Study of SV Application in US Gas Storage - Risk Analysis

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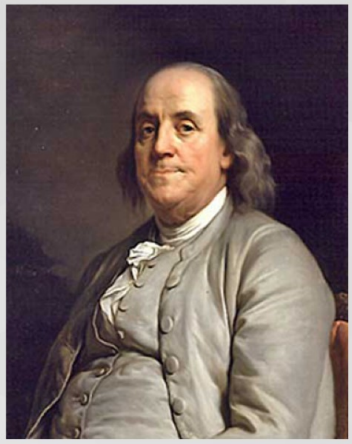
Why is the Study of SV Application a Risk Management Question?



Ben Franklin:
"Those who would give up essential Liberty, to purchase a little temporary Safety, deserve neither Liberty nor Safety"

Paraphrased Merriam-Webster Definition of *liberty*
…the quality or state of being free, to make one's own choices, against physical restraint or arbitrary or despotic control, for the positive enjoyment of rights and privileges…

Wiki discussion:
…liberty involves free will as contrasted with determinism…absence of arbitrary restraints, accounting for the rights of all involved…exercise of liberty is …limited by the rights of others (and) entails the responsible use of freedom under the rule of law…

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Why is the Study of SV Application a Risk Management Question?

Safety
the condition of being protected from or unlikely to cause danger, risk, or injury

How do we measure safety?

Liberty and Responsible Choice:
Being Safe requires love of self and love of others

I do not want the things on which I work to hurt me or others because my work is mine and thus is dignified (all my labors should be an effort of love) – but my work is undignified if it is destructive

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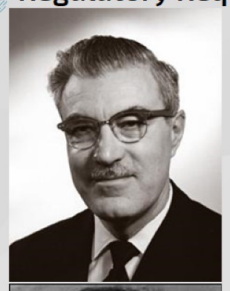
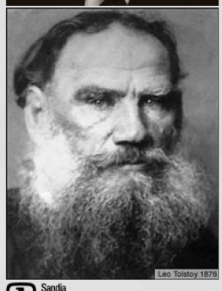
Regulatory Requirements and Decisions Amid Risk





API 1171 Clause 6.2.5

Automatic or remote-actuated emergency shutdown valves (wellhead, side-gate, or subsurface) are not required for most storage wells; however, ***the operator shall evaluate the need for any type of emergency shutdown valve by reviewing the following:***

— distance from dwellings, other buildings intended for human occupancy, or other well-defined outside areas where people assemble such as campgrounds, recreational areas, or playgrounds;
— gas composition, total fluid flow, and maximum flow potential;
— distance between wellheads or between a wellhead and other facilities, and access availability for drilling and service rigs and emergency services;
— added risks created by installation and servicing requirements of safety valves;
— risk to and from the well related to roadways, rights of way, railways, airports, and industrial facilities;
— alternative protection measures that could be afforded by barricades or distance or other measures; and
— present and predicted development of the surrounding area, topography, and regional drainage systems and environmental considerations.

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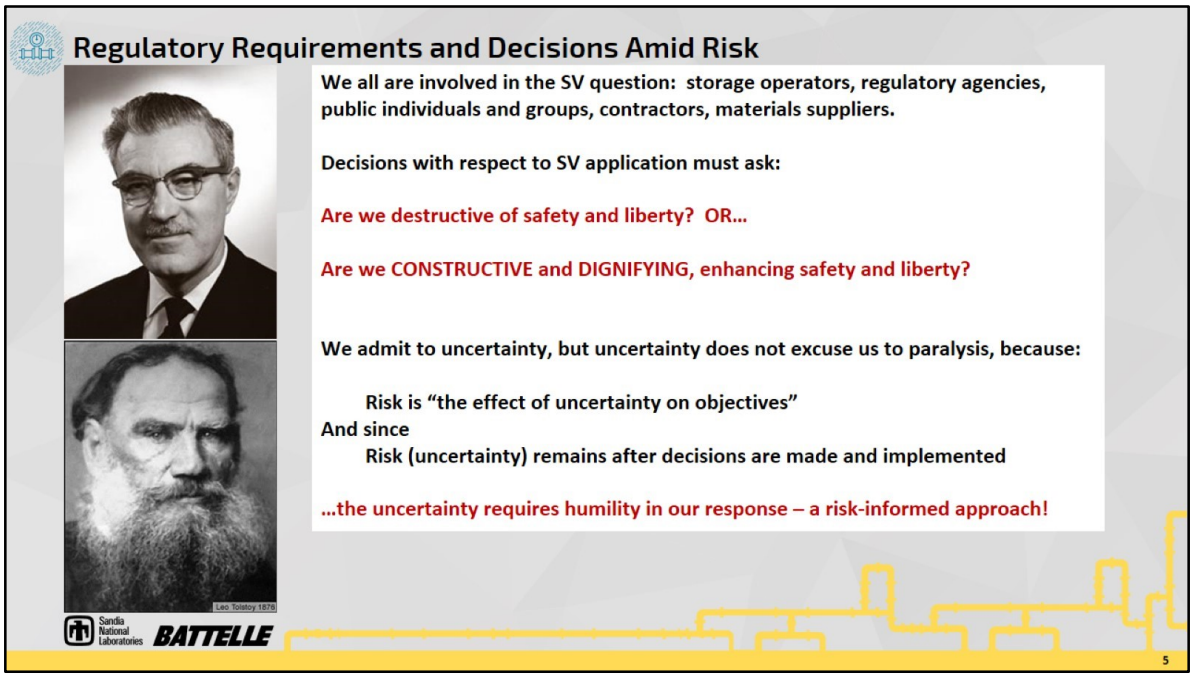
If you are here today thinking “no well ever needs a SV”, I would wonder why you came. Likewise, if you are here thinking “all or most wells should have a SV”, I wonder why you came. The application of SV is properly a risk-informed decision.

We should approach risk-informed decisions with humility. Tolstoy: We can know only that we know nothing. And that is the highest degree of human wisdom. Proverbs 11:2 says: “When pride comes, then comes disgrace, but with humility comes wisdom”. So, humility is freedom from pride or arrogance, the state of being humble.

For this we need to ask about what we can know, what we can see as “truth”, but that the truth is like an onion, as Tolstoy said – we need to peel that onion layer-by layer to get closer to the truth and test our assumptions about the truth. We need the qualities of Dr. Katz – distinguish the trivial from the important, and lead with vigor, energy, imagination, and insight in solving problems.



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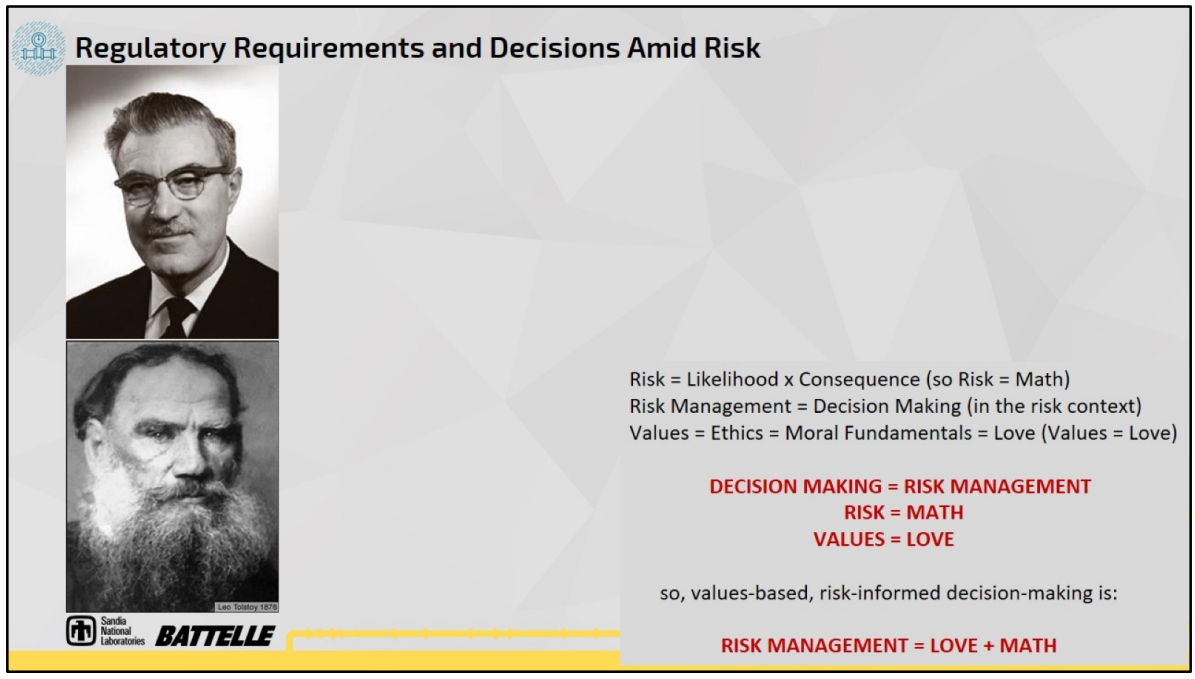

