Reliability of Subsurface Safety Valves – Cost/ Benefit Analysis for SSSVs in UGS Wells

Battelle/ Sandia National Laboratories

January 13, 2021

Agreement No.693JK31810016

U.S. DEPARTMENT OF ENERGY
NNSA National Nuclear Security Administration

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Outline

- Battelle/ Sandia team
- Problem statement & objective of this project
- Task outline & budget
- Battelle/ Sandia risk model
- Results of the Battelle/ Sandia risk model
- Knowledge & technology transfer
- Recommendations
- Acknowledgements

Battelle/ Sandia team

Battelle:

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- Giorgia Bettin – Co-PI
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Problem statement & Objective of the project

PHMSA
Pipeline and Hazardous Materials Safety Administration

- UGS wells can fail, causing safety, environmental and financial consequences
- The potential for failure and the range of consequences must be understood
- The objective of this project was <u>to assess the role of subsurface safety valves (SSSVs) in improving UGS safety</u>, specifically for wells in storage fields developed in depleted hydrocarbon reservoirs
- This project fits into the broader PHMSA mandate to improve UGS safety

Task outline & budget

	Task	Q1			Q2			Q3			Q4			Q5			Q6			Q7			Q8		
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	**Task 1 - Literature Review**																								
1.1	Kick-Off Meeting	◆																							
1.2	Open Lit and Case Study Review					◆																			
1.3	Interview SMEs					◆																			
1.4	Review Individual State Occurences					◆																			
1.5	Task 1 Final Report						◆																		
2	**Task 2 - Develop Evaluation Criteria**																								
2.1	Evaluate Failure Criteria								◆																
2.2	Review API Standards										◆														
2.3	Task 2 Final Report												◆												
2.4	Sponsor Industry Workshop																		◆						
3	**Task 3 - Develop Recommendations and Improvements**																								
3.1	Review Success/Failure Info																◆								
3.2	Review Existing Product-Line Offerings																				◆				
3.3	Develop Recommendations for Product Line Revisions																								◆
4	**Task 4 - PM and Reporting**																								
4.1	DOT Project Review Meeting			◆												◆									
4.2	Mid-Term Team Meeting													◆											
4.3	Final Team Meeting																								◆
4.4	Quarterly and Final Project Reports			◆			◆			◆			◆			◆			◆			◆			◆
4.5	Publish Papers and Present																								◆

◆ = Objective Deadline = Period of Performance

Period of performance:

09/28/2018 – 09/30/2020

Total budget: $749,080

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Battelle/ Sandia Risk Model

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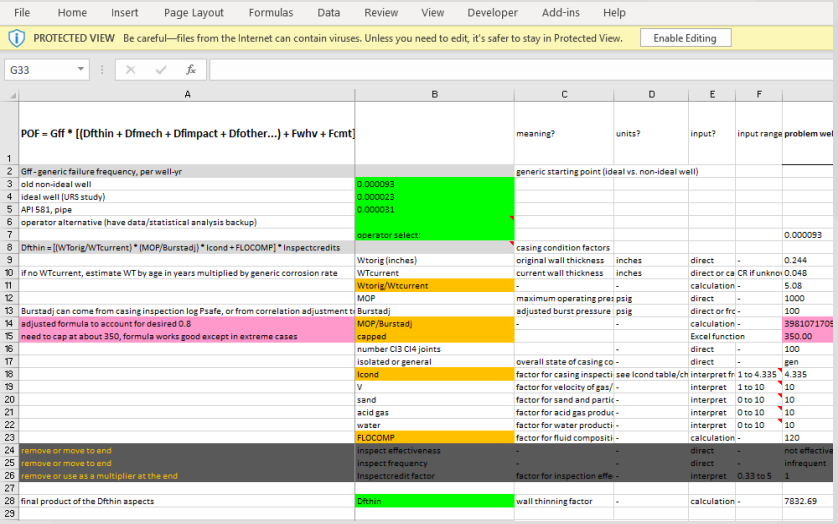
Battelle/ Sandia adapted JITF API 581 approach

- American Petroleum Institute (API) 581 Risk-Based Inspection Technology is applicable to pressurized systems – like UGS
- PHMSA: (see Pipeline Risk Modeling - Overview of Methods and Tools for Improved Implementation) indicates evolution to quantitative, probabilistic risk models for natural gas integrity management systems
- API-AGA-INGAA Joint Industry Task Force (JITF) Risk Management work group adapted API 581 methods to model risks in UGS wells; some UGS operators use this or a company-adapted version
- Both likelihood and consequence of failure are included; permits cost-benefit analysis; consequence of failure for both surface and subsurface events; JITF model did not include workover risk
- Battelle/ Sandia team adapted this approach as an elegant and practical method to analyze risks and guide design, safety, and management decisions

Features of the Battelle/ Sandia risk model

- Quantitative – estimates likelihood and consequence for loss of control events
- Practical, simple and flexible – Excel format adaptable to Python; users have multiple options for input variance
- Adaptable – Battelle/ Sandia added workover risk equations; reliability expressions; human factors and deliverability
- Effective platform for continual improvement in risk analysis – a set of few equations and several underlying numerical assumptions that can be discussed and improved in a constructive way.



