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REDUCTION OF RADON DAUGHTER CONCENTRATIONS IN STRUCTURES

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ABSTRACT

A structure was identified in Salt Lake City wherein uranium mill tailings had been used in the construction and where unusually high levels of radon daughter concentrations (RDC's) existed. The physical and radiological characteristics of the structure were assessed. Ventilation techniques were investigated to assess their effectiveness in reducing RDC's. A preferred set of equipment was identified, installed in the structure and operated to reduce RDC's. Parametric studies were conducted to determine if supplying fresh air or recirculating air through electrostatic precipitators is more effective in reducing RDC's. Fresh air was found to be more effective in reducing RDC's. RDC's have been reduced to levels at or near the target of 0.03 WL under optimal ventilation conditions.

Natural gas consumption with the new equipment is about 39% higher than with the original equipment. Electrical energy usage and electrical demand are respectively 50 and 44% higher with the new equipment than with the original equipment.

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CHAPTER ONE

INTRODUCTION

1.0 INTRODUCTION

Ford, Bacon & Davis Utah Inc. (FBDU) under contract to Sandia Laboratories (Contract Number 49-5743) has conducted an investigation for the U.S. Department of Energy, Albuquerque Operations Office to determine the cost-effectiveness of various methods of reducing radon daughter concentrations (RDC's) in buildings. This report consists of background information, a description of the property at which these investigations were conducted, an evaluation of alternatives considered, a description of the newly installed equipment and its effect on the RDC's, and a comparison of original and current energy consumption.

1.1 HISTORY AND BACKGROUND INFORMATION

Between the years of 1951 and 1964, the Vitro Corporation processed uranium ores at what is currently known as the Vitro site in Salt Lake County, Utah. The site is located southwest of downtown Salt Lake City.⁽¹⁾ Upon conclusion of operations, the site was fenced and control was relinquished by the Vitro Corporation, according to requirements which prevailed at the time.

Since access to the Vitro site was essentially uncontrolled, tailings were used in the construction of several buildings and as backfill at many locations away from the site itself.⁽²⁾ Such use has been shown to result in higher exposure rates to those who frequent the affected buildings and

locations. Numerous occurrences of tailings use in buildings have been noted in Grand Junction, Colorado and near other inactive uranium mill sites.(3,4)

In some cases,(3) remedial action already has been accomplished. In others,(4,5,6) interim corrective action has been taken to reduce the risk to workers, prior to the permanent remedial action presently authorized by Congress.(7) In cases where interim corrective action has been taken, dilution ventilation and electrostatic precipitators have been installed to reduce the radon daughter concentrations.

In this study, a site was identified where tailings had been used as engineered fill material and where owners were amenable to investigations of the control of RDC's. The offices and warehouse of Mountain States Supply, Inc. (MSS), a private Utah corporation, were found to have been built on uranium mill tailings. Extensive investigations had been conducted by local and federal agencies(8,9) to determine the severity of the problem at the MSS facilities.

Data reported in the radiological survey at MSS(8) showed that RDC's greater than 2.0 working levels existed prior to interim corrective action. In similar situations where interim corrective actions have been undertaken,(4,5,6) reduction of RDC's by a factor of about 10 have been experienced where dilution ventilation and/or electrostatic precipitators were used. Another option which has been considered but which has

not been implemented is the installation of high-efficiency filters. Capital, operating costs and operating characteristics made this equipment unattractive, and no consideration was given to this possibility.

1.2 DESCRIPTION OF MOUNTAIN STATES SUPPLY, INC. FACILITY

The Mountain States Supply, Inc. facility is located at 184 W. 3300 So. Street in South Salt Lake City, Utah. The principal structure is slab on grade and elevated slab with cinder block walls. The layout of the MSS property is depicted in Figure 2.1, which shows the facility to be divided between the office and display area (south portion--hereafter referred to as the office area) and the warehouse (north portion).

Although there is a corrugated steel building (quonset hut) to the north of the warehouse, no consideration was given to RDC's in this structure since there is substantial fresh air exchange through cracks, open doors, etc. Thus, in this outbuilding RDC's are low under normal conditions, despite any contamination which might exist beneath the structure.

The original heating and ventilating systems in the office area and warehouse were sized to independently maintain temperatures within reasonable comfort limits under normal conditions. However, no provision existed for the forced supply of fresh air to the office area and only a small source of forced fresh air was provided for the warehouse, and then only during the cooling season.

1.3 STUDY OBJECTIVES AND METHODS

The objectives of this study were (1) to assess methods to cost-effectively reduce RDC's at the MSS facility, (2) to install a cost-effective system at the MSS facility, (3) to determine the effectiveness of the installed system in reducing RDC's and (4) to determine the impact of the new system on energy consumption at the MSS facility.

The physical and radiological characteristics of the MSS facility were first assessed or verified. Next, candidates for components of the ventilation system were identified and evaluated and a reasonable set of equipment selected. The equipment was specified and installed under FBDU direction. The effectiveness of fresh air and precipitator flow rates were examined during parametric studies under heating and cooling conditions. Acceptable operating conditions were determined and the system was set to operate at those conditions. The RDC's and utility use have been monitored periodically.

1.4 THE NATURE OF RADON-222

Because the behavior of radon is unfamiliar to many who might read this report, a brief description of its characteristics is in order. Radon-222 (radon) is a radioactive gas which decays by alpha emission to Polonium-218, a "daughter" of radon. Radon has a half-life of 3.84 days; i.e., in 3.84 days, half the initially-existing radon in a given volume will remain where no source of radon exists. The balance of the radon will have decayed to the various daughter products in the same time.

Radon is produced by the radioactive decay of Radium-226, one of the radioactive constituents of uranium mill tailings. The daughters of radon (Polonium-218, Lead-214, Bismuth-214, and Polonium-214) are themselves radioactive with half-lives of about 3 minutes, 27 minutes, 20 minutes and 164 microseconds, respectively. Thus, because of the relatively short half-lives of the radon daughters, their decays proceed relatively rapidly on the average once the radon decays. Radon daughter decays continue beyond Polonium-214 until finally the stable isotope Lead-206 is formed.

Under undisturbed conditions, such as exists in uranium ore, the activities (or rates of decay) for Radium-226, Radon-222 and their daughters are equal. This condition is known as secular equilibrium. However, in the particular situation existing at the MSS facilities, the radon diffuses away from the radium, is released to the air above the floor, and may be evacuated, depending on ventilation conditions. Therefore, secular equilibrium does not generally exist in the air spaces at the MSS facilities. Inhalation of radon daughters constitutes the major hazard associated with exposure to uranium mill tailings. If either radon or its daughters can be removed from or reduced in a particular environment, the excess risk of lung cancer can be eliminated or substantially reduced.

Because radon and its daughters may exist in any proportions, depending on prevailing conditions, it is generally impossible to measure the associated hazard based on the

concentration of any single component of the mixture. Therefore, the typical measure of mixtures of radon and its daughters is the "working level," abbreviated WL. A working level is defined as any combination of Radon-222 daughters which deposit 1.3×10^5 MeV of alpha energy. An expression for converting concentrations of Radon-222 daughters to working levels is presented at the conclusion of Appendix A.

Radon, being a gas, diffuses readily through such media as air, sand, soil and concrete. However, high moisture content in the attenuating medium, and clay and epoxy coatings have been demonstrated to form effective barriers to radon migration. (10,11,12)

Based on the theory of diffusion, it can be shown that the rate of migration from a radon source to an adjacent volume of air will be slower if the concentration of radon in the adjacent volume is higher. This accounts for the unusual behavior of the radon release rate (flux) from the floor and the MSS facility described in Chapter 2. The flux was observed to be high during the day (when concentrations in the facility were low due to traffic into and out of the building) and low at night (after the radon concentration had built up in the closed, inactive facility).

Although the U.S. Environmental Protection Agency (EPA) has promulgated interim and proposed standards and is in the process of amending standards for the cleanup of properties contaminated with uranium mill tailings, they were not available when this

project was initiated. Therefore, DOE personnel agreed that a reasonable target RDC would be one-tenth the maximum allowed for uranium miners, or 0.03 WL. This target was used in all subsequent evaluations, designs and operations at the MSS facility during this investigation.

CHAPTER TWO

ORIGINAL CHARACTERISTICS

OF THE

MOUNTAIN STATES SUPPLY, INC. FACILITY

2.0 ORIGINAL CHARACTERISTICS OF THE MOUNTAIN STATES SUPPLY, INC. FACILITY

In this chapter the basic characteristics and parameters describing the MSS facility are presented. The general layout of the structure is treated in Section 2.1. Section 2.2 describes the original heating and ventilating system. The radiological conditions which existed at the MSS facility prior to interim corrective action are presented in Section 2.3.

2.1 GENERAL LAYOUT

The MSS facility was constructed about 1960. The general layout of the facility is presented in Figure 2.1. The total floor area of the office at the south end of the structure was estimated to be 4,500 ft², with a ventilated volume of about 39,000 ft³. In the warehouse (north end of building) the floor area was estimated to be 11,300 ft² and the ventilated volume to be 157,000 ft³.

There are two doors and a window which connect the office area and warehouse. The west door was originally kept open at all times and the east door was in constant use. The usage rate of the east door was estimated to be approximately once per minute⁽¹³⁾ and the resulting air exchange rate was estimated to total about 50 cfm through both doors, assuming the window was normally closed. By assuming that this exchange rate resulted in air movement from the warehouse area to the office area, model predictions of the RDC's (described in Appendix A)

are consistent with observations under typical working-day conditions.

Exterior walls are constructed with cinder blocks. The office area walls are relatively airtight, but in the warehouse the loose delivery doors allow substantial air exchange, whether open or closed.

The floor is concrete slab-on-grade in the office area, while in the warehouse it is a slab elevated about 4 ft above natural grade. Apparently, all floors in the structure have been constructed over tailings.(8)

2.2 ORIGINAL HEATING AND VENTILATING SYSTEMS

The layouts of the original heating and ventilating systems also are depicted in Figure 2.1. The only interaction between ventilating systems of the office area and the warehouse resulted from air exchange through the open doors and the window which connect the two areas (see Section 2.1).

2.2.1 Office Area

A central heating and air conditioning system existed for ventilating the office area. The distribution system is shown in Figure 2.1 and is adequate to sustain air circulation of at least 12,000 cfm or about 18 air changes per hour. There was no provision for fresh air supply in the original system.

The original oil burner of the furnace was replaced with a gas burner prior to these investigations. The heating capacity

of the modified furnace is unknown. The furnace was manufactured by Mueller (Model 253-350).

The air conditioning system relied on a water chiller and had a duty of about 90,000 BTU/hr. The compressor and coils were manufactured by Worthington Corporation (Model 2JF5-7.5).

In an effort to reduce RDC's during fair weather, natural circulation of fresh air was encouraged by leaving outside doors open. In 1977, an electrostatic precipitator was installed for dust control. The precipitator (Honeywell Model F47B) was rated for air flow rates up to 5,000 cfm.