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In order to move forward with the approach to the SV question, we want to use a methodology, as Slawek already presented, that had certain advantageous aspects. These advantages include:

- Use of data – failure rates, quantitative aspects of barrier information, and consequence forms set to equalized quantitative scales (such as USD)
- Comprehensive likelihood and consequence analysis so the human mind cannot easily know the outcomes – to focus on data inputs and not subjectively on outcomes, let the outcomes surprise us - that in itself can be a test of bias reduction properties
- Focus on knowable unknowns – operators must be able to gather the information relative to likelihood and consequence and not be subject to untestable or unverifiable aspects
- Rather than weightings, the model must use systems that have reference points backing up values related to safety, environment, or other values aspects.
- To monitor and manage bias, the model must explicitly emphasize values aspects in the risk equation. Emphasis on data and usable sources of data limit bias by focusing on vetted information rather than untestable anecdotes. Power-law use in the model also acts to limit bias by emphasizing the issues of scalability or non-scalability of consequence outcomes.
- Ability to range uncertainty and test sensitivity to specific variables in the analysis as well as in comparison of risk treatment alternatives – must be able to compare the cost/benefit of alternatives and identify benefit with respect to safety, environmental stewardship, service reliability, and financial stewardship, or other aspects.
- Gives a range showing acceptability or non-acceptability and identify differences even when inside a wide “tolerable risk” region; give realization to risk reduction as well as risk remaining.

SSSV Risk Change Study – The Path Followed

Create Well Type Cases
- *Range Likelihood of Failure Potential*

Create Consequence Environment Cases
- *Range Consequence Potential*

Safety Focus
- *also Environment, Service Reliability, Financials*

Broad Use of O&G/Storage Industry Information

Consistent Application of Risk Model
- *Adaptive to Question Variations*

Results as Directional Guidance vs. Deterministic Outcome

Emphasize:
- *Risk Evaluation, Treatment Alternatives Analysis*
- *Risk Remains after Treatment*

Collaboration Needed for WBE Reliability Information

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So our slides include a review of the hypothetical case studies, creating "well types" and ranging some of the properties of those well types for time dependent and time independent variables to provide a range of likelihood of failure over 6 orders of magnitude, then creating consequence environment cases focused on population proximity and density to provide close-in as well as widespread ranges that could be affected by storage well failure in the surface or subsurface.

The analysis accounts distinctly for safety, environmental values (air, water, land use, soil stability and productivity), and service-reliability-financial aspects.
We will show, briefly, how industry information was brought into the analysis to provide vetted ranges of parameters used in the analysis. We can provide references, if you desire.

We adapted the risk equations to the variations around the question: wells without SV, with SV, w/ shallow- or deep-set SV, w/ and w/o workover, and w/ or w/o additional human factors issues.
We focused the outcomes of the analysis on the **annualized expected risk reduction value.** Actual cost/benefit in any given well situation must be determined by the operator, since the life cycle cost for installation and maintenance of any SV system is site specific and application specific.

We emphasize that SV application is only one risk treatment alternative. Operators should compare risk treatment alternatives. Risk remains after treatment – so the need manage integrity is always there. Last, to advance learning, we must collaborate on reliability engineering data warehousing and analysis.

SV Risk Change

Assumptions – Risk Reduction

1. SV = consequence mitigation device
2. SV placement (shallow, deep), mechanical component and general reliability affect risk reduction
   a. Shuts off event occurring downstream w/ enough dp or dQ to actuate system
   b. Shuts off event IF system functions as intended:
      1. Control system
      2. Mechanical valve operation
      3. Solids buildup
      4. Valve wear/erosion

Assumptions – Risk Increase

1. SV type and re-entry frequency affect risk due to potential for loss of containment while servicing. All/most re-entries become more complex. Might affect deliverability-reliability
2. Human/org factors risk increase: SV system increases life-cycle monitoring, maintenance, and re-entry complexity – requires knowledge, skills, experience, process safety management system

Diagram from ISO 16530-1, Annex E

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Annex E
(informative)

Example of possible well leak paths

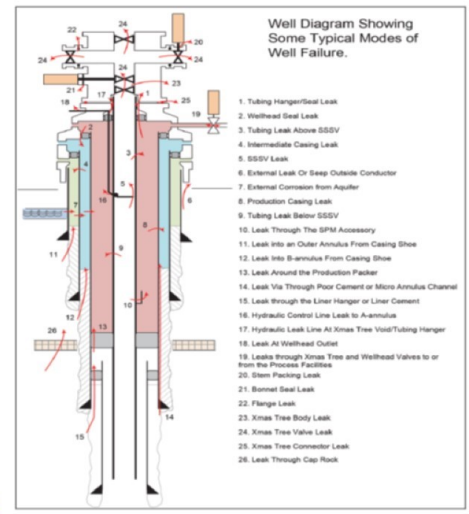
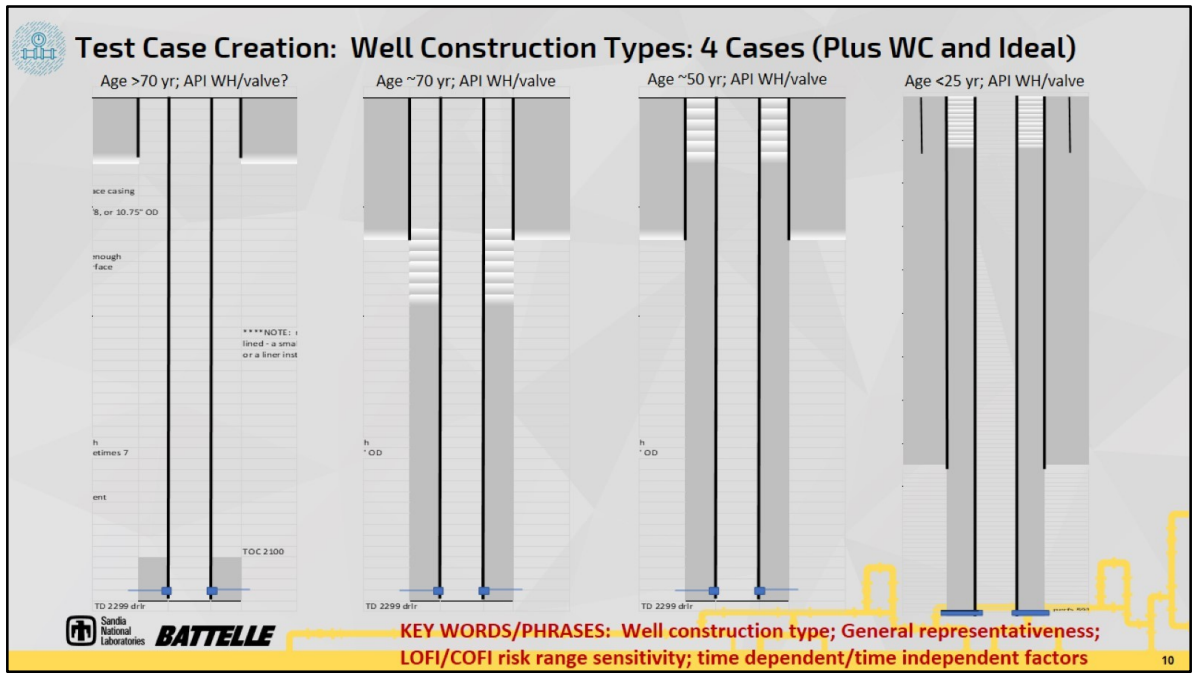


Figure E.1 — Well diagram showing some typical modes of well failure via leakage

The efficacy of downhole safety valves with respect to net risk change should be carefully evaluated to determine if guidance can be provided for prudent application, understanding risk reduced and risk remaining with or without safety valve implementation

We hope to show, by way of example models that represent a wide range of probable actual well types and consequence potentials, that the net risk change can be satisfactorily modeled with the “JITF Risk Model”.

