Rubidium material hazard analysis

Version 0 (Rev 3)

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07 July 2016

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Incompleteness Record

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1   Introduction

1.1   Purpose

This document reviews the potential hazards associated with the handling and use of rubidium in the context of the AWAKE experiment.

It is based on a review of available literature and includes supporting calculations to assess the hazard implications.

1.2   Audience

The audience for this document is restricted to project members from Max Planck Institute (MPP) or CERN.

1.3   Abbreviations

FMEA	Failure mode effects analysis
MPP	Max Planck Institute
MSDS	Material safety data sheet
PPE	Personal protective equipment
Rb	Rubidium
RH	Relative humidity
SOP	Standard operating procedure

1.4   References

[1]   ESPI Metal Material Safety Data Sheet (included in appendix 1 for convenience)
[2]   MSDS rubidium

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2 Hazard summary

2.1 Hazard classification summary

There may be up to 3kg of rubidium present within the AWAKE plasma cell and vapour sources. Depending on the experimental operating status, the Rb may be in solid form or in a mixture of liquid and vapour. Rubidium will be loaded into flasks in a separate area, transported to the experimental area and fitted to the experimental set up. The loading of rubidium will likely require handling of Rb in solid and liquid states. Transportation of the rubidium from the loading area to the experimental area will be done at ambient temperatures so Rb will be in solid state.

The specific hazards associated with rubidium are:
H260 – In contact with water releases flammable gases which may ignite spontaneously
H314 – Causes severe skin burns and eye damage

Other precautionary hazard statements are listed in the manufacturers MSDSs [1][2] (see appendix A).

2.2 Hazard summary in Intended Use

Risk	Hazard	Mitigation
Accidental exposure to water source	Explosion hazard (Release of H_2)	Prevent access to water sources in order to limit reaction potential
	Fire	Fire prevention and handling procedures
	Release of corrosive fumes leading to respiratory tract burns, skin burns, eye burns	Appropriate PPE
Release of toxic fumes due to Rb decomposition when heated	Release of corrosive fumes leading to respiratory tract burns, skin burns, eye burns	Appropriate PPE; Heating temperature limits
Accidental exposure to oxygen/ moisture source (air)	Fire	Limit access to moisture sources
	Release of corrosive fumes leading to respiratory tract burns, skin burns, eye burns	Fire prevention and handling procedures; Appropriate PPE
Accidental human contact to Rb during loading and unloading of system.	Respiratory tract burns, skin burns, eye burns	Appropriate PPE must be worn to handle; Dual operator procedure recommended

2.3 Summary/conclusions

The analysis associated with this review identifies the specific hazards that the use of Rb presents. The next steps should include:

- Generation of the formal FMEA analysis for all sub-systems and work processes to define the specific hazards and appropriate mitigations using the worksheet methodology proposed by CERN. This document can provide the basis for hazard severity estimation used in the methodology.

- The severity of hazard associated with Rb is estimated in this document based on a review of literature. It is prudent that a review of chemical reactions and analysis should be done by an independent peer to check the assumptions made appear reasonable and correct.

- The energy release associated with Rb exposure to air is a key part of the hazard estimation within the context of use in the Rb Vapour source. It would be prudent to perform a verification of reaction of rubidium on small scale to check the measured physical response matches the expected behaviour noted in this document. This could be achieved by a small scale laboratory test.

3 Accidental exposure to water sources

3.1 Background chemistry

Rubidium reacts very rapidly with water to form a colourless solution of rubidium hydroxide (RbOH) and hydrogen gas (H_2). The resulting solution is basic because of the dissolved hydroxide. The reaction is very exothermic.

$$2Rb(s) + 2H_2O \rightarrow 2RbOH(aq) + H_2(g)$$
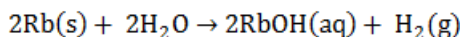
Standard enthalpy of formation (RbOH) = −413.8 kJ/mol

The resulting hydrogen gas is an explosion hazard.

3.2 Hazard assessment in Intended Use

There is a serious fire and/or explosion hazard due to hydrogen gas formation during reaction with water. All water sources should be removed to minimise this risk.

3.2.1 Water sources within plasma cell & vapour sources

No sources of water are intended to be used.

