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Technical Conference Paper

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SMRI Spring 2017 Technical Conference
23 – 26 April, 2017
Albuquerque, New Mexico

Solution Mining Research Institute Spring 2017 Technical Conference
Albuquerque, New Mexico, 23 – 26 April 2017

An Asset Integrity Management System for Underground Natural Gas Storage in Solution-Mined Salt Caverns

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Abstract

This paper describes an Asset Integrity Management System (AIMS), originally developed to manage natural gas storage cavern operations in Europe, which has been modified to address the requirements for compliance with the PHMSA Interim Final Rule, the Interstate Oil and Gas Compact Commission, the Louisiana Department of Conservation, and the State of California. The approach provides a comprehensive, modular, and cost-effective three-step process (Screening, Evaluation, and Mitigation) that could be used to bring a storage facility of any type into compliance with the new regulations. It draws from oil-and-gas and storage industry experience in subsurface containment and risk management to simply and logically collate and maintain key information for regulatory compliance.

Key words: underground natural gas storage, salt caverns, asset integrity, risk assessment and mitigation

1. Introduction

In the wake of the massive Aliso Canyon, California blowout from October 23, 2015 through February 4, 2016, new federal regulations have been put into place for all intrastate and interstate underground natural gas storage (UGS) facilities nationwide. The Interim Final Rule (IFR) published in December 2016 by the Pipeline and Hazardous Materials Safety Administration (PHMSA; [1]) applies an initial set of common minimum standards (based on two American Petroleum Institute (API) recommended practices (RP) ─ API RP 1170 and RP 1171) that all operators will be expected to comply with. The goal of the IFR is to increase the reliability of the combined transport (pipeline) and storage system.

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A holistic Asset Integrity Management System (AIMS), described in this paper, has been designed to help underground storage operators efficiently meet the requirements of the PHMSA IFR as well as the California regulations and provide the basis for maintaining compliance going forward. This system could help to simply and logically collate and display key information for regulatory compliance and audit response, provide the methodology and plans for making risk-based operational and economic decisions, to compare geologically different facilities (e.g., reservoir [porous-rock] storage, including depleted oil and gas fields and aquifers; solution-mined salt cavern storage) across an operator's asset portfolio, and track risk reduction progress through time.

2. Reliability of Underground Natural Gas Storage Facilities

According to data from the US Energy Information Administration [2], the majority (333, or ~80%) of the ~418 UGS facilities in the US (data as of 2015) utilize depleted oil and gas fields; 46 (11%) occupy aquifers, and 39 (9%) are in solution-mined salt caverns. Reservoir storage then represents ~91% of UGS facilities, with solution-mined salt caverns comprising the remainder. The values compiled by EIA do not include an estimated 70 additional facilities storing propane and/or related natural-gas liquids developed in mined hard-rock caverns [3] that are not considered in this paper.

Historical occurrences of natural gas leakage events inform the risk assessment process and have been described in detail elsewhere (e.g., [4,5,6,7,8,9]). Of the underground gas storage facilities in the United States, approximately 74, or 15%, are considered to have experienced some type of subsurface natural gas leak at some point in their operational life-cycle through 2005 [5].

Following studies by Papanikolau et al. [7] and Folga et al. [9], the currently incident frequency estimates for underground natural gas storage are listed and compared in Table 1.

Table 1: Estimated leakage frequencies from underground natural gas storage facilities

		Leakage frequency, /facility/year		Leakage frequency from well-integrity loss, /well/year	
Facility Type	**Cause**	Papanikolau et al. [7][3]	Folga et al. [9][4]	Papanikolau et al. [7]	Folga et al. [9][4]
Depleted oil and gas field	Well integrity	5.1×10^{-3}	6.9×10^{-4} 5.6×10^{-4}	2.1×10^{-5}	1.8×10^{-5} 9.8×10^{-6}
	Subsurface integrity		1.6×10^{-3} 1.3×10^{-3}		
	Operations		1.1×10^{-3} 8.9×10^{-4}		
Aquifer	Well integrity		9.9×10^{-5} 8.1×10^{-5}		2.5×10^{-6} 1.4×10^{-6}
	Subsurface integrity		1.6×10^{-3} 1.3×10^{-3}		
	Operations		1.5×10^{-4} 1.2×10^{-4}		
Salt cavern	Well integrity		3.9×10^{-4} 3.2×10^{-4}		1.0×10^{-5} 5.6×10^{-6}
	Subsurface integrity		2.5×10^{-4} 2.0×10^{-4}		
	Operations		3.5×10^{-4} 2.8×10^{-4}		

[3] Incidents were not broken out into separate causes
[4] First value listed uses facility year and well-year frequencies from 2005 (ref [7]); second value listed uses estimated frequencies for 2016.

