



# Underground Natural Gas Storage Systems

## Risk Assessment, Mitigation, and Research Needs

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- > PHMSA Pipeline Safety Research and Development Forum
- > November 16-17, 2016
- > Cleveland, OH

# Overview

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- > Storage Leadership / Management / Execution Pyramid
- > Complex Threats and Interactions
- > Risk Reduction – What Needs to be Done
- > Risk Reduction – How to Do It
- > Desired End Result
- > Research Needs Related to Storage Risk Assessment and Management
- > Appendix – GTI / GRI / IGT Partial List of Storage Research Projects (17 slides for reference)

# Operations of a Natural Gas Storage Asset Leadership/Management/Execution Pyramid

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# Storage System Threats and Interactions



- > Most system failures and incidents are the result of multiple, interacting causes, not a single threat.
- > Individual threats can each be at “acceptable” levels but when overlaid result in a significant threat to the storage system or even a failure.

# Storage System Risk Reduction – What Needs to be Done

## To Define Risk and Enhance Failure Prevention and Mitigation

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1. Define the problem and commit resources
2. Identify threats, failure pathways, and root causes
3. Quantify likelihoods of failures
4. Quantify consequences of failures
5. Calculate and prioritize risks
6. Identify and summarize existing enterprise: controls, measures, plans, procedures, and working practices for storage assets; relate these to industry best practices
7. Gap analysis between possible risks and existing practices
8. Develop improvement plan to close this gap
9. Repeat 1-8, ensuring continuous process improvements
10. Diversify knowledge base to further increase system reliability and resiliency

# Storage System Risk Reduction – How To Do It (1/4)

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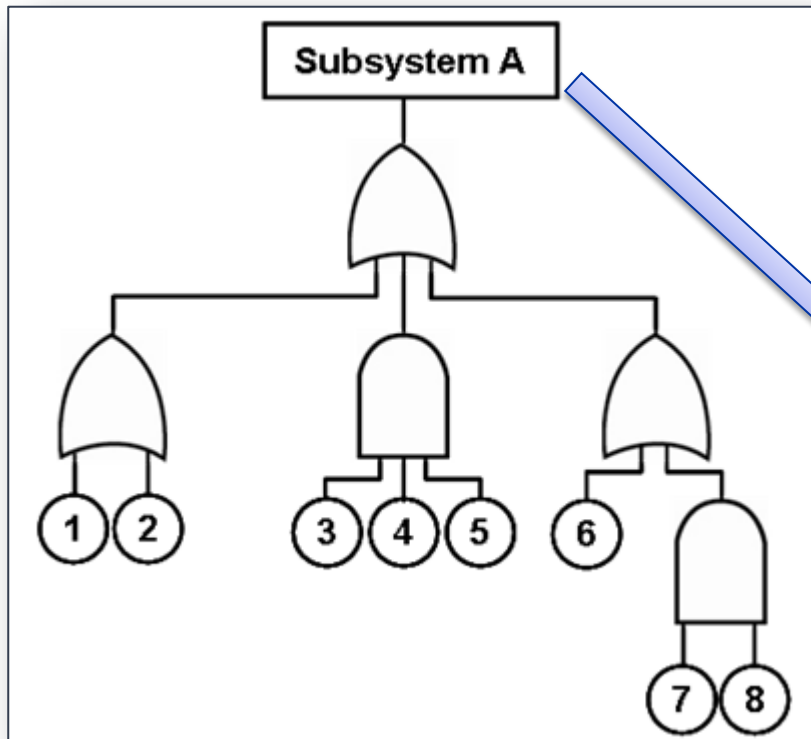
- 1. Problem.** Develop the problem statement with *leadership* and management to define and focus the improvement areas; must have leadership buy in via policy, strategy, and resource allocation
- 2. Threats.** *Qualitatively* identify threats and fault causes
  - Methods, Machines, Materials, Manpower
  - Procedures, People, Places, Policies
  - Systems, Supplies, Surroundings, Skills
  - Tools: Cause-effect/Ishikawa, 5 whys, Mind maps, Brainstorm
  - Knowledge: SMEs, Literature, Lessons Learned, Near Misses, Historic Failures
- 3. Likelihoods.** Assign *quantitative* probabilities/likelihoods of failure with associated uncertainties
  - Fault Tree Analysis (FTA)
- 4. Consequences.** Map out failure pathways and associated *consequences* with uncertainties
  - Event Tree Analysis (ETA)