	A	B	C	D	E	F	
1	POF = Gff * [(Dfthin + Dfmech + Dfimpact + Dfother...) + Fwhv + Fcmt]		meaning?	units?	input?	input range	problem wel
2	Gff - generic failure frequency, per well-yr		generic starting point (ideal vs. non-ideal well)				
3	old non-ideal well	0.000093					
4	ideal well (URS study)	0.000023					
5	API 581, pipe	0.000031					
6	operator alternative (have data/statistical analysis backup)						
7		operator select:					0.000093
8	Dfthin = [(WTorig/WTcurrent) * (MOP/Burstadj) * Icond + FLOCOMP] * Inspectcredits		casing condition factors				
9		Wtorig (inches)	original wall thickness	inches	direct	-	0.244
10	if no WTcurrent, estimate WT by age in years multiplied by generic corrosion rate	WTcurrent	current wall thickness	inches	direct or ca	CR if unknov	0.048
11		Wtorig/Wtcurrent	-	-	calculation	-	5.08
12		MOP	maximum operating pres	psig	direct	-	1000
13	Burstadj can come from casing inspection log Psafe, or from correlation adjustment t	Burstadj	adjusted burst pressure	psig	direct or fro	-	100
14	adjusted formula to account for desired 0.8	MOP/Burstadj	-	-	calculation	-	3981071705
15	need to cap at about 350, formula works good except in extreme cases	capped			Excel function		350.00
16		number Cl3 Cl4 joints		-	direct	-	100
17		isolated or general	overall state of casing co	-	direct	-	gen
18		Icond	factor for casing inspecti	see Icond table/ch	interpret fr	1 to 4.335	4.335
19		V	factor for velocity of gas/	-	interpret	1 to 10	10
20		sand	factor for sand and partic	-	interpret	0 to 10	10
21		acid gas	factor for acid gas produc	-	interpret	0 to 10	10
22		water	factor for water producti	-	interpret	0 to 10	10
23		FLOCOMP	factor for fluid compositi	-	calculation	-	120
24	remove or move to end	inspect effectiveness	-	-	direct	-	not effective
25	remove or move to end	inspect frequency	-	-	direct	-	infrequent
26	remove or use as a multiplier at the end	Inspectcredit factor	factor for inspection effe	-	interpret	0.33 to 5	1
27							
28	final product of the Dfthin aspects	Dfthin	wall thinning factor	-	calculation	-	7832.69
29							

$$LOFI_{workover} = Frequency_{workovers} \times Likelihood\ of\ failure_{workover} \times Credit_{mgm\text{-}workover}$$

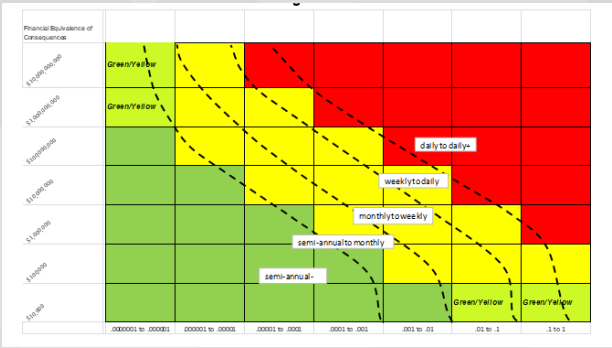
API 581 approach

Likelihood of Failure Index (LOFI) estimation [likelihood/year]

Consequence of Failure Index (COFI) estimation [$/failure]

Details of LOFI and COFI estimates provide valuable insights about system design and risk management

Risk matrix



Annualized risk (LOFI×COFI) estimation [$/year]

The API 581 approach provides:

- Can be applied with limited failure rate data because it starts with an assumed generic failure frequency
- Effective way to guide risk decisions as it provides annualized risk cost/ benefits that can be evaluated in a common way

JITF model LOFI estimate – what is included

$$LOFI = Gff \times [(Df_{thin} + Df_{mech} + Df_{impact}) + F_{whv} + F_{cmt}] \times Credit_{mgm}$$

Gff - general failure frequency – from industry data/experience

Df_{thin} - wall thinning –MOP, wall thickness, corrosion rate, age and/or years since last inspection, burst strength, wall condition

Df_{mech} - mechanical damage – vibration, previous failures, earth forces, physical barriers, well work stresses

Df_{impact} - impact damage – vehicular impact, falling objects, preventive controls

F_{whv} - wellhead failure factor – design (API, non-API), condition, pressure rating, testing

F_{cmt} - cement sheath factor – cement condition, annular flow factor, cement functionality factor

$Credit_{mgm}$ - management system credit – API 1171 implementation, test completion factor, maturity of inspection program

JITF model COFI estimate – what is included

$$COFI=(COFI_{safety\text{-}surface}+COFI_{safety\text{-}subsurface}+COFI_{environmental}+COFI_{financial})\times Credit_{mitig}$$

$COFI_{safety\text{-}surface}$ – safety consequences of surface gas release with fire, heat impact radius, population density in the critical heat impact radius, PHMSA accident safety pipeline effect statistics

$COFI_{safety\text{-}sub\ surface}$ – safety consequences of sub surface gas release with no fire, volume of released gas, population density within 9-mile radius, safety consequence distribution

$COFI_{environmental}$ – estimated consequences of gas release to air, water, soil, and associated environmental degradation

$COFI_{finantial}$ – estimated financial costs due to emergency response, product loss, repairs, public reputation, other

