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Integrated Methane Monitoring Platform Design

Final Report: Integrated Methane Monitoring Platform Design

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Executive Summary

As the urgency for understanding methane emissions and the number of methane monitoring technologies being deployed have increased in the last two decades, there is an opportunity and a need to integrate the numerous disparate data sources to enable the detection, quantification, contextualization, and reporting of methane emissions along the oil and gas supply chain. Such an integration would enable emissions reductions through early detection of super emitters, data-driven mitigation strategies, and improved greenhouse gas inventories. The GTI Energy ("GTI") project team ("the team") worked with a multitude of industry experts, stakeholders, and subject matter experts (SMEs) to collect guidance, insights, and information to inform the requirements and subsequent engineering, design, deployment, and operations of an integrated methane monitoring platform (IMMP). This final report describes the results of the team's effort to execute the **Integrated Methane Monitoring Platform Design** project, ultimately providing an engineering, design, deployment, and operating plan (EDDOP) for the IMMP.

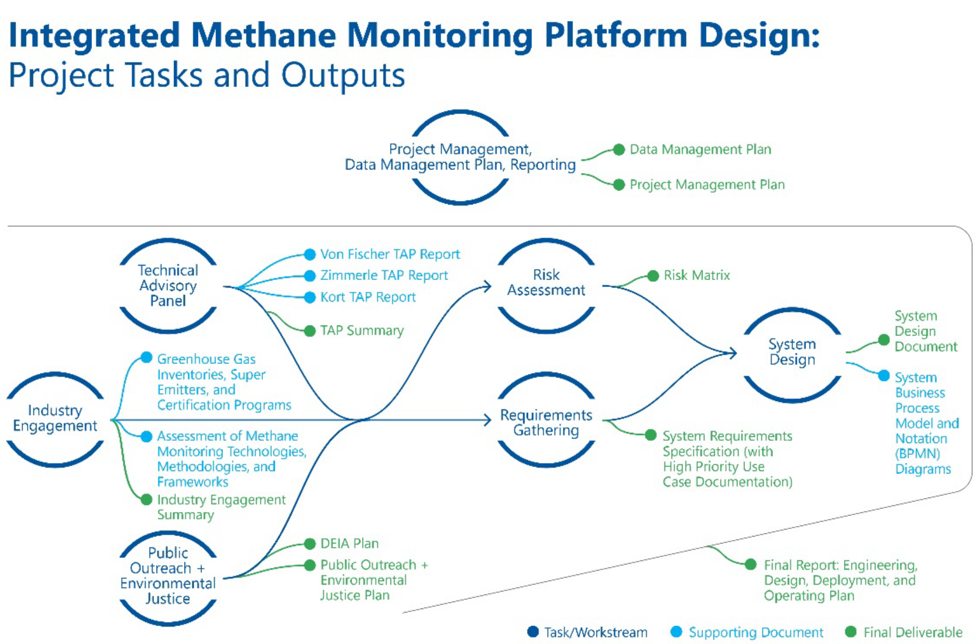

Figure 1: Project tasks, workflows, and outputs. This project comprised seven key tasks, each instrumental in supporting the design of an ideal IMMP. The tasks are depicted in circles and the results of each task are shown with arrows pointing to documents and final deliverables. The figure displays the flow of information (from left to right) to illustrate how information and insights gained from earlier tasks fed into the execution of later tasks and, ultimately, the final report.

This final report summarizes and integrates the project tasks' results and outputs. Figure 1 diagrams the tasks and workflows executed throughout the project and the resulting documents.

The critical first step to designing the IMMP was to conduct a thorough stakeholder analysis involving outreach and engagement with a technical advisory panel (TAP), various industry entities, and the public. The TAP comprised academics, and industry engagement included discussions with operators, regulators, technology providers, and GTI SMEs. Public outreach included a public survey and community meetings. The team used the results of stakeholder engagement to identify critical gaps and needs that the IMMP could fill. In this process, the team identified five high priority users and use cases that could substantially impact methane emissions reduction efforts. Through stakeholder engagement, the team also identified barriers to the IMMP's effective application and developed strategies for overcoming them. The use cases developed through this extensive input were used to identify and document the IMMP software system requirements, which drove the software system design. Finally, the team created the IMMP deployment and operating plan. The team took a methane monitoring technology and supply chain segment agnostic approach throughout the project, acknowledging that all methane monitoring technologies have relative strengths and weaknesses and that the IMMP could address emissions challenges across the supply chain. This final report summarizes each of these tasks and their primary findings. The final report is associated with a Supporting Information (SI) document containing task-specific deliverables and other comprehensive documents containing details of the project results.

Proposed IMMP

Stakeholder engagement revealed several key considerations for developing the IMMP. First, the IMMP could serve various users and use cases, posing a challenge to platform development and necessitating the prioritization and identification of high-impact applications. Next, data integration is critical for many of the platform's envisioned use cases. Non-monitoring data, such as infrastructure or operational information, may comprise a large proportion of the data hosted on the IMMP. However, infrastructure or wind (environmental) data are not always high quality or easily accessible. Additionally, methods for integrating the results of multiple monitoring technologies are in the early stages of development and not widely available or deployed. Another important finding is that there are a variety of existing methane data platforms and software systems, which tend to serve a narrow group of users or fail to integrate multiple data sources. The TAP Summary, Industry Engagement, and Public Outreach and Environmental Justice Plan documents describe the complete results of stakeholder engagement.

The team documented barriers and risks to the effective implementation of the IMMP through a risk matrix. This matrix lists and categorizes risks as 1) technical and engineering risks, 2) external risks, or 3) platform management and administration risks. The team identified the four biggest potential risks: a lack of programmatic support for the IMMP, the challenges associated with obtaining data, ensuring data quality, and maintaining system security. Other risks include managing a potentially broad range of stakeholders, rapidly changing monitoring technologies, and integrating or interfacing with a wide range of data sources. The team developed risk mitigation strategies for each of the documented risks. The Risk Matrix document in the SI gives a comprehensive description of risks, barriers, and mitigation strategies.

Stakeholder engagement and feedback informed the possible use cases of the IMMP. The team identified five high priority use cases (HPUCs) that could significantly impact emissions reduction efforts or close existing gaps in data availability. These HPUCs include 1) regulator super emitter notification program, 2) operator super emitter response, 3) operator emissions inventory, 4) regional emissions estimates, and 5) environmental justice and diversity, equity, inclusion, and accessibility (EJ/DEIA) data availability. The team used the HPUCs to identify and document requirements for the IMMP software system. The requirements were broadly categorized as functional (features supporting the system's internal workings) or non-functional (features supporting the user experience). These requirements reflect the necessary and desired functionalities needed to deliver the outputs for the HPUCs. The HPUCs and system requirements are provided in the System Requirements Specification document in the SI, and the Assessment of Methane Monitoring Technologies, Methodologies, and Frameworks document in the SI reviews monitoring approaches that could be used in the HPUCs.

The team used the system requirements to create an engineering and design plan for the IMMP software system. The System Design Document in the SI provides a comprehensive description of the architecture, functionality, and performance of the software system of the IMMP using business process model and notation (BPMN) diagrams. It is a detailed guide that provides a blueprint for the software development team, clearly communicating the system's specifications. The System Design Document is essential to successfully building, deploying, and maintaining the IMMP software system. It provides use case screen mockups, documents all workflow processes and procedures, and a high-level design description addressing software/hardware technologies, data architecture and flow, and development frameworks.

Finally, the team developed a phased approach for the platform's deployment and operation. The first phase would continue to engage stakeholders to finalize and update requirements and create a pilot version of the software system. Any new monitoring efforts would be identified and planned during the initial phase. Next, the pilot phase would involve user testing and feedback to refine functionalities and identify bugs. The platform would then move to a deployment and maintenance phase, making it more widely available and supporting users through training, updates, and support. This final phase would also include continued stakeholder engagement to identify new use cases, the addition of new functionalities, and scaling the platform as required. These phases or parts of phases could be conducted in parallel.

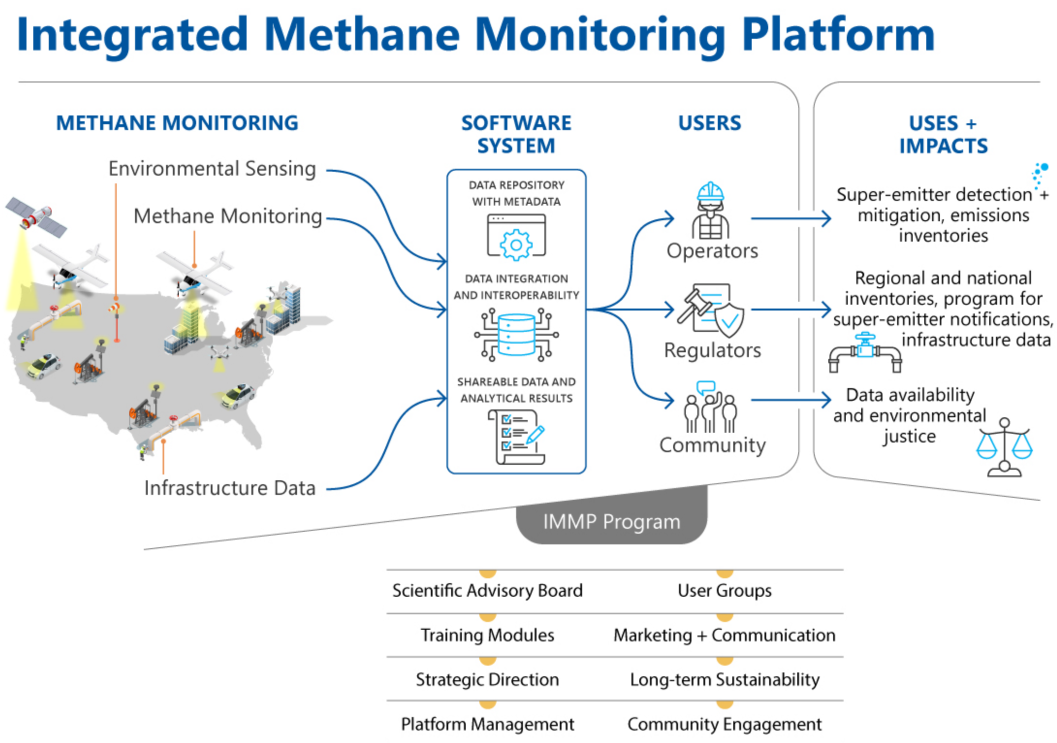

Figure 2: A conceptual diagram of the IMMP envisioned in this project supported by an IMMP program. The IMMP could provide value to different types of end users by deploying technologies, providing data, and providing analytical functionalities to address their needs and desired use cases. Critical to the software system is an emphasis on data integration and interoperability enabled through metadata documentation. An IMMP Program supporting the platform would ensure that the platform adapts and scales to have broad impacts and continually addresses evolving methane emissions challenges.

