LA-UR- 98-1995

Title:

POLONIUM RELEASE FROM AN ATW BURNER SYSTEM WITH LIQUID LEAD-BISMUTH COOLANT

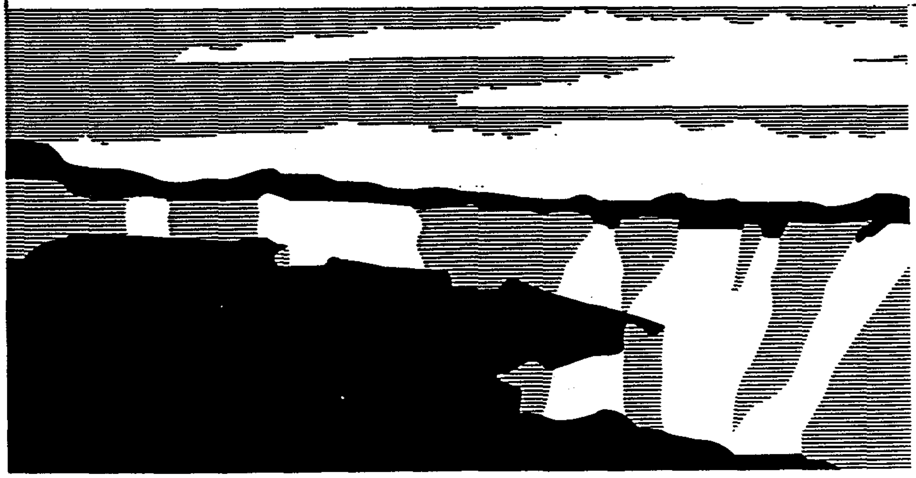
RECEIVED
OCT 05 1998
OSTI

Author(s): Ning Li, Los Alamos National Lab.
E. Yefimov, D. Pankratov, Inst. of Physics & Power Eng., Obninsk, Russia

Submitted to: Report - Informal Distribution

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED



Los Alamos
NATIONAL LABORATORY

DISCLAIMER

Polonium Release from an ATW Burner System with Liquid Lead-Bismuth Coolant

N. Li
ATW Project, Los Alamos National Laboratory, U. S. A.
E. Yefimov, D. Pankratov
Institute of Physics and Power Engineering, Obninsk, Russia
April, 1998

Abstract

We analyzed polonium release hazards in a conceptual pool-type ATW burner with liquid lead-bismuth eutectic (LBE) coolant. Simplified quantitative models are used based on experiments and real NPP experience. We found little Po contamination outside the burner under normal operating conditions with nominal leakage from the gas system. In sudden gas leak and/or coolant spill accidents, the Po contamination level can reach above the regulation limit but short exposure would not lead to severe health consequences. We are evaluating and developing mitigation methods.

Polonium-210 emits α particles as it decays to Pb-206 with a half-life of 138.4 days. Because of its relatively short half-life, Po-210 has very high specific activity and poses serious radiological hazards. In an ATW burner with liquid lead-bismuth coolant, there is significant production of Po-210 due to Bi-209(n, γ)Bi-210 reaction and the subsequent β decay to Po-210 in 5 days. In a pool-type ATW burner, LBE coolant spill (as analyzed before[1]) is much more unlikely than in a boiler-type reactor. However, Po can accumulate in the cover gas space and other parts of the gas system. Po release from the gas system is possible, and the release is much faster in case of a cover seal breach than in a coolant spill, although the amount of Po in the gas system is much smaller than that in the coolant. This report explores the Po hazard under normal and off-normal operating conditions for a conceptual ATW burner.

The ATW-burner is approximated by a cylindrical container of $5m$ in diameter, $16m$ tall with a $15m$ deep LBE coolant pool. The cover space volume $V_g = 19.6m^3$, LBE evaporation surface $S_e = 19.6m^2$. The mass of the LBE coolant is about 3000 tons. We use a high estimate of the Po specific activity in LBE, $a_0 = 1$ *Ci/kg* (many later results on Po activities are proportional to this value).