$Credit_{mitig}$ – credit for mitigation system(s) and their reliability. The mitigation system must be technical/ hardware, not human or procedural

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Battelle/ Sandia model

The Battelle/ Sandia model adopted most parts of the JITF model with a few additions:

- Effects of SSSV on different components of COFI were estimated
- SSSV workover risks were added to the LOFI estimates
- Several common UGS well construction styles and reservoir/ population density scenarios were considered within the model
- Effects of deliverability impairment due to the use of SSSV were evaluated
- Risk reduction/ increase due to SSSV installation were evaluated
- Cases where SSSV installation is/ is not beneficial were identified

COFI credits due to SSSV application – during regular operations

Type of consequence	COFI Credit	
	Shallow-set SSSV	Deep-set SSSV
Surface release with fire	$(1-R_{SSSV}) \times C_{Del}$	$(1-R_{SSSV}) \times C_{Del}$
Long-term gas release due to subsurface and surface release without fire	$0.5+0.5 \times C_{Del} \times (1-R_{SSSV})$	
Service and financial		
Fluid flow, toxins and pollutants release		
Greenhouse gases (GHG) emissions	$(1-R_{SSSV}) \times C_{Del} + C_{leakage}$	$(1-R_{SSSV}) \times C_{Del} + C_{leakage}$
Soil stability, vegetation health, soil productivity, water supply security	1	$(1-R_{SSSV}) \times C_{Del}$

R_{SSSV} is reliability of SSSV
C_{Del} is a deliverability reduction factor for SSSV
$C_{leakage}$ is a leakage component of credit, assumed to be 0.5% of the reservoir volume per year plus 0.1 MMcf per year

Estimation	Reliability of SSSV	
	Shallow-set	Deep-set
Very low	0.60-0.67	0.36
Low	0.80	0.67
Medium	0.905	0.84
High	0.985	0.94

SSSVs handled as mitigation devices, adjustments go to COFI

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LOFI estimate for workover operations

$$LOFI_{workover} = Frequency_{workover} \times FailureRate_{workover} \times Credit$$

Net increase of likelihood of loss of control (LOC) event during workovers per year

Estimated net increase of workover frequency due to SSSV addition. This frequency is dependent of well type, operator procedures, regulatory environment

Estimated rate of LOC during workovers. This rate is dependent on type of entry.

Credit accounting for management and human factors

Table 8: Combined workover frequency, baseline and SV-related interventions.

Estimate	Combined re-entry frequency		Method of estimation
	Interventions per year	Interval between re-entry (yr)	
Low	0.073	13.6	Low estimate for newer storage wells + low estimate for SV
Medium	0.225	4.4	Medium estimate for mid-age storage wells + medium estimate for SV
High	0.4	2.5	High estimate for old, converted wells + high estimate for SV
California mandate	0.5	2.0	California mandated SV inspection rate

Table 9. Workover LOC rates – approximate or estimated Average from various sources.

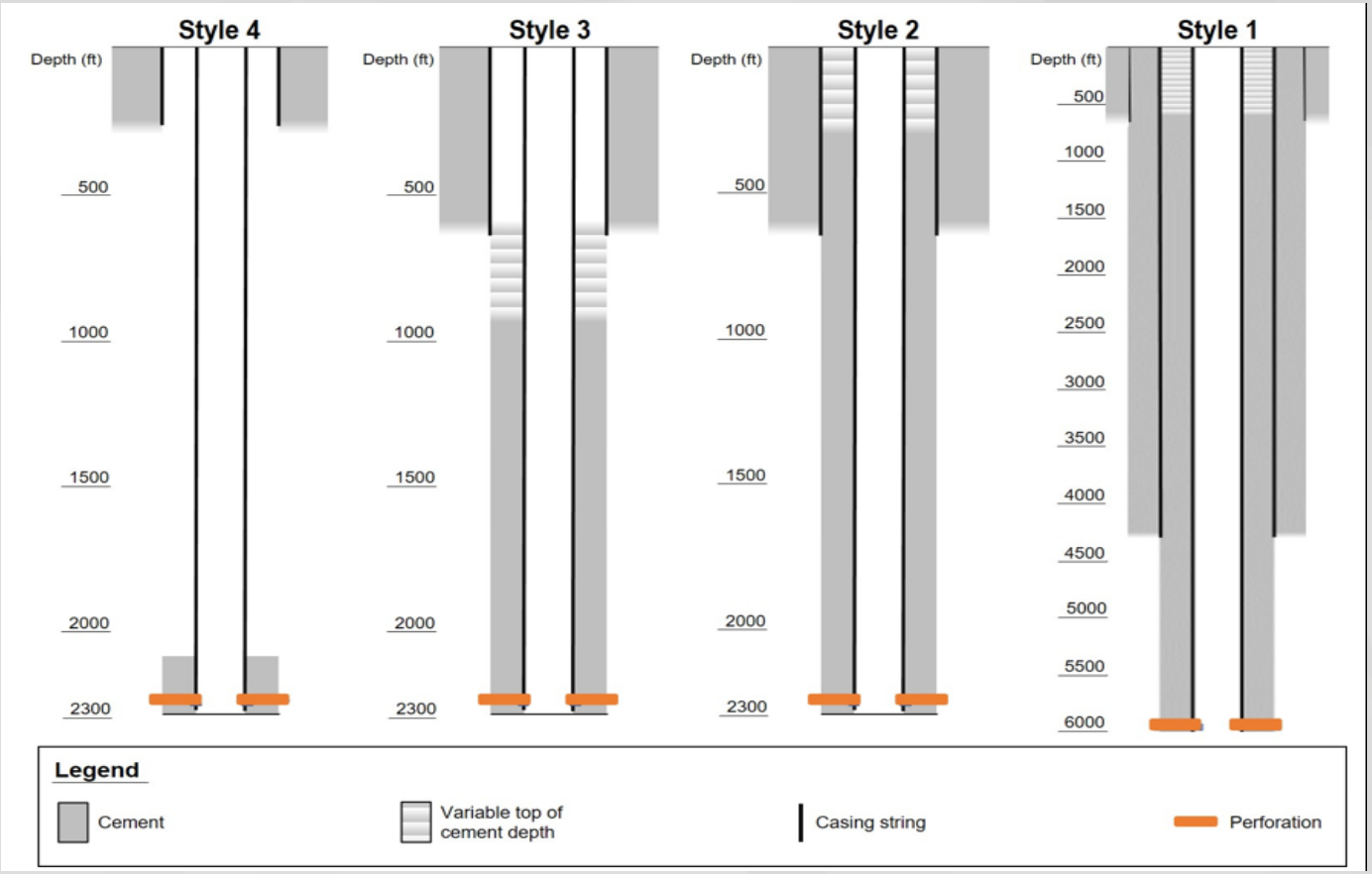
Intervention Loss of Control (LOC) (per entry event)	
Tubing-conveyed entries, low estimate	0.0004
Tubing-conveyed entries, high estimate	0.0025
Wireline-conveyed entries, low estimate	0.00007
Wireline-conveyed entries, high estimate	0.00015