3.2.2 Water sources in the experimental environment (tunnel)

CERN to confirm any water sources in tunnel area

3.2.3 Water sources in the loading and handling area

CERN to confirm location of loading and handling room and confirm water sources

3.3 Anticipated mitigations

The following mitigations are anticipated:
- Remove water sources from experimental area (all sources if possible)
- Remove water sources from Rb handling and loading area
- Inform all AWAKE personnel of water hazard via training
- Inform CERN firefighting team of water hazard and response via training
- Protection from water for any flask or containing holding rubidium
- Clear labelling of any water sources that cannot be removed
- SOP for rubidium loading and handling

3.4 Emergency procedures

Exposure of rubidium to water would require emergency procedures to be followed. These will likely include:
- Immediate evacuation of the AWAKE experimental area or handling area
- Initial response by the CERN firefighting team using emergency SOP

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4   Release of toxic fumes when heated

4.1   Background chemistry

Rubidium metal reacts with oxygen to form rubidium oxide (Rb_2O) and rubidium superoxide (RbO_2). Both reactions are exothermic causing heating. This could lead to temperatures greater than the intended use temperatures. When heated to decomposition rubidium may emit toxic fumes of rubidium oxide and rubidium hydroxide [1].

Production of rubidium oxide will occur if rubidium is exposed to oxygen. The melting point (possibly also decomposition temperature) is defined as >500°C[1]:

$$4Rb(s) +\ O_2(g) \rightarrow 2Rb_2O(s) \xrightarrow{>500°C} 2Rb_2O(v?)$$
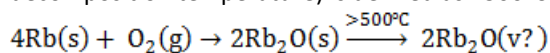
Production of rubidium superoxide can also occur. The melting point (possibly also decomposition temperature) is defined as 412°C[2]:

$$Rb(s) +\ O_2(g) \rightarrow RbO_2(s) \xrightarrow{412°C} RbO_2(v?)$$
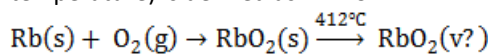
In addition, rubidium dioxide can form rubidium peroxide at 290°C[3]:

$$RbO_2(s) \xrightarrow{290°C} Rb_2O_2(s?) +\ O_2(g)$$
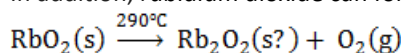
4.2   Hazard assessment in Intended Use

Excessive temperatures may cause fumes (rubidium oxide, rubidium superoxide or rubidium peroxide) that are basic and could cause respiratory, eye and skin damage to local personnel. Fumes would be limited if the temperature exceeded safe limits but the vacuum was maintained. Any excessive plasma cell or vapour source temperature in combination with a loss of vacuum would present a greater fume hazard.

4.2.1   Sources of oxygen

The main source of oxygen in the AWAKE experiment is the tunnel air.

4.2.2   Sources of heating

Heating to decomposition temperatures could be via uncontrolled electrical heating in the system or via self-heating from exothermic reactions of rubidium with oxygen and moisture.

4.3   Anticipated mitigations

The following mitigations are anticipated:
- Appropriate PPE worn by personnel working in the experimental area when system is hot
- Secondary protection of all heating circuits to prevent active heating above 230°C
- Monitoring of all system temperatures
- Safety mechanisms to monitor any loss of vacuum and minimise oxygen (air) ingress

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[1] https://en.wikipedia.org/wiki/Rubidium_oxide
[2] http://www.webelements.com/compounds/rubidium/rubidium_superoxide.html
[3] https://de.wikipedia.org/wiki/Rubidiumperoxid
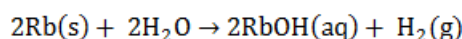
4.4   Emergency procedures

If temperatures exceed 250°C, then an emergency procedure will need to be followed. This will likely include:
- Immediate evacuation of the AWAKE experimental area
- Initial response by the CERN firefighting team using emergency SOP
- Emergency SOP will require:
  - PPE to prevent inhalation of basic vapour
  - PPE to protect against high temperatures and hot surfaces
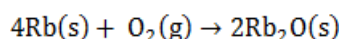 - PPE to prevent skin or eye contact with basic vapour

5   Accidental exposure to air/moisture sources
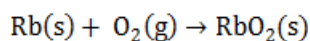
5.1   Background chemistry

Rubidium will react with oxygen and water vapour in air. All reactions are exothermic.

$$2Rb(s) + 2H_2O \rightarrow 2RbOH(aq) + H_2(g)$$

Standard enthalpy of formation (RbOH) = −413.8 kJ/mol

$$4Rb(s) + O_2(g) \rightarrow 2Rb_2O(s)$$

Standard enthalpy of formation (Rb$_2$O) = −339 kJ/mol[4]

$$Rb(s) + O_2(g) \rightarrow RbO_2(s)$$

Standard enthalpy of formation (Rb$_2$O) = −278.7kJ/mol[5]

