Appendix S. Air Emissions

S-1. Overview

This appendix describes the estimation of toxic organic and toxic heavy metal air emissions from the late 1940s to the present from the following SSFL activities: (a) rocket engine tests; (b) pre- and post-degreasing of rocket engines; (c) storage tanks, stripping towers, and other evaporative sources of toxic organic emissions; and (d) open pit burning of waste material. Before developing the emission inventory, the UCLA study team reviewed the available activity reports and plotted the known activities on a timeline.

S-2. Rocket Engine Exhaust

One can estimate emissions from rocket engine exhaust by multiplying fuel use by emission factors. Data regarding the fuel used at SSFL by fuel type and year were obtained from the facility operators. Air toxic emission test data by fuel type were obtained from literature reviews and specific reports of testing at SSFL. Estimates of air toxic emissions released to the atmosphere from rocket engine tests were computed from these data.

Fuel Types and Historical Annual Usage

No fuel usage data are available for the time before 1955 or after 1990. In analyzing the available data (Sullivan, 1999), the study team learned that more than 60% of the fuel combusted in rocket engine tests—by weight in tons, from 1955 to 1990—was liquid kerosene (**Table S-1**). The second most common fuel used at SSFL was liquid hydrogen (35%). Lesser amounts of isopropyl alcohol (1.4%), hydrazine derivatives (0.5%), and pentaborane fuel (0.006%) were also combusted.

A more in-depth analysis of the available fuel usage data (**Figure S-1**) reveals that more than 80% of fuel usage took place prior to 1970:

- 80% of kerosene fuel usage took place from 1956 through 1969.
- 80% of unsymmetrical dimethylhydrazine usage took place between 1956 and 1965.
- 96% of pentaborane usage took place in 1963.

Because no fuel usage data were made available to the study team for 1948 to 1954 and all years after 1990, the amount of air toxic emissions resulting from fuel combustion from 1948 to 1954 and 1991 to the present cannot be determined. Review of the ATSDR report (1999) establishes that ethanol, kerosene, and hydrazine fuels were combusted in engines before 1955 and fuels using ethanol, kerosene, and MMH (a hydrazine derivative) were combusted in engines after 1990 (**Table S-2**).

Table S-1. Reported Fuel Usage at SSFL from 1955 through 1990

Fuel Name	Tons
Kerosene	173435
Liquid hydrogen	98351
Isopropyl alcohol	3765
Hydrazine and derivatives	1491
Pentaborane	16

Note: No data were reported for beryllium or ethanol; no data were reported for any fuels from 1948 to 1954 or beyond 1990. **Source:** Sullivan, 1999.

