Units*—The values are presented in SI units. Imperial units are provided parenthetically, as appropriate. Units in the annexes are provided in Imperial and metric units when commonly associated with standard materials.

1.6 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.7 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

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² The boldface numbers in parentheses refer to the list of references at the end of this standard.

2. Referenced Documents

2.1 ASTM Standards:³

- E2531** Guide for Development of Conceptual Site Models and Remediation Strategies for Light Nonaqueous-Phase Liquids Released to the Subsurface
- E2993** Guide for Evaluating Potential Hazard in Buildings as a Result of Methane in the Vadose Zone
- E3163** Guide for Contaminated Sediment Site Risk-Based Corrective Action—Selection and Application of Analytical Methods and Test Procedures
- E3240** Guide for Risk-Based Corrective Action for Contaminated Sediment Sites
- E3242** Guide for Developing Representative Background Concentrations at Sediment Sites—Data Evaluation and Development Methodologies
- E3248** Guide for NAPL Mobility and Migration in Sediment—Conceptual Models for Emplacement and Advection
- E3300** Guide for NAPL Mobility and Migration in Sediment—Evaluating Ebullition and Associated NAPL/Contaminant Transport
- E3344** Guide for Developing Representative Background Concentrations at Sediment Sites—Selection of Background Reference Areas
- E3382** Guide for Developing Representative Background Concentrations at Sediment Sites—Framework Overview, Including Conceptual Site Model Considerations

3. Terminology

3.1 Definitions:

3.1.1 *biogenic, adj*—resulting from the activity of living organisms. **E2993**

3.1.2 *conceptual site model (CSM), n*—the integrated representation of the physical and environmental context, the complete and potentially complete exposure pathways and the potential fate and transport of potential contaminants of concern at a site. **E3242**

3.1.2.1 *Discussion*—The CSM should include both the current understanding of the sediment site and an understanding of the potential future conditions and uses for the sediment site. It provides a method to conduct the exposure pathway evaluation, inventory the exposure pathways evaluated, and determine the status of the exposure pathways as incomplete, potentially complete, or complete.

3.1.3 *cone sampler, n*—a sampler that uses an inverted cone or funnel of sufficient size to trap and measure gas released from the sediment. **E3300**

3.1.4 *contaminant, n*—substance not normally found in an environment at the observed concentration. **E2993**

3.1.5 *ebullition, n*—a process of gas (primarily methane) generation in sediments where the quantity of gas generated is sufficient for gas bubbles to nucleate, grow, fracture the

sediment, and then escape into the overlying water body. **E3300**

3.1.5.1 *Discussion*—Depending on the composition of a particular sediment, the gas bubbles generated and released by ebullition may strip constituents out of the sediment and transport these into the overlying water.

3.1.6 *ebullition active area, n*—a subarea within a larger ebullition study area where gas ebullition occurs consistently during an ebullition survey. **E3300**

3.1.7 *ebullition rate, n*—the rate of volumetric gas production from the sediment, measured in micromoles of gas per unit surface area of sediment per unit of time. **E3300**

3.1.8 *flux, n*—mass crossing a unit area per unit time in any phase (for example, LNAPL, dissolved-phase, vapor-phase). **E2531**

3.1.8.1 *Discussion*—For ebullition, the unit area of interest is the sediment–water interface.

3.1.9 *flux chamber, n*—a device with an isolation chamber that can trap gas bubbles rising through the water column. **E3300**

3.1.9.1 *Discussion*—For the purposes of this guide, the flux chamber is a type of cone sampler used in nearshore environments to measure ebullition and EFT of NAPL/contaminants.

3.1.10 *labile organic matter, n*—carbon-based materials that can be consumed and broken down by microorganisms, with the typical eventual metabolic end products being methane or carbon dioxide, or both. **E3300**

3.1.11 *methanogenesis, n*—the generation of methane by microorganisms, typically through the consumption of labile organic matter (OM). **E3300**

3.1.12 *NAPL, n*—chemicals that are insoluble or only slightly soluble in water that exist as a separate liquid phase in environmental media. **E3248**

3.1.12.1 *Discussion*—NAPL may be less dense than water (Light Non-Aqueous Phase Liquid [LNAPL]) or more dense than water (Dense Non-Aqueous Phase Liquid [DNAPL]).

