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Explosion Testing for the Container Venting System

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EXPLOSION TESTING FOR THE CONTAINER VENTING SYSTEM

ABSTRACT

As part of the study of the hazards of inspecting nuclear waste stored at the Hanford Site, the U.S. Department of Energy and Westinghouse Hanford Company have developed a container venting system to sample the gases that may be present in various metal drums and other containers. In support of this work, the U.S. Bureau of Mines has studied the probability of ignition while drilling into drums and other containers that may contain flammable gas mixtures. The Westinghouse Hanford Company drilling procedure was simulated by tests conducted in the Bureau's 8-liter chamber, using the same type of pneumatic drill that will be used at the Hanford Site. There were no ignitions of near-stoichiometric hydrogen-air or methane-air mixtures during the drilling tests. The temperatures of the drill bits and lids were measured by an infrared video camera during the drilling tests. These measured temperatures are significantly lower than the ~500 °C autoignition temperature of uniformly heated hydrogen-air or the ~600 °C autoignition temperature of uniformly heated methane-air. The temperatures are substantially lower than the 750 °C ignition temperature of hydrogen-air and 1,220 °C temperature of methane-air when heated by a 1-mm-diameter wire.

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LIST OF TERMS

A/D	analog to digital
CH ₄	methane
CVS	Container Venting System
DOE	U.S. Department of Energy
H ₂	hydrogen
IR	infrared
PC	personal computer
TiN	titanium nitride
WHC	Westinghouse Hanford Company

1.0 INTRODUCTION

The Hanford Site in the state of Washington has been a defense production facility for the U.S. Department of Energy (DOE) and its predecessors for many years. The Site is presently managed by Westinghouse Hanford Company (WHC). Substantial solid waste volumes were generated during defense material production. Some of these wastes were placed in metal drums and other containers and stored in underground trenches covered with earth. Hydrogen (or other flammable gases) could be present in the waste drums, resulting from organic decay and/or radiolysis. The DOE and WHC are committed to waste cleanup and characterization, placing worker safety and environment protection paramount during this effort. Therefore, WHC has designed special retrieval equipment to move the waste drums from underground storage to an aboveground storage and inspection facility. A key piece of retrieval equipment is the Container Venting System (CVS). This system features drum piercing, drum-gas sampling/purging capability, drum lifting, and filter installation. Key components are a pneumatic drill (Quackenbush¹ Model 158QGDABV-S150) equipped with a 5/16-in. titanium nitride- (TiN-) coated drill bit that penetrates the waste drum lid.

As part of the DOE and WHC study of the hazards of nuclear waste cleanup at the Hanford Site, the U.S. Bureau of Mines was contracted to determine whether ignition might occur while using the CVS to drill into a container filled with a flammable gas mixture. This Bureau research was not meant to be a comprehensive safety evaluation of all aspects of the CVS. The Bureau only evaluated the question of whether drilling through drum lids could ignite flammable hydrogen-air or methane-air mixtures. The results of this study will be used by the DOE and WHC as part of the overall safety evaluation of the CVS.

The particular gases tested were near-stoichiometric mixtures of hydrogen-air or methane-air. First, the flammability of these gases was studied by using a spark ignition source. Then the question of whether or not the CVS could ignite the flammable gas mixtures was investigated. The WHC drilling procedure was simulated by tests conducted with the Bureau's 8-L chamber. The Quackenbush pneumatic drill was used to drill through test coupons (lids of various thickness). An infrared video system was used to measure temperatures of the test coupons and drill bits during drilling.

2.0 EXPERIMENTAL EQUIPMENT AND INSTRUMENTATION

2.1 TEST CHAMBER

The instrumentation and test procedures used for this project were similar to those used for the previous research project that the Bureau conducted for the DOE and WHC (Cashdollar et al. 1992). The ignitability tests were conducted in an 8-L chamber (Figure 1). Instrumentation for

¹The Quackenbush drill is a trademark of the Industrial Tool Division, Dresser Industries, Inc.