In this paper, the frequencies for Folga et al.'s [9] dataset, which incorporates that of [5], were calculated two ways: (1) by using the values from [7] (cumulative years of natural gas storage facilities, 20,271 facility years; and well operations, 791,547 well-years); and (2) by adjusting the values to 2016, the approximate date of Folga et al.'s more recent study (an additional 11 years from the approximate 2005 date of [7]), by using (20,271 facility years + [16 years*415 facilities]) = 24,836 cumulative years. The cumulative well-year value was adjusted to 2016 by using (791,547 well-years + [16,205 wells * 39.05 wells/facility]) = 1,424,325 cumulative well-years. The number of wells was calculated by using (791,547 well-years / 20,271 facility years) = 39.1 wells/facility; then (39.1 wells/facility * 415 storage facilities) = 16,205 wells (given uncertainties in the number of active wells and facilities per year and the operational lifetimes of each facility considered by [7] and [9]). The adjustments to Folga et al.'s [9] data described here contribute to smaller frequency values of 82% and 56%, respectively, than would be calculated by using their 2016 data with the 2005 facility year and well-year rates of [7] directly, suggesting that incidents over the past ~15 years in all facility types might have decreased somewhat from the longer-term average, which may be consistent with the findings of a recent industry group study that focused on reservoir storage [6].

The values listed in Table 1 suggest that the **frequency of leakage** (in the subsurface) from all types of underground natural gas storage facilities in the US ranges between approximately

- 8.4×10^{-4} /facility/year, or once in ~1,192 facility years (using data from Papanikolau et al. [7]);
- 6.2×10^{-3} /facility/year, or once in ~161 facility years (using data from Folga et al. [9], which incorporates incidents through 2016 but uses facility years and well-year values from [7] dating from approximately 2005); and
- 5.1×10^{-3} /facility/year, or once in ~197 facility years (using data from Folga et al. [9] with facility years and well-years estimated for 2016, the date of their study).

The values calculated by using the data from Folga et al. [9], using both datums (2005 and 2016), are generally consistent with those reported by [9] from the literature. For example, the leakage frequency noted by [9] for major incidents at underground natural gas storage facilities from the literature, 8.4×10^{-4} to 6.0×10^{-3} per facility year (see ref [9], their table 4.2-5), is within the ranges calculated in this paper and described here. However, the incident rates for both facility year and well-year calculated in this paper by using the major incident data from Folga et al. [9] and using either datum (2005 or 2016), that are distinguished by cause, are larger by perhaps an order of magnitude than those listed in that study's literature review (ref [9], their table 4.2-5).

In general, many more incidents (126 major subsurface incidents; an additional 79 surface incidents are not considered in this paper) were reported by Folga et al. [9] than in the study of Papanikolau et al. [7] (17 incidents). The additional events imply a significant reduction, from years to months, in the average frequency of occurrence of major events at underground natural gas storage facilities. For example, assuming ~415 storage facilities on average, the frequency of leakage values correspond to a major incident occurring every 2.9 years, 4.7 months, or 5.7 months, respectively.

Correspondingly, the **frequency of an incident involving a loss of well integrity** at all types of underground natural gas storage facilities in the US ranges between approximately

- 1.0×10^{-5} /well/year, or once in ~98,943 well-years of well operation (using data from Folga et al. [9], which incorporates incidents through 2016 but uses facility years and well-year values from [7] dating from approximately 2005); and
- 5.6×10^{-6} /well/year, or once in ~178,041 well-years of well operation (using data from Folga et al. [9] with facility years and well-years estimated for 2016).

However, the additional events in [9] compared to [7] imply a corresponding increase in the average frequency of occurrence of subsurface events at the wells. For example, assuming a constant value of ~16,205 storage wells on average, the frequency of well-year leakage values correspond, in perhaps a more useful fashion, to a major well-related incident occurring every 6.1 years (using the 2005 datum) or 11 years (2016 datum), respectively.