3.1.13 *sediment, n*—a matrix of porewater and particles including gravel, sand, silt, clay, and other natural and anthropogenic substances that have settled at the bottom of a tidal or nontidal body of water. **E3163**

3.1.14 *sediment site, n*—the area defined by the likely physical distribution of COCs from a source area and the adjacent areas required to implement the corrective action; a site could be an entire water body or a defined portion of a water body. **E3382**

3.1.15 *sheen blossom, n*—the emergence of NAPL transported by a gas bubble at the water surface followed by spreading of NAPL into a sheen at the air–water interface. **E3300**

3.2 Definitions of Terms Specific to This Standard:

3.2.1 *bathymetric survey, n*—hydrographic survey that maps the depths and shape of the underwater terrain.

3.2.1.1 *Discussion*—Bathymetric surveys can be used to illustrate underwater sediment topography and are reported

³ For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at www.astm.org/contact. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

by color or contour lines (or both) to represent sediment bed elevations. Bathymetric surveys in conjunction with local hydrologic data (tidal elevations, river gauges) can be used to determine ranges in water depth at a sediment site.

3.2.2 *ebullition-facilitated transport (EFT), n*—the transport or flux of NAPL or contaminants (or both) from sediment to surface water via gas ebullition.

3.2.2.1 *Discussion*—NAPL and other organic contaminants are hydrophobic and preferentially coat the hydrophobic gas bubble surface rather than remaining in porewater. These hydrophobic contaminants attached to a gas bubble can be transported to the surface of the water body and may spread to form a sheen.

3.2.3 *sediment bed, n*—the sediment column below the interface between the sediment surface and the overlying surface water.

4. Significance and Use

4.1 Ebullition in sediment is a concern primarily when it causes EFT of NAPL/contaminants, resulting in potential risk to humans or ecological receptors; a perceptible water quality issue such as sheening, known as narrative water quality

standards in some US states; or combinations thereof. Ebullition is also a key design consideration when capping has been selected as part of a site remedy. It is important to quantify the transport of gas and EFT of NAPL/contaminants from sediment to surface water to support decision making regarding risks, remedy selection, and remedy design.

4.2 Ebullition is common in the natural environment; however, when ebullition occurs in areas collocated with NAPL/contaminants, hydrophobic contaminants in the sediment matrix may adhere to the surface of gas bubbles. Additionally, petroleum hydrocarbons (PHCs) can contribute to methanogenesis through anaerobic degradation of PHCs (1). The upward migration of the bubbles may also result in redistribution of NAPL/contaminants from deeper sediment. NAPL/contaminant-coated gas bubbles released from the sediment may create sheen blossoms at the water surface, thereby enhancing contaminant transport to the surface water column from the sediments. In addition, the gas bubbles may resuspend contaminated surficial sediment in the water column (see Fig. 1).

