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Hydrogen in Pipes and Ancillary Vessels (HPAV)

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ABSTRACT

During the end of World War II and through the Cold War, the nation was rushing to produce plutonium at the Hanford Site to aid with the production of atomic and nuclear weapons. Unfortunately, the production of this element came with a heavy cost. Today there are 53 million gallons of radioactive waste stored in underground tanks at the Hanford Site in Washington. The U.S. Department of Energy Environmental Management Division has been tasked with dealing with this waste. In order to complete this task, a new, never before built, Waste Treatment Plant (WTP) is being constructed at Hanford in order to process and vitrify the waste for safe storage.

The waste that will be processed at the WTP is known to generate hydrogen, nitrous oxide, and nitrogen. This potentially explosive mixture of gas can build up in the pipes within the black cells as well as the hot cells of the WTP and can cause unwanted occurrences such as detonation, deflagrations, and detonation to deflagration transition (DDT). These occurrences can lead to permanent deformation of the pipes in the aforementioned areas of the WTP. This is an issue especially within the black cells since they are to last for the entire 40 years of service life. The problem lies in that the buildup of these gases can cause a rapid chemical reaction which converts the chemical potential energy of the gases into thermal and kinetic energy. The products of the combustion go on to cause any adjacent un-burnt gas to react. This wave of burning gas continues from the ignition source down to the other end of the pipe. There are three main ways in which the combustion of these flammable gases can cause damage within the pipe: deflagration, detonation, and deflagration-to-detonation transition (DDT).

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1. INTRODUCTION

The Hanford Site in Washington currently stores an estimated 53 million gallons of radioactive waste contained in large underground tanks throughout the site. One of the main tasks assigned to the U.S. Department of Energy's Environmental Management Office is to contain the waste in a manner that will pose as small a threat as possible to the environment. There are many concerns in regards to the storage and movement of radioactive waste but the one that this report will focus on is the generation of hydrogen gas within waste containers and the pipes used to transport the waste throughout the site as well as within the waste treatment plant (WTP).

Figure 1. Aerial view of the High-Level Waste Facility.

Gas generation in high-level radioactive tank waste is one of the major safety issues at the Hanford Site. Out of the gases generated from tank waste, such as nitrogen, nitrous-oxide, ammonia, and methane, hydrogen is of primary concern. Understanding how hydrogen is generated in the waste and the ability to predict the gas generation rate is essential for controlling and preventing the flammable gas hazards which may occur during interim storage, waste transfers, retrieval, and treatment.

Figure 2. Aerial view of construction of one of the tank farms.

Determining the analysis and design criteria for hydrogen in piping and ancillary vessels (HPAV) occurrences has been an arduous task since, until very recently, there has only been limited test information or industry experience to fully understand the hydrodynamic phenomena and the resulting reactions and forces associated with such occurrences.

The WTP has been constructed with hot cells and black cells in order to protect workers from the high levels of radiation associated with the high-level waste. The problem with these cells, especially the black cells, is that they are virtually inaccessible for maintenance and repair. They have been designed to last for the entire 40 years of service life of the WTP. The black cells contain a great deal of pipes in which hydrogen build up may occur. This highlights the need for HPAV studies and research in order to be sure that such events do not cause any permanent damage and if this cannot be ensured then some type of control must be implemented in order to vent any hydrogen build up.

Figure 3. WTP piping module.

2. EXECUTIVE SUMMARY

This research work has been supported by the DOE-FIU Science & Technology Workforce Initiative, an innovative program developed by the U.S. Department of Energy's Environmental Management (DOE-EM) and Florida International University's Applied Research Center (FIU-ARC). During the summer of 2012, a DOE Fellow intern, Janty Ghazi, spent 10 weeks doing a summer internship at DOE-HQ under the supervision and guidance of Mr. James Poppiti. The intern's project was initiated on June 4, 2012, and continued through August 10, 2012 with the objective of understanding HPAV as it pertains to the WTP, especially within the black cells and hot cells.

3. RESEARCH DESCRIPTIONS

Hydrogen Generation

The chemical content as well as the radioactive nature of the material within the waste can lead to the generation of hydrogen gas. Hydrogen is generated in the waste through four main mechanisms: thermolysis, water radiolysis, organic radiolysis, and corrosion.

Thermolysis

N_2, N_2O, and H_2 generation have been shown to result from the oxidative degradation of hydroxyethylenediaminetriacetate (HEDTA) ions. Formaldehyde is one of the products of the decomposition of HEDTA and it happens to be an important organic source of hydrogen. Formaldehyde can react with a base and release hydrogen.

$$H_2CO + H_2O\ (OH^-) \rightarrow HCOO^- + H_2$$

Studies of gas generation have indicated that the reaction rate is dependent on the temperature and are subject to Arrhenius behavior in which the generation rate increases exponentially with temperature.

$$Rate_{thm} = A\ e^{-E/RT}$$

Where:

A = a constant
E = the activation energy

Water Radiolysis

When water is exposed to radiation it can generate hydrogen along with hydroxyl radicals and solvated electrons. This makes water in a radioactive environment a source of hydrogen generation.

$$H_2O + \text{radiation} \rightarrow H^- + H^+ + OH^- + e_{aq}^-$$

$$e_{aq}^- + H + H_2O \rightarrow H_2 + OH^-$$

$$H + H \rightarrow H_2$$

The presence of salts such as nitrate and nitrite greatly suppresses the hydrogen generated through the radiolysis of water by consuming the hydrogen and solvated electrons that are generated.

$$e_{aq}^- + NO_3^- \rightarrow NO_3^{2-}$$

$$H^- + NO_2^- \rightarrow NO^- + OH^-$$

Organic Radiolysis

Hydrogen radicals formed by water radiolysis can remove hydrogen from organic compounds and cause an oxidation reaction with the organic complexants as well as the organic solvents and generate hydrogen gas.

$$H + R\text{-}H \rightarrow H_2 + R$$

Where:

R-H = an organic component with a hydrogen atom

Corrosion

Hydrogen gas can also be generated through corrosion. This typically occurs when caustic liquids come into contact with the carbon steel tank walls.

$$2H_2O + Fe \rightarrow Fe(OH)_2 + H_2$$

The presence of salt inhibits the corrosion of the carbon steel as well as consumes the generated hydrogen.

Laboratory Measured Hydrogen Generation Rates

Pacific Northwest National Laboratory did tests to determine gas generation rates of waste samples which are heated and maintained at different temperatures. The rate measured at different temperatures is referred to as the thermolysis rate. Since the dose rate from the individual samples is relatively small compared to the dose it would receive in the tank, and external dose of radiation was introduced in order to simulate the radiolytic reaction.

Table 1. Laboratory Measurements of Hydrogen Generation Rates With or Without External Radiation at Different Temperatures

Tanks	Temperature (°C)	Rate without External Rad. (mole H_2/ kg sample/day)	Rate With External Rad. (mole H_2/ kg sample/day)	Effective Radiolysis Rate (mole H_2/ kg sample/day)
241-A-101[1]	60	6.90E-07	6.80E-06	6.11E-06
	60	8.70E-07	8.90E-06	8.03E-06
	90	9.60E-06	4.60E-05	3.64E-05
	90	1.10E-05	4.90E-05	3.80E-05
	120	1.70E-04	2.60E-04	9.00E-05
	120	1.80E-04	2.80E-04	1.00E-04
241-S-102[2]	60	1.20E-06	1.60E-05	1.48E-05
	60	1.70E-06	1.50E-05	1.33E-05
	80	7.00E-06	3.20E-05	2.50E-05
	80	7.30E-06	2.80E-05	2.07E-05
	100	2.70E-05	9.60E-05	6.90E-05
	100	2.70E-05	9.50E-05	6.80E-05
	120	1.60E-04	2.70E-04	1.10E-04
	120	2.20E-04	2.70E-04	5.00E-05
241-S-106[3]	60	1.10E-06	9.90E-06	8.80E-06
	60	1.20E-06	1.00E-05	8.80E-06
	90	9.40E-06	3.60E-05	2.66E-05
	90	1.40E-05	4.30E-05	2.90E-05
	120	5.50E-05	1.70E-04	1.15E-04
	120	8.70E-05	1.70E-04	8.30E-05
241-U-103[4]	60	3.20E-06	2.30E-05	2.05E-05
	60	3.70E-06	3.70E-05	3.45E-05
	90	2.70E-05	1.40E-04	1.04E-04
	90	2.10E-05	9.60E-05	5.96E-05
	120	5.20E-04	NA	NA
	120	5.60E-04	NA	NA
241-AN-105[5]	61	5.34E-06	NA	NA
	58	4.79E-06	NA	NA
	82	3.01E-05	NA	NA
	78	2.23E-05	NA	NA
	102	1.97E-04	NA	NA
	96	1.25E-04	NA	NA
	103	1.72E-04	NA	NA
	96	7.38E-05	NA	NA

Table 2. Laboratory Measurements of Hydrogen Generation Rates With or Without External Radiation at Different Temperatures (Continued)

Tanks	Temperature (°C)	Rate without External Rad. (mole H_2/ kg sample/day)	Rate With External Rad. (mole H_2/ kg sample/day)	Effective Radiolysis Rate (mole H_2/ kg sample/day)
241-SY-103[6]	60	7.20E-06	2.80E-05	2.08E-05
	60	9.10E-06	2.50E-05	1.59E-05
	75	2.50E-05	4.00E-05	1.30E-05
	75	2.70E-05	3.40E-05	9.00E-06
	90	7.20E-05	8.50E-05	1.20E-05
	90	7.30E-05	8.30E-05	1.10E-05
	105	2.80E-04	2.20E-04	NA
	105	4.60E-04	2.50E-04	NA
	120	1.10E-03	6.70E-04	NA
	120	1.20E-03	8.00E-04	NA
241-AW-101[7]	60	8.80E-06	1.20E-04	1.11E-04
	60	9.00E-06	1.00E-04	9.10E-05
	90	1.60E-04	5.60E-04	4.00E-04
	90	1.70E-04	4.40E-04	2.70E-04
	120	2.20E-03	2.00E-03	NA
	120	2.30E-03	2.00E-03	NA

Tables 1 and 2 depict the results from some of the tanks sampled. They are representative of the different tanks found at the different tanks farms. The tests were conducted with at least two samples from each tank subjected to each of the conditions examined. The tables list the highest measured rates from samples from seven different tanks with and without external radiation sources and at different temperatures. The difference between the two measured rates is also shown.