Leakage events from underground natural gas storage facilities have occurred from a variety of causes (Table 1). Many can be related to a loss of well integrity, whereas others can be attributed to a loss of subsurface integrity (such as confining zone/caprock sequence failure, salt movement, or roof collapse) or operations (for example, procedures not followed). Folga et al. [9] show that 28% of depleted oil-and-gas facilities experienced incidents that led to significant supply interruptions (including above-ground and below-ground losses of product), whereas 54% of aquifer facilities, and 49% of solution-mined salt caverns, experienced such disruptions. Many events are related to multiple causes and not all leakage events can be attributed solely to a loss of well integrity. In many cases, the facilities were operated according to established guidelines, while in others operators failed to follow procedures. In all cases, the risk of leakage events could potentially be reduced by improved guidelines for wells, geologic characterization, and operations.

Using the values of Folga et al. [9], with facility years and well-years adjusted for the 2016 date of their study, the **frequency of leakage at solution-mined salt cavern facilities** in the US is estimated to be approximately

- 3.2×10^{-4} /facility/year, or once in ~3,105 facility years for well integrity;
- 2.0×10^{-4} /facility/year, or once in ~4,967 facility years for subsurface integrity; and
- 2.8×10^{-4} /facility/year, or once in ~3,548 facility years for operations.

Correspondingly, the **frequency of an incident involving a loss of well integrity at solution-mined salt cavern facilities** in the US may also be approximately

- 5.6×10^{-6} /well/year, or once in ~178,041 well-years for well integrity.

For solution-mined salt caverns, the total average frequency of occurrence of major events at underground natural gas storage facilities (including those due to well integrity, subsurface integrity, and operations) corresponds to ~8.4×10^{-4} /facility/year, or assuming 39 storage facilities on average [9], once in ~31.8 facility years. For example, the frequency of leakage values correspond to a major incident (assuming 39 facilities) occurring every 80 years related to well integrity only (3.2×10^{-4} /facility/year), 127 years related to subsurface integrity only (2.0×10^{-4} /facility/year), or 91 years related to operations only (2.8×10^{-4} /facility/year), respectively.

Independent studies confirm that wells constitute a fundamental risk element for product loss, although the geological and geomechanical integrity of the cavern or reservoir in underground natural gas storage facilities is also of primary concern [10,11]. These risk elements are consistent with the values discussed in this paper. Gas or liquids can escape confinement from their intended subsurface zone by means of multiple mechanisms including accessing faults and fracture sets [10,12,13], failure of confining zone sequences [14], and structural spill points. Failures of reservoir/cavern integrity and leakage of gas are well documented for the main types of UGS facility (reservoir storage and solution-mined salt caverns), along with storage in abandoned mines [5,15,16,17].

The data in Table 1, and summarized above, confirm that solution-mined salt cavern storage is the safest means (e.g., [18]), with aquifer storage having a greater average leakage frequency of about 1.5×10^{-3} /facility/year, or once in ~14 facility years, assuming 46 facilities [9]. Most UGS facilities in the US are in depleted oil and gas fields, with an average rate of about 2.7×10^{-3} /facility/year, corresponding to an average leakage occurrence rate of about once in ~1.1 facility years, assuming 328 facilities [9]. This rate is considered to be quite low given that many UGS facilities in the US have been operated for about a century and it is orders of magnitude smaller than leakage rates of above-ground facilities such as tanks and pipelines [5]. In general, loss of well integrity is the primary factor in UGS leakage events with failures of subsurface integrity and operations being important secondary contributors.

The values noted in this paper were computed and compared as simple averages, following work in the literature on incident frequency (e.g., [7,9,19]). More robust methods such as those described by Hubbard [20] may lead to different probabilities or frequencies of facility and well leakage rates, and a corresponding difference in risk, for underground natural gas storage facilities. For example, depending on the actual distribution of events and their magnitudes, the average frequency may overestimate the median, leading to an underestimate of the frequency of occurrence of large-magnitude events and a corresponding increase in risk (and decrease in time interval between them) for those larger events.

3. PHMSA's Regulatory Approach to Risk Mitigation

On December 19, 2016, PHMSA's Interim Final Rule was published in the Federal Register [1]. The IFR incorporated by reference two API recommended practices (API RP 1170, "Design and Operation of Solution-Mined Salt Caverns used for Natural Gas Storage" [21] and API RP 1171, "Functional Integrity of Natural Gas Storage in Depleted Hydrocarbon Reservoirs and Aquifer Reservoirs" [22]). The IFR requires storage operators to comply expeditiously with both the mandatory and non-mandatory provisions of the recommended practices, with different sections required for new versus existing facilities; for non-mandatory requirements, operators have the option to opt out of a specific recommended practice with technical justification to be reviewed by auditors. The IFR also provides for additional reporting requirements beyond those noted in the RPs for facility operators [23].