Figure 1. Schematic of 8-Liter Test Chamber and Pneumatic Drill.

the chamber included two strain-gauge pressure transducers and a 320- μm (12.5-mil) Type K thermocouple, which was used to monitor the chamber gas temperature. The Quackenbush pneumatic drill was mounted to the top flange of the chamber, as shown in Figure 1. The test coupons, mounted below the drill, were 76 mm (3 in.) in diameter and were made from 1.5-mm- (16-gauge-) thick steel drum lids or 6.5-mm ($\frac{1}{4}$ -in.) carbon steel plates. An internal fan, mounted through the side wall of the chamber, was used to mix the gases. The two spark electrodes could be used to ignite the gas mixtures for the flammability tests.

The data from the pressure transducers were recorded with a personal computer (PC) equipped with a high-speed analog-to-digital (A/D) board. A Bureau-designed computer software program converted the sensor data to engineering units and plotted the results versus time. These plots were used to obtain the maximum pressure and maximum rate of pressure rise values. Data from the two pressure transducers were compared and averaged. The calibrations of the two pressure transducers were checked daily using the internal calibration resistors provided by the manufacturers. The data from the tests were permanently stored on both the PC hard disk and on floppy disks.

2.2 VIDEO CAMERAS

A regular (visible light) video camera and an infrared (IR) video camera observed the 8-L chamber flammability and ignitability tests. Each video camera observed the test coupon from above at an angle of about 45 degrees. The regular video camera gave a visual image of the drilling process and would observe any possible sparks or flames. The IR video system (Hughes Probeye² Model 7300) was used to record the temperature changes of the test coupon and drill bit during the drilling process. The IR video measures radiation at wavelengths of about 2 to 5 μm . This radiation is then converted to a temperature display at 30 frames per second on the video monitor. The IR video, therefore, provides a false color image of the drill assembly, test coupon, and 8-L chamber during each test. The colors are correlated to temperature through a temperature color key at the right side of the video image. The maximum temperature in the field of view can be obtained after the test through a frame-by-frame evaluation of the IR video recording.

The IR video system was calibrated using both a blackbody reference source and a hotplate. The blackbody source confirmed the manufacturer's temperature calibration over the range of 300 °C to 800 °C. The IR video was also calibrated at lower temperatures with the hotplate before, during, and at the end of the drilling tests. The hotplate temperature was measured with a Type K surface thermocouple, which was calibrated to within 1 °C in ice water and in boiling water. The test coupons (steel plates and drum lids) were placed on the hotplate, and the IR video calculated the temperature using various emissivity settings. Readings were taken at temperatures ranging from room temperature to 400 °C. The emissivity setting that agreed best with the surface thermocouple reading throughout the temperature range was the setting used for later observations of the drilling procedure. The best-fit emissivity of the $\frac{1}{4}$ -in. steel plates was 0.8 and that of the 16-gauge steel

²Probeye is a trademark of Hughes Aircraft Company.

drum lids was ~ 0.2 . The emissivity of the drum lid was lower than that of the carbon steel plate because the drum lid was shinier and more reflective. The emissivity of the TiN drill bit could not be measured by this method.

During the calibration and testing, the IR video temperature scale was found to be nonlinear. At the high end of the range, the IR temperature measurements were accurate. At the low end of the range, the IR video reading was higher than the actual temperature. The wider the temperature range, the greater the error in temperature in the lower end of the temperature range. The result of this nonlinearity was that the initial IR video temperature reading at the start of the drilling procedure was higher than the actual room temperature. However, and more importantly, the maximum temperatures (at the upper part of the temperature range) measured by the IR video during the drilling procedure were much more accurate. For example, if the reading was at the upper part of the temperature range of the video system, the temperature would be uncertain by about ± 20 °C at 200 °C for a 20% uncertainty in the emissivity value.

Furthermore, during the course of the project, it was discovered that the focusing mechanism of the IR video camera was inoperable. The result was that the earlier video images (Tests 15 through 78, Appendix B) were not in sharp focus. At the 1-m observation distance used for these measurements, this blurred image resulted in the averaging of the temperature over an approximately 4-cm-diameter area. The later observations (Tests 79 through 93, Appendix B) were made at a closer (0.3-m) observation distance. The IR video camera was in sharp focus at this distance and its spatial resolution was slightly better than 1 mm.