Field-Observed Hydrogen Generation Rates of Tank Waste

Based on waste level measurements, hydrogen monitoring data, gas composition data, etc., the hydrogen generation rate of the Hanford Site tanks can be estimated. The total generation rate is the sum of the steady release rate and the gas retention rate in the tank waste. The release rate is estimated using the following equation:

$$R_{H2} = V_r / [(1[H_2])-1]$$

Where:

V_r = airflow rate in cfm

R_{h2} = hydrogen release rate in the dome space in cfm

$[H_2]$ = concentration in volume percent

Table 3. Tank 241-AY-102 Hydrogen Concentration, Vent Rate, and Hydrogen Release Rate

Month	$[H_2]$ (ppm)	Vent Rate (ft^3/min)	Release Rate (ft^3/day)
Jun 1998	62.8	267	23.8
Jul 1998	58.6	258	23.3
Aug 1998	72.6	215	22.3
Sep 1998	63.7	266	23.5
Oct 1998	47.9	361	24.9
Nov 1998	49.7	348	24.7
Dec 1998	55.4	277	21.9
Average	58.7	284	23.5

Note:
ppm = parts per million

Tank 241-AY-102 is equipped to monitor these rates and the monthly averages from June 1998 to December 1998 are depicted in Table 3.

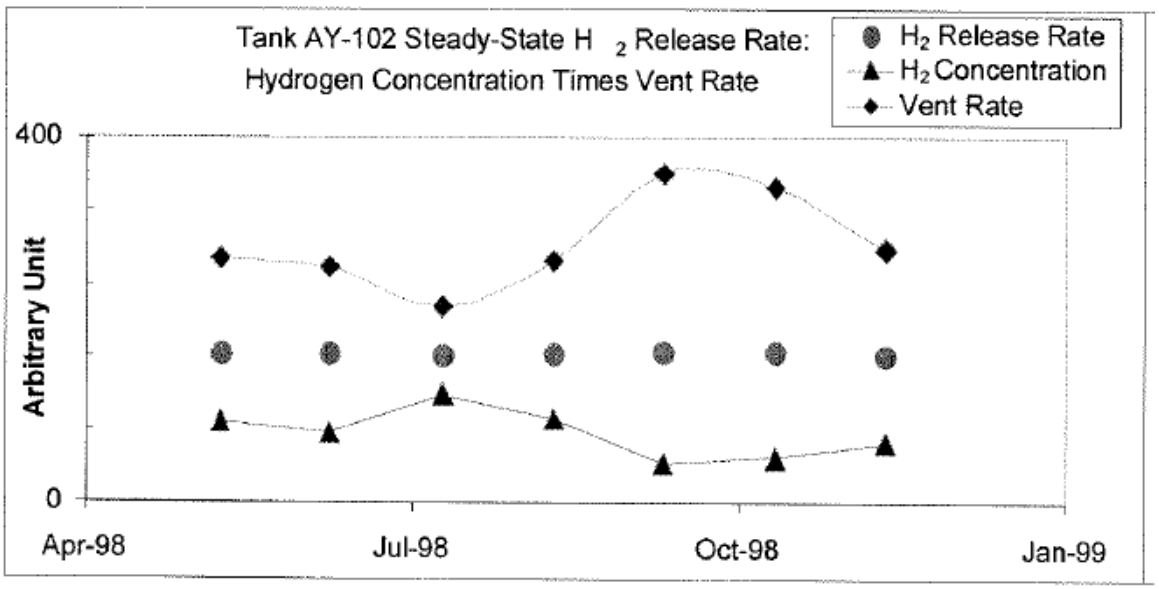

Figure 4. The hydrogen release rate, hydrogen concentration, and vent rate in the headspace of Tank 241-AY-102.

Figure 4 is a graphical representation of the data in Table 3. The hydrogen concentration data and vent rate are precisely 180° out of phase, and the product of these two curved lines gives a straight line of hydrogen release rate in the middle. Although this data is not available for all the tanks on the site, the hydrogen generation rates can be estimated with the data that is available.

Table 4. Field-Estimated Hydrogen Accumulation Rate, Release Rate, and Generation Rate for Hanford Tank Waste

Tanks	Accumulation Rate		Release Rate		Generation Rate	
	ft^3/min	L/day	ft^3/min	L/day	ft^3/min	L/day
241-SY-101	1.34E-02	545	1.10E-02	449	2.44E-02	993
241-SY-102	0	0	7.26E-04	30	7.26E-04	30
241-SY-103	1.25E-03	51	2.30E-03	94	3.54E-03	145
241-AW-101	6.74E-04	27	2.50E-03	102	3.17E-03	129
241-AN-101	0	0	2.50E-04	10	2.50E-04	10
241-AN-103	1.91E-03	78	2.85E-03	116	4.76E-03	194
241-AN-104	0	0	2.55E-03	104	2.55E-03	104
241-AN-105	7.65E-04	31	2.30E-03	94	3.06E-03	125
241-AN-107	0	0	5.25E-03	214	5.25E-03	214
241-AY-102	0	0	1.70E-02	691	1.70E-02	691
241-AZ-101	0	0	9.44E-03	385	9.44E-03	385
241-AZ-102	0	0	1.90E-02	775	1.90E-02	775
241-A-101	0	0	2.14E-03	87	2.14E-03	87
241-C-104	0	0	2.21E-03	90	2.21E-03	90
241-C-106	0	0	9.03E-03	368	9.03E-03	368
241-S-102	3.28E-04	13	1.31E-03	53	1.64E-03	67
241-SX-101	0	0	4.20E-04	17	4.20E-04	17
241-SX-103	0	0	1.27E-03	52	1.27E-03	52
241-SX-104	0	0	2.51E-04	10	2.51E-04	10
241-SX-105	0	0	4.82E-03	197	4.82E-03	197
241-SX-106	0	0	1.24E-03	50	1.24E-03	50
241-SX-109	0	0	2.70E-04	11	2.70E-04	11
241-U-102	0	0	1.10E-03	45	1.10E-03	45
241-U-103	6.73E-05	3	1.41E-03	58	1.48E-03	60
241-U-105	2.56E-04	10	1.35E-03	55	1.61E-03	65
241-U-106	0	0	6.62E-04	27	6.62E-04	27
241-U-107	1.58E-04	6	6.69E-04	27	8.27E-04	34
241-U-108	2.96E-04	12	8.15E-04	33	1.11E-03	45
241-U-109	0	0	6.16E-04	25	6.16E-04	25
241-U-111	0	0	7.11E-04	29	7.11E-04	29

Table 4 shows the gas generation rates for some of the other tanks which are important to consider for HPAV studies because this will determine the hydrogen generation rate of the waste that will be going through the pipes in the WTP.

Fundamental Gaseous Explosion Characteristics

There exist three main types of hydrogen ignition events in pipes: deflagration, detonation, and deflagration-to-detonation transition (DDT). The combustion wave starts by some ignition source and continues by propagating at a relatively low, subsonic velocity. This

subsonic mode of combustion is known as a deflagration. In a deflagration, the unburned gas upstream of the combustion wave is disturbed, causing some of this unburned gas to move away from the ignition end of the pipe before the self-propagating combustion wave arrives. When this occurs, the observed deflagration speed (in a fixed reference frame) is the sum of the displacement flow velocity of the expanding reaction products and the burning velocity. In a deflagration event, the pressure in the pipe is assumed to be the same at any given time with the exception of minor compression waves formed ahead of the reaction front as a result of displacement flow.

A combustion mode that is supersonic is referred to as a detonation. Since the reacting shock wave is moving faster than the speed of sound within the unburned gas, it moves into a field of unreacted/undisturbed gas. Detonations, because of their nature, have extremely strong pressure gradients across their compression shock wave. The pressure in the pipe remains at the initial pressure until it immediately rises due to the arrival of the flame front. This is then followed by rapid pressure decay as the reaction products behind the compressive shock wave expand and decelerate to stationary conditions.

Since deflagrations affect the environment that they propagate into, there are a number of feedback mechanisms that generate turbulence and cause the flame to accelerate. When the flame front accelerates to the point where it approaches about half of the equilibrium detonation velocity, the flame suddenly jumps from deflagration to detonation burning mode. This phenomenon is known as deflagration-to-denotation transition (DDT). DDT produce peak pressures several times higher than the subsequent detonation over a short distance which causes them to be of interest to HPAV because of the higher peak pressures produced.

Deflagration

Deflagrations are characterized by a gradual pressure rise in comparison with a detonation. Figure 6 shows a typical deflagration trace. Deflagration occurs in the range of milliseconds to seconds and the associated pressure rise takes place over a timescale in excess of 1 millisecond before a peak is reached.

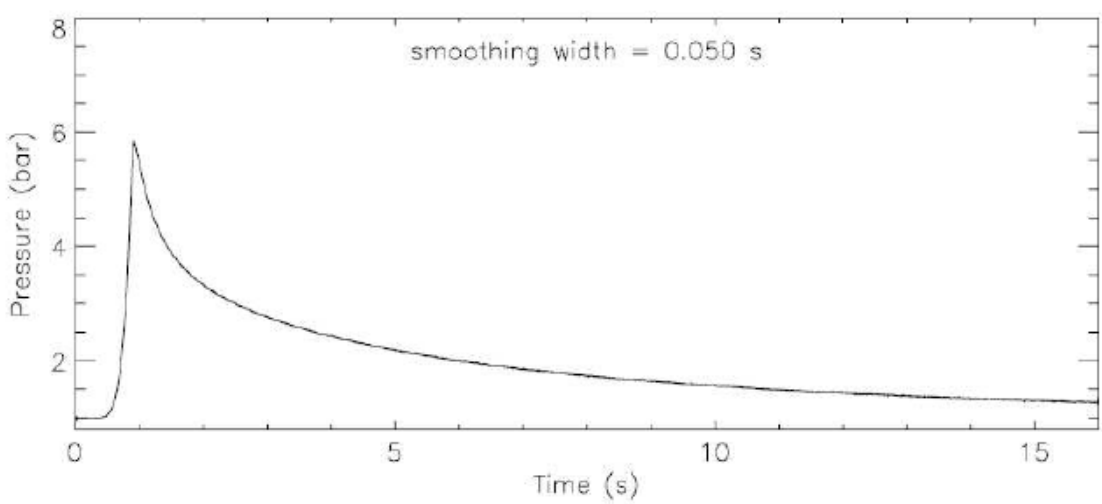

Figure 5. Typical HPAV deflagration pressure-rise.