PHMSA utilized the API RPs as an initial basis for its regulation of underground storage facilities. Described by Rittenhour [24] and others, API RP 1170 was published in 2015 to provide recommendations for salt cavern facilities used for natural gas storage service and covers facility geomechanical assessments, cavern well design and drilling, solution-mining techniques and operations, monitoring, and maintenance and documentation practices. API RP 1171, also published in 2015, applies to natural gas storage in depleted oil and gas and aquifer reservoirs, and focuses on storage well, reservoir, and fluid management for functional integrity in design, construction, operation, monitoring, maintenance, and documentation practices.

4. Asset Integrity Management ─ Where Do You Stand?

When new regulations are issued, operators need to develop an understanding of where they stand, by asking questions such as "Am I in full compliance? What am I missing? What do I need to do?"

The first step in any risk mitigation program is to identify and assess the risks, or threats, to the integrity of the storage facility which could become potential causes of gas or fluid migration out of the reservoir or cavern. As noted above, leakage events from underground natural gas storage facilities are well known to have occurred from a number of causes and in the case of salt caverns, almost equally attributed to a loss of well integrity (37.9%) and to a loss of subsurface integrity (44.8%), with a lesser attribution to operational causes (13.7%) [5]. In all cases, the risk of leakage events could potentially have been reduced by using improved guidelines for wells, geologic characterization (e.g. [11, 25]), and operations. The approach described in this paper parallels and perhaps complements risk-mitigation strategies already deployed in the storage industry (e.g., [26]).

Building on guidelines laid out in the American Petroleum Institute's recommended practices 1170 (for salt cavern storage) and 1171 (for reservoir storage), PHMSA's Interim Final Rule, and the State of California in their collective responses to the Aliso Canyon event, and drawing from analogous risk-mitigation work in the oil and gas industry [27], seven major elements can be identified that can provide a foundation for the assessment and management of storage integrity [28]. These elements are:

1. Exposure
2. Action Plans
3. Wells
4. Subsurface (including reservoir and/or caverns)
5. Area of Review
6. Monitoring
7. Operations

Each of these elements can be broken down into a set of sub-elements as shown in Figure 1 on which to focus the integrity assessment.

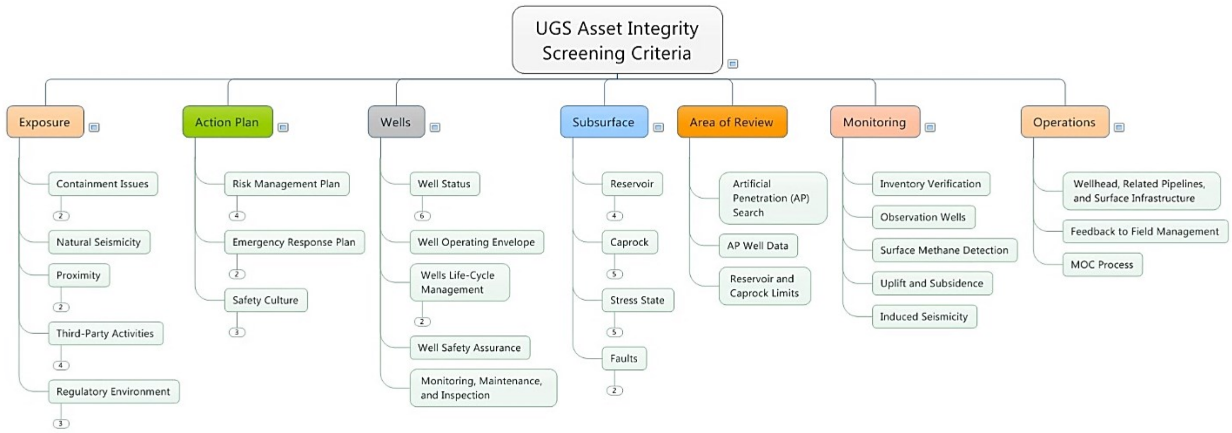

Figure 1. Hierarchy of UGS asset integrity elements.