3.0 EXPERIMENTAL PROCEDURES

At the start of the test, the 8-L chamber was evacuated, and then the flammable gas and air were added at the partial pressures required to give the desired mixture composition at the desired test pressure. The two flammable gases tested were hydrogen (H_2) and methane (CH_4). Based on the precision of the pressure transducers used for monitoring the addition of gases by partial pressures, the precision of the gas mixture compositions ranged from $\pm 0.2\%$ at 10.0% to $\pm 0.5\%$ at 30.0%. The internal fan was used to mix the gases. During mixing tests in a 120-L chamber for the earlier Hanford Site research (Cashdollar et al. 1992), there was essentially no difference in the measured H_2 concentrations from the start to the end of the fan mixing time period (5 min). This showed that the gases were well mixed (even before the fan was turned on). Nevertheless, to be cautious, the gases in the 8-L chamber were mixed by the fan for at least 2 min before each test. The fan was turned off before the flammability or drilling tests.

For tests conducted at an elevated initial temperature, the 8-L chamber was wrapped with electrical heater tape, and the internal gas temperature was measured with the 320 μm thermocouple. The IR video was used to confirm that the test coupon was also heated to the required initial temperature before starting the test.

Before the drilling tests were conducted, flammable mixtures of H_2 -air or CH_4 -air were ignited in the 8-L chamber to determine the maximum explosion

pressure generated. For these flammability tests, an electric spark ignited the gas mixture, and the maximum explosion pressure was measured by the pressure transducers. These flammability tests were conducted both with the 8-L chamber entirely closed and with a 5/16-in. vent hole in the chamber top. For the vented tests, the vent hole was covered with masking tape while the chamber was evacuated and the gases were added.

During a drilling test, the drill bit would puncture the test coupon and enter the 8-L chamber that was filled with a flammable gas mixture. The pressure transducers would measure any pressure rise if the gas would ignite. If the gas did not ignite, the pressure would drop slightly as the drill bit punctured the test coupon because the initial chamber pressure was slightly above local atmospheric pressure. The regular video camera would record any flame exiting the chamber through the drill hole if the gas would ignite. The IR video system was used to record the temperatures of the drill bit and test coupon during the drilling process.

The standard cycle for the drill operation consisted of several steps. First, a solenoid valve opened to allow pressurized gas to enter the pneumatic drill. The standard working pressure of the drill was 6.2 bar (90 psi). This pressure was measured close to the point at which the gas entered the drill. As the drill was pressurized, the bit would rotate and advance at rates related to the pressure. At a pressure of 6.2 bar (90 psi), the rotational speed was ~640 rpm and the advance rate was ~13 cm/min (5.1 in./min). In the standard cycle of the drill, it would advanced about 2 to 3 cm (~1 in.) in about 10 to 15 s. Then it would automatically return to its starting position and stop.

4.0 FLAMMABILITY AND IGNITABILITY OF HYDROGEN AND METHANE IN AIR

Hydrogen in air is flammable over the range from 4% to 75% H_2 , and the stoichiometric value is 29.5% H_2 (Cashdollar et al. 1992, Kuchta 1985, Zabetakis 1965). The maximum measured explosion pressure and the maximum calculated adiabatic temperature are found at 30% H_2 (Cashdollar et al. 1992). Methane in air is flammable over the range from 5 to 15% CH_4 , and the stoichiometric value is 9.4% CH_4 (Kuchta 1985 and Zabetakis 1965). The maximum measured explosion pressure and the maximum calculated adiabatic temperature are found at 10% CH_4 (Cashdollar et al. 1992). Near-stoichiometric mixtures of H_2 -air or CH_4 -air are easily ignited with an electric spark. The spark ignition energy of H_2 -air is relatively independent of gas concentration near the stoichiometric value (Lewis 1951). The minimum ignition energy (Kuchta 1985) of H_2 -air is 0.02 mJ, and the minimum ignition energy of CH_4 -air is 0.3 mJ. (The minimum ignition energies of other gases and vapors are listed in Table 13 [Kuchta 1985].) The autoignition temperature of H_2 -air is 500 °C to 520 °C and the autoignition temperature of CH_4 -air is 600 °C to 630 °C (Conti 1988, De Soete 1975, and Kuchta 1985). (The autoignition temperatures of other gases and vapors are listed in Table 15 [Kuchta 1985].) The autoignition temperatures of H_2 and CH_4 are relatively independent of gas concentration near the stoichiometric values (Conti 1988). The autoignition temperatures were measured in closed-volume chambers (Conti 1988, De Soete 1975, and Kuchta 1985) with all walls uniformly heated so that there was a large area of contact with the gas and the entire