Deflagration burning modes are inherently unstable. Due to this, as they propagate through the gas space, they will generally accelerate until they transition to detonations given enough propagation distance under appropriate boundary conditions. If the correct boundary conditions are not met, the deflagration will propagate far below sonic velocity. This is usually referred to as “weak deflagration” and normally occurs whenever the speed of the propagating wave is below the speed of sound through the un-burnt gas ahead of the flame.

A “weak deflagration” does not produce significant pressure gradients across the reaction zone, since the gas ahead of the flame front has sufficient time to move in the direction of flame propagation in order to accommodate the expansion of the pressurized products of the reaction behind the flame front. For a closed piping system, the pressure tends to rise and approach a peak that is only achieved when the reaction has consumed the entire gas pocket in the pipe. In Figure 5, the deflagration had traveled through the entire piping system in approximately 1.0 seconds where it reached a peak of about 6 bars and then slowly fell as heat transferred to the pipe walls, causing the reaction products to cool back to near ambient conditions in the following 20 seconds.

Deflagration-to-Detonation Transition (DDT)

When conditions are favorable and the flame is able to accelerate up to the maximum deflagration speed, given that there is sufficient run-up distance (distance from ignition source to point where detonation begins), the deflagration will eventually transition to detonation, a phenomenon referred to as deflagration-to-detonation transition (DDT).

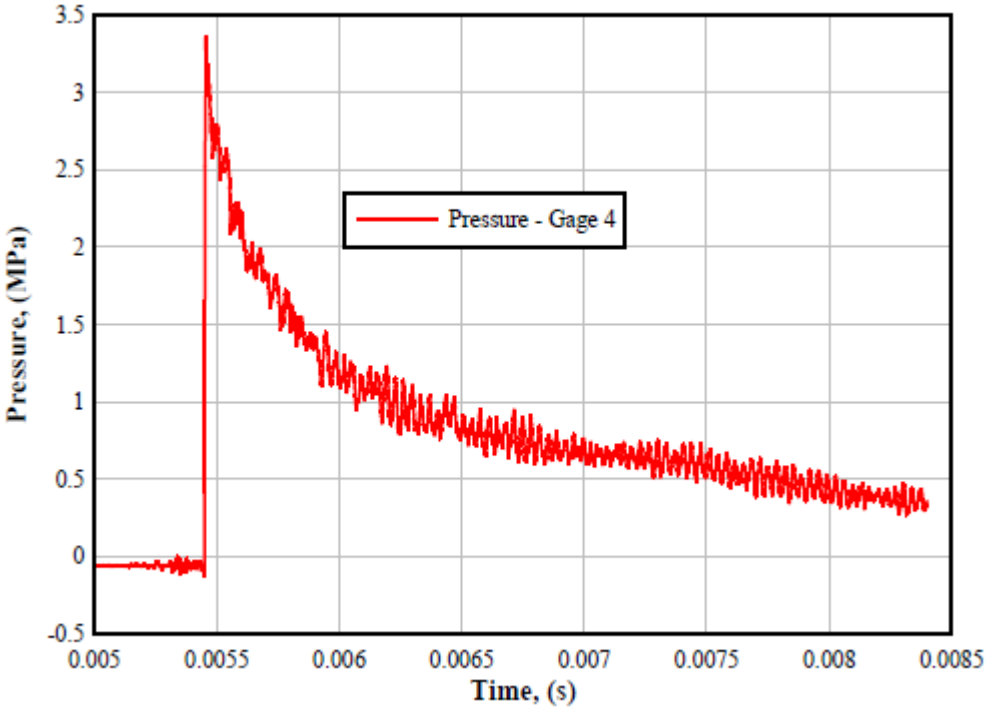

Figure 6. Typical HPAV detonation pressure trace.

As can be seen in Figure 6, the time scale of a detonation is in the order of microseconds to milliseconds as opposed to that of deflagration which is in the order of milliseconds to seconds. The pressure rise is nearly instantaneous in detonation and the peak pressure is approximately twice that of deflagration.

Mechanisms Involved in DDT

Deflagrations usually require much less energy for ignition than do detonations. Deflagrations require fractions of milli-joules while detonations require joules to kilo-joules. Since it is difficult to foresee such large ignition energy sources to cause detonation within the piping in the WTP, it is assumed that any detonations will start off as deflagrations and through DDT transition into a detonation.

The mechanisms in a DDT are divided into two phases: flame acceleration to maximum deflagration velocity, and detonation onset phase. The initial flame acceleration during a DDT event is determined by various factors which include chemical reaction rates, heat loss to pipe walls, energy loss and turbulence associated with pipe wall roughness, acoustic interaction with flexible boundaries, and the shape of the confining boundary. These factors affect the point at which the necessary velocity for DDT is reached. Once the necessary velocity is attained, the ensuing detonation can occur due to one of several different mechanisms which include: merging of precursor shock waves leading to a high-temperature interface where auto-ignition and subsequent formation of the detonation occur; local hot spots that spontaneously form in the turbulent reaction zone leading to a “detonation bubble” and a resonation wave back into the combustion products; and interactions between a compression pulse in the reaction zone and a precursor shock, where corners and concave walls can cause “shock focusing” which strengthen the interactions between the compression pulse and the reflected precursor shocks.

4. RESULTS AND ANALYSIS

Structural Analysis and Test

The greatest area of concern in regard to HPAV is the strain and possible permanent deformation that may result from the pressure build up due to a hydrogen ignition event. Since the pipes in the black cells are extremely difficult if not impossible to repair or replace, they must undergo strenuous testing in order to ensure they will survive any and all expected HPAV events.

In October of 2007, it was decided that an HPAV test program was necessary in order to better understand the effects as they pertain to the WTP. Various contractors, including Bechtel National, Inc. (BNI), Dominion Engineering, Inc. (DEI), Southwest Research Institute (SwRI), and California Institute of Technology (CIT), were given the task of performing tests on deflagration, detonation, and deflagration-to-detonation transition (DDT) as well as the hydrodynamics and structural dynamics of the related piping systems.

Table 5. Tests Performed Related to HPAV

Testing Performed	CIT	SwRI 2008	SwRI 2009	DEI
Asymmetry/Factors	√			
Deflagrations	√	√	√	
DDT	√	√	√	
R-DDT	√	√	√	
Structural Response	√	√		
Components		√	√	
Gas Retention				√
Bubble Formation				√
Vertical Gas pockets			√	
Horizontal Min Detonable Geometry	√			

Table 5 shows the various tests conducted by the different contractors and the topics each dealt with. For the purpose of this report, only some of these tests will be discussed.

2009 SwRI HPAV DDT Test Description

The two main objectives of this test was to quantify how a steady state detonation develops in open- and close-ended pipes and to quantify the maximum DDT distance in 4-inch diameter pipes. The test apparatus consisted of a 120 foot long 4-inch diameter schedule 40 pipe. The apparatus was equipped with 20 blast pressure transducers and 18 biaxial strain gauges. The gas inside was ignited using a standard glow plug at one end of the pipe. In this test, three gas mixtures with different concentrations of H_2 were used, including 11%, 11.5%, and 12.0%.

Figure 7. SwRI 2009 experimental apparatus.

Throughout these experiments no detonations where observed and it is believed to be due to the fact that the minimum H_2 concentration for detonation is between 12 and 12.5%.

2009 SwRI HPAV R-DDT Test Description (L/D Effects)

The purpose of these experiments was to determine the length-to-diameter (L/D) effects for run up in R-DDT in 4-inch diameter pipes. The apparatus used in the test was 4-inch diameter spools assembled into lengths of 18, 36, and 56 feet. The detonation was again initiated with a glow plug and blast pressure transducers along with biaxial strain gauges were used to measure the results.

Figure 8. SwRI 2009 R-DDT experimental apparatus.

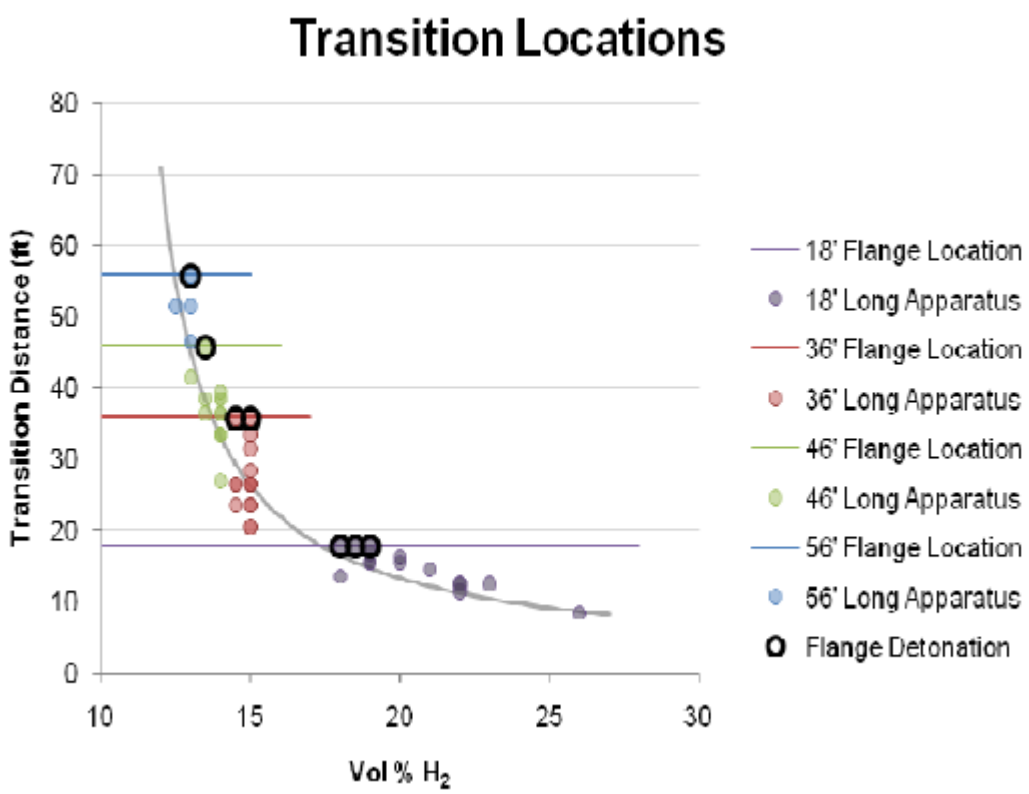

Figure 9. SwRI 2009 R-DDT distance for different pipe lengths.