# Risk Reduction – How to Do It (2/4)

## System Response → Fault & Event Trees

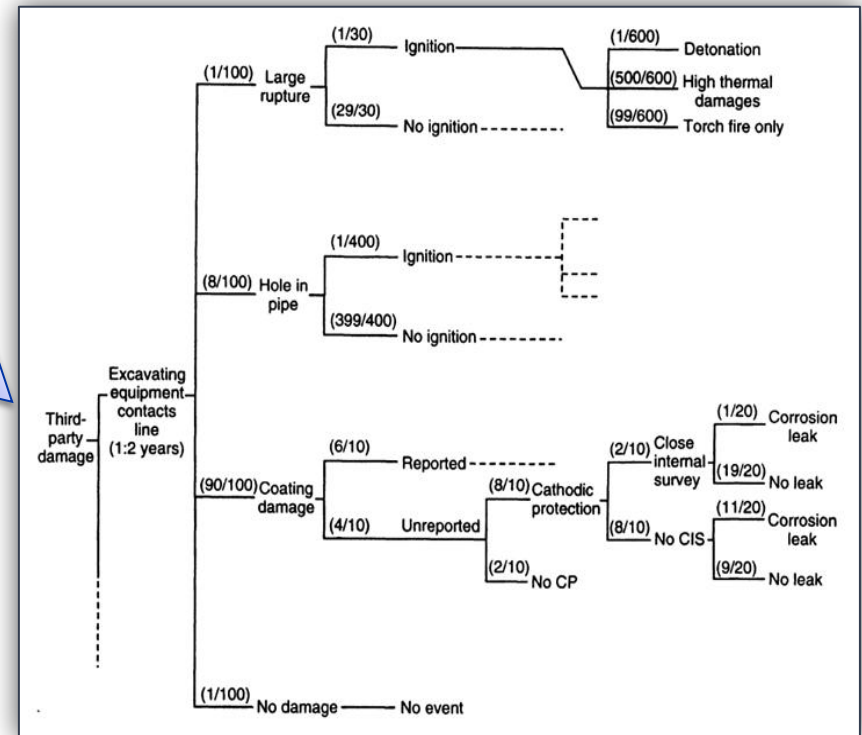
### Fault Tree Analysis

Bottom up approach of sequential combinations of faults that will result in a failure.



### Event Tree Analysis

Probability/likelihood of post failure events occurring and impact on consequence.



# Risk Reduction - How To Do It (3/4)

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5. **Risk.** Calculate and prioritize risk based on likelihoods and consequences.
  - Monte Carlo Simulation (MCS), and
  - Quantitative/Probabilistic Risk Assessment (QRA/PRA)
6. **Status Quo.** Identify current state of enterprise practices related to storage assets - controls, measures, plans, procedures, and working practices; relate to industry best practices
7. **Gaps.** Perform 1st pass gap analysis with Failure Mode Assessment and Assignment (FMAA)
  - SMEs fully describe the failure causes for highest risks and their likelihoods
  - Assign how to evaluate the sub-event/threat inputs
  - Formulate detailed follow-on actions to proactively prevent these triggers in the future; i.e., “break the chain” towards failure



# Risk Reduction - How To Do It (4/4)

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- 8. Improvements.** Develop improvement plans and enhancements to the status quo
  - Risk Assessment (RA) and Risk Management (RM) – Moving towards quantitative methods
  - Preventative and Mitigative (P&M)
  - Technology Implementation
  - Plan-Do-Check-Act (PDCA)
  - Management of Change (MOC)
  - Continuous Process Improvement (CPI)
- 9. Transparency.** Self audit, summarize, and publish to achieve transparency, education, and awareness across the enterprise
- 10. Diversify.** Repeat this process and further diversify knowledge base; look outside storage industry to other fields, as well as international knowledge and information