Table 13. Proposed human factors three-tiered scoring system.

Expertise and Management Systems	Management System Factor (MSF)	Behaviors	Near Miss Adjustment Factor (NMA)	MSF×NMA
Weak	3	Near misses ignored	40	120
Average	1	Inconsistent/uncertain handling of near misses	15	15
Better	0.3	Near misses addressed	3	0.9

COFI routine added for workover operations, with appropriate adjustments

Four (six) styles of UGS wells used in analysis



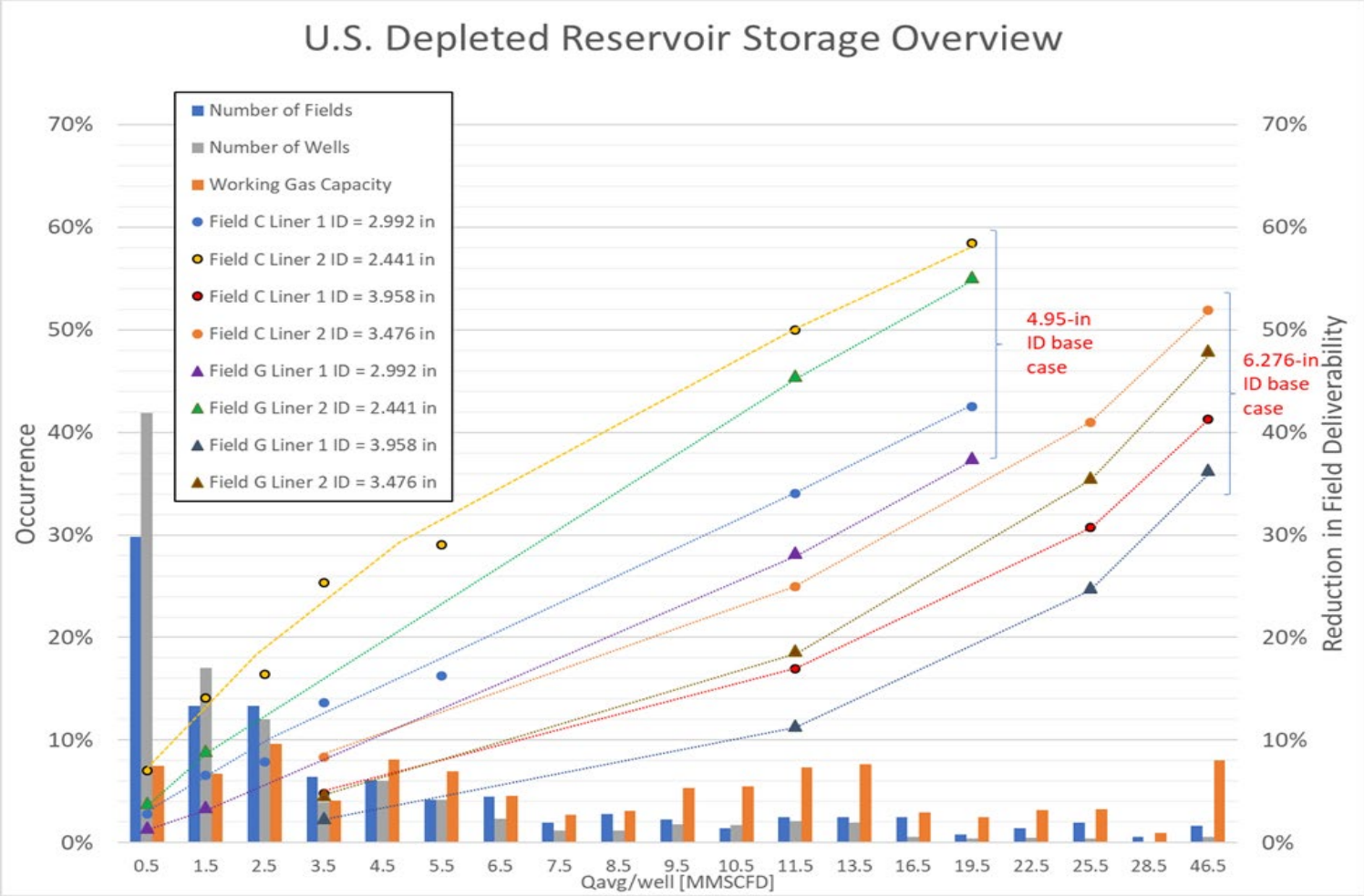
- The selected well styles are intended to represent a broad range of hypothetical but commonly used UGS wells
- This created a range of LOFIs covering six orders of magnitude