We assume that the surface temperature is 400°C, or 673K (which is an upper-limit estimate of the surface coolant temperature). It is assumed that 99.8% Po evaporates as PbPo, 0.2% as pure Po. The specific evaporation rates of PbPo and Po in vacuum can be read from the chart [2] as[1]

$$w_{PbPo} \approx 2.27\times 10^{-5}\,\frac{Ci}{m^2 s}/\frac{Ci}{kg},$$
$$w_{Po} \approx 2.06\times 10^{-2}\,\frac{Ci}{m^2 s}/\frac{Ci}{kg}.$$

The gross evaporation rates are:

$$g_{PbPo} = w_{PbPo}/1000\times a_0 \times 99.8\%\times S_e = 4.45\times 10^{-7}\,\frac{Ci}{s},$$
$$g_{Po} = w_{Po}/1000\times a_0 \times 0.2\%\times S_e = 8.07\times 10^{-7}\,\frac{Ci}{s},$$

where a factor of 1000 reduction for evaporation in the cover gas under atmospheric pressure has been taken into consideration. It is quite clear that the PbPo formation drastically reduces the evaporation of Po. The total evaporation rate is:

$$g_0 = g_{PbPo} + g_{Po} = 1.25\times 10^{-6}\,\frac{Ci}{s}.$$

The Po activity in the cover space comes from the following contributions: PbPo and Po evaporation from the LBE coolant, Po deposition to other surfaces, volatile H_2Po formation with moist in air (dissociates to PoO_2 quickly at elevated temperatures), secondary sublimation from the deposit, radioactive decay and gas system leakage. To illustrate clearly the key mechanism in Po releases, we use the following simplified model: the activity of Po in the cover space reaches an equilibrium corresponding to saturated vapor pressures of PbPo and Po.

---

[1] The specific evaporation rates can be approximated as:

$$\log w_{PbPo} = -\frac{4793}{T} + 2.476,\ \log w_{Po} = -\frac{2929}{T} + 2.664,\ w\text{'s in unit of}\left[\frac{Ci}{m^2 s}/\frac{Ci}{kg}\right].$$

They can not be derived directly from the Langmuir equation relating the evaporation rate to the saturated vapor pressure[2].

The vapor pressures of PbPo and Po can be obtained from the literature[2]. We use the IPPE formula:

$$\log P_{PbPo}[Pa] = -\frac{7270}{T} + 9.06,$$

$$\log P_{Po}[Pa] = -\frac{5440}{T} + 9.46.$$

We need to convert the specific activity of Po in LBE to concentration for further calculation, using $1\,Ci$ Po = 0.223 mg Po:

$$c_{PbPo} = a_{Po} \times 0.223 mg / Ci \times 0.998 \times 2 = 4.45 \times 10^{-7},$$

$$c_{Po} = a_{Po} \times 0.223 mg / Ci \times 0.002 = 4.46 \times 10^{-10}.$$

where a factor of 2 is used to accommodate for PbPo's molecular weight difference from Po.

We also assume that the activity coefficients of PbPo and Po in LBE are one[3], so at 400°C the partial vapor pressures above the LBE coolant are

$$P'_{PbPo} = c_{PbPo} P_{PbPo} = 8.10 \times 10^{-9}\, Pa,$$

$$P'_{Po} = c_{Po} P_{Po} = 1.07 \times 10^{-8}\, Pa.$$

For the ideal PbPo and Po gases in the cover space:

$$n_{Po} = \frac{(P'_{PbPo} + P'_{Po})V_g}{RT} = 6.59 \times 10^{-11}\, mole,$$

the total activity of Po is

$$A_{Po} = 6.2 \times 10^{-5}\, Ci,$$

and the specific activity of Po is

$$a_{Po} = \frac{A_{Po}}{V_g} = 3.2 \times 10^{-9}\, Ci/l = 1.1 \times 10^{4}\, LPC_{US}.$$

This agrees with a more complete analysis by IPPE specialists. Obviously the cover gas contains rather high level of Po contamination and care must be taken to prevent direct personnel exposure.

---

[2] $\log P_{Po}[Pa] = -\frac{5377.8}{T} + 9.3593$, [3].

[3] For dilute Po in Bi, this activity coefficient has been measured to be much less than 1. Its temperature dependence can be approximated by[3] $\log \gamma_{Po} = -\frac{2728.3}{T} + 1.1176$.

However, when the system is nominally tight and sufficient ventilation is provided the Po level in the operating room can be easily kept well below the regulatory level. Even an accidental breach of seal and the subsequent release of Po from the gas system would not pose severe radiological hazard if the evacuation time is reasonably short.

Since Po can quickly deposit onto cold surfaces, deploying a Po collection system which is colder than the coolant surface temperature and with very large surface area could reduce the Po activity in the gas system. This system can also be deployed only when a gas system leak accident occurs, so as to function as an emergency radiological protection system.

We can estimate how much Po deposits onto colder surfaces in the gas system. Assuming that Po in vapor or gas phase have reached equilibrium, then almost all the Po evaporation should deposit and only radioactive decay would reduce it. This leads to about 15Ci deposits. If the majority can be collected with the aforementioned collection system and stays undisturbed during refueling or other maintenance operations, then the radiological hazard from the Po surface contamination is much reduced.