5.2   Hazard assessment in Intended Use

The main hazards if rubidium is exposed to air are:
- Fire and explosion hazard due to hydrogen gas formation during reaction with water vapour
- Chemical hazard (alkali) due to products of rubidium reaction with air
- Heat and fire hazard due to energy given out from exothermic reactions

5.2.1   Reaction with water vapour in air

The following analysis assumes that the vapour source is filled with tunnel air (p = 101325Pa, T = 20°C, RH = 20%) and contains 3kg of rubidium. This represents the endpoint of a scenario where the vapour source is rapidly filled with air due to a large leak. The assumption is that the reaction is limited by the quantity of air (i.e. the reaction takes place in a fixed limited volume).

The rubidium will react with the water vapour in the air according to the following chemical equation:

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[4] http://www.chemguide.co.uk/inorganic/group1/reacto2.html
[5] http://www.chemguide.co.uk/inorganic/group1/reacto2.html

$$2Rb(s) + 2H_2O \rightarrow 2RbOH(aq) + H_2(g)$$

The total amount of water vapour (n_{vapour}) in the air in the plasma cell & vapour sources volume is given by:

$$n_{vapour} = \frac{RH_{air}\rho_{vapour}V_c}{M_{air}} = \frac{20\% \times 17.3gm^{-3} \times 0.17m^3}{28.97gmol^{-1}} = 0.033 \; moles$$

The water vapour density is dependent on the tunnel air temperature (20% RH assumption should be verified)

Using the stoichiometric ratios:
The total amount of rubidium consumed is 0.033 moles = 2.8g
The total amount of rubidium hydroxide formed is 0.033 moles
The total amount of H_2 formed is 0.016 moles

The total volume of H_2 gas formed is given by:

$$V_{H_2} = \frac{n_{H_2}RT_{air}}{p_{atmos}} = \frac{0.016 \; moles \times 8.314JK^{-1}mol^{-1} \times 293K}{101325Pa} = 0.00039 \; m^3 = 0.39 \; litres$$

The content per volume of the plasma cell and vapour sources is given by:

$$\%_{H_2} = \frac{V_{H_2}}{V_{system}} = \frac{0.39 \; litres}{170 \; litres} = 0.0024 = 0.24\%$$

The following table represents the flammability and explosion risk for hydrogen gas:

Level	Percentage	Safety factor
Level of hydrogen gas in system	0.24%	-
Lowest flammable level (LFL)[6]	4%	16.6
Lowest explosion level (LEL)[7]	18.3%	76.3

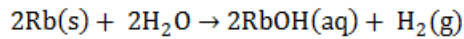There is a reasonable factor of safety before the hydrogen gas created could cause a fire or an explosion.

5.2.2   Reaction with oxygen in air

The following analysis assumes that the vapour source is filled with tunnel air (p = 101325Pa, T = 20°C, RH = 20%) and contains 3kg of rubidium. This represents the endpoint of a scenario where the vapour source is rapidly filled with air due to a large leak. The assumption is that the reaction is limited by the quantity of air (i.e. the reaction takes place in a fixed limited volume).

There are two possible reactions of rubidium with oxygen either forming rubidium oxide (Rb_2O) or rubidium superoxide (RbO_2). The analysis below assumes that the reaction proceeds via the rubidium oxide route:

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[6] https://en.wikipedia.org/wiki/Flammability_limit
[7] https://en.wikipedia.org/wiki/Flammability_limit

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$$4Rb(s) + O_2(g) \rightarrow 2Rb_2O(s)$$
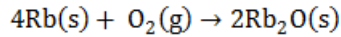
This reaction has the highest enthalpy of formation (-339kJ/mole) so is most likely and releases most energy.

The total amount of air (n_{air}) in the plasma cell & vapour sources volume is given by:

$$n_{air} = \frac{p_{atmos}V}{RT_{air}} = \frac{101325Pa \times 0.17m^3}{8.314JK^{-1}mol^{-1} \times 293K} = 7.07 \ moles$$

The total amount of oxygen (n_{oxygen}) in this volume of air is given by:

$$n_{oxygen} = O_c n_{air} = 20.95\% \times 7.07 \ moles = 1.48 \ moles$$

Using the stoichiometric ratios:
The total amount of rubidium consumed is 5.93 moles = 506g
The total amount of rubidium oxide formed is 2.96 moles

The total energy released during this reaction is given by:

$$E_{released} = n_{Rb_2O}\Delta H^o_{f(Rb_2O)} = 2.96 \ moles \times 339kJmol^{-1} = 1.00MJ$$

If all of this energy was used to heat the expansion chambers, then the temperature increase would be:

$$T_f = T_i + \frac{E_{released}}{m_{chambers} \times c_{stainless \ steel}} = 20°C + \frac{1.00MJ}{206kg \times 510J \, kg^{-1}K^{-1}} = 29.7°C$$

This ~10C temperature increase would only pose a limited hazard.