Twelve consequence environments used in analysis

Environment	Well Flow (AOF)	30-day flow volume	Population Density
Base	Very high rate well	High feed volume	High population density, even distribution
	Modest high rate well	Moderate feed volume	Moderate population density, even distribution
	Low rate well	Low feed volume	Low population density, even distribution
	Very low rate well	Very low feed volume	Very low population density, even distribution
Inverted	Low rate well	Moderate feed volume	High population density, even distribution
	Low rate well	Moderate feed volume	Moderate population density, even distribution
	Very high rate well	High feed volume	Low population density, even distribution
	Very high rate well	High feed volume	Very low population density, even distribution
Mixed	High rate well	High feed volume	Wider population density moderately high, nearby population density low
	High rate well	High feed volume	Wider population density moderately high, nearby population density nil
	High rate well	High feed volume	Wider population density moderate, nearby population density low
	High rate well	High feed volume	Wider population density moderate, nearby population density nil

- The consequence environments represent a broad range of reservoir volumes, flow rates, and nearby population densities common for UGS wells
- This created a range of COFIs covering over five orders of magnitude

Deliverability impairment/ replacement model



AOF (MMSCFD)	Deliverability adjustment factor C_{Del} used		Replacement wells needed per well	
	Shallow set SSV	Deep set SSSV or Tubing	Shallow set SSV	Deep set SSSV or Tubing
300	0.95	0.55	0.05	0.45
100	0.965	0.68	0.035	0.32
60	0.98	0.72	0.02	0.28
10	0.995	0.93	0.005	0.07
1	1	0.99	0	0.01

The Battelle/ Sandia model provides evaluation of deliverability impairment effects introduced by SSSV or T&P application.

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Results of the Battelle/ Sandia Risk Model, Reccomendations

