Lunar Volatiles Package for Lunar Exploration: L-VRAP Definition

Final Presentation

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Agenda

- Introduction to L-VRAP Study [SB]
- Task 1: Literature & Requirements Review
  - Science Review [CTP]
  - Requirements Review [SB]
  - Technology Assessment [ADM]
- Task 2: Contamination & Surface Alteration Effects Analysis [JM]
- Task 3: L-VRAP Definition & Preliminary Design
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  - Scientific performance assessment [SB]
  - Lander & environment interfaces [SB]
  - Resource requirements [SB]
- Task 4: L-VRAP Development Plan [SB]
- Summary and Conclusions [SB/CTP]

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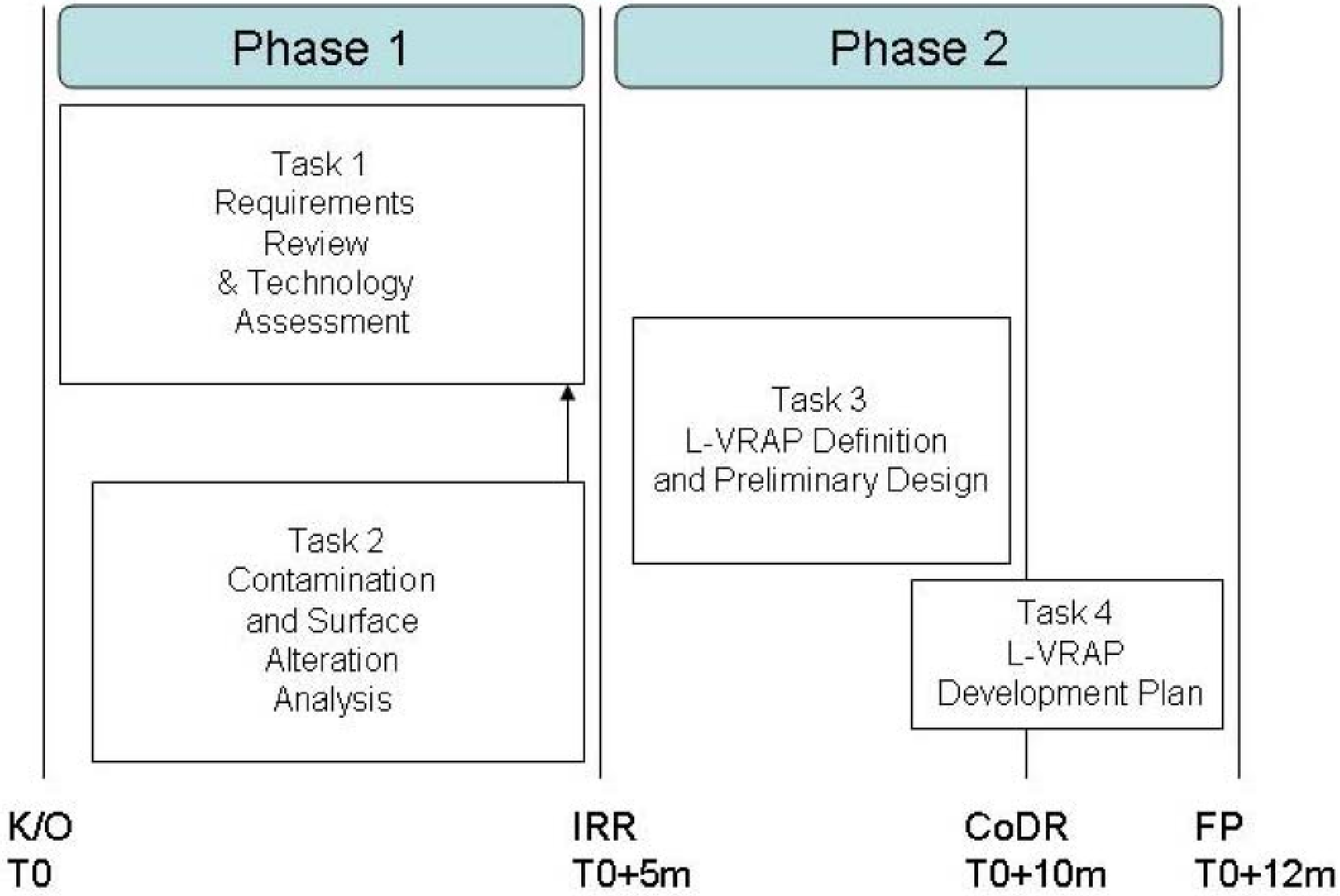
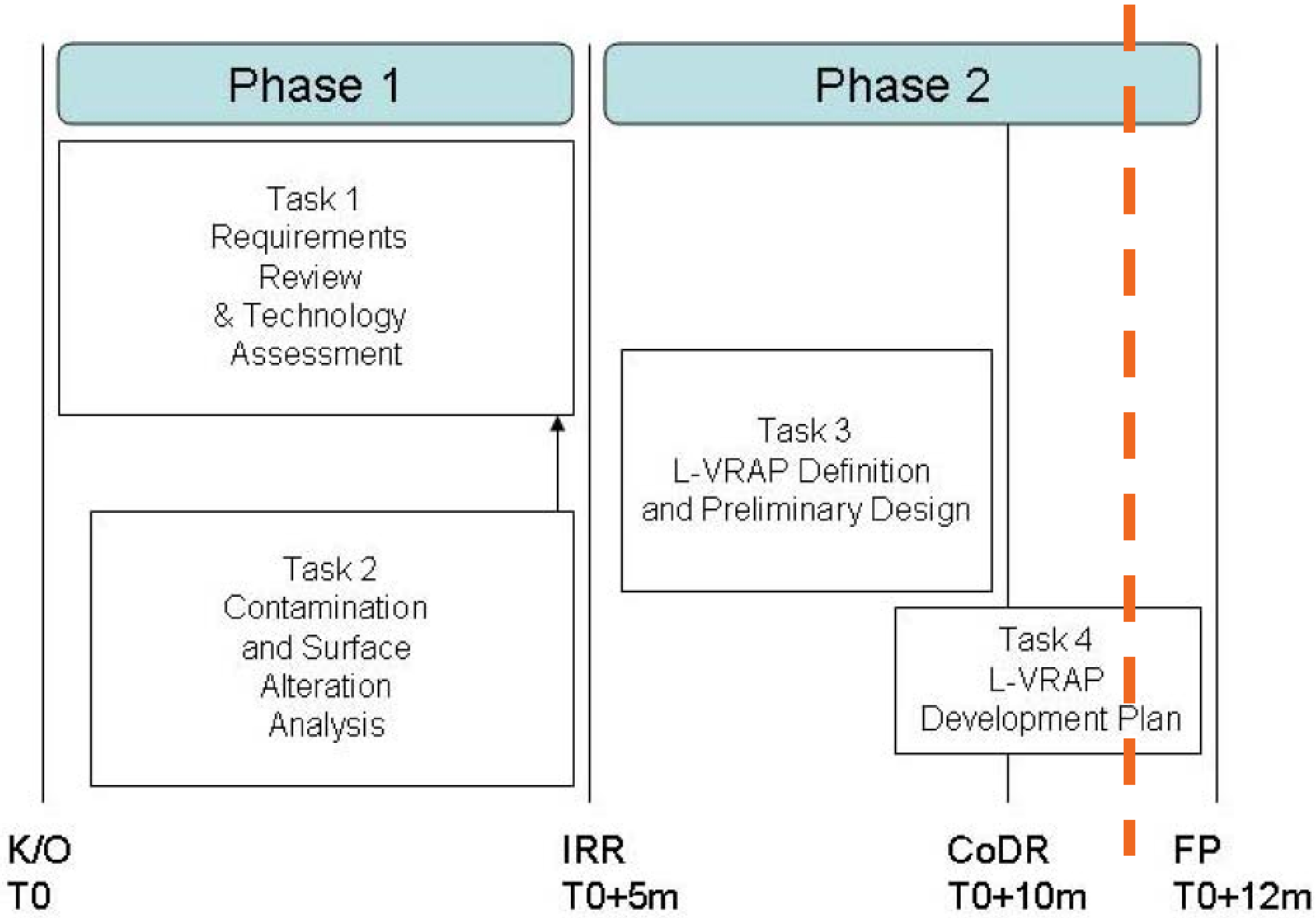
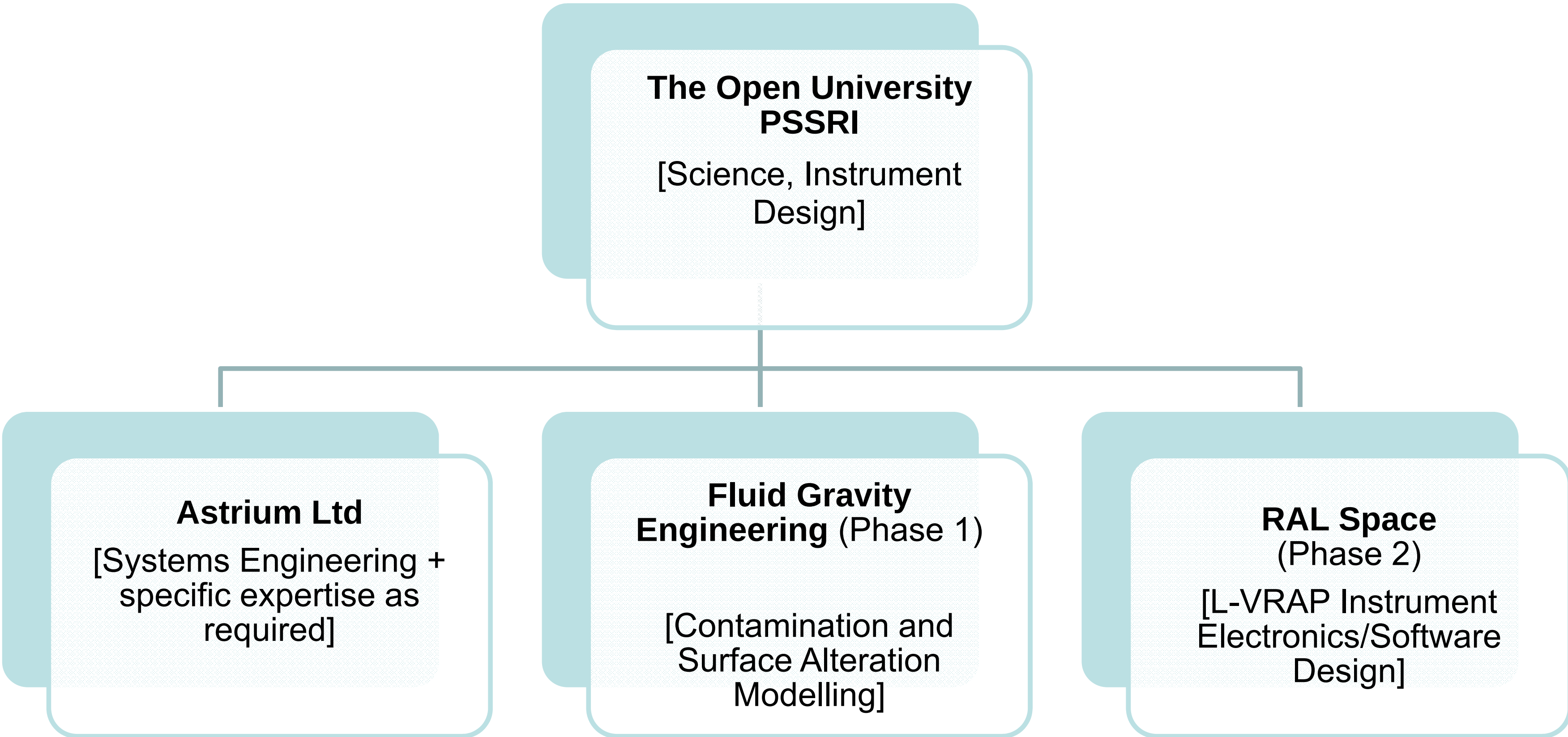
Introduction: L-VRAP Study Plan