# Desired End Result

## Optimized Storage System Decisions and Minimized Risks

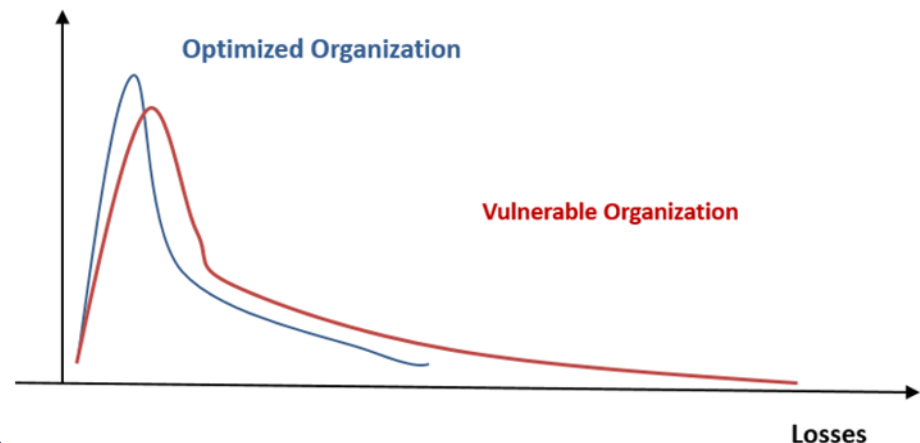
- Regulations
- Constraints – Capital / Mission
- Operations Mgt. and Process

- Modeling
- Data Analysis
- Field Surveys

- Subject Matter Expertise
- Institutional Knowledge
- Historical Information

- Decision, Risk, and Cost Optimization
- Balanced Lifecycle Management
- Mission Success

### Managed Risk vs. Catastrophic Losses



# Research Needs Related to Natural Gas Storage System Risk Assessment and Management

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Operators need to understand the interaction of multiple threats that can cause storage leaks, the likelihood of failures, and their consequence in order to calculate risk and prioritize proactive actions.

Required, storage-related research to close these gaps includes:

- 1. Interactive Threats.** Develop a compilation of storage field *threats* and how these could interact; provide a set of baseline fault trees and event trees that map out the failure pathways and potential incident consequences in storage fields.
- 2. Component Failure Rates.** Develop a set of quantitative probabilities/likelihoods of failure of storage field *components* with associated uncertainties.
- 3. Map out Storage Process/Practices.** Identify current state of enterprise *practices* related to storage assets - controls, measures, plans, procedures, and working practices; relate to and/or roll-up industry best practices of the same.
- 4. Preventative and Mitigation Strategies.** Develop an *enterprise decision program* that guides operators to putting in place preventative and mitigation plans and technology to close the identified, high risk gaps.

# Summary

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# Questions

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# Appendix: Partial List of GTI / GRI / IGT Storage Related Research

Title	Report Number Date of Publication
Vertical Well CNG Storage	UTD Project - ongoing (2012-2017)
RGD X-Ray Technology Feasibility Study For Gas Storage Wellbore Assessment	SMP Project (2010)
Hydrate Control for Gas Storage Operations; Hydrate Control in Gas Storage wells and Gathering Lines during Rapid Withdrawal Operations	FG26-02NT41652/ (2008)
Gas Storage Technology Applicability to CO2 Sequestration; Quantification of Geologically Controlled Gas Leakage From Gas Storage Fields	DE-FC26-01NT41145 (2005)
Technology Enhancements for (1) Inventory Assessment and Mechanical Integrity Testing of Gas-Filled Solution Mined Caverns and (2) Mechanical Integrity Tests of Solution Mining and Liquid Storage Caverns.	GRI-05/0175

# Appendix: Partial List of GTI / GRI / IGT Storage Related Research

Title	Report Number Date of Publication
Geomechanical Analysis and Design Criteria for Thin-Bedded Salt Caverns.	GRI-05/0174
Determination of Measurement Resolution Capabilities of High Resolution Axial Flux Leakage Casing Inspection Tools.	GRI-05/0173
Well Bore Integrity--Development of Methods for Assessing Corrosion Metal Loss Defects in Casing Strings.	GRI-05/0171
Monitoring of Damage in Gas Storage Wells.	GRI-05/0146
Improved Detection and Prevention of Microbial Corrosion of Metal and Plastic Pipes Using Molecular Genetics of Unculturable Microorganisms.	GRI-05/0122
Reservoir Property Analysis, McAlester and Hartshorne Formations, Krebs Group, Arkoma Basin.	GRI-04/0181
Reservoir Property Analysis, Hinthorn #CW1, Marmaton & Cherokee Groups, Cherokee Basin.	GRI-04/0180