Normal Operating Conditions

According to IPPE's estimate, the gas system could have small leaks up to 0.5% volume of gas per day. In a room of V_r=100m^3, the activity leakage rate is

$$g_{leak} = \frac{0.5\% \times 6.2 \times 10^{-5}\,Ci}{24 \times 3600s} = 3.6 \times 10^{-12}\,Ci/s.$$

The Po activity in the operating room consists of contributions from various processes

$$\frac{dA_{Po}}{dt} = g_{leak} - \lambda_{vent}A_{Po} - \lambda_{dep}A_{Po} - \lambda_{decay}A_{Po},$$

where λ_{vent} is the ventilation rate, λ_{dep} is the Po aerosol deposition rate, λ_{decay} is Po decay rate. A typical ventilation rate is one volume turnover every hour. The aerosol mean lifetime is about 100 seconds[4]. The half-life of Po-210 is 138.4 days. Thus

---

[4] According to IPPE, Po aerosol lifetimes range from 60-80s on equipment to 100-150s in the room.

$$\lambda_{vent} = \frac{1}{3600s} = 2.78\times10^{-4}s^{-1},$$

$$\lambda_{dep} = \frac{1}{100s} = 1.0\times10^{-3}s^{-1},$$

$$\lambda_{decay} = \frac{1}{138.4\times24\times3600s} = 8.36\times10^{-8}s^{-1}.$$

The equilibrium Po activity in the room air is

$$\overline{A}_{Po} = \frac{g_{leak}}{\lambda_{vent}+\lambda_{dep}+\lambda_{decay}} = 3.5\times10^{-10}Ci,$$

$$\overline{a}_{Po} = \frac{\overline{A}_{Po}}{V_r} = 3.5\times10^{-15}Ci/l = 0.012LPC_{US}.$$

If there is no ventilation, the Po activity is

$$\overline{A}'_{Po} = \frac{g_{leak}}{\lambda_{dep}+\lambda_{decay}} = 3.6\times10^{-10}Ci,$$

$$\overline{a}'_{Po} = \frac{\overline{A}'_{Po}}{V_r} = 3.6\times10^{-15}Ci/l = 0.012LPC_{US}.$$

We can conclude that as long as the Po aerosol deposits to surfaces quickly, there is little danger of Po inhalation during normal operation. However, the surface accumulation of Po can be problematic. The deposition process can be modeled in the following way:

$$\frac{dA^s_{Po}}{dt} = \lambda_{dep}A_{Po} - \lambda_{decay}A^s_{Po} \approx \lambda_{dep}\overline{A}_{Po} - \lambda_{decay}A^s_{Po}, (t >> 100s),$$

$$\overline{A}^s_{Po} = \frac{\lambda_{dep}\overline{A}_{Po}}{\lambda_{decay}} = 4.2\times10^{-5}Ci.$$

This amount of Po distributed over a 150m^2 surface leads to a specific activity of $2.8\times10^{-7}Ci/m^2$, A person with 2m^2 surface area can be potentially contaminated with 0.56μCi. This strongly suggests that thorough body showering and clothes washing are necessary after each shift. It also suggests to have large deposition area strategically located beyond personnel contact area to cut down the specific surface activity.

Accidents

We have already analyzed the coolant spill accident and concluded that even a massive spill would not lead to fatal or damaging Po contamination if exposure duration is kept short. For completeness sake, we include a brief analysis of coolant spill in accident scenario 3. The more likely accident scenario is the sudden release of gases from the gas system when there is a breach of seals.

Scenario 1.

To start, let's examine a worst case scenario in which the Po in the gas system releases into the room all at once with no ventilation and no aerosol deposition. The personnel evacuation time is 10 minutes. The room Po specific activity is

$$a_{Po}^{r} = \frac{A_{Po}}{V_r} = 6.2 \times 10^{-10}\, Ci/l.$$

Personnel inhalation rate of air is $R_{air} = 0.23 l/s$. The total inhaled Po activity is

$$A_{inhaled} = R_{air} \Delta t \times a_{Po}^{r} = 8.6 \times 10^{-8}\, Ci = 0.086 \mu Ci.$$

This is well below the 50-50 chance lethal dose extrapolated from experiments on mice, which is about $3mCi$. The US regulation on Po inhalation limit is about $0.6\mu Ci$ for 2000 hours per year work time. So a person exposed to the above mentioned amount of Po has about 290 hours equivalent dose. While it is no light matter, this scenario is certainly within controllable limits. The real life consequence should be less severe as we analyze a more realistic scenarios.

