# Remarks
# By
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# Defense Nuclear Facilities Safety Board

At the
EFCOG Safety Basis Panel Session on Risk Assessment Approaches
to Improve Nuclear Safety in Facilities Containing Hydrogen Hazards

To the
**The Department of Energy Facility Contractors Group (EFCOG)**
**and its Safety Basis Subgroup**

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## HYDROGEN SAFETY STRATEGY AT DEFENSE NUCLEAR FACILITIES[1]

Good morning. Before I begin I would like to thank Kevin O'Kula, the Program Chairman of the Hydrogen Safety Interest Group, for inviting me to participate in this panel discussion and the EFCOG Safety Basis Working Group for sponsoring this session on Hydrogen Hazards.

I'd also like to emphasize that the opinions and observations that I am about to express are mine and do not necessarily represent those of the Defense Nuclear Facilities Safety Board.

I recently read in the press that in the eyes of the public, the Board is "a federal watchdog agency that has repeatedly forced DOE to address inconvenient and expensive safety issues…." The hazards associated with hydrogen and quantitative or probabilistic risk assessment have been inconvenient safety issues that the Board has recently pursued. In this talk I will try to marry the two together and illustrate some of the challenges and opportunities associated with them.

Hydrogen is commonly generated in nuclear wastes by radiolysis of hydrogenous materials. It is also generated by other means, including dissolution of metals by acid, battery off gas, and metal corrosion. Hydrogen is a flammable gas that can ignite in the presence of low energy ignition sources like static electricity. This makes quantifying the likelihood of ignition in nuclear facilities very difficult. If left unaccounted for in design, hydrogen deflagrations, and - equally important – detonations, are capable of generating peak pressures that can exceed the system design pressure and breach the pressure boundary.

[1] The views expressed are solely my own and no official support or endorsement of these remarks by the Defense Nuclear Facilities Safety Board is intended or should be inferred.

Figure 1

These bulged bottles are examples of gas generated in just a couple months, if left unattended.

As recently as 2001, postulated hydrogen detonations ruptured piping systems in boiling water reactors in both Germany and Japan with an ignition source that was never conclusively identified. The threat of these explosions occurring in nuclear facilities is exacerbated by the potential release of radioactive material. For this reason, even though no major hydrogen-related explosions have occurred in DOE nuclear facilities, the results of such an event justify careful consideration.

Worldwide, tens of industrial hydrogen explosions of varying degrees of severity occur each year. I suspect that because most are industrial accidents, and have not involved radioactive materials, we only hear about those that involve a serious injury. Let me remind you of a few historic events that were associated with nuclear materials, or were near misses.

On December 12, 1952, a partial meltdown of the NRX nuclear core at Chalk River, Ontario, occurred. This was the first serious nuclear reactor accident in the world. Operator error and sticking control rods caused an unexpected increase in reactor power, at the same time that the normal coolant water supply had been altered for a test. Overheating of the fuel rods caused the cladding to burst, resulting in the generation of hydrogen and other gases by chemical reactions in the fuel rods. The helium gas blanket over the reactor was also lost, and the inrush of air caused a hydrogen/oxygen explosion. Although the containment did not rupture during the explosion, considerable radioactive coolant water leaked onto the floor of the reactor building, resulting in massive contamination, followed by an enormous cleanup operation.

During the 1980s, one of the 177 high-level waste (HLW) tanks at DOE's Hanford Site in Washington state – Tank SY-101 – experienced several near misses involving hydrogen releases. The underground tank contained one million gallons of HLW comprising a sludge layer and a floating supernatant layer. The buildup of radiolytically produced gases, mainly hydrogen, in the heavier sludge layer caused portions of the sludge to attain neutral buoyancy, eventually rising to the supernatant layer. At that point, large quantities of hydrogen were released in a short period of time. As a result, the vapor space above the supernatant layer attained the lower flammability limit (LFL) for hydrogen in air for short periods before the tank ventilation system diluted the hydrogen. Contact with an ignition source during this time would have caused a deflagration with consequences ranging from a slightly damaged ventilation system to a large release and the spread of highly radioactive materials into the surrounding environment.