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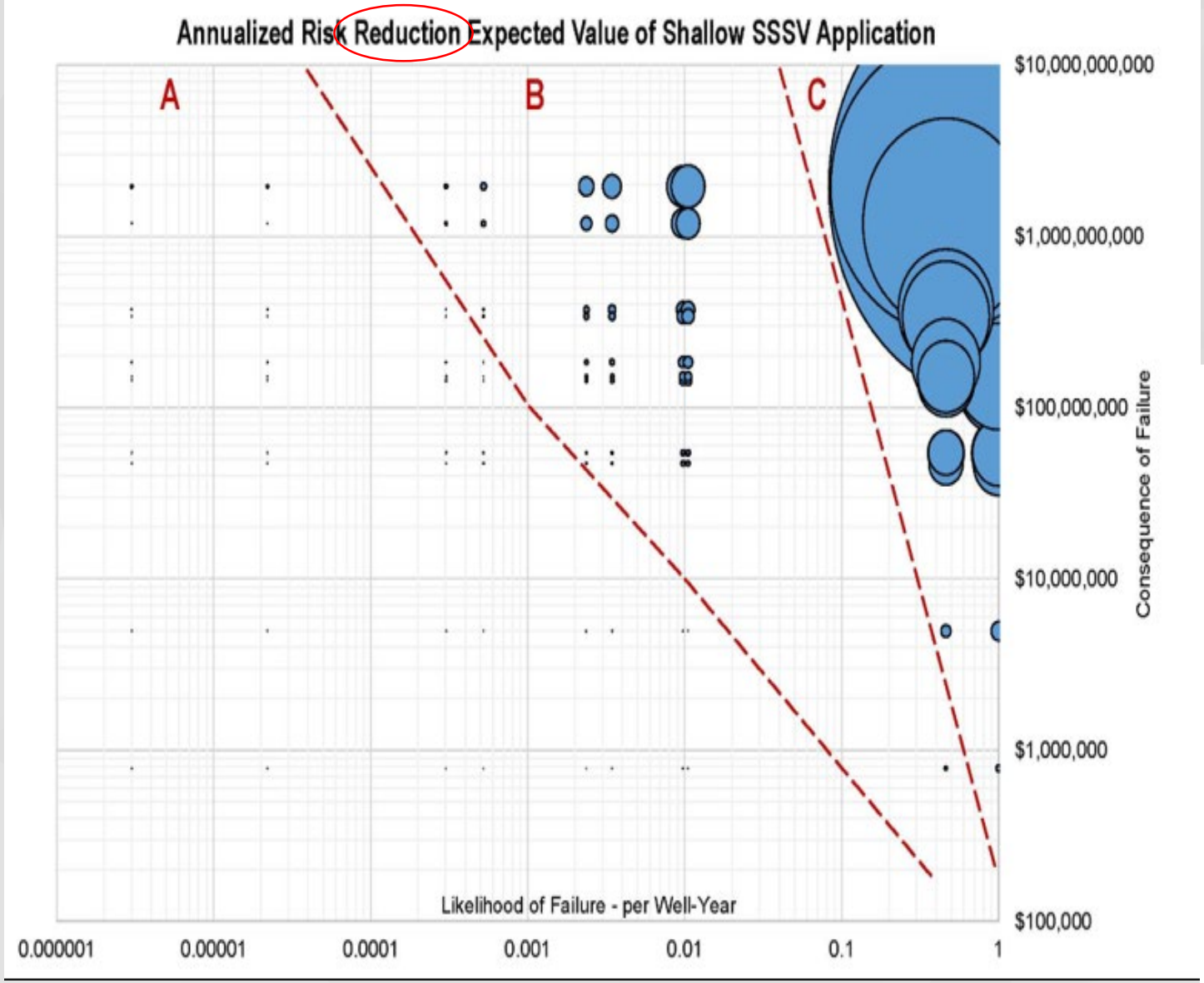
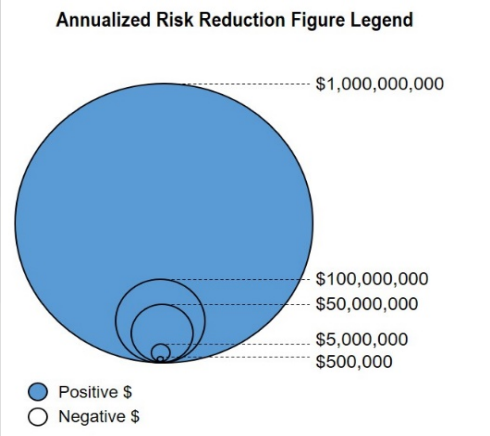
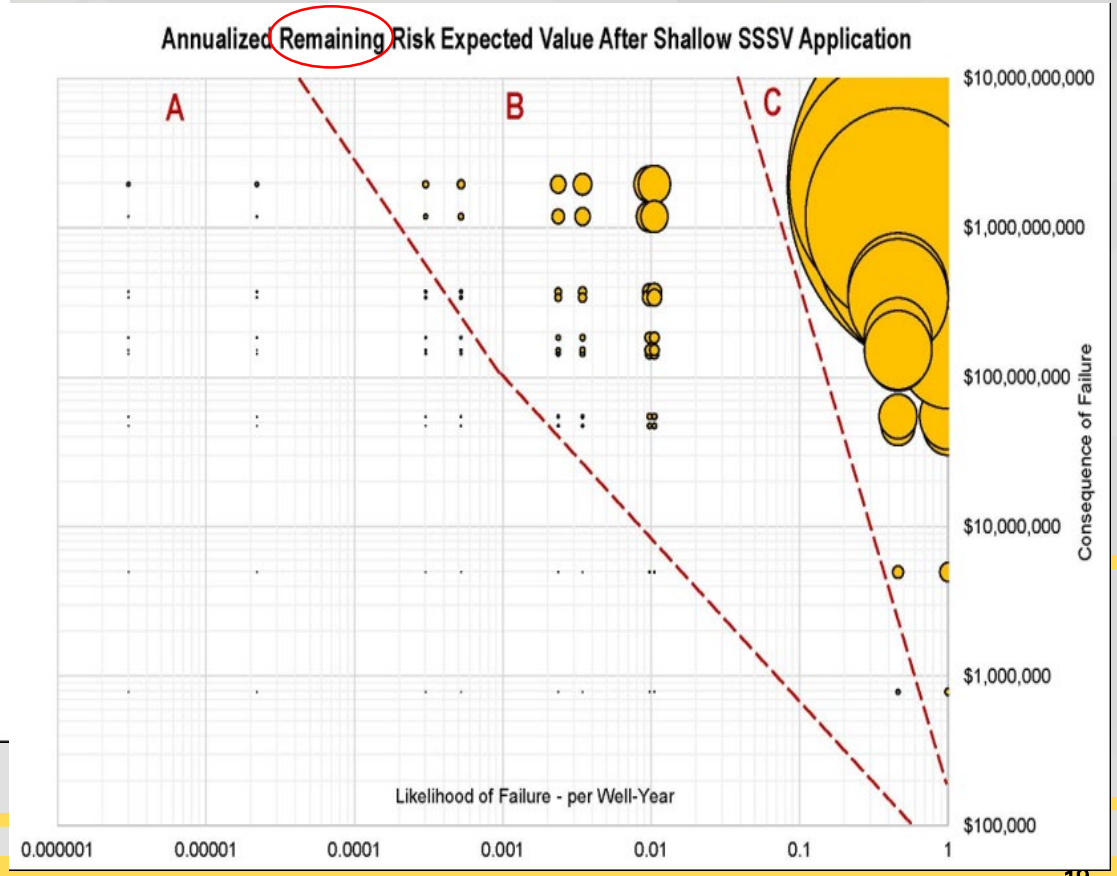
Applicability of SSSV needs to be evaluated on a well-by-well basis