Introduction: L-VRAP Study Plan



Introduction: Study Team



Open University

- Planetary & Spaces Sciences
  - UK's largest planetary science research group
- Laboratory-based analysis of extraterrestrial samples
  - Light element and stable isotope studies of meteorites and lunar samples (PI Apollo programme since 1968)
- Space flight instrumentation
  - Sample analysis packages based on mass spectrometry for Rosetta (Ptolemy) and Beagle 2 (GAP)

Fluid Gravity Engineering Ltd

- Landing site contamination from propulsive descent and landing:
  - High speed flow dynamics
  - Gas surface interaction
  - Two phase flow
  - Materials response

ASTRIUM
AN EADS COMPANY

- Systems engineering and interfaces
- Support in mechanical and thermal engineering
- Specific expertise in gas analysis instrumentation

RAL Space

Imaging Systems Division

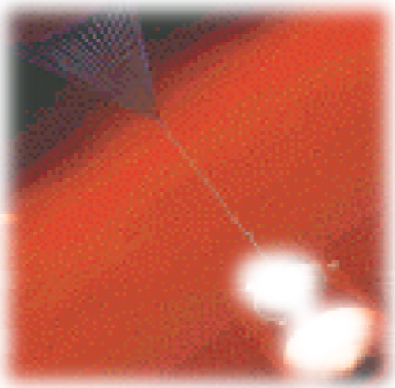
- Electronics Design, Manufacture, Test
- Optical Design, test.
- Sensors: Visible/EUV/X-ray/IR.
- Instrument System Design.

- Extensive experience in planetary missions, especially lunar science
  - SMART-1 (D-CIXS)
  - Chandrayaan-1 (C1XS)
- Rosetta Lander
- Huygens Lander

Comets

Rosetta

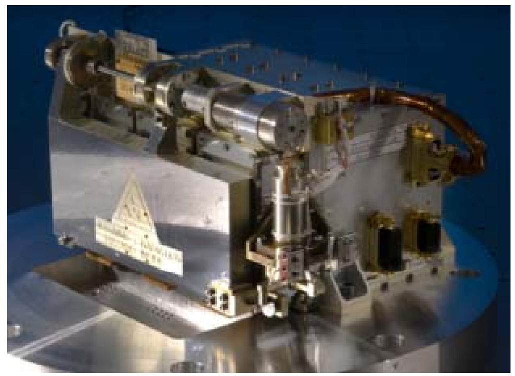
Outer SS



Cassini/Huygens

Moon

SMART-1



C1XS

Introduction: Documents

ESA Ref	Organisation responsible		L-VRAP Document Identifier	Milestone
DELIVERABLE DOCUMENTS				
TN1	OU	TN1: L-VRAP Requirements Specification and Concept Recommendation	AO6620-LVRAP-TN1	IRR (Issue 1); CoDR (Update)
TN2	OU	TN2: Instrument Technology Assessment Report	AO6620-LVRAP-TN2	IRR (Issue 1)
TN3	FGE	TN3: Contamination and Surface Alteration Report	AO6620-LVRAP-TN3	IRR (Issue 1)
TN4	OU	TN4: L-VRAP Preliminary Design Report	AO6620-LVRAP-TN4	CoDR
TN5	OU	TN5: L-VRAP Science performance report	AO6620-LVRAP-TN5	CoDR
TN6	OU	TN6: L-VRAP Development Plan	AO6620-LVRAP-TN6	FRev
TN7	OU	TN7: L-VRAP Payload Interface Document	AO6620-LVRAP-TN7	IRR (Draft); CoDR (Issue 1); FRev (Issue 2)
ES	OU	ES: L-VRAP Executive Summary	AO6620-LVRAP-ES	FRev
FR	OU	FR: L-VRAP Final Report	AO6620-LVRAP-FR	FRev
CA	OU	CA: L-VRAP Cost Assessment	AO6620-LVRAP-CA	FRev
OTHER DOCUMENTS				
n/a	OU	TN8: L-VRAP Inputs to Sampling System Requirements	AO6620-LVRAP-TN8	n/a
n/a	OU	TN9: L-VRAP Requirements List	AO6620-LVRAP-TN9	n/a
n/a	OU	TBC	Master Equipment List	n/a

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Volatile studies of the Moon

- Laboratory lunar sample analysis (rocks and soils from Apollo/Luna missions)
- Observations by orbiting spacecraft (Clementine, Lunar Prospector, Smart 1)
- Ground-based radar measurements
- Investigation using in situ instrument packages (ALSEP)
- Impacts studies (LCROSS)

Volatiles in/from lunar samples

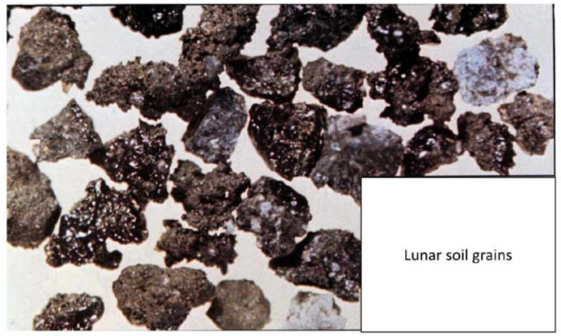
- Identified as "trapped"
  - Noble gases, methane, $C_2/C_3/C_4$ hydrocarbons
- Trapped and/or bound
  - Hydrogen, water, nitrogen
- Volatile after treatment ("volatile precursors")
  - Carbon monoxide, carbon dioxide, carbon associated with finely divided iron (C_{hyd}), sulphur dioxide

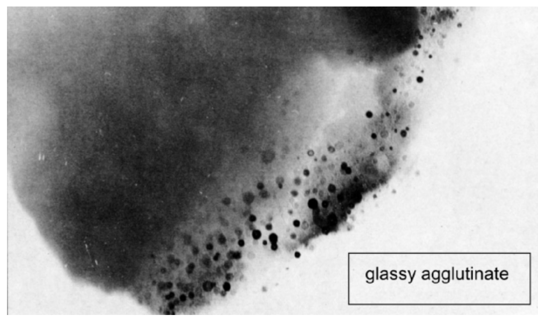
Origins of lunar volatiles

- Indigenous to the Moon
- Solar wind implanted atoms
- Comet and meteorite impacts

Location of volatiles

- Surface of grains
- Mineralogy/chemistry dependent
- Aggregated particles (agglutinates)





Abundance of volatiles

- From sample analysis - up to 100-150ppm by weight, again mineral and exposure history dependent, levels of contamination unknown
- Possibly several per cent water concentrated in polar “shaded” locations

Isotopic compositions

- Ill-defined because of contamination
- Some water recognised as solar wind origin because of absence of deuterium
- Nitrogen in lunar samples shows large incompletely explained isotopic variations

What is L-VRAP?

- A gas analysis package
- Qualitative, quantitative and isotopic analysis
- Solids, ices and gas samples
- Capable of operation on a static platform
- Needs a sample delivery and processing system
- Would prefer sub-surface samples

- Capabilities enhanced by:
  - mobile payload element for sample collection
  - laboratory studies of descent engine contamination

L-VRAP Overall Science Goals

- Quantify & establish origin of condensed volatiles (water, hydrogen, hydrocarbon species, others) and volatile precursors (CO, CO_2)
- Establish resources potential
- Investigate roles of solar wind and/or meteorite/cometary impacts
- Establish role of lunar atmosphere

L-VRAP for a lunar lander

- Objectives on a polar lander:
  - Extract, identify, quantify and origin of volatiles (particularly H_2O and forms of carbon) in lunar regolith
    - As a function of depth, time, illumination etc. lateral distance from lander if possible
    - Understanding of descent engine induced contamination
  - Identify and quantify species in lunar exosphere
    - As a function of source, time, illumination etc.
    - Long term monitoring of environmental change on the Moon

Enhancement by mobility

- A mobile payload element could assist L-VRAP by minimising contamination issues to allow genuine lunar processes by providing samples:
  - at some distance from lander
  - or places shielded from the exhaust plume (e.g. from behind rocks)
  - from shaded areas to aid study of effects due to sun illumination
  - or disturbed surfaces regolith to study natural release of volatiles into the exosphere

Science Review - Summary

State of knowledge w.r.t. lunar polar volatiles

Species	*Concentration and comment*
H_2	1 cm^3/gram Definitely present in Apollo samples
H_2O	Present exact amount unknown because of contamination. Orbiter studies predict % levels, Apollo samples ppm
C	Up to 150ppm but contaminated in returned samples even the so-called lunar environment special container samples
CH_4	Up to 5 ppm bulk soils not a contaminant much greater amounts – some higher h/cs up to C_4 in finer grains and agglutinates
C_{Hyd}	Up to 25 ppm bulk soils identified. Higher concentrations in magnetic soil fractions (agglutinates and micro breccia). The species measures carbon in solid solution in iron metal and is contamination free.
CO, CO_2	Both liberated by heating. Amounts up to 100ppm relative abundance is variable result probably compromised by contamination and physical state of the carbon unknown probably as implanted individual atoms.
N_2	Undoubtedly present as individual atoms but released as N_2 Other forms of nitrogen not identified because extraction method causes chemical changes. Probably contaminated by descent engine exhaust products in Apollo samples. Total N concentration up to 100 ppm.