Figure S-1. Percent of Fuel Consumed over Life of Facility by Fuel Type

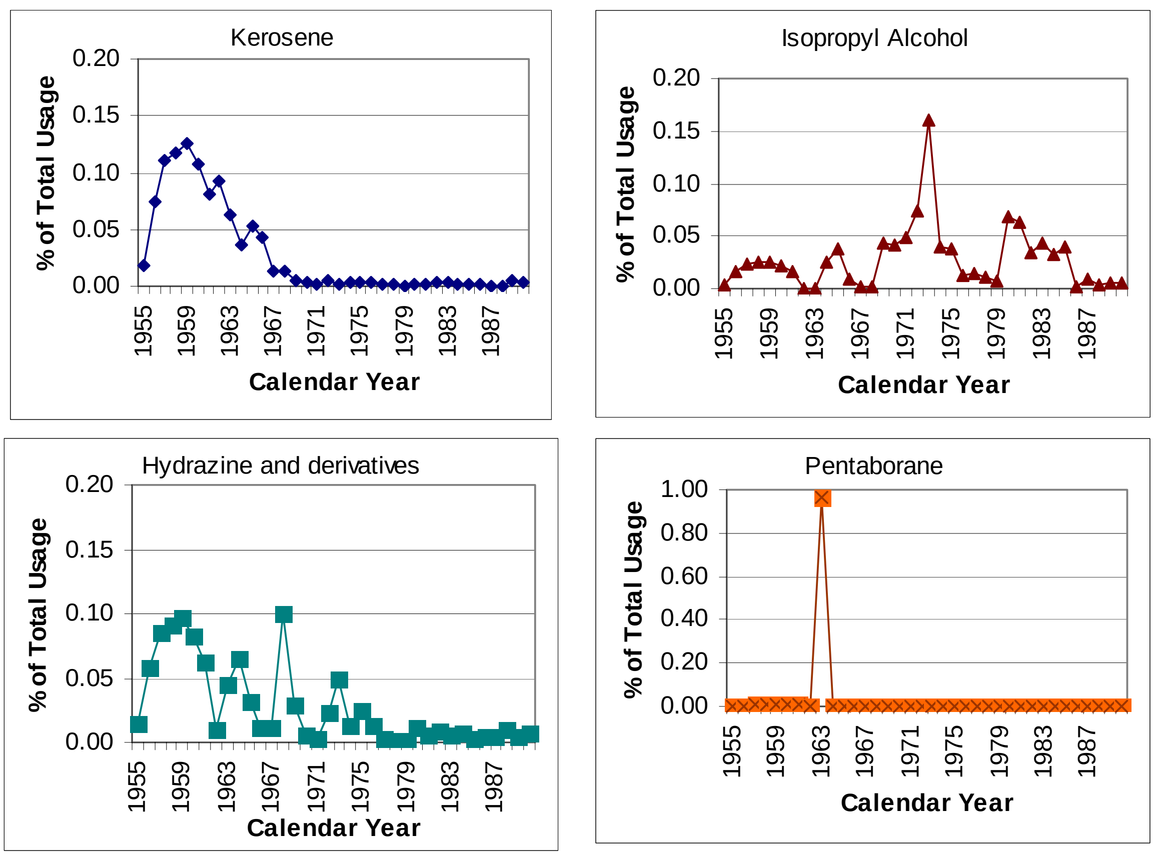

Table S-2. Overview of Rocket Engine Testing Programs at SSFL

Program	**Fuel**	**Oxidizer**	**Duration**	**Test Area**
RS-27 Delta	Kerosene	LOx	1971–present	Alfa
Atlas	Kerosene	LOx	1954–present	Alfa, Bravo, Bowl, Coca, and Delta
Navaho	Kerosene	LOx	1949–57	Alfa, Bravo, Bowl
Jupiter	Kerosene	LOx	1958–63	Alfa, Delta, Canyon
Thor	Kerosene	LOx	1956–79	Alfa, Delta, Canyon, and Bravo
3.5-inch injectors	Kerosene	LOx	1978–79	APTF
5.7-inch injectors	Kerosene	LOx	1989–91	APTF
HHC Hit with Azine	Kerosene	LOx	1991	APTF
Liquid flyback booster	Kerosene	LOx	1998	APTF
OMS	Ethanol	LOx	1998	APTF
RS-44	Hydrogen	LOx	1984–89	APTF
RS-68 gas generator	Hydrogen	LOx	1997	APTF
Advanced Experimental Thrust Program	MMH	NTO	1967	APTF
Pulse engine	MMH	NTO	Early 1980s	APTF
Static Pulse Engine	MMH	NTO	1983–86	APTF
MK-51 Turbopump	MMH	NTO	1984–85	APTF
XLR-132	MMH	NTO	1989–91	APTF
Lance	UDMH	IRFNA	1962–70	APTF, Delta
Redstone	Ethanol	LOx	1951–59	Bowl
F-1 Saturn V components	Kerosene	LOx	1959–71	Bravo
H-1 Saturn 1B	Kerosene	LOx	1958–68	Canyon
J-2 Saturn V	Hydrogen	LOx	1960–71	Coca and Delta
SSME	Hydrogen	LOx	1971–88	Coca
L-1 and L-4	Kerosene	LOx	1956–61	Delta
E-1 (pre F-1)	Kerosene	LOx	1956–60	Delta and Bravo
Transtage	Hydrazine*	NTO	1953	STL IV
Gemini	Hydrazine*	NTO	1953–54	STL IV
Liquid aircraft rockets	Hydrazine*	NTO	1955–58	STL IV
Beech	Hydrazine*	NTO	1959–66	STL IV
SE5	Hydrazine*	NTO	1960–68	STL IV
Apollo reentry	Hydrazine*	NTO	1962–69	STL IV
Condor (RS-19)	Hydrazine*	CTF	1967–70	STL IV
LEM	Hydrazine*	NTO*	1967–70	STL IV
RS-14 Minuteman	Hydrazine*	NTO*	1968–77	STL IV
OEM-6K	Hydrazine*	NTO*	1973	STL IV
RCS-600	Hydrazine*	NTO*	1973	STL IV
LE3	Hydrazine*	NTO*	1973–76	STL IV
RS21	Hydrazine*	NTO*	1975	STL IV
X70	MMH	NTO	1977–78	STL IV
EXO	MMH	NTO	1978	STL IV
MX Peacekeeper	MMH	NTO	1978–94	STL IV
MKV	MMH	NTO	1979	STL IV
HOE	MMH	NTO	1979	STL IV
KEW	MMH	NTO	1993–present	STL IV

* Other types of fuels, such as pentaborane and oxidizers, were used in these tests. **Source:** ATSDR Draft Preliminary Site Evaluation of the Santa Susana Field Laboratory (SSFL), Ventura County, California, December 3, 1999.

Table S-3. Estimates of Toxic Organics Emissions (Tons/Year) Associated with Liquid Kerosene Rocket Engine Test Exhaust

Year	Benzene	1,3-Butadiene	Chloroform	Vinylidene Chloride	Methylene Chloride	Toluene	Trichloroethylene	Vinyl Chloride	Xylene (Total)
1955	1.0	0.3	0.001	0.000	0.000	0.3	0.006	0.000	0.2
1956	4.0	1.3	0.003	0.001	0.001	1.0	0.027	0.001	0.7
1957	5.9	2.0	0.004	0.001	0.001	1.5	0.040	0.001	1.0
1958	6.3	2.1	0.005	0.001	0.001	1.6	0.042	0.001	1.1
1959	6.7	2.2	0.005	0.001	0.002	1.7	0.045	0.002	1.1
1960	5.7	1.9	0.004	0.001	0.001	1.5	0.038	0.001	1.0
1961	4.3	1.4	0.003	0.001	0.001	1.1	0.029	0.001	0.7
1962	5.0	1.7	0.004	0.001	0.001	1.3	0.033	0.001	0.8
1963	3.4	1.1	0.002	0.001	0.001	0.9	0.022	0.001	0.6
1964	1.9	0.6	0.001	0.000	0.000	0.5	0.013	0.000	0.3
1965	2.9	1.0	0.002	0.001	0.001	0.7	0.019	0.001	0.5
1966	2.3	0.8	0.002	0.000	0.001	0.6	0.016	0.001	0.4
1967	0.8	0.3	0.001	0.000	0.000	0.2	0.005	0.000	0.1
1968	0.7	0.2	0.001	0.000	0.000	0.2	0.005	0.000	0.1
1969	0.2	0.1	0.000	0.000	0.000	0.1	0.002	0.000	0.0
1970	0.1	0.0	0.000	0.000	0.000	0.0	0.001	0.000	0.0
1971	0.1	0.0	0.000	0.000	0.000	0.0	0.001	0.000	0.0
1972	0.2	0.1	0.000	0.000	0.000	0.1	0.002	0.000	0.0
1973	0.1	0.0	0.000	0.000	0.000	0.0	0.001	0.000	0.0
1974	0.2	0.1	0.000	0.000	0.000	0.0	0.001	0.000	0.0
1975	0.1	0.0	0.000	0.000	0.000	0.0	0.001	0.000	0.0
1976	0.1	0.0	0.000	0.000	0.000	0.0	0.001	0.000	0.0
1977	0.1	0.0	0.000	0.000	0.000	0.0	0.001	0.000	0.0
1978	0.1	0.0	0.000	0.000	0.000	0.0	0.001	0.000	0.0
1979	0.0	0.0	0.000	0.000	0.000	0.0	0.000	0.000	0.0
1980	0.1	0.0	0.000	0.000	0.000	0.0	0.000	0.000	0.0
1981	0.1	0.0	0.000	0.000	0.000	0.0	0.001	0.000	0.0
1982	0.2	0.1	0.000	0.000	0.000	0.0	0.001	0.000	0.0
1983	0.1	0.0	0.000	0.000	0.000	0.0	0.001	0.000	0.0
1984	0.1	0.0	0.000	0.000	0.000	0.0	0.001	0.000	0.0
1985	0.1	0.0	0.000	0.000	0.000	0.0	0.001	0.000	0.0
1986	0.1	0.0	0.000	0.000	0.000	0.0	0.000	0.000	0.0
1987	0.0	0.0	0.000	0.000	0.000	0.0	0.000	0.000	0.0
1988	0.0	0.0	0.000	0.000	0.000	0.0	0.000	0.000	0.0
1989	0.2	0.1	0.000	0.000	0.000	0.1	0.002	0.000	0.0
1990	0.2	0.1	0.000	0.000	0.000	0.1	0.001	0.000	0.0