If ventilation and deposition mechanisms are available, then the room Po activity can be modeled as

$$\frac{dA_{Po}^{r}}{dt} = -\lambda_{eff} A_{Po}^{r},$$

$$A_{Po}^{r} = A_{Po}^{r}(0)(1 - e^{-\lambda_{eff} t}).$$

The total inhaled Po for one person after 10 minutes is

$$A_{inhaled} = \int_{0}^{600s} R_{air} \frac{A_{Po}^{r}}{V_r} dt = 1.38 \times 10^{-8}\, Ci = 0.014 \mu Ci.$$

The surface deposition can be calculated in the following way:

$$\frac{dA^s_{Po}}{dt} = \lambda_{dep} A^r_{Po} - \lambda_{decay} A^s_{Po},$$

$$A^s_{Po}(0) = \overline{A}^s_{Po} = 4.2 \times 10^{-5}\, Ci,$$

$$A^s_{Po} = (\overline{A}^s_{Po} - \frac{\lambda_{dep} A^r_{Po}(0)}{\lambda_{decay} - \lambda_{eff}})e^{-\lambda_{decay} t} + \frac{\lambda_{dep} A^r_{Po}(0)}{\lambda_{decay} - \lambda_{eff}} e^{-\lambda_{eff} t},$$

$$A^s_{Po}(3600s) = 1.02 \times 10^{-4}\, Ci.$$

Scenario 2.

This scenario consists of 100 seconds of complete Po discharge from the gas system, 10 minutes of personnel evacuation time with ventilation and aerosol deposition. For the time scale under consideration, Po decay is negligible. Then

$$g_{leak} = \frac{A_{Po}}{\Delta t} = \frac{6.2 \times 10^{-5}\, Ci}{100s} = 6.2 \times 10^{-7}\, Ci/s,$$

$$\lambda_{eff} = \lambda_{vent} + \lambda_{dep} = 1.03 \times 10^{-2}\, s^{-1}.$$

For $0 < t < 100s$:

$$\frac{dA^r_{Po}}{dt} = g_{leak} - \lambda_{eff} A^r_{Po},$$

$$A^r_{Po} = \frac{g_{leak}}{\lambda_{eff}}(1 - e^{-\lambda_{eff} t}).$$

For $100s < t < 600s$:

$$\frac{dA^r_{Po}}{dt} = -\lambda_{eff} A^r_{Po},$$

$$A^r_{Po} = A^r_{Po}(100s) e^{-\lambda_{eff}(t-100)}.$$

The total personnel inhalation is

$$A_{inhaled} = \int_0^{600s} R_{air} \frac{A^r_{Po}}{V_r} dt = 1.38 \times 10^{-8}\, Ci = 0.014 \mu Ci.$$

This is equivalent to 47 hours inhalation dose at the US regulation limit.

Scenario 3.

This is a massive coolant spill accident scenario. The analysis is based on an IPPE report[1]. In the case of coolant spill, the release of Po from the LBE is by volatile polonium hydride formation through interaction with moist in the room air. According to experimental data and real NPP experience, the H_2Po release rate at 20°C is approximately q=1.5E-9 $(Ci/s)/Ci$. Suppose the solidified coolant has an exposed surface area S and a specific surface activity of a_0(the same as in the bulk), in the same room as used in the previous analysis, with V_r=100m^3. The aerosol deposition rate is about 0.01s^{-1}. Then the room Po activity evolves as

$$\frac{dA_{Po}}{dt} = qA^{s}_{Po} - \lambda_{vent}A_{Po} - \lambda_{dep}A_{Po} - \lambda_{decay}A_{Po},$$

$$A^{s}_{Po} = a_0 V_{LBE-surface-layer}\rho_{LBE} = a_0 S\delta\rho_{LBE},$$

where $\delta = 0.05mm$ is the volatile formation surface layer thickness (Russian experience). The equilibrium activity in the room is

$$\overline{A}_{Po} = \frac{qa_0 S\delta\rho_{LBE}}{\lambda_{vent} + \lambda_{dep} + \lambda_{decay}}$$

$$= \frac{1.5\times10^{-9}s^{-1}\times 1Ci/kg\times 10^{5}cm^{2}\times 0.005cm\times 0.01kg/cm^{3}}{2.78\times10^{-4}s^{-1} + 0.01s^{-1} + 8.36\times10^{-8}s^{-1}} = 7.6\times10^{-7}Ci,$$

$$\overline{a}_{Po} = \frac{\overline{A}_{Po}}{V_r} = 7.6\times10^{-12}Ci/l = 25LPC_{US}.$$

The personnel inhalation dose can be calculated the same way as in scenario 2. If sufficient ventilation is provided, this activity level should decrease considerably.