Measurements of actual flow rates of the existing ventilating system indicated that the circulation was very poor. It appeared that the total recirculating flow rate was less than 2,800 cfm. Thus, in spite of the presence of the precipitator, the low recirculation rate limited the potential for radon daughter removal. This fact, coupled with the lack of fresh air supply, resulted in the relatively high measured RDC's, caused by radon which diffused through the floor slab from the tailings below.

2.2.2 Warehouse

At the time of the FRDU investigation there was no central heating and ventilating system in the warehouse. Heating in the winter was accomplished with seven space heaters, located as shown in Figure 2.1. These space heaters (Mueller Models

160-200 and 167-175) had individual input heating capacities of 125,000 and 160,000 BTU/hr, respectively.

In summer, cooling was accomplished only by natural passive circulation resulting from doors purposely left open and by forced air supply from a small evaporative cooler (about 4,200 cfm capacity) near the counter (southeast corner of the warehouse).

2.3 ORIGINAL RADIOLOGICAL CONDITIONS

2.3.1 Previous Surveys

In August 1979, an engineering assessment of the property was conducted to document the original radiological characteristics of the site.⁽⁸⁾ In this assessment, external gamma radiation (EGR) was measured within the buildings at "waist level" (about 3 ft above the floor) and at "contact" with the floor. The results of the EGR survey are presented in Figure 2.2. The following average EGR levels in excess of background were observed at waist level:

<u>Location</u>	<u>Maximum EGR Level* (μR/hr)</u>	<u>Minimum EGR Level* (μR/hr)</u>	<u>Average EGR Level* (μR/hr)</u>
Office	45		17
Warehouse area	40	12	28
Quonset hut	13	0+	2
Wooden platform	275	6	94
Loading dock	59	20	35
Entire structure	--	--	35

*At waist height above the floor.

Two sets of radon and radon daughter samples were taken and analyzed. Generally, each set consisted of grab samples taken simultaneously from the seven interior locations noted on Figure 2.2. The first set of samples, shown below, was taken during the afternoon of a typical workday with the air conditioner operating, and with the office and warehouse doors open. The second set was taken at 7:00 a.m., after the entire structure had been closed, with the air conditioning secured and with no occupancy for the previous 14 hours. The results are presented below:

<u>Date</u>	<u>Location*</u>	<u>Average Radon-222 (pCi/l)</u>	<u>Average RDC (WL)</u>
July 12, 1979	Office (Locations, 1,2,3&4)	14.1	0.026
	Warehouse (Locations 5 & 6)	26.2	0.010
	Quonset Hut (Location 7)	10.3	0.001
	Entire Structure (Average)	18.8	0.011
July 14, 1979	Office (Locations 1,2,3&4)	147.2	0.277
	Warehouse (Locations 5&6)	510.2	2.366
	Quonset Hut (Location 7)	6.4	0.021
	Entire Structure (Average)	221.3	0.888

From the data above, it is apparent that under unfavorable conditions, RDC's are very high, even exceeding the occupational limit for uranium miners (0.3 WL). The RDC's in the quonset hut were lower than those in other areas, presumably because of the high rate of fresh air exchange through doors and cracks in the

*See Figure 2.2 for locations.

structure and possibly because there may not be significant quantities of tailings under the structures.

Other RDC data were obtained by the EPA, as reported in Reference 8, and are presented below:

<u>Date</u>	<u>Location*</u>	<u>RDC (WL)</u>
June 2, 1978	Office (Location 3)	1.468
February 16, 1979	Office (Location 3)	0.978
	Warehouse (Locations 5&6)	1.869
February 28, 1979	Office (Location 3)	1.515
	Warehouse (Locations 5&6)	1.829
March 12, 1979	Office (Location 3)	1.096
	Warehouse (Locations 5&6)	1.872

These data also indicate very high levels of RDC's.

During the radiological assessment, the depths of tailings below the structure were estimated with the aid of drill holes through the concrete floors. The observed depths of tailings below the floor slabs are also shown in Figure 2.2 and range from 16 in. on the south side of the office area to 74 in. in the northeast corner of the warehouse.

2.3.2 Data From This Investigation

During the present study, the original radiological conditions were investigated briefly. However, attention was

*See Figure 2.2 for locations.

focused on RDC's and radon fluxes and various locations and various times of day.

Radon daughter concentrations were measured using the modified Kusnetz method(14) at five distinct times and locations throughout the structure, for six full days and two partial days. In addition, several locations referred to as "rovers" were "spot checked" for a day at a time. The daily averages calculated for each location are presented in Table 2.1. The overall averages at each location with their standard deviations also are given as a function of the time of day.

Based on the averages presented as a function of time of day, the RDC levels apparently begin high and decrease as the working day proceeds. This is intuitively reasonable: while the building is secured during the night the radon daughters accumulate--hence the high levels at the beginning of business on the following day. As the day's activities proceed, the high RDC's are lowered by dilution with fresh air introduced as a result of traffic into and out of the building. In spite of this transient behavior, the daily averages have merit in establishing the high RDC's that existed under original conditions. The overall averages for the office area and warehouse were calculated as functions of time of day and location as follows:

<u>Time of Day</u>	<u>Office Area (WL)</u>	<u>Warehouse (WL)</u>
07:00	1.17±0.42	2.01±0.39
08:40	1.15±0.38	1.69±0.66
10:00	1.00±0.25	1.00±0.38
13:00	0.76±0.23	0.99±0.42
14:00	0.86±0.41	0.72±0.39

Again, the high initial RDC's and the declining RDC's as the day proceeds are apparent. It is also apparent that the RDC's are very high.

Radon flux was measured by exposing charcoal canisters to the flux⁽¹⁵⁾ for several hours at a time at several locations. The locations are identified in Figure 2.3. The results, presented in Table 2.2 indicate a significant variation as a function of time of day. At first inspection, the flux appears to be inconsistent with the temporal variation of RDC's. However, the following may be adequate to explain the behavior: Since radon diffuses because of a concentration gradient, the highest flux is expected when the radon concentration above the floor slab is at a minimum, i.e., when the concentration gradient is highest. It was explained in paragraph 2.3.2 that during the night when the building is secured the RDC's (as well as the radon concentrations) buildup. As the buildup occurs, the concentration gradient is reduced and the flux decreases. In contrast, as the radon concentration falls because of dilution by fresh air from business traffic, the concentration

gradient is increased and the flux increases. Therefore, the behavior noted in Table 2.2 is predictable.

The overall radon flux averages for the office area and the warehouse as a function of the time of day and location were estimated as follows:

<u>Time of Day</u>	<u>Office Area</u> <u>(pCi/m²-s)</u>	<u>Warehouse</u> <u>(pCi/m²-s)</u>
07:00-12:00	23.5 $\pm$ 12.3	27.3 $\pm$ 17.9
12:00-16:00	16.6 $\pm$ 6.3	19.6 $\pm$ 14.4
16:00-07:00	5.2 $\pm$ 1.9	10.2 $\pm$ 4.7

It can easily be seen that the flux is greatest during working hours when the RDC's are lowest (see Table 2.1) and are lowest overnight when the RDC's are believed to be highest.

The efficiency of the existing precipitator in removing radon daughters from the office area also was examined. The precipitator was thoroughly cleaned prior to data collection. Thereafter, working level measurements were taken every half hour at the inlet to the precipitator (cold air return) and at the outlet from the precipitator (warm air air vent). The ratio of any of these values at any time, subtracted from unity, is a measure of the efficiency with which the precipitator removes radon daughters from the air stream.

The data collected during the test period are presented in Table 2.3. Note that the efficiencies range from a low of 10% to a high of 45%, and that the mean efficiency is $27 \pm 10\%$. It

also should be noted that an efficiency of less than 20% was observed only once.

Comparison of the data from the office area and from the warehouse counter between these tests and those described in Table 2.1, indicates that this day was typical and that the measured RDC's at both locations are comparable.

Based on these results, the precipitator efficiency in removing radon daughters was conservatively estimated to be 20%, as discussed in Appendix B.

TABLE 2.1

RDC MEASUREMENTS AT MSS UNDER ORIGINAL CONDITIONS

Date (1980)	Sampling Locations*					RDR(**) (WL)	Average Office Area RDC (WL)
	Office RDC-1 (WL)	Office RDC-2 (WL)	Counter RDC-3 (WL)	Ware- house RDC-4 (WL)	Ware- house RDC-5 (WL)		
Jan 28	0.45	0.86	1.00	0.93	0.83	0.46(1)	0.59
Jan 29	0.66	1.17	1.36	0.87	0.72	0.65(2)	0.92
Jan 30	0.78	1.11	1.68	1.17	1.20	1.18(3)	1.02
Jan 31	0.83	1.34	1.57	1.21	1.15	1.26(4)	1.09
Feb 1	0.74	1.14	1.44	1.18	0.94	1.25(5)	0.94
Feb 4	0.73	1.13	1.43	0.91	0.83	0.70(6)	0.93
Feb 6	1.02	1.56	1.77	1.49	1.35	1.67(7)	1.29
Feb 11	0.81	1.58	1.20	1.24	2.11	1.95(8)	1.20

Averages

by Time
of Day

07:00	0.80 $\pm$ 0.05	1.54 $\pm$ 0.27	2.26 $\pm$ 0.15	2.20 $\pm$ 0.16	1.85 $\pm$ 0.42	NA
08:40	0.78 $\pm$ 0.18	1.47 $\pm$ 0.25	2.10 $\pm$ 0.47	1.56 $\pm$ 0.65	1.39 $\pm$ 0.70	NA
10:00	0.82 $\pm$ 0.21	1.19 $\pm$ 0.07	1.27 $\pm$ 0.34	0.89 $\pm$ 0.39	0.81 $\pm$ 0.25	NA
13:00	0.58 $\pm$ 0.14	0.94 $\pm$ 0.15	1.21 $\pm$ 0.40	0.94 $\pm$ 0.39	0.83 $\pm$ 0.45	NA
14:00	0.79 $\pm$ 0.46	0.94 $\pm$ 0.37	0.82 $\pm$ 0.24	0.74 $\pm$ 0.59	0.61 $\pm$ 0.27	NA