gas volume would be heated to the test temperature. The minimum ignition temperatures are much higher if the heated area is much smaller and only part of the gas volume is heated. For example, the ignition temperature of H_2 -air was 750 °C and that for CH_4 -air was 1,220 °C when they were heated by a 1-mm-diameter Nichrome³ wire (Kuchta 1985).

5.0 EXPERIMENTAL DATA

5.1 FLAMMABILITY TESTS IN CLOSED OR VENTED CHAMBER

The detailed data for the flammability tests are listed in Appendix A. The mixtures of H_2 in air or CH_4 in air were ignited with an electric spark in the 8-L chamber. The date and run number are listed in columns one and two. The percentage and type of flammable gas are listed in columns three and four. The percentage of air in the chamber is listed in column five. The initial chamber pressure (absolute) and maximum explosion pressure (absolute) are listed in columns six and seven, respectively. To determine the explosion pressure rise for each test, subtract the value in column six from the value in column seven. The explosion pressure ratio listed in column eight is the maximum explosion pressure divided by the starting pressure. Because the starting pressure is approximately 1 bar or 1 atm, the pressure ratio is approximately the absolute explosion pressure in bars or atmospheres. The last column lists the initial chamber test temperature.

As part of the gas flammability tests, the maximum pressures and rates of pressure rise were measured for both the constant volume and vented cases. The vent hole had a diameter of 5/16 in. (the size of the standard TiN drill bit). The stoichiometric H_2 -air mixtures burned so fast that the maximum pressure for the vented explosions was only slightly less than that for the closed-volume tests. The average maximum pressure for the vented CH_4 -air explosions was ~1 bar lower than for the closed-volume tests. The explanation is that stoichiometric CH_4 -air burns more slowly than stoichiometric H_2 -air, and the small vent had more time to be effective in reducing the pressure. For both the H_2 -air and CH_4 -air in the 8-L chamber, the maximum explosion pressures for the constant volume tests were lower than those measured previously (Cashdollar et al. 1992) in the 120-L chamber because the larger, spherical chamber was more adiabatic.

5.2 DRILLING TESTS

The detailed data from the drilling tests are listed in Appendix B. The first six columns are the same as in Appendix A. The seventh column lists the initial chamber test temperature. The drill bit type and serial number are listed in column eight. The standard 5/16-in.-diameter titanium nitride drill bit is denoted as TiN. The test coupon type and serial number are listed in column nine. The 16-gauge drum lids are denoted as DL, and the 1/4-in. carbon steel plates are denoted as CS. The pneumatic drill feed pressure is listed in column ten. The maximum temperature of the test coupon and drill bit, as

³Nichrome is a trademark of National Westminster Bank, U.S.A.

measured by the IR video camera, is listed in column eleven. This temperature was measured from a frame-by-frame analysis of the video recording. In a few of the tests, the temperature from the video was corrected and/or estimated because the emissivity was set incorrectly for the test or because the maximum temperature was greater than the range on the IR video monitor.

The test conditions that were varied during this drill ignitability project included the following:

- Test coupon type
- Drill feed pressure
- Initial chamber pressure
- Initial chamber temperature
- Flammable gas (H_2 or CH_4)
- Drill bit type and size.

The standard drill bit for these tests and for the Hanford CVS was the 5/16-in.-diameter TiN coated bit. For several tests, a worn TiN drill bit was used. As noted in Appendix B, this worn bit was used 50 times to drill through a 1/4-in.-thick carbon steel plate before using it for the ignitability tests (43 through 45). Also tested were a 5/16-in.-diameter standard steel bit and a 1/4-in.-diameter carbide tipped steel bit.