4.3 Using flux chambers for measuring EFT of NAPL/contaminants is the primary activity addressed by this guide.

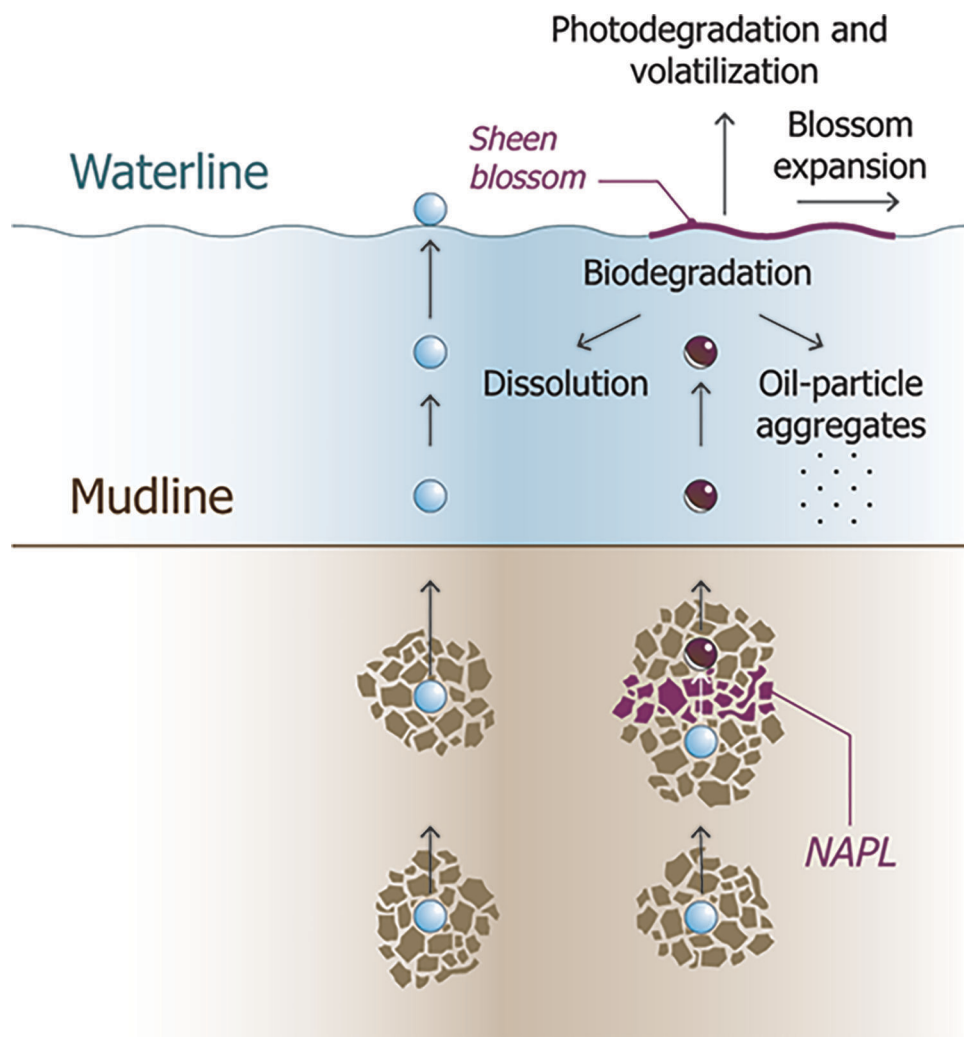


FIG. 1 Depiction of Ebullition and EFT of NAPL/Contaminants

4.4 There are varying equipment options, deployment strategies, and data collection techniques available depending on the conditions of the sediment site. This guide provides instruction and considerations for addressing these conditions most appropriately.

4.5 This guide assumes that a CSM (Guide E3240) has been developed that includes the characterization of the nature and extent of NAPL/contaminants in sediment. This CSM would include an understanding of (1) the hydrological setting, (2) the physical and chemical characteristics of the sediment and water body, (3) the physical and chemical characteristics of the NAPL/contaminants, (4) mechanism(s) of NAPL/contaminant emplacement, (5) the physical extent of the NAPL/contaminant zone, and (6) the potential for human and ecological receptor exposure to NAPL/contaminants in sediment, or via NAPL/contaminant release to overlying surface water. The means and methods for collecting this information are not addressed in this guide.

4.5.1 This guide assumes that the CSM developed establishes that ebullition and the EFT of NAPL/contaminants occur at a magnitude and prevalence that warrants further evaluation. This is typically accomplished by performing ebullition surveys at the sediment site (Guide E3300). The CSM should be updated and refined as more information becomes available.

4.6 This guide is intended to be used as a reference for the design of, deployment of, and data collection from ebullition flux chambers. This guide is not intended to provide specific guidance on sediment site investigation, risk assessment, monitoring, or remedial action.

4.7 This guide may be used by various parties involved in a sediment site, including regulatory agencies, project sponsors, environmental consultants, site remediation professionals, environmental contractors, analytical testing laboratories, data reviewers and users, and other stakeholders.

4.8 This guide does not replace the need for engaging competent project planning and field personnel to evaluate ebullition and EFT of NAPL/contaminant fluxes from sediments. Activities necessary to design, build, and use flux chambers should be conducted by persons familiar with NAPL/contaminant-impacted sediment site characterization techniques, physical and chemical properties of NAPL/contaminants in sediments, fate and transport processes, remediation technologies, and sediment evaluation protocols. The users of this guide should consider assembling a team of experienced project professionals with the expertise to scope, plan, and execute data acquisition activities.