*See Figure 2.3 for locations

**"Rover" locations

TABLE 2.2

RADON FLUX MEASUREMENTS AT MSS UNDER ORIGINAL CONDITIONS

Date (1980)	Time	Sampling Locations*					RFR**
		RF1 (pCi/m ² s)	RF2 (pCi/m ² s)	RF3 (pCi/m ² s)	RF4 (pCi/m ² s)	RF5 (pCi/m ² s)	
Jan 28	10:50-16:00	20.2	14.8	12.8	5.8	14.8	RFR-1 9.4
Jan 28	16:00 to						
Jan 29	07:30	3.8	3.4	8.5	11.7	3.5	3.6
Jan 29	07:00-12:00	12.1	26.9	21.0	8.2	13.1	RFR-2 13.9
Jan 29	12:00-16:00	14.5	14.1	34.4	15.1	7.9	15.8
Jan 29	16:00 to						
Jan 30	07:00	4.3	7.9	6.4	12.2	7.2	10.0
Jan 30	07:00-12:00	11.2	17.0	66.0	12.0	9.0	RFR-3 19.4
Jan 30	12:00-16:00	5.8	14.6	16.5	7.0	3.4	12.8
Jan 30	16:00 to						
Jan 31	07:00	6.2	5.6	8.6	13.8	8.3	11.9
Jan 31	07:00-12:00	23.8	18.7	46.7	19.8	20.8	RFR-4 13.8
Jan 31	12:00-16:00	13.2	19.9	17.5	16.2	23.5	12.5
Jan 31	16:00 to						
Feb 1	07:00	7.5	2.9	13.7	21.6	7.3	19.0
Feb 1	07:00-12:00	29.1	49.4	43.5	38.2	28.8	RFR-5 55.8
Feb 1	12:00-16:00	18.8	30.0	58.0	23.5	37.8	25.2
Mean	07:00-12:00	19.1±8.8	28.0±14.9	44.3±18.4	19.6±13.3	17.9± 8.8	NA
	12:00-16:00	14.5±5.7	18.7± 6.8	27.8±18.8	13.5± 7.3	17.5±13.7	NA
	16:00-07:00	5.5±1.7	5.0± 2.3	9.3± 3.0	14.8± 4.6	6.6± 2.1	NA

*See Figure 2.3 for locations

**"Rover" Locations

TABLE 2.3

DATA CHARACTERIZING PRECIPITATOR EFFICIENCY*

Time	Location				Precipitator Efficiency (%)
	Warm Air Vent. (WL)	Cold Air Return (WL)	Office Area** (WL)	Warehouse Counter** (WL)	
10:30	0.57	0.77	0.88	-	26
11:00	0.41	0.59	-	1.01	31
11:30	0.31	0.51	-	-	39
12:00	0.24	0.44	0.31	-	45
12:30	0.32	0.45	0.63	-	29
13:00	0.35	0.46	-	0.79	24
13:30	0.37	0.46	0.37	-	20
14:00	0.33	0.41	0.39	-	20
14:30	0.28	0.40	-	-	30
15:00	0.36	0.40	-	0.56	10

Average Efficiency 27 ± 10

*Data Taken February 13, 1980

**Only for comparison to data base presented in Table 2.1

FIGURE 2.1 MOUNTAIN STATES SUPPLY, INC. LAYOUT

END

SPACE HEATER WITH DIRECTION OF DISCHARGE SHOWN.

T AND ORIGINAL CONFIGURATION OF HVAC SYSTEM.

LEGEND

- (56") DEPTH OF CONTAMINATION
- [4] RADON SAMPLING LOCATION
- $\frac{50}{80}$ UPPER VALUE UNCONTAMINATED RADIOACTIVE
- LOWER VALUE UNCONTAMINATED RADIOACTIVE

FIGURE 2.2 PREVIOUS RADIOACTIVE SURVEILLANCE

RADON AND RDC DATA

	<u>DATE (1979)</u>	<u>LOCATION</u>	<u>RADON (pCi/l)</u>	<u>RDC (WL)</u>
LOCATION, INCHES	JUL 12	1	10.3	0.019
		2	16.3	--
		3	12.9	0.021
		4	16.9	0.024
		5	5.4	--
		6	47.1	0.017
		7	10.3	--
CORRECTED EXTERNAL GAMMA RADIATION AT WAIST LEVEL (uR/hr)	JUL 14	1	123.	0.177
		2	141.	--
		3	148.	0.356
		4	177.	0.312
		5	531.	--
		6	490.	2.27
		7	6.4	--
CORRECTED EXTERNAL GAMMA RADIATION AT FLOOR LEVEL (uR/hr)		1	10.3	0.019
		2	16.3	--
		3	12.9	0.021
		4	16.9	0.024
		5	5.4	--
		6	47.1	0.017
		7	10.3	--

VEY RESULTS AT MOUNTAIN STATES SUPPLY, INC.

FIGURE 2.3 LOCATIONS OF WORKING LEVEL AND FLUX MEASUREMENTS
AT MOUNTAIN STATES SUPPLY, INC.

CHAPTER THREE

EVALUATION OF CANDIDATE SOLUTIONS

3.0 EVALUATION OF CANDIDATE SOLUTIONS

In this FBDU investigation, two basic approaches for reducing RDC's have been addressed. The first is dilution of the radon in the structure through a sustained introduction of fresh air. The effects of the ever-present source of radon can be minimized effectively by removing the radon from the occupied volume before it can decay to its daughters. If the average residence time of the typical radon molecule is short relative to its half-life (3.84 days) then not only are the radon concentrations lowered, but the reduction of RDC's is compounded because the source of radon daughters (Radon-222) is exhausted by the continuous exchange of fresh air. In this approach, the very source of the problem is effectively removed by the introduction of fresh air, albeit at the expense of increased electrical power and natural gas consumption.

The second approach is to remove radon daughters from the air with an electrostatic precipitator. This is possible since the radon daughters are electrocally charged as they form, and consequently readily attach themselves to dust particles and aerosols in the air. As the air is circulated, the dust of other suspended particles is removed by the precipitator. However, since the efficiency of the precipitator is lower than previously believed (see Appendix B), and since the longest half life of any radon daughter is less than 30 minutes, the air must be circulated at a much greater rate than that required to achieve the same result by dilution by fresh air. Therefore,

given an equilibrium radon concentration in air, the air must be circulated rapidly so a given radon daughter molecule can pass through the precipitator enough times to ensure that the probability of the molecule being removed by the precipitator is greater than the probability that it already will have decayed. The unfortunate result, however, would be bulk air movement sufficient to make occupancy very uncomfortable.

A mathematical model was developed to predict the behavior of RDC's in the office area and warehouse, as described in Appendix A. The model included the effects of the radon sources, the fresh air supply (or infiltration), the air and radon exchange between the office area and the warehouse, the electrostatic precipitator, the air exhaust rates, and the decay of radon and its daughters. Using the model under conditions representative of those at the MSS facilities, the predicted behavior of the RDC levels was examined for different ventilation conditions, as characterized by fresh air supply rate, precipitator efficiency, and air flow rate through the precipitator. Figure 3.1 presents the results of these parametric variations. The use of fresh air to exhaust the radon before it decays appears to be much more effective in reducing RDC's than reliance on electrostatic precipitation to remove radon daughters after they have formed.

Consideration was given to utilizing an air-to-air heat exchange to heat the supply air stream by recovering heat from the exhaust air stream. Although this would have saved

thermal energy, additional electrical energy would have been required to move the same amount of air through equipment with significantly higher resistance to flow. Furthermore, when the capital cost of such equipment was compared with the maximum potential energy savings (even disregarding higher electrical power consumption), it was concluded that secondary energy recovery is not economically feasible. No further consideration was given to this possibility.

In determining the total system cost, estimates were made for all equipment options on a consistent basis for the purchase and installation costs, expressed here in 1982 dollars. Energy (electricity and natural gas) costs were determined by assuming straight line increases between 1980 unit costs and those projected for 1982 (30% higher). Energy usage was estimated for each month's operation with each equipment option, and the resulting costs for 2 years of operations were determined. The present worth of all operating costs was determined for each option, assuming the interest rate is one percent per month. The present worth of operating costs for 2 years of operations was added to the estimated purchase and installation costs to produce the total system cost.

In the following sections, various combinations of equipment and operating conditions which produce acceptable RDC levels are described and evaluated. For purposes of this investigation, FBDU determined with DOE representatives that

acceptable RDC levels were those less than one tenth that allowed for uranium miners, i.e., 0.03 WL.

3.1 EQUIPMENT OPTIONS FOR OFFICE AREA

Investigations indicated that there were design features in the original MSS facility which contributed to the problem of radon and its daughters in the office area. These features included: no provision for fresh air supply, the low rate of recirculation of air (about 2,800 cfm), and low efficiency of the existing precipitator (as demonstrated in Appendix B).

Since there was no forced fresh air supply, radon remained essentially until it decayed once it entered the office area. The only fresh air available was the result of infiltration, but was available in such small quantities as to be overwhelmed by the radon source. If fresh air could be introduced into the office area at a rate sufficient to remove most of the radon before it decayed, the RDC's could have been dramatically reduced. This condition is demonstrated in Figure 3.1 which shows that if fresh air alone were supplied to the office area at a rate of about 1,500 cfm, the predicted RDC's would be about 0.03 WL.

In contrast, Figure 3.1 suggests that actual flow rates through electrostatic precipitators would have to exceed 150,000 cfm (assuming an actual precipitator efficiency of 20%) to reduce RDC's to the acceptable range. Such a massive flow rate is impractical in a ventilated volume of this size.

3.1.1 Install New Heating and Ventilating Equipment

Since fresh air was found to be so much more effective than precipitators, an option which would rely only on fresh air was identified and evaluated. In this option, fresh air would be supplied at a rate of 2,000 cfm (about 3.1 air changes per hour). A duct heater with an approximate duty of 300,000 BTU/hr input capacity would provide the required 230,000 BTU/hr heating for this fresh air flow rate. A 15-ton air-cooled mechanical refrigeration air conditioner would also be provided.

Recirculation through the precipitator at a rate of 4,000 cfm would be provided although the presence of the precipitator is incidental to this option and no credit was taken for its influence on radon daughters.

To make maximum use of energy spent to heat or cool the fresh air supplied to the office area, the equipment would operate at a positive pressure relative to the warehouse. With this feature, some tempered air would flow from the office area to the warehouse and thus help to heat or cool the warehouse.

The purchase and installation cost of this option was estimated to be \$13,900 and the present worth of 2 years of operating costs was estimated to be \$8,100, for a total estimated cost of about \$22,000.

3.1.2 Ten Percent Fresh Air

In order to investigate the economics of significant

reliance on precipitators, an option was identified which would provide 1,350 cfm fresh air (2.1 air changes per hour) and 11,000 cfm recirculated air (through precipitators). Larger total air circulation rates are considered imprudent. As proposed, this option would circulate air in the office area at the rate of about 19 times per hour, a rate considered very high.

In this option, two new heaters with an approximate total input capacity of 600,000 BTU/hr and a new air-cooled mechanical refrigeration air conditioner of 15-ton cooling capacity would be required. The large heating capacity would be provided only because of the large flow rate, which requires a large surface area and thus a large capacity. The actual heating requirement to maintain comfort is much less. In other words, because of the high air flow rate, with relatively small heating and cooling requirements, the unit would operate at significantly less than capacity.

As with the previous option, air would flow from the office area to the warehouse due to the pressure differential which would exist.

The purchase and installation cost of this option was estimated to be \$28,900 and the present worth of 2 years of operating costs was estimated to be \$14,400, for a total estimated cost of about \$43,300.

3.1.3 Comparison of Options in Office Area

Because the options described for the office area were designed to produce the desired RDC's, the benefits of the options would be identical. Therefore, the cost alone is a reasonable indicator of the cost-effectiveness of the options. It was concluded that installing new heating and ventilating equipment would result in a system with greater operating flexibility, a feature desired for the purpose of this investigation. Therefore, new equipment was installed in the office area as described below.