A corollary to this analysis is to assume the that the reaction is not limited by the quantity of air (i.e. the reaction has a constant feed of tunnel air) and that all 3kg of rubidium is allowed to react with oxygen. Although this situation may be unlikely in operation is does represent a scenario where a large amount of energy is released (via the exothermic reaction) and therefore provides a worst case benchmark.

The total number of moles in 3kg of rubidium is given by:

$$n_{Rb} = \frac{m_{Rb}}{M_{Rb}} = \frac{3000g}{85.47gmol^{-1}} = 35.10 \ moles$$

Using the stoichiometric ratios, the total amount of rubidium oxide created is 17.55 moles. Therefore, the total energy released (if all rubidium reacted with oxygen) is given by:

$$E_{released} = n_{Rb_2O}\Delta H^o_{f(Rb_2O)} = 17.55 \ moles \times 339kJmol^{-1} = 5.90MJ$$

If all of this energy was used to heat the vapour source chambers, then the temperature increase would be:

$$T_f = T_i + \frac{E_{released}}{m_{chambers} \times c_{stainless \ steel}} = 20°C + \frac{5.90MJ}{206kg \times 510J \, kg^{-1}K^{-1}} = 76.2°C$$

This temperature increase does pose a more significant hazard as surfaces will be hot.

5.2.3   Reaction with water vapour and oxygen due to slow loss of vacuum

The above analysis in sections 5.2.1 and 5.2.2 provides the endpoint if the plasma cell and vapour sources were filled rapidly with air.

A slow loss of vacuum (via a system air leak) would cause the same effects as those described in the previous two sections but over a longer time period.

The following analysis attempts to estimate the timescale for the system to fill with air through a small (0.2mm by 12mm) crack.

The following assumptions are made:
- Flow is incompressible
- Crack can be modelled using an orifice plate approximation
- Area before the orifice plate (outside the chamber) can be modelled using a 50mm diameter air tube
- Area of orifice plate is equal to crack area (and geometry doesn't have a significant effect)

The following equation can be used to calculate mass flow rate into the system:

$$Q = C_d A_2 \left(\frac{2(p_1 - p_2)}{\rho \left(1 - \left(\frac{A_2}{A_1}\right)^2\right)} \right)^{0.5}$$

Where:

p_1 = pressure outside chamber = 101325Pa

p_2 = pressure inside the chamber = 1×10^{-6}Pa initially

C_d = discharge coefficient = 0.61

A_1 = Area outside of chamber = $\pi \times 25mm^2$ = 1.96×10^{-3} m^2

A_2 = Area of the crack = 10mm x 0.2mm = 2.40×10^{-6} m^2

ρ = density of air (at 20°C) = 1.003 kg/m3

The pressure, p_2 will vary with time as the air mass flow into the system will increase the pressure and reduce the flow until steady state is reached at atmospheric pressure.

The following plot shows the pressure over time for the system assuming air inrush from a small crack. This suggests that the plasma cell & vapour sources would fill with air to atmospheric pressure in approximately 10 minutes.
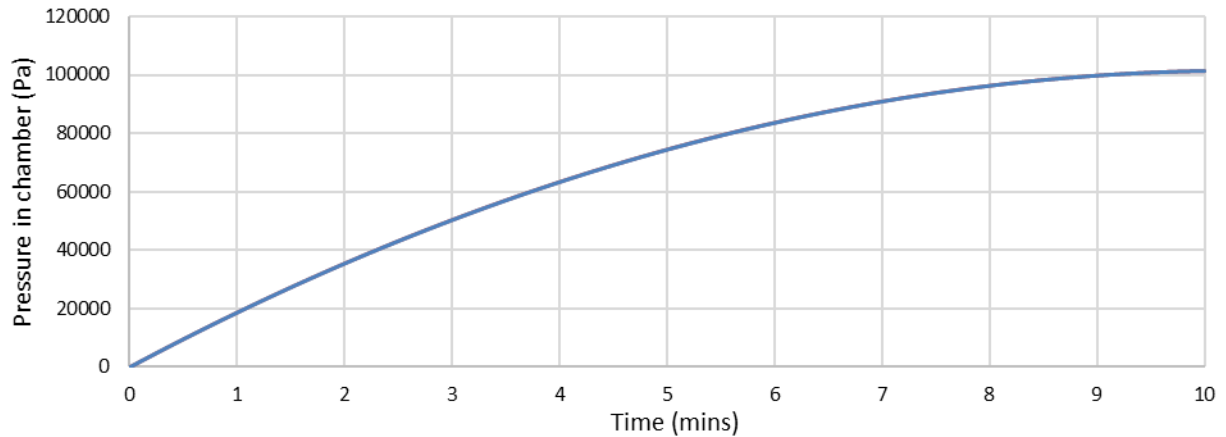
The following final analysis allows an assessment of the amount of air that will enter the system before a safety pressure threshold is triggered.