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Title	Report Number Date of Publication
Reservoir Property Analysis, Kansas City, Marmaton, and Cherokee Groups, Forest City Basin.	GRI-04/0179
CO2 Sequestration and Enhanced Gas Recovery in Depleted Gas Reservoirs: Quantification of Fundamental Chemical and Mechanical Processes Affecting Flow and Injectivity.	GRI-04/0177
Reservoir Property Analysis, Mangels 24-2SD, Woodford Shale, Cherokee Basin.	GRI-04/0060
Reservoir Property Analysis, Crane 12-4, Adaville Coal, Overthrust Region.	GRI-04/0059
Reservoir Property Analysis, W. Stein Unit #2, Athens Gas Field.	GRI-04/0057
Reservoir Property Analysis, Kerr-McGee Corporation Wells, Laramie Formation, Denver-Julesburg Basin.	GRI-04/0056
Frontier Coalbed Resource and Production Potential Assessments. Final Summary Report.	GRI-04/0055



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Title	Report Number Date of Publication
Frontier Coalbed Resource and Production Potential Assessments. Final Summary Report.	GRI-04/0055
Geologic Assessment of Natural Gas from Coal Seams in the Western Interior Coal Region, USA.	GRI-04/0054
Salt Cavern Thermal Simulator Version 2.0.	GTI-04/0044
Reservoir Property Analysis, Pappy Draw Federal 4-1, Wasatch & Fort Union Formations, Great Divide Basin.	GRI-03/0198
Systematic Testing of Formation Damage Potential in Gas Storage Fields.	GRI-03/0177
Well Treatment Expert System.	GRI-02/0243
Geomechanical Analysis of Pressure Limits for Thin Bedded Salt Caverns.	GRI-02/0242
New and Novel Fracture Stimulation Technologies for the Revitalization of Existing Gas Storage Wells.	GRI-00/0251

# Appendix: Partial List of GTI / GRI / IGT Storage Related Research

Title	Report Number Date of Publication
Diagnosis, Treatment and Monitoring of Microbiologically Influenced Productivity in Natural Gas Storage Facilities.	GRI-00/0056
Geomechanical Analysis of Pressure Limits for Gas Storage Reservoirs	GRI-98/0198
Investigation into Storage Well Damage Mechanisms	GRI-98/0197
Determining Downhole Damage--The GRI/DOE Study	GRI-97/0419
Guidelines for Implementation and Risk Assessment of Inert Base Gas Projects	GRI-96/0407
Integrated Reservoir Description of the Lexington Gas Storage Field	GRI-96/0189
Inert Base Gas Field Experiment.	GRI-95/0466
Howell Storage Field Horizontal Well Field Experiment.	GRI-95/0455
Risk Assessment of Converting Salt Caverns to Natural Gas Storage.	GRI-95/0377

# Appendix: Partial List of GTI / GRI / IGT Storage Related Research

Title	Report Number Date of Publication
Operational and Cost Parameters for Natural Gas Storage.	GRI-95/0348
Natural Gas Storage: Historical Development and Expected Evolution.	GRI-95/0214
Practical Analytical Tools for Diagnosing and Managing Migration of Stored Gas.	GRI-95/0060
Natural Gas Deliverability.	GRI-95/0038
Environment and Safety: Microbiologically Influenced Souring (MIS): Finding the Answers for Effectively Treating H <sub>2</sub> S Contamination.	GRI-95/0032-0004
Gas Storage and Production: OMEGAPLUS for the Modeling of Gas Reservoirs.	GRI-95/0032-0003
Gas Storage as a Strategic Planning Tool. Summary of the Thirteenth Gas Research Institute Energy Seminar for the GRI Board of Directors and Advisory Council, August 3, 1994, Snowbird, Utah.	GRI-94/0478