IMMP Program

The IMMP proposed here is designed to address the biggest challenges related to methane monitoring for the oil and gas industry. As a result, the IMMP software system should be developed and supported within an IMMP Program to ensure maximum impact and relevancy (see Figure 2). The IMMP must be more than methane monitoring coupled with a software system. An IMMP Program would not only manage the monitoring efforts and software development but also provide strategic direction, outreach to industry entities and community groups representing different users, and training for system users to maximize adoption and engagement. The IMMP Program will be supported by a Scientific Advisory Board of SMEs and stakeholders to guide development. Due to the complexity of the IMMP, both scientifically and with the diversity of potential users and uses, an organization with expertise in methane emissions monitoring technologies, software development, education and training, marketing, program management, and existing collaborations with various industry stakeholders should administer and execute an IMMP Program.

IMMP Creation

The first phase in the platform's development should be to create a methane data specific repository to house oil and gas infrastructure information and methane monitoring data from federally funded research efforts such as the Innovative Methane Measurement, Monitoring, and Mitigation (iM4)

Technologies and Methane Emissions Reduction Program (MERP) projects. This would address difficulties in accessing infrastructure information and centralize the data from numerous existing or soon-to-be-launched measurement campaigns across the United States. This data repository would serve as a foundational component of the IMMP, enabling users to access and download the data and develop mapping and analytical capabilities that utilize the data.

Additional IMMP development should be executed through continued stakeholder and industry engagement to ensure the platform addresses the highest priority and most impactful methane emission challenges. While this project produced an EDDOP for the IMMP, the methane emissions landscape is constantly evolving. The IMMP must also evolve to adapt and scale to new user needs, maintain relevancy, and maximize impact. Platform development should be executed in phases, starting with system pilots and then scaled and adapted as needed to address new and evolving industry needs. The organization building the IMMP should utilize and emphasize a coordinated and collaborative approach to bring value to a variety of stakeholders so that the IMMP provides a meaningful and impactful tool to support emissions reductions.

Introduction

Project Background and Objectives

As the availability and deployment of methane monitoring technologies have rapidly increased over the last two decades, new data has improved our understanding of methane emissions by detecting previously unknown emissions and quantifying many emissions events. At the same time, these new data have revealed open questions about emissions, such as reasons for the differences in estimates derived from top-down and bottom-up approaches, emissions duration, ways to integrate monitoring technologies, and the accuracy of emissions inventories. Answers to these and other questions will ultimately enhance the “big picture” of the oil and gas emissions landscape, enabling data-driven emissions reductions, accurate emissions inventories, and critical insight into the causes and durations of emissions. One of the ways to move toward these answers and achieve the desired impacts is by creating an integrated methane monitoring platform. An integrated methane monitoring platform (IMMP) is defined as a collection of methane detection and measurement tools acting at all levels, coupled with environmental sensing tools, across multiple temporal frequencies and across a wide geographic range, the collected data from which is processed and analyzed using appropriate models via a centralized software system to deliver accurate estimates of oil and natural gas sector methane emissions, both chronic and super emitter volumes, on a relatively continuous fashion.

The project objectives were to 1) gather requirements for the IMMP and 2) create an engineering, design, deployment, and operating plan (EDDOP). The team developed and executed an approach for creating and long-term implementation of the IMMP. This approach enabled the team to achieve these objectives and provide a breadth and depth of insights and information on the IMMP. This final report summarizes the project findings and describes an EDDOP for the IMMP.

Project Tasks and Approach

The team achieved the project objectives through a series of tasks that gathered pertinent information from stakeholders, synthesized the information into a set of platform requirements, and created an EDDOP based on the information. Figure 1 displays the tasks and resulting documents they produced. First, the team engaged with internal and external subject matter experts, including methane emissions researchers, monitoring technology providers, regulators, and operators. The team also convened a technical advisory panel (TAP) of academics and solicited feedback from the public. After gathering and synthesizing the information, the team identified potential risks and developed a set of IMMP use cases and software system requirements. These requirements were used to develop an engineering and design plan for an IMMP software system. Finally, the team identified a deployment and operating plan to build and sustain an IMMP.

One of the biggest challenges of developing an EDDOP for an IMMP is the potential breadth of users and applications of such a platform. Take, as an example, a comparison of operators and federal regulators. Both users could benefit from an IMMP. However, operators and regulators have access to different data sources, monitoring needs at vastly different scales, and different target audiences (e.g., operators may use a platform to communicate with field crews, regulators may use a platform to serve the public). Our approach considered this breadth of users and applications and remained agnostic to specific methane monitoring technologies, supply chain segments, and underlying software technology. This enabled the development of an IMMP that could provide value to multiple types of users and have broad impacts, interacting not only with a variety of users but also with a variety of existing or new systems. The team approached the creation of an EDDOP by considering potential high-impact applications of an IMMP, identifying the requirements to support those applications, and designing a software system that could support the variety of these applications. These use cases could have a variety of targeted users, requiring multiple types of access and functionality within the same system. This use-case-driven method reflects and demonstrates the team's recommended approach to refine and execute the EDDOP and supports flexibility and scaling in the final platform.

About GTI Energy

As a non-profit research organization, GTI was well-positioned to execute the project objectives through our collaborative relationships with various stakeholders in the oil and gas industry. GTI's work in the energy industry is widely collaborative. We work with academics, federal and state government agencies, oil and gas operators, monitoring technology providers, communities, and other non-profits to answer scientific questions and develop solutions for decarbonizing energy systems. In addition to this collaborative work, GTI is home to numerous energy systems and methane emissions experts. The project team's expertise covers a breadth and depth of relevant subjects required for an IMMP, from sensors to surveying, fieldwork to data analysis, and statistics to software development. The project team utilized these SMEs and a network of existing relationships to gather diverse perspectives and input to inform an IMMP.

About this Document

This final report summarizes and highlights the most important findings of the team's work across the project tasks. The rest of the document is organized as follows, and collectively, these sections describe an EDDOP for an IMMP. The stakeholder engagement and inputs section describes the findings from industry engagement, the project's technical advisory panel, and public outreach. The information from these efforts was used to identify barriers and strategies for overcoming them (IMMP Risks and Barriers section), and it was used to create an extensive document describing various monitoring technologies, including their relative advantages and shortcomings (SI: assessment of methane monitoring technologies, methodologies, and frameworks). The team also used stakeholder feedback and engagement to develop IMMP use cases and their associated requirements, exploring high-impact applications for the platform and documenting the steps required for a software system (System Requirements section). The software System Design section describes the system workflows, provides screen mockups, and identifies system architectures. The IMMP Program section describes a deployment and operating plan for building, sustaining, and maximizing the impacts of an IMMP. The report concludes with a short discussion and proposal for the next steps.

The original funding opportunity announcement (FOA) listed 13 components that should be included in an IMMP's EDDOP. These components are covered throughout the final report and in the SI. Table 1 below lists where each of these elements is discussed. The final report's SI contains detailed descriptions of many components.

Table 1: A list of IMMP engineering, design, deployment, and operating plan (EDDOP) components in the original funding opportunity announcement (FOA) and the associated document(s) where they have been addressed. Many of these components are addressed in detail in the final report's supporting information (SI).