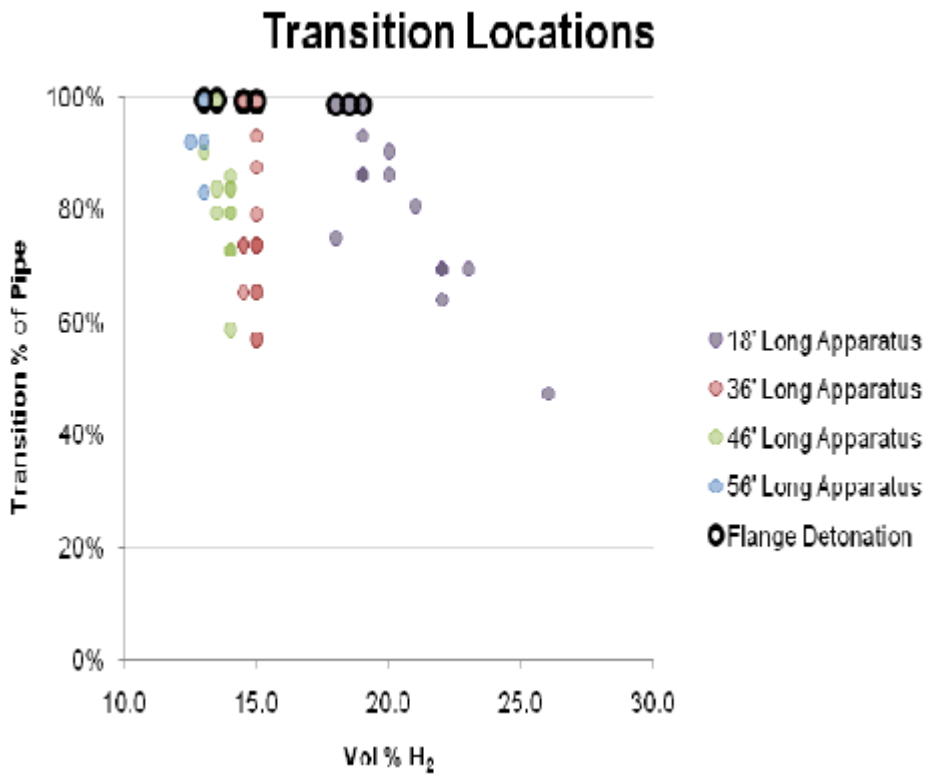

Figure 10. SwRI 2009 R-DDT distance as a percentage of pipe length.

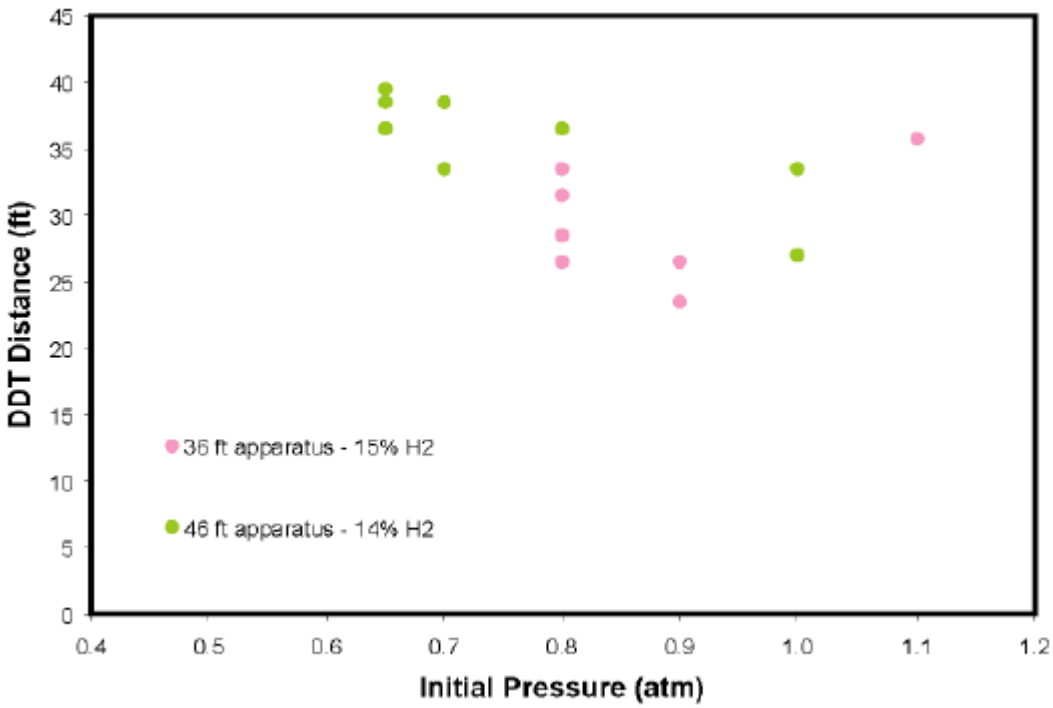

Figure 11. SwRI 2009 R-DDT distance vs. initial pipe pressure for the 36 ft and 46 ft apparatus.

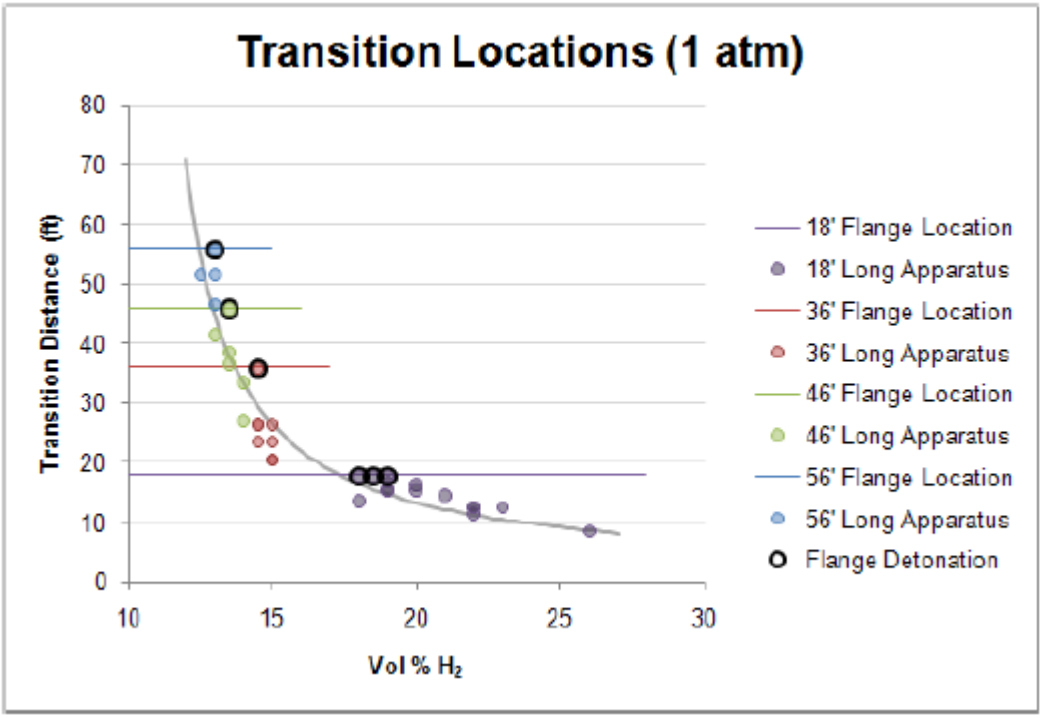

Figure 12. SwRI 2009 R-DDT distance at an initial pressure of 1 atm.

Table 6. SwRI 2009 Test Results

Test No.	Length (ft)	Vol % H_2	Est. DDT Trans. (ft)	Est. DDT Trans. (% Length)	Test Pressure (atm)
DDT4G2T29	18	26.0	8.5	47%	1.00
DDT4G2T30	18	26.0	8.5	47%	1.00
DDT4G2T31	18	26.0	8.5	47%	1.00
DDT4G2T23	18	23.0	12.5	69%	1.00
DDT4G2T24	18	23.0	12.5	69%	1.00
DDT4G2T25	18	23.0	12.5	69%	1.00
DDT4G2T19	18	22.0	12.5	69%	1.00
DDT4G2T20	18	22.0	11.5	64%	1.00
DDT4G2T21	18	22.0	12.5	69%	1.00
DDT4G2T22	18	22.0	12.5	69%	1.00
DDT4G2T26	18	21.0	14.5	81%	1.00
DDT4G2T27	18	21.0	14.5	81%	1.00
DDT4G2T28	18	21.0	14.5	81%	1.00
DDT4G2T15	18	20.0	16.25	90%	1.00
DDT4G2T16	18	20.0	15.5	86%	1.00
DDT4G2T17	18	20.0	15.5	86%	1.00
DDT4G2T18	18	20.0	15.5	86%	1.00
DDT4G2T4	18	19.0	15.5	86%	1.00
DDT4G2T5	18	19.0	15.5	86%	1.00
DDT4G2T6	18	19.0	15.5	86%	1.00
DDT4G2T11	18	19.0	16.75	93%	1.00
DDT4G2T12	18	19.0	15.5	86%	1.00
DDT4G2T13	18	19.0	17.75*	99%	1.00
DDT4G2T14	18	19.0	17.75*	99%	1.00
DDT4G2T7	18	18.5	17.75*	99%	1.00
DDT4G2T8	18	18.5	17.75*	99%	1.00
DDT4G2T9	18	18.5	17.75*	99%	1.00
DDT4G2T10	18	18.5	17.75*	99%	1.00
DDT4G2T1	18	18.0	13.5	75%	1.00
DDT4G2T2	18	18.0	17.75*	99%	1.00
DDT4G2T3	18	18.0	17.75*	99%	1.00
DDT4G2T32	36	15.0	20.5	57%	1.00
DDT4G2T33	36	15.0	23.5	65%	1.00
DDT4G2T34	36	15.0	23.5	65%	1.00
DDT4G2T75	36	15.0	20.5	57%	1.00
DDT4G2T76	36	15.0	26.5	74%	1.00
DDT4G2T77	36	15.0	26.5	74%	1.00
DDT4G2T79	36	15.0	26.5	74%	0.90