# Appendix: Partial List of GTI / GRI / IGT Storage Related Research

Title	Report Number Date of Publication
Effectiveness and Potential Environmental Impacts of Biocides and Corrosion Inhibitors in the Natural Gas Industry.	GRI-94/0321
Physicochemical Properties of Methane Storage and Transport in Devonian Shale: Appendix A.	GRI-94/0114.2
Physicochemical Properties of Methane Storage and Transport in Devonian Shale.	GRI-94/0114.1
Production Management Techniques for Water-Drive Gas Reservoirs. Field #4: Mid-Continent Aquifer Gas Storage Reservoir. Volume II.	GRI-94/0005.2
Production Management Techniques for Water-Drive Gas Reservoirs. Field #4: Mid-Continent Aquifer Gas Storage Reservoir. Volume I.	GRI-94/0005.1

# Appendix: Partial List of GTI / GRI / IGT Storage Related Research

Title	Report Number Date of Publication
Microbiologically Influenced Souring (MIS): Assessment of MIS in Natural Gas Storage Fields.	GRI-93/0420
Geologic Controls on Gas Production, GRI Experimental Development Research Area, Pike County, Kentucky. Volume I.	GRI-93/0197.1
Development of Casing Leak Measurement and Repair Tools. Volume II, Supplement: Casing Leak Tests.	GRI-93/0185.2
Development of Casing Leak Measurement and Repair Tools. Volume I.	GRI-93/0185.1
Physicochemical Properties of Methane Storage and Transport in Devonian Shale.	GRI-93/0158
Status Report: Transport and Storage Research.	GRI-93/0093
Development and Demonstration of a Membrane Process Technology for Reducing Base Gas Requirements in Underground Natural Gas Storage Facilities.	GRI-93/0060

# Appendix: Partial List of GTI / GRI / IGT Storage Related Research

Title	Report Number Date of Publication
Critical Performance Parameters for Horizontal Well Applications in Gas Storage Reservoirs.	GRI-93/0024
Horizontal Storage Well Field Experiment.	GRI-93/0021
Development of Technologies and Techniques to Enhance Underground Natural Gas Storage Operations. Topical Report No. 1: State-of-Technology Assessment and Evaluation of Gas Storage Well Productivity Enhancement Techniques.	GRI-93/0001
Reservoir Engineering and Treatment Design Technology: Comparison of Antrim Shale Isotherm Measurements Performed on the NOMEKO Bagley East B3-11 Well, Otsego County, MI.	GRI-92/0582
Evaluation of United States Natural Gas Storage Operations.	GRI-92/0467

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Title	Report Number Date of Publication
Technical and Economic Barriers to Innovative Gas Storage.	GRI-92/0422
Gaffney: Horizontal Well Application for Gas Storage.	GRI-92/0348
Natural Gas Transmission System Database: TRANSDAT. Overview of Storage Data.	GRI-92/0331
Physicochemical Properties of Methane Storage and Transport in Devonian Shale.	GRI-92/0278
Interactive PC-Based Software for Analysis of Pressure Buildup Tests in Gas Storage Reservoirs.	GRI-92/0254
Geologic Evaluation: Ashland Exploration, Inc., E.J. Evans No. 91, GRI Comprehensive Study Well No. 4A, Breathitt County, Kentucky.	GRI-92/0228
Status Report, 1991 Projects: Transport & Storage Research Program.	GRI-92/0076

# Appendix: Partial List of GTI / GRI / IGT Storage Related Research

Title	Report Number Date of Publication
Physicochemical Properties of Methane Storage and Transport in Devonian Shale (Data II).	GRI-91/0296.3
Physicochemical Properties of Methane Storage and Transport in Devonian Shale (Data I).	GRI-91/0296.2
Physicochemical Properties of Methane Storage and Transport in Devonian Shale.	GRI-91/0296.1
Load Balancing Issue.	GRI-91/0242
Geophysical and Geological Reservoir Characterization of the Devonian Shales. Application of Single-Fold Seismic Data, Natural Fracture and Lithological Characterization of the Comprehensive Study Wells, and Preliminary Geologic Study Experimental Development Well Site Selection Area. Volume I of II.	GRI-91/0238.1