Another example: there are thousands of drums containing radioactive waste stored at various sites in the defense nuclear complex. Before the clean-up was completed in 2005, the Rocky Flats Site in Colorado stored 17.5 metric tons of combustible residues containing 0.5 metric tons of plutonium in drums. Because there was no permanent repository for these drums, all were moved to other sites for temporary storage. Many were moved to Idaho. The residues consisted of filters, resins, wood, various plastics, and small amounts of oils and solvents. The radiolytic generation of hydrogen and other flammable gases within sealed drums was a concern, and hydrogen levels as high as 60 percent were found in some drums. Most of the drums were vented to prevent pressure buildup and accumulation of hydrogen; some were not. This is an issue as is illustrated in the following incidents. At the Idaho National Laboratory in August 2003, a brief fire occurred when an obviously over-pressurized waste drum was being vented. The fire was attributed to hydrogen mixing with atmospheric oxygen during drum venting. And on November 21, 2005, again at the Idaho National Laboratory, a drum in a retrieval trench deflagrated generating a fireball approximately 8 feet high and 4 feet in diameter. The explosion expelled the drum's contents onto an adjacent drum, igniting it as well.

So how are hydrogen hazards addressed today? Within the commercial industry there are regulations, standards, and guidelines for the handling, storage, and transportation of hydrogen in the commercial environment. The Department of Energy treats hydrogen as an ordinary flammable gas and follows national standards, such as NFPA 69, for the control of flammable gases. However, because of hydrogen's unique properties (Figure 2) and because it is commonly found in proximity with nuclear materials at defense nuclear sites, it is my opinion that the Department of Energy needs to adopt generic and specific regulations, standards, or guidelines for the design of hydrogen safety controls in radioactive environments.

| Property | Hydrogen | Methane | Propane | Gasoline |
|---|---|---|---|---|
| Density @ STP (kg/m$^3$ ) | 0.084 | 0.65 | 2.42 | 4.4 |
| Heat of vaporization (kJ/kg) | 445.6 | 509.9 | - | 250-400 |
| Lower heating value (kJ/kg) | 119,930 | 50,200 | 46,350 | 44,500 |
| Higher heating value (kJ/kg) | 141,800 | 55,300 | 50,410 | 48,100 |
| Gas thermal conductivity @ STP (W/m/K) | 0.1897 | 0.033 | 0.018 | 0.0112 |
| Diffusion coefficient in air @ STP (cm$^2$/s) | 0.61 | 0.16 | 0.12 | 0.05 |
| LFL to UFL limits in air (vol%) | 4–75 | 5.3–15 | 2.1– 9.5 | 1-7.6 |
| Detonation limits in air (vol%) | 18.3–59 | 6.3–13.5 | - | 1.1–3.3 |
| Limiting oxygen (vol%) | 4* | 12.1 | - | 11.6 |
| Stoichiometric composition (vol%) | 29.53 | 9.48 | 4.03 | 1.76 |
| Minimum ignition energy (mJ) | 0.017 | 0.29 | 0.26 | 0.24 |
| Autoignition temperature (°C) | 1131 | 1086 | 1033 | 773- 1017 |
| Flame temperature in air (°C) | 2591 | 2421 | 2658 | 2743 |
| Maximum burning velocity in @ STP (m/s) | 3.46 | 0.45 | 0.47 | 1.76 |
| Detonation velocity in air @ STP (km/s) | 1,480–2,150 | 1,400–1,640 | 1,850 | 1,400–1,700 |
| Explosion energy (gTNT/g) | 24 | 11 | 10 | 10 |
| Explosion energy @ STP (gTNT/m$^3$) | 2.02 | 7.03 | 20.5 | 44.2 |

*a recent change in NFPA 69 (used to be 5%)

Figure 2: Combustion Properties of Hydrogen and Other Common Flammable Gases.

DOE uses three basic principles to prevent deflagration for common flammable gases (i.e., limiting fuel, limiting oxidants, and controlling ignition). These principles are not uniformly applied to the unique properties of hydrogen at DOE nuclear facilities.

I have asked the Board's staff to study strategies that can be used to develop specific controls for hydrogen hazards in nuclear facilities. Four preventive and two mitigative principles were identified to prevent or mitigate deflagrations or detonations of hydrogen in contact with, or in proximity to radioactive materials. These principles are tailored to the unique properties of hydrogen and could be used systematically to design safety strategies for processes that generate, use, store, retain, or release hydrogen.

