Statement
By
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HYDROGEN SAFETY STRATEGY IN DEFENSE NUCLEAR FACILITIES

Good morning. Before I begin I would like to thank Kevin O'Kula the Assistant Program Co-Chairman for inviting me to participate in this panel discussion, and the Nuclear Installation Safety Division of the American Nuclear Society for sponsoring this topical series on Hydrogen.

For those of you that are not familiar with the Defense Nuclear Facilities Safety Board, let me begin with a few words on the origin and mission of the Board. As some of you may know- the Department of Energy and all its predecessors – going back to the Atomic Energy Commission have been self regulating agencies. In 1975 Congress separated commercial nuclear activities from the federal activities and placed commercial activities under the regulatory authority of the Nuclear

Regulatory Commission (NRC). Government nuclear energy and weapons activities remain to this day under the regulatory authority of the Secretary of Energy - except in those cases where Congress has specifically placed federal government nuclear activities under the regulatory authority of the NRC.

However, in 1988 Congress responded to growing public concern about the lack of external oversight of federal activities and enacted legislation creating the Board as "an independent establishment in the Executive Branch" with the purpose of recommending actions to the Secretary of Energy that "the Board determines are necessary to ensure adequate protection of public health and safety." The Senate Armed Services Committee Report that accompanied the legislation was clear in what the Board was intended to accomplish.

> "The Board is expected to raise the technical expertise of the Department substantially, to assist and monitor the continued development of DOE's internal Environmental Safety and Health organization, and to provide independent advice to the Secretary. Above all, the Board should be instrumental in restoring public confidence in DOE's management capabilities...."

Today, twenty-one years later, how well has the Board met the Congressional intentions in its advisory role to the Secretary of Energy? Well, in response to Board recommendations and suggestions - and in a number of cases its own initiative - DOE has made significant improvements in its safety activities. Each year, the Board in its Annual Report to the Congress lists the DOE improvements, and that information and accompanying discussions are available to the public on the Board's Web page. DOE, which includes the NNSA, continues to face exceptional challenges in conducting work safely. DOE writes its own policies, orders, standards, guides and manuals and the Board comments on whether or not DOE is meeting its self imposed guidance.

In the eyes of the public, as reported recently in the press, the Board is "a federal watchdog agency that has repeatedly forced DOE to address inconvenient and expensive safety issues…."

The types of safety issues run the full spectrum: from extreme potential hazards beyond that of any commercial industry, - that is, working with nuclear weapons -, to industrial hazards common to almost all commercial operations. This brings us to hydrogen and the subject of this forum.

But before I go on, let me stop for a minute and make a disclaimer. 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.

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, e.g. static electricity. This makes quantifying the likelihood of ignition in nuclear facilities difficult. If left unaccounted for in design, hydrogen deflagrations, and more importantly detonations, are capable of generating peak pressures that can exceed the system design pressure and/or breech the pressure boundary. For example, in 2001, postulated hydrogen detonations ruptured piping systems in boiling water reactors in both Germany and Japan with an ignition source that was not conclusively identified. The threat of these explosions occurring in nuclear facilities is exacerbated by the potential release of radioactive material. Although the probability of these events occurring is uncertain, the accumulation of hydrogen in a radioactive environment can lead to high consequences. For this reason, even though no major hydrogen-related explosions have occurred in DOE nuclear facilities, the results of such an event justify strong controls.

A number of misconceptions have evolved regarding hydrogen and its safety—some positing that hydrogen is merely a perceived risk and some the opposite. Worldwide, tens of industrial hydrogen explosions of varying degrees of gravity occur each year. I suspect that because they are industrial accidents and do not involve radioactive materials we only hear about those that involve a serious injury. Let me remind you of a few additional 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, 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 caused 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. When reaching the supernate layer, 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 spread of highly radioactive materials.

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.