To determine where an operator stands relative to the new regulations, a series of questions can be asked within the AIMS approach with the answers based upon the level of action taken by an operator to address the concern for each sub-element. Each level is defined by actions that provide successively greater reduction of risk and uncertainty in the key elements described in this section. The levels are:

- **Level 1 —** Element not being done or not considered; highest risk category.
- **Level 2 —** Element is acted upon, being developed, and resourced in an *ad-hoc,* reactive, or inconsistent manner.
- **Level 3 —** Element is regularly acted upon, deployed, and resourced at an adequate amount; compliant with API RP 1170/1171.
- **Level 4 —** Element is acted upon proactively and resourced at a robust amount and regularly assessed for its effectiveness (i.e., optimized); compliant with all applicable regulations and guidelines.

The highest risk condition is for all elements to have a (low) score of 1.0, corresponding to Level 1, where, for example, little has been done to identify and mitigate risks to subsurface integrity loss. Level 2 is probably where most operators are who have not *systematically* focused their attention on integrity management. Level 3 is where the main risks have been identified and resources have been directed toward their mitigation. Level 3 corresponds to a base-level condition where the operator meets regulatory requirements and risk-reduction goals, although it might be accomplished in a sub-optimal fashion. The lowest risk condition (Level 4) is achieved when an operator has plans, procedures, and resources in place, using risk-based and optimized monitoring and maintenance plans, to monitor and prevent deteriorating conditions that may lead to an adverse event. The operator has a full understanding of the current conditions of the not only the wells, but the reservoir or cavern and impacts and activities within an appropriate area of review. In this condition, the operator also has proactive interaction with emergency response authorities and other local stakeholders.

A presentation and evaluation of the results of this assessment can provide the operator with a roadmap for coming into compliance with the new regulations by building upon the current status and focusing work on the gaps that need to be addressed.

5. An Asset Integrity Management System (AIMS) for Solution-Mined Salt Caverns

Current approaches to asset integrity combine technical and human-centered barrier elements [26,27,29,30,31] that span areas such as well integrity, subsurface (geologic) integrity, operations, and facility management. The integrity of solution-mined salt caverns has been discussed extensively in the literature (e.g., [16,18,32,33,34]) and also informs the present approach to storage asset integrity.

The AIMS process provides a storage operator a workflow to:

- Organize and maintain well files and operating records.
- Identify all well barrier elements, the expected operational performance envelope, and the monitoring and control requirements for storage wells.
- Identify and assess elements critical to maintaining reservoir or cavern integrity.
- Identify and assess artificial penetrations in the Area of Review.
- Develop a *Risk Management Plan* for the storage facility which includes monitoring and maintenance plans designed to mitigate failure risk and provide a basis for system management decision-making.

Geostock Sandia's AIMS uses a modular three-step process:

1. **Screen**
   - Q&A to identify current state of your integrity management process and identify gaps
   - Input from multiple organizational levels; management, engineering, operations
   - Can be applied to a single asset or a portfolio of assets
2. **Evaluate**
   - Collate, organize, and evaluate data for each component; identify data gaps
   - Identify and analyze storage well barriers, reservoir/storage integrity, area of review integrity
   - Develop risk management plans, monitoring programs, and risk-based maintenance plans
3. **Mitigate**
   - Take mitigation actions to fill data gaps, reduce the risk of releases, meet compliance requirements, and enact risk-based maintenance programs

The *Screening Assessment* is accomplished by a questionnaire based upon the seven elements of storage integrity shown in Figure 1.

In the *Evaluation* step, the operator can follow the workflow shown in Figure 2. The workflow identifies four components of storage integrity that can be worked on sequentially or in parallel. These components are:

1. Data Management
2. Well Integrity
3. Reservoir/Cavern Integrity
4. Area of Review Integrity

Geostock Sandia has developed specific tools and processes to help operators come into and maintain compliance with the new regulations and facilitate regulatory audits. The tools address the issues or requirements identified on the outer rim of the diagram in Figure 2. The system can be implemented in a modular fashion, where the operator need only address the gaps identified in the Screening Assessment or already known to exist. The four components each may contain one or more of the integrity elements, as shown in Figure 2. For example, a Risk Management Plan draws information from each of these four storage integrity components, as required by the new federal (PHMSA) and State regulations.

Figure 2. Relationship between the four storage integrity components and selected containment elements in the AIMS approach.