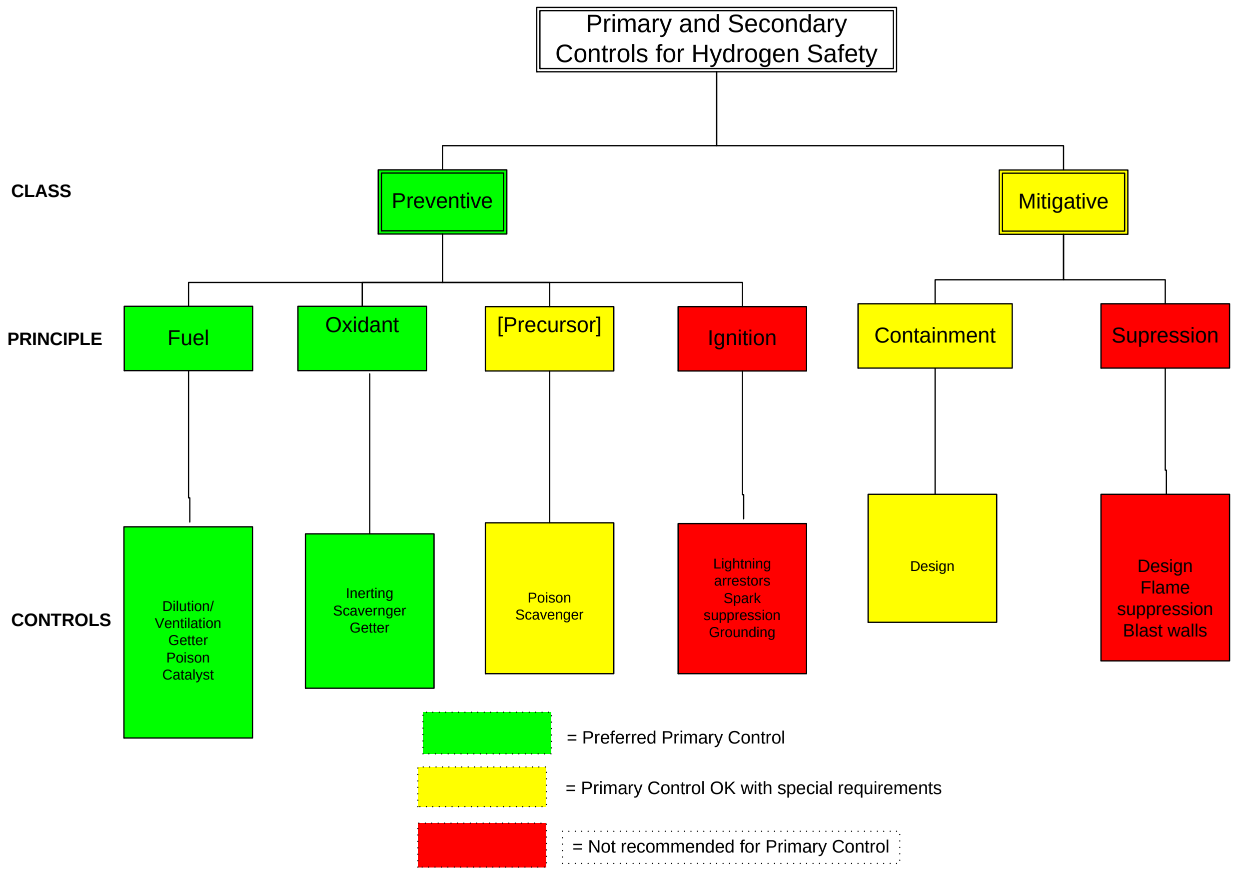


Figure 3. Four Preventive and Two Mitigative Principles for Hydrogen Safety

Controls can be separated into two classes: preventive and mitigative. A preventive control would eliminate the conditions that could result in a hydrogen deflagration or detonation, and a mitigative control would contain or minimize the consequences of a deflagration or detonation should it occur.

In defense nuclear facilities, where hydrogen is usually generated by radiolysis, several examples of fuel-related principle controls are employed that involve altering key phenomenology or process activities such as generation, dilution, process control, scavenging, and physical intervention (Figure 3). There are a few examples of oxidant principle controls that involve inerting for flammable gas as well as hydrogen safety. There is an example at Pantex where gravel gerties employ the suppression principle to contain the potential dispersal of radioactive material in the event high explosives were to inadvertently detonate, but I am unaware of an example where that principle has been applied to a potential inadvertent hydrogen detonation.