3.1.4 New Heating and Ventilating System for the Office Area

A central heating, ventilating and air conditioning (HVAC) system (Trane Company Model No. SFCA-150-3-L) was installed on the roof of the office area. This unit consists of gas-fired heater, blower, and a two-stage compression air conditioning unit. The unit has a cooling capacity of 180,000 BTU/hr, an input heating capacity of 300,000 BTU/hr, and is rated for air flow of 7,000 cfm at a pressure differential of 1.25 inches water gauge. The unit is equipped with an economizer and rheostat control to permit the remote manual selection of any fresh outside air flow rate in the range of 0 to about 2,000 cfm.

The previously existing electrostatic precipitator was relocated and installed in the intake system of the HVAC unit to permit clean-up of recirculated air. A timer control was added

to the precipitator control to actuate the wash cycle each day at about 6:00 a.m.

Figure 3.2 presents the schematic flow diagram of the unit as installed. The HVAC unit has the capacity of operating with 100% recirculated air through the precipitator or completely bypassing the precipitator through the bypass branch, or at any conditions between the two extremes. In addition, outside air could be provided and varied between 0 and about 2,000 cfm.

Hand-operated volume dampers were provided at the precipitator outlet and in the bypass branch to control the amounts of air flow through these branches. The fresh air flow is controlled by outside air dampers located in the economizer section of the HVAC unit. These dampers are controlled manually by the rheostat located in the vicinity of other instrumentation.

The operation of the HVAC unit is controlled by a digital temperature control (thermostat) system in the office area. The thermostat allows remote automatic or manual operation of the air conditioning unit and the heater unit, as well as operation of the fan alone. In the automatic mode, the set temperature (comfort level) and outside ambient conditions determine the mode of HVAC operation. An adequate dead band between heating and cooling settings was provided to protect the system from excessive on/off cycling.

Air flow in the ducts is measured with Annubar Airbars (Model No. AIR-79-RC-#-C04). These devices measure the averages of the pressure distributions across the ducts for both static and dynamic pressures. The pressure differentials are indicated by Eagle Eye pressure indicators (Model No. EFW-FI-ACFM-8000XNM), calibrated in hundredths of an inch of water. This calibration was subsequently judged to be marginal, since finer resolution would have been desirable.

3.2 EQUIPMENT OPTIONS FOR THE WAREHOUSE

Four basic options which would reduce the high radon daughter concentrations originally existing at MSS in the warehouse to acceptable levels were identified. These options would rely on various combinations of fresh air supply and electrostatic precipitators to remove radon and radon daughters from the warehouse. The resulting RDC was estimated to be about 0.03 WL for all options. These options are discussed in the following sections.

In the warehouse under existing conditions, only a small cooling capacity was originally provided in hot weather. The doors were opened to provide natural circulation. It is believed that this natural circulation was sufficient to reduce RDC's to acceptable levels, without requiring forced circulation. Even so, in estimating operating costs for hot weather, the fresh air supply and circulating air fans were assumed to operate.

Seven space heaters originally provided the entire heating capacity available in the warehouse. This existing heating capacity has been considered in all evaluations of equipment options for the warehouse. In addition, as proposed in Section 3.1, the office area would operate under positive pressure with respect to the warehouse. Thus, in the absence of any exhaust system for the office area, there would be a substantial flow of heated or cooled air from the office area to the warehouse. The heating effect of this flow of tempered air has been included in determining the heating duty which must be provided by means of these equipment options.

In the evaluation which follows, a single fresh air supply fan has been assumed. The distribution of air within the warehouse is equally effective, regardless of the number of fresh air supply fans used, since essentially the same distribution ductwork was considered for all configurations. An additional consideration was the flexibility provided by multiple air supply fans. It was reasoned that two supply fans would allow desired flexibility for purposes of this investigation.

All systems described in the following sections produce essentially the same reduction of RDC levels. Therefore, the total cost alone is a reasonable representation of the cost-effectiveness of the options.

3.2.1 Once-Through Ventilation

In the first case, only fresh air was considered, without recirculation through precipitators. Predictions indicated that a fresh air flow rate of about 9,200 cfm (about 3.5 air changes per hour) would reduce the RDC's to acceptable levels. This fresh air supply rate would require an additional input heating capacity of 600,000 BTU/hr. Air would be exhausted at the same rate at which it was supplied in this option.

The capital and installation costs were estimated to be \$14,200 for this option, and the present worth of operating costs for 2 years was estimated to be \$5,100, for a total system cost of about \$19,300.

3.2.2 Fifty Percent Fresh Air

In this option, a total of about 16,000 cfm air circulation would be provided. Of that total, 8,200 cfm (3.1 air changes per hour) of fresh air would be supplied and an additional 8,000 cfm would be recirculated through electrostatic precipitators. Because of the fresh air being provided, an additional 600,000 BTU/hr input heating capacity would have to be provided. A precipitator or precipitators with a combined capacity of 7,000 cfm would also have to be provided. Air would be exhausted at virtually the same rate it was supplied in this solution.

The capital and installation costs were estimated to be \$21,900 for this option, and the present worth of operating

costs for 2 years was estimated to be \$6,700, for a total system cost of about \$28,600.

3.2.3 Thirty Percent Fresh Air

In this option, a total of about 23,200 cfm air circulation would be provided. Of this total, fresh air would be provided at a rate of 7,200 cfm (2.8 air changes per hour) and air recirculated through precipitators at the rate of 16,000 cfm. Additional input heating capacity of 600,000 BTU/hr would be required because of the large surface area demanded by the large total flow rate. A precipitator or precipitators with a combined capacity of 16,000 cfm would also have to be provided. Air would be exhausted at virtually the same rate it was supplied in this option.

The capital and installation costs were estimated to be \$25,900 for this option, and the present worth of operating costs for 2 years estimated to be \$8,200, for a total system cost of about \$34,100.

3.2.4 Twenty Percent Fresh Air

In this option, a total of about 30,200 cfm air circulation would be provided. Of that total, fresh air would be provided at the rate of 6,200 cfm (2.4 air changes per hour) and air would be recirculated at a rate of 24,000 cfm. Additional input heating capacity of about 600,000 BTU/hr would be required because of large surface area demanded by the large flow rate. The precipitator would have to accommodate a flow of 24,000 cfm.

Air would be exhausted at a virtually the same rate it was supplied in this option.

The capital and installation costs were estimated to be \$29,500 for this option, and the present worth of operating costs for 2 years was estimated to be \$9,100, for a total system cost of about \$38,600.

3.2.5 New Heating and Ventilating System for the Warehouse

Because fresh air is so much more effective than recirculation through precipitators in reducing RDC's, less air must be moved. Consequently, smaller equipment can be used. Furthermore, although energy requirements for heating and cooling fresh air are greater, the increase is more than offset by savings resulting from moving significantly less air. Therefore, the total present worth of system costs utilizing only fresh air for reduction of RDC's is less than those resulting from a system utilizing precipitators. Thus, relying only on fresh air to reduce the potential health hazard in the warehouse of MSS was judged to be most cost-effective.

The only interaction between the HVAC system of the office area and that in the warehouse is the flow of tempered air from the office area to the warehouse. This flow rate is roughly equal to the rate at which fresh air is supplied to the office area.

Two horizontal blower/duct furnace combinations (ITT Renzor Company Model No. RXE-300) capable of providing 4,600 cfm

of outside air each, at 0.75 inches of water gauge, were installed on the roof of the warehouse. Each unit has input capacity of 300,000 BTU/hr. Four exhaust fans (Loren Cook Company, Model 18C4WB) capable of displacing 2,800 cfm each at 0.1 inches of water gauge were also installed, equally spaced on the west wall of the warehouse about 10 ft above the warehouse floor.

Figure 3.3 presents the schematic layout of the new equipment in the warehouse. The previously existing space heaters and evaporative coolers are not shown on this drawing.

The operation of the blower/heater units is controlled remotely and manually. The exit temperature from the heater unit is measured, and controls the heating of air supplied to the warehouse. The control logic of the blower/heater units is designed so that the blower fans operate at all times during the working day, independent of the furnace operation. This feature is incorporated to maintain the required air exchange in the warehouse regardless of meteorological conditions (see Section 4.1).

The operation of the exhaust fans also is interlocked with the operation of the blower/heater units. This arrangement requires the exhaust fans to operate whenever a blower/heater fan is operating, therefore allowing a better distribution of outside air throughout the warehouse building.

A mechanical control (timer) system was provided for the blower/heater units and exhaust fans to de-energize the system during off-hours and to energize the system 1 hour before starting time on work days.

The current control system does not influence the operation of the previously existing space heaters and evaporative cooler.

**FIGURE 3.1 PREDICTED 24-HOUR AVERAGE RADON DAUGHTER
CONCENTRATIONS UNDER THREE FLOW CONDITIONS**

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FIGURE 3.2 SCHEMATIC DIAGRAM OF NEW HVAC SYSTEM FOR OFFICE AREA OF MOUNTAIN STATES SUPPLY, INC.

FIGURE 3.3 SCHEMATIC DIAGRAM OF NEW HVAC SYSTEM FOR WAREHOUSE OF MOUNTAIN STATES SUPPLY, INC.

CHAPTER FOUR

RESULTS OF OPERATION WITH NEW HVAC SYSTEM

4.0 RESULTS OF OPERATION WITH NEW HVAC SYSTEM

The most cost effective equipment for reducing RDC'S was identified and then specified, procured, and installed. After startup, the equipment function was monitored to assure acceptable performance and to characterize the effect on RDC's. The results of these observations are described below.

4.1 PHYSICAL CONDITIONS WITHIN THE MSS FACILITY

Once the typical startup problems were solved, the system operated basically as intended. However, there have been some adjustments necessary to improve comfort and assure correct function.

Because the existing ductwork was used with the new equipment, dust that had accumulated over the years has steadily been discharged into the office area to become a major nuisance. There are apparently no commercial vacuum services in Salt Lake City which have equipment capable of eliminating this problem. Consequently, the larger ducts were disassembled, vacuumed and washed by MSS personnel. Too little time has passed to evaluate the effectiveness of this action.

It was discovered after a few months of operation that the belt tension in the heater/air conditioner for the office area was substantially less than specified, apparently the result of the belts stretching. This condition allowed slippage between the motor and fan, causing insufficient air flows. Once

the belts were replaced and tension properly adjusted, the required air flows were restored. Whereas the equipment was provided with a one-belt pulley between motor and compressor, a modification has been made so the load is now shared by two belts. This change has largely eliminated premature stretching of the belts.

Semi-annual servicing has been required in order to maintain the units and to assure adequate performance.

In the winter of 1981-82, outside temperatures were significantly lower than the selected design temperature for the warehouse system ($\leq 20^{\circ}$ F). Therefore, fresh air was supplied at a temperature of about 50° F under the worst conditions, in addition to the relatively high air speeds with which the air is supplied. These conditions resulted in an extremely uncomfortable environment for workers and customers in the warehouse. To sustain business operations, the proprietor directed that the supply and exhaust systems be secured and that the original space heaters be activated. Although no confirmatory measurements were made at the time, it is suspected the RDC's in the warehouse may have been similar to those which existed prior to the installation of the new equipment. When more moderate weather returned, the supply and exhaust systems were reactivated to reduce the RDC's as intended.