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Requirements: requirements tree

SCIENCE Requirements SCI-0xxx		
ACCOMMODATION, INTERFACE and ENVIRONMENTAL requirements AIE-2xxx		
INSTRUMENT requirements INS-4xxx		
	Atmospheric Sample Inlet Requirements INS-41xx	
	Solid Sample Inlet and Characterisation Requirements INS-42xx	
	Initial volatile characterisation Requirements INS-43xx	
	Sample Processing Requirements INS-44xx	
	Sample Analysis Requirements INS-45xx	
LUNAR LANDER PLATFORM Requirements LLP-6xxx		
	Payload Servicing Requirements LLP 61xx	
	Contamination Requirements 63xx	
		Contamination Requirements for AIV 632x
		Contamination Requirements for Launch 634x
		Contamination Requirements for Cruise 636x

Science requirements

High Priority Requirements:

RQ 1 Volatiles shall be liberated from lunar regolith.
RQ 2 The species of volatiles liberated shall be identified.
RQ 3 The quantities of volatiles extracted shall be determined.
RQ 4 The chemical and isotopic abundances and concentrations of those species in the lunar regolith shall be determined.
RQ 5 Concentrations of H_2O and OH on the surface shall be measured for concentrations greater than 10 ppm.

Medium Priority:

RQ 6 Measure the number density and composition of neutrals in the lunar exosphere (nominally to include the following species: Ne, Ar, H, He, Na, K, CH4, H2O, OH, CO2, NH3).
RQ 7 Measure the number density and composition of ions in the lunar exosphere (nominally to include the following species: Ne, Ar, H, He, Na, K, CH4, H2O, OH, CO2, NH3).

Science Requirements - drivers

- RQ1: Liberation of volatiles vs in-situ analysis
- RQ2: Identify a wide range of liberated volatiles
- RQ3: Quantification of extracted species
- RQ4: relate above measurements back to the starting materials in the regolith (extraction efficiency, discrimination, losses, contamination…)
- Key question:
  - Is the aim to understand what has been liberated? Or what was there in the first place? Or both?
    - volatiles can be created during the process of liberation
    - volatiles can be changed during the process of liberation
- → **"Science to enable exploration"**

- RQ5: H_2O and OH in top ~1mm is for ground truth wrt orbital measurements
- → **driver on sample collection system**

- RQ6: exospheric neutrals are different analytical challenge to regolith volatiles
- RQ7: exospheric ions are different analytical challenge to exosphere neutrals

Accommodation & interface requirements

RQ 8 The L-VRAP shall be capable of satisfying the science requirements at a landing site post-landing, which has been exposed to an engine exhaust associated with the following Lander characteristics:

- Propulsion sub-system: MON/MMH bi-propellant system
- Terminal descent carried out with a single 500N main engine (EAM-derived), accompanied by up to 6 x 220N assist engines – all firing until engine cutoff which is triggered when the lander footpads contact the ground (minimum height of engines when firing = 0.5m)

RQ 9 Maturity margins shall be applied for mass calculations to take into account the technology maturity of the constituting units. The maturity margin of a unit or equipment shall be calculated as follows:

- 5% for recurrent equipment
- 10% for modified equipment
- 20% for new development

RQ 10 The total mass conceived for the package (including margins) shall be < 6 kg.

Accommodation & interface requirements

RQ 11 Data compression and storage shall be assumed to be performed by the lander platform.

RQ 12 L-VRAP shall provide its own instrument control.

RQ 13 The L- VRAP package shall include redundancy in data and power interfaces to the lander.

RQ 14 Power interface to the lander shall be 28V DC.

RQ 15 L- VRAP shall provide its own DC-DC conversion.

RQ 16 L-VRAP shall provide its own thermal control.

RQ 17 L- VRAP shall be attached to the Lander external surface and shall be exposed to the environment defined in AD1.

Accommodation and interface requirements - drivers

- RQ 8: Contamination and surface alteration from Lunar Lander engine exhausts
- RQ10: Mass
- RQ12: L-VRAP to provide own instrument control
- RQ16: L-VRAP to provide own thermal control
- RQ17: L-VRAP to be attached to Lander external surface

Science Requirements SCI-0xxx

REQUIREMENT ID	Type /Status	Requirement	Comment (T)	SOURCE/ORIGIN Doc & Reqt ID	Requirement
SCI-0100-R	R(U)	Volatiles and/or their volatile precursors shall be liberated from lunar regolith samples from known locations		SoW RQ1	Volatiles shall be liberated from lunar regolith samples
SCI-0200-R	R(M)	L-VRAP shall determine the chemical identity of species comprising >5% of the total volatile content of the volatiles liberated from lunar regolith samples obtained from known locations	It is desirable to constrain the number of species to be identified by setting a relative abundance threshold below which it is not necessary to identify all species liberated.	SoW RQ2	The species of volatiles liberated shall be identified
SCI-0300-R	R(M)	L-VRAP shall provide a quantitative measure of the total volatile yield (accuracy TBD) and the yields for individual volatiles (accuracy TBD) as a function of the sample size. Where appropriate it should quantify any precursor within the regolith which produces a volatile during the extraction process to an accuracy of (TBD)	The accuracy target should be derived from accuracy requirements concerning ISRU viability. A value of +/- 50% is suggested as appropriate to future ISRU aspirations?	SoW RQ3	The quantities of volatiles extracted shall be determined
SCI-0400-R	R(M)	VRAP shall determine the isotopic abundance of volatile species lunar regolith samples from known locations	The accuracy target shall be derived from science recuirements	SoW RQ4	The chemical and isotopic abundances and concentrations of those species in the lunar regolith shall be determined
SCI-0450-R	R(M)	L-VRAP shall determine the isotopic composition of hydrogen in volatile species in lunar regolith samples from known locations, δD, with an accuracy of 100‰	**To enable distinguishing primary sources of lunar hydrogen as Solar Wind is -1000 per mil; terrestrial water is -100 per mil; cometary organics +1000 per mil**	SoW RQ4	The chemical and isotopic abundances and concentrations of those species in the lunar regolith shall be determined
SCI-0460-R	R(M)	L-VRAP shall determine the isotopic composition of carbon in volatile		SoW RQ4	The chemical and isotopic abundances and concentrations of those species in

Solid Sample Inlet and Characterisation Requirements - INS-42xx

REQUIREMENT ID	Type/Status	Requirement	Comment (T)	SOURCE/ORIGIN Doc & Reqt ID
INS-4210-R	**D**	The sample inlet system shall determine the mass of regolith sample with an accuracy of ±20%	**Target value for overall quantitation is +/50%.**	**SCI-0300-R**
INS-4230-G	**D**	The sample inlet system should image the regolith sample	Helps characterise sample and gain an estimate of mass	**SCI-0300-R**
INS-4240-R	**D**	L-VRAP shall extract volatiles from regolith samples by heating to +1200°C (TBC)	The proposed system will extract volatiles by heating	SCI-0100-R
INS-4245-R	**D**	The Sample inlet system shall be cabable of analysing at least 10 samples	Potential samples: 2 from surface top 1mm, depth profile at 1, 2, 3, 4, 5, 7 and 10 cm (TBA), changing illumination conditions	**SCI-0100-R** **SCI-0500-R** **AIE-2080-R**
INS-4250-G	D	The sample inlet system should measure the pressure of extracted **volatiles** with **a resolution** of 1mbar	Assume 10% of 100mg sample is water, sample inlet volume $12cm^3$ gives pressure of 1000mBar. Capable of measuring 200ppm water at ±50%	**SCI-0100-R** **SCI-0300-R**
INS-4260-R	D	The sample inlet system shall be capable of heating to at least to +100°C	Required to measure water	**SCI-0100-R**
INS-4270-R	D	The sample inlet system shall have a water trap	Necessary to remove high concentrations of water so other volatiles can be identified	**SCI-0200-R** **SCI-0300-R**
INS-4280-R	D	The sample inlet system shall have a sample aliquoting system	Required to reduce the pressure of high concentrations of volatiles low enough for the sample inlet mass spectrometer.	**SCI-0200-R** **SCI-0300-R**

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Technology Assessment

- Aim: to identify candidate technologies to meet scientific goals (and environmental constraints) with appropriate TRL
- Aim is for TRL5 by mid 2014 for an assumed 2018 mission
- Involved a top level review of the various analytical technologies, followed by more detailed assessment and trade-off

Technology Top Level Review

- Raman
  - Measures chemical bonds
  - OH and H_2O distinguished
- Infrared camera.
  - Large area, surface volatiles
- Infrared microscope (Rosetta – ÇIVA)
  - ATR (Attenuated Total Reflection) (ESA study - WatSen)
  - Mineralogy of sample.
- LIBS (Laser induced breakdown spectroscopy) (MSL – ChemCam; ExoMars – Pasteur)
  - Sample vaporised up to 7m distance.
  - Elements detected (isotopes?)
- Mass Spectrometry (e.g. Rosetta – Ptolemy; Phoenix – TEGA)
  - Many types tailor to requirement specifications and constraints. Chemical and isotopic composition. Samples need to be collected.