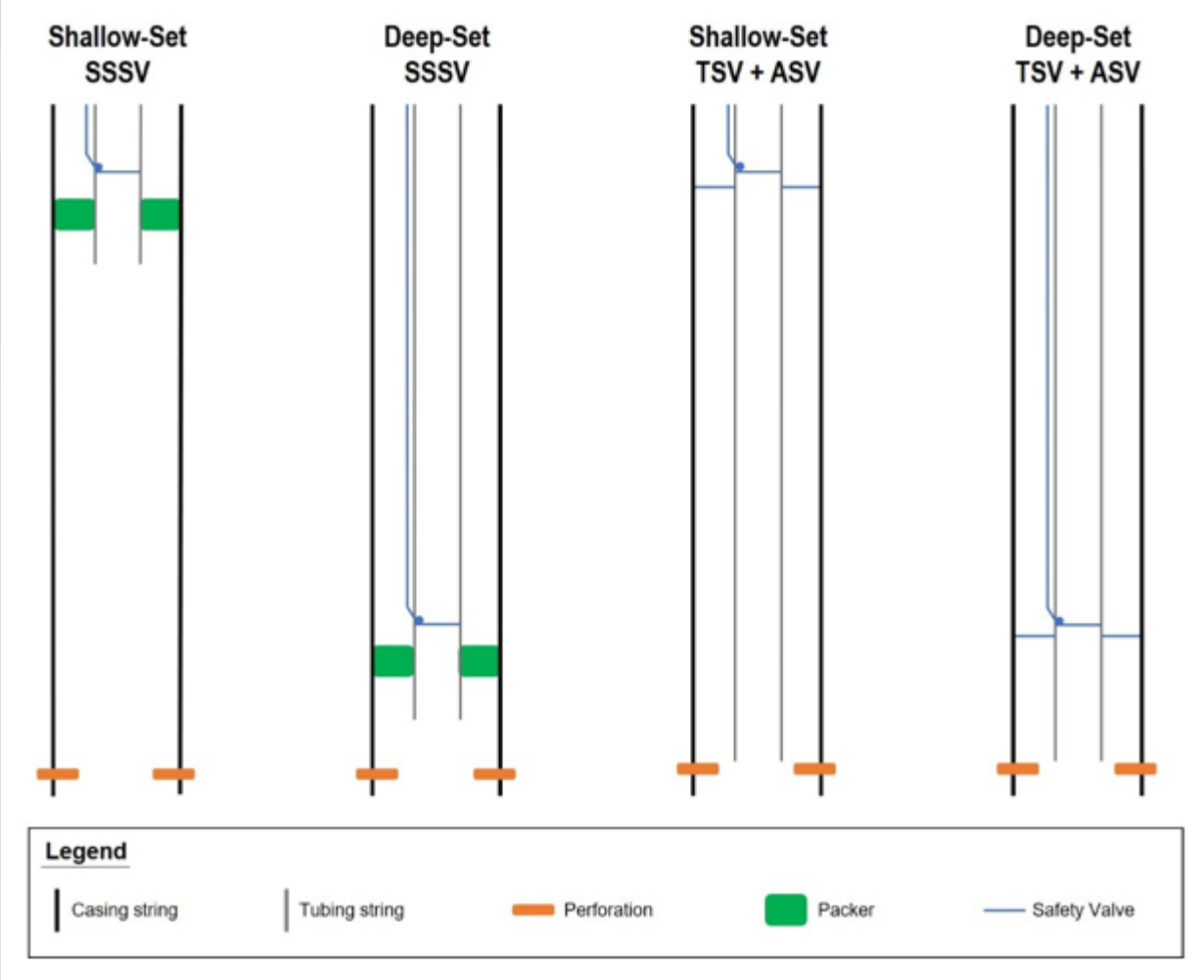




3 Regions of Applicability

Zone	Criteria identifying this zone	Interpretation	SSSV applicable?
A	The annualized risk reduction, estimated by the risk model, less than $10,000 -$40,000 per year, or even negative	Addition of SSSV increases risk or risk reduction in negligible	No
B	Intermediate LOFI and COFI values	Addition of SSSV reduces risk in meaningful or significant ways	Yes, but compare to other possible risk treatments
C	Very high LOFI approaching or exceeding 0.1 per year combined with COFI exceeding ~$10,000,000	Addition of SSSV reduces risk by substantial amounts, but substantial LOFI also remains	Yes, but remaining risk might be too high to tolerate and more immediate risk treatment might be necessary, particularly for reducing LOFI