Assume that secondary system protection is implemented if the pressure **exceeds 1mbar**.

The total amount of air (n_{air}) in the plasma cell & vapour sources volume to show a 1mbar pressure is given by:

$$n_{air} = \frac{p_{trigger}V}{RT_{air}} = \frac{100Pa \times 0.17m^3}{8.314JK^{-1}mol^{-1} \times 293K} = 0.0070 \; moles$$

Following the same analysis as section 5.2.1 then:

The total amount of rubidium consumed would be ~0.5g and the total energy released from the creation of rubidium oxide would be less than 1kJ. This would represent a limited hazard.

5.3   Anticipated mitigations

The following mitigations are anticipated:
- Protection mechanisms to prevent a rapid inrush of air into plasma cell and vapour sources
- Safety mechanism(s) to monitor any loss of vacuum and minimise oxygen (air) ingress
- Equivalent protection during transportation and handling of containers holding rubidium

5.4   Emergency procedures

If an uncontrolled loss of vacuum occurs, then an emergency procedure will need to be followed. This will likely include:
- Immediate evacuation of the AWAKE experimental area
- Closure of all valves for isolation
- Initial response by the CERN firefighting team using emergency SOP

6 Accidental human contact to Rb during loading and unloading

6.1 Background information

Since rubidium reacts with water and oxygen then any contact with human skin, eyes or via inhalation or ingestion can cause acute and chronic health effects which are detailed in [1][2].

6.2 Hazard assessment in Intended Use

The main hazards during intended use are:
- Accidental spillage of rubidium solid or liquid onto clothing or skin causing irritation or burns
- Accidental contact with eyes causing burns
- Accidental inhalation of fumes causing respiratory tract damage which can be chronic
- Accidental ingestion of solid or liquid causing gastric damage

6.3 Anticipated mitigations

The anticipated mitigations when handling rubidium are:
- Wearing of suitable PPE (skin, face, eye protection, suitable clothing, respiration equipment where appropriate)
- Training of any personnel involved with any Rb handling (including rehearsal training)
- Two-person SOP with protocol checklist

6.4 Emergency procedures

If rubidium comes in contact with any personnel, then the response should be guided by the information provided in the MSDS [1][2] and an emergency SOP. This will likely include:
- Clear instructions for medical professionals if hospitalisation is required
- Suitable washdown facilities if large scale skin or eye wash out is needed
- Suitable tongs, tweezers or scrapers for removal of solid rubidium

7   Appendix A- ESPI Metals MSDS

SAFETY DATA SHEET

1   PRODUCT AND SUPPLIER IDENTIFICATION

Product Name: Rubidium
Formula: Rb

Supplier: ESPI Metals
                    1050 Benson Way
                    Ashland, OR 97520
Telephone: 800-638-2581
Fax: 541-488-8313
Email: sales@espimetals.com
Emergency: Infotrac 800-535-5053 (US) or 352-323-3500 (24 hour)
Recommended Uses: Scientific Research

2   HAZARDS IDENTIFICATION

GHS Classification (29 CFR 1910.1200): Substances and mixtures which, in contact with water, emit flammable gases, category 1, Skin corrosion/irritation, category 1B, Eye damage/irritation, category 1.
GHS Label Elements:

Signal Word: Danger
Hazard Statements: H260 In contact with water releases flammable gases which may ignite spontaneously, H314 Causes severe skin burns and eye damage.
Precautionary Statements: P223 Keep away from any possible contact with water, because of violent reaction and possible flash fire, P231+P232 Handle under inert gas. Protect from moisture, P260 Do not breath dust or fume, P264 Wash skin thoroughly after handling, P280 Wear protective gloves/protective clothing/eye protection/face protection, P301+P330+P331 IF SWALLOWED: rinse mouth. Do NOT induce vomiting, P303+P361+P353 IF ON SKIN (or hair): Remove/Take off immediately all contaminated clothing. Rinse SKIN with water/shower, P335+P334 Brush off loose particles from skin and immerse in cool water/wrap in wet bandages, P304+P340 IF INHALED: Remove victim to fresh air and keep at rest in a position comfortable for breathing, P305+P351+P338 IF IN EYES: rinse cautiously with water for several minutes. Remove contact lenses, if present and easy to do. Continue rinsing, P310 Immediately call a POISON CENTER or doctor/physician, P363 Wash contaminated clothing before reuse, P370+P378 In case of fire: Use class D metal extinguishing agent for extinction, do not use water, P402+P404 Store in a dry place. Store in a closed container, P405 Store locked up, P501 Dispose of contents/container in accordance with local, state or federal regulations.

3   COMPOSITION/INFORMATION ON INGREDIENTS

Ingredient: Rubidium
CAS#:   7440-17-7
%:   100
EC#:   231-126-6

4   FIRST AID MEASURES

General information: It is advisable to have tongs, tweezers, scrapers or some kind of implement on hand to remove bits of metal from skin or clothing in the event of an accident. Large amounts of water should be used to rinse or flood the area of contact as small amounts of water may do more harm than good.
INHALATION: Remove the victim to fresh air. Seek immediate medical attention.

INGESTION: Quickly wipe material from mouth and rinse with water. Do not induce vomiting. Seek medical attention immediately.

SKIN: Remove contaminated clothing if necessary. Brush off any visible solids. Wash the affected area with water for at least 15 minutes. Seek medical attention.

EYES: Immediately flush eyes with copious amounts of water, including under eyelids for at least 10-15 minutes. A victim may need assistance in keeping their eyelids open. A 5% solution of boric acid may be used to neutralize any remaining caustic. Seek immediate medical attention.

Most Important Symptoms/Effects, Acute and Delayed: May cause severe irritation and burns. See section 11 for more information.

Indication of Immediate Medical Attention and Special Treatment: This product is corrosive and reacts violently with water. Treatment should first remove as much of the material as possible as quickly as possible and then flush with very large quantities of water. Ingestion presents a singular problem as emesis may produce esophageal damage and/or aspiration damage; dilution with water or other water-containing materials may produce a reaction that exacerbates the corrosive activity. Consideration may be given to gastric lavage with a large diameter tube for removal of material and then dilution with large amounts of water. Esophagoscopy may be of assistance in this procedure and to assess extent of damage. Treatment is otherwise symptomatic and supportive.

5   FIREFIGHTING MEASURES

Extinguishing Media: USE CLASS D metal extinguishing agent such as Met-L-X, dry sand or graphite powder. If the chosen extinguishing agent is capable of absorbing moisture, provision must be made to keep it dry.

Unsuitable Extinguishing Media: DO NOT USE water, carbon dioxide or carbon tetrachloride.

Specific Hazards Arising from the Material: Violent reaction with water. Contact with water releases flammable gases. When heated to decomposition rubidium may emit toxic fumes of rubidium oxide and rubidium hydroxide.

Special Protective Equipment and Precautions for Firefighters: Full face, self-contained breathing apparatus and full protective clothing to prevent contact with skin and eyes. Material can reignite after fire is initially extinguished. Never leave extinguished fire unattended. Alkali metal fires may produce large quantities of white, opaque smoke that is caustic and may react with nearby materials. Flames may be practically invisible.

6   ACCIDENTAL RELEASE MEASURES

Personal Precautions, Protective Equipment, and Emergency Procedures: Wear appropriate respiratory and protective equipment specified in section 8. Isolate spill area and provide ventilation. Avoid breathing dust or fume. Avoid contact with skin and eyes. Eliminate all sources of ignition.

Methods and Materials for Containment and Cleaning Up: The material may ignite spontaneously in air. Burning material may release toxic fumes. Leave the area unless fitted with a self-contained breathing apparatus. Use completely dry non-sparking tools only. Do not use water for clean-up. Soda ash (powdered lime) or dry sand should be used to completely smother and cover any small spill that occurs. Sweep or scoop up. Place in a dry metal container equipped with a lid and replace the lid promptly. This can be done even if the metal is burning. With the lid in place oxygen will be excluded and the fire will go out.