There were no ignitions of stoichiometric H_2 -air mixtures during a total of 42 tests under any of the test conditions. A few tests were made with stoichiometric CH_4 -air instead of H_2 -air mixtures, and there were no ignitions of the CH_4 either.

As observed in the regular video for many of the tests, the drill bit tip wandered around on the surface of the test coupon before cutting into the surface because it was not center punched. In several cases, the center of the hole was as much as one-bit-diameter (5/16-in.) off from the center of the test coupon. This would cause some horizontal stress on the bit.

During one of the tests (40, Appendix B), a standard steel bit broke before it punctured the 1/4-in. carbon steel test coupon. In this test, the bit caught in the plate, and a piece broke off and remained lodged in the plate. After the piece broke off, the drill began to rotate again and frictional sparks were observed in the regular video. The IR video recorded higher temperatures than for similar tests (41 and 42) in which the drill bit did not break.

The temperatures of the drill bits and lids were measured by the IR video system during the drilling tests. Using the standard TiN drill bit, the measured IR temperatures were significantly lower than the $\sim 500^\circ C$ autoignition temperature of H_2 -air or the $\sim 600^\circ C$ autoignition temperature of CH_4 -air. For the early tests (6 through 78, Appendix B), the IR video camera was not in sharp focus and, consequently, the temperature was averaged over a 4-cm-diameter area. Under this condition, the average maximum IR temperature for a total of 26 tests, while drilling through the 1/4-in. carbon steel plates, was $109^\circ C (\pm 11^\circ C)$ at drill feed pressures of 6.2 to 7.6 bar (90 to 110 psi). During these tests, the maximum temperature lasted for about 5 s while drilling through a steel plate. In the standard tests, the IR video system observed the test coupon from above at an angle of about 45 degrees from the horizontal. To see if the temperature would be higher on the bottom of the

test coupon as the bit punctured it, some tests were made with the test coupon held in a bench vise with the IR video camera observing from the bottom. In these tests (61 through 64), the average maximum temperature was somewhat higher (136 °C). For the 16-gauge steel drum lids viewed from above, the average maximum IR temperature was 141 °C (± 30 °C) for a total of 13 tests at a drill feed pressure of 6.2 bar (90 psi). During these tests, the maximum temperature lasted for about 2 to 3 s while drilling through a drum lid.

There was no significant difference in measured temperatures while drilling with the 5/16-in.-diameter steel bit. The measured temperatures were significantly higher, however, when using the 1/4-in.-diameter carbide tipped steel bit (Tests 55 through 59 and 77 and 78, Appendix B). The reason for this is probably that the larger diameter results in a larger area of frictional contact between the bit and the plate or drum lid. In addition, the linear velocity at the periphery of the bit tip would be higher for the larger diameter bit at the same rotational speed. An additional problem with the 1/4-in.-diameter bit was that it deformed the drum lids while drilling, producing a concave surface. Therefore, it would not be advisable to use larger drill bits in the CVS.

For the later tests (79 through 93, Appendix B), the IR video camera was in sharp focus, and the spatial resolution of the temperature measurements was better than 1 mm. Under this condition, the maximum measured temperatures were considerably higher but confined to much smaller areas. The average maximum IR temperature for six tests while drilling through the 1/4-in. carbon steel plates was 245 °C (± 13 °C) at drill feed pressures of 6.2 to 7.6 bar (90 to 110 psi). The average maximum IR temperatures while drilling through the 16-gauge drum lids were 353 °C (± 9 °C) for three tests at a drill feed pressure of 6.2 (90 psi) and 388 °C (± 10 °C) for three tests at a drill feed pressure of 7.6 (110 psi). From the IR video recordings, it appeared that the hottest objects observed while drilling into the steel plates were drill shavings, and they may have had emissivities lower than the value of 0.8 used for the oxidized surface of the plate. If this was so, the true maximum temperatures for the steel plate tests may have been higher, closer to those measured for the drum lid tests. These temperatures measured with the IR video camera in sharp focus are most appropriately compared with the ignition temperatures obtained using the 1-mm-diameter, heated Nichrome wire (Kuchta 1985), as described in Section 4.0. For thermal ignition by a small contact area, the ignition temperature of H₂-air was 750 °C and that of methane-air was 1,220 °C when they were heated by the 1-mm-diameter Nichrome wire. Again, the measured temperatures (Appendix B) during the drilling process were significantly lower than these gas ignition temperatures.