Table S-4. Estimates of Heavy Metal Emissions (Tons/Year) Associated with Liquid Kerosene Rocket Engine Test Exhaust

Year	Arsenic	Beryllium	Cadmium	Chromium (total)	Chromium (hexavalent)	Copper	Lead	Manganese	Mercury	Nickel	Selenium	Zinc
1955	0.001	0.001	0.003	0.004	0.001	0.056	0.001	0.018	0.000	0.011	0.001	0.071
1956	0.003	0.004	0.013	0.018	0.004	0.231	0.002	0.073	0.001	0.046	0.003	0.292
1957	0.004	0.006	0.019	0.027	0.005	0.341	0.004	0.108	0.002	0.068	0.004	0.431
1958	0.004	0.007	0.020	0.029	0.006	0.366	0.004	0.115	0.002	0.073	0.004	0.462
1959	0.004	0.007	0.021	0.031	0.006	0.387	0.004	0.122	0.002	0.077	0.004	0.489
1960	0.004	0.006	0.018	0.026	0.005	0.331	0.004	0.104	0.002	0.066	0.004	0.418
1961	0.003	0.005	0.014	0.020	0.004	0.249	0.003	0.079	0.001	0.050	0.003	0.315
1962	0.003	0.005	0.016	0.023	0.005	0.288	0.003	0.091	0.002	0.058	0.003	0.363
1963	0.002	0.004	0.011	0.015	0.003	0.194	0.002	0.061	0.001	0.039	0.002	0.245
1964	0.001	0.002	0.006	0.009	0.002	0.110	0.001	0.035	0.001	0.022	0.001	0.139
1965	0.002	0.003	0.009	0.013	0.003	0.165	0.002	0.052	0.001	0.033	0.002	0.208
1966	0.001	0.003	0.007	0.011	0.002	0.134	0.001	0.042	0.001	0.027	0.001	0.169
1967	0.000	0.001	0.002	0.003	0.001	0.043	0.000	0.014	0.000	0.009	0.000	0.055
1968	0.000	0.001	0.002	0.003	0.001	0.042	0.000	0.013	0.000	0.008	0.000	0.053
1969	0.000	0.000	0.001	0.001	0.000	0.014	0.000	0.004	0.000	0.003	0.000	0.017
1970	0.000	0.000	0.000	0.001	0.000	0.009	0.000	0.003	0.000	0.002	0.000	0.011
1971	0.000	0.000	0.000	0.001	0.000	0.007	0.000	0.002	0.000	0.001	0.000	0.009
1972	0.000	0.000	0.001	0.001	0.000	0.014	0.000	0.004	0.000	0.003	0.000	0.018
1973	0.000	0.000	0.000	0.000	0.000	0.005	0.000	0.002	0.000	0.001	0.000	0.006
1974	0.000	0.000	0.001	0.001	0.000	0.009	0.000	0.003	0.000	0.002	0.000	0.011
1975	0.000	0.000	0.000	0.001	0.000	0.008	0.000	0.002	0.000	0.002	0.000	0.010
1976	0.000	0.000	0.000	0.001	0.000	0.008	0.000	0.003	0.000	0.002	0.000	0.010
1977	0.000	0.000	0.000	0.000	0.000	0.006	0.000	0.002	0.000	0.001	0.000	0.008
1978	0.000	0.000	0.000	0.000	0.000	0.004	0.000	0.001	0.000	0.001	0.000	0.006
1979	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.001
1980	0.000	0.000	0.000	0.000	0.000	0.004	0.000	0.001	0.000	0.001	0.000	0.005
1981	0.000	0.000	0.000	0.000	0.000	0.005	0.000	0.002	0.000	0.001	0.000	0.007
1982	0.000	0.000	0.000	0.001	0.000	0.009	0.000	0.003	0.000	0.002	0.000	0.011
1983	0.000	0.000	0.000	0.001	0.000	0.008	0.000	0.002	0.000	0.002	0.000	0.010
1984	0.000	0.000	0.000	0.000	0.000	0.006	0.000	0.002	0.000	0.001	0.000	0.008
1985	0.000	0.000	0.000	0.000	0.000	0.006	0.000	0.002	0.000	0.001	0.000	0.008
1986	0.000	0.000	0.000	0.000	0.000	0.004	0.000	0.001	0.000	0.001	0.000	0.004
1987	0.000	0.000	0.000	0.000	0.000	0.002	0.000	0.001	0.000	0.000	0.000	0.003
1988	0.000	0.000	0.000	0.000	0.000	0.002	0.000	0.001	0.000	0.000	0.000	0.003
1989	0.000	0.000	0.001	0.001	0.000	0.013	0.000	0.004	0.000	0.003	0.000	0.017
1990	0.000	0.000	0.001	0.001	0.000	0.012	0.000	0.004	0.000	0.002	0.000	0.016