Technology Assessment

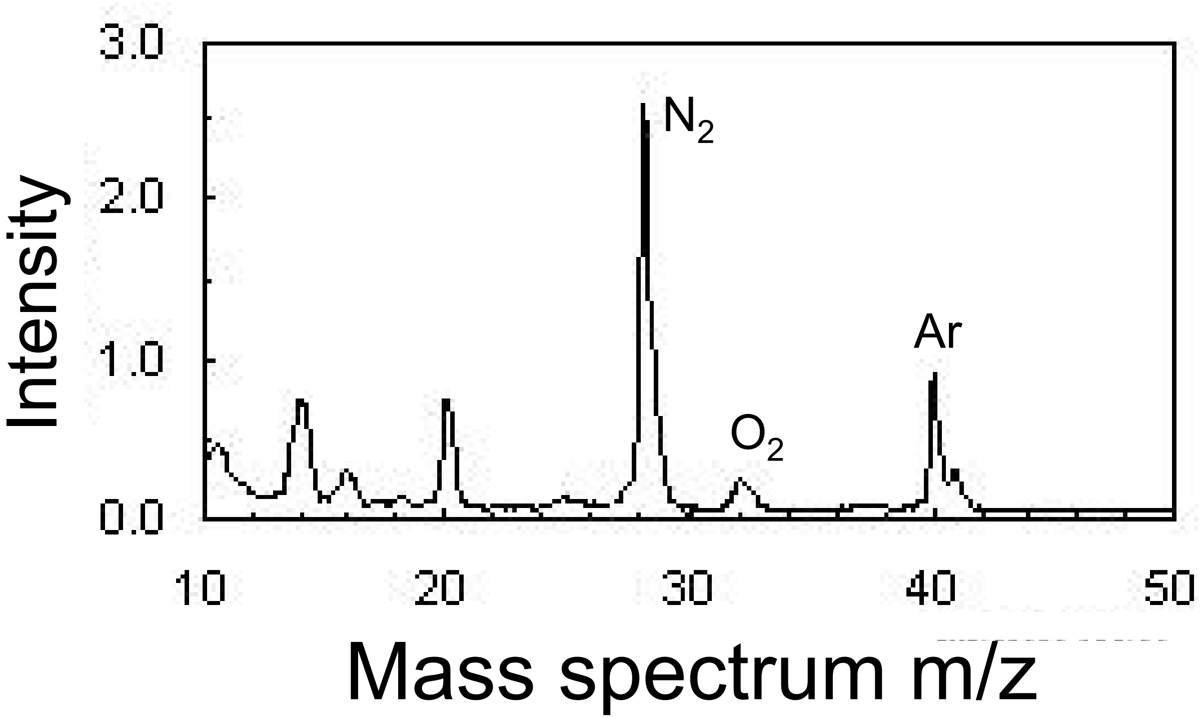
Requirement (High Priority)	Raman	Infrared camera	Microscopy	LIBS	Mass Spectrometry
Liberate Volatiles	0	0	0	3	3
Identify Volatiles	3	1	2	0	3
Determine Quantities	1	1	1	2	2
Measure Isotopes	0	0	0	1	3
Measure water of surface	3	3	3	2	2
Requirement (Medium Priority, 50% weighting)					
Measure Exosphere Neutrals	0	0	0	0	3
Measure Exosphere Ions	0	0	0	0	2
Total	**7**	**5**	**6**	**8**	**15.5**

Mass Spectrometry – Basic eq.

$$F = ma$$

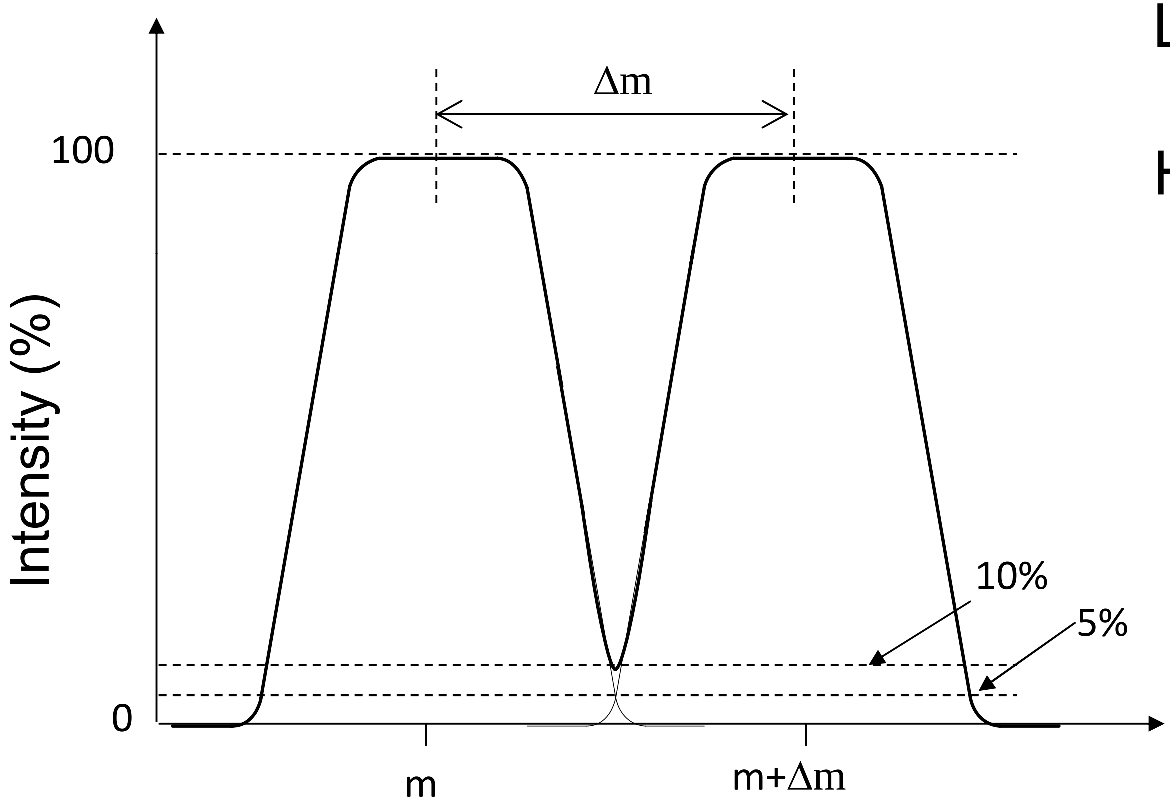
$$F = z\,(E + v \times B)$$

$$m/z = (E + v \times B)/a$$



Mass Resolution

Mass resolution = $M/\Delta M$



Low mass resolution <200

High mass resolution > 1000

High Mass Resolution

DH	3.021927	-
H_3	3.023475	1950
^{3}He	3.016030	508
^{13}C	13.003354	-
^{12}CH	13.007825	3030
^{15}N	15.000108	-
^{14}NH	15.010899	1390

^{17}O	16.999133	-
^{16}OH	17.002740	4713
^{18}O	17.999160	-
^{17}OH	18.006885	2300
^{16}OD	18.009017	1826
$^{12}C^{16}O$	27.994915	-
$^{14}N_2$	28.006148	2500

Resolve isotopes

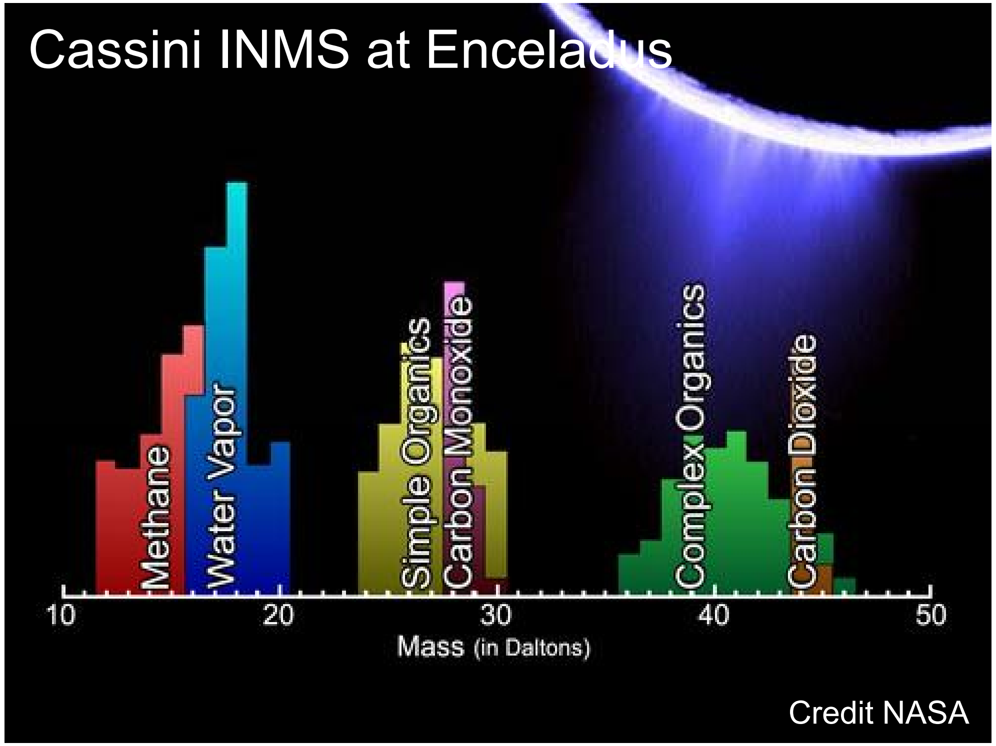
Resolve isobaric interferences

Low Mass resolution

Cannot resolve isobaric interferences

- De-convolution

Molecular peak (m/z)	Peak intensity relative to main molecular peak (m/z 28) = 100	
	Carbon monoxide (CO)	Nitrogen (N_2)
29	1.1	0.7
28	100.0	100.0
16	2.1	0.0
14	0.0	13.9
12	4.6	0.0