The Russian submarine reactor refueling time is between 3 to 10 years and the refueling operation is basically whole-core replacement, which gives us little information for ATW type short refueling cycles. Other experience suggests that there is little Po effect on the oxide films and the surface material properties, for 5~10*Ci/kg* Po activities in the LBE coolant.

In the US, Po production for military and space use continued from 1940s to 1980s. Mound Laboratory's extensive production and handling of Po stopped in 1970s. Radiological workers monitoring revealed no significant does-response trends for all causes combined, all cancers combined[4]. Minute quantities of Po can still be commercially purchased from the Oak Ridge National Laboratory.

The radiological protection procedures deployed in the Russian reactor operation include protective clothing, body showering, respirators (less effective for polonium hydride), ventilation, and negative pressure in Po compartment. Surface contaminant Po can be removed by a sticky paint. It should be mentioned that there is polonium in natural environment due to the uranium-radium radioactive decay. Many articles and treatises have been written on the subject of polonium safety[5]. It is generally agreed by the specialists who are familiar with the Russian reactor experience and other Po handling situations that the Po hazard associated with lead-bismuth use as reactor coolant, although not entirely negligible, can be mitigated and kept well below regulation limits. In fact, the LBE coolant itself is perhaps the safest place to contain polonium[1]. We are also currently evaluating and developing means to remove polonium in case we need to do that[6].

References

[1] E. Yefimov *etal*, "Removal and Containment of Polonium from Liquid Lead-Bismuth Eutectic", Reg. No. 21-24/155, Institute of Physics and Power Engineering, State Scientific Center of Russian Federation, Obninsk, Russia (1996).

[2] IPPE data (1997).

[3] H. V. Moyer *etal.* "Polonium", US AEC report, TID-5221 (1956).

[4] L.D. Wiggs *etal.* "Mortality among a Cohort of Workers Monitored for 210Po Exposure: 1944-1972", Health Physics, Vol. 61, No. 1, 71(1991).

[5] N. B. Borisov *etal.* "Radiation Safety in Working with Polonium-210" "(English translation), Moscow, Atomizdat (1980).

[6] Quarterly reports #1, #2 and #3 on fulfillment works under the Contract 625UU0005-35 between IPPE and LANL (1997-1998).

Appendix

The Po release models are formulated in a spreadsheet for convenience of repeated calculations for different scenarios and parameters. The following 3 spreadsheets contain Po release results for 3 different levels of Po specific activity in the LBE coolant: 1, 0.5, and 5 *Ci/kg*.

Polonium Release Models

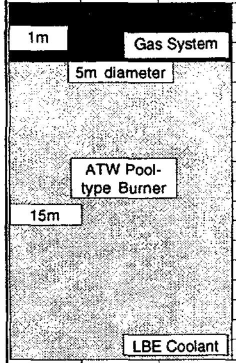
This spreadsheet contains the polonium release models used for estimating polonium hazards in ATW systems.

The text is in LA-UR report "Polonium Release from an ATW Burner with Liquid Lead-Bismuth Coolant" by Ning Li and Evgeny Yefimov, April 1998.

- Ning Li, April 1998

System Parameter and LBE Properties Definitions

- ATW Burner and Coolant



Input	
burner diameter[m]: D_s	5
gas system height[m]: h_g	1
coolant depth[m]: h_LBE	15
coolant temp[oC]: tc_LBE	400
gas temp[oC]: tc_g	400
coolant activity[Ci/kg]: as_0	1.0
LBE density[g/cm^3]: rho_LBE	10.4
fraction of PbPo evap: f_PbPo	0.998
fraction of Po evap: f_Po	0.002
US Po-210 LPC[Ci/l]: LPC	3.00E-13
allowed inhalation dose[uCi/yr]: ann_inh	0.6
Po-210 decay constant[1/s]: decay	8.36E-08
Output	
coolant temp[K]: T_LBE	673
gas temp[K]: T_g	673
evap. surface[m^2]: S_e	19.6
gas volume[m^3]: V_g	19.6
coolant volume[m^3]: V_LBE	295
coolant mass[tons]: M_LBE	3063
Po activity in LBE[Ci]: A_0	3.06E+06

- LBE Properties

Input	
specific evap rate[Ci/m^2s/Ci/kg]:	
PbPO: w_PbPo	2.27E-05
Po: w_Po	2.06E-02
in_vacuum-in_air reduction: beta	1.00E-03
pure vapor pressure[Pa]: PP_PbPo	1.82E-02
pure vapor pressure[Pa]: PP_Po	2.39E+01
Output	
gross evap rate[Ci/s]:	
PbPo: g_PbPo	4.45E-07
Po: g_Po	8.07E-07
PbPo+Po: g_0	1.25E-06
1Ci Po210 = 0.223mg:	
coolant PbPo concentration: c_PbPo	4.45E-07
coolant Po concentration: c_Po	4.46E-10
vapor pressures in gas system[Pa]:	
PbPo: P_PbPo	8.10E-09
Po: P_Po	1.07E-08
Po in gas[mole]: n_Po	6.59E-11
Po activity *in* gas[Ci]: A_Po	6.20E-05
specific Po activity[Ci/l]: as_Po	**3.16E-09**
# of times US LPC	1.05E+04
Po deposition on cold surface[Ci]	15.0