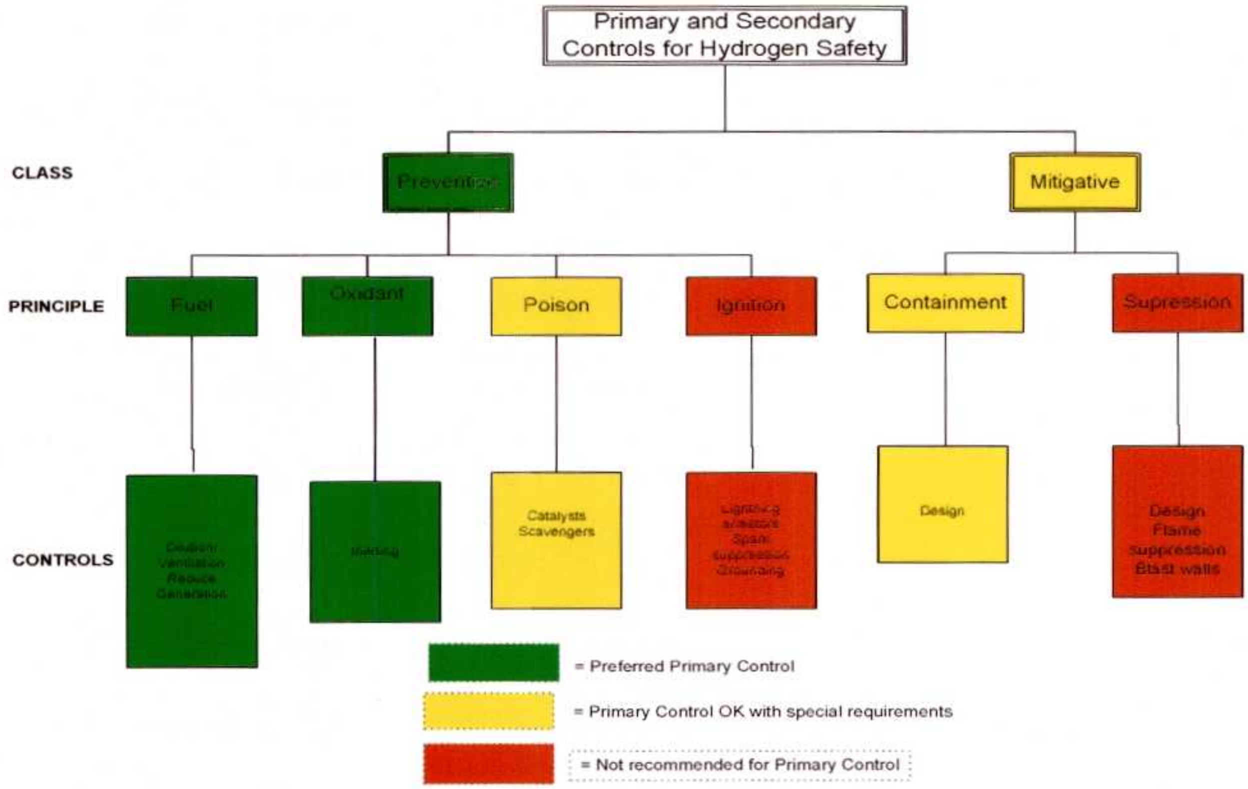
At the Idaho National Laboratory in August 2003, a brief fire occurred when an obviously over-pressurized waste drum was being vented. The fire was attributed to hydrogen mixing with atmospheric oxygen during drum venting. On November 21, 2005, at the Idaho National Laboratory, a drum in a retrieval 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.

These past events remind us of the potential hydrogen hazards existing at defense nuclear sites. Among the planned future activities being currently examined are the estimated hydrogen concentrations in the off gas systems from fluidized bed steam reforming, the generation of hydrogen from enhanced chemical cleaning using oxalic acid to dissolve the heels in waste tanks, and the generation of hydrogen from radiolysis and thermolysis during processing of high level radioactive waste at the Waste Treatment Plant. These studies are balanced against the validation of the conservatism of calculations supporting accident analysis and opportunities to justify downgrading functional classification of safety related equipment.

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. Because of hydrogen's unique properties 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. DOE uses the 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 for the unique properties of hydrogen throughout DOE nuclear facilities.

I have asked the Board's staff to study strategies that can be used to develop specific controls for hydrogen safety in nuclear facilities. Four preventive and two mitigative principles were identified to prevent or mitigate deflagrations or detonations of hydrogen in contact 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.



The Four Preventive and Two Mitigative Principles for Hydrogen Safety

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 or a 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 as robust but more conservative than secondary controls. Some controls should not be used as a primary control because they do not provide enough conservative margin.