IMMP EDDOP component	Where covered in the report
Assessments of bottom-up and bridge technologies that can integrate bottom-up analysis with top-down analysis	SI: Assessment of monitoring technologies, methodologies, and frameworks
Assessments of state-of-the-art methane emissions quantification technologies and methods including their probability of detection of emissions rates between 0.01 kg/day and 1,000,000 kg/day	SI: Assessment of monitoring technologies, methodologies, and frameworks
Explanation of new, imminent, large-scale monitoring efforts in the next three years that could be leveraged	SI: Assessment of monitoring technologies, methodologies, and frameworks
Cost assessment of available, state-of-the-art, and cutting-edge technologies that would be considered for use within an IMMP	SI: Assessment of monitoring technologies, methodologies, and frameworks
Role, if any, that existing GHG surface monitoring networks can be leveraged. Example is NIST's Urban GHG measurement testbeds	SI: Assessment of monitoring technologies, methodologies, and frameworks; SI: TAP Member Report – IMMP Report for GTI
Explanation of existing computational models (inversion models), including application and gaps that need to be addressed	SI: Assessment of monitoring technologies, methodologies, and frameworks; SI: TAP

	Member Report – IMMP Report for GTI
Explanation of existing gaps across all monitoring frameworks that need to be addressed	Methane Monitoring Technologies and Data; SI: Assessment of monitoring technologies, methodologies, and frameworks
Assessments of data management practices that could be utilized for an IMMP an how those practices would integrate with existing GHG inventories	SI: Greenhouse gas inventories, super emitters, and certification programs
Assessments of potential methane emissions, specifically "super emitters", and how those emissions would be detected and quantified	SI: Greenhouse gas inventories, super emitters, and certification programs; SI: System requirements specification document
A discussion on how to utilize the platform to enable more accurate estimates of methane emissions, timely identification of "super emitters", more accurate attribution of emissions to specific processes/sources, discovery of missing sources or processes, detection of spatial and temporal trends, and improved confidence in the data generated used to make decisions by industry and government	High Priority Use Cases; SI: Assessment of monitoring technologies, methodologies, and frameworks
An assessment of how this platform can be used, if applicable, to validate various newly developed methane certification programs	SI: Greenhouse gas inventories, super emitters, and certification programs
An assessment and discussion of the possible barriers to the effective application of such a platform, including an assessment of the likelihood of data sharing by industry players, the likelihood of state regulations that encourage data sharing across lease boundaries, and the likelihood of data sharing by international satellite data collection entities	SI: Risk assessment matrix
A clear description of the strategy to overcome all implementation barriers identified and described above	SI: Risk assessment matrix

Stakeholder Engagement and Input

Background

To begin the project, the team used stakeholder engagement and analysis to identify important gaps and needs that an IMMP could address and inform general design and implementation considerations. Stakeholder engagement included the following efforts:

1. Regular meetings with a technical advisory panel (TAP) of academics.
2. Industry engagement via meetings with regulators, methane monitoring technology providers, and oil and gas operators.
3. Public outreach and engagement.

4. Discussions with and soliciting feedback from internal GTI SMEs, especially those leading federally funded projects, working with operators, involved in collaborative projects (e.g., with academics or state agencies), or having experience using monitoring technologies.

The team also identified and reviewed several existing data and software platforms to identify functionalities and potential gaps the IMMP could utilize or fill. The remainder of this section summarizes the results of efforts (1.)-(3.) above and the data and software platform review. We list the supporting documentation containing a detailed description of the results of efforts (1.)-(3.). Insights from (4.) are incorporated throughout this report and the supporting documentation.

Technical Advisory Panel Summary

The GTI Energy project team established a Technical Advisory Panel (TAP) of methane emissions experts to provide feedback on the programmatic and structural design of an IMMP. The TAP and GTI had ten meetings, following a roughly biweekly cadence over six months to discuss IMMP requirements. Through these engagements, GTI developed five high priority case studies that acted as guideposts for the platform. Additionally, TAP members provided the project team with key insights regarding data types, formats and scales, which further informed the platform design. The primary takeaways from these meetings were that the IMMP must have clearly defined goals and target stakeholders, it must be designed to ingest multiple types of data, some critical infrastructure and environmental data may not be readily available, a trusted third-party is essential if the system ingests non-anonymized data. A scientific review board (SRB) is recommended to ensure data quality in the system.

The TAP consisted of four methane monitoring experts: Dr. Joe von Fischer, Dr. Eric Kort, Dr. Anna Hodshire, and Dan Zimmerle. Dr. Von Fisher is a Professor in the Department of Biology at Colorado State University and a notable ecosystem ecologist who has studied greenhouse gas emissions initially from soil microbes and more recently from the oil and gas supply chain. Dr. Kort is an Associate Professor in Climate and Space Sciences and Engineering at the University of Michigan and has an established research program focused on making high quality atmospheric observations of long-lived greenhouse gases and linking observed atmospheric abundances to underlying fluxes. He is also a member of Carbon Mapper's Science and Measurement Committee. Dr. Anna Hodshire is a research scientist at the Energy Institute at Colorado State University and has expertise in coordinating field campaigns for top-down/bottom-up surveys and basin-wide surveys of oil and gas methane emissions. Dan Zimmerle is the Director of the Methane Emissions Technology Evaluation Center (METEC) and the Remote and Distributed Energy Center in the Energy Institute at Colorado State University, and he has served as the principal investigator on several major studies on methane emissions in the natural gas supply chain.

There were six key takeaways from the TAP meetings, each detailed below.

1. **Many users would be interested in engaging with the IMMP, which could serve numerous use cases. Specific use cases should be identified and used to inform requirements.** A critical message from the TAP in the first few meetings was that there would be many interested parties in an IMMP. This includes academics, regulators, oil and gas operators, technology providers, and auditors. Small or medium operators may be most interested in a platform as they are less likely to have advanced internal data infrastructure. The potential use cases are also vast and include

emissions monitoring and mitigation, estimation, and auditing, as well as technology evaluation, regulatory enforcement, and developing inventories. While these discussions revealed the numerous possible applications of an IMMP and the wide-ranging needs of potential users, they also highlighted difficulties in creating a multi-functional platform. We followed the TAP's recommendations to focus on use cases and identified five high priority case studies to lay the foundation for our IMMP engineering, design, deployment, and operating plan. All TAP members agreed that the number one priority should be reducing the frequency of super emitters as this would have the largest impact on national emissions.

2. **The IMMP must enable the integration of various data types and data at different spatial and temporal scales.** Methane measurement data is necessary to reliably quantify the oil and gas emissions for a site, operator, or basin. However, key contextual information, such as operator activity information, operator infrastructure information, and environmental data, can greatly enhance the value of the measurement data. For this reason, it is possible that measurement data may not comprise most of the data in an IMMP. In addition, depending on the user and the use case, the measurement data may need to be shared at different temporal and spatial resolutions. While raw data is often thought to be ideal, it is relatively useless for methane monitoring technologies as complex algorithms are needed to transform the raw concentration or spectral data into quantities regulators and operators commonly work with (e.g. emission rates, detections, and locations).
3. **Even though operators and regulators may share the goal of reducing methane emissions, designing a system that engages both may be difficult**. Operators will likely be wary of sharing any data with a system where others are given access to their information, even in aggregate form. Operators are now being tasked with testing and deploying measurement technologies, maintaining regulatory compliance and voluntary initiatives, new regulations, and participating in research campaigns. The continuum of voluntary and regulatory reporting and the constantly changing reporting requirements have increased operator caution around sharing any information about their emissions that is not required.
4. **Often, quality geospatial infrastructure and activity data are not readily available.** In the public domain, infrastructure data is not complete or granular enough to provide the information required to create quality inventories. For example, there is little public data on midstream facilities and poor equipment inventories. For operators, data is often siloed within their organization, making it difficult to obtain complete infrastructure or activity data. Notably, a key ingredient for the EPA's new super emitter program is detailed operator geospatial infrastructure information so that when a large methane plume is detected, the EPA knows what operator to notify. It is unclear where this data will come from. Satellite or aircraft imagery paired with artificial intelligence methods is one possible way that geospatial infrastructure and activity data could be improved.
5. **Data formats vary, but Excel/CSV remains the most common file type. A scientific or data quality review board is needed to vet data uploads.** While ground-based instrument monitoring data is almost exclusively collected in a CSV file type, the is a lack of a data standard for satellite and aerial emissions data. The data formats also vary by technology vendors with more uniformity seen from satellite providers. There could be a need to ingest unstructured text describing operator activity or observations. Since technologies are changing quickly, creating a scientific or data quality review board may be the most viable path toward ensuring that the

platform accepts only quality data. Many vendors now provide very detailed measurement reports with specific emission rates and equipment sources, but the TAP cautioned the accuracy of some data fields, and some vendors have not been well vetted.

6. **The IMMP should be managed by a trusted third party, particularly if it ingests non-anonymized emissions data from technology vendors or sensitive data from operators.** Publicly available, anonymized emissions and operational data have a significant scientific benefit. However, data anonymization carries liability and can be resource-intensive, as the process must be tailored to the analysis's end goals. There is little incentive for technology vendors and operators to create and share data. The TAP noted that vendors and operators would likely be much more willing to share data with a trusted third party responsible for data security and ensuring appropriate anonymization than with a state or federal entity.

The technical advisory panel was instrumental in helping GTI develop the five high priority case study scenarios and establish the technical requirements for each scenario. Their deep understanding of methane technologies and their strengths and limitations informed the system's development. Additional details of the TAP meeting are provided in the SI.

To support project development, the TAP members each developed a report on a topic to further enhance system development. Dr. Kort's focused on current and emerging observational capabilities, with a particular lens on point source versus area emissions quantification. Dr. Zimmerle and Dr. Hodshire's report described non-emissions data that is helpful for contextualizing monitoring data for a single operator, and Dr. Von Fischer's report proposes frameworks with an eye toward environmental justice. All TAP reports are available in the SI.

Industry Engagement Summary

An IMMP could take many forms and have many different functions, but a platform will have the greatest impact if it aligns with the industry's pressing needs today and serves multiple stakeholder groups. With this in mind, GTI met with two upstream oil and gas operators, three emissions measurement technology providers, and representatives from two state agencies to understand their current needs. The key findings from those meetings are summarized here. The team also gathered information from subject matter experts (SMEs), especially those leading active, relevant projects (e.g., Veritas and Project Astra). During the project, project team members disseminated knowledge and some findings publicly, such as at conferences and stakeholder visits. More comprehensive summaries are available in the SI.