6.0 CONCLUSIONS

There were no ignitions of either stoichiometric H_2 -air or CH_4 -air mixtures during the drilling tests. The temperatures of the drill bits and lids were measured by an IR video system during the drilling tests and found to be significantly lower than the $\sim 500^\circ C$ autoignition temperature of H_2 -air or the $\sim 600^\circ C$ autoignition temperature of CH_4 -air. Although there were no ignitions of the flammable gas mixtures during these drilling tests, it is recommended that the CVS be operated remotely. Note that these conclusions refer only to the specified conditions of tests and may not include all possible safety considerations for the operation of the CVS. This report should be used along with other engineering studies as part of the overall safety evaluation of the CVS.

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Appendix A

Flammability Tests in 8-Liter Chamber, With Electric Spark Ignition.

Date	Run	Gas %	Gas Type	Air %	P _{initial} , psia	P _{max} , psia	Pressure Ratio	Chamber Temp, °C
Electric Spark Ignition of Hydrogen-Air in Closed Chamber								
11/16/92	1	21.0	H ₂	79.0	15.0	99.6	6.64	~20
	2	20.0	H ₂	80.0	15.0	95.3	6.35	~20
	3	30.0	H ₂	70.0	15.0	111.6	7.44	~20
	4	30.0	H ₂	70.0	15.0	110.2	7.35	~20
11/17/92	5	29.8	H ₂	70.2	15.1	111.5	7.38	~20
Electric Spark Ignition of Hydrogen-Air in Chamber with 5/16" Vent Hole								
11/18/92	8	29.7	H ₂	70.3	15.1	110.9	7.33	~20
	9	30.0	H ₂	70.0	15.0	109.7	7.32	~20
	10	30.1	H ₂	69.9	15.0	107.6	7.19	~20
	11	30.0	H ₂	70.0	15.0	108.7	7.25	~20
	12	30.1	H ₂	69.9	14.9	107.7	7.21	~20
	13	30.2	H ₂	69.8	14.9	106.5	7.15	~20
	14	30.0	H ₂	70.0	15.0	108.1	7.21	~20
Electric Spark Ignition of CH ₄ -Air in Chamber with 5/16" Vent Hole								
12/17/92	46	9.9	CH ₄	90.1	15.2	85.4	5.62	~40
12/18/92	47	9.9	CH ₄	90.1	15.1	95.7	6.35	~40
	48	9.9	CH ₄	90.1	15.2	99.0	6.51	~40
12/22/92	49	10.0	CH ₄	90.0	15.0	99.9	6.66	~22
Electric Spark Ignition of CH ₄ -Air in Closed Chamber								
12/22/92	50	10.0	CH ₄	90.0	14.9	109.8	7.35	~22
	51	10.0	CH ₄	90.0	15.0	108.8	7.25	~22

Appendix B

Tests of Drilling Into 8-Liter Chamber Containing Flammable Gas.

Date	Run	Gas %	Gas Type	Air %	Initial Pressure, psi	Chamber Temp, °C	Drill Bit	Test Coupon	Drill Pressure, psi	T _{exp} , °C
Drilling Test, Chamber Filled with Air										
11/17/92	6	0.0		100.0	15.2	-20	TiN-1	CS-1	90	
	7	0.0		100.0	40.1	-20	TiN-1	CS-2	90	
Standard Drilling Tests, Chamber Filled with H ₂ -Air										
11/20/92	15	39.8	H ₂	60.2	12.1	-20	TiN-1	CS-3	90	118
	16	30.0	H ₂	70.0	16.0	-20	TiN-1	CS-4	90	73
11/24/92	17	29.3	H ₂	70.7	16.4	-20	TiN-1	CS-5	90	114
	18	29.9	H ₂	70.1	16.0	-20	TiN-1	CS-6	90	111
	19	30.0	H ₂	70.0	16.0	-20	TiN-1	CS-7	90	116
	20	30.1	H ₂	69.9	15.9	-20	TiN-1	CS-8	90	89
12/02/92	21	29.8	H ₂	70.2	16.3	-20	TiN-1	DL-1	90	-110
	22	29.8	H ₂	70.2	16.1	-20	TiN-1	CS-9	40	105
	23	29.8	H ₂	70.2	16.1	-20	TiN-1	CS-10	40	94
	24	30.3	H ₂	69.7	15.9	-20	TiN-1	CS-11	40	99
Drilling Tests, Elevated Initial Pressure, Chamber Filled with H ₂ -Air										
12/03/92	25	30.0	H ₂	70.0	25.0	-20	TiN-1	CS-12	90	102
	26	30.4	H ₂	69.6	24.7	-20	TiN-1	CS-13	90	104
	27	30.1	H ₂	69.9	24.9	-20	TiN-1	CS-14	90	--
Drilling Tests, Elevated Initial Temperature, Chamber Filled with H ₂ -Air										
12/07/92	28	30.0	H ₂	70.0	16.0	-38	TiN-1	CS-15	90	110
	29	29.9	H ₂	70.1	16.1	-38	TiN-1	CS-16	90	106
	30	30.2	H ₂	69.8	15.9	-38	TiN-1	CS-17	90	116