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

In defense nuclear facilities where hydrogen is generated by radiolysis, several examples of fuel principle controls are employed that involve altering generation, dilution, process control, scavenging, and physical intervention (Table 3). There are a few examples of oxidant principle controls that involve inerting for flammable gas as well as hydrogen safety (Table 3). There is an example within DOE where the suppression principle has been employed 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 (Table 3-Gravel Gerties).

But it is my belief that much more study and research needs to be done. The control of the generation rate of hydrogen from nuclear wastes and process streams requires a thorough understanding of the mechanisms involved and there is a need for a greater understanding of these mechanisms. Hydrogen has an affinity to being retained in solid particle systems such as sludge and non-Newtonian liquids – yet there is too little research ongoing in this poorly understood area. DOE in support of the Waste Treatment Plant project has recently conducted deflagration and deflgration-to-detonation transition testing with hydrogen-nitrous oxide gas mixtures in piping systems. Dr. Joe Shepherd at Cal Tech has been doing related experiments; all of which suggests to me that there remains much to be learned and understood in this area.

In conclusion: at defense nuclear facilities, most of the hydrogen, either generated, stored, or used as a process chemical, is in direct contact with or in close proximity to radioactive materials. Existing standards for flammable gases are not tailored to the unique properties of hydrogen, nor do they take into account its proximity to radioactivity. Examples of where hydrogen is found include large underground high–level radioactive waste tanks, process vessels and piping, waste drums, battery rooms, pump pits, laboratory experimental equipment, and tritium storage vessels. 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 better 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.

Appendix: Backup Slides (PowerPoint pages).

Table 1-Combustion Properties of Hydrogen and Other Common Flammable Gases.

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%)

Table 2 Unmitigated Consequences of Deflagration in Selected Defense Nuclear Facilities

Facility	Event	MOI[a]	Worker Consequences	References
Tritium Extraction Facility (SRS)	Earthquake induced multiple room fire (extremely unlikely)	1.6 REM	Prompt fatality Acute life threatening or permanently disabling injury >100 REM	WSRC-SA-1.2-Vol4 Rev 0 Aug 2005
Tank Farms (SRS)	Waste Tank Explosion (extremely unlikely)	>25 REM	>100 REM	Wsrc-SA-2002-00007 Rev 3
PDCF[b] (SRS)	Seismic induced three room fire	>25 REM	>100 REM	S-PAS-F-00001, Rev B July 21, 2004
IWTU[c] (INL)	CRR Vessel Deflagration	0.00024 REM	1.5 REM @100m	SAR-219 Rev 3
H Canyon (SRS)	Dissolver hydrogen deflagration	>5 REM	>25 REM @600m potential prompt death	WSRC-SA-2001-00008 (Rev 6)

[a] Maximum Exposed Off-Site Individual

[b] Pit Disassembly and Conversion Facility

[c] Integrated Waste Treatment Unit

System/component	Primary			Secondary		
	Class	Principle	Control	Class	Principle	Control
Sintering furnace	Preventive	Fuel	Lean fuel burnoff	Mitigative Mitigateive	Suppression Containment	Flame curtain Robust design
SRS HLW tank	Preventive	Fuel	Dilution	Preventive Preventive	Fuel Fuel	Ignition Scavenging
Tritium Extraction Facility	Mitigative	Containment	Design	Preventive Preventive	Oxidant Fuel	Inerting Removal
Hanford HLW tank with organics	Preventive	Fuel	Dilution	Preventive Preventive	Fuel Fuel	Ignition Temperature
DWPF	Preventive	Fuel	Alter generation	Mitigative	Containment	Design
Pulse Jet Mixer	Preventive	Fuel	Physical intervention	Mitigative	Containment	Design
BWR with hydrogen injection	Mitigative	Containment	Design	Preventive	Fuel	Recombination
Steam reforming	Preventive	Fuel	Process control	Mitigative	Containment	Design
Gravel Gertie	Mitigative	Suppression	Design	Preventive	Fuel	Administrative
Tritium Facility	Mitigative	Containment	Design			
Battery Room	Preventive	Fuel	Dilution	Preventive	Fuel	Monitor
Hanford HLW BDGRE tank	Preventive	Fuel	Dilution	Preventive	Fuel	Physical intervention (mixer pump)
IMUST	Preventive	Fuel	Ignition	None	n/a	n/a
SRS Tank 48	Preventive	Oxidant	Inerting	Preventive	Fuel	Dilution

Table 3-Examples of Deflagration/Detonation Safety Hierarchy