Table S-5. Estimate of Hydrazine and Derivatives Emissions (Tons/Year) Associated with Rocket Engine Test Exhaust

Year	Hydrazine	UDMH	MMH
1955	0.01	0.02	0.00
1956	0.04	0.09	0.00
1957	0.06	0.13	0.00
1958	0.06	0.14	0.00
1959	0.06	0.15	0.00
1960	0.05	0.13	0.00
1961	0.04	0.10	0.00
1962	0.02	0.00	0.00
1963	0.07	0.02	0.02
1964	0.06	0.05	0.03
1965	0.01	0.04	0.03
1966	0.01	0.00	0.01
1967	0.01	0.01	0.01
1968	0.10	0.10	0.03
1969	0.02	0.02	0.02
1970	0.00	0.00	0.01
1971	0.00	0.00	0.00
1972	0.03	0.00	0.03
1973	0.04	0.04	0.03
1974	0.01	0.01	0.01
1975	0.03	0.02	0.00
1976	0.02	0.01	0.00
1977	0.00	0.00	0.00
1978	0.00	0.00	0.00
1979	0.00	0.00	0.00
1980	0.00	0.00	0.02
1981	0.00	0.00	0.01
1982	0.00	0.00	0.02
1983	0.00	0.00	0.01
1984	0.00	0.00	0.02
1985	0.00	0.00	0.01
1986	0.00	0.00	0.01
1987	0.00	0.00	0.01
1988	0.00	0.00	0.02
1989	0.00	0.00	0.01
1990	0.00	0.00	0.02

Table S-6. Estimate of Trichloroethylene Emissions (Tons/Year) Associated with Rocket Engine Degreasing

Year	Trichloroethylene
1955	56
1956	231
1957	341
1958	366
1959	387
1960	331
1961	249
1962	284
1963	191
1964	114
1965	169
1966	134
1967	43
1968	42
1969	21
1970	16
1971	16
1972	27
1973	34
1974	16
1975	14
1976	10
1977	9
1978	7
1979	2
1980	17
1981	17
1982	15
1983	15
1984	12
1985	2
1986	1
1987	1
1988	0
1989	2
1990	2

Table S-7. Estimates of Emissions (Tons/Year) Associated with Other Evaporative Sources

Year	Methylchloroform	Trichloroethane	Trichloroethylene
1955	18.7	12.8	13.3
1956	18.7	12.8	54.8
1957	18.7	12.8	80.9
1958	18.7	12.8	86.6
1959	18.7	12.8	91.8
1960	18.7	12.8	78.4
1961	18.7	12.8	59.1
1962	18.7	12.8	67.3
1963	18.7	12.8	45.4
1964	18.7	12.8	27.0
1965	18.7	12.8	40.1
1966	18.7	12.8	31.8
1967	18.7	12.8	10.2
1968	18.7	12.8	9.9
1969	18.7	12.8	5.1
1970	18.7	12.8	3.8
1971	18.7	12.8	3.7
1972	18.7	12.8	6.5
1973	18.7	12.8	8.1
1974	18.7	12.8	3.9
1975	18.7	12.8	3.4
1976	18.7	12.8	2.4
1977	18.7	12.8	2.0
1978	18.7	12.8	1.6
1979	18.7	12.8	0.5
1980	18.7	12.8	4.0
1981	18.7	12.8	4.0
1982	18.7	12.8	3.6
1983	18.7	12.8	3.6
1984	18.7	12.8	18.9
1985	18.7	12.8	3.1
1986	18.7	12.8	0.9
1987	18.7	12.8	0.9
1988	18.7	12.8	0.8
1989	18.7	12.8	3.3
1990	18.7	12.8	3.1

Table S-8. Estimates of Emissions (Tons/Year) Associated with Open Pit Burning

Year	Benzene and Derivatives	Hydrazine and Derivatives	Toluene
1955	—	—	—
1956	—	—	—
1957	—	—	—
1958	—	—	—
1959	0.0875	0.658	0.0875
1960	0.0875	0.658	0.0875
1961	0.0875	0.658	0.0875
1962	0.0875	0.658	0.0875
1963	0.0875	0.658	0.0875
1964	0.0875	0.658	0.0875
1965	0.0875	0.658	0.0875
1966	0.0875	0.658	0.0875
1967	0.0875	0.658	0.0875
1968	0.0875	0.658	0.0875
1969	0.0875	0.658	0.0875
1970	0.0875	0.658	0.0875
1971	0.0875	0.658	0.0875
1972	0.0875	0.658	0.0875
1973	0.0875	0.658	0.0875
1974	0.0875	0.658	0.0875
1975	0.0875	0.658	0.0875
1976	0.0875	0.658	0.0875
1977	0.0875	0.658	0.0875
1978	0.0875	0.658	0.0875
1979	0.0875	0.658	0.0875
1980	0.0875	0.658	0.0875
1981	0.0875	0.658	0.0875
1982	0.0875	0.658	0.0875
1983	0.0875	0.658	0.0875
1984	0.0875	0.658	0.0875
1985	0.0875	0.658	0.0875
1986	0.0875	0.658	0.0875
1987	0.0875	0.658	0.0875
1988	0.0875	0.658	0.0875
1989	0.0875	0.658	0.0875
1990	—	—	—

S-3. Emission Test Data by Fuel Type

Liquid Kerosene Rocket Engine Test Results

From 1990 to 1992, ABB Environmental Services, Inc., conducted air sampling of kerosene-combusted rocket engine exhaust to analyze for toxic organics and toxic heavy metal combustion byproducts. Air emission samples were taken from several types of rocket engine exhaust (e.g., booster and sustainer). **Table S-9** lists the average measured emission rate of toxic organics and heavy metals from MA5 and MA5A booster rocket engine tests (ABB Environmental Services, Inc., 1992).