Environmental Precautions: Do not allow to enter drains or to be released to the environment.

7   HANDLING AND STORAGE

Precautions for Safe Handling: It is strongly recommended that at least two persons be involved in the handling and use of this material. Rubidium should only be handled by trained personnel wearing proper protective clothing and equipment specified in section 8. Handle in an enclosed, controlled process under dry protective gas such as argon. Make certain that all equipment and tools to be used in handling are absolutely dry. Protect from air and moisture. Protect from heat, flame and sources of ignition. It is advisable to keep a container of dry sand or soda ash readily available in the work area. Keep combustible materials out of the work area. Avoid contact with skin and eyes. Avoid creating dust. Avoid breathing dust or fumes. Wash thoroughly before eating or smoking.

Conditions for Safe Storage, Including Any Incompatibilities: Protect from oxygen and water. Protect from moisture/humidity. Store under dry inert gas such as argon. Store in a sealed container. Storage containers should be labeled to indicate their contents. Containers should be inspected periodically to check for container integrity. Storage area should be free of combustibles and ignition sources. Do not store together with acids, oxidizers and halogens. See section 10 for more information on incompatible materials.

8   EXPOSURE CONTROLS AND PERSONAL PROTECTION

Exposure Limits: Rubidium
OSHA/PEL: No exposure limit established
ACGIH/TLV: No exposure limit established
Appropriate Engineering Controls: Handle in an inert gas such as argon. Handle in an enclosed, controlled process. Use local exhaust to maintain exposure at low levels. Whenever possible the use of local exhaust ventilation or other engineering controls is the preferred method of controlling exposure to airborne dust and fume to meet established occupational exposure limits. Do not use tobacco or food in work area. Wash thoroughly before eating or smoking. Do not blow dust off clothing or skin with compressed air. Prepare for the possibility of a fire. Keep extinguishing agents, tools for handling and protective clothing readily available.
Individual Protection Measures, Such as Personal Protective Equipment:
Respiratory Protection: Wear a NIOSH/MSHA approved respirator when high concentrations are present.
Eye Protection: Always wear approved chemical splash proof goggles.
Skin Protection: Rubber gloves, flame retardant protective work clothing.

9   PHYSICAL AND CHEMICAL PROPERTIES

Appearance:
Form: Solid
Color: Silver-white metallic
Odor: Not determined
Odor Threshold: Not determined
pH: N/A
Melting Point: 38.9 ℃
Boiling Point: 686 ℃
Flash Point: N/A
Evaporation Rate: N/A
Flammability: Flammable solid
Upper Flammable Limit: No data
Lower Flammable Limit: No data
Vapor Pressure: 1 mm at 297 ℃
Vapor Density: N/A
Relative Density (Specific Gravity):   1.532 g/cc
Solubility in H$_2$O: Decomposes
Partition Coefficient (n-octanol/water):   Not determined
Autoignition Temperature: No data
Decomposition Temperature: No data
Viscosity: N/A

10   STABILITY AND REACTIVITY

Reactivity: No data
Chemical Stability: Stable under recommended storage conditions.
Possibility of Hazardous Reactions: Rubidium reacts violently with water releasing flammable hydrogen gas.
Incompatible Materials: Water/moisture, steam, alcohols, oxidizers, oxygen, carbon dioxide, halogens, halocarbons, acids, liquid bromine, mercury, phosphorus, vanadium chloride oxide.
Hazardous Decomposition Products: Rubidium oxides, hydrogen gas, rubidium hydroxides.

11 TOXICOLOGICAL INFORMATION

Likely Routes of Exposure: Product as shipped does not present an inhalation or contact hazard. However subsequent operations may create dusts or fumes or debris which could be inhaled or come into contact with skin or eyes.

Symptoms of Exposure: Inhalation of dust will severely irritate the nasal cavity and respiratory tract. Ingestion will cause burns and perforations of the gastrointestinal tract. Severe thermal burns, corrosion and ulceration of the skin any eyes may occur on direct contact.

Acute and Chronic Effects: Rubidium reacts readily with moisture to form rubidium hydroxide which is severely corrosive to tissue. Corrosive materials are acutely destructive to the respiratory tract, eyes, skin and digestive tract. Eye contact may result in permanent damage and complete vision loss. Inhalation may result in respiratory effects such as inflammation, edema, and chemical pneumonitis. May cause coughing, wheezing, laryngitis, shortness of breath, headache, nausea, and vomiting. Ingestion may cause damage to the mouth, throat and esophagus. May cause skin burns or irritation depending on the severity of the exposure.