SV are consequence mitigation devices. Their effectiveness varies depending on total risk, their setting location (depth) and functional reliability.
SV can come with risk increase: more parts that have reliability issues, more potential well re-entry, more impacts to reliability due to “safe failures”.



Approach

1. Classified Well Construction Types into Four (4) Groups: old converted well, old storage well, mid-age storage well, newer storage well (see diagrams for general model well profiles)

To these four well types, we also had book-ends of a “problem well” at failure or about to fail, and an “ideal well” with very robust construction and little chance for failure

LOFI Ranges by Well Construction Type

Well types, w/book-end "problem" well at/near failure and an "ideal" well, give LOFI range over six orders of magnitude

Well Type	Generic Failure Frequency (failure/well-year)	Corrosion Rate Ranged (mm/yr)	Adjustment for Class 3 and 4 Joints	DfWork	DfImpact	Fwhv	Fcmt	Minimum LOFI (failure/well-yr)	Maximum LOFI (failure/well-yr)
Well Type Case 1	0.000100	.018 - .045	1.6	5	2	0 - 100	90 - 4500	0.009742	0.461212
Well Type Case 2	0.000067	.018 - .045	1.2	3	2	0	30 - 150	0.002363	0.010505
Well Type Case 3	0.000033	.018 - .045	1.02 - 1.2	2	2	0	5 - 100	0.000302	0.003446
Well Type Case 4	0.000010	.018 - .045	1 - 1.2	2	2	0	0.1 - 50	0.000022	0.000523
Ideal Well	0.000010							0.000003	0.000003
Problem Well	0.000100							1.000000	1.000000

Assumed all casing 5.5" OD 15.5 ppf J/K-55 and assumed max pressure of 2000 psi.

Corrosion rate, cement/annular flow condition, and non-API materials are biggest drivers in LOFI.

NOTE: site specific conditions w/internal corrosion/erosion potential, outside impacts/natural forces, could drive LOFI to higher levels. This analysis set such parameters to mid- or minimal levels on a uniform basis for all cases.

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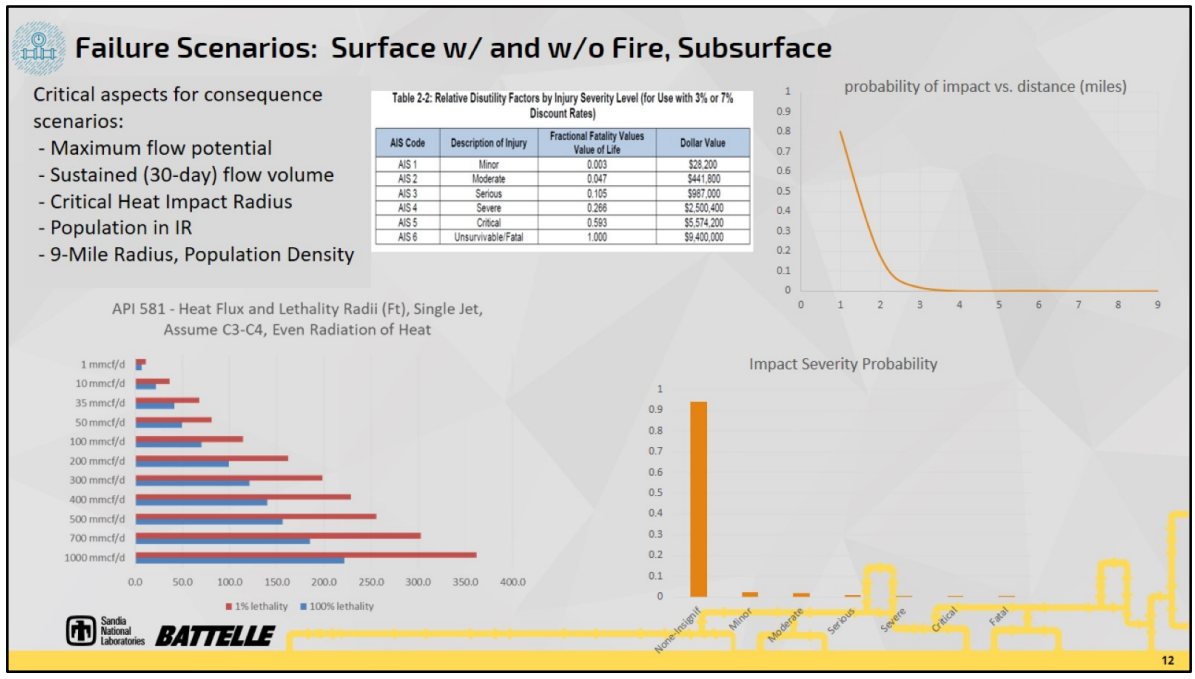
2. Estimated ranges of Likelihood of Failure Index (LOFI) for each well type: standardized on casing diameter, weight, grade and max reservoir pressure; ranged corrosion rate, annular contents/flow conditions, and wellhead/valve condition; held most other factors (such as vibration, flow composition, outside forces, etc.) to common mid- or minimum values

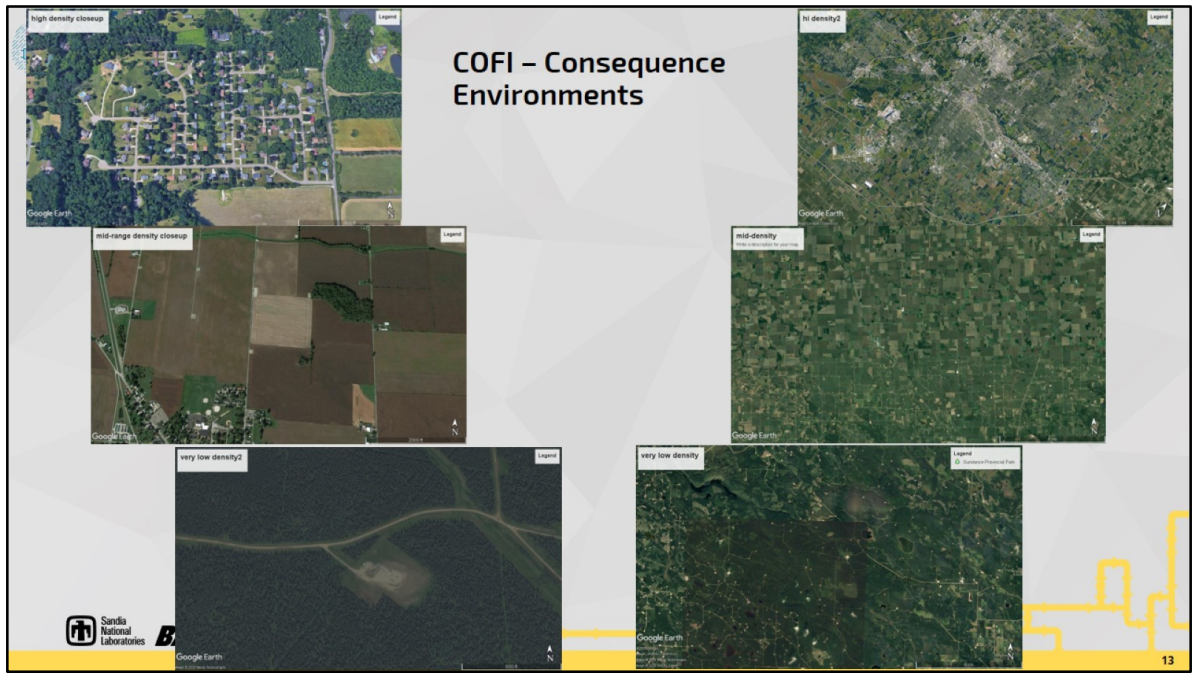
Here we see some of the variations in starting "generic failure frequency", corrosion rate and corrosion extensiveness, amount of well work, and wellhead/valves and cement.