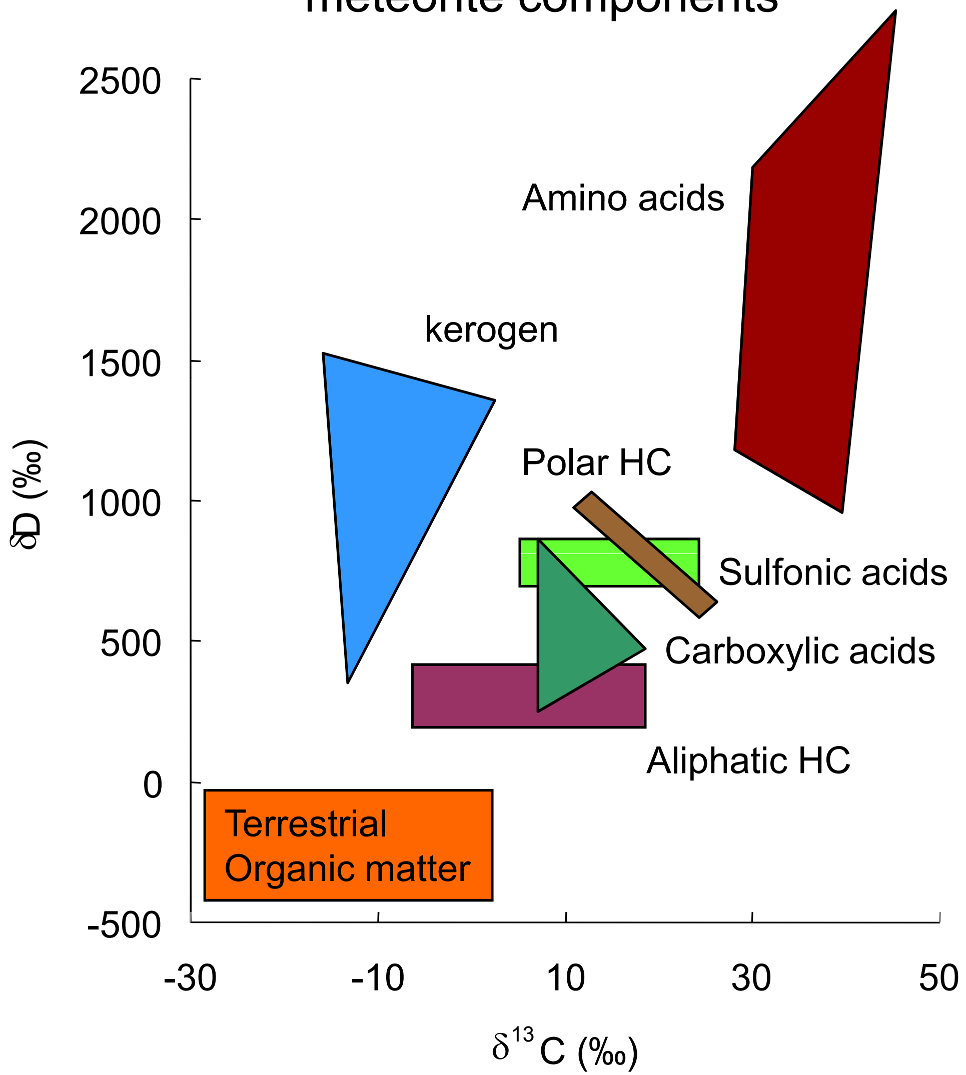
- Separate components before mass spectrometer

Isotopes – Primary source

Lunar D/H_2

- Solar wind >0.000001
- Terrestrial ~0.000160
- Cometary <0.000320

Carbon and hydrogen isotope ratios of meteorite components



- Current knowledge
  - bulk isotopic analysis (averages)
- D-enrichment is an unequivocal signature of the survival of interstellar material

Isotopes – Secondary fractionation

Mass fractionation

- Diffusion
- Evaporation

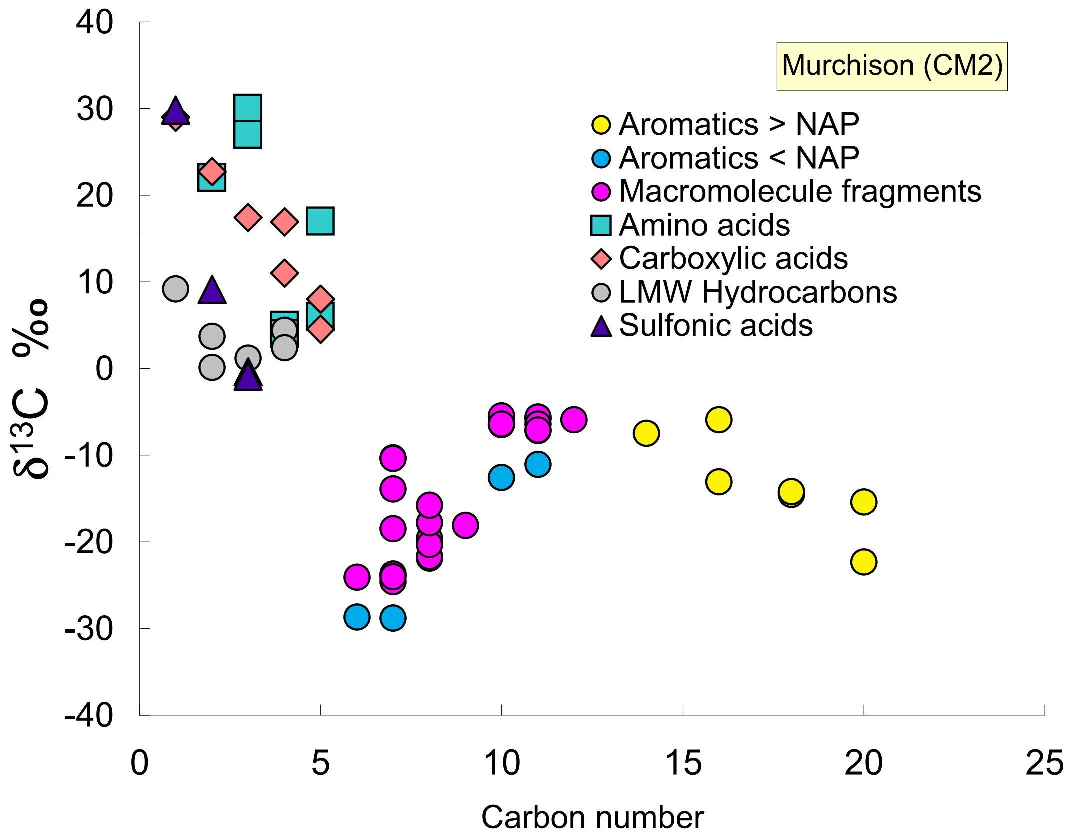
Chemical fractionation

Delta notation

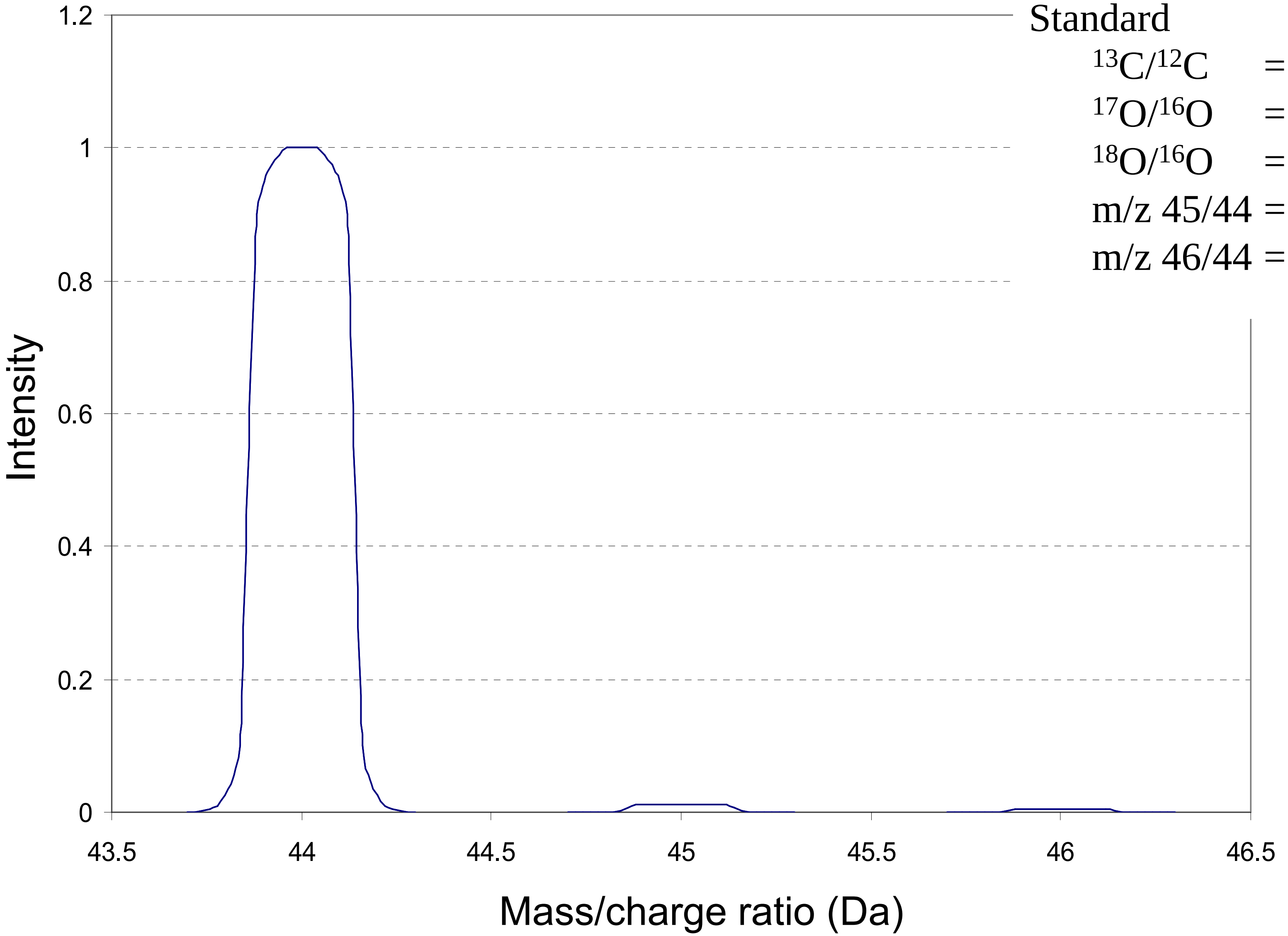
$$\delta^H I = \left(\frac{\left({}^H I / {}^L I \right)_{sample}}{\left({}^H I / {}^L I \right)_{reference}} - 1 \right) \times 1000‰$$