A design modification will eliminate the problem described above. Motor speed controllers will be installed and will control the fresh air supply rate to maintain the supply

temperature of about 70° F. Although this will solve the comfort problem during extremely cold weather, the solution will be achieved at the temporary expense of higher RDC's. It is expected that the RDC's will rise somewhat faster than inversely proportional to the reduction of fresh air supply rate. Nevertheless, the RDC's will be significantly lower than those which originally existed and will be experienced for only relatively short periods during extremely cold winter spells.

4.2 RADIOLOGICAL CONDITIONS

The newly installed HVA systems have successfully reduced RDC's, essentially to the target levels. Parametric studies were conducted in the office area only to assess the effectiveness of fresh air supply and of precipitator flow rate in reducing RDC's. Parameters which were monitored included total flow rate, flow rate through the bypass branch, flow through the precipitator branch, supply air temperature, return air temperature, the conditions of doors and windows, and the operation of all HVAC equipment. No effort was made to monitor meteorologic conditions.

4.2.1 Parametric Studies--Cooling Season

Between August 7 and August 18, 1980, parametric studies in the office area during the cooling season were conducted. These consisted of two separate sets of tests: (1) the system operated with varying fresh air supply rates without recirculation through the electrostatic precipitator, and (2) the system

operated with no fresh air supply and with varying amounts of air recirculated through the electrostatic precipitator. All tests were conducted for a minimum of 2 days each during working hours.

The objective of the "fresh air test" was to evaluate the effectiveness of mixing outside air with the recirculated air to reduce RDC's. The precipitator was isolated for this test and all recirculated air was directed through the bypass branch as shown schematically in Figure 4.1. During these studies, weather was clear and hot.

With the precipitator damper shut, the bypass damper and fresh air damper in the economizer were adjusted to vary the outside flow rate from 0 to 1,800 cfm. The total air (cooled air) supplied to the office area was maintained at about 6,200 cfm. Radiological and environmental parameters as noted above were monitored and recorded at two locations in the office area during the fresh air test. Working levels were measured and recorded six times each day at each location. Working-day average RDC measurements for the office area are presented in Table 4.1.

The maximum average RDC level of 0.130 WL resulted when the fresh air flow rate was zero and the minimum of 0.036 WL occurred with a fresh air flow rate of 1,800 cfm.

These data are presented as a function of fresh air flow rate in Figure 4.2. The variation was found through a least-

squares technique to be well described by the exponential expression:

$$RDC = 0.144 \text{ EXP } (-7.8 \times 10^{-4} Q_{FA})$$

where the RDC is the working day average RDC (working levels) which results from a fresh air flow rate of Q_{FA} (cfm). The fresh air flow rate can be normalized by the volume of the ventilated space (39,000 ft³ in this case) to provide a more general expression of this behavior:

$$RDC = 0.144 \text{ EXP } (-30.5 Q_{FA}^V)$$

In this case, Q_{FA}^V is the fresh air flow rate, expressed as volumes (39,000 ft³) supplied per minute. The value of Q_{FA}^V is found by dividing the actual fresh air flow rate (cfm) by the volume (ft³) of the ventilated space.

The coefficient of correlation resulting from the least-square fitting procedure was found to be 0.98, indicating a very good fit. The coefficients determined by the least-square technique are those presented above.

The objective of the "precipitator tests" was to evaluate the effectiveness of the precipitator with no outside air introduced into the system.

Figure 4.3 shows the flow schematic of the recirculated air through the HVAC system. In this test, 100% of the return air (suction to HVAC) was through the precipitator and the precipitator bypass branches in varying proportions. The

fresh air intake manifold (located at the inlet to the economizer) was physically blocked to exclude outside air during this test.

To cover a wide range of flow conditions, the precipitator flow was varied between 0 and 3,600 cfm, with the balance of the required return air flow passing through the bypass branch. The supply air to the office area was maintained at about 6,100 cfm. The total duration for the precipitator tests was 6 days. During each day, the RDC measurements were recorded for each flow condition, 6 times at each location.

Working-day average RDC measurements for the office area are also presented in Table 4.1. The data show that RDC's decline only slightly as the air flow through the precipitator increases.

For the office area and with no outside air, a maximum RDC level of 0.130 WL resulted with no flow through the precipitator. The minimum observed was 0.062 WL and occurred at the maximum air flow through the precipitator (3,600 cfm).

These data are also presented as a function of the air exchange rate (flow rate through the precipitator) in Figure 4.2. This variation was found through a least-squares technique to be well described by the exponential expression:

$$RDC = 0.123 \text{ EXP } (-20 \times 10^{-4} Q_{EP})$$

In this case, Q_{EP} is the flow rate through the electrostatic

precipitator, expressed as volumes (39,000 ft³) supplied per minute. The value of Q_{Ep} is found by dividing the actual flow rate through the electrostatic precipitator (cfm) by the volume (ft³) of the ventilated space.

The coefficient of correlation resulting from the least-squares fitting procedure was about 0.95, indicating a good fit. The coefficients determined by the least-squares technique are those presented above.

It is obvious that reducing RDC's with fresh air requires significantly less air to be moved in the ventilated volume than is necessary without fresh air and relying only on recirculation through precipitators. Therefore, aside from energy consumption considerations (which were addressed in Chapter 3) it appears preferable to control RDC's by introducing fresh air instead of recirculating the same air through electrostatic precipitators.

4.2.2 Parametric Studies--Heating Conditions

Between January 21 and February 17, 1981, parametric studies in the office area during the heating season were conducted. These also consisted of two separate sets of tests, as did the studies during cooling conditions: (1) the system operated with varying fresh air supply rates and without recirculation through the electrostatic precipitator and (2) the system operated with no fresh air supply and with varying amounts of air recirculated through the electrostatic precipitator. The objective of the "fresh air test" under heating

conditions was the same as that described in Section 4.2.1 for the "fresh air test" under cooling conditions. The procedure was the same except that the system operated in the heat mode instead of the cool mode. The system configuration of the tests is presented in Figure 4.1. The outside air flow rate was varied from 0 to 2,000 cfm, and the supply rate to the ventilated volume was maintained at about 6,000 cfm.

During these tests, weather was typical for the season, with temperatures ranging from 26° to 50° F. Generally overcast conditions prevailed and winds were moderate.

Working-day average RDC's measured in the office area are presented in Table 4.2. The maximum RDC of about 0.113 WL existed when no fresh air was supplied and when there was no flow through the precipitator. The minimum RDC of about 0.027 WL was achieved with a fresh air flow rate of about 1,900 cfm.

A least-squares technique was used to determine an exponential relationship between the fresh air flow rates and the resulting working-day RDC levels:

$$RDC = 0.115 \text{ EXP } (-7.8 \times 10^{-4} Q_{FA})$$

where RDC and Q_{FA} were defined earlier. When the fresh air flow rate is normalized by the ventilated volume, the expression reduces to:

$$RDC = 0.115 \text{ EXP } (-30.5 Q_{FA}')$$

where Q_{FA} was earlier defined. This curve (and the data which support it) is also presented in Figure 4.2.

Again the data base is small but the coefficient of correlation which resulted (0.99) indicates a very close fit of the data.

The objective of the "precipitator tests" was the same as that defined in Section 4.2 for the cooling season. The procedure was essentially the same except that the system operated in the heating mode instead of the cooling mode. The system configuration is shown in Figure 4.3.

The flow rates through the precipitator ranged from 0 to about 3,500 cfm, with the balance of the required return air passing through the bypass branch. The rate of supply air to the office area was maintained at about 6,000 cfm.

Working-day average RDC measurements for the office areas are also presented in Table 4.2. For the office area and with no flow through the precipitator, a maximum RDC level of about 0.113 WL was observed with no outside air supply. The minimum observed RDC level during this test was about 0.030 WL and occurred with about 3,500 cfm through the precipitator and no fresh air supply.

The data are also presented in Figure 4.2 as a function of flow rate through the precipitator. The data were well described using an exponential relationship based on a least-squares technique:

$$RDC = 0.113 \text{ EXP } (-3.8 \times 10^{-4} Q_{EP})$$

where RDC and Q_{EP} were earlier defined. If Q_{EP} were normalized by the ventilated volume, the expression would be:

$$RDC = 0.113 \text{ EXP } (-14.9 Q_{EP}^1)$$

where Q_{EP}^1 was earlier defined. This curve (and the data which support it), are also presented in Figure 4.2.

Although the data base is small, the data are represented extremely well, as indicated by the coefficient of correlation, which was almost 1.00.

4.2.3 Comparison of Parametric Studies

Reference to Figure 4.2 reveals that relying on fresh air for RDC control is much more effective (in terms of the amounts of air that must be moved) than relying on flow through a precipitator--a conclusion supported by the physical explanation presented in Chapter 3.

There appears to be little difference in the function relationships between RDC's and fresh air flow rate during the cooling season and those during the heating season. Given the limited data bases which produced the two curves, it seems reasonable to describe the RDC as a single function of fresh air flow rate with a relation similar to:

$$RDC = 0.13 \text{ EXP } (-8.0 \times 10^{-4} Q_{FA})$$

$$RDC = 0.13 \text{ EXP } (-31.1 Q_{FA}^1)$$

where RDC, Q_{FA} and Q_{FA}^1 have been previously defined. Using all data from "fresh air tests" for both cooling and heating seasons, the least-squares procedure produced the coefficients above with a coefficient of correlation of about 0.95.

By comparison, RDC control with an electrostatic precipitator appears to be much less effective than that based on fresh air in terms of total amount of air which must be moved. The assumption was made that there is no difference between the behavior during the cooling and heating seasons. The two data bases were combined into a single data base and the data were analyzed using the least-squares technique. The resulting relation was:

$$\begin{aligned} \text{RDC} &= 0.12 \text{ EXP } (-2.8 \times 10^{-4} Q_{EP}) \\ \text{or} \\ \text{RDC} &= 0.12 \text{ EXP } (-10.9 Q_{EP}^1) \end{aligned}$$

where RDC, Q_{EP} , and Q_{EP}^1 have been previously defined. The corresponding coefficient of correlation would be 0.77, indicating a less than impressive fit of the data.

These relations are plotted in Figure 4.4. Again, it is apparent that controlling RDC's using fresh air is more effective than using flow through the precipitator in terms of the amount of air which must be moved.

4.3 LONG TERM RADIOLOGICAL MONITORING

After the new HVAC equipment was installed, RDC's were monitored periodically to confirm that they were of acceptable magnitude. The measurements were made at the same locations

where RDC measurements were made under original conditions, as depicted in Figure 2.3. As described in Section 2.3.2, the RDC measurements were generally taken at each location six times each day that data were recorded.