Safety strategies for flammable gases usually employ more than one control. The controls are usually designated as a primary control or a defense-in-depth (secondary) control or controls. A logical strategy for the selection of a primary or secondary control is benefited by functionally categorizing them. For the purposes of this discussion, I define primary controls as ones that provide the first line of assurance for hydrogen safety, and secondary controls as those that provide defense-in-depth. Whenever possible, a primary control should be engineered rather than administrative. Once it is determined whether a control to be selected is a primary control versus secondary control, a set of decisions can be made to select the best control. The primary and secondary distinction is important because the primary controls should be robust and more conservative than secondary controls. Some controls should not be used as a primary controls because they do not provide enough safety margin.

But these principles for hydrogen safety controls are elementary, and it is my belief that much more study and research needs to be done. The control of the hydrogen generation rate from nuclear wastes and process streams requires a thorough understanding of the mechanisms of generation and chemistry involved. While it is known that hydrogen has an affinity to being retained in solid particle systems such as sludge and non-Newtonian liquids, there is too little research ongoing in this poorly understood area. A strategy for determining the controls needed to protect the public, the environment, and workers against a hydrogen explosion in proximity with radioactive materials needs to be systematized.

To ensure that these controls are both adequate and cost effective will require a greater understanding of the mechanisms involved in the hydrogen generation rate, a greater understanding of the physics involved with hydrogen ignition and flame propagation, and a greater understanding of the retention of hydrogen in Newtonian and non-Newtonian fluids. Developing such a technical basis and the resultant hydrogen control strategy would lead to consistency in the application of hydrogen safety controls throughout the Department of Energy nuclear complex.

My predecessor, Dr. Herb Kouts, stated a key principle as well as I think it can be said. He said, "protective measures aimed at accident prevention and accident mitigation must be in place and reliable, directed to ensuring that members of the public are not exposed to radiation doses of any appreciable amount, and that workers are protected from injury."[2]

Because of the large uncertainties related to hydrogen hazards, the use of probabilistic risk assessment (PRA) methodology could aid in decisions about hydrogen controls. DOE tried and evaluated PRA in several ways during the 1990s. Indeed, federal government agencies

[2] "Uses and Misuses of Probabilistic Safety Assessment at DOE's Defense Nuclear Facilities" presented at the PSA-99, International Topical Meeting on Probabilistic Safety Assessment, Willard Inter-Continental Hotel, Washington, DC, August 23, 1999, by Dr. Herbert Kouts, Member, Defense Nuclear Facilities Safety Board.

responsible for management of safety and health were required by the 1993 Executive Order to "consider, to the extent reasonable, the degree and nature of the risks posed by … activities within its jurisdiction."[3] At that time, the NRC was well along the path towards implementation of PRA. Individual commercial nuclear power plants had begun the ten year effort to study PRA in response to NRC's 1988 generic letter GL-88-20. And later, in 1995, NRC issued their PRA policy statement.

In parallel with NRC's implementation of PRA during the 1990s, DOE also applied probabilistic safety analyses to selected activities to evaluate their utility.

Such an analysis was performed for the K-Reactor at the Savannah River Site and for some of the DOE research reactors. These methodologies and computations benefitted from NRC's large databases on commercial reactors. However, the commercial data was not specifically relevant to the specialized activities at DOE nuclear facilities and resulted in larger uncertainties. As a result, the improvement of safety at DOE reactors did not benefit significantly from this effort.

In the early 1990s, DOE also conducted what was called the *Tri-Lab Study* to determine whether the safety of operations on the B-57 and B-83 weapon systems could be improved through the use of quantitative risk assessment (QRA). Because there was so little data upon which to base the study, it relied heavily upon experts to estimate both consequence and probability, and it concluded that the "real benefit of the [probabilistic] methodology was to be found in reduction of risk through improvements in design processes and safety features."[4]

Again, in 1994, Los Alamos National Laboratory, the Sandia National Laboratories, and the Pantex Plant conducted a comparison study on disassembly of the B-61-0 nuclear weapon. This study compared two methodologies: a combination of deterministic analysis and simplified probabilistic methodologies which some have called a "Semi-quantitative estimation of risk" – compared to a complete PRA. The study concluded that the expense and time required for the full PRA was not justified when compared to the simpler semi-quantitative method.

In summary, in the 1990s DOE studied and concluded that DOE activities are so diverse and the existing data was so sparse that the expense of a credible PRA was not justified. And that is why DOE Orders continue to require the use of deterministic methods to define the selection of measures necessary to protect workers and the public.