Test No.	Length (ft)	Vol % H_2	Est. DDT Trans. (ft)	Est. DDT Trans. (% Length)	Test Pressure (atm)
DDT4G2T80	36	15.0	23.5	65%	0.90
DDT4G2T81	36	15.0	31.5	88%	0.80
DDT4G2T82	36	15.0	26.5	74%	0.80
DDT4G2T83	36	15.0	33.5	93%	0.80
DDT4G2T85	36	15.0	26.5	74%	0.80
DDT4G2T86	36	15.0	26.5	74%	0.80
DDT4G2T88	36	15.0	28.5	79%	0.80
DDT4G2T96	36	15.0	35.75*	99%	1.10
DDT4G2T41	36	14.5	23.5	65%	1.00
DDT4G2T42	36	14.5	26.5	74%	1.00
DDT4G2T43	36	14.5	26.5	74%	1.00
DDT4G2T44	36	14.5	35.75*	99%	1.00
DDT4G2T45	36	14.5	35.75*	99%	1.00
DDT4G2T46	36	14.5	26.5	74%	1.00
DDT4G2T47	36	14.5	26.5	74%	1.00
DDT4G2T49	36	14.5	26.5	74%	1.00
DDT4G2T50	46	14.0	27	59%	1.00
DDT4G2T51	46	14.0	33.5	73%	1.00
DDT4G2T52	46	14.0	33.5	73%	1.00
DDT4G2T97	46	14.0	33.5	73%	1.00
DDT4G2T98	46	14.0	36.5	79%	0.80
DDT4G2T100	46	14.0	38.5	84%	0.70
DDT4G2T101	46	14.0	33.5	73%	0.70
DDT4G2T102	46	14.0	39.5	86%	0.65
DDT4G2T103	46	14.0	36.5	79%	0.65
DDT4G2T104	46	14.0	38.5	84%	0.65
DDT4G2T57	46	13.5	45.75*	99%	1.00
DDT4G2T58	46	13.5	38.5	84%	1.00
DDT4G2T59	46	13.5	38.5	84%	1.00
DDT4G2T60	46	13.5	36.5	79%	1.00
DDT4G2T62	46	13.5	36.5	79%	1.00
DDT4G2T63	46	13.5	36.5	79%	1.00
DDT4G2T53	46	13.0	41.5	90%	1.00
DDT4G2T105	56	13.0	51.5	92%	1.00
DDT4G2T106	56	13.0	46.5	83%	1.00
DDT4G2T109	56	13.0	55.75*	100%	1.00
DDT4G2T64	56	12.5	51.5	92%	1.00

*Detonation on Flange

Seventy three of the tests resulted in detonations. The results were also consistent with other tests since they showed considerable change in DDT distance for gas mixtures with lower H_2 concentrations.

2008 SwRI HPAV Structural System Response (SSR) Test Description

The purpose of this test was to understand the loads and forces imposed by internal detonation on piping systems. In order to do this, a mock-pipeline was constructed to mimic some of the routes that are to be encountered within the WTP. The instrumentation used to measure the results were dynamic pressure transducers, TOA indicators, biaxial and uniaxial strain gauges, and LVDT displacement transducers.

Figure 13. SwRI 2008 SSR experiment (2 different views).

Table 7. SwRI 2008 SSR Detonation Velocities Between Pressure Transducers

Test	Velocity(m/s)									
	Branch 1					Branch 2		Branch 3 (Branch Line)		
	1-2	2-3	3-4	4-5	5-6	6-7	7-8	6-9	9-10	10-11
SSRT5	-1833.6	-2074.7	-2183.3	-2151.8	-2090.8	-2179.6	-1969.9	2114.6	2098.9	2120.9
SSRT6	-1833.6	-2074.7	-2183.3	-2151.8	-2090.8	-2179.6	-2005.5	2114.6	2098.9	2120.9
SSRT7	-1839.2	-2079.8	-2183.3	-2316.5	-2092.6	-2185.0	-2007.6	2120.8	2105.3	2132.0
SSRT37	-1802.5	-2072.1	-2177.1	-2151.8	-2090.1	-2178.5	-2469.4	2108.5	2098.9	2120.9
SSRT38	-1828.1	-2074.7	-2183.3	-2151.8	-2090.8	-2178.5	-1964.6	2108.5	2098.9	2118.1
SSRT39	-1758.3	-2076.0	-2183.3	-2141.6	-2090.8	-2178.9	-1901.9	2108.5	2098.9	2118.1
SSRT40	-1759.6	-2076.0	-2183.3	-2151.8	-2090.5	-2179.3		2106.5	2098.9	2118.1
SSRT42		-2065.7	-2146.5	-2415.0	-2077.0	-2171.8	-1964.6	2100.4	2094.8	2083.0
SSRT43	-1826.8	-2065.7	-2170.9	-2141.6	-2085.3	-2205.0	-1926.3	2116.7	2085.9	2137.6
SSRT44	-1821.3	-2065.7	-2274.3	-2182.8	-2078.4	-2205.0	-1924.7	2116.7	2089.5	2126.4
SSRT45	-1829.5	-2073.4	-2189.6	-2141.6	-2093.2	-2182.8		2110.5	2102.5	2120.9
SSRT46	-1828.1	-2072.1	-2183.3	-2151.8	-2091.9	-2180.3	-1966.2	2108.5	2101.6	2120.9
SSRT47	-1824.0	-2069.5	-2183.3	-2151.8	-2091.5	-2179.3	-1974.0	2110.5	2100.7	2120.9
SSRT54	-1828.1	-2069.5	-2170.9	-2102.0	-2088.4	-2176.8	-1958.5	2106.5	2094.8	2115.4
SSRT55	-1829.5	-2068.3	-2170.9	-2102.0	-2087.3	-2172.1	-1958.1	2110.5	2093.5	2112.7
Average	**-1817.3**	**-2071.9**	**-2184.4**	**-2173.7**	**-2088.6**	**-2182.2**	**-1999.3**	**2110.8**	**2097.5**	**2119.1**
St Dev	26.1	4.3	26.9	82.6	4.9	9.8	144.3	5.1	5.0	11.8

Table 8. SwRI 2008 Estimated DDT Distance

Test No.	Obstruction	Pipe length	H_2 %	Transition Distance	Test No.	Obstruction	Pipe length	H_2 %	Transition Distance
G1T32	Open end	120	15	11.3	G2T50	Closed end	43	12.5	23.1
G1T33	Open end	120	15	11.0	G2T51	Closed end	43	12.5	14.5
G1T34	Open end	120	15	11.4	G2T40	Closed end	71	12.5	38.0
G1T38	Open end	120	13	19.9	G2T41	Closed end	71	12.5	25.0
G1T39	Open end	120	13	28.2	G2T42	Closed end	71	12.5	26.0
G1T40	Open end	120	13	25.9	G3T10	90 Bend	18	14	17.6
G1T48	Open end	120	30	3.5	G3T11	90 Bend	18	14	17.6
G2T6	Closed end	7	18	6.5	G3T12	90 Bend	18	14	18.0
G2T12	Closed end	7	18	4.5	G3T13	90 Bend	18	14	16.6
G2T13	Closed end	7	18	5.5	G3T14	45 Bend	18	14	18.4
G2T14	Closed end	7	18	6.0	G3T15	45 Bend	18	14	21.3
G2T67	Closed end	27	14	16.7	G3T16	45 Bend	18	14	18.4
G2T76	Closed end	27	13	22.9	G3T17	45 Bend	18	14	18.4
G2T77	Closed end	27	13	22.9	G3T18	45 Bend	18	14.5	16.6
G2T78	Closed end	27	13	22.5	G3T19	45 Bend	18	14.5	18.0
G2T79	Closed end	27	13	20.0	G3T20	45 Bend	18	14.5	17.6
G2T16	Closed end	18	18	8.5	G3T21	Elbow	18	14	18.0
G2T19	Closed end	18	16	7.5	G3T22	Elbow	18	14	18.0
G2T21	Closed end	18	15	13.4	G3T23	Elbow	18	14	17.6
G2T22	Closed end	18	15	13.0	G3T24	Elbow	18	14	17.6
G2T23	Closed end	18	14	17.0	G3T25	Elbow	18	14	16.6
G2T24	Closed end	18	14	15.5	G3T26	Elbow	18	14	16.6
G2T25	Closed end	18	14	16.0	G3T27	Elbow	18	14	19.9
G2T26	Closed end	18	14	15.0	G3T28	Elbow	18	14	18.8
G2T27	Closed end	18	13.5	16.5	G3T29	Elbow	18	14	18.8
G2T29	Closed end	18	13.5	16.0	G3T30	Elbow	18	14	18.8
G2T34	Closed end	18	13	16.0	G3T31	Elbow	18	14.5	15.6
G2T35	Closed end	18	13	16.0	G3T32	Elbow	18	14.5	15.1
G2T37	Closed end	18	13	16.0	G3T33	Elbow	18	14.5	15.6
G2T38	Closed end	18	13	16.0	G3T1	90 Bend	27	13	22.5
G2T48	Closed end	43	12.5	22.9	G3T2	90 Bend	27	13	19.2
G2T49	Closed end	43	12.5	19.8					