We were able to create a range of LOFI over 6 orders of magnitude. These six well types were run with consequence environment cases to generate risk profiles.



The Battelle-Sandia adapted JITF model COFI analysis looks at failure scenarios at the surface (blowout w/ and w/o fire, occurring at maximum pressure/flow conditions) and a full failure in the subsurface, for up to 30-days duration.

The model accounts for critical heat impact radius, injury equivalent consequence, and probability-severity ranging with distance and with event. Distributions are generally adapted from accident severity statistics in transportation industries, but particularly the gas pipeline industry. Storage industry efforts were used in ranging the impact probability vs. distance.



3. We estimated range of consequences for any set of events depending on overall setting, including proximal population, 9-mi radius population density, flow capability and 30-day feed volume; set other consequence factors (environmental, service, reliability, financial) to index off the safety consequence assessment. We created three sets of consequence environments that mixed population densities with well capabilities in terms of AOF and 30-day feed volume potential.

Here is an example of population density variations, both in close 1000-200' radius view and 6-mile radius view. Note that mid-range densities can be complex, with no population immediately in the vicinity of the well but with greater population within a wider radius. Somewhat book-ending the mid-range density (which is closer to true for many storage fields) is the high density case at the top and the very low density case at the bottom.

COFI Cases

				COFI Estimate	% Safety + Environmental	% Subsurface
BASE	v. high rate well	high feed volume	high population density, even distribution	$1,954,711,323	83	73
	modest rate well	moderate feed volume	moderate population density, even distribution	$54,352,517	34	54
	low rate well	low feed volume	low population density, even distribution	$4,964,519	22	56
	very low rate well	minimal feed volume	very low population density, even distribution	$784,822	9	52
INVERTED	low rate well	moderate feed volume	high population density, even distribution	$1,188,331,148	87	92
	low rate well	moderate feed volume	moderate population density, even distribution	$47,267,387	38	55
	v. high rate well	high feed volume	low population density, even distribution	$143,642,850	20	51
	v. high rate well	high feed volume	very low population density, even distribution	$54,657,799	8	51
MIXED	high rate well	high feed volume	wider pop density moderately high, nearby pop density low	$373,530,042	48	64
	high rate well	high feed volume	wider pop density moderately high, nearby pop density nil	$341,217,972	43	70
	high rate well	high feed volume	wider pop density moderate, nearby pop density low	$184,141,112	37	48
	high rate well	high feed volume	wider pop density moderate, nearby pop density nil	$151,829,042	24	58

Safety consequence declines as a percentage of the total consequence as COFI tier severity decreases. Subsurface event percentages are a substantial portion of the total as a wide area could be impacted

**In high consequence cases, financial costs might exceed safety costs; JITF model prioritizes safety consequence emphasis

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The model estimates consequences in equivalent units – US Dollars. The COFI drivers include well AOF, feed volume available, population within heat impact radius, and population density in widespread radius (important primarily during long-duration events). We were able to range consequence cases across 5 orders of magnitude.

Note that the model is able to distinguish that safety and environmental consequences are a much higher proportion of total consequences in higher population densities; this might not be the actual outcome in real events, but this shows that the model is emphasizing the safety value aspect by giving it a certain pre-eminence in the consequence analysis.

Certain environmental factors and service/reliability/financial factors could be important in specific sites, but for this analysis we assumed all things were equal in those aspects except where affected by the well rate, feed volume, and potentially affected population – in each of the 4 consequence tiers, there is a general order of magnitude shift in those consequence factors among the tiers.

The COFI analysis produced a set of base conditions – high population with high well rate and feed, low with low, etc.; inverted cases where we inverted well potential vs. population density, and mixed cases where we used high rate and feed wells across variable mid-range population density.

SV Reliability and Risk Change Assumptions (ISO 16530 Table)

Surface-controlled sub-surface safety valve (SCSSV)	Safety valve device installed in the production tubing string that is held open, usually by the application of hydraulic pressure in a control line. If there is loss of control-line hydraulic pressure, the device is designed to close automatically	Lack of control line communication and functional control Leaking above acceptance criteria Failure to close on demand Failure to close within the acceptable closing time

SSSV decreases consequences:

- of surface releases, by the reliability value, R, of the SSSV
- of subsurface releases, by R, but varies shallow vs. deep set

- of environmental consequences: shallow-set: air impacts reduced by reliability of SSSV, toxins by 50%, soil, vegetation and water effects not reduced; for deep-set, all reduced by R

- assumed ~50% (shallow), 100% (deep) mitigation of financial/service/reliability consequences, multiplied by R

Compared COFI w/ and w/o SSSV for both shallow and deep-set SV and isolated on safety; safety + environmental; and total consequence reductions

From industry and world data, *functional reliability of SV (perform on demand, critical failures, safe failures, partial closures), per year*

Range	shallow-set R	deep-set R
v. low	.60	.36
low	.80	.67
mid	.905	.84
high	.985	.94

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When we modified the equations for use of safety valve, we assumed that risk of certain events would be reduced by the functional reliability of the SV – in other words, to close effectively on demand. SV functionality could be impaired due to some of the aspects identified in this table from ISO 16530 Well Integrity.

In the surface release w/fire routine – directly used the reliability value to estimate reduced consequences; subsurface release routine, used 50% of the consequence multiplied by reliability value to estimate consequence reduction

Workover Risk Due to SV Reliability and Increased Complexity of All Re-entry Workovers (Max Workover Risk Approach)

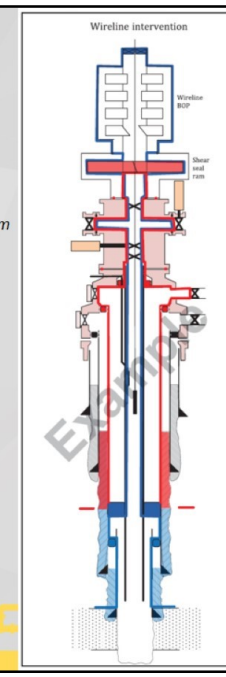
$$LOFI_{workover} = Frequency_{workover} \times FailureRate_{workover} \times Credit_2$$

Frequencyworkover is the net increase of workover frequency due to SSSV application
FailureRateworkover is the failure rate during workover operations
Credit2 is the management systems credit accounting for human and organizational factors.

ISO 16530 Intervention Barrier Diagram

	Frequency-workover: Critical - Re-entry Rate, per year	Failure Rate-workover: LOC chance, per entry	Mgmt System Factor ("Credit2")
High	0.5	0.00040	5
Mid	0.13	0.00015	1
Low	0.05	0.00010	0.5
Very Low	0.015	0.00007	0.1

- estimated COFI for a workover event (focused on surface release, fire)
- get "expected annual risk (in USD) due to workover" ranges (before mgmt system factor) from LOFImax x COFImax (~$50,000/yr) and LOFImin x COFImin (~$35/yr)
- Most of COFI for workover LOC events is human safety (on site workers)
- Human factors management, or lack thereof, can impact this risk (mgmt. system factor)



We looked at this two ways: assumption that critical failures requiring well re-entry are less than the total functional reliability failures applied to the "operating well" COFI analysis, and estimated risk of net additional well re-entry due to SV reliability issues. Then we also assumed all re-entries are more complex and increase human factors risk of each re-entry – and that the reliability rate dictates additional re-entry frequency.

We ranged loss of containment (LOC) due to loss of well control during entry, and for tubing-conveyed systems (higher rate) vs. wireline-conveyed systems (lower rate), and looked at higher rate as in drilling LOC. Then we assessed COFI for a LOC event during workover for each consequence case, same as base COFI analysis and other COFI examples. This provided an annualized expected risk.

We have a 'credit' in the LOFI and COFI workover equations for safety management system maturity and effectiveness as applicable during well intervention (measured operational discipline). We suggest that human factors issues might range the LOFI-COFIworkover impact by one-half to one order of magnitude. Here, we estimate that significant human factors risk increases LOFI-COFI workover risk by roughly 5 times over similar workovers without SSSV removal and reinsertion.