During the third step, risks to storage integrity are *Mitigated* by developing and completing work plans to bring monitoring programs up to date and for mitigation actions selected in the risk management plan and maintenance plans. Following Bonnier et al. [35] and others, these work plans might include drilling new observation or monitoring wells, workovers to correct newly identified deficiencies or issues such as corrosion, implementation of inspection and maintenance schedules, safety audits of key performance indicators, and organizational changes to streamline communications and accountability.

As viewed in Figure 2, the sequential AIMS workflow represented as **Screen ● Evaluate ● Mitigate** provides the operator with a continuous improvement cycle that can work to drive down risks in a storage facility over time by meeting or exceeding the applicable regulations.

A synoptic view of Geostock Sandia's AIMS methodology is illustrated in Figure 3 where the relationship between the three-step process, the storage integrity elements, and the storage integrity components is captured. Identifying the risks to product loss are fundamental to asset integrity, but acting on them by defining and implementing the needed technical work, such as data collection, analysis and archival, and well inspection and maintenance programs, are key to risk reduction and regulatory compliance (e.g., [27]). As noted by Paté-Cornell [36], Hubbard [20] and others, risk analysis and mitigation such as the approach described in this paper involve both technical and organizational (human-centered) elements that may collectively promote increased safety for underground gas storage. A two-day summit sponsored by the Society of Petroleum Engineers [37] also emphasized the critical need to include such human factors in risk-based decision-making. Improving communication flows and providing clear lines of sight within a storage operator can be cost-effective strategies for risk mitigation.

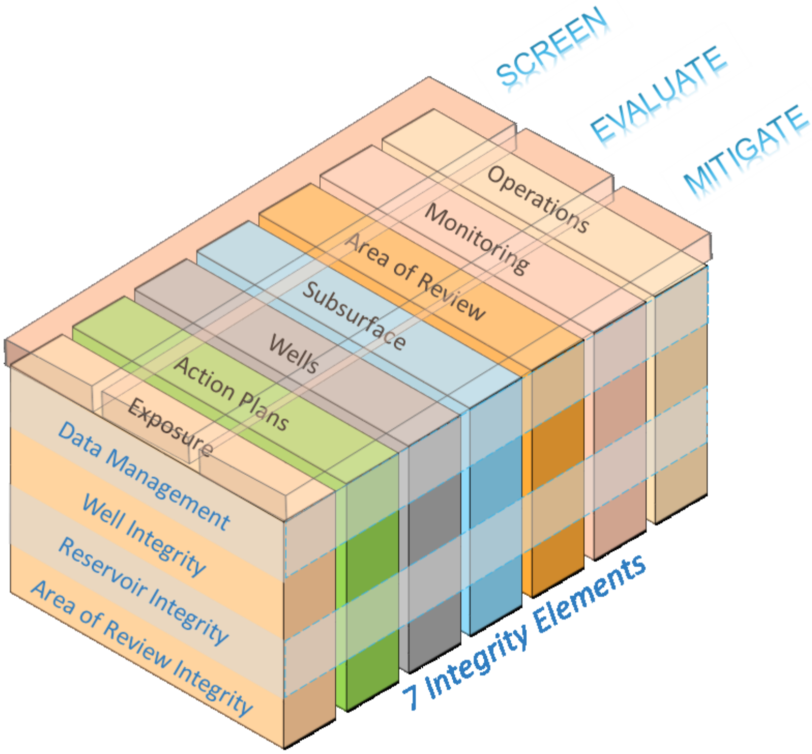

Figure 5. Capsule summary of the AIMS approach showing the relationship between: (1) storage integrity elements, (2) storage integrity components, and (3) three-step workflow.

The AIMS screening assessment and workflow is currently available for use by underground natural gas storage facility operators. Early results indicate that the workflow can provide a comprehensive framework for assessing the main categories of risks, for creation of risk management plans and related documents, and for complying with federal and State regulations.

Acknowledgements

Many of our friends and colleagues in the storage industry participated in the effort to produce this system and we are grateful for their insights and suggestions, including Kurt Looff, Capucine Courault, Oakley Cuevas, Alan Mitsdarffer, Troy Gillan, Varsha Bhat, Bruno Paul-Dauphin, Nicolas Bonnier, and Louis Londe. Comments by Scott Rouze helped us to sharpen the discussion of occurrence rates in the final paper.

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