Oil and Gas Operators

The team met with two mid-sized upstream oil and gas operators, who are likely more technologically advanced and proactive about emissions monitoring than most operators. The four primary takeaways from these meetings were the following:

1. **Operator data for infrastructure, operations, emissions monitoring, and LDAR records were scattered across different systems.** One operator noted that some data sets were stored in CSV files. However, emissions reports from technology providers were frequently delivered in PDF. One operator now stores most data on a server; however, some data sources are still not yet

integrated. Furthermore, reconciling emissions detections with operational activity requires substantial manual processing.

2. **Numerous emissions monitoring technologies are being used and tested internally.** Due to the lack of consensus over the best methane emissions monitoring technologies and the continual growth in the number of options, both companies have deployed numerous technologies and are performing internal testing to evaluate the value added by each. One company noted that their assets were geographically relatively compact, with few other operators in the area, so large-scale monitoring information is helpful. Both companies rely heavily on their SCADA systems for operational information; however, monitoring emissions down the equipment level is extremely challenging given existing technologies.
3. **Operators will be willing to share certain types of data.** One operator noted hearing "horror stories" due to too much data sharing. Both noted that some data is already publicly available but specifically mentioned that granular production data would never be shared, and they are uncomfortable with imagery of facilities being openly available. In general, geospatial information was viewed as sensitive. One operator attributed hesitations in sharing data to the public not understanding oil and gas operations well enough to interpret the data fairly (e.g. understanding the purpose of blowdowns). Regarding incentivizing data sharing, one operator expressed that it would be very helpful to know how their emissions compare to other operators at the equipment level as this would aid in diagnosing fixable issues. The other operator cited the high cost of aerial surveys and offered that they might be willing to share additional data if measurement campaigns were provided for them.
4. **Emissions monitoring is affected by geography, topography, and weather, so comparisons of raw emissions data across different basins should be performed with caution.** Aggregating and comparing emissions data nationally is challenging since basins differ substantially in terms of geography, topography, and weather, which all impact emissions.

State Agencies

The Colorado Department of Public Health & Environment (CDPHE) and California Air Resource Board (CARB) are two of the more active state agencies regulating methane emissions for oil and gas operators in their respective states. Notably, CARB has executed a large-emitter detection program for the last three years using remote sensing that sends email alerts to operators when there is a confident detection of a large plume from one of their sites. Operators are mandated to respond to alerts and CARB has felt the program has been very successful detecting many emission events that were unknown to operators, enabling operators to document causes and enact mitigation. In discussions with CDPHE and CARB, they shared the biggest current challenges in their work. The five key takeaways were the following:

1. **Data wrangling and processing is extremely challenging and time consuming.** CDPHE shared they have substantial amounts of data from operators in Excel format due to state regulatory reporting requirements; however, due to internal information technology (IT) challenges, they have struggled to get all the data in a centralized, useable database. They acknowledged the need for a long-term software solution to enable data storage and reconciliation between reported data and state-funded measurement campaigns. They also emphasized the importance of understanding the data within the system, the caveats to interpretations, and the degree of confidence in the reported measurement. CARB also noted they spend considerable time

performing quality assurance/quality control on methane plume detections to ensure alerts for their super emitter program are only sent to operators associated with infrastructure that is currently emitting methane.

2. **Technology providers are hesitant to work with the state agencies and perform third-party monitoring. Some states are not putting funds toward monitoring so big gaps in publicly available data nationwide.** Currently, there are only a few aerial emissions monitoring companies collecting data at the facility or finer. These service providers are wary of conducting "third party monitoring" to support CDPHE's state monitoring efforts, fearing they will lose their customer base. The current solution to this problem is for the state to partner with academic entities so all data runs through the other entity. Only anonymized and aggregated data is then shared back with the state. While California's methane emission monitoring program and the measurement campaigns it relies upon are well-funded by the state, that is not the case for other states. Thus, funding methane monitoring (e.g. satellite data acquisition) for less-resourced states so that more uniform policies and regulations could be enforced nationally would make a big impact.
3. **Satellite data being used for super emitter detection, but limited resourcing for data processing and follow-up investigation limits the impact of these data.** CDPHE recently performed a pilot project using satellite data to identify large emissions and deployed investigators to follow up. Due to limits on follow-up efforts, they attempted to identify emissions events that could not be mitigated (e.g., those from controlled releases) to allocate investigative resources elsewhere; however, this data processing and filtering was a costly manual procedure. A software system that ingests satellite data, analyzes it, and sends notifications would be very useful. Low latency notification is key for mitigation, while high latency monitoring is useful for understanding trends.
4. **A single system supporting state and federal regulatory reporting, and one that hosts publicly available data would be useful to the agencies and operators.** CDPHE acknowledged the value of having a single reporting system or systems that integrate well with each other at the state and federal level to support streamlined reporting by operators and avoid duplicate, disparate records. CARB expressed interest in a data platform that stored plume images from various technology vendors so they could cross-reference alerts found by their measurement campaigns to assess the validity of detections. Again, low latency would be key for publicly available data to enable rapid mitigation effort deployment.
5. **Establishing collaborative relationships with operators surrounding data sharing is possible and leads to change.** CARB's electronic notifications for their super emitter program are intentionally written with a cooperative, rather than accusatory tone and overall have been well-received by operators. Operators frequently provided CARB with follow-up information describing the cause of the emissions. It is worth noting that California has some of the most stringent restrictions on oil and gas operations in the country and operators regularly interact with state regulatory agencies. Thus, such alerts may not be as welcomed by operators in other states.

Technology Providers

GTI held discussions with three technology vendors that offer methane monitoring services, each based on a different monitoring technology. Specifically, the vendors included (1) a satellite monitoring provider that offers routine surveillance for any location in the world on a 3–4-day cadence, (2) an aerial surveillance company that flies manned aircraft with methane sensors over designated sites, and (3) a ground surface-level, fixed sensor, continuous monitoring technology provider. The GTI team described the idea of an IMMP and asked for their feedback on various aspects of the design, purpose, and requirements. While there were some shared perspectives across vendors, there were also distinct opinions about the requirements for an ideal system. The six key takeaways were the following:

1. **Vetting of technology providers is key, including controlled release experimental testing of new technologies.** Multiple vendors emphasized that a critical first step before performing data integration or reconciliation is well-characterizing measurement techniques to clarify to what degree each type of data can be trusted. They stressed that if the original data feeds cannot be trusted (i.e. their performance in controlled, experimental settings has not been vetted), no one will trust an integrated data product. One vendor noted that low-cost devices still provide value, but their measurement data needs to be seen through a different lens than that used to interpret more expensive, comprehensive technologies.
2. **The industry needs clear methods for data integration and reconciliation. The DOE/EPA is well-positioned to fund this work, and technology vendors want to support these efforts.** In contrast, one vendor noted that many companies focus on developing super emitter detection systems. Some vendors have developed software tools that allow operators to overlay measurement data from multiple technologies and view them simultaneously. However, these platforms do not integrate the data in any way to create a single/best emissions estimate for a single event. Combining data with high temporal and spatial coverage drives more accurate insights and requires a single software system. Vendors expressed interest in being involved in DOE/EPA initiatives to develop these integration and reconciliation methods so that they can share their best practices and understanding of technology performance. One vendor noted they have felt left out of existing federal initiatives and cautioned this could lead to incorrect data utilization.
3. **Data integration is critical to (re)establish and maintain trust in monitoring technologies' abilities to detect and quantify methane emissions**. Operators are often skeptical of monitoring technologies, and this distrust does not help move the oil and gas industry toward more measurement-informed leak detection and repair or inventory practices. Technology vendors emphasized they did not want to be pitted against one another, but without a platform to integrate their data streams appropriately, this is what is happening. They all agreed more measurement data and studies validating the technologies are important to building public confidence and trust in its capabilities.
4. **Operator infrastructure and/or activity data shared with technology providers was often incomplete, outdated, or unreliable**. Some vendors heavily relied on operator data to interpret measurements and create customized data products summarizing emission rates and events. In contrast, others noted they were focusing on improving their technology and services without such data. Two vendors shared that they deploy their aerial surveys to develop blueprints of production sites to ensure reliable geospatial operator infrastructure information before regularly monitoring them for methane emissions.
5. **Aggregated data presents fewer public disclosure concerns than site-specific data so the IMMP should first focus on providing aggregated data.** One vendor noted that substantial data

will be collected as part of existing federally funded research projects, and it would be worth centralizing this data. Some vendors noted they would hesitate to supply data to the DOE/EPA directly for a regulatory program, such as the newly proposed super emitter program, as it could compromise their relationships with operators. However, all vendors noted their willingness to participate in scientific research studies to increase trust in their data.

6. **Environmental data, most notably wind data, is critical to measurement interpretation and quality; publicly available data is lacking.** Spatially granular and geographically comprehensive, ground-level wind data would assist many vendors in translating raw measurement data into the desired emissions outputs, such as emission rates.

Public Engagement, Environmental Justice, and Diversity, Equity, Inclusion, and Accessibility Summary

In addition to the gaps identified in emissions monitoring and related data, the team also identified gaps and IMMP opportunities related to environmental justice and diversity, equity, inclusion, and accessibility (DEIA). These opportunities were identified through a survey on community priorities, in-person community engagement meetings, and collaboration with Colorado State University (CSU). The SI: Public Outreach and Environmental Justice Plan comprehensively describes public engagement and community outreach efforts.