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Date	Run	Gas %	Gas Type	Air %	P _{initial} , psi	Chamber Temp, °C	Drill Bit	Test Coupon	Drill Pressure, psi	T _{eq} , °C
Standard Drilling Tests, Chamber Filled with H ₂ -Air										
12/08/92	31	30.1	H ₂	69.9	16.1	-20	TIN-1	DL-2	90	-98
	32	29.9	H ₂	70.1	16.0	-20	TIN-1	DL-3	90	-93
	33	30.0	H ₂	70.0	16.0	-20	TIN-1	DL-4	90	-101
Drilling Tests, Elevated Initial Temperature, Chamber Filled with H ₂ -Air										
12/09/92	34	29.4	H ₂	70.6	16.3	-40	TIN-1	CS-18	110	113
	35	29.8	H ₂	70.2	16.1	-40	TIN-1	CS-19	110	122
	36	29.8	H ₂	70.2	16.1	-40	TIN-1	CS-20	110	123
Standard Drilling Tests, Chamber Filled With H ₂ -Air										
12/15/92	37	30.0	H ₂	70.0	16.0	-23	TIN-1	CS-21	110	-95
Drilling Tests, Elevated Initial Temperature, Chamber Filled with H ₂ -Air										
12/16/92	38	30.1	H ₂	69.9	15.9	-38	TIN-2	CS-22	110	107
	39	30.2	H ₂	69.8	15.9	-38	TIN-2	CS-23	110	108
Drilling Tests, Elevated Initial Temperature, Chamber with H ₂ -Air, Steel Bits										
12/16/92	40	30.1	H ₂	69.9	16.0	-38	5/16" steel	CS-24	110	>150*
	41	29.7	H ₂	70.3	16.1	-38	5/16" steel	CS-25	90	100
	42	30.1	H ₂	69.9	15.9	-38	5/16" steel	CS-26	110	103
Drilling Tests, Elevated Initial Temperature, Chamber Filled with H ₂ -Air, TIN Bit No. 1, After Drilling a Total of 50 Times Through 1/4" Steel Plate										
12/17/92	43	29.9	H ₂	70.1	16.1	-40	TIN-1	CS-27	110	108
	44	29.8	H ₂	70.2	16.1	-40	TIN-1	CS-28	110	125
	45	29.8	H ₂	70.2	16.1	-40	TIN-1	CS-29	110	115