Configurations used for analysis

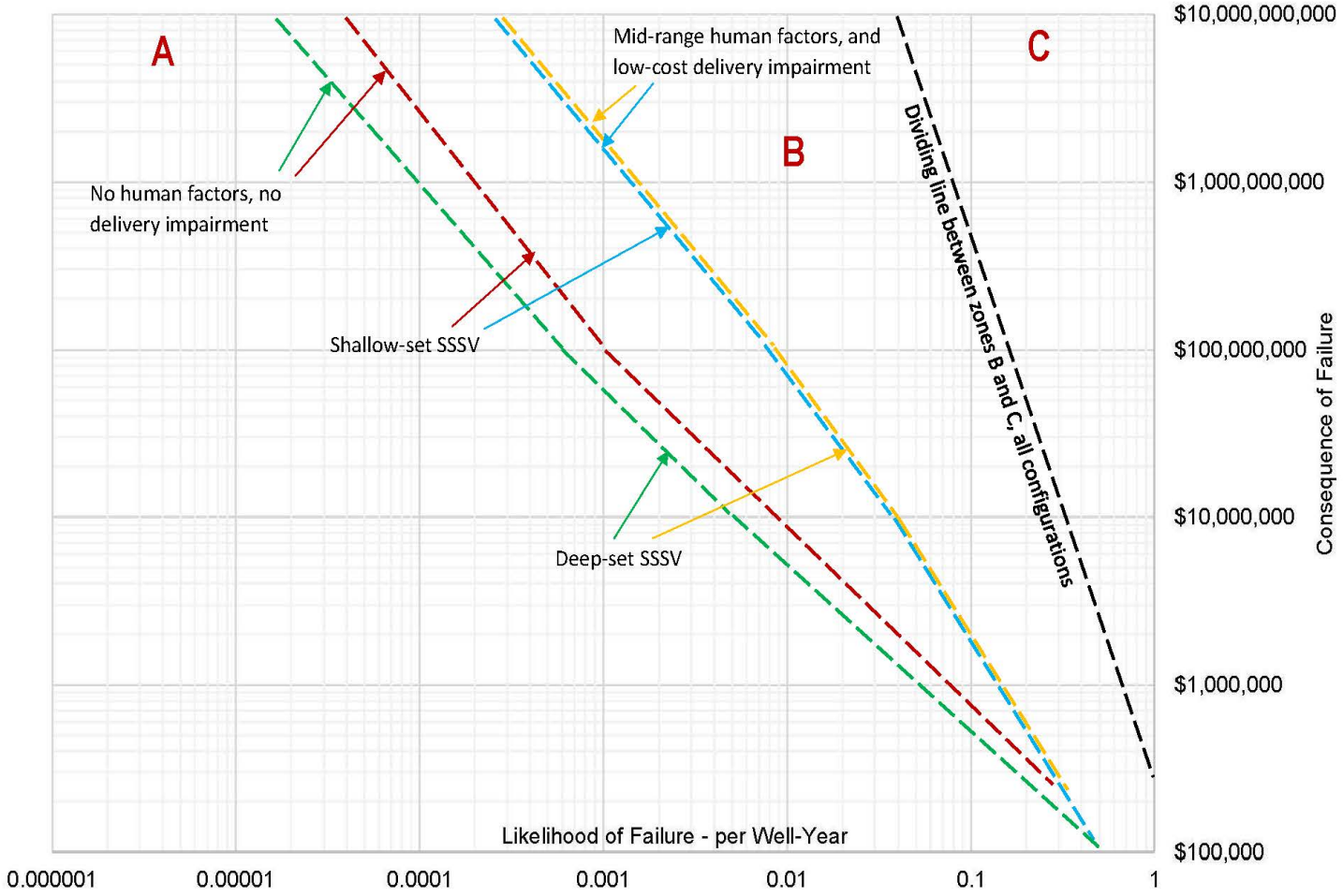


The model was applied to four types of configurations:

- Wells with shallow-set SSSV
- Wells with deep-set SSSV
- Wells with shallow-set TSV + ASV
- Wells with deep-set TSV + ASV

See the final project report for results of these simulations

Effect of human factors, deliverability impairment effects



Human factors:

- "no human factors" = credit (multiplier) of 1 in the LOFI workover equation
- "mid-range human factors" = credit (multiplier) of 15 in the LOFI workover equation

See the final project report for more information about these effects

Knowledge & Technology Transfer

- Battelle/ Sandia organized a 1½ -day workshop in Denver, CO on March 4-5, 2020, attended by ~40 USG reps, PHMSA, and national laboratories.
- Phone conferences with several UGS operators were facilitated by INGAA.
- Interactions with PG&E (PG&E workshop presentation, exchange of preliminary model results).
- Interviews with SSSV experts with extensive hands-on experience with installation and maintenance of SSSVs
- Project deliverables:
  - Final Project Report
  - Excel Implementation of the Model
  - Denver Workshop Presentations
  - Final Information Dissemination Presentation
  - Python Code
  - Journal Article (to be published)

Recommendations

- Application of SSSV might reduce risk in some but not all UGS wells
- Applicability of SSSV in UGS wells should be assessed for each well instead of a broad regulation that mandates the use of SSSV for all UGS wells
- Broader use of quantitative risk models should be encouraged
- Assessment of SSSV applicability in UGS should include effects of workover operations and possible deliverability restrictions
- Standardized data collection and analysis on well barrier element reliability information, including SSSV
- Further research related to effects of human factors and management quality should be carried out with respect to SSSV maintenance, reliability and repair

The results of this project can be obtained from:

- The project deliverables are available from the PHMSA web site: https://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=743
- Journal article outlining the risk model approach and its results will be published, likely in the Journal of Petroleum Science and Technology

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- All participants of the Denver workshop for their input and helpful comments
- PG&E for the workshop presentation and review of the model and its results
- The SME's for participation in the interview
- INGAA for facilitating industry contacts and organizing data transfer
- UGS operators for numerous discussions, comments about our approach, failure data

Q & A

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