Community members expressed a desire for educational materials to enhance understanding of the data provided on an IMMP and the impact of methane emissions. These materials would foster community accessibility and usability, empowering them to engage in addressing issues stemming from methane emissions. Community stakeholders also suggested contextualizing emissions data with social, health, and environmental indicators to support a holistic view of community impacts and concerns. Many survey respondents reside in disadvantaged communities (DACs), and these communities should be an area of focus for methane emissions monitoring and data reporting. More broadly, as discussed in the CSU report on environmental justice, methane emissions data should be made available at the most granular level possible, but at a minimum, reporting and mapping at the census tract level would support analyses that identify inequities.

Review of Existing Data and Software Platforms

Numerous methane monitoring software systems and data platforms are rapidly being developed and deployed with new companies and services becoming available. However, these platforms typically target a single class of users (e.g., operators) and offer specific services. Although software systems are beginning to diversify, they tend to offer primary services around one of the following categories:

1. Aggregation of publicly available infrastructure data: state databases, Enverus, Rextag.
2. Emissions monitoring data management for operators: Project Canary, Highwood Emissions Management, SensorUp, Envana, (and many others).
3. Infrastructure, equipment, SCADA, and LDAR data management systems for operators: GIS systems, MethaneTrack.
4. Third party monitoring or environmental sensing: CarbonMapper, Environmental Defense Fund (MethaneSAT), International Methane Emissions Observatory (IMEO), National Institute for

Standards and Technology (NIST), National Oceanic and Atmospheric Administration (NOAA), National Aeronautical and Space Administration (NASA) (US GHG Center).

We describe these data and software platforms in the remainder of this section. In the Summary and Conclusions we describe how the IMMP envisioned here differs from these platforms and fills in gaps around data integration and accessibility.

Oil and gas production and some infrastructure data are available via state-provided public databases or commercial platforms that ingest, process, and aggregate the publicly available data. Accessing data through state databases is challenging and time-consuming due to various data formats and a lack of easily accessible and interpretable metadata. Furthermore, these databases can be stale and slow to update. Commercial platforms such as Enverus are widely used, however these often rely on state databases so inherit all issues in data quality and subscriptions are costly.

Environmental sensing or methane emissions monitoring platforms typically provide emissions data from large-scale monitoring or targeted third-party monitoring of oil and gas facilities. These platforms include CarbonMapper, the Environmental Defense Fund-led efforts of MethaneAIR, MethaneSAT, and PermianMAP, International Methane Emissions Observatory (IMEO), as well as data from other government agencies like National Institute for Standards and Technology (NIST), National Oceanic and Atmospheric Administration (NOAA), and National Aeronautical and Space Administration (NASA). The data provided by large-scale monitoring efforts are typically considered top-down emissions estimates that reflect methane emissions from several sources (e.g., oil and gas, agriculture, landfills) across a large area. The data provided by third-party monitoring is typically from either satellites, which cover large regions but cannot detect small emissions, or localized to a specific basin. Thus, there are monitoring gaps due to the limited availability of data on small emissions across regions and comprehensive basin-level monitoring with more sensitive technologies. Furthermore, without the ability to easily co-locate emissions with oil and gas facilities, this monitoring data provides information about gas concentrations but not emissions cause.

Another class of data and software platforms is designed for operators to manage and analyze emissions monitoring data. Numerous technology providers now offer operators a platform to view the data they collect for them and provide PDF reports of detections. Some of these platforms allow operators to upload additional data to contextualize emissions and analyze historical data, but they are designed for the specific technology trumpeted by the parent company. Other commercial platforms, such as SensorUp, Highwood Emissions Management, and Envana, now offer platforms to upload multiple types of emissions monitoring data. In general, all of these systems are targeted at operators and are designed primarily for leak detection and repair. Processes for creating an annual inventory are increasing in availability, but due to the lack of a standard approach, each company has devised its own method for "reconciliation".

Operators use various other data management systems to store and track data from operations. These data include infrastructure and equipment inventories, leak detection and repair (LDAR) programs, and supervisory control and data acquisition (SCADA) systems. These data are not typically integrated with emissions monitoring data.

Finally, other miscellaneous platforms have publicly available methane emissions data. However, each seems to contain select pockets of data, and none seem to serve as a central database for methane emission data. Furthermore, each appears directed at a specific group of stakeholders (e.g. community advocates, academics). Some of these platforms include the National Energy Technology Laboratory (NETL) Energy Data Exchange (EDX), GitHub, academic journal websites (e.g. supplemental information), the Global Methane Initiative (GMI), PHMSA, International Energy Agency (IEA).

IMMP Risks and Barriers

Background

The GTI project team identified possible risks and barriers to the effective application of an IMMP through engagement with internal GTI SMEs and external stakeholders. The team documented risks and barriers (hereafter, collectively "risks") and described strategies to mitigate and overcome them. The Risk Assessment Matrix in the SI catalogs three categories of risk and associated mitigation strategies: (1) IMMP technical and engineering risks, (2) external IMMP impacts, and (3) IMMP project management and administration risks.

The team identified the three biggest potential risks: a lack of programmatic support for an IMMP, the challenges associated with obtaining data and ensuring data quality and maintaining system security. Other risks include managing a potentially broad range of stakeholders, rapidly changing monitoring technologies, and integrating or interfacing with a wide range of data sources. We summarize the three biggest risks in the remainder of this section. The Risk Assessment Matrix in the SI comprehensively describes risks and identifies mitigation strategies.

Notable Risks and Barriers

One of the biggest risks to the successful application of an IMMP is a lack of programmatic support for its development, deployment, and sustainability. A successful IMMP will require more than the deployment of methane monitoring technology and the creation of a software system. It will require an associated program to develop and lead the vision for the platform and create and track success metrics. This program will ensure adoption and integration with existing systems, long-term sustainability and relevancy, and education and training for maximum impact and utilization. Without this support, the platform could quickly become irrelevant or forgotten by stakeholders. To ensure platform success, this risk can be mitigated by creating a funded program, in tandem or potentially separate from technology deployment and software development.

Another significant risk to an IMMP is obtaining data and ensuring its quality. Obtaining data can be challenging for several reasons, but one of the biggest is oil and gas operators' unwillingness to share it. This unwillingness can stem from concerns about misinterpretation, legal or privacy concerns, and reporting conflicts. Data quality concerns can arise because of, but not limited to, a lack of data, lack of data standards, and/or misinterpretation of data. Data sharing risks can be mitigated by funding a trusted third party to manage the IMMP, incentivizing sharing through the development and implementation of anonymization approaches and creating a collaborative environment where entities sharing data are provided tools for analyzing and interpreting the data. Data quality risks can be mitigated by providing automatic data quality checks, developing data/metadata standards, and enforcing those standards in the IMMP.

The third big risk to an IMMP is ensuring software system security. An IMMP could house sensitive company-specific information and be connected to various data sources, making it a target for cyberattacks or malicious actors. This risk can be mitigated by utilizing best practices and adhering to relevant compliance standards. This includes encryption, (multi-factor) authentication, and access controls to protect data during transfer and storage.

High Priority Use Cases

Background

After soliciting feedback from stakeholders and considering the applications listed in the FOA, the team used brainstorming sessions to identify possible ways to use an IMMP. Given the potential breadth of IMMP applications, this initial phase of creating an EDDOP allowed the team to set and manage system expectations and narrow the scope and purpose of the IMMP. Through the refinement process, high priority use cases (HPUCs) emerged. These use cases provided the team guidelines for shaping the application's purpose and determining the underlying supporting functions. The intent was to develop a scalable and flexible application design that focuses on the industry's critical needs but one that would also bring users equal value.

Through use case refinement, the team identified five HPUCs for an IMMP. Use cases represent one of the first stages of the software development life cycle and describe how a system user or external system will use the proposed system to accomplish some tasks. The purpose of use case modeling is to capture and inform the user requirements or "tasks" by detailing them in scenarios that the users will be performing. The use cases provide a description and narrative for a sequence of events from a user's perspective using the system to complete a specific task. It may also provide the context for each task and governing business rules. A use case should not be confused with a requirement. Use cases inform the requirements via their narratives and descriptions. They also detail how requirements are fulfilled but are not, by and of themselves, requirements.

While there are many potential users of an IMMP, the high priority users are oil and gas operators, regulators, and community stakeholders. The team used these high priority user groups and associated use cases to identify and develop the System Requirements specifications (SRS). The high priority use cases were 1) regulator super emitter notification program, 2) operator super emitter response, 3) operator emissions inventory, 4) regional emissions estimates, and 5) EJ/DEIA data availability. The remainder of this section briefly describes these use cases, including their rationale and potential impact. The System Requirements Specification Document in the SI provides a comprehensive description and details of each use case.

High Priority Use Case Summaries

The *Operator Emissions Inventory* use case describes the process of a natural gas operator managing and integrating their own emissions data and infrastructure information into the IMMP to perform an analysis that results in an annual emissions estimate (i.e., a measurement-informed annual emissions inventory). The functionality allows operators to understand and track their emissions on an annual basis, enabling them to identify opportunities for emissions reductions. Measurement informed inventories are also being used to track ESG goals and for responsible natural gas certification programs. The impacts of this use case include improved understanding of emissions that can be used to inform mitigation approaches and standard approaches for creating measurement informed emissions inventories.

The *Operator Super Emitter Program* use case describes how a natural gas production operator will upload snapshot emissions data and set super emitter thresholds to monitor for super emitter emissions from their assets. The intent is to allow the operator to determine where super emitters are occurring to use this information to deploy field crews to investigate. Operators could then track super emitters over time to understand their causes and identify ways to prevent large emissions. This use could significantly reduce oil and gas methane emissions by increasing operator awareness and rapid response to super emitters.