12C bonds preferably made and broken
Carboxylic acids formed by solid phase reactions with carbonates

Organics in meteorites



Isotopes CO_2



Standard

$^{13}C/^{12}C$ = 0.01100000

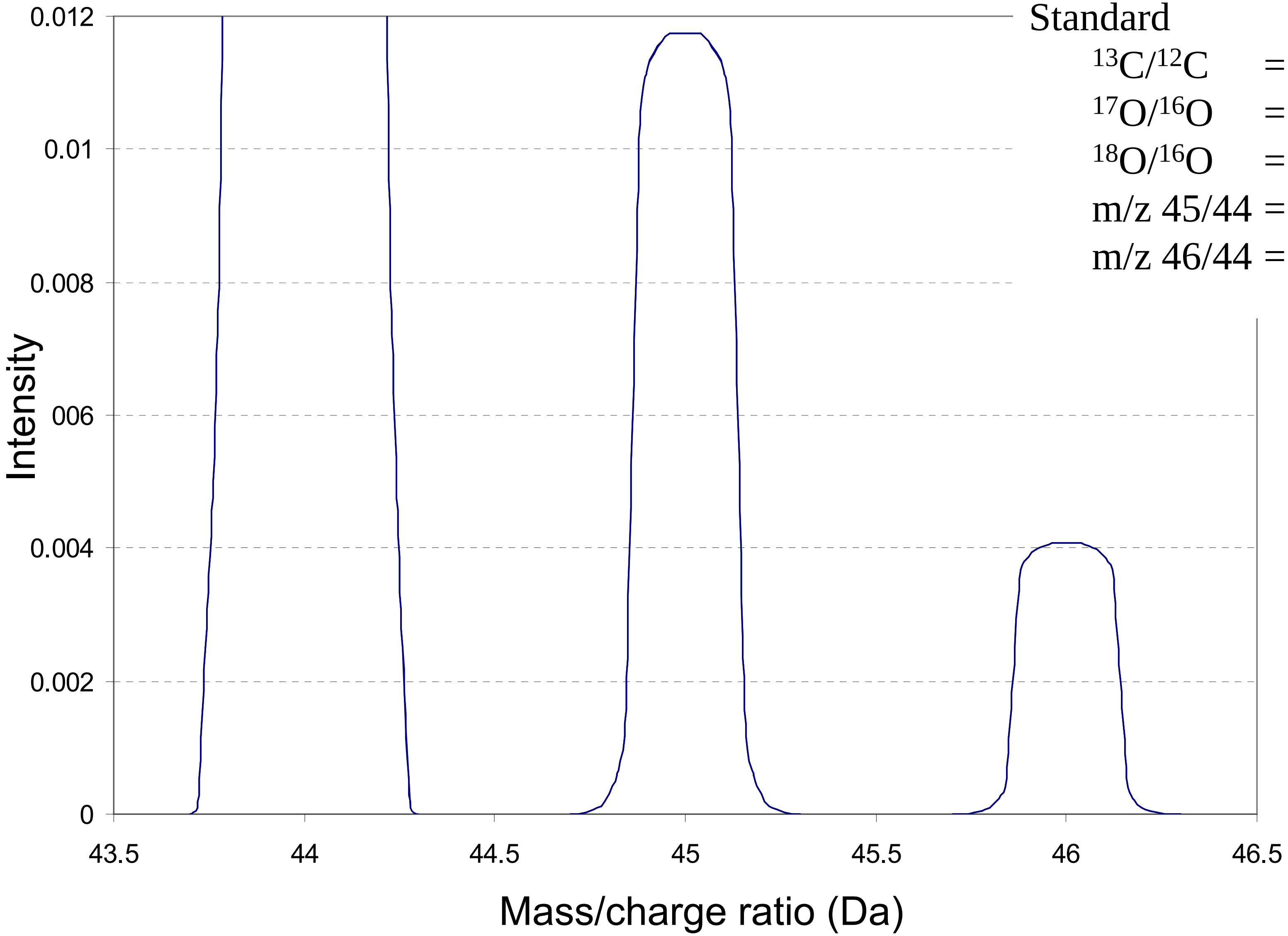
$^{17}O/^{16}O$ = 0.00037000

$^{18}O/^{16}O$ = 0.00408000

m/z 45/44 = 0.01174000

m/z 46/44 = 0.00408000

Isotopes CO_2 - Intensity × 100



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m/z 45/44	= 0.01174000
m/z 46/44	= 0.00408000

Intensity × 10000

Standard

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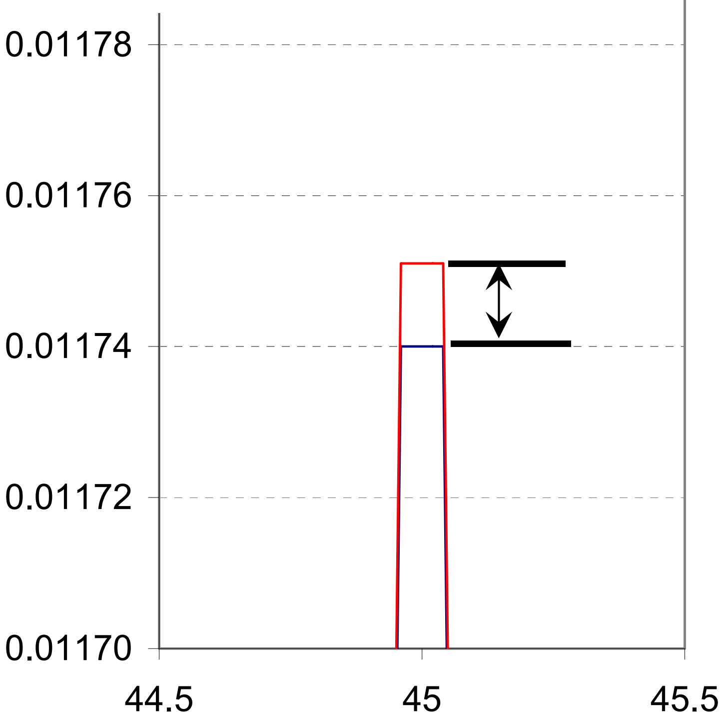
$^{18}O/^{16}O$ = 0.00408000
m/z 45/44 = 0.01174000
m/z 46/44 = 0.00408000

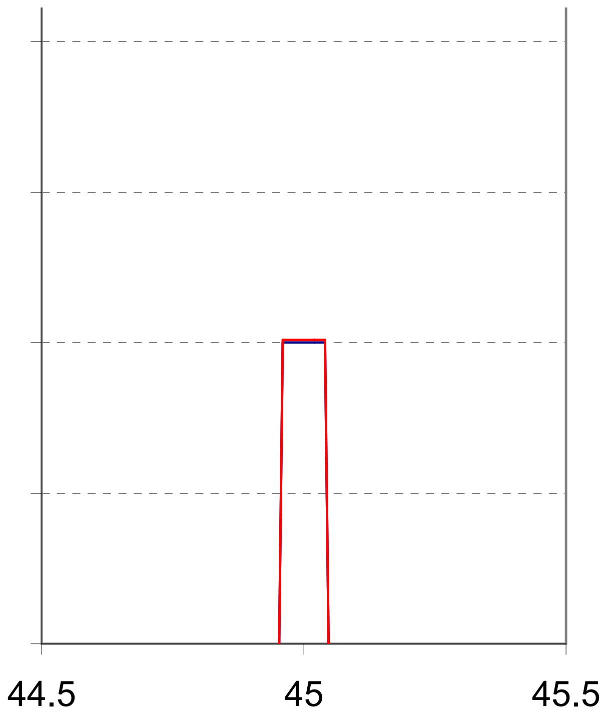
Sample 1 $\delta^{13}C$ +1‰

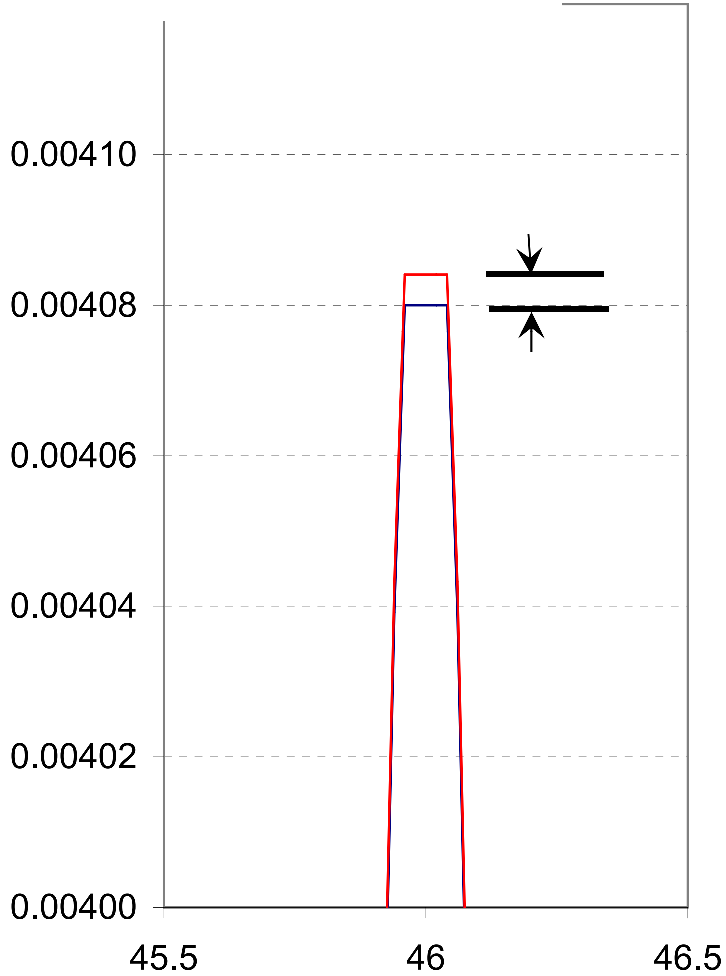
$^{13}C/^{12}C$ = 0.01100000
$^{17}O/^{16}O$ = 0.00037000
$^{18}O/^{16}O$ = 0.00408000
m/z 45/44 = 0.01175100
m/z 46/44 = 0.00408000