But where large uncertainties exist, the deterministic approach often demands unrealistic conservatism. To quote a letter written in 2003 to the Secretary of Energy by former Board Chairman Conway, "The Board recognizes that unrealistic conservatism can undermine the process for the development and implementation of safety controls. Consequently, the Board

[3] Executive Order 12866, *Regulatory Planning and Review.*
[4] "Uses and misuses of probabilistic safety assessment at doe's defense nuclear facilities", presented at the PSA-99, International Topical Meeting On Probabilistic Safety Assessment, Willard Inter-Continental Hotel, Washington, DC, August 23, 1999, by Dr. Herbert Kouts, Member, Defense Nuclear Facilities Safety Board.

had encouraged DOE to take advantage of opportunities to reduce this type of conservatism in the development of [Documented Safety Analyses]."[5]

Over the next several years, the Board encouraged DOE to develop policies and guidance on PRA, but frankly, the directives remained unchanged. Finally, on July 30, 2009, the Board issued Recommendation 2009-1, *Risk Assessment Methodologies at Defense Nuclear Facilities*. The essence of this recommendation was that DOE should establish a policy on the use of quantitative risk assessment, establish related requirements and guidance in the DOE directives, evaluate current ongoing uses of QRA methodologies to determine if interim guidance was needed, and perform a gap analysis to identify additional research needed to reduce uncertainty in the use of QRA.

It is my belief that there is much to be gained by a deliberative process to study, define, and implement risk-informed methodologies at defense nuclear facilities. We should not forget that the first such attempt by NRC, the *Reactor Safety Study*, also known as the Rasmussen Report, was much criticized at the time. However, four years after the report the Three Mile Island incident validated the concerns about small loss of coolant accidents that the *Reactor Safety Study* had, with very high confidence, assigned unanticipated large probabilities. That fact – alone – should cause us all to renew our interest in this subject.

Let me read an example from a recent report presented to the Board on the subject of hydrogen generation hazards, known as *Hydrogen in Piping and Ancillary Vessels (HPAV)*, at the new Hanford Waste Treatment Plant. The contractor had chartered an Independent Review Team (IRT), to evaluate the contractor's design approach, and this is what the IRT wrote:

> The new design approach combines probabilistic and deterministic techniques. The IRT understands this to be a precedent setting effort by DOE to use risk insights to inform design choices for hazardous facilities. This approach has gained wide acceptance in the commercial nuclear industry with the encouragement of the Nuclear Regulatory Commission, the Nuclear Energy Institute, the Electric Power Research Institute, and the national standards setting organizations such as ASME and the American Nuclear Society. There is consensus among these organizations that the risk-informed approach has led to both improved levels of safety and better allocation of resources towards those areas most important to safety. The IRT lauds DOE for this initiative. The experience gained will aid DOE in its efforts to develop guidance on future uses of risk insights to inform safety decisions.[6]

This does not sound completely unreasonable. We are all seeking increased levels of confidence in the safety of DOE's nuclear activities.

In the section on phenomenological uncertainties, the HPAV report goes on to say that "it is questioned whether there are additional sources of uncertainty embedded within the

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[5] Letter from Board Chairman John Conway dated September 23, 2003.

[6] Report by Independent Review Team to Bechtel National Corporation "Hydrogen in Piping and Ancillary Vessels (HPAV) Implementation and Closure Plan," document number 24590-WTP-RPT-ENG-10-021, Rev 0 dated August 19, 2010, Section 1.13 'Use of Conservatism to account for uncertainty.'

deterministically treated rules and equations, and whether the applied conservatisms are sufficient to bound the effects of those uncertainties."

But before I go further, let me now temper any perceived new enthusiasm for PRA by reminding you that, in accident analysis, we are attempting to determine what might happen regardless of the perceived probability. Niels Bohr once said "prediction is very difficult, particularly if it is about the future." I would add that the devil is always in the details.

So now I would like to consider three specific DOE facilities I am concerned about related to hydrogen hazards and PRA. The first two illustrate the hydrogen hazard, and the third illustrates the challenges of applying PRA to develop hydrogen controls.