The *Environmental Justice and Diversity, Equity, Inclusion and Accessibility* use case describes how regulators, government agencies, and community advocates access publicly available data collected and organized within the IMMP to evaluate human and environmental impacts of oil and gas operations. The platform will host data, make it available for download, and provide maps at spatial scales (e.g., census tracts) that support environmental justice and other human-impact analyses. Critical data to support these functionalities include oil and gas infrastructure, oil and gas production data, or super emitter data. The availability and mapping of these data are expected to support awareness of, and advocacy related to EJ issues to provide better air quality, reduction of GHG emissions, and improvements to human health.

The *Regulator Super Emitter Program* use case describes how regulators can monitor super emitter emission events within their jurisdiction by utilizing approved third-party provided snapshot emission measurement data. This use case is like the operator super emitter program but adopted to allow regulators to identify super emitters within an area of interest and notify the operators of the assets suspected to be responsible for the emissions. The IMMP will support the creation of a list of alerts to be sent to owners/operators of the infrastructure where a super emitter has been detected (within the occurrence of a 15-day limit), containing a display of detection on a GIS map. Like the operator use case, this use case could reduce emissions through the timely identification and response to large emissions events.

The *State/Regional/National Measurement-Based Emissions Inventory* use case describes how a state agency, federal agency, or community advocate can access and utilize emissions data approved by the SRB to create a measurement-based regional (e.g. county, state, basin) estimate of methane emissions. This workflow will leverage oil and gas infrastructure data and information reported from previous and future federally funded projects. This use case would support methane data accessibility and availability for researchers, advocacy groups, and regulators to enhance understanding of emissions at various spatial scales. This use case supports the development of up-to-date and accurate emissions inventories to strengthen regional and national estimates.

IMMP Monitoring Technologies and Other Data

Background

The HPUCs utilize methane monitoring technologies and a software system to integrate different data types to perform analyses that address industry needs. As identified through stakeholder feedback and discussed below, data within an IMMP software system should include methane monitoring data and environmental, infrastructure, and operational data. This section describes monitoring technologies and non-monitoring data that could be used within an IMMP.

The IMMP designed here is methane monitoring technology agnostic, focusing on enabling data interoperability through metadata, and is open to collecting and aggregating data from various methane monitoring technologies. This approach is driven by the necessity of multiple methane monitoring technologies for addressing different goals of emissions monitoring. For example, satellite monitoring offers clear advantages for tracking super emitters, but they would be inadequate for developing comprehensive, source-level emissions factor estimates. There is no single best monitoring technology. This section summarizes the relative advantages and shortcomings of different monitoring technologies. We comprehensively describe and discuss various monitoring technologies and approaches in SI: Assessment of Methane Monitoring Technologies, Methodologies, and Frameworks.

While methane monitoring data is a critical and necessary part of an IMMP, non-monitoring data provides context and greater utility for emissions information and, in most cases, is necessary for informing actions to mitigate emissions. As a result, only a fraction of the data housed on an IMMP software system would be monitoring data. Non-monitoring data that could be included in an IMMP includes oil and gas infrastructure, operational activity data, environmental sensing, and non-O&G emissions source data. We describe these data sources and their potential role in an IMMP below.

Methane Monitoring Technologies and Data

We use methane monitoring to collectively describe technologies and approaches that perform methane detection, localization, attribution, and/or emissions quantification. Methane monitoring frequently refers to *monitoring solutions*, a combination of measurement devices and instruments, how they are deployed, and the methods used to analyze the results to create derivative data products. For example, an imaging spectrometer can be deployed on a human-piloted aircraft, and the resulting data is integrated with wind information in a model to produce methane emissions detections and quantification.

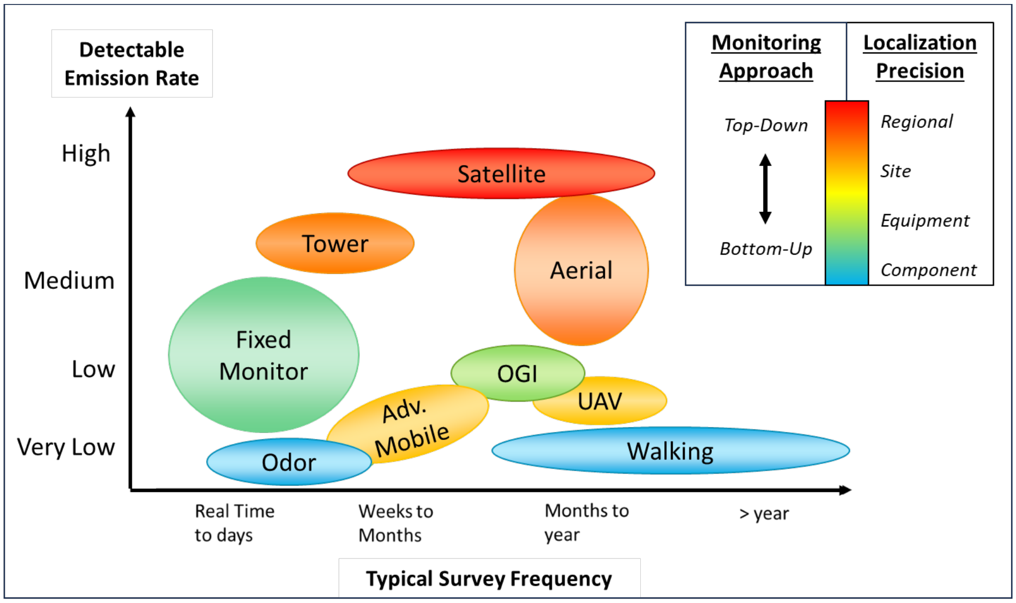

Figure 3: A summary of emissions monitoring approaches and their relative capabilities. The horizontal axis describes the typical survey frequency, while the vertical axis describes the ability to detect methane emissions as a function of emission rate. The color gradient specifies the attribution level to which each platform can localize or attribute a source. This characterization of monitoring approaches reflects general and relative capabilities and does not necessarily characterize the performance of any individual technology solution.

Figure 3 displays different deployment methods and demonstrates their relative capabilities for detection, temporal coverage, and emissions localization. In general, there is a tradeoff between the ability to detect small emissions while providing precise localization and the ability to cover large areas rapidly. Handheld instruments used during walking or field surveys are typically very sensitive, and a major advantage of this monitoring solution is the ability to confirm emissions presence, origin, and/or cause. It also allows for the necessary identification of and response to potential safety issues. Field crew surveys are limited by their ability to cover large areas rapidly due to the time required to conduct thorough surveys (e.g., due to walking an area or driving from site to site). Broad spatial or high-resolution temporal coverage is the primary advantage of many advanced emission monitoring approaches developed in recent years. However, each of these approaches tends to have a “blind spot,” such as difficulty detecting small emissions (satellites), bounding emissions duration (aerial approaches), estimating emission rates (continuous monitors), or disentangling biogenic and anthropogenic sources (tower networks). These limitations necessitate integrating various monitoring technologies to illuminate the entire emissions picture.

There are several challenges and gaps related to methane monitoring across the supply chain. SI: Assessment of Methane Monitoring Technologies, Methodologies, and Frameworks thoroughly discusses gaps and challenges, some of which are summarized here. Common challenges across segments include the co-location of other methane-emitting sources, uncertainty in emissions estimates derived from remote sensing technologies, and the need for mature methodologies that integrate the results of multiple monitoring technologies to enhance emissions inventory estimates. Other challenges are segment specific. Pre-production, offshore, and gathering line emissions are not well-characterized in the upstream segment. In the midstream segment, analytical methods to utilize commonly used monitoring techniques of snapshot measurements and continuous monitoring are just beginning to be developed. In local distribution, disentangling the distribution system, customer end-use, and co-located sources (e.g., landfills) emissions continues to be challenging.

Non-Methane Monitoring Data

Oil and gas infrastructure data includes locations of facilities and pipelines across the oil and gas supply chain. Typically, this data is reported in a geographic information system (GIS) file format, but it can also be shared as a spreadsheet with latitude and longitude coordinates. This information is important for attributing emissions from remote sensing approaches to facilities and, at a more granular level, facility equipment. This attribution is, in turn, critical for building accurate emissions inventories and informing mitigation pathways. In upstream segments, oil and gas well locations are typically publicly reported, but production facility equipment information such as tanks, separators, and gathering pipelines are not. In the midstream segments, there is limited or incomplete information on compressor stations and processing plants.

Operational activity data is another data type that could be hosted on an IMMP software system. This includes oil and gas production data, which, when coupled with a measurement-informed emission inventory, can be used to estimate an emission intensity. Other activity data includes results of field crew investigations (e.g., as part of a leak detection and repair program) or SCADA systems. The results of field crew investigations can be used to perform cause analysis that attributes emissions to specific activities or sources. This data input can improve the accuracy of measurement-informed inventories. Similarly, SCADA data could identify the start and stop times of emissions (e.g., as indicated by a drop in pipeline or tank pressure).

Wind and other environmental data are a third category of non-monitoring data that could be hosted on an IMMP software system. As discussed in the Assessment of Methane Monitoring Technologies, Methodologies, and Frameworks document in the SI, models for emission rate estimation frequently couple methane concentration measurements with wind information. Localized wind information is typically unavailable, so estimates of local wind information (e.g., via a nearby sensing station or wind re-analysis data products) are substituted, creating uncertainty. Local wind information (e.g., via an enhanced sensor network or as part of already deployed continuous monitoring systems) could improve emissions estimates.