COFI Cases (Shallow-Set SSSV Example)

				COFI Estimate	Residual Consequences W/SSSV (highest reliability)	Residual Consequences of Surface Events Only - w/ SSSV	Residual Consequences of Subsurface Events - w/ SSV	Workover LOC Consequences
BASE	v. high rate well	high feed volume	high population density, even distribution	$1,954,711,323	$832,036,581	$17,096,570	$814,940,012	$493,713,130
	modest rate well	moderate feed volume	moderate population density, even distribution	$54,352,517	$24,772,092	$450,463	$24,321,629	$50,877,626
	low rate well	low feed volume	low population density, even distribution	$4,964,519	$2,411,838	$38,873	$2,372,965	$33,816,194
	very low rate well	minimal feed volume	very low population density, even distribution	$784,822	$390,716	$6,002	$384,714	$32,574,244
INVERTED	low rate well	moderate feed volume	high population density, even distribution	$1,188,331,148	$603,389,746	$8,907,737	$594,482,009	$105,759,813
	low rate well	moderate feed volume	moderate population density, even distribution	$47,267,387	$21,166,110	$397,481	$20,768,629	$48,669,513
	v. high rate well	high feed volume	low population density, even distribution	$143,642,850	$72,806,994	$1,078,719	$71,728,275	$78,658,030
	v. high rate well	high feed volume	very low population density, even distribution	$54,657,799	$26,687,725	$425,940	$26,261,785	$49,339,360
MIXED	high rate well	high feed volume	wider pop density moderately high, nearby pop density low	$373,530,042	$178,484,242	$2,970,241	$175,514,001	$130,843,504
	high rate well	high feed volume	wider pop density moderately high, nearby pop density nil	$341,217,972	$177,999,561	$2,485,560	$175,514,001	$98,531,434
	high rate well	high feed volume	wider pop density moderate, nearby pop density low	$184,141,112	$82,369,360	$1,549,824	$80,819,536	$105,103,504
	high rate well	high feed volume	wider pop density moderate, nearby pop density nil	$151,829,042	$81,884,679	$1,065,143	$80,819,536	$72,791,434

Overall consequence reduction with a SSSV ranges from 43-59%. Surface event w/fire consequence reduction with a SSSV is in the range of 87-99+%. All surface events consequence reduction with a SSSV is in the range of 82-99%. Subsurface event consequences are, of course, persistent

Workover COFI: safety consequences dominate – BASE CASES example below - a little over 75% in intermediate to high consequence cases to 96%-99% in the low and minimum consequence cases, basing out at a persistent level due to the issue of worker safety – they are directly in harm's way.

Safety	$381,435,000	$38,790,000	$32,518,950	$32,337,930
Environmental	$3,972,130	$194,426	$14,864	$1,486
Financial	$108,306,000	$11,893,200	$1,282,380	$234,828
Estimate - Surface LC	**$493,713,130**	**$50,877,626**	**$33,816,194**	**$32,574,244**

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Now, when we go back and re-estimate COFI for the four consequence types including the assumption of SV presence and a 3-tiered range of SV reliability (.8 - .905 - .985), we are able to see how consequence changes. In this example we are showing COFI cases for shallow-set SV.

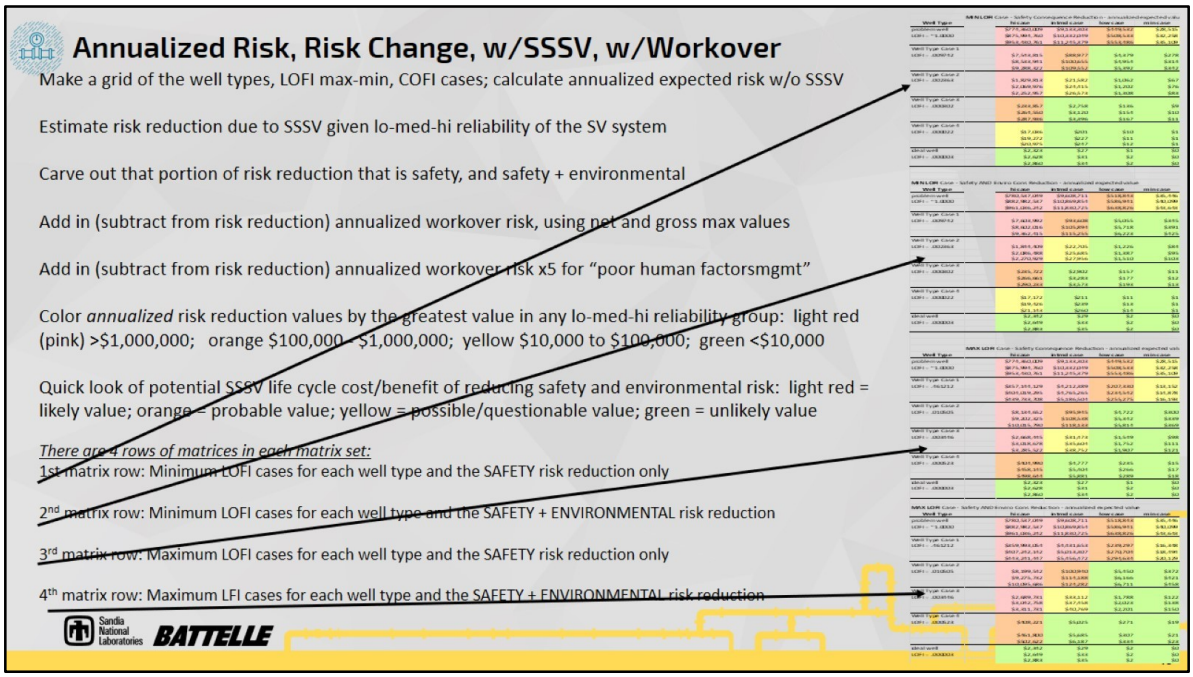
a. COFI safety-surface much reduced, certain environmental factors (GHG) reduced;

b. SV subsurface reduced only by ~50%, w/ additional SV reliability adjustment (the JITF routine for subsurface includes two scenario subtypes – a subsurface release and an extended surface release; the SV will reduce the risk of an extended surface release but not affect the subsurface release consequence assessment)

c. Environmental factors of soil stability and productivity, vegetation health, groundwater and surface water effects not reduced, pollutants/toxicity reduced by ~50% w/ SV reliability adjustment

c. service, reliability, financial consequences reduced by ~50% (w/SV reliability adjustment)

Note that Workover COFI shows how safety consequences dominate across all consequence environments, especially in low population densities, because we now have a number of people on site during well work.



Now, we can work the math of risk analysis and create matrices of outcomes for our six well types, the three sets of consequence cases, and range within each type by a range of safety valve reliability.

The result provides a matrix of LOFI ranges for each well type and COFI ranges for four consequence types. Applying the JITF COFI estimates for each consequence type to the JITF LOFI for each well type, we get a swath of risk representing the probable vast majority of actual well cases in existence. We show here the risk reduction value in terms of annualized expected risk reduction in USD. We should remember:

a. the cases used are hypothetical but meant to represent a wide range of possible outcomes to LOFI and COFI

b. the LOFI and COFI estimates in this study are just that – estimates!

There is a lot of output from running all these cases, but we felt we could best illustrate this by coloring the matrices. Also, when we show the full grid of matrices, we need to explain the ordering of rows and columns within each set of matrices.