4.9 This guide is intended to be applicable at a broad range of local, state, tribal, federal (such as the Comprehensive Environmental Response, Compensation and Liability Act), or international jurisdictions, each with its own regulatory framework. As such, this guide does not provide a detailed discussion of the requirements or guidance associated with any of these regulatory frameworks, nor is it intended to supplant applicable regulations and guidance. The user of this guide will need to be aware of the regulatory requirements and guidance in the jurisdiction where the work is being performed.

4.10 The user of this guide should review the overall structure and components of this guide before proceeding with use, including:

Section 1	Scope
Section 2	Referenced Documents
Section 3	Terminology
Section 4	Significance and Use
Section 5	Flux Chamber Sampling Locations and Timing
Section 6	Flux Chamber Design
Section 7	General Procedures
Section 8	Keywords
Annex A1	Example Flux Chamber Design for Shallower Environments
Annex A2	Example Flux Chamber Design for Deeper Environments
Annex A3	Example Automated Flux Chamber Design for Deeper Environments

References

5. Flux Chamber Sampling Locations and Timing

5.1 Overview:

5.1.1 Ebullition from sediments is episodic in nature, with ebullition flux influenced by multiple factors including site conditions (water depth, tides, and sediment temperature), sediment physical characteristics, and biogeochemical conditions that introduce spatial and temporal variability in ebullition at a sediment site. A more detailed description of the factors influencing ebullition is presented in Guide E3300. The sections below provide general guidance for characterizing the variability of ebullition and EFT of NAPL/contaminant fluxes.

5.2 General Considerations for Characterizing Spatial Variability of Ebullition and EFT of NAPL/Contaminants:

5.2.1 Before developing a sampling plan for measuring fluxes of ebullition and EFT of NAPL/contaminants, several key preceding steps are recommended. Ebullition and EFT measurements of NAPL/contaminant flux should be focused in active ebullition areas identified during the screening process (such as during field ebullition surveys). Some areas of the sediment site may be more ebullition-active than others, and the ebullition and EFT of NAPL/contaminant flux measurement locations selected should capture the variability of ebullition activity. Whether ebullition results in transport of NAPL/contaminants to the water column or has the potential to influence remedy evaluation and selection are key considerations. Field ebullition surveys are typically used to screen for ebullition and assess the need for a more detailed evaluation, such as ebullition and EFT of NAPL/contaminant flux measurement (Guide E3300).

5.2.2 If ebullition has been established as a NAPL/contaminant transport mechanism that needs to be addressed (Guide E3300), the next step is to assess the spatial extent of ebullition occurrence and identify areas where ebullition measurement efforts can be focused to collect ebullition and EFT data.

5.2.3 In addition to identifying study areas for ebullition flux measurements, there are other site-specific data that can be collected and used in developing a sampling plan. These site-specific data are related to factors that influence the spatiotemporal variability in ebullition flux (Guide E3300) and are listed below:

5.2.3.1 Ebullition rates generally increase with decreased hydrostatic pressure associated with decreases in water depth, among other factors (Guide E3300).

be used to identify areas with shallow/deep water depths to assist in selection of locations with a range of water depths for ebullition flux and (where required) EFT of NAPL/contaminant sampling.

5.2.3.2 Sediment physical properties (such as sediment strength, porosity, and bulk density) influence the ease of biogenic gas bubble formation and release from the sediment matrix (1). Sediment physical properties and sediment thickness data may be used to select locations for ebullition and EFT of NAPL/contaminant flux measurements.

5.2.3.3 Ebullition rates are influenced by the availability of labile OM that can be biodegraded to form biogenic gases (mostly methane). Total organic carbon (TOC) content data from sediment cores or grab samples can be used to assess TOC spatial variability and aid in the selection of sampling locations for ebullition flux measurement. It should be noted that the presence of high TOC content does not always translate to high gas production rates. Microbial activity is influenced by a variety of factors, such as oxidation/reduction potential, temperature, and availability of competing electron acceptors (see Guide E3300). The presence of combined sewer discharges, storm sewer discharges, permitted industrial and non-industrial discharges, non-point discharges (such as surface runoff), and tree cover near the sediment site can influence the amount of labile OM in surficial sediment. These external carbon sources should be considered in selecting locations for measuring ebullition and EFT of NAPL/contaminant fluxes.