Table S-9. Average Toxic Organic and Heavy Metal Emissions from Liquid Kerosene Booster Rocket Tests as Reported by ABB Environmental Services, Inc. (1992)

Toxic Organic	**Emissions** (g/s)	**Heavy Metal**	**Emission Rates** (g/s)
Benzene	66	Arsenic	0.042 (ND)
1,3-Butadiene	22	Beryllium	0.071 (ND)
Chloroform	0.049	Cadmium	0.21
Vinylidene chloride	0.014 (ND)	Chromium (total)	0.30
Methylene chloride	0.015 (ND)	Chromium (hexavalent)	0.061 (ND)
Toluene	17	Copper	3.8
Trichloroethylene	0.44	Lead	0.41
Vinyl chloride	0.015 (ND)	Manganese	1.2
Xylene (total)	11	Mercury	0.021
Fuel	**Usage Rate** (g/s)	Nickel	0.76
		Selenium	0.042 (ND)
Kerosene	213,000	Zinc	4.8

ND = not detected, reported emissions at detection limit.

Seven chemical species (vinylidene chloride, methylene chloride, vinyl chloride, arsenic, beryllium, hexavalent chromium, and selenium) were not detected in the ABB measurement tests. Because arsenic, beryllium, and selenium exist in the kerosene fuel, it is likely that they are emitted in the exhaust. The conservative assumption made in this study was that the emission rates of these undetected chemicals are just below their measurement detection limits, even though the actual emissions could be lower. Note that reliance on these test results could understate actual emissions in prior years, if environmental regulations on fuel (if any) in effect at the time of testing (1990 to 1992) limited toxic organic and heavy metal content in kerosene relative to earlier time periods (e.g., 1948 to 1969).

Hydrogen

Data for air toxic byproducts from the rocket engine combustion of hydrogen could not be located.

Ethanol and Isopropyl Alcohol

Data for air toxic byproducts from the rocket engine combustion of ethanol and isopropyl alcohol were not found.

Hydrazine and Its Derivatives (MMH and UDMH)

In 1981, Rockwell International (1981) measured MMH in rocket exhaust. Ambient concentrations 20 feet downwind of the exhaust chamber ranged from 0.075 to 0.13 mg/m^3. The corresponding air flow rates necessary to accurately quantify emission rates from these engine tests were not reported. However, the air flow rate at 200 feet downwind of kerosene-combusted rocket engine tests was reported as 2.56×10^4 m^3/s to 8×10^4 m^3/s by Rockwell International (1984). *If SSFL MMH rocket engine tests had comparable air flow rates to those from kerosene rocket engine tests*, MMH emissions would be 1.92 g/s[1] (see **Table S-10**), equivalent to 0.15%[2] of the MMH fuel that was used in rocket engine tests but passed through to the exhaust without being burned.

Table S-10. MMH Concentration at the Exhaust Outlet and Emission Estimate

Concentration (µg/m^3)	**Air Flow Rate** (m^3/s)	**Estimated Emissions** (g/s)	**Uncombusted %**
0.075*	$2.56 \times 10^{4\dagger}$	1.92	0.15

* 20 feet downwind
† 200 feet downwind of a kerosene combusted rocket engine

Beryllium Hydride Solid Rocket Engine Tests

From 1969 to 1973, SSFL sampled engine exhaust from beryllium solid rockets. The SSFL sampling setup consisted of either one large 1,000-gallon tank or two 500-gallon (approximately) tanks in series. Water was sprayed into the tanks to capture solids emitted during a test. After a test, the tank(s) were drained and water passed through both a pre-filter and an ultra-filter to remove any beryllium solids captured. The tanks were rinsed and the rinse water was analyzed for beryllium prior to disposal.

Table S-11 lists average measured beryllium concentrations for each test day of data (Rockwell International, 1984). Individual concentrations ranged from undetected to 0.28 µg/m^3 (Rockwell International, 1999). Neither the minimum detection limit for measuring beryllium nor the corresponding exhaust flow rates from these engines were reported.

---

[1] MMH emission rate (g/s) = 0.075 mg/m^3 * 2.56 x 10^4 m^3/s = 1.92 g/s

[2] MMH has a liquid density of 1.01 g/cc, comparable to that of water (1 g/cc). Each MMH combustion test (Rockwell International, 1981) consisted of five separate "rocket" combustions of about 5 seconds' duration, for a total of 25 seconds of firing. Each firing combusted the contents of a 35-liter (35,000 cc) vessel. If MMH occupied 20% of the vessel (consistent with an optimum oxidizer-to-fuel ratio of roughly 4), then 7,000 grams of MMH were present in each vessel. Given this information, 0.15% is the fraction of MMH released uncombusted. (The study team obtained this by multiplying the MMH by a 5-second combustion process, then dividing the result by the 7,000 grams of MMH expected to be in the vessel.)

As noted previously, measured air flow rates 200 meters downwind of engine combustion with liquid kerosene vary from 2.56×10^4 m^3/s to 8×10^4 m^3/s (Rockwell International, 1984). If solid rocket engine tests had comparable exhaust flow rates to those from kerosene rocket engine tests, then beryllium emissions likely averaged 0.007 g/s.

Table S-11. Beryllium Concentration at Exhaust Outlet and Corresponding Emission Estimate

Date	**Concentration** (μg/m^3)	**Estimated Emissions** (g/s)
December 11, 1968	0.15	0.012
December 12, 1968	0.10	0.008
July 11, 1969	Not detected	0
Average	0.09	0.007

Since the exhaust sampling design used by Rockwell International (1984) did not guarantee 100% capture of beryllium emissions, it is believed that the measurement approach may understate actual beryllium emissions. A more conservative approach would have been to assume all beryllium combusted in the beryllium hydride rocket test entered the atmosphere.