Acute Toxicity: LD50 intraperitoneal - mouse - 1200mg/kg

Carcinogenicity: **NTP**: Not identified as carcinogenic   **IARC**: Not identified as carcinogenic

To the best of our knowledge the chemical, physical and toxicological characteristics of the substance are not fully known.

12 ECOLOGICAL INFORMATION

Ecotoxicity: No data

Persistence and Degradability: No data

Bioaccumulative Potential: No data

Mobility in Soil: No data

Other Adverse Effects: Do not allow material to be released to the environment. No further relevant information available.

13 DISPOSAL CONSIDERATIONS

Waste Disposal Method:

Product: Dispose of in accordance with Federal, State and Local regulations.

Packaging: Dispose of in accordance with Federal, State and Local regulations.

14 TRANSPORT INFORMATION

UN Number: UN1423
UN Proper Shipping Name: Rubidium
Transport Hazard Class: 4.3
Packing Group: I
Marine Pollutant: No
Special Precautions: Warning, substances which, in contact with water, emit flammable gases.

15 REGULATORY INFORMATION

TSCA Listed: All components are listed.

Regulation (EC) No 1272/2008 (CLP): Substances and mixtures which, in contact with water, emit flammable gases, category 1, Skin corrosion/irritation, category 1B, Eye damage/irritation, category 1.

Canada WHMIS Classification (CPR, SOR/88-66): Substances and mixtures which, in contact with water, emit flammable gases, Skin corrosion/irritation, Serious eye damage/eye irritation.

HMIS Ratings: **Health**: 3   **Flammability**: 3   **Physical**: 2

NFPA Ratings: **Health**: 3   **Flammability**: 3   **Instability**: 2   **Special Hazard**: W

Chemical Safety Assessment: A chemical safety assessment has not been carried out.

16 OTHER INFORMATION

Prepared by: ESPI Metals
Revised/Reviewed: July 2015

8 Appendix B: System properties & constants

8.1 System properties

The following table defines the system properties used in safety calculations.

Vapour source operating pressure (mbar)	1.0E-06	mBar
Vapour source operating pressure (Pa)	**0.0001**	Pa
Chamber volume	79	l
Plasma cell volume	12	l
Total volume	**170**	l
Vapour source volume (m3)	**0.170**	m3
Rubidium in system	3	kg
Expansion chamber mass	103	kg
Chamber surface area	1098251	mm2
Plasma cell surface area	1277811	mm2
Total system surface area	**3474313**	mm2
Total system surface area	**34743.1**	cm2
Total system surface area	**3.474**	m2

8.2 Tunnel environment properties

The following table defines the experiment environment properties used in safety calculations.

Tunnel pressure	101325	Pa
Tunnel humidity	20	%
Tunnel temperature	20	C

8.3 Constants

Avagadros constant	6.02E+23	mol^{-1}
R constant	8.314	J/K mol
Atomic mass of rubidium	85.4678	g/mol
Atomic mass of argon	39.948	g/mol
Molecular mass of air	28.97	g/mol

Molecular mass of water	18.01528	g/mol
Density of air (@STP)	1.003	kg/m3
Density of argon (@STP)	1.7837	kg/m3
Oxygen content of air (@20C)	20.95	%
Maximum water content of air (@20C)	17.3	g/m3
Rubidium density (solid)	1532	kg/m3
Rubidium density (liquid)	1460	kg/m3
Rubidium heat of fusion	2.9	kJ/mol
Rubidium heat of vaporisation	69	kJ/mol
Rubidium specific heat capacity	31.06	J/molK
RbOH enthalpy of formation	-413.8	kJ/mol
Rb_2O enthalpy of formation	-339	kJ/mol
RbO_2 enthalpy of formation	-278.7	kJ/mol
Specific heat capacity (stainless steel)	510	$Jkg^{-1}K^{-1}$
Specific heat capacity (Rubidium)	335	$Jkg^{-1}K^{-1}$

9   Appendix C - Estimate of pressure change following leak

The following chart shows the theoretical pressure change if argon gas is introduced into the plasma cell and vapour sources via a 16mm port at atmospheric pressure (101325Pa). Analysis follows the same orifice plate assumptions as defined in section 5.2.3. This analysis suggests that the system could be filled with argon gas in approximately 5 seconds.

Flow of argon into vapour source through 16mm diameter flood port