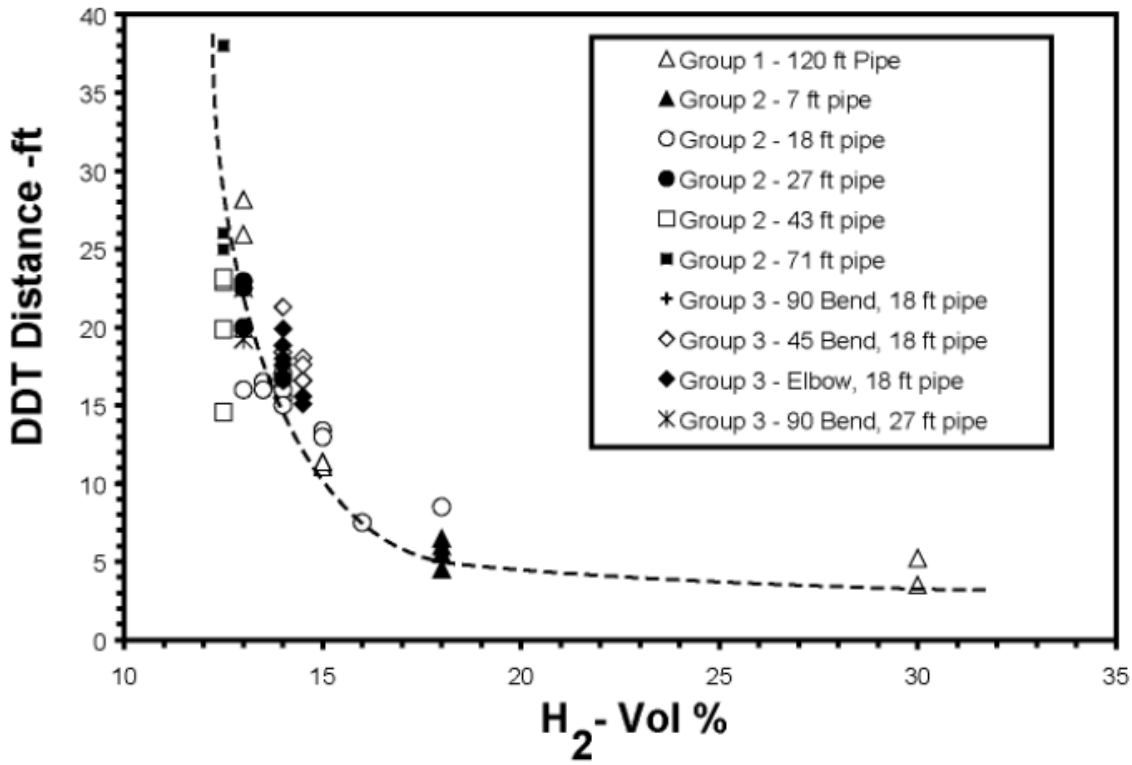

Figure 14. SwRI 2008 DDT distance vs. hydrogen concentration.

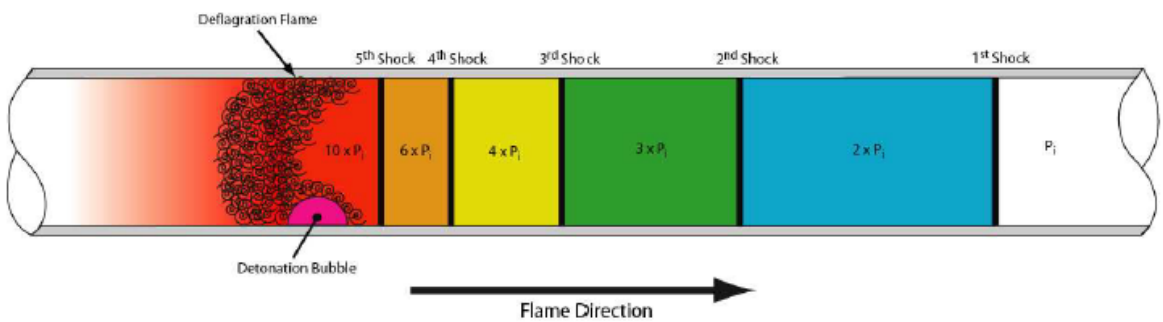

Figure 15. SSR layout.

Eighty experiments were conducted in the SSR apparatus. Detonation experiments were conducted and initiated from different ends of the apparatus. Steady detonations were achieved in all experiments using a gas mixture of 30% H_2 and the resulting velocities are demonstrated in the preceding tables. In an attempt to initiate stable high-speed deflagrations, twenty eight experiments were conducted with hydrogen concentrations of 12%. In none of these was a stable high-speed deflagration achieved.

5. CONCLUSION

The results from the various experiments show that even in the worst case R-DDT scenario, there is still insufficient energy to cause any permanent damage to the pipe. The nuclear grade stainless steel pipes that will be used in the WTP are highly ductile with high fracture toughness. The strain rates seen in the HPAV experiments are within the elastic and elastic-plastic regimes for this material. The energies associated with worst case R-DDT events are still two orders of magnitude less than that of TNT, which is what is necessary for fragmentation of the pipe material. The pipes subjected to many of the HPAV tests showed no detectable signs of degradation due to the repeated HPAV detonations.

It is strongly believed that for geometrically small gas pockets, the overall global system structural response would become negligible. The detonation of small gas pockets will have local effects on pipes which may reach yield depending on the size of the gas pockets. The minimum gas pocket size which can cause yielding of the pipe in excess of 0.2% within the black and hot cells and 2.8% anywhere else within the WTP must be adequately assessed.

The pipes in the black cell and hot cell area serve as the primary confinement/barrier as per the definition of a primary confinement system stated in DOE-HDBK-1132-99 which states: “Primary confinement consists of barriers, enclosures, glove boxes, piping, vessels, tanks, and the like that contain radioactive or other hazardous material.” Its primary function is to prevent release of radioactive or hazardous material to areas other than those in which processing operations are normally conducted. It goes on to state: “The enclosure system, including its internal and external support structures, should therefore be designed to withstand the effects of normal operating conditions, anticipated events, and accidents.” A hydrogen ignition event falls under anticipated events and accidents and, therefore, should be considered in the design so if the pipe weakens significantly due to one of these events based on the limits set forth, it would not meet with the standards set in DOE-HBK1132-99.

Due to the obvious importance of the pipes within the black cells and hot cell areas of the WTP, further testing is planned in order to be certain that an HPAV event will not damage these crucial components. It has been proposed that in order to address the issues related to HPAV, a Quantitative Risk Assessment (QRA) analysis will be conducted.

First, the schedule 40 pipe will undergo tests in order to simulate the various hydrogen ignition events that may occur during WTP operation. Should the test prove that the schedule 40 is resistive enough to the strains caused by the various events, it would be used as planned.

If, however, it surpasses the limits set forth in regards to allowable ware of inner lining and strain, a QRA analysis would then be conducted using schedule 80 pipes. The schedule 80 pipes will undergo the same tests as the schedule 40. The allowable strain limit for the schedule 80 pipe is 7.2%, which is greater than the limit of 0.2% set for the schedule 40 pipe. Should the schedule 80 pipe perform within the limits, the design of WTP will then use this pipe instead of the schedule 40.

Should the schedule 80 pipe also fail these tests, then an active control will be implemented in the design of the tank in order to remove the generated hydrogen from the tanks in order to prevent such ignition events. The exact type of active control has not yet been specified and will be addressed if need for it arises.

6. REFERENCES

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APPENDIX

Appendix A DOE-HDBK-1132-99

SECTION 1

SYSTEMS

This section of the handbook treats systems (e.g., confinement systems, radiation protection, and effluent monitoring and controls) typically used in nuclear facilities to control radiation or radioactive material. The specifics of designing these systems are developed in an iterative fashion by considering hazards and opportunities (alternatives) for prevention and mitigation of accidents involving the hazards. This section provides information based on experience, which the designer may use when developing the design.

1.1 CONFINEMENT SYSTEMS

1.1.1 Introduction and Scope. Safety ventilation and off-gas systems are generally designed to operate in conjunction with physical barriers to form a confinement system that limits the release of radioactive or other hazardous material to the environment and prevents or minimizes the spread of contamination within the facility. Confinement systems should be designed to—

- prevent (if possible) or minimize the spread of radioactive and other hazardous materials to occupied areas;
- minimize the release of radioactive and other hazardous materials in facility effluents during normal operation and anticipated operational occurrences;
- minimize the spread of radioactive and other hazardous materials within unoccupied process areas; and
- limit the release of radioactive and other hazardous materials resulting from accidents, including those caused by severe natural phenomena and man-made events.

The specifics of confinement system design, as they relate to a particular facility, should be guided by an iterative process between safety analyses and design. Safety analyses define the functional requirements of the design, such as the type and severity of accident conditions that the confinement system must accommodate. The design should also consider sources of functional design requirements including maintenance, operability, and process requirements. This section discusses primary, secondary, and tertiary confinement systems, design of confinement ventilation systems, and aspects of confinement system design by nuclear facility type. The American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) *HVAC Applications Handbook* provides general information regarding heating, ventilation, and air conditioning (HVAC) design for confinement systems.

1.1.2 General Considerations. Confinement system features, including confinement barriers and associated ventilation systems, are used to maintain controlled, continuous airflow from the environment into the confinement building, and then from uncontaminated

areas of the building to potentially contaminated areas, and then to normally contaminated areas.

For a specific nuclear facility, the number and arrangement of confinement barriers and their design features and characteristics are determined on a case-by- case basis. Typical factors that affect confinement system design are the type, quantity, form, and conditions for dispersing the hazardous material, including the type and severity of potential accidents. In addition, alternative process and facility design features may reduce potential hazards and the resulting requirements for confinement system design. Engineering evaluations, trade-offs, and experience are used to develop a practical design that achieves confinement system objectives.

Because the number and arrangement of confinement systems required for a specific nuclear facility design cannot be predicted, this discussion describes a conservative confinement system design that uses the three principal confinement systems described below. The discussion assumes that three levels of confinement are necessary or justified. Design decisions for a specific facility should address that facility's hazards and other factors.

- Primary confinement is usually provided by piping, tanks, glove boxes, encapsulating material, and the like, and any off-gas system that controls effluent from within the primary confinement. It confines hazardous material to the vicinity of its processing.
- Secondary confinement is usually provided by walls, floors, roofs, and associated ventilation exhaust systems of the cell or enclosure surrounding the process material or equipment. Except for glove box operations, the area inside this barrier provides protection for operating personnel.
- Tertiary confinement is provided by the walls, floor, roof, and associated ventilation exhaust system of the facility. Tertiary confinement provides a final barrier against release of hazardous material to the environment.

1.1.3 Primary Confinement System. Primary confinement consists of barriers, enclosures, glove boxes, piping, vessels, tanks, and the like that contain radioactive or other hazardous material. Its primary function is to prevent release of radioactive or hazardous material to areas other than those in which processing operations are normally conducted.

Primary confinement of processes that involve readily dispersible forms of material (e.g., solutions, powder or small fragments, gases) is provided by glove boxes or other confining enclosures. Hoods are used when hazards are acceptably low, as indicated by the quantity of the material involved, the specific operation to be performed, and the hazardous nature and chemical form of material involved. The confinement philosophy described below should be applied to any component that serves a primary confinement function, such as conveyor systems, material transfer stations, and ventilation/off-gas systems.