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Date	Run	Gas %	Gas Type	Air %	P initial, psi	Chamber Temp, °C	Drill Bit	Test Coupon	Drill Pressure, psi	T _{max} °C
Drilling Tests, Elevated Initial Temperature, Chamber Filled with CH ₄ -Air										
12/22/92	52	10.2	CH ₄	89.8	23.6	~40	TiN-2	CS-30	110	98
	53	10.0	CH ₄	90.0	16.0	~40	TiN-2	CS-31	110	111
	54	10.0	CH ₄	90.0	16.0	~40	TiN-2	CS-32	110	108
Drilling Tests, 1/2" Carbide Tipped Steel Bit, Chamber Filled with H ₂ -Air										
12/29/92	55	29.8	H ₂	70.2	16.1	~20	1/2" steel	CS-33	90	>150
	56	30.1	H ₂	69.9	16.0	~20	1/2" steel	CS-34	90	~201
	57	30.1	H ₂	69.9	15.9	~20	1/2" steel	CS-35	90	~207
	58	30.0	H ₂	70.0	16.0	~20	1/2" steel	CS-36	110	244
	59	29.9	H ₂	70.1	16.0	~20	1/2" steel	CS-37	110	230
Drilling Tests, TiN Bit, Flange and Lid in Vise, Viewed From Top Side of Lid										
12/30/92	60					~23	TiN-2	CS-38	90	112
Drilling Tests, TiN Bit, Flange and Lid in Vise, Viewed From Bottom of Lid										
12/30/92	61					~23	TiN-2	CS-39	90	136
	62					~23	TiN-2	CS-40	90	133
	63					~23	TiN-2	CS-41	110	140
	64					~23	TiN-2	CS-42	110	134
Drilling Tests, TiN Bit, Flange and Lid in Vise, Viewed From Top Side of Lid										
01/11/93	65					~23	TiN-2	DL-5	110	77
	66					~23	TiN-2	DL-6	110	~167
	67					~23	TiN-2	DL-7	90	~160
	68					~23	TiN-2	DL-8	90	~161
	69					~23	TiN-2	DL-9	90	~164
	70					~23	TiN-2	DL-10	90	~141

Date	Run	Gas %	Gas Type	Air %	P _{initial} , psi	Chamber Temp, °C	Drill Bit	Test Coupon	Drill Pressure, psi	T _{max} , °C
01/11/93	71					-23	TIN-2	CS-43	90	118
	72					-23	TIN-2	DL-11	90	-157
Standard Drilling Tests, Chamber Filled with H ₂ -Air										
01/14/93	73	30.0	H ₂	70.0	16.0	-20	TIN-2	DL-12	90	-167
	74	28.9	H ₂	71.1	16.6	-20	TIN-2	DL-13	90	169
	75	30.0	H ₂	70.0	16.0	-20	TIN-2	DL-14	90	163
	76	29.9	H ₂	70.1	16.1	-20	TIN-2	DL-15	90	-150
Drilling Tests, 1/2" Carbide Tipped Steel Bit, Chamber Filled with H ₂ -Air										
01/14/93	77	30.2	H ₂	69.8	15.9	-20	1/2" steel	DL-16	90	164
	78	30.1	H ₂	69.9	15.9	-20	1/2" steel	DL-17	90	-210
Drilling Tests, 5/16" TIN Bit, Higher Resolution and Sharper Focus, Chamber Filled with Air										
02/04/93	79			100.0		-20	TIN-2	CS-44	90	253
	80			100.0		-20	TIN-2	CS-45	90	227
	81			100.0		-20	TIN-2	CS-46	90	259
	82			100.0		-20	TIN-2	CS-47	110	257
	83			100.0		-20	TIN-2	CS-48	110	243
	84			100.0		-20	TIN-2	CS-49	110	232
	85			100.0		-20	TIN-2	DL-18	90	363
	86			100.0		-20	TIN-2	DL-19	90	345
	87			100.0		-20	TIN-2	DL-20	90	352
	88			100.0		-20	TIN-2	DL-21	110	-400
	89			100.0		-20	TIN-2	DL-22	110	385
	90			100.0		-20	TIN-2	DL-23	110	380

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Date	Run	Gas %	Gas Type	Air %	Initial psi	Chamber Temp, °C	Drill Bit	Test Coupon	Drill Pressure, psi	Temp °C
Drilling Tests, 1/2" Carbide Tipped Steel Bit, Higher Resolution and Sharper Focus, Chamber Filled with Air										
02/05/93	91			100.0		-20	1/2" steel	CS-50	90	395
	92			100.0		-20	1/2" steel	CS-51	90	>400
	93			100.0		-20	1/2" steel	CS-52	90	>400

*Drill bit broke during Test 40, before drilling completely through coupon.

Notes: DL = 16 gauge drum lid
CS = 1/4" thick steel plate

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