Accidents Analysis: Basic Kinetic Modeling of Po Release

- Normal Operating Condition

Input	
gas system leak rate[1/d]: leak_rate	0.005
op room volume[m^3]: V_r	100
personnel inhalation rate[l/s]: inhale	0.23
room ventilation rate[1/s]: vent	2.78E-04
Po aerosol deposition rate[1/s]: dep	1.00E-02
Output	
Po leak rate[Ci/s]: g_leak	3.59E-12
effective decay constant[1/s]: eff	1.03E-02
room Po activity[Ci]: Ar_Po	3.49E-10
specific activity[Ci/l]: asr_Po	**3.49E-15**
# of times US LPC	1.16E-02
room Po activity w/o vent[Ci]	3.59E-10
specific activity[Ci/l]:	**3.59E-15**
surface Po deposition[Ci]: Ad_Po	4.18E-05

- Accident Scenario 1 : gas releases all at once, evacuation time 10 min, no ventilation, no aerosol deposition (worst case)

Input	
evac time[s]: t_e1	600
Output	
room Po activity[Ci]: Ar1_Po	6.20E-05
room Po activity[Ci/l]: asr1_Po	6.20E-10
inhaled Po[uCi]: Po_inh	**8.56E-02**
percentage of allowed annual dose(%):	14.3
if ventilation and deposition available	
Po inhalation[uCi]	**1.39E-02**
surface Po activity[Ci]	1.02E-04
time when Po activity down to LPC[hr]	0.21

- Accident Scenario 2 : gas releases in 100s, evacuation time 10 min, normal ventilation, with aerosol deposition

Input	
leak time[s]: t_leak	100
Output	
Po leak rate[Ci/s]: g_leak2	6.20E-07
0<t<100s	
room Po activity at 100s[Ci]: A_100	3.88E-05
Po inhalation[uCi]: A_inh100	5.21E-03
100s<t<600s	
Po inhalation[uCi]: A_inh500	8.62E-03
total Po inhalation[uCi]:	**1.38E-02**
percentage of allowed annual dose(%):	2.30
time when Po activity down to LPC[hr]	0.22

- Accident Scenario 3 : coolant spill into operating room, solidifies quickly and release Po via volatile hydride formation with moist in room, aerosol deposition rate is 0.01s^-1

Input	
spilled coolant surface[m^2]: S_s	10
H2Po release rate[Ci/s/Ci]: q	1.50E-09
H2Po formation layer[cm]: delta	0.005
Output	
Po activity in room[Ci]:	7.59E-07
specific Po activity in room[Ci/l]:	**7.59E-12**
# of times US LPC	2.53E+01

Polonium Release Models

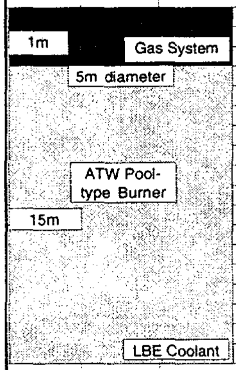
This spreadsheet contains the polonium release models used for estimating polonium hazards in ATW systems.

The text is in LA-UR report "Polonium Release from an ATW Burner with Liquid Lead-Bismuth Coolant" by Ning Li and Evgeny Yefimov, April 1998.

- Ning Li, April 1998

System Parameter and LBE Properties Definitions

- ATW Burner and Coolant



Input	
burner diameter[m]: D_s	5
gas system height[m]: h_g	1
coolant depth[m]: h_LBE	15
coolant temp[oC]: tc_LBE	400
gas temp[oC]: tc_g	400
coolant activity[Ci/kg]: as_0	**0.5**
LBE density[g/cm^3]: rho_LBE	10.4
fraction of PbPo evap: f_PbPo	0.998
fraction of Po evap: f_Po	0.002
US Po-210 LPC[Ci/l]: LPC	3.00E-13
allowed inhalation dose[uCi/yr]: ann_inh	0.6
Po-210 decay constant[1/s]: decay	8.36E-08
Output	
coolant temp[K]: T_LBE	673
gas temp[K]: T_g	673
evap. surface[m^2]: S_e	19.6
gas volume[m^3]: V_g	19.6
coolant volume[m^3]: V_LBE	295
coolant mass[tons]: M_LBE	3063
Po activity in LBE[Ci]: A_0	1.53E+06