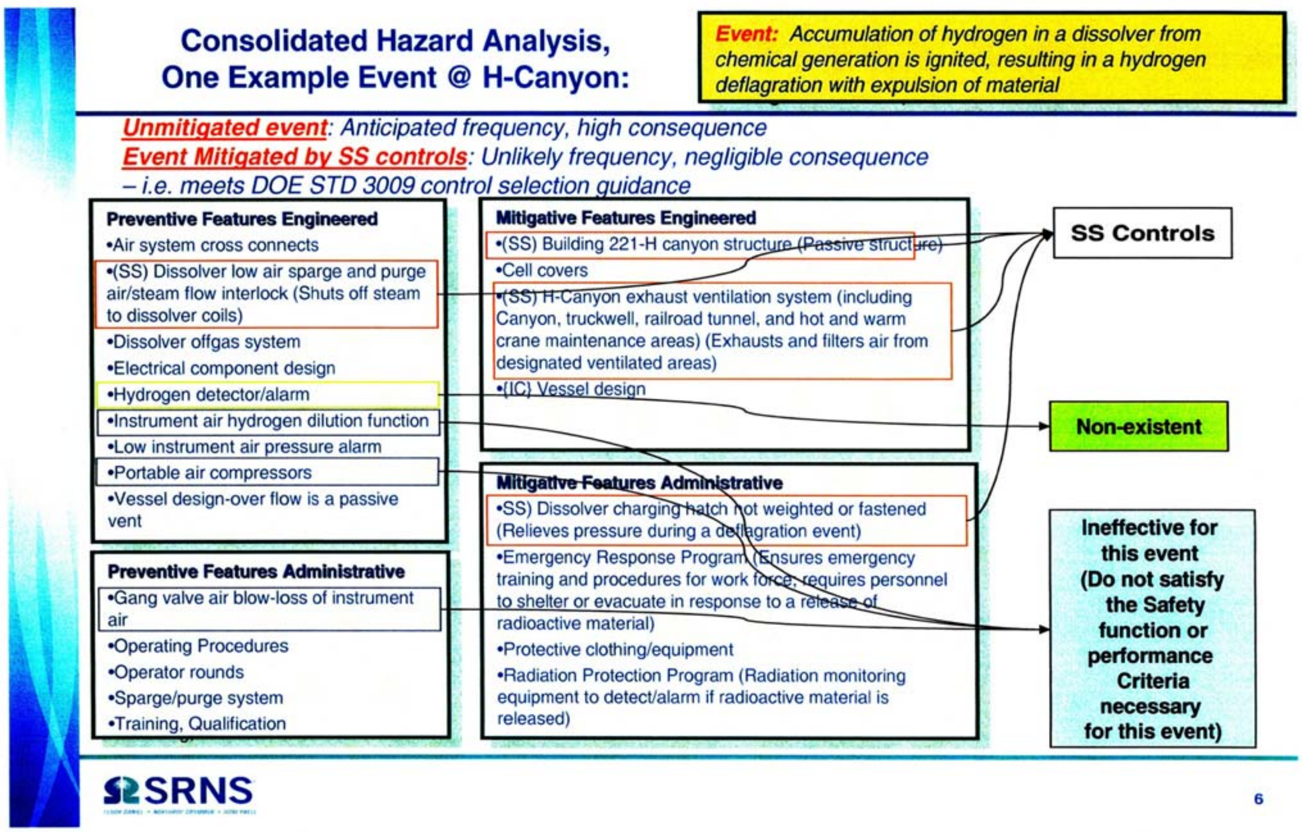


Figure 4. Addressing hydrogen in H Canyon Consolidated Hazard Analysis

The "Consolidated Hazardous Analysis" in Figure 4, above, was recently presented by Savannah River Nuclear Solutions, LLC, during a Board visit to the Savannah River Site. It was part of a generic presentation on hazard control program improvements, and is a facility specific example of the difficulty of developing controls for hydrogen. Yesterday, Andrew Vincent's presentation "Hazard Controls Update" discussed the challenges of determining hydrogen generation in real time, and used this figure to illustrate the non-existence of adequate hydrogen detectors and the ineffectiveness of some postulated controls. I believe it illustrates how difficult it is to apply controls to hydrogen in real environments.

My second example is the hydrogen control strategy at the Hanford Tank Farms. The initial concerns were spelled out in a Board letter last August and are summarized in Figure 5 below.