On a comparative basis, worst-case beryllium emissions from liquid kerosene rocket tests were estimated to be 10 times greater (0.071 g/s; see Table S-3) than the 0.007 g/s estimates associated with beryllium hydride rocket tests. This may be physically unrealistic, given the expected greater amount of beryllium in beryllium hydride–fueled rocket tests. This suggests that either greater emissions occurred from beryllium hydride solid rocket tests than was stated in the data analyzed or beryllium emissions from kerosene fuels were well below the minimum detection limit emission estimate used in this report.

S-4. Air Toxic Emissions by Fuel Type

Emission estimates were derived by multiplying supplied fuel consumption data by fuel type and year by air toxic emission factor by fuel type found in the test data. Accordingly, estimates of the amount of air toxic emissions released into the atmosphere from these SSFL rocket engine tests are presented below.

Liquid Kerosene

Table S-12 shows cumulative toxic organic and heavy metal emissions from 1955 to 1990, estimated by multiplying annual kerosene usage rates (see Figure S-1) by the emission factors for toxic organic and metal emissions for kerosene fuel usage from testing[3] (see Table S-12).

[3] ABB Environmental Services, Inc. (1992) reports that the kerosene fuel usage rate equaled 222 and 205 kg/s for two of the MA5A booster engine tests. The average kerosene fuel usage rate from these two tests is 213 kg/s. Toxic organic and heavy metal emissions were determined by multiplication of the Boeing-provided annual kerosene usage rates (see Figure 5-1) by the ABB Environmental Services, Inc. (1992) toxic organic and heavy metal emissions (see Table 5-2).

Table S-12. Kerosene Fuel Rocket Engine Exhaust Emissions of Toxic Organic and Heavy Metal Emissions (tons) from 1955 to 1990

Toxic Organic	**Emissions** (Tons)
Benzene	54
1,3-Butadiene	18
Chloroform	0.04
Vinylidene chloride	0.01 (ND)
Methylene chloride	0.01 (ND)
Toluene	14
Trichloroethylene	0.36
Vinyl chloride	0.01 (ND)
Xylene (total)	9

Heavy Metal	**Emissions** (Tons)
Arsenic	0.03 (ND)
Beryllium	0.06 (ND)
Cadmium	0.17
Chromium (total)	0.24
Chromium (hexavalent)	0.05 (ND)
Copper	3.1
Lead	0.03
Manganese	1.0
Mercury	0.02
Nickel	0.6
Selenium	0.03 (ND)
Zinc	3.9

ND = not detected

Benzene is the greatest source of toxic organic emissions from kerosene engine tests. Cumulative benzene emissions from liquid kerosene rocket test exhausts total 54 tons[4] from 1955 to 1990. Cumulative emissions for three other toxic organics (1,3-butadiene, toluene, and xylene) exceed 5 tons during the same time period.

Zinc and copper are non-toxic metals with the greatest estimated metal emissions. From 1955 to 1990, cumulative zinc and copper emissions totaled 3.9 and 3.1 tons, respectively. Cumulative emissions of cadmium and chromium during the same time period totaled 0.17 and 0.24 tons, respectively. Because the ambient concentrations of arsenic, beryllium, hexavalent chromium, and selenium were not detected in the tests performed, a conservative assumption was made that those concentrations equaled the measurement detection limit. Beryllium emissions determined in this manner total 0.06 tons (that is, 120 pounds or 54,000 grams).

Liquid Hydrogen Rocket Engine Test Data

Toxic organics and toxic metal emissions from the combustion of liquid hydrogen are assumed to be negligible. However, if fuel combustion resulted in temperatures conducive to metal vaporization from the walls of combustion and exhaust chambers, then toxic metal emissions would be present in the exhaust.

Ethanol and Isopropyl Alcohol

While combustion of ethanol and isopropyl alcohol with LOX would likely result in toxic organic emissions, it was not possible to estimate emissions of toxic organics from the combustion of ethanol and isopropyl alcohol, since no exhaust samples were ever taken.

[4] For comparison purposes, these results can be calculated by multiplying the reported kerosene fuel usage at SSFL from 1955 to 1990 of 170,000 tons by the EPA-recommended benzene emission factor from rocket engine tests of 0.0002 lb/lb kerosene (http://www.epa.gov/ttn/chief/le/benzene/benz_apa.pdf).

Hydrazine and Its Derivatives (MMH and UDMH)

The reported annual quantity of hydrazine, MMH, and UDMH fuel usage in rocket tests at SSFL (Table 3-2) was multiplied by 0.15% to estimate hydrazine, MMH, and UDMH uncombusted air emissions. Using this method, cumulative 1955 to 1990 hydrazine, MMH, and UDMH air emissions totaled 0.74, 0.41, and 1.1 tons respectively.

Beryllium

Emission estimates of beryllium are uncertain. In the 1950s and 1960s, some limited research and testing of solid fuel engines was performed at SSFL (Agency for Toxic Substances and Disease Registry, 1999; ERG, 2001). Because the amount of beryllium consumed during these rocket tests was not provided, it was not possible to estimate beryllium emissions for this time period. Beryllium release controls were not in place in the 1950s and 1960s.

Another source of beryllium emissions was a 1967 malfunction incident during which Froines (1999) reports that 0.87 pounds (395 grams) of beryllium were released. This one incident released the equivalent of 15.6 hours of 0.007 g/s of beryllium emissions from solid fuel rocket engine tests. Beryllium emissions may also have resulted at SSFL from separate Peacekeeper program tests, as at least one of the rocket engine parts (the thrust chamber) in the upper stage was made from metallic beryllium.