The working-day average RDC's are tabulated in Table 4.3. From the table, RDC's are seen to have been significantly reduced below those which existed prior to installation of the new equipment. Whereas under original conditions the average RDC's in the office area ranged from just less than 0.6 WL to nearly 1.3 WL (as observed in this investigation), they have now been reduced to level ranging from 0.023 to 0.169 WL, depending on the ventilation conditions. Under typical ventilation conditions in which fresh air is supplied at the rate of about 1,500 cfm with no flow through the precipitator, the expected overall working-day day average RDC in the office area with the new equipment operational (including many observations with significantly less than 1,500 cfm fresh air) was determined to be about 0.066 WL.

From Table 4.3, it is also apparent that RDC's in the warehouse are consistently maintained at less than the target level of 0.03 WL. This is because the fresh air in the warehouse has a residence time of less than 20 minutes. Thus, any radon released from the floor slab into the warehouse is exhausted before an appreciable fraction decays to daughter products. Therefore, RDC's are low, as expected.

Whereas the working-day average RDC's under original conditions in the warehouse ranged from 0.72 to 2.11 WL, they have now been reduced to levels ranging between 0.002 and 0.068 WL depending on ventilation conditions, with an overall average of about 0.017 WL.

4.4 RISK ASSESSMENT

Given the RDC's observed at the MSS facility since installation of the new HVAC equipment, and the typical worker's exposure of 40 hours per week to this hazard, the excess risk of lung cancer can be estimated. In the office area, with working-day average RDC's ranging from 0.023 to 0.169 WL and with an overall average of about 0.066 WL, the maximum excess risk of lung cancer experience by each full-time worker in the office areas was estimated to range from 4.1×10^{-5} to 3.0×10^{-4} lung cancers per year with an overall average of 1.2×10^{-4} lung cancers per year. This means that the chance of an office worker contracting lung cancer caused by exposure to RDC's in the office area is increased by not more than one in 3,000, each year.

In Utah, the annual risk of lung cancer from all causes, is about one in 5,000. Consequently, the risk to MSS office workers is greater by a factor of about 1.7 because of their exposure to RDC's remaining after the new equipment was installed.

In the warehouse, the excess risk remaining after installation of new equipment is less significant. The maximum risk was

calculated to be less than 3.1×10^{-5} lung cancers per person per year, or about one chance in 33,000 each year. This is less than 20% of the risk of lung cancer due to all causes in Utah.

Caution should be exercised in the use of these risk estimates. They are based on data and results presented in the recent National Academy of Science Publication, "Biological Effects of Ionizing Radiation" (BEIR-III)(16). These risk estimates are upper limits on the actual risk, which, according to the BEIR-III committee, range from near zero to the estimates reported above.

4.5 ENERGY CONSUMPTION

Having concluded that dilution of the radon-laden air with fresh air is the preferable method for controlling RDC's, the system was adjusted to operate with an average fresh air supply rate of roughly 1,500 cfm, with the balance of the total flow (about 6,000 cfm) recirculated. Of the recirculated flow, about 900 cfm passed through the precipitator and about 3,600 cfm through the bypass branch, on the average. The system is presently operated in this configuration under routine conditions.

Because the new system was moving, heating and cooling much more air than by the original system, an investigation was initiated to determine a pattern for historic consumption (with the original system), given key meteorological parameters. This pattern provided a basis for comparing actual energy consumption

by the new system with expected historic consumption, had the original system remained in place.

Electrical consumption is characterized by two parameters; the peak demand in kilowatts (kw) and the energy usage in kilowatt-hours (kwh). In each billing period, the peak demand is defined as the maximum demand which was sustained for at least 15 minutes during the billing period. The usage is defined as the actual energy consumption, continuously integrated.

Natural gas usage is characterized by hundreds of cubic feet (ccf) of gas actually consumed.

A measure of the potential cooling requirement is the degree days of cooling (DDC) in a given time period. The degree days of heating (DDH) is similarly a measure of the potential heating requirement in a given time period. The National Weather Service at the Salt Lake City Airport each month compiles and publishes the number of DDC and/or DDH experienced during the month. The DDC and DDH in a month are based on hourly ambient temperature observations, a reference temperature (65° F), and are defined by the equations:

$$DDC = \sum_{j=1}^N \frac{(T_j - 65)}{24} \quad , T_j > 65^{\circ}\text{F}$$

$$DDH = \sum_{j=1}^N \frac{(65 - T_j)}{24} \quad , T_j < 65^{\circ}\text{F}$$

where T_j is the hourly dry bulb temperature observation (°F) and

N is the number of hours in each month. Based on the meteorological data, October through May have been defined to be the heating season, while June through September represent the cooling season.

4.5.1 Historic Energy Consumption

To determine the differential energy consumption between the old and new HVAC systems at MSS, utility billing information and meteorological data were compiled and analyzed. Personnel at MSS were able to provide monthly records of electrical and gas consumption for the two years (1978 and 1979) preceeding the installation of the new system. Meteorological data (DDC and DDH) for the same time period at the Salt Lake City Airport were obtained from the National Weather Service.

The monthly electrical consumption (for the cooling and heating seasons) and the monthly gas consumption (during heating season only) were plotted as functions of DDC or DDH, as appropriate for their respective month, to identify possible trends. These plots are presented as Figures 4.6, 4.7 and 4.8.

Since the utility companies billing periods (mid-month meter readings) do not coincide with the recording periods for meteorological data (calendar months), the actual electricity and gas consumptions were adjusted by the actual number of days in a given billing period which were in a particular month. The assumption is that consumption is constant throughout a billing

period. Although this assumption is obviously erroneous, it will be shown that, for the intended application, the predicted total consumption differs only slightly from the actual total consumption. Therefore, the assumption is justified. Further, for the purposes of the investigation, it was concluded that monthly consumptions could be expressed as linear functions of DDC or DDH, where coefficients were determined through least-squares techniques.

Figures 4.6 and 4.7 show the adjusted monthly electrical usage as functions of degree days of cooling and of heating for 1978 and 1979, respectively. The least-squares linear expressions which describe these sets of data are:

$$\text{Cooling season; } Q_{EC} = 7893. + 4.2 \text{ DDC} \quad , r^2=0.22$$

$$\text{Heating Season: } Q_{EH} = 6956. + 1.6 \text{ DDH} \quad , r^2=0.44$$

where Q_{EC} is the adjusted monthly electrical consumption during the heating season (kwh)

Q_{LH} is the adjusted monthly electrical consumption during the heating season (kwh)

DDC is the degree days of cooling in the period

DDH is the degree days of heating in the period

r^2 is the coefficient of correlation

These coefficients of correlation are not impressive, but the fit is sufficient for the purposes of this investigation.

The average historical demand for the cooling and heating seasons were 34 and 30 kw, respectively.

Figure 4.8 shows the adjusted monthly gas usage as a function of degree days of heating during the heating season only for the period of 1978 and 1979. The least-squares linear curve which describes the data is

$$Q_G = -143 + 2.6 \text{ DDH} \quad , r^2=0.92$$

where Q_G is the adjusted monthly gas consumption measured in hundreds of cubic feet (ccf), and where DDH and r^2 have been previously defined.

Once the least-squares functional relationships between historical energy consumption and the meteorological parameters (DDC and DDH) were determined the equations were evaluated month by month, as shown in Table 4.4. Although there are significant variances between the adjusted usage for demand and the calculated usage or demand in a given month, the total adjusted actual usage or actual demand and the total calculated usage or calculated demand over the two-year period differ only nominally. The conclusion then is that the least-squares representation of the data accurately predict what the cumulative historic usage or average demand would be, given the meteorological conditions as represented by DDC and DDH.

4.5.2 Comparison of Historic Energy Consumption to Energy Consumed by the New System

Using the relationships identified in the previous section,

the expected historic energy usages have been calculated month by month since the new HVAC system was installed and compared with the respective actual usages. These results are presented in Table 4.5, which shows a significant increase in both electrical and gas energy consumption.

As expected, the electrical usage increased primarily because of the larger cooling load and of the need to move significantly larger quantities of air. The gas usage is expectedly larger because so much more heat must be provided to temper the large amounts of cool or cold outside air being supplied to control RDC levels. Table 4.5 shows that over nearly 2 years, electrical energy usage has been higher by about 50%, electrical demand higher by about 44%, and gas energy consumption higher by about 39%.

TABLE 4.1
WORKING-DAY AVERAGE RDC LEVELS (COOLING SEASON)
MSS OFFICE AREA

Date (1980)	Precipitator Flow(cfm)	Fresh Air Flow(cfm)	RDC Level Office Area (WL)*
Aug 7 Aug 8	3,600	0	0.062
Aug 5 Aug 6	1,650	0	0.080
Aug 11 Aug 12	0	0	0.130
Aug 13 Aug 14	0	750	0.092
Aug 15 Aug 18	0	1,800	0.036
*Working-Day Average RDC			

TABLE 4.2

WORKING-DAY AVERAGE RDC LEVELS (HEATING SEASON)
MSS OFFICE AREA

Date (1980)	Precipitator Flow(cfm)	Fresh Air Flow(cfm)	RDC Level Office Area (WL)*
Feb 17	0	1,910	0.027
Jan 21	0	1,720	0.027
Jan 23	0	1,210	0.048
Feb 20	0	0	0.113
Feb 19	740	0	0.086
Feb 18	3,490	0	0.030

*Working-Day Average RDC

TABLE 4.3

RADON DAUGHTER CONCENTRATION MEASUREMENTS
AFTER INSTALLATION OF NEW EQUIPMENT

Year	Date	Fresh Air Flow Rate (cfm)	Precipitator Flow Rate (cfm)	Sampling Location*						Average Office Area RDC (WL)
				RDC-1 (WL)	RDC-2 (WL)	RDC-3 (WL)	RDC-4 (WL)	RDC-5 (WL)	RDC-()** (WL)	
1980	Jul 30	1,110	0	0.044	0.055	0.004	0.008	0.006	0.047(6)	0.049
	Jul 31	1,280	0	0.036	0.063	0.003	0.008	0.013	0.054(4)	0.050
	Aug 1	1,280	0	0.059	0.061	0.007	0.015	0.008	0.048(1)	0.056
	Aug 4	2,040	1,160	0.040	0.051	0.007	0.014	0.010	0.038(2)	0.046
	Aug 5	520	1,650	0.145	0.099	0.013	0.005	0.003	0.087(3)	0.110
	Aug 6	970	1,270	0.058	0.041	0.002	0.008	0.006	0.083(4)	0.050
	Aug 7	970	3,680	0.044	0.038	0.003	0.021	0.022	0.021(5)	0.041
	Aug 8	200	3,490	0.054	0.086	0.003	0.014	0.013	0.123(6)	0.070
	Aug 11	350	0	0.160	0.191	0.004	0.012	0.011	0.157(1)	0.169
	Aug 12	480	0	0.111	0.084	0.009	0.011	0.087	0.080(2)	0.098
	Aug 13	480	0	0.087	0.122	0.002	0.012	0.009	0.076(3)	0.095
	Aug 14	730	0	0.077	0.105	0.011	0.014	0.007	0.071(4)	0.091
	Aug 15	1,580	0	0.031	0.032	0.004	0.008	0.009	0.015(5)	0.031

TABLE 4.3 (Cont)