A final category of non-monitoring data that could be hosted on an IMMP is the locations of other methane-emitting sources. Coal mines, landfills, and agriculture (manure ponds or concentrated cattle feeding operations) can be significant emissions sources. Understanding where these sources are located can support emissions attribution to improve (e.g.,) super emitter notification programs and more accurate emissions inventories.

Software System Engineering and Design

Background

The IMMP software system design is based on the core principle of enabling data interoperability through metadata and the ability to ingest and store numerous data types. It was designed based on the use cases and identified requirements. The team used the high priority use cases to identify system requirements and then used these requirements to create a system design document. The results of these efforts are summarized in the remainder of this section. The System Requirements Specification Document document comprehensively describes the requirements and the use cases, and the System Design Document provides an in-depth description of the system design.

System Requirements

Gathering requirements is one of the first steps of the software development life cycle. The team used the high priority use cases to identify and document IMMP software system requirements. Each requirement was classified as either functional or non-functional. The functional categories include basic mapping (BM), data management (DM), data mapping and analysis (DMA), data security (DS), data services (DSR), notifications and alerts (NO), system management (SM), and user management (UM). The Data Mapping and Analysis category of functions, for example, defines the functionalities required to support the specific needs of the HPUCs. The user management function category addresses user access, registration, role assignment, etc., whereas the data management category addresses requirements for data upload, metadata collection, and various other data management needs. The non-functional requirements apply to the needs of the user's experience. Non-functional requirements categories include high-level, proposed approaches for security, capacity/performance, compatibility, reliability, scalability, maintainability, useability, data integrity, data security, data quality, and data capacity.

The Systems Requirement Specification (SRS) document in the SI details the results of the requirements gathering effort. The SRS lists and categorizes the functional and non-functional requirements. Each requirements category is "coded", and each function is indexed with an ID number for tracking and traceability. For example, FR.BM.xx indexes functional requirements (FR) related to basic mapping (BM). The notation "xx" is used as a counter (e.g., FR.BM.05) and does not imply an ordering of importance. Each requirement is tagged with an expected software system release timeline (e.g., release 1, 2, or future). This timeline is used to manage the scope of system development and identify critical functionalities foundational to the system. It also reflects the potential evolution of the platform, and the many potential functionalities identified during the project. The phases reflect the application's broad potential, scalability, and flexibility.

The SRS also identifies the application's intended users, serves as the foundation for the system design documentation (SDD), guides the application development, and will be adopted as stakeholder acceptance criteria. The SRS serves as the point of reference and a blueprint for the project stakeholders to understand the scope of the application and the intended product. Reducing ambiguity for the stakeholders, the SRS is also the documentation used as the guideline for creating and executing test cases during the IMMP software system testing and deployment phase.

System Design

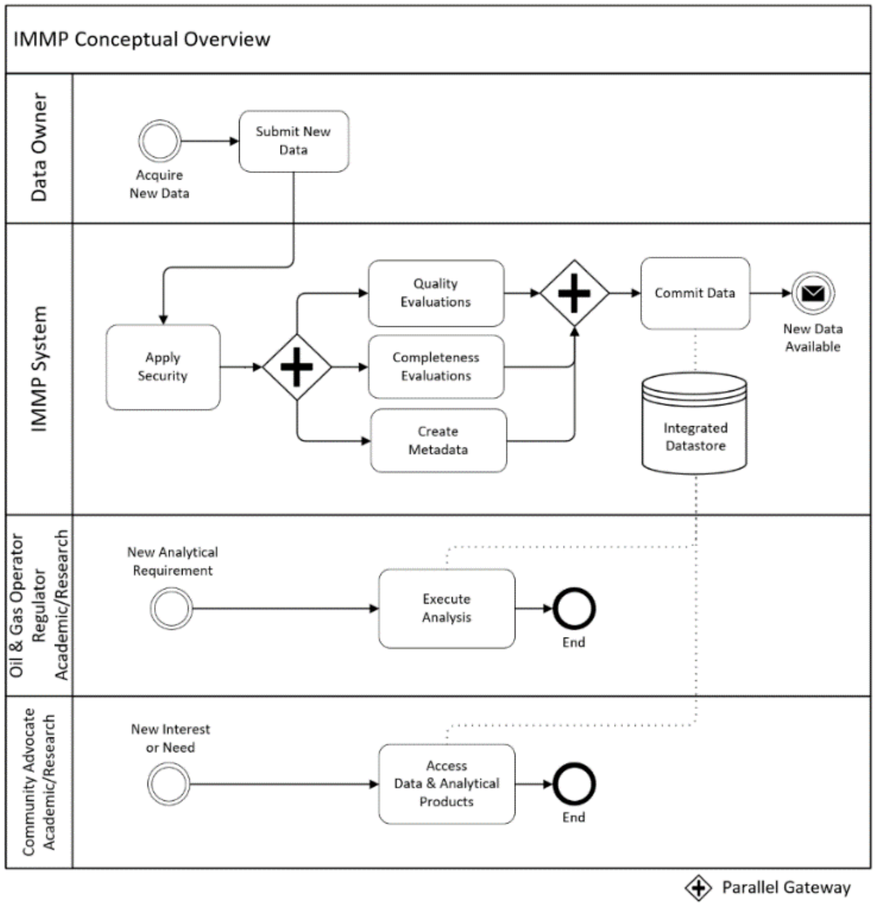

Figure 4: A high-level conceptual diagram of the IMMP software system. This diagram is a business process model and notation (BPMN) model, a global standard for documenting business processes. The IMMP software system is designed to ingest data, catalog metadata, check data quality, and then utilize the data for a variety of potential users and use cases.

The System Design Document in the SI provides a comprehensive description of the architecture, functionality, and performance of the software system of an IMMP. It is a detailed guide that provides a blueprint for the software development team, clearly communicating the system's specifications. Additionally, the SDD is a reference guide for future updates, scaling, and maintenance. It helps ensure the system remains consistent and coherent over time, even as new features and functionality are added. The SDD is essential to successfully building, deploying, and maintaining the IMMP software system in the subsequent phases of this program. The SDD briefly describes the use cases, provides use case screen mockups, documents all workflow processes and procedures, and provides a high-level design description addressing software/hardware technologies, data architecture and flow, and development frameworks.

Figure 4 shows a conceptual overview of the IMMP software system using a business process model and notation (BPMN) diagram. Broadly, the IMMP software system design is intended to acquire data, ensure documentation through metadata, and then store the data to make it available for analysis. The analyses are driven and developed through focused use cases to provide information for targeted impacts such as super emitter mitigation. The team used BPMN models through the system design to provide a consistent and detailed approach to developing the IMMP software blueprint. BPMN is a global standard for documenting business processes, enabling workflow visualization and communication to support efficiency and streamlining.

IMMP Deployment and Operating Plan

Background

While the system design document provides a blueprint for the engineering and design of an IMMP software system, this section proposes an approach for deploying and operating the IMMP software system and a broader IMMP Program. The approach described here is preliminary and would require additional scoping to finalize the desired use cases and impacts. We propose a phased approach to deploying an IMMP supported by an IMMP Program to ensure impact and sustainability.

IMMP Program

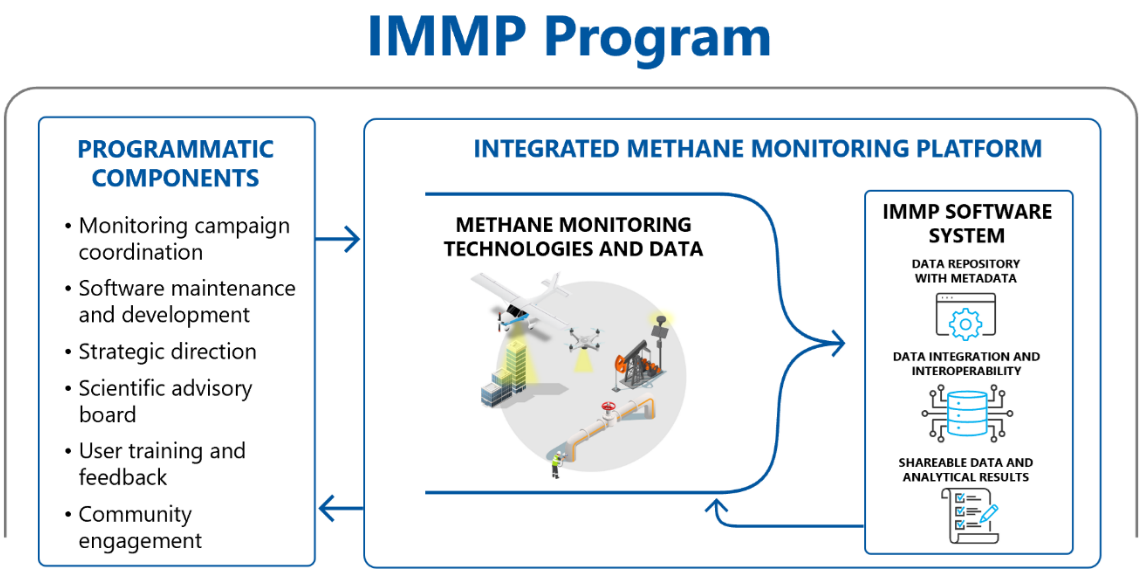

Figure 5: The relationship between an IMMP Program and the IMMP. An IMMP Program should be established to support the development, deployment, and operation of the IMMP. The Program would administer the IMMP by providing strategic direction, maintaining stakeholder engagement, and providing user training. This Program would ensure that the IMMP adapts to and addresses new industry needs and an evolving technology landscape.