S-5. TCE Evaporation from Cleaning of Rocket Test Engines

TCE applications were made to rocket engines[5] prior to and after tests. Analysis of records (CH2M Hill, 1993) suggests 50 to 100 gallons of TCE, on average, was applied per engine flush. TCE air emissions result from evaporation of the applied TCE liquid.

If 50 gallons of TCE were applied both before and after each engine test, 1.1 million gallons of TCE would have been consumed[6] on site for the purpose of kerosene rocket engine test flushes from 1955 to 1990. While TCE was also applied both before and after ethanol engine tests, no data were provided for the number of ethanol engine tests made. Therefore, the study team was unable to estimate the likely quantity of TCE used to clean ethanol-fueled engine tests.

Sullivan (1999) reports that 3,765 tons of isopropyl alcohol were consumed during rocket engine tests. The minimum quantity consumed was 6 tons in any one year. If 6 tons of isopropyl alcohol were consumed per test, then 628 tests were made. Assuming that 50 gallons of TCE were applied both pre- and post-testing to degrease these engine tests, 62,800 gallons of TCE were applied to clean isopropyl alcohol rocket engine tests.

---

[5] Hydrocarbon fuels (e.g., kerosene, ethanol, and isopropyl alcohol) combusted with liquid oxygen (LOx).

[6] This estimate was developed as follows. ABB Environmental Services, Inc. (1992) test data reveal that roughly 15,000 kg of kerosene were consumed per engine test conducted. SSFL records show that total kerosene consumption from 1955 to 1990 equals 170,000 tons (160 million kg). In other words, kerosene was probably combusted with LOx in 11,000 rocket engine tests (160 million kg kerosene consumed / 15,000 kg kerosene per test). 11,000 tests multiplied by 100 gallons equals 1.1 million gallons.

Combining the above uses, the total estimated TCE consumed was 1.16 million gallons. Note that this is nearly twice the 530,000 gallons reported by CH2M Hill (1993) and above the upper range of 400,000 to 800,000 gallons reported by GRC (1988a-b). It is estimated that about half of the TCE applied to clean the engines immediately evaporated into the atmosphere (i.e., 3,200 tons), as shown in **Table S-13.**

Table S-13. Estimate of Trichloroethylene Atmospheric Emissions from Cleaning Ethanol-, Isopropyl Alcohol–, and Kerosene-Combusted Engine Tests for 50% of 50 Gallons Applied Before and After Each Engine Test Entering the Atmosphere

Statistic	**Usage** (U.S. Tons)				
	1955–1961	**1962–1972**	**1973–1983**	**1984–1990**	**Total**
Ethanol	—	—	—	—	—
Isopropyl alcohol	16	33	57	5*	111
Kerosene	1,946	1,025	99	15*	3,085
Total	1,962	1,058	156	20*	3,196

* SSFL installed a recovery system in 1984 that reportedly provides an 85% control factor.

S-6. Other Evaporative Activities

The Rockwell International (1992a-b, 1994) Toxic Release Inventory (TRI) submittals for 1990 and 1992 were examined to identify other potentially significant evaporative sources of toxic organics. In 1990, the principal source of TCE emissions (**Table S-14**), excluding engine flushes, was storage tank releases (95%) followed by stripping towers (5%).

Table S-14. Trichloroethylene Emissions for 1990 and 1992 from Engine Flush, Storage Tanks, and Stripping Towers as Reported by Rockwell International

Year	**Engine Flush** (Tons/Year)	**Storage Tank** (Tons/Year)	**Stripping Towers** (Tons/Year)
1990	1.7	0.42	0.022
1992	0.38	0.06	0.022

TCE storage tanks would have to have been present since 1948 at the start of TCE engine flushes. Given the higher volume of TCE usage (up to 25 times more) reported in years prior to 1990, it is reasonable to assume that TCE evaporation emissions from storage tanks were greater in earlier years. To correct for this expectation, the study team estimated earlier years of TCE emissions by multiplying 1990 emissions by the ratio of the TCE volume applied in earlier years to flush engines relative to 1990. According to this method, an estimated 134 tons of TCE were emitted to the atmosphere from storage tanks from 1955 to 1990 (see **Table S-15)—**about 5% of what was estimated from engine flushes.

Table S-15. Trichloroethylene Atmospheric Emissions from Storage Tanks

Statistic	**Usage** (tons)				
	1955–1961	**1962–1972**	**1973–1983**	**1984–1990**	**Total**
Total	79	43	6	5	134

The TRI documents show that methyl chloroform and TCA were also emitted from SSFL in 1990 and 1992. These toxic organics were emitted (Rockwell International, 1992b, 1994) in excess of TCE in 1990 and 1992 (see **Table S-16**). Since no documentation of the history of emissions of these two chemicals could be found, the annual methyl chloroform and TCA emission rates reported in the TRI documents were used as the annual emission rates of these chemicals from 1955 to present. Emissions of methyl chloroform or TCA could have been significantly greater or lower in earlier years.

Table S-16. Evaporative Chemicals Emitted in Substantial Quantities in 1990 or 1992 as Reported by Rockwell International (1992b, 1994)

Year	**Methyl Chloroform** (tons)	**TCA** (tons)	**TCE** (tons)
1990	18.7	N/A	2.1
1992	N/A	12.8	3.9

Notes: N/A = not available.

Accidental spills of TCE also occurred at the SSFL site. A search of TCE releases reported by CH2M Hill (1993) revealed that as many as 8,865 gallons (50 tons) were accidentally spilled from 1975 to 1990. Although reports of accidental releases are unavailable from 1948 to 1974, there is no basis for assuming that such releases did not take place over the above time period. The TCE volume accidentally spilled from 1955 to 1974 was potentially 600 tons, assuming that volume was proportional to the amount applied for engine flushing. In total, 650 tons of TCE may have been accidentally spilled from 1955 to 1990. Other toxic organics may have been spilled as well, but these but are unquantifiable from the data made available.