Breaches in the primary confinement barrier that cannot be totally avoided or ruled out (e.g., due to glove or seal failure) should be compensated for by providing adequate inflow of air or safe collection of spilled liquid. Occasional breaches required for anticipated maintenance should be made only under carefully controlled conditions. Primary confinement should

provide for storage of in-process material elsewhere, temporary alternative barriers, and adequate inflow of air to provide contamination control.

The supply and exhaust ventilation system should be sized to maintain in-facility radiation doses at levels as low as reasonably achievable (ALARA) in the event of the largest credible breach. Process equipment and the process itself should be designed to minimize the probability of fire, explosion, or corrosion that might breach the confinement barrier. When handling pyrophoric forms (e.g., chips, filings, dust) of materials in the confinement enclosure, the guidance of DOEHDBK-1081, *Primer on Spontaneous Heating and Pyrophoricity*, should be considered. Halon systems should not be used with pyrophoric metals due to the oxidizing reaction between halon and hot metal.

Primary confinement barrier(s) should be provided between the process material and any auxiliary system (e.g., a cooling system) to minimize risk of material transfer to an unsafe location or introduction of an undesirable medium into the process area. Differential pressure across the barrier(s) should be used where appropriate.

The effectiveness of each confinement barrier should be checked analytically against challenges it is expected to withstand without loss of function. This applies to any form of the hazardous material (gas, liquid, or solid) and its carrying medium (i.e., airborne or spilled in a liquid).

To protect the integrity of process confinement systems, fire protection systems should include the following features:

- Automatic and redundant fire detection devices.
- A fire-extinguishing system that actuates automatically to—
  - – rapidly remove heat produced by fire to prevent or minimize pressurization of a process confinement and
  - – rapidly extinguish a fire to minimize the loading of ventilation system filters with combustion products.

  (See DOE-STD-1066, *Fire Protection Criteria*, and DOE-STD-3020, *Specifications for HEPA Filters Used by DOE Contractors.)*
- The introduction of the extinguishing agent in a way that does not result in overpressurization of the confinement barriers.
- Provisions to collect liquid agents when a wet suppression agent is used.

Enclosures (as primary confinement). Enclosures are physical barriers (e.g., cells, cubicles, glove boxes, fume hoods, conveyor tunnels) that, together with their ventilation and operating systems, prevent the release of radioactive or other hazardous material to the work space or the environment. Accordingly, their structural and confinement integrity is a design consideration. [See the American Conference of Governmental Industrial Hygienists (ACGIH) *Industrial Ventilation: A Manual of Recommended Practice* (ACGIH 2090); American Society of Mechanical Engineers (ASME) *Code on Nuclear Air and Gas Treatment* (ASME AG-1); and Energy Research and Development Administration (ERDA) *Nuclear Air Cleaning Handbook* (ERDA-76-21).]

Enclosures should be designed to prevent exposure of personnel to airborne contamination and to implement ALARA concepts to minimize operator exposures. The enclosure system, including its internal and external support structures, should therefore be designed to withstand the effects of normal operating conditions, anticipated events, and accidents. Criticality considerations, when needed, should include water or other liquid sources, potential liquid level in the enclosure (during operations or fire fighting), drains to limit liquid level in the enclosure, and liquid collection in depressions, walls, and other areas.

The following additional considerations should be addressed in designing enclosures:

- Where practical, equipment not functionally required to operate directly in the presence of radioactive materials should be located outside the enclosure. Equipment that must be located within the enclosure should be designed to allow for in-place maintenance and/or replacement.
- The design and operation of support and protection systems, such as fire protection, should not promote the failure of the enclosure system integrity or the loss of confinement.
- Noncombustible or fire-resistant, corrosion-resistant materials should be used for enclosures and, to the maximum extent practicable, for any required radiation shielding. In no case should the total combustible loading located in a fire area exceed the fire resistance rating of the structural envelope. (See National Fire Protection Association (NFPA)
Fire Protection Handbook for guidance on the relationship of combustible loading versus fire resistance rating.)
- In conjunction with their ventilation systems, enclosures should be capable of maintaining confinement (i.e., negative pressure with respect to the surrounding operating area).
- To reduce migration of contamination, closure devices or permanent seals should be provided on entrances to and exits from piping, ducts, or conduits penetrating confinement barriers. Such closures or seals should have an integrity equal to or greater than the barrier itself.
- Where pertinent to safety, enclosure design should consider heat generation in the enclosure. Such heat sources may be from processes, lighting, chemical reactions, and the decay of radioactive material. Consideration of radioactive material as a heat source is particularly applicable to storage enclosures.
- Consideration should be given to modular construction, versatility, relocation, and incorporation of shielding. Structural support should be provided to accommodate any anticipated loading resulting from shielding. The type of shielding used and its placement should allow for adequate fire-fighting access.

Enclosure specifications should address the following standardized features, where applicable:

- Windows and mountings.
  - Windows should be appropriately sized (and as small as practicable) and located to provide operators with visual access to the enclosure interior.

– Windows should be constructed of noncombustible or approved fire-resistant materials.
– Resistance of the selected material to impact and radiation damage should be considered.
– The use of Mylar™ -glass laminates should be considered for use as viewing windows and lighting fixture covers in hydrofluoric acid environments.
– Windows should be designed to minimize the risk of releasing contamination to the working area during window replacement.
– Window material should be selected based on specific process, combustible loading, and radiological safety considerations.

• Glove ports (size, location, and height).
– Glove ports should be located to facilitate both operations and maintenance work inside the enclosure.
– Gloves should be flexible enough for operating personnel to access interior surfaces and equipment.
– Gloves should be designed to allow replacement without losing contamination control and with minimum exposure to the operator.
– When gloves are not in place, a noncombustible shield or cover for each glove port should be provided.

• Exhaust air filters to minimize contamination of ductwork.
• Ease of cleaning (radius corners, smooth interior and exterior surfaces, minimal protuberances, and accessibility of all parts).
• Specific coatings for boxes containing halides to permit long life and ease of decontamination.
• Adequate interior illumination (from fixtures mounted on the exterior where feasible).
• Connections for service lines, conduits, instrument leads, drains, and ductwork.
• Pressure differential monitors and heat detection.
• Fire barriers and filter installation.
• Sample removal ports for filter testing.

Consideration should be given to incorporating transfer systems (such as double-door, sealed transfer systems or chain conveyors) for removal of hazardous material from a glove box. Various types of removal and transfer systems are discussed in International Atomic Energy Agency (IAEA) Safety Series No. 30. These systems are designed to allow entry and removal of material without breaching the integrity of the glovebox. (See ERDA 76-21, *Nuclear Air Cleaning Handbook*, for additional information.)

1.1.4 Secondary Confinement. The secondary confinement system consists of confinement barriers and associated ventilation systems that confine any potential release of hazardous material from primary confinement. For example, when gloveboxes provide primary confinement for radioactive or hazardous material processing, the functional requirements for secondary confinement refer to the operating area boundary and the ventilation system serving the operating area.

Design features incorporated into the secondary confinement system should have been proven effective by extensive experience in similar applications or by formal prototype testing. Such design features include the following:

- Continuous monitoring capability should be provided to detect loss of proper differential pressure with respect to the process area. Operating areas should also be continuously monitored. Commensurate with the potential hazards, consideration should be given to the use of redundant sensors and alarms.
- Permanent penetrations of the secondary confinement (e.g., pipes, ducts) should have positive seals or isolation valves or double closure with controlled secondary to primary leakage on pass-through penetrations (e.g., personnel air locks and enclosed vestibules).
- Ventilation systems associated with secondary confinement should be designed with adequate capacity to provide proper direction and velocity of airflow in the event of the largest credible breach in the barrier.
- Secondary and tertiary barriers may exist in common such as a single structural envelope (e.g., walls, roof slab, floor slab), provided the barrier can withstand the effects of external events, and does not contain access ways that allow the routine transfer of personnel, equipment, or materials directly to the exterior of the facility. Access ways into the interior of the single structural envelope should be designed so that the access way is entered from another level of confinement.
- Special features (e.g., air locks, enclosed vestibules) should be considered for access through confinement barriers to minimize the impact of facility access requirements on the ventilation system and to prevent the release of radioactive airborne materials.
- The use of stack-vented rupture disks, seal pots, or bubbler traps should be considered to prevent overpressurization and potential explosive disruption of the secondary confinement system.
- When a pipe is used as the primary confinement barrier for materials, and the pipe exits a secondary confinement, the secondary confinement should be provided by a double-walled pipe of other encasement. In areas within the facility, the use of double-walled pipe should be considered. Leakage monitoring should be provided to detect leakage into the space between the primary pipe and the secondary confinement barrier. (See Resource Conservation and Recovery Act requirements in 40 Code of Federal Regulations (CFR) 264.193, *Containment and Detection of Releases,* and 40 CFR 265.193, *Containment and Detection of Releases.*)
- When primary confinement includes ductwork, the considerations in the previous bullet should be applied to the ductwork. Transition from primary to secondary confinement typically occurs downstream of air cleaning devices, such as high-efficiency particulate air (HEPA) filters and adsorbers.

1.1.5 Tertiary Confinement. Tertiary confinement is provided by the building or outer structure of the facility. For some accidents, it represents the final barrier to release of hazardous material to the environment; for others, it is a barrier that protects other parts of the facility from damage.

ALARA concepts should be incorporated in tertiary confinement system design to minimize exposure to operators, the public, and the environment.

1.1.6 Confinement Ventilation Systems. The design of a confinement ventilation system ensures the desired airflow at all times and specifically when personnel access doors or hatches are open. When necessary, air locks or enclosed vestibules may be used to minimize the impact of open doors or hatches on the ventilation system and to prevent the spread of airborne contamination within the facility.