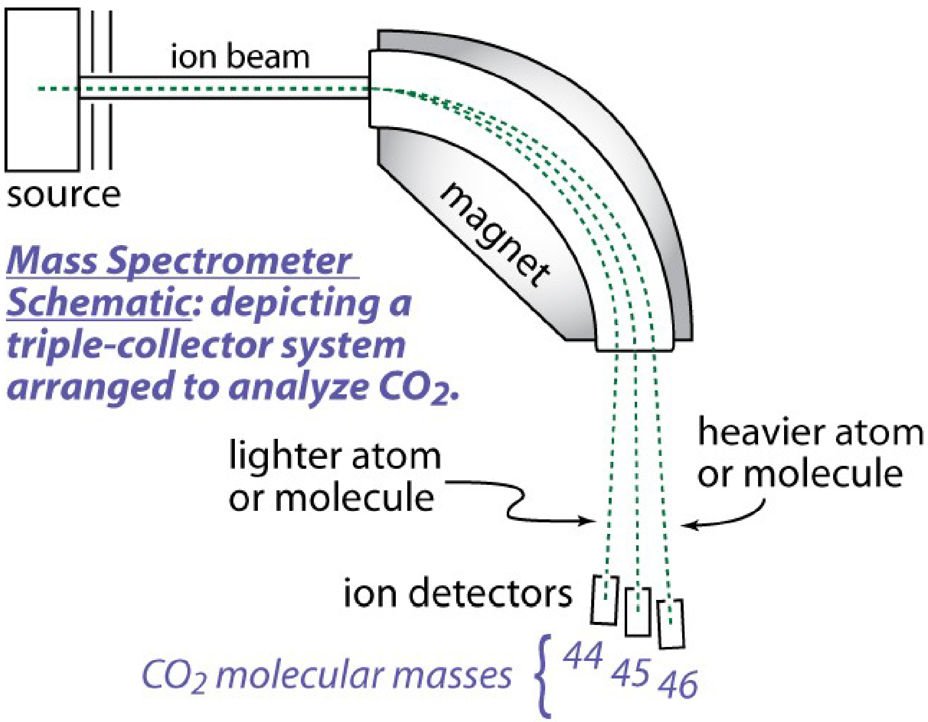
Sample 2 $\delta^{18}O$ +1‰

$^{13}C/^{12}C$ = 0.01100000
$^{17}O/^{16}O$ = 0.00037019
$^{18}O/^{16}O$ = 0.00408408
m/z 45/44 = 0.01174038
m/z 46/44 = 0.00408408





Magnetic sector



$$m/z = \frac{B^2 r^2}{2V}$$

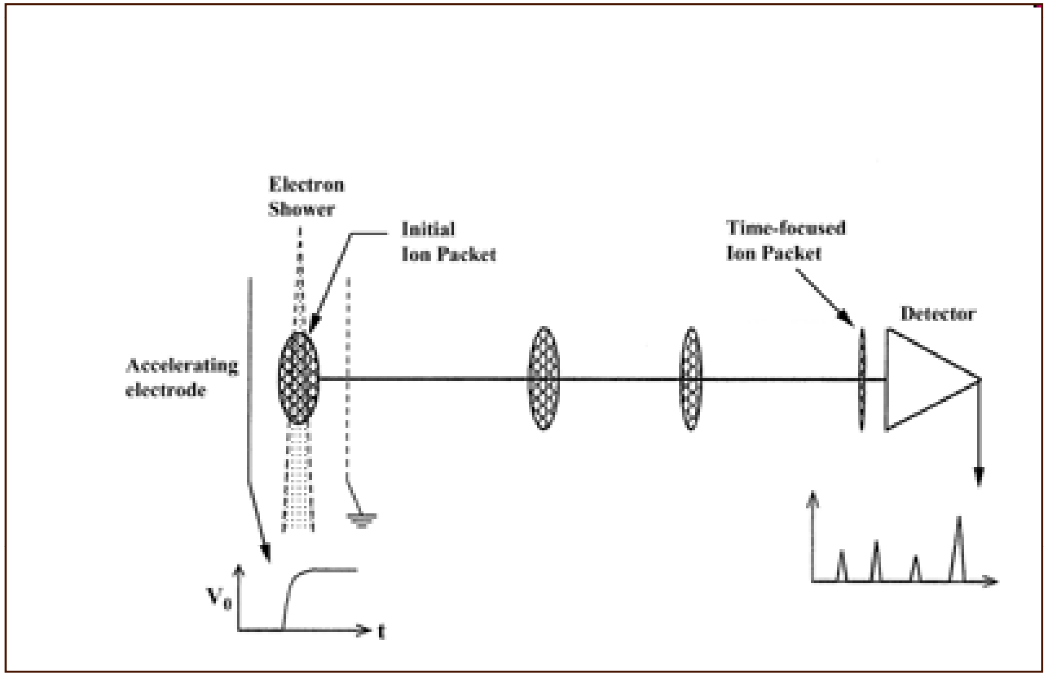
Simultaneous collection
– separate ions in space
Faraday cup collectors
Flat topped peaks
No high frequency electric fields

Slow scan speed
Heavy magnet

Chemical processing
Reference material

Space heritage:
Apollo 17 LACE
Phoenix MS
Beagle2 GAP

Time Of Flight



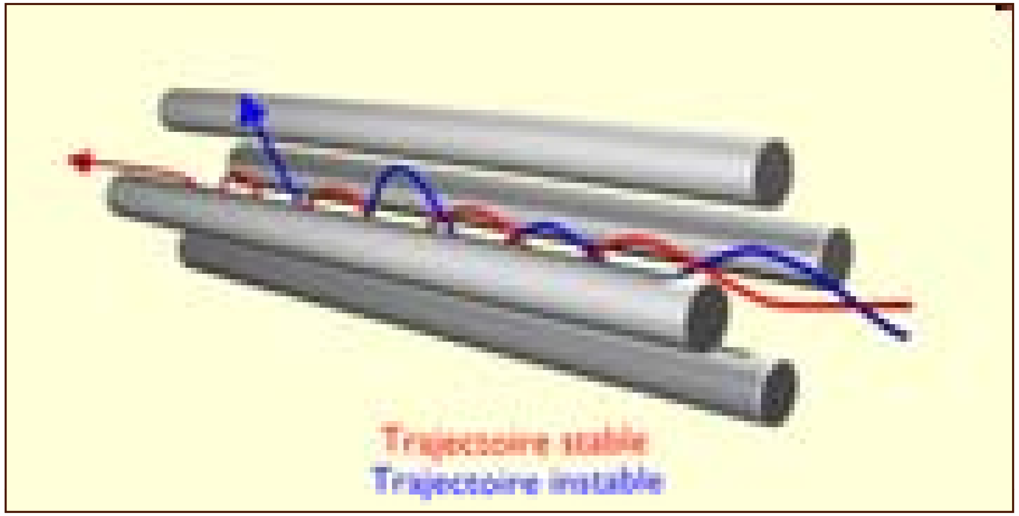
$$m / z = \frac{2VL^2}{t^2}$$

High mass resolution
Fast scanning speed
No magnetic fields
No high frequency electric fields

Ions detected as high intensity bunches, not suitable for accurate isotope analysis

Space heritage:
Rosetta – ROSINA & COSAC

Quadrupole



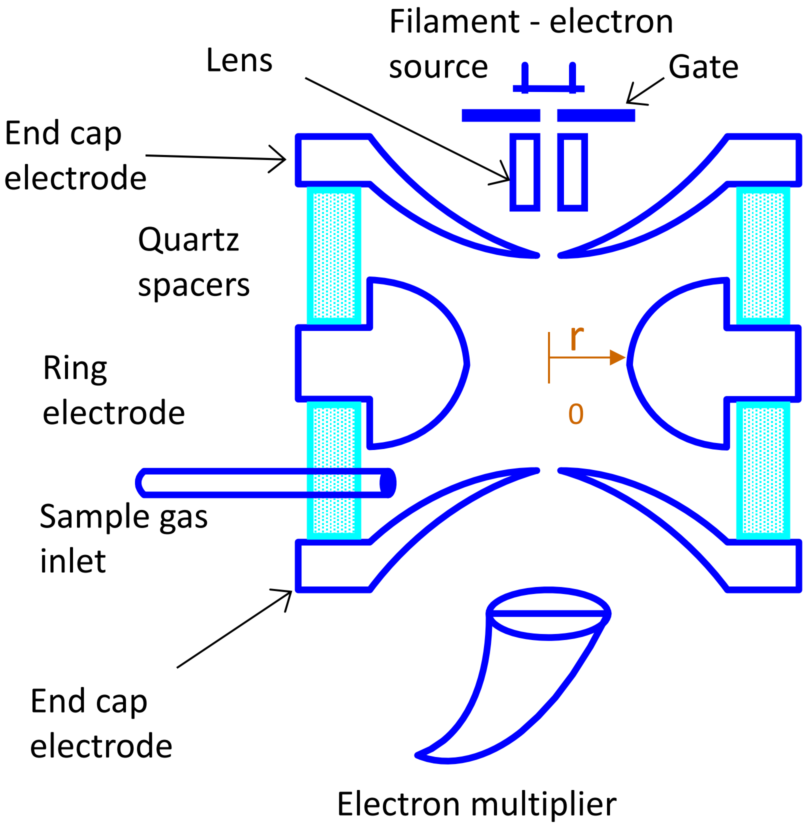
Ions subjected to a combination of DC and AC electric fields as they travel towards detector
Only ions within narrow mass/charge range stable