S-7. Thermal Treatment Facility

The Thermal Treatment Facility (TTF) is an open pit area constructed in 1958 to dispose of waste. An analysis of monthly disposal records (Rocketdyne, 1960) for 1959 and 1960 show that, during that period, 1,900 gallons, 130 pounds, and 5 cylinders of material were disposed of by burning each month on average (see **Table S-17**). Note that an additional 30 gallons of toluene should be added to this amount for occasions when disposal of pentaborane took place.[7]

For illustrative purposes, the study team used individual monthly records to make a more detailed analysis of the assorted materials disposed of. These records show that 45 drums and 1,650 gallons of assorted mixtures of UDMH and hydrazine were disposed of in September 1958 and March 1960. In May 1960, Rocketdyne (1960) reports, 951 gallons and 180 pounds of material were processed (see **Table S-18**). In May 1960, materials disposed of in this manner included chemicals, fuels, oxidizers, and explosives. In August 1959, Rocketdyne (1959) reports, 220 gallons of a combination of benzene and ethyl benzene were disposed of, among other items. In December 1959, 300 pounds of magnesium shavings (again, among other items) were disposed of in this manner.

[7] Before disposing of pentaborane, the SSFL operating manual recommends personnel deposit and ignite 30 gallons of toluene (North American Aviation, Inc., 1960). Based on available historical records, pentaborane appears to have been disposed of in the TTF in two out of every three months.

Table S-17. Quantity of Material Disposed Of at the TTF by Month in 1959 and 1960

Calendar Month and Year	Quantity Disposed Of		
	Liquid Gallons	**Solid Pounds**	**Gas Cylinders**
February 1959	385	none	5
March 1959	> 4,000	none	none
April 1959	2,460	none	none
May 1959	2,545	none	none
July 1959	505	none	none
August 1959	5,750	none	6
September 1959	3,870	150	23
October 1959	1220	150	none
November 1959	851	none	none
December 1959	1,181	325	none
January 1960	10	none	none
February 1960	1,950	318	3
March 1960	3,685	none	27
April 1960	770	none	18
May 1960	951	180	none
June 1960	1,265	710	none
July 1960	1,560	456	none
August 1960	991	none	none
Average	1,900	130	5

Table S-18. List of Materials Disposed Of at the TTF for Certain Months (Rocketdyne, 1959, 1960)

Chemical and/or Fuel	**September 1958** (Gallons)*	**March 1960** (Gallons)*	**May 1960** (Gallons)*
Nitrogen tetroxide	—	—	350
Hydrochloric and nitric acid	—	1,160	250
Acteone, pentaborane, and RP-1	—	330	126
RP-1 and TEA	—	—	55
UDMH and hydrazine	45 drums	1,650	100
Lab, hydraulic, and lube oil	—	520	—
Solid propellant and heptane	—	25	—
TEA	—	—	20
Propane	—	—	50
Bromine pentafluoride, chlorine trifluoride, fluorine	—	—	180 pounds
Total	45 drums	3685 gallons and 27 cylinders	951 gallons and 180 pounds

* Except as noted.

Table S-19 presents the monthly average amount of toxic material estimated to have been emitted from the open pit burning operation. The study team developed this estimate by averaging September 1959 and March and May 1960 material processing records; it was assumed that 10% of all volatile organics (e.g., benzene, toluene) deposited in the pit either evaporated prior to burning or went uncombusted. In 1990, SSFL received permission to conduct open burning of explosive waste in 5-pound batches on designated burn days. This permit substantially limited the amount of material that could be disposed of in this manner.

Table S-19. Estimate of Monthly Average Amounts of Material Disposal at the TTF and Annual Average Air Emissions

Chemical and/or Fuel	**TTF Monthly Inventory** (Gallons)*	**Toxic Emission (Tons/Year)**†
Benzene (and derivatives)	20	0.0875
Nitrogen tetroxide	120	NT
Hydrochloric and nitric acid	570	NT
Acteone, pentaborane, and RP-1	150	NT
RP-1 and TEA	150	UN
UDMH and hydrazine	650	NDMA and NMA
Lab, hydraulic, and lube oil	200	NT
Solid propellant and heptane	10	NT
TEA	10	UN
Propane	20	NT
Bromine pentafluoride, chlorine trifluoride, and fluorine	130 pounds	NT
Total disposed of	1,520 gallons and 130 pounds	0.0875 tons/year + NDMA and NMA
Toluene for pentaborane combustion	20 gallons	0.0875 tons/year‡
Overall total	1,900 gallons	0.175 tons/year + NDMA and NMA

* Except as noted. † 300 pounds of magnesium emitted in 1959; inventory applies from 1959 to 1989. ‡ Limited to period of pentaborane usage.
NT = Not a toxic or expected not to produce significant toxic byproducts relative to other known sources of toxic missions at SSFL. UN = The study team does not know what "TEA" stands for, and therefore cannot say whether TEA is toxic.

S-8. Summary of SSFL Air Toxic Emission Inventory (1955–1990)

A total of 4775 tons of toxic organics (including hydrazine derivatives) and 9.2 tons of heavy metal emissions were released from SSFL to the atmosphere from 1955 to 1990 (see Table 3-4, Chapter 3). TCE air releases from engine flushes are by far the largest source of toxic organic emissions, at 3,196 tons. Other evaporative losses total 1,918 tons from the release of methyl chloroform (673 tons), TCA (461 tons), and TCE (784 tons). Rocket engine tests and the Thermal Treatment Facility released the following additional organics in sufficient quantity: benzene (57 tons), hydrazine and hydrazine derivatives (23 tons), 1,3-butadiene (18 tons), toluene (17 tons), and xylene (9 tons). The most significant source of heavy metal emissions is kerosene rocket engine tests. Zinc (3.9 tons), copper (3.1 tons), and manganese (1.0 tons) represent the largest sources of heavy metal emissions. Cadmium and chromium emissions totaled 0.17 and 0.24 tons, respectively.