Air cleanup systems provided in confinement ventilation exhaust systems are typically used to limit the release of radioactive or other hazardous material to the environment and to minimize the spread of contamination within the facility. To the extent practical, discrete processing steps should be performed in individual process confinements to reduce the amount of hazardous material that can be released by a single or local failure of the confinement system. The following general cleanup system features should be considered, as appropriate, for ventilation system design:

- The level of radioactive material in confinement exhaust systems should be continuously monitored. Alarms should annunciate when activity levels above specified limits are detected in the exhaust stream. Appropriate manual or automatic protective features that prevent an uncontrolled release of radioactive material to the environment or workplace should be provided.
- Elevated confinement exhaust discharge locations can limit onsite doses and reduce offsite doses by enhancing atmospheric dispersion. An elevated stack should be used for confinement of exhaust discharge. Provisions should be made to provide an adequate ventilation exhaust discharge path in the event of stack failure. The stack should be located so that it cannot fall on the facility or an adjacent facility. Alternatively, the stack may be constructed to remain functional following accidents, including those caused by severe natural phenomena and man-made external events. Stack location and height should also consider intakes on the facility and adjacent facilities to preclude uptake.
- Guidance for air sampling locations is provided in ACGIH/ASHRAE criteria. Sample collecting devices should be located as close to the sampling probe as possible. Guidance for air cleaning device test port locations is provided by ASME N510, *Testing of Nuclear Air-Treatment Systems*.
- The number of air filtration stages required for any area of a facility should be determined based on the quantity and type of radioactive materials to be confined.
- Air filtration units should be installed as close as practical to the source of contaminants to minimize the contamination of ventilation system ductwork.
- Ducts should be sized for the transport velocities needed to convey particulate contaminants to filter media while minimizing the settling of those contaminants in the ducts.
- Ducts should be welded (transverse or longitudinal). Connections to equipment should be made using companion angle flanges.
- Air filtration units should be located and provided with appropriate radiation shielding to maintain occupational doses ALARA during operations and maintenance.
- Air filtration units should be designed to facilitate recovery of fissile material and other materials capable of sustaining a chain reaction.

• The cleanup system should have installed test and measuring devices (see ASME N510) and should facilitate monitoring operations, maintenance, and periodic inspection and testing during equipment operation or shutdown, as appropriate.
• Misters to cool inlet air and demisters to prevent soaking HEPA filters should be installed. Manual control of misters from the facility control center should be considered. The inlet should have a temperature sensor with a readout on the facility control center monitor screen.
• Where spaces, such as a control room, are to be occupied during abnormal events, filtration systems on the air inlets should be considered to protect the occupants. Control rooms should also be protected from the entry of smoke or other toxic gases through ventilation air intakes. Compressed (bottled) air storage could be used to pressurize the control room if toxic gases are present at the air intake. Alternatively, two intakes, separately located, could lessen the likelihood of toxic gas intake.
• Either HEPA filtration or fail-safe backflow prevention for process area intake ventilation systems should be provided.
• Consideration should be given to specify cadmium-free HEPA filters to avoid generating mixed waste.
• Roughing filters or prefilters upstream of a HEPA filter should be considered to maximize the useful life of the HEPA filter and to reduce radioactive waste volume.
• When ducts with fire dampers penetrate the secondary confinement, boots may be needed for the clearance between the structure and the damper sleeve.

Hot cell exhaust systems considerations are as follows:

• Exhaust prefilters and HEPA filters should be installed to facilitate filter replacement and repair. Use of a bag-in/out type filter house can lessen personnel exposures.
• Standby filters should be considered to provide backup protection and facilitate primary filter replacement without shutting down the exhaust fans. Standby filters should be installed outside the cell and sealed in an acceptable enclosure for direct maintenance. Note: Air leakage through isolation valves/dampers should be evaluated to avoid the bypassing of filtration devices; the reduction of exhaust flow from recirculation through the standby filters; the exposure of personnel changing the isolated filter elements; and the premature loading of the standby filters.
• Exhaust systems should have monitors that provide an alarm if the concentration of radioactive material in the exhaust exceeds specified limits.
• If radioiodine may be present, consideration should be given to the installation of radioiodine-absorber units.

In facilities where plutonium or enriched uranium is processed, the following are additional considerations:

• Wherever possible, the designer should provide enclosures for confining process work on plutonium and enriched uranium. When these confinement enclosures are specified and designed, consideration should be given to whether room ventilation air for either a secondary or tertiary confinement can be recirculated. If a recirculation

ventilation system is provided, the design should provide a suitable means for switching from recirculation to once-through ventilation.

• If advantageous to operations, maintenance, or emergency personnel, the ventilation system should provide for independent shutdown. Such a shutdown should be considered in light of its effect on the airflow in other interfacing ventilation systems. When a system is shut down, positive means of controlling backflow of air to uncontaminated spaces should be provided by positive shutoff dampers, blind flanges, or other devices.

• Equipment to continuously monitor oxygen levels should be provided for occupied working areas of facilities equipped with significant quantities of inert or oxygen-deficient process glove box lines. Allowable leakage rates for ductwork systems should be taken into consideration.

• The supply of air to primary confinement, such as enclosures that confine the processing of plutonium and enriched uranium, should be filtered by HEPA filters at the ventilation inlets to the enclosures and area confinement barriers to prevent the transport of radioactive contamination in the event of a flow reversal.

• If room air is recirculated, the recirculation circuit should provide at least one stage of HEPA filtration. The design should include redundant filter banks and fans. If recirculation systems are used, contaminated process enclosure air should be prevented from exhausting into the working area rooms. Process enclosure air (from hoods, glove boxes, etc.) should be treated and exhausted without any potential for recirculation to occupied areas.

• The designer should specify and locate components in the exhaust systems to remove radioactive materials and noxious chemicals before the air is discharged to the environment. These components should be capable of handling combustion products safely. Exhaust system design should safely direct effluents through the appropriate ventilation ducts and prevent spread beyond the physical boundary of the ventilation system until treated.

• HEPA filters should be installed at the interface between the enclosures that confine the process and the exhaust ventilation system to minimize the contamination of exhaust ductwork. Prefilters should be installed ahead of HEPA filters to reduce HEPA filter loading. The filtration system should be designed to allow reliable in-place testing of the HEPA filter and to simplify filter replacement.

• Separate exhaust ventilation system ductwork and the initial two stages of filtration should be designed for exhaust air from enclosures that confine the process (e.g., glove boxes). These systems should maintain a negative pressure inside the enclosure with respect to the operating area. These systems should be designed to remove moisture, heat, explosive and corrosive gases, and other contaminants. These systems should also be designed to automatically provide adequate inflow of air through a credible breach in the enclosure confinement.

• Enclosures that confine the process and are supplied with gases at positive pressure should have positive-acting pressure-relief valves that relieve the exhaust system to prevent over-pressurization of the process confinement system.

• The design of air cleaning systems for normal operations, anticipated operational occurrences, and accident conditions should consider use of the following equipment as appropriate:

– prefilters,
– scrubbers,
– HEPA filters,
– sand filters,
– glass filters,
– radioiodine absorbers,
– condenser distribution baffles, and
– pressure and flow measurement devices.

Airborne contaminant cleaning systems should be designed for convenient maintenance and the ability to decontaminate and replace components in the supply, exhaust, and cleanup systems without exposing maintenance or service personnel to hazardous materials. Filtration systems should be designed so that a bank of filters can be completely isolated from the ventilation systems during filter element replacement.

Where the confinement system's ventilation ducting penetrates fire barriers, fire dampers should be appropriately used to maintain barrier integrity. However, the closure of such dampers should not compromise confinement system functions where the loss of confinement might pose a greater threat than the spread of fire. In such cases, alternative fire protection means (e.g., duct wrapping) should be substituted for fire barrier closure. In no case should a sprinkler system be considered a fire barrier substitute. (All penetrations of a fire barrier should be sealed, including conduit, cable trays, piping, and ductwork. In the selection of seals, requirements for pressure and watertightness should be considered.

Appendix B DOE G 420.1-1

5.2.2.2 Process Equipment

The usual safety function of process equipment is to provide primary confinement and prevent or mitigate radioactive and/or hazardous material releases to the environment. Process equipment that would be required to provide primary confinement includes the following: piping, tanks, pressure vessels, pumps, valves, and glove boxes. These examples represent process system components that could be used to contain radioactive or toxic materials directly. Process equipment for some applications can provide secondary confinement. Examples include double walled piping systems, double-walled tanks, and glove boxes.

Safety-class and safety-significant process equipment providing passive confinement (piping, tanks, holding vessels, etc.) must be designed to suitably conservative criteria; redundancy in their design is not required. The redundancy criteria as described in Section 5.1.1.2 of this Guide must be applied to the design of safety-class SSCs that involve active confinement process equipment (pumps, valves, etc.). The redundancy criteria should be considered in the design of safety-significant SSCs that involve active confinement process equipment. See Table 5.3 for the relevant codes.

Table 5.3. Codes for Safety-Significant and Safety-Class Process Equipment.

Process Equipment	Safety Significant	Safety Class
Pressure vessels	ASME Boiler and Pressure Vessel Code, Section VIII, Division 1 or 2	ASME Boiler and Pressure Vessel Code, Section VIII, Division 1 or 2
Tanks (0-15 psig)	API-620; ASME Boiler and Pressure Vessel Code, Section VIII, Division 1 or 2	API-620; ASME Boiler and Pressure Vessel Code, Section VIII, Division 1 or 2
Tanks (containing flammable liquids)	ANSI/API-620; ANSI/API-650; NFPA 30	ANSI/API-620; ANSI/API-650; NFPA 30
Tanks (atmospheric pressure)	ANSI/API-650; AWWA-D100; ANSI/ASME-B96.1	ANSI/API-650; AWWA-D100; ANSI/ASME-B96.1
Pumps	ANSI/API; ANSI/ASME B73.1M, B73.2M; ASME Boiler and Pressure Vessel Code, Section VIII; AWWA; Hydraulic Institute Standards	ANSI/API; ANSI/ASME B73.1M, B73.2M; ASME Boiler and Pressure Vessel Code, Section VIII; AWWA; Hydraulic Institute Standards
Piping	ANSI/ASME B31.3	ANSI/ASME B31.3; ANSI-N278.1
Valves	ANSI/ASME B16.5, B31.3	ANSI/ASME B16.5, B31.3
Heat exchangers	ASHRAE Handbook; ASME Boiler and Pressure Vessel Code, Section VIII, Division 1; TEMA B, C, or R	ASHRAE Handbook; ASME Boiler and Pressure Vessel Code, Section VIII, Division 1; TEMA B, C, or R
Gloveboxes	ANSI/ASTM C852; ANS 11.16	ANSI/ASTM C852; ANS 11.16