- LBE Properties

Input	
specific evap rate[Ci/m^2s/Ci/kg]:	
PbPO: w_PbPo	2.27E-05
Po: w_Po	2.06E-02
in_vacuum-in_air reduction: beta	1.00E-03
pure vapor pressure[Pa]: PP_PbPo	1.82E-02
pure vapor pressure[Pa]: PP_Po	2.39E+01
Output	
gross evap rate[Ci/s]:	
PbPo: g_PbPo	2.22E-07
Po: g_Po	4.04E-07
PbPo+Po: g_0	6.26E-07
1Ci Po210 = 0.223mg:	
coolant PbPo concentration: c_PbPo	2.23E-07
coolant Po concentration: c_Po	2.23E-10
vapor pressures in gas system[Pa]:	
PbPo: P_PbPo	4.05E-09
Po: P_Po	5.33E-09
Po in gas[mole]: n_Po	3.29E-11
Po activity in gas[Ci]: A_Po	3.10E-05
specific Po activity[Ci/l]: as_Po	**1.58E-09**
# of times US LPC	5.26E+03
Po deposition on cold surface[Ci]	7.5

Accidents Analysis: Basic Kinetic Modeling of Po Release

- Normal Operating Condition

Input	
gas system leak rate[1/d]: leak_rate	0.005
op room volume[m^3]: V_r	100
personnel inhalation rate[l/s]: inhale	0.23
room ventilation rate[1/s]: vent	2.78E-04
Po aerosol deposition rate[1/s]: dep	1.00E-02
Output	
Po leak rate[Ci/s]: g_leak	1.79E-12
effective decay constant[1/s]: eff	1.03E-02
room Po activity[Ci]: Ar_Po	1.75E-10
specific activity[Ci/l]: asr_Po	**1.75E-15**
# of times US LPC	5.82E-03
room Po activity w/o vent[Ci]	1.79E-10
specific activity[Ci/l]:	**1.79E-15**
surface Po deposition[Ci]: Ad_Po	2.09E-05

- Accident Scenario 1 : gas releases all at once, evacuation time 10 min, no ventilation, no aerosol deposition (worst case)

Input	
evac time[s]: t_e1	600
Output	
room Po activity[Ci]: Ar1_Po	3.10E-05
room Po activity[Ci/l]: asr1_Po	3.10E-10
inhaled Po[uCi]: Po_inh	**4.28E-02**
percentage of allowed annual dose(%):	7.1
if ventilation and deposition available	
Po inhalation[uCi]	**6.93E-03**
surface Po activity[Ci]	5.10E-05
time when Po activity down to LPC[hr]	0.19

- Accident Scenario 2 : gas releases in 100s, evacuation time 10 min, normal ventilation, with aerosol deposition

Input	
leak time[s]: t_leak	100
Output	
Po leak rate[Ci/s]: g_leak2	3.10E-07
0<t<100s	
room Po activity at 100s[Ci]: A_100	1.94E-05
Po inhalation[uCi]: A_inh100	2.60E-03
100s<t<600s	
Po inhalation[uCi]: A_inh500	4.31E-03
total Po inhalation[uCi]:	**6.91E-03**
percentage of allowed annual dose(%):	1.15
time when Po activity down to LPC[hr]	0.20

- Accident Scenario 3 : coolant spill into operating room, solidifies quickly and release Po via volatile hydride formation with moist in room, aerosol deposition rate is 0.01s^-1

Input	
spilled coolant surface[m^2]: S_s	10
H2Po release rate[Ci/s/Ci]: q	1.50E-09
H2Po formation layer[cm]: delta	0.005
Output	
Po activity in room[Ci]:	3.79E-07
specific Po activity in room[Ci/l]:	**3.79E-12**
# of times US LPC	1.26E+01

Polonium Release Models

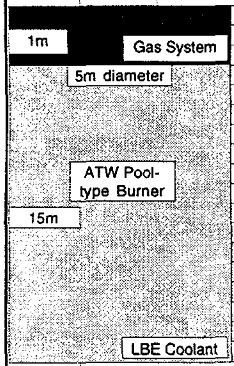
This spreadsheet contains the polonium release models used for estimating polonium hazards in ATW systems.

The text is in LA-UR report "Polonium Release from an ATW Burner with Liquid Lead-Bismuth Coolant" by Ning Li and Evgeny Yefimov, April 1998.