Annualized Risk, Risk Change, w/SSSV, w/Workover

Well Type	MIN LOFI Case - Safety Consequence Reduction - annualized expected value				W/Max annual net workover risk (subtract from risk reduction)				w/ Max annualized WO risk for all reentries				w/Max WO risk all reentries plus poor human/org factors			
	hi case	intmd case	low case	min case	$9,874	$1,018	$676	$651	$49,371	$5,088	$3,382	$3,257	$246,857	$25,439	$16,908	$16,287
problem well	$774,360,009	$9,133,303	$449,532	$28,515	$774,350,135	$9,132,285	$448,856	$27,864	$774,310,638	$9,128,215	$446,150	$25,258	$774,113,153	$9,107,864	$432,624	$12,228
LOFI = ~1.0000	$875,994,760	$10,332,049	$508,533	$32,258	$875,984,886	$10,331,031	$507,857	$31,606	$875,945,389	$10,326,961	$505,152	$29,000	$875,747,904	$10,306,610	$491,625	$15,971
	$953,430,761	$11,245,379	$553,486	$35,109	$953,420,887	$11,244,362	$552,810	$34,458	$953,381,390	$11,240,291	$550,105	$31,852	$953,183,905	$11,219,940	$536,578	$18,822
Well Type Case 1																
LOFI = .009742	$7,543,815	$88,977	$4,379	$278	$7,533,941	$87,959	$3,703	-$374	$7,494,444	$83,889	$998	-$2,980	$7,296,959	$63,538	-$12,529	-$16,009
	$8,533,941	$100,655	$4,954	$314	$8,524,067	$99,637	$4,278	-$337	$8,484,570	$95,567	$1,573	-$2,943	$8,287,084	$75,216	-$11,954	-$15,973
	$9,288,322	$109,552	$5,392	$342	$9,278,448	$108,535	$4,716	-$309	$9,238,951	$104,465	$2,010	-$2,915	$9,041,466	$84,114	-$11,516	-$15,945
Well Type Case 2																
LOFI = .002363	$1,829,813	$21,582	$1,062	$67	$1,819,938	$20,564	$386	-$584	$1,780,441	$16,494	-$2,319	-$3,190	$1,582,956	-$3,857	-$15,846	-$16,220
	$2,069,976	$24,415	$1,202	$76	$2,060,101	$23,397	$525	-$575	$2,020,604	$19,327	-$2,180	-$3,181	$1,823,119	-$1,024	-$15,706	-$16,211
	$2,252,957	$26,573	$1,308	$83	$2,243,083	$25,555	$632	-$569	$2,203,586	$21,485	-$2,074	-$3,174	$2,006,100	$1,134	-$15,600	-$16,204
Well Type Case 3																
LOFI = .000302	$233,857	$2,758	$136	$9	$223,982	$1,741	-$541	-$643	$184,485	-$2,330	-$3,246	-$3,249	-$13,000	-$22,681	-$16,772	-$16,279
	$264,550	$3,120	$154	$10	$254,676	$2,103	-$523	-$642	$215,179	-$1,967	-$3,228	-$3,248	$17,694	-$22,319	-$16,755	-$16,277
	$287,936	$3,396	$167	$11	$278,062	$2,379	-$509	-$641	$238,565	-$1,692	-$3,214	-$3,247	$41,080	-$22,043	-$16,741	-$16,277
Well Type Case 4																
LOFI = .000022	$17,036	$201	$10	$1	$7,162	-$817	-$666	-$651	-$32,335	-$4,887	-$3,372	-$3,257	-$229,821	-$25,238	-$16,898	-$16,286
	$19,272	$227	$11	$1	$9,398	-$790	-$665	-$651	-$30,099	-$4,860	-$3,370	-$3,257	-$227,585	-$25,212	-$16,897	-$16,286
	$20,975	$247	$12	$1	$11,101	-$770	-$664	-$651	-$28,396	-$4,840	-$3,369	-$3,257	-$225,881	-$25,191	-$16,896	-$16,286
ideal well	$2,649	$27	$1	$0	-$7,351	-$990	-$675	-$651	-$47,046	-$5,060	-$3,380	-$3,257	-$244,531	-$25,411	-$16,907	-$16,287
LOFI = .000003	$2,628	$31	$2	$0	-$7,246	-$987	-$675	-$651	-$46,743	-$5,057	-$3,380	-$3,257	-$244,228	-$25,408	-$16,907	-$16,287
	$2,860	$34	$2	$0	-$7,014	-$984	-$675	-$651	-$46,511	-$5,054	-$3,380	-$3,257	-$243,996	-$25,405	-$16,906	-$16,287

In each of the three matrix sets:

1st column of matrices: net risk change with SSSV, by well type and by SSSV functional reliability (lo-med-hi), expressed as a positive value in USD.

2nd column of matrices: net risk change (in the 1st column of matrices) reduced by net workover increase max workover LOC annualized risk.

3rd column of matrices: net risk change (in the 1st column of matrices) reduced by workover LOC annualized risk for all workovers due to job complexity increase w/downhole SV.

4th column of matrices: net risk change (in the1st column of matrices) reduced by a 5-fold increase in max-max workover LOC risk.

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Three sets of matrices (each is a “matrix set”) were produced for each set of consequences: Base Cases, Inverted Cases, Mixed Cases, as previously described. Each of six well types is run for its minimum and maximum LOFI against 4 consequence types for the matrix set.

Est. Annualized Risk Change w/ SSSV (Shallow Set): What do we see?

BASE

Safety Portion				
low Rel	0.849	0.380	0.217	0.089
mid Rel	0.849	0.380	0.217	0.089
hi Rel	0.849	0.380	0.217	0.089
Environmental Portion				
low Rel	0.007	0.020	0.033	0.022
mid Rel	0.007	0.020	0.033	0.022
hi Rel	0.007	0.020	0.033	0.022
Service/Financial/Reliability Portion				
low Rel	0.144	0.600	0.750	0.889
mid Rel	0.144	0.600	0.750	0.889
hi Rel	0.144	0.600	0.750	0.889

INVERTED

Safety Portion				
low Rel	0.866	0.431	0.098	0.002
mid Rel	0.866	0.431	0.098	0.002
hi Rel	0.866	0.431	0.098	0.002
Environmental Portion				
low Rel	0.001	0.012	0.107	0.113
mid Rel	0.001	0.012	0.107	0.113
hi Rel	0.001	0.012	0.107	0.113
Service/Financial/Reliability Portion				
low Rel	0.132	0.557	0.794	0.884
mid Rel	0.132	0.557	0.794	0.884
hi Rel	0.132	0.557	0.794	0.884

MIXED

Safety Portion				
low Rel	0.476	0.374	0.373	0.087
mid Rel	0.476	0.374	0.373	0.087
hi Rel	0.476	0.374	0.373	0.087
Environmental Portion				
low Rel	0.036	0.043	0.069	0.101
mid Rel	0.036	0.043	0.069	0.101
hi Rel	0.036	0.043	0.069	0.101
Service/Financial/Reliability Portion				
low Rel	0.488	0.583	0.558	0.812
mid Rel	0.488	0.583	0.558	0.812
hi Rel	0.488	0.583	0.558	0.812

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Red = annualized risk reduction greater than $1 million; Orange = annualized risk reduction between $100,000 and $1,000,000
Yellow = annualized risk reduction between $10,000 and $100,000; Green = annualized risk reduction less than $10,000

What is Apparent in the Examples?

Risk reduction is significant in moderately high to high consequence cases, although significant risk remains with respect to subsurface events. In high consequence cases, workover LOC risk also is greater

Risk reduction is of decreasing value in moderately low to lower consequence cases and it is offset by increased workover LOC risk

For certain low-LOFI well types, and for low-consequence environments, the safety risk is low and there is no obvious or probable cost-effective safety benefit attending to use of SSSV

SV reliability affects the risk perspective - therefore efforts should be made to increase SV reliability AND to increase safety culture and safety management systems effectiveness

When:
LOFI < 1 x 10E-05 (<0.00001) per well-year: SSSV almost never cost-beneficial

1 x 10E-05 < LOFI < 1 x 10E-04 per well-year: SSSV might be beneficial but only in very high consequence areas AND if risk of workover LOC is not high

1 x 10E-04 < LOFI < 1 x 10E-03 per well-year: SSSV might be beneficial in high to very high consequence areas AND if risk of workover LOC is not high

1 x 10E-03 < LOFI < 1 x 10E-02 per well-year: SSSV might be beneficial in moderate-high and v high consequence areas

LOFI > 1 x 10E-02 per well-year: SSSV might be beneficial in all cases except certain v low consequence cases

Analysis of SSSV benefit depends on:
- LOFI x COFI and workover risk
- SSSV install-maintain life cycle cost analysis
- "Values Basis" can override cost/benefit utility analysis!
- Management of controllable LOFI/COFI drivers and alternatives analysis – lower LOFI COFI, less need for mitigation

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Let's address some of the findings…

Compare Analysis: Shallow-Set and Deep-Set SV

Deep Set consequences

	need new well for deliverability/relial
lo rate well	0 - .10 wells per SV
mid rate well	.10 - .30 wells per SV
hi rate well	.30 - .50 wells per SV
v. hi rate well	.50 - .70 wells per SV