5.2.3.4 Sediment NAPL/contaminant concentrations can also be useful in identifying potential EFT areas and assist in the selection of EFT of NAPL/contaminant sampling locations. Ebullition and EFT of NAPL/contaminant data should be collected from areas with a range of sediment contaminant concentrations and NAPL occurrence depths to cover a wide range of site conditions.

5.2.3.5 Flux chambers measure ebullition and EFT of NAPL/contaminant fluxes from a finite surface area above the sediment surface. Multiple EFT measurement locations are needed to collect sufficient data to extrapolate the point measurements to the entire sediment site, or a particular reach within a larger sediment site. Field studies have utilized a wide range of measurement densities, and a recommended measurement density has not been reported in the literature. The heterogeneity in site conditions, such as spatial variability in observed ebullition activity, contaminant concentrations, availability of labile OM, water depth, sediment thickness, and sediment physical properties, along with the amount of data needed to support a decision on how ebullition and EFT of NAPL/contaminants need to be handled during any potential remedial options, should guide the selection of flux chamber deployment spacing and density.

5.3 General Considerations for Characterizing Temporal Variability of Ebullition and EFT of NAPL/Contaminants:

5.3.1 Ebullition is known to vary temporally due to factors such as seasonal temperature changes, diurnal temperature changes, tidal influence, seasonal leaf fall, and combined sewer discharges that contribute labile OM to the sediment zone. In colder climates, gas production is greater in early spring to late fall, with minimal gas production reported at sediment tem-

peratures below 4 °C. In warmer climates, gas production from ebullition occurs throughout the year. Sampling design should consider the use of both short- and long-term measurements. Remedial designs often need to account for long-term ebullition rates for design criteria (such as annual loads), as well as the maximum ebullition rates over short periods. The following factors should be considered in characterizing temporal variability:

5.3.1.1 Field ebullition surveys conducted over multiple seasons can be a useful first step in evaluating the degree of seasonal variability at a sediment site and identify periods of high and low ebullition fluxes.

5.3.1.2 Measurements should be collected over multiple seasons and time scales to evaluate short- and long-term variability in ebullition and EFT of NAPL/contaminant fluxes. Data measurements spanning greater time can be used to estimate the annual ebullition flux. In colder climates, higher ebullition rates are generally observed between spring and fall due to the accumulated OM loading combined with peak sediment temperatures.

5.3.1.3 Ebullition flux measurements at sediment sites with tidal influence should target flux chamber measurements during a range of tidal stages. Reduced hydrostatic pressure results in increased ebullition, so ebullition and EFT of NAPL/contaminant flux measurements should be obtained over a range of tide levels (including low tide, when ebullition is typically most active due to lower hydrostatic pressure).

5.3.1.4 Other factors such as atmospheric pressure changes due to large storm events, water level changes due to waterway operations, periods of boat traffic (that is, propeller wash), and high flow conditions should be considered in evaluating temporal variability of ebullition and EFT of NAPL/contaminant fluxes.

5.3.1.5 The frequency of ebullition and EFT measurements should be based on site-specific conditions (such as ebullition activity and physical disturbances) and flux chamber design. Data collection intervals ranging from days to weeks have been reported in the literature (10). Additionally, the development of automated gas collection chambers with integrated sensors allows for continuous ebullition flux measurements (11). The continuous ebullition data from automated flux chambers can be analyzed at varying timescales to characterize temporal variability in ebullition rates and assess the magnitude and frequency of discrete ebullition events.

6. Flux Chamber Design

6.1 Design Considerations:

6.1.1 Flux chamber design should consider site conditions such as slopes (bathymetric survey), range of water depths, hydrologic conditions (tidal cycles, flow rates), sediment physical properties (organic carbon, grain size, strength), and potential physical disturbances (vessels, debris, recreational use). Bathymetric survey and water depth data are critical in the selection of a flux chamber design. Shallow water depths may limit the size of the funnel and gas collection chamber; whereas sites with deeper water allow for more flexibility in flux chamber designs. Sloping sediment surfaces may pose challenges for positioning the flux chamber over the desired