- Ning Li, April 1998

System Parameter and LBE Properties Definitions

- ATW Burner and Coolant



Input	
burner diameter[m]: D_s	5
gas system height[m]: h_g	1
coolant depth[m]: h_LBE	15
coolant temp[oC]: tc_LBE	400
gas temp[oC]: tc_g	400
coolant activity[Ci/kg]: as_0	5.0
LBE density[g/cm^3]: rho_LBE	10.4
fraction of PbPo evap: f_PbPo	0.998
fraction of Po evap: f_Po	0.002
US Po-210 LPC[Ci/l]: LPC	3.00E-13
allowed inhalation dose[uCi/yr]: ann_inh	0.6
Po-210 decay constant[1/s]: decay	8.36E-08
Output	
coolant temp[K]: T_LBE	673
gas temp[K]: T_g	673
evap. surface[m^2]: S_e	19.6
gas volume[m^3]: V_g	19.6
coolant volume[m^3]: V_LBE	295
coolant mass[tons]: M_LBE	3063
Po activity in LBE[Ci]: A_0	1.53E+07

- LBE Properties

Input	
specific evap rate[Ci/m^2s/Ci/kg]:	
PbPO: w_PbPo	2.27E-05
Po: w_Po	2.06E-02
in_vacuum-in_air reduction: beta	1.00E-03
pure vapor pressure[Pa]: PP_PbPo	1.82E-02
pure vapor pressure[Pa]: PP_Po	2.39E+01
Output	
gross evap rate[Ci/s]:	
PbPo: g_PbPo	2.22E-06
Po: g_Po	4.04E-06
PbPo+Po: g_0	6.26E-06
1Ci Po210 = 0.223mg:	
coolant PbPo concentration: c_PbPo	2.23E-06
coolant Po concentration: c_Po	2.23E-09
vapor pressures in gas system[Pa]:	
PbPo: P_PbPo	4.05E-08
Po: P_Po	5.33E-08
Po in gas[mole]: n_Po	3.29E-10
Po activity in gas[Ci]: A_Po	3.10E-04
specific Po activity[Ci/l]: as_Po	1.58E-08
# of times US LPC	5.26E+04
Po deposition on cold surface[Ci]	74.8

Accidents Analysis: Basic Kinetic Modeling of Po Release

- Normal Operating Condition

Input	
gas system leak rate[1/d]: leak_rate	0.005
op room volume[m^3]: V_r	100
personnel inhalation rate[l/s]: inhale	0.23
room ventilation rate[1/s]: vent	2.78E-04
Po aerosol deposition rate[1/s]: dep	1.00E-02
Output	
Po leak rate[Ci/s]: g_leak	1.79E-11
effective decay constant[1/s]: eff	1.03E-02
room Po activity[Ci]: Ar_Po	1.75E-09
specific activity[Ci/l]: asr_Po	**1.75E-14**
# of times US LPC	5.82E-02
room Po activity w/o vent[Ci]	1.79E-09
specific activity[Ci/l]:	**1.79E-14**
surface Po deposition[Ci]: Ad_Po	2.09E-04

- Accident Scenario 1 : gas releases all at once, evacuation time 10 min, no ventilation, no aerosol deposition (worst case)

Input	
evac time[s]: t_e1	600
Output	
room Po activity[Ci]: Ar1_Po	3.10E-04
room Po activity[Ci/l]: asr1_Po	3.10E-09
inhaled Po[uCi]: Po_inh	**4.28E-01**
percentage of allowed annual dose(%):	71.3
if ventilation and deposition available	
Po inhalation[uCi]	**6.93E-02**
surface Po activity[Ci]	5.10E-04
time when Po activity down to LPC[hr]	0.25

- Accident Scenario 2 : gas releases in 100s, evacuation time 10 min, normal ventilation, with aerosol deposition

Input	
leak time[s]: t_leak	100
Output	
Po leak rate[Ci/s]: g_leak2	3.10E-06
0<t<100s	
room Po activity at 100s[Ci]: A_100	1.94E-04
Po inhalation[uCi]: A_inh100	2.60E-02
100s<t<600s	
Po inhalation[uCi]: A_inh500	4.31E-02
total Po inhalation[uCi]:	**6.91E-02**
percentage of allowed annual dose(%):	11.52
time when Po activity down to LPC[hr]	0.26

- Accident Scenario 3 : coolant spill into operating room, solidifies quickly and release Po via volatile hydride formation with moist in room, aerosol deposition rate is 0.01s^-1

Input	
spilled coolant surface[m^2]: S_s	10
H2Po release rate[Ci/s/Ci]: q	1.50E-09
H2Po formation layer[cm]: delta	0.005
Output	
Po activity in room[Ci]:	3.79E-06
specific Po activity in room[Ci/l]:	**3.79E-11**
# of times US LPC	1.26E+02