Deep set analysis required use of somewhat lower reliability factors (R=.67, .84, .94) as well as financial allocation for additional wells related to loss of deliverability-reliability
(LOFIwell x COFI well)SSSV + (LOFIworkover x COFIworkover) + (LOFIreplacementwells x COFI replacementwells)

SV risk reduction - number of LOFI-COFI reliability groupings with red (>$1 million), orange (>$100K), yellow (>$10K), or green (<$10K)
all cases comparing case with workover and max (poor) mgmt system; deep SV case, all consequence cases include cost of replacements wells (not included in analysis for safety and environmental risk reduction rows)

	Shallow BASE				Deep BASE				Shallow INVERTED				Deep INVERTED				Shallow MIXED				Deep MIXED			
	Red	Orange	Yellow	Green	Red	Orange	Yellow	Green	Red	Orange	Yellow	Green	Red	Orange	Yellow	Green	Red	Orange	Yellow	Green	Red	Orange	Yellow	Green
Min LOFI, Safety Cons Reduction Only	4	1	3	16	4	3	1	16	5	1	3	15	5	2	3	14	4	3	2	15	6	3	0	15
Min LOFI, Safety+Env Cons Reduction	4	1	3	16	4	3	2	15	6	1	2	15	6	3	3	13	4	4	2	14	6	4	0	14
Min LOFI, All Consequences Reduction	5	2	1	16	4	1	0	18	6	5	2	11	6	0	0	18	6	5	1	12	4	2	0	18
Max LOFI, Safety Cons Reduction Only	6	3	3	12	6	3	2	13	8	1	4	11	8	1	2	13	8	5	1	10	9	4	0	11
Max LOFI, Safety+Env Cons Reduction	6	3	3	12	6	3	3	12	10	2	2	10	10	3	1	10	8	5	2	9	10	4	1	9
Max LOFI, All Consequences Reduction	8	4	1	11	8	2	0	14	10	5	2	7	10	0	1	13	10	6	0	8	8	2	0	14

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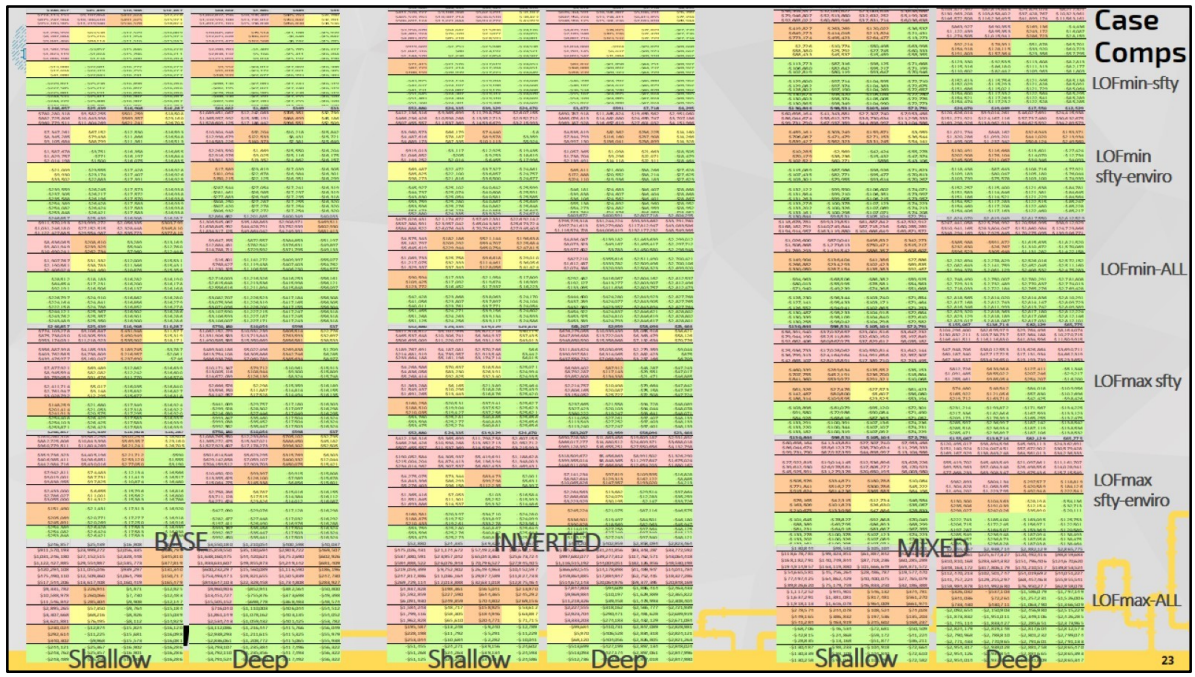
For deep-set SV, we used different, lower reliabilities, and we included in the total consequences (financial part) an allocation for the cost of deliverability replacement, assuming the deep site SV were on tubing strings that restricted the flow ID from the pre-SV case.

The results of the deep SV analysis can be surprising.
While the annualized risk reduction magnitudes go way up, they can only go up so high and depend on the original, or pre-SV annualized risk – in other words, small risk to begin with, small risk reduction with the SV.
The bigger risk groups show bigger risk reduction with deep SV, but the matrices get more polarized since the negatives for deep SV also magnify against an initially small risk, say, for low risk wells (the “ideal” well of course, and often for well type 4 and well type 3).
This polarization is even more stark when we go to “all consequences” and add in the cost of drilling and maintaining the fractional extra well to make up for lost deliverability. We end up with matrices that have some strongly red cells, maybe a little orange or yellow, and then strongly green cells (many of which are strongly negative).

This analysis gives an even more clear direction on deep SV as there is a narrower “in between” range between red and green cells.



These show, for the shallow-set cases, the matrices with max workover risk (but not with the 5x factor for poor mgmt. system effectiveness)

Risk Reduction Alternatives: Operators Should Be Motivated to Decrease…

Likelihood of Failure

Employ: Surface protection measures, engineered barriers (per API 1171 Clauses 10.2, 10.3) ****LOFI credits*

Perform: Passive barrier regular inspection/condition assessment; active barrier functional performance tests

Eliminate: Knowable unknowns in WBE: baseline/repeat condition assessments to establish damage mechanisms, degradation rates; cement condition/annular isolation; verify pressure containment capability; establish leak rate thresholds, operating windows, performance criteria

Construct: New wells, well repairs, replacements to robust safety standards, high safety factors; employ rigorous technical and human factors mgmt. standards

Consequence of Failure

Decrease: Footprint impact to population, environment

Implement: Operating windows/limits, thresholds, associated detection and alarm protocols; manage human factors in interpretation and oversight

Develop/Implement: Trained, rapid response to alarms, abnormal conditions, incidents, emergencies; relationships fostering engineered intervention/response to exceedances

Employ: Other detection, isolation, and mitigation devices - increase detection and response and/or limit duration and severity of an event. ****COFI credits*

Develop/Implement: Human factors management esp. in drilling/servicing good practices - API 54, 76, 75L, API 97…

Compare: Risk Reduction value of alternative measures
Learn: from past incidents and others' failures; collaborate in reliability engineering studies of well barrier elements