**Double Shell Tank (DST) Ventilation System**

- 5 of 28 DSTs currently have quantities of flammable gas retained in the waste >200% LFL and 6 others have quantities >100%
- retained flammable gas can be released either spontaneously or due to an induced gas release event
- All DSTs, during steady state conditions, continuously generate flammable gas and can develop >100% LFL in the headspace without adequate ventilation
- Downgraded in favor of Flammable Gas Control SAC (see discussions below)
- Offsite consequences of detonation ~5 rem, deflagration also significant

**Flammable Gas Monitoring SAC**

- Undetectable failure in rubber tubing would result in a false low flammable gas reading.
- Acceptance criteria is inadequate (with ventilation running 0% should be expected, however action threshold is 25%)
- Minimum oxygen concentration and prescribed temperature range not specified in the surveillance procedure
- Performed by a single operator with no provisions for independent verification.

**Passive Ventilation**

- Vaguely defined, implicit crediting of weather related phenomena
- Ineffective for spontaneous and induced gas release events
- No defined surveillance criteria

Figure 5. Hanford Tank Farms

The safety analyses at the Hanford Tank Farms show that 5 of the 28 double shell tanks (DST) currently have gas retained in the waste in quantities greater than 200 percent of the LFL, which could be released either spontaneously or due to an induced gas release event. Six others have retained gas quantities of greater than 100 percent of the LFL. Further, irrespective of the gases currently retained in the tank waste, all the DSTs currently generate flammable gases and will eventually develop 100 percent of the LFL in the headspace in the absence of adequate ventilation. Consequently, preventing the accumulation of flammable gas in the headspace is a critical safety strategy at the Tank Farms.

The Hanford Tank Farm DST ventilation system was previously categorized as a safety-significant, and this preventive, engineered control was credited in certain flammable gas scenarios. However, in the revised DSA, the ventilation system is reduced to defense-in-depth and replaced by a Specific Administrative Control (SAC) for flammable gas monitoring. In addition to the Board's concerns regarding the appropriateness of downgrading a safety significant, preventive, engineered control in favor of a SAC, which is counter to DOE's stated preferred hierarchy of controls, the staff determined that the SAC has a number of weaknesses that collectively render it inadequate as a safety control.

In response to these concerns, the Office of River Protection (ORP) and the site prime contractor now propose to credit a strategy involving so-called "passive ventilation" to prevent the accumulation of flammable concentrations. Though the details of this strategy are not yet developed, it appears that such an approach will require implicit crediting of weather related phenomena and will not address the mitigative effects of forced ventilation for the spontaneous and induced gas release events.

My third example is from the Board's recent two day hearing at Hanford, where unresolved issues at DOE's Waste Treatment Plant were discussed. Those issues associated with hydrogen hazards, and the use of QRA, remain controversial. Our staff has dug down into the specifics of using QRA, and many questions remain unresolved.

The Board's staff believes that QRA will be a complicated undertaking, made even more difficult by the fact that WTP is a first-of-a-kind facility. Having no DOE standards and requirements for the use of QRA, nor any published expectations for controlling the assumptions supporting the QRA, will complicate the safety basis. Furthermore, in the near term, the findings of the Independent Review Team (IRT) must be resolved. The Board's staff believes the following IRT findings in particular will demand considerable effort and will be difficult to accomplish:

- Finding F2-4: <u>Need to consider Plant Level Events in QRA models</u>. This finding requires the QRA to be expanded to address plant wide events that contribute to event duration distributions.
- Finding: 2-7: <u>Enhanced Treatment of Phenomenological Uncertainties</u>. This finding addresses uncertainties regarding phenomena associated with gas pocket formation and hydrogen combustion.
- Findings 3-6 and 3-7: <u>Justification regarding simulant selected for gas testing</u>. The IRT found that the simulant used to perform gas testing was not properly documented and that the range of yield stresses used in gas testing and QRA calculations must be revised or justified in terms of the expected behavior of the waste.

The staff believes that these latter two findings, if not adequately addressed, will prevent the QRA's use because the calculations to determine bubble size form the basis for determining the frequency and severity of hydrogen explosions.

These three specific examples illustrate the pervasive hazard and the difficulties of developing effective hydrogen control strategies. I believe they also illustrate the importance of workshops like this to increase awareness among safety basis practitioners and solicit new and relevant strategies that reduce uncertainty and increase confidence in the safety at DOE defense nuclear facilities.

I look forward to hearing your views on safety decision making as it relates to hydrogen hazards in defense nuclear facilities and hearing your views on what remains to be done.

END