1980	Aug 18	1,580	0	0.043	0.038	0.020	0.020	0.012	0.031(6)	0.041
	Aug 19	2,440	2,330	0.014	0.032	0.014	0.011	0.012	0.012(7)	0.023
	Aug 20	1,960	2,330	0.019	0.031	0.008	0.017	0.011	0.024(1)	0.025
	Aug 28	1,430	0	0.058	0.055	0.013	0.015	0.021	0.051(6)	0.056
	Sept 5	1,030	0	0.232	0.139	0.033	0.018	0.008	0.127(1)	0.166
	Oct 5	1,430	0	0.055	0.074	0.009	0.033	0.030	0.050(1)	0.060
	Oct 3	1,580	0	0.057	0.061	0.038	0.021	0.017	0.080(2)	0.059
	Oct 7	1,300	0	0.073	0.090	0.025	0.033	0.021	0.058(1)	0.074
	Oct 8	1,460	0	0.079	0.109	0.040	0.034	0.038	0.035(3)	0.074
	Oct 23	—	—	0.103	0.099	0.068	0.046	0.029	0.135(4)	0.101
	Dec 2	1,680	0	0.010	0.011	0.011	0.024	0.019	0.009(6)	0.011
	Dec 16	1,910	2,380	0.063	0.052	0.041	0.018	0.044	0.056(—)	0.057
	Dec 30	2,400	1,690	0.060	0.041	0.042	0.020	0.011	0.064(—)	0.051
1981	Jan 15	2,640	1,650	0.043	0.071	0.020	0.030	0.015	0.044(—)	0.057
	Jan 19	2,640	1,650	0.021	0.042	—	—	—	0.058(3)	0.040
	Jan 20	2,640	1,650	0.037	0.026	—	—	—	0.023(3)	0.029
	Jan 21	1,580	0	0.013	0.034	—	—	—	0.033(3)	0.027

TABLE 4.3 (Cont.)

1961	Jan 23	930	0	0.026	0.063	—	—	—	0.057(3)	0.049
	Jan 26	870	0	0.085	0.051	—	—	—	0.076(3)	0.070
	Jan 27	1,670	2,850	0.138	0.087	—	—	—	0.050(3)	0.092
	Jan 28	1,930	2,850	0.033	0.088	—	—	—	0.071(3)	0.064
	Jan 29	2,510	2,650	0.022	0.028	—	—	—	0.022(3)	0.024
	Jan 30	1,620	1,160	0.030	0.019	—	—	—	0.026(3)	0.025
	Feb 17	1,910	0	0.043	0.020	—	—	—	0.033(3)	0.032
	Feb 18	2,060	0	0.032	0.030	—	—	—	0.052(3)	0.038
	Feb 19	2,330	1,160	0.080	0.114	—	—	—	0.135(3)	0.110
	Feb 20	930	0	0.135	0.098	—	—	—	0.093(3)	0.109
	May 13	—	—	0.011	0.023	0.040	0.009	0.006	0.033(3)	0.022
	May 14	—	—	0.017	0.026	0.009	0.006	0.008	0.016(3)	0.020

*See Figure 2.3 for locations

**"Rover" locations

TABLE 4.4

COMPARISON OF ADJUSTED AND CALCULATED HISTORIC
UTILITY CONSUMPTION AT MSS (1978 and 1979)

Year	Month	DDC	DDH	Actual Electrical Usage (kwh)	Predicted Electrical Usage (kwh)	Actual Electrical Demand (kw)	Predicted Electrical Demand (kw)	Actual Gas Usage (ccf)	Predicted Gas Usage (ccf)
1978	Jan	—	880	8,960	8,364	29	30	2,575	2,145
	Feb	—	697	8,800	8,071	28	30	2,456	1,670
	Mar	—	522	7,360	7,791	27	30	1,947	1,215
	Apr	—	433	6,960	7,649	27	30	744	963
	May	—	293	6,640	7,425	25	30	601	619
	Jun	167	—	7,820	8,595	33	34	NA	NA
	Jul	411	—	8,320	9,620	34	34	NA	NA
	Aug	299	—	11,180	9,149	35	34	NA	NA
	Sep	120	—	8,900	8,397	35	34	NA	NA
	Oct	—	284	7,340	7,410	33	30	244	596
	Nov	—	714	7,360	8,098	29	30	928	1,714
	Dec	—	1,178	8,660	8,841	28	30	2,919	2,920

TABLE 4.4 (Cont)

1979	Jan	--	1,327	8,600	9,079	29	30	2,958	3,308
	Feb	--	902	8,700	8,399	31	30	2,816	2,203
	Mar	--	666	10,080	8,021	31	30	1,678	1,589
	Apr	--	414	6,760	7,618	30	30	1,242	934
	May	--	196	7,760	7,270	29	30	412	367
	Jun	214	--	10,200	8,792	35	34	NA	NA
	Jul	439	--	10,320	9,737	37	34	NA	NA
	Aug	336	--	8,780	9,305	35	34	NA	NA
	Sep	208	--	8,240	8,767	32	34	NA	NA
	Oct	--	270	6,660	7,388	31	30	140	559
	Nov	--	846	7,660	8,310	29	30	1,331	2,057
	Dec	--	987	8,120	8,535	32	30	2,622	2,424
<hr/>									
Total or				200,200	200,631	31.0	31.3	25,613	25,303
Average									
Variance					+0.02%		+0.3%		-1.2%

TABLE 4.5

COMPARISON OF HISTORICAL TO ACTUAL ENERGY CONSUMPTION AT MSS
(1980 and 1982)

Year	Month	DLC	DDH	Historic Electrical Usage (kwh)	New Electrical Usage (kwh)	Historic Electrical Demand (kw)	New Electrical Demand (kw)	Historic Gas Usage (ccf)	New Gas Usage (ccf)
1980	Jun	159	—	8,561	10,100	34	52	—	—
	Jul	399	—	9,509	12,680	34	52	—	—
	Aug	301	—	9,157	14,720	34	55	—	—
	Sep	99	—	8,309	14,040	34	48	—	—
	Oct	—	379	7,562	10,660	30	43	842	274
1981	Nov	—	704	8,082	12,380	30	44	1,687	1,207
	Dec	—	965	8,500	13,260	30	42	2,366	4,238
	Jan	—	1,013	8,577	13,640	30	43	2,491	3,622
	Feb	—	742	8,143	13,140	30	45	1,786	4,060
	Mar	—	641	7,982	13,260	30	41	1,524	2,096
1982	Apr	—	346	7,510	12,240	30	42	757	2,090
	May	—	230	7,329	10,780	30	51	462	819

TABLE 4.5 (Cont.)

1981	Jun	190	—	8,691	11,760	34	52	—	—
	Jul	412	—	9,623	14,660	34	53	—	—
	Aug	409	—	9,611	16,380	34	48	—	—
	Sep	145	—	8,502	13,560	34	49	—	—
	Oct	—	444	7,666	12,280	30	43	1,011	691
	Nov	—	614	7,938	11,480	30	39	1,453	1,489
	Dec	—	879	8,362	11,760	30	38	2,142	2,505
1982	Jan	—	1,087	8,695	10,320	30	37	2,683	3,578
	Feb	—	909	8,410	12,100	30	40	2,220	2,909
	Mar	—	668	8,025	11,860	30	39	1,594	2,308
<hr/>									
Total or				184,804	277,060	31.5	45.3	23,019	31,886
Average									
Average									
Increase									
				50%			44%		39%

FIGURE 4.1 CONFIGURATION OF HVAC SYSTEM IN OFFICE AREA DURING FRESH AIR TESTS.

LEGEND

	COOLING SEASON		HEATING SEASON	
	DATA SYMBOL	CURVE	DATA SYMBOL	CURVE
FRESH AIR (NO PRECIPITATOR)	▲	A	▲	C
PRECIPITATOR (NO FRESH AIR)	⊙	B	⊠	D

NOTE: VENTILATED VOLUME 39,000 ft³

FIGURE 4.2 RDC LEVELS AS FUNCTIONS OF AIR EXCHANGE RATE FOR FRESH AIR AND PRECIPITATOR TEST DURING COOLING AND HEATING SEASONS

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FIGURE 4.3 CONFIGURATION OF HVAC SYSTEM IN OFFICE AREA DURING PRECIPITATOR TESTS.

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NOTE: VENTILATED VOLUME 39,000 FT³

FIGURE 4.4 SUMMARY OF RDC LEVELS AS FUNCTIONS OF AIR EXCHANGE RATE FOR FRESH AIR ONLY AND PRECIPITATOR ONLY.

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FIGURE 4.5 RESULTS OF LONG-TERM RDC MONITORING
AT MOUNTAIN STATES SUPPLY, INC.

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FIGURE 4.6 ADJUSTED ELECTRICAL ENERGY CONSUMPTION
AS A FUNCTION OF DEGREE DAYS OF COOLING
(FOR THE COOLING SEASON ONLY)

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**FIGURE 4.7 ADJUSTED ELECTRICAL ENERGY CONSUMPTION
AS A FUNCTION OF DEGREE DAYS OF HEATING
(FOR THE HEATING SEASON ONLY)**

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FIGURE 4.8 ADJUSTED GAS CONSUMPTION AS A FUNCTION OF DEGREE DAYS OF HEATING (FOR THE HEATING SEASON ONLY)

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CHAPTER FIVE

SUMMARY AND CONCLUSION

5.0 SUMMARY AND CONCLUSION

In these investigations, physical and radiological conditions at the Mountain States Supply, Inc. facility have been characterized. It was found that radon daughter concentrations (RDC's) exceeded acceptable levels in unrestricted areas. The existing physical facilities (notably the heating, ventilating, and air conditioning--HVAC--system) did not allow for a significant reduction of the hazard, whether by dilution with fresh air or by removal of radon daughters through electrostatic precipitation. Therefore, new equipment was specified and installed to reduce RDC's by reliance primarily on dilution by fresh air.

With the new equipment in place, parametric studies were conducted, under both cooling and heating conditions, to determine the effectiveness of fresh air supply and electrostatic precipitators in reducing RDC's. It was found that RDC's are much more effectively controlled through dilution with fresh air.

It was also confirmed through long-term monitoring that the hazards associated with RDC's at the facility have been reduced to significantly lower levels which approach the target level of 0.03 WL.

Energy consumption of the new equipment was compared with that of the original equipment. Electrical energy usage over

almost 2 years increased by about 50%, while electrical demand was higher by about 44%. Natural gas usage was higher by about 39%.

Based on the observations described above, dilution with fresh air appears to be an effective interim means of reducing the hazards associated with elevated RDC's in structures.

APPENDIX A

PREDICTING RADON DAUGHTER CONCENTRATIONS AT
MOUNTAIN STATES SUPPLY, INC.

APPENDIX A

PREDICTING RADON DAUGHTER CONCENTRATIONS AT MOUNTAIN STATES SUPPLY, INC.