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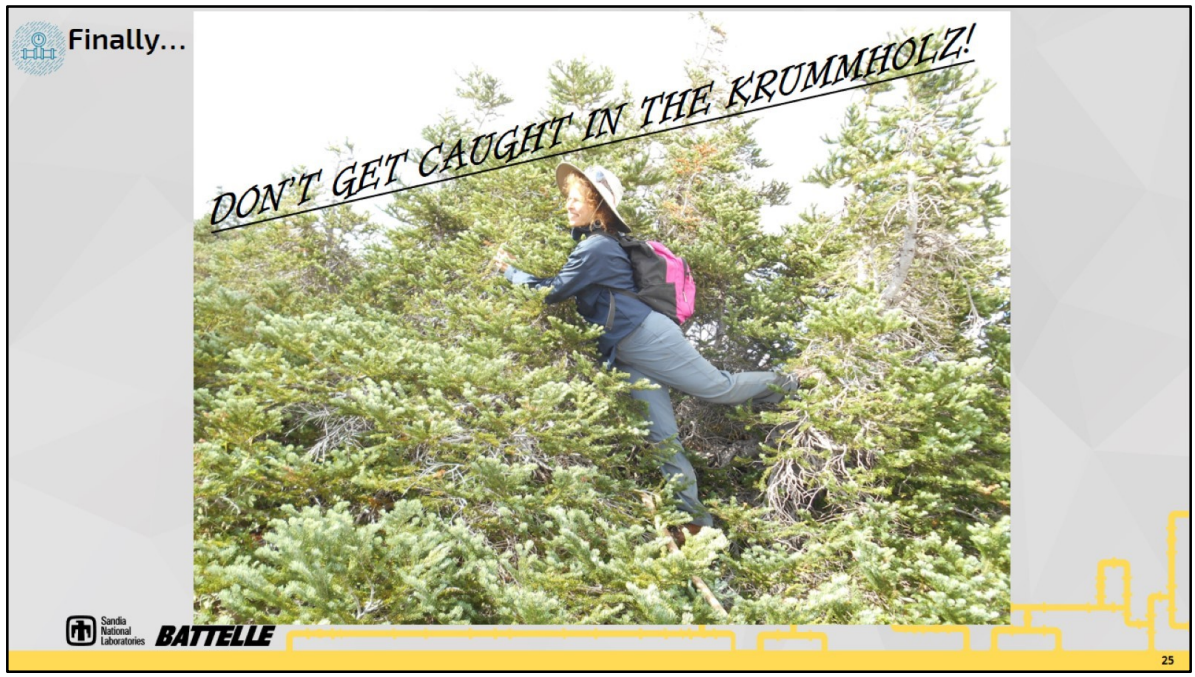
In addition to this analysis, the cost-benefit of SV application is a site-specific analysis that must be done by storage operators, as the type of SV, the well construction, and the site-specific risk estimates are required.

The approach is a suggested beginning point. Enhanced effort at understanding well barrier element reliability - particularly of "active" or "on-demand" barrier elements and their components - is important to the efficacy of risk-informed integrity management.

We suggest:
Storage industry collaboration to develop/maintain a well equipment reliability data warehouse
Continued efforts to use quantitative, probabilistic information in risk assessment and study other risk model perspectives on the SV question



Don't get caught in the krummholz. While there appears to be a lot of fine detail, and there can be confusion due to different forms of risk analysis, the basic approach points to a common system of known good practices approach in risk management. What can seem complicated comes down to some common roots.

In concluding:

1) We hope that some companies will want to try this model on some of their wells and compare to their own risk analysis. The research team is happy to take some volunteers and do some analysis for real world examples.
2) We would love to compare the results of the analysis using this Battelle-Sandia adapted model to result that you might have obtained using your own models.
3) We also believe that this form of model can be a bridge to more fully probabilistic / quantitative models, as it builds data sets around well barrier element information that can further inform terms in probability analyses – such as reliability, failure, and prior probabilities.
4) The ability to express risk in common, utility-based terms, such as annualized expected risk in USD, helps to drive decisions on effectiveness of risk reduction and on choices between risk treatment alternatives. There is risk in confusion if such common terms are not used and in variance in approach which when tested might be found to be wanting.
5) It is not difficult to apply this adapted model: it can exist in spreadsheet form and be replicated to produce outcomes fairly rapidly after inputting site-specific information. But the emphasis is on pointing out where additional information is of greatest value.
6) So again, we invite you to engage in discussion and to take up our offers of testing some real examples. We also encourage you to develop industry-led collaboration on risk management performance and WBE reliability information.

Other Slides / Backup

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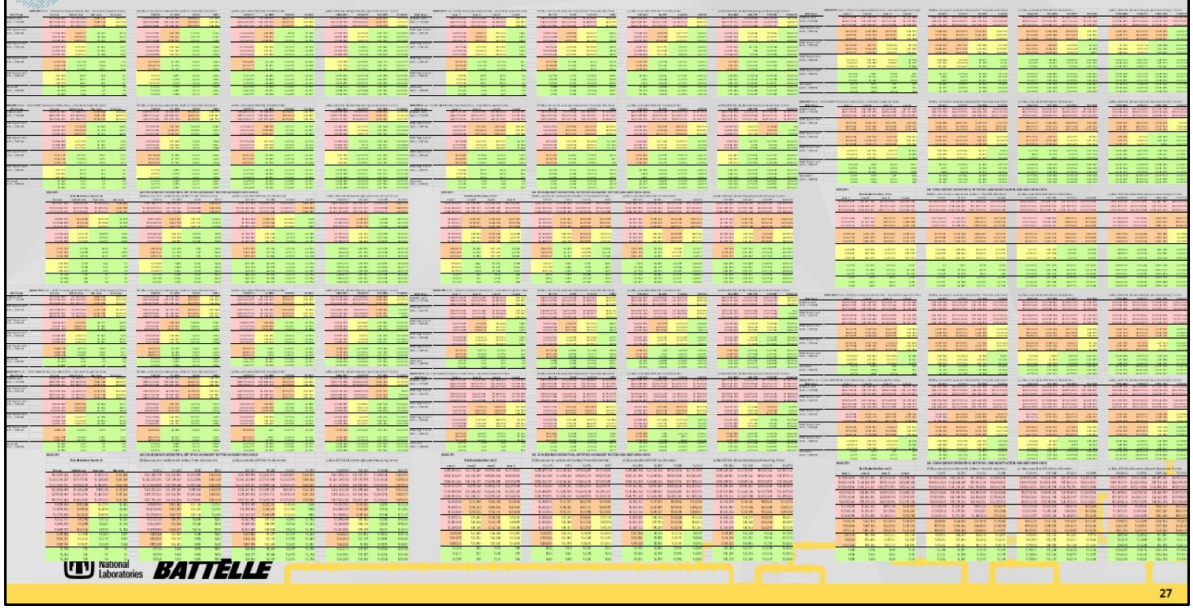
Shallow-Set SV Net Annualized Risk Reduction Matrices



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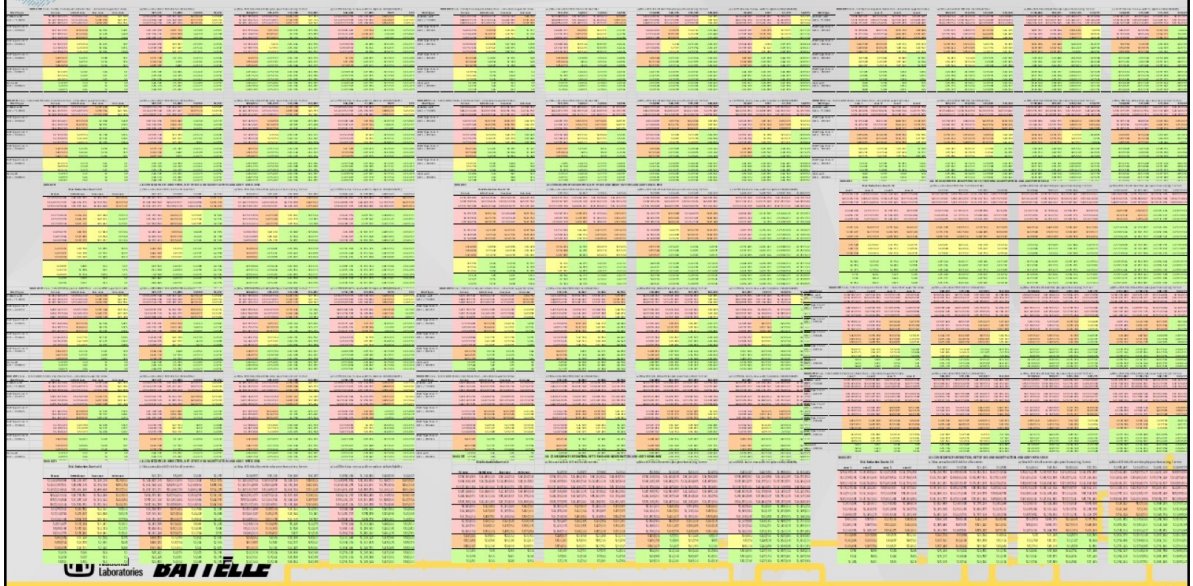
Deep-Set SV Annualized Risk Reduction Matrices



Note

The presented model results are preliminary and may be modified by the Battelle/Sandia team. The final version of the results will be provided in the final project report.

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