To ensure a large-scale and sustained impact, the IMMP will require more than a basic deployment of monitoring technology and the creation of a software platform. Figure 5 above demonstrates the role of an IMMP Program in relation to the IMMP. An IMMP Program should first be established to support the IMMP's creation, deployment, and operation. This program should provide oversight and strategic direction for the platform, guiding monitoring technology deployment and software system development. It should also administer supporting functions such as a scientific advisory board, user groups, training modules, communications, and community engagement. A trusted organization or a collaborative of organizations with experience and expertise in methane emissions monitoring technologies, data analysis, software development, communication and marketing, education and outreach, and working collaboratively with various stakeholders should administer the IMMP program.

Software System Phased Deployment and Operation

Deploying and operating an IMMP software system should follow a phased approach to accomplish the following general development stages. The first phase should continue to engage stakeholders to finalize any required monitoring technologies or campaigns, system users, and refine software system requirements. This initial phase should also identify upload mechanisms (e.g., data curation), automation (e.g., API integration), and existing and soon-to-be-available data that the software system could begin to integrate and make available for access. After finalizing the software system requirements, the IMMP Program should focus on building and deploying the software system. This software system could be built on existing software systems or developed using widely available technologies (e.g., Microsoft, Amazon, etc.). The initial software system should be piloted with common monitoring data types, and a focused user group should provide feedback to identify bugs and system improvement. Next, the software system should move to an operation, maintenance, and scaling phase. The software system should be made widely available to targeted users and be ready to integrate data from existing or new monitoring efforts. The IMMP Program should support identifying new users and use cases, planning and coordinating new measurement campaigns, and orchestrating and directing software development. The Program should provide education and outreach to support users and enhance platform adoption.

GTI Energy Approach

GTI proposes that the IMMP be built using the programmatic, phased approach described above, applying it to address high priority use cases as identified through this project. The team would update and finalize system requirements through continued stakeholder engagement. Then, the team would develop and pilot an IMMP software system, establishing a group of test users to provide feedback. This pilot phase would be critical to de-risking IMMP creation, identifying unanticipated barriers, and getting early user feedback to identify necessary changes.

GTI proposes constructing a pilot software system that establishes a methane specific data repository and addresses a single high priority use case. The data repository would ingest and host various data types. Critical to this data repository are 1) oil and gas infrastructure data and 2) methane monitoring data from federally funded efforts such as the DOE-funded iM4 Technologies and MERP programs. Additional data integration methods, such as API connections or data upload functionalities, could be identified and used to enhance the data repository. This would create a recognized, centralized, and publicly available repository for methane emissions data, enabling the data to be easily accessed and downloaded. It would also be the foundation for developing new functionalities that transform, analyze, map, or otherwise utilize the underlying data. The team would then develop the functionality to address a high priority use case such as super emitter detection.

The IMMP Program should also be established in parallel to the software pilot. Like the software system pilot, the Program pilot would de-risk the Program, identify unanticipated barriers, and scope the necessary roles and resources. It would identify new data acquisition and integration opportunities and coordinate new monitoring campaigns conducted specifically for platform integration. The Program would support continued stakeholder engagement to identify and prioritize new requirements and user training opportunities. It could also establish other supporting functionalities of the IMMP such as a scientific advisory board, community engagement opportunities, and marketing/communications.

After the pilot phases, the Program and the IMMP would move to an operation, scaling, and maintenance phase. This operating phase would include various activities to support the IMMP, including coordination of new measurement campaigns, collection and curation of new data, and user support and training. Software system scaling could include developing new use cases and functionalities or expanding the application to handle new data types. Software system maintenance would include bug fixes, testing, and system updates.

The IMMP proposed here would provide publicly available data to regulators, researchers, and the public. A methane-specific platform providing integrated data for public access currently does not exist and offers multiple benefits for these users. For regulators, it provides a single place to reference data to inform policy or develop up-to-date emissions inventories. This would enable benchmarking and tracking the effectiveness of regulations. For the research community, it provides common, accessible data sets that can be used to test and benchmark new analytical approaches. This creates a more transparent and collaborative user community that will drive advances in modeling and emissions inventories. These data sets can also be utilized at colleges and universities to support workforce development. For the public, the platform will enable greater transparency and access to data through mapping and downloading.

Summary and Conclusions

An IMMP could serve a broad range of users and address various gaps and needs in methane monitoring. An IMMP could host various data types critical for improving our understanding of methane emissions. The platform could identify super emitters, strengthen greenhouse gas inventories, and improve overall emissions analysis along the natural gas supply chain. This breadth of potential users and applications poses a significant challenge in developing and deploying an IMMP and ensuring it makes an impact to support emissions reductions.

The project team took on this challenge by engaging and considering input from a breadth of potential stakeholders. The industry engagement efforts identified gaps and needs that an IMMP could fill, revealing identifying high priority users and use cases that could have substantial impacts. These use cases were used to guide the design of an IMMP. Through stakeholder engagement, the team identified the risks and barriers to its effective application and developed strategies for overcoming them. The use cases were used to identify and document the IMMP software system requirements. These requirements drove the software system design. The team created a deployment and operating plan executed through an IMMP Program. Throughout the project, the team took a methane monitoring technology approach, acknowledging that these technologies have relative strengths and weaknesses. These trade-offs necessitate a multi-monitoring approach for some applications, while others can be executed with a single technology. The team also used a supply chain agnostic approach, recognizing that emissions reduction challenges exist across the supply chain.

The IMMP envisioned in this project would have capabilities that intersect with those of existing platforms and could even integrate collaboratively with existing software platforms. The IMMP would pull data from systems with publicly available data (e.g., through API connections) and, likewise, push data and analysis to other systems. However, three primary differentiators exist between existing software systems/data platforms and the IMMP envisioned and designed here. First, the IMMP software system proposed here is designed to be agile, guided by scientific and technical experts, to immediately address the pressing needs of the industry while being flexible enough to serve new demands from regulators, operators, and communities as they arise. Second, the software system is one component of a broader IMMP ecosystem that would be supported and sustained through an IMMP program. The IMMP could include monitoring technologies, measurement campaigns, and software. A trusted third party would plan, develop, and operate this platform under an IMMP Program to support stakeholder engagement, outreach, and broad impacts. This program would enable the platform to be adopted by various users and developed by considering multiple stakeholder needs. Third, the IMMP software system envisioned here is designed to integrate data to enable interoperability. It is not designed for a particular data type or user or tailored to a single service. The importance and requirement of metadata underpins this integration and interoperability. The IMMP would integrate infrastructure and methane emissions monitoring data into a single place and collect the data from multiple sources. For example, data from third-party monitoring like satellites could be merged with infrastructure data and made available to operators, or these data could be aggregated at the census tract level and reported publicly. This integrated approach enables data accessibility, allowing analytics to be developed and executed more easily, efficiently, and rapidly.

To succeed, the IMMP must evolve and adapt to a changing landscape of technology, analytical approaches, and opportunities to reduce emissions. Importantly, this effort identified the need for an IMMP Program to support not only the monitoring technology and software system components of an IMMP but also to guide the platform's strategic direction through continued stakeholder engagement. This program would ensure the IMMP's relevance, sustainability, and impact. Engaging with a multitude of stakeholders will ensure that the IMMP evolves to meet the industry's high priority needs and consistently provides value for a range of users. This approach will ensure the IMMP's sustainability and desired impacts.

Appendix

Table of Acronyms

Acronym	Definition
API	Application Programming Interface
BM	Basic mapping
BPMN	Business process model and notation
CARB	California Air Resource Board
CDPHE	Colorado Department of Public Health & Environment
CSU	Colorado State University
DAC	Disadvantaged community
DEIA	Diversity, equity, inclusion, and accessibility
DM	Data management
DMA	Data mapping and analysis
DOE	Department of Energy
DS	Data security
DSR	Data services requirements
EDDOP	Engineering, design, deployment, and operating plan
EDX	Energy Data Exchange
EJ	Environmental justice
EPA	Environmental Protection Agency
ESG	Environmental, social, and governance
FECM	Fossil Energy and Carbon Management
FOA	Funding opportunity announcement
FR	Functional requirements
GHG	Greenhouse gas
GIS	Geographic Information System
GMI	Global Methane Initiative
HPUC	High Priority Use Cases
IEA	International Energy Agency
iM4	Innovative methane measurement, monitoring, and mitigation
IMEO	International Methane Emissions Observatory
IMMP	Integrated Methane Monitoring Platform
IT	Information technology
LDAR	Leak detection and repair
MERP	Methane Emissions Reduction Program
METEC	Methane Emissions Technology Evaluation Center
NASA	National Aeronautical and Space Administration
NETL	National Energy Technology Laboratory
NIST	National Institute for Standards and Technology
NO	Notifications and alerts

Acronym	Definition
NOAA	National Oceanic and Atmospheric Administration
O&G	Oil and Gas
PHMSA	Pipeline and Hazardous Materials Safety Administration
SAB	Scientific Advisory Board (program-level advising)
SCADA	Supervisory control and data acquisition
SDD	Software Design Document
SI	Supporting information
SM	System management
SME	Subject matter expert
SRB	Scientific Review Board (IMMP software system data review)
SRS	Software Requirements Specification
SRS	System Requirements specifications
TAP	Technical advisory panel
UM	User management