A mathematical model which predicts transient radon daughter concentrations (RDC's) at Mountain States Supply, Inc. (MSS) was developed to estimate the RDC's which would result under various ventilation conditions. The model was used to approximate the original conditions. The model also was used to predict the reduction in risk from RDC's which might result from installation of various equipment at MSS. Using estimated infiltration and recirculation rates, the predicted working day average RDC's were calculated to be conservatively higher than actual measurements of RDC's. The model is described below.

The accumulation rates of radon or its daughters are estimated to be the difference between their respective production (or addition) rates and their destruction (or subtraction) rates within the volume of concern. The equation defining this relationship for Radon-222 is:

$$\frac{dN_R}{dt} = \phi_R'' A - \lambda_R N_R - \frac{QN_R}{V}$$

where N_R = numbers of radon atoms

t = time, min

ϕ_R'' = radon flux, atoms/m²-min

A = floor area, m²

λ_R = decay constant of radon, min⁻¹

Q = flow rate of air leaving the building, l/min

V = volume of building, l

This equation can be made more descriptive of the situation at MSS by adding terms describing a precipitator, the air flow between the office and the warehouse by allowing the different air flow rates, and concentrations in the office area and the warehouse. The resulting equations for radon in the office area (subscript "o") and in the warehouse (subscript "w") are respectively:

Office;

$$\frac{dN_{Ro}}{dt} = \phi_{Ro}A_o - \lambda_R N_{Ro} - \frac{Q_{1o}N_{Ro}}{V_o} - \eta \frac{Q_{2o}N_{Ro}}{V_o} + \frac{Q_3N_{Rw}}{V_w}$$

Warehouse;

$$\frac{dN_{Rw}}{dt} = \phi_{Rw}A_w - \lambda_R N_{Rw} - \frac{Q_{1w}N_{Rw}}{V_w} - \eta \frac{Q_{2w}N_{Rw}}{V_w} - \frac{Q_3N_{Rw}}{V_w}$$

In addition to the variables earlier defined, the following definitions apply:

Q_1 = the air exhaust rate (equivalent to the fresh air supply rate, l/min

Q_2 = the recirculation air rate, l/min

Q_3 = the rate of air passing from the warehouse to the office, l/min

η = the efficiency of the precipitator (zero only for radon, 0.20 for radon daughters as described in Appendix B).

These equations can be changed from numbers of atoms to concentrations by dividing by appropriate volumes:

$$\frac{dC''_{Ro}}{dt} = \frac{\phi''_{Ro} A_o}{V_o} - \lambda_R C''_{Ro} - \frac{Q_{1o} C''_{Ro}}{V_o} - \eta \frac{Q_{2o} C''_{Ro}}{V_o} + \frac{Q_3 C''_{Rw}}{V_o}$$

and similarly:

$$\frac{dC''_{Rw}}{dt} = \frac{\phi''_{Rw} A_w}{V_w} - \lambda_R C''_{Rw} - \frac{Q_{1w} C''_{Rw}}{V_w} - \eta \frac{Q_{2w} C''_{Rw}}{V_w} - \frac{Q_3 C''_{Rw}}{V_w}$$

where C'' is concentration, atoms/l

ϕ'' is the flux, atoms/m²-min.

Atoms when they disintegrate can be expressed as Curies. The disintegration rate is multiplied by the decay constant and divided by 3.7×10^{10} disintegrations/sec per/Curie. Since it is more convenient to express concentration and flux in terms of picoCuries, this conversion can be made by multiplying by 10^{12} pCi/Ci. Thus concentration and flux can be converted from terms of atoms to terms of picoCuries by multiplying by the nuclide-specific conversion factor,

$$F = 27.03 \lambda^*$$

where λ^* is the nuclide-specific decay constant in units of inverse seconds (sec⁻¹).

The differential equations given above for radon are converted by multiplying by F_R , the radon conversion factor (which has a value of 5.67×10^{-5} pCi/atom):

$$\frac{dC_{Ro}}{dt} = \frac{\phi_{Ro} A_o}{V_o} - (\lambda_R V_o + Q_{1o} + \eta Q_{2o}) \frac{C_{Ro}}{V_o} + \frac{Q_3 C_{Rw}}{V_o}$$

and

$$\frac{dC_{Rw}}{dt} = \frac{\phi_{Rw} A_w}{V_w} - (\lambda_R V_w + Q_{1w} + \eta Q_{2w}) \frac{C_{Rw}}{V_w} - \frac{Q_3 C_{Rw}}{V_w}$$

where C is concentration, pCi/l

and ϕ is the flux, pCi/m²-min

In this unique case, F_R appears in each term and therefore disappears from the equation.

Similarly, the concentrations (in pCi/l) of the radon daughters can be expressed as follows.

In the office area:

$$\text{Polonium-218} \quad \frac{dC_{Po}}{dt} = \frac{F_R \lambda_R C_{Ro}}{F_P} - (\lambda_P V_o + Q_{1o} + \eta Q_{2o}) \frac{C_{Po}}{V_o} + \frac{Q_3 C_{Pw}}{V_o}$$

$$\text{Lead-214} \quad \frac{dC_{Lo}}{dt} = \frac{F_P \lambda_P C_{Po}}{F_L} - (\lambda_L V_o + Q_{1o} + \eta Q_{2o}) \frac{C_{Lo}}{V_o} + \frac{Q_3 C_{Lw}}{V_o}$$

$$\text{Bismuth-214} \quad \frac{dC_{Bo}}{dt} = \frac{F_L \lambda_L C_{Lo}}{F_B} - (\lambda_B V_o + Q_{1o} + \eta Q_{2o}) \frac{C_{Bo}}{V_o} + \frac{Q_3 C_{Bw}}{V_o}$$

In the warehouse:

$$\text{Plonium-218} \quad \frac{dC_{Pw}}{dt} = \frac{F_R \lambda_R C_{Rw}}{F_P} - (\lambda_P V_o + Q_{1w} + \eta Q_{2w}) \frac{C_{Pw}}{V_w} - \frac{Q_3 C_{Pw}}{V_w}$$

$$\text{Lead-214} \quad \frac{dC_{Lw}}{dt} = \frac{F_P \lambda_P C_{Pw}}{F_L} - (\lambda_L V_o + Q_{1w} + \eta Q_{2w}) \frac{C_{Lw}}{V_w} - \frac{Q_3 C_{Lw}}{V_w}$$

$$\text{Bismuth-214} \quad \frac{dC_{Bw}}{dt} = \frac{F_L \lambda_L C_{Lw}}{F_B} - (\lambda_B V_o + Q_{1w} + \eta Q_{2w}) \frac{C_{Bw}}{V_w} - \frac{Q_3 C_{Bw}}{V_w}$$

In these above equations the following definitions apply:

F_R is the conversion factor for radon (5.67×10^{-5})

F_P is the conversion factor for polonium (1.02×10^{-1})

F_L is the conversion factor for lead (1.17×10^{-2})

and F_B is the conversion factor for bismuth 1.58×10^{-2})

The subscripts R, P, L and B refer to radon-222, polonium-218, lead-214 and bismuth-214, respectively. The subscripts o and w refer to the office area and warehouse, respectively.

In this system of simultaneous ordinary differential equations, instantaneous complete mixing of all ventilation flow rates throughout the ventilated volumes is assumed. All source terms such as radon flux and ingrowth from parent decay are also assumed to be instantaneously and completely mixed throughout the volumes.

These assumptions are well justified when the ventilation distribution system is well designed and when air circulation rates (room volumes per hour) are large compared to the half-life of the parent nuclide, radon-222. These conditions are satisfied in the office area. In the warehouse, natural circulation is considered sufficient to justify the assumption.

These equations were programmed using the digital-analog simulation language, MIMIC, and were easily solved numerically on a digital computer.

Radon daughter concentrations are frequently described in terms of working levels. One working level is defined as any combination of radon-222 daughters ((polonium-218, lead-214 and bismuth-214) which deposits 1.3×10^5 MeV of alpha energy. The number of working levels of any mixture of radon-222 daughters can be obtained from the concentrations of the daughters (in picoCuries per liter) by the expression:

$$WL = 1.045 \times 10^{-3} C_P + 5.158 \times 10^{-3} C_L + 3.797 \times 10^{-3} C_B$$

where WL represents working levels of RDC.

APPENDIX B

EFFECTIVENESS OF ELECTROSTATIC PRECIPITATORS FOR
RADON DAUGHTER REMOVAL

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The efficiency of an electrostatic precipitator in removing radon daughters is a primary factor in estimating results of new equipment installations. In order to evaluate the effectiveness of the existing precipitator at Mountain States Supply, Inc. (MSS), special testing was conducted in this study. The working levels at a cold-air return were measured and compared with those measured at a warm-air vent, at essentially the same time with no fresh air being supplied. Since air is taken from the cold-air return directly to the precipitator, and then through the furnace heat exchanger to the warm-air vent, the ratio of radon daughter concentrations (RDC's) at the warm-air vent to those at the cold-air return is an effective measure of the precipitator efficiency. The data taken in the special test program are presented in Table 2.3, and the average efficiency was found to be 27%.

This efficiency was compared with other tests completed using electrostatic precipitators in similar applications. A study of RDC's was undertaken in a private residence built with uranium mill tailings.⁽⁵⁾ This study used a precipitator in one bedroom with a flow rate of 310 cfm (9.37 room volumes circulated per hour). In one hour, the RDC's dropped from 0.85 to 0.06.

The efficiency of this precipitator is approximated by:

$$\eta = 1 - \frac{C_1}{C_i}$$

where C_1 is the RDC after a single pass through the precipitator and C_i is the initial RDC.

Rearranged, C_1 is expressed as:

$$C_1 = C_i(1-\eta)$$

The concentration, after a second pass through the precipitator (C_2) is:

$$\begin{aligned} C_2 &= C_1(1-\eta) \\ &= C_i(1-\eta)^2 \end{aligned}$$

The final concentration after n passes through the precipitator is given by:

$$C_n = C_i(1-\eta)^n$$

Therefore, the efficiency is expressed generally as:

$$\eta = 1 - \left(\frac{C_n}{C_i} \right)^{1/n}$$

The efficiency of the precipitator discussed in Reference 5 was estimated using this method to be:

$$\begin{aligned} \eta &= 1 - \left(\frac{0.06}{0.85} \right)^{\frac{1}{9.37}} \\ &= 0.25 \end{aligned}$$

A second configuration of the precipitator in the previously referenced study placed the precipitator in the basement of the home with a flow rate of 310 cfm or an air exchange rate of 1.86 air changes per hour. The RDC's after 1.5 hours operation (2.79 room volumes circulated) dropped from 0.114 to 0.044. This indicates an efficiency of about 29%.

A study of RDC's conducted in a bowling alley⁽⁴⁾ also built on uranium mill tailings suggests approximately the same efficiency. The precipitator-fan system produced about 5.8 air changes per hour. After 2 hours (11.7 room volumes circulated), the RDC's had dropped from 0.212 to 0.0277. The efficiency of the precipitator is therefore estimated to be 16%.

In parametric studies conducted during this investigation, electrostatic precipitators were estimated to remove radon daughters with an efficiency of 20%. This efficiency is considered reasonable yet conservatively low for the intended application.

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REFERENCES

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