# Appendix: Partial List of GTI / GRI / IGT Storage Related Research

Title	Report Number Date of Publication
Status Report, 1990 Projects: Transport and Storage Research Program.	GRI-91/0140
Natural Gas Storage: Pricing Outlook and Implications for the 1990s.	GRI-91/0061
OMEGA: Gas Reservoir Simulator.	GRI-90/0387
Identification of Injected Storage Gas.	GRI-90/0337
Physicochemical Properties of Methane Storage and Transport in Devonian Shale (Data II).	GRI-90/0232.3
Physicochemical Properties of Methane Storage and Transport in Devonian Shale (Data I).	GRI-90/0232.2
Physicochemical Properties of Methane Storage and Transport in Devonian Shale.	GRI-90/0232.1
Development of Technologies and Techniques to Enhance Underground Natural Gas Storage Operations: Well Casing Leak Repair.	GRI-90/0229

# Appendix: Partial List of GTI / GRI / IGT Storage Related Research

<b>Title</b>	<b>Report Number Date of Publication</b>
Field Implementation Plan for Inert Base Gas Use in Underground Storage Fields in the United States.	GRI-90/0080
Gas Research Institute Status Report, 1989 Projects: Transport and Storage Research Program.	GRI-90/0077
Development of Improved Technologies and Techniques for Reducing Base Gas Requirements in Underground Gas Storage Facilities: Simulation Study of Hanson Field Gas Storage Reservoir.	GRI-89/0234
Feasibility Analysis and Development of Foam Protected Underground Natural Gas Storage Facilities.	GRI-89/0211

# Appendix: Partial List of GTI / GRI / IGT Storage Related Research

Title	Report Number Date of Publication
Gas Research Institute Contract Status Reports - Status of Projects on January 1, 1988 - Transmission Operations Research.	GRI-88/0361
New Technologies for the Gas Industry: GRI's Transport and Storage Program.	GRI-88/0191
Characterization of Produced Waters From Underground Natural Gas Storage Reservoir Operations: Volume II - Appendix D. Analytical Data Report.	GRI-88/0080.2
Characterization of Produced Waters From Underground Natural Gas Storage Reservoir Operations: Volume I.	GRI-88/0080.1
Development of Improved Technologies and Techniques for Reducing Base Gas Requirements in Underground Natural Gas Storage Facilities.	GRI-88/0004.1

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Title	Report Number Date of Publication
Development of Improved Technologies and Techniques for Reducing Base Gas Requirements in Underground Natural Gas Storage Facilities.	GRI-88/0004
Development of Improved Technologies and Techniques for Reducing Base Gas Requirements in Underground Natural Gas Storage Facilities: Mathematical Model.	GRI-87/0336.1
Development of Improved Technologies and Techniques for Reducing Base Gas Requirements in Underground Natural Gas Storage Facilities: Mathematical Model.	GRI-87/0336
Physicochemical Properties of Methane Storage and Transport in Devonian Shale.	GRI-87/0254
Gas Distribution Utility Model.	GRI-87/0253
Development of a Data Base for Onsite Natural Gas Storage.	GRI-86/0240

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Title	Report Number Date of Publication
Low Pressure Storage	IGT Project 46025 (5/1985-6/1986)
Research and Development Needs for Gas Storage. State-of-the-Art Summary.	GRI-85/0086
Storage of Natural Gas at Reduced Pressure	IGT Project 20217 (3/1981-8/1981)
Underground Storage Reservoirs Storage Gas of Different Compositions than Natural Gas	IGT Project 40177 (5/1980-10/1981)
Assessment of Storage and Peaking Strategies.	GRI-80/0091
Underground Storage of Hydrogen	IGT Project 9545 (8/1978-3/1980)

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<b>Title</b>	<b>Report Number Date of Publication</b>
Storage of Fuel Gas	US Patent 4147456 (assigned to Institute of Gas Technology) (1979)
Seasonal Energy Storage Requirements	IGT Project 8982 (6/1976- 8/1976)
Investigation of Underground Storage	IGT Project 8372 (2/1967- 6/1967)