Operate in poor vacuum conditions 10^{-5} mbar
No magnetic fields
Can select single mass (single ion monitoring)
– Faraday detectors possible
High mass range

Stable mass range ~0.3 amu
High frequency (MHz) electric fields

Space heritage:
Curiosity – SAM

Ion Trap



$$m / z = \frac{4eV}{r_0^2 \Omega^2}$$

Can operate in poor vacuum 10^{-4} mbar
Ions trapped
- pseudo simultaneous detection

Small compact device
No magnetic fields

High frequency (MHz) electric fields
Maximum mass ~600 Da
Ions below storage voltage not detected
Maximum ions trapped 105
Ion-molecule reactions

Space heritage:
Rosetta – Ptolemy

Orbitrap

High mass resolution M/ΔM ~100000
Ions trapped
- pseudo simultaneous detection

Small compact device
No magnetic fields
No high frequency electric fields

Good vacuum required 10^{-10} mbar
Maximum ions trapped 5×10^{4}
Ions need to be focussed into trap
- additional hardware

Ions trapped by static electric fields
Ions detected by current imaging (FFT)

Space heritage:
None – TRL3

Sample Processing

No Processing

- simple samples or
- high mass resolution

Gas Chromatography

- Use GC to separate complex mixture
- Identification requires fast scanning MS
- Hardware – Injectors, gas tanks pressure regulation

Sample Processing

Static sample processing

- Removal of the main constituents of the sample by chemical or physical means to increase the relative concentration of the target molecule
  - Molecular sieve to remove water
  - Cold trap to remove CO_2
- Removal of isobaric interferences by chemical conversion of the interfering molecules to molecules with a different mass from the molecules on interest
  - E.g. Remove CO from N_2 by combustion with CuO
  - Hardware – Chemical reactors, heaters, chemical reagents

Isotope analysis – reference gases

Sample Processing

	Gas Chromatography	Static Gas Processing	
		Dynamic MS	Static MS
Minimum sample size	1 ng	500 ng	0.1 ng
Isotopic precision (CO_2)	1‰	0.02‰	1‰
Complex organics	Very good	Poor	Poor
Identify volatiles	Very good	Good	Poor
Carbon dioxide	OK	Very Good	OK
Nitrogen	Poor	Very Good	Good
Methane	Very poor	Good	Very Good
Noble gases	Very poor	Good	Very Good
Hydrogen	Very poor	Very Good	Not possible
Specific Hardware	Carrier Gas tanks Pressure regulator	Change-over valve	Gate valve

Space Heritage

Name	Mission	Target	Mass (kg)	Analyser	M/Z range	Sample handling
LACE	Apollo 17	Moon	9.1	Magnetic sector	1-110	No
GC-MS	Viking	Mars	15	Magnetic sector	12-220	Yes
TEGA	Phoenix	Mars	11.4	Magnetic sector	1-140	Yes
SAM	Curiosity	Mars	~30	Quadrupole	2-535	Yes
GAP	Beagle 2	Mars	5.7	Magnetic sector	2-150	Yes
MOMA	ExoMars	Mars	6.1	Ion trap	10-2000	Yes
Ptolemy	Rosetta	Comet	4.5	Ion Trap	10-140	Yes
COSAC	Rosetta	Comet	4.9	Time of Flight	1-300	Yes
Rosina	Rosetta	Comet	22.0	Time of Flight Magnetic Sector	1-300 12-150	No No

Summary

Mass Spectrometer systems ~6kg possible

High precision isotope analysis	→	Magnetic sector MS
Simple chemistry	→	Static processing
H_2, accurate CO_2	→	dynamic MS inlet
ng samples (Noble gases, CH_4, N_2)	→	static MS inlet
Chemical identification	→	fast scanning MS (Quad, ion trap, ToF)

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2nd July 2012

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Lunar Regolith Contamination and Surface Alteration from Propulsive Descent and Landing

J A Merrifield

Fluid Gravity Engineering Ltd,
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Study Contents

- **Study Objective**
  - Assess likely level of surface alteration resulting from propulsive descent and landing
  - Literature review
  - Numerical analysis (a first assessment)
- **Study Activities**
  - Use of engineering models to provide a first-cut assessment of important phenomena
  - Characterisation of the Lunar Lander's propulsions system
  - Calculation of the exhaust gas flow field
  - Assessment of surface fluxes resulting from time varying flow
  - Calculation of in-depth flow solution from rocket plume impingement
- **Potential Applications**
  - Support geological surveying
  - Plume regolith interaction with lander and surface systems

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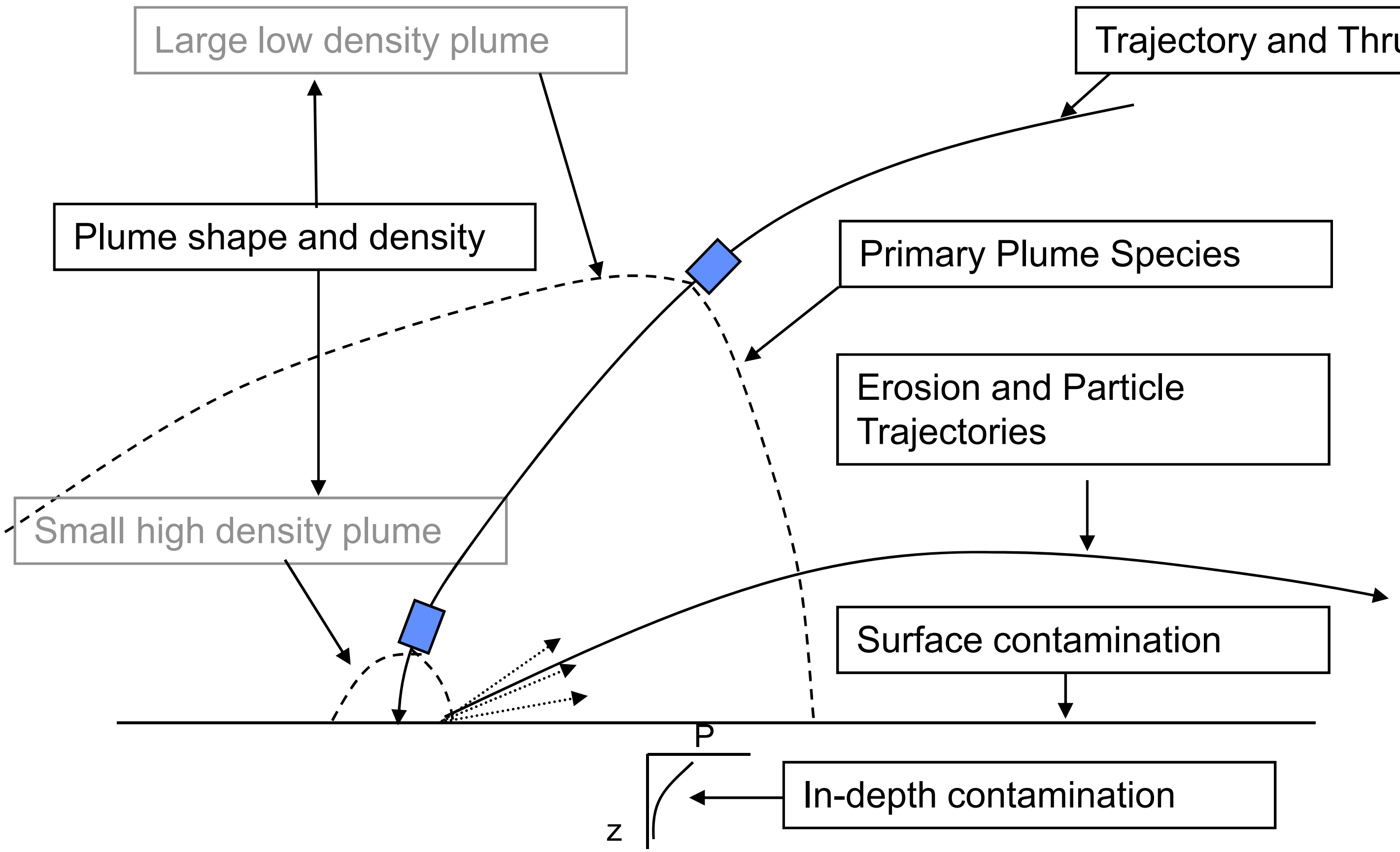
Problem breakdown



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The Flowfield Model: Point Source Formulation

- **Approach is largely analytic**
- **Calculate surface properties using Newtonian assumption**

$$P = C_p \frac{1}{2} \rho v_{\lim}^2 \sin^2(\theta)$$

- **Plume quickly expands to close to limiting velocity (*v_{lim}*)**
- **Need to predict density based on how quickly the plume diverges**
  - **Nozzle lip angle**
  - **Exit Mach number (Prandtl Meyer Expansion)**
- **Pressure important: other BL edge properties obtained from it**
  - **Isentropic expansion of stagnation conditions**
  - **Edge velocity set by conservation of total enthalpy**

$$\frac{\rho}{\rho_s} = \left(\frac{P}{P_s}\right)^{\frac{1}{\gamma}} \quad \frac{T}{T_s} = \left(\frac{P}{P_s}\right)^{1-\frac{1}{\gamma}} \quad u_e^2 = 2(H_0 - h_e)$$

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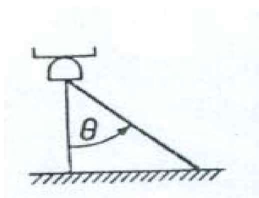
The Flowfield Model: Point Source Formulation

- **Several expressions exist for plume divergence**
  - **Parameters needed for models derived from CEA calculations (engine characteristics provided by ESA)**

- **Boynton/Legge**
  - **Explicit dependence on nozzle lip angle and PM turning angle**

$$\frac{\rho}{\rho^*} = A_p \left(\frac{r^*}{r}\right)^2 \left(\cos\left(\frac{\pi\theta}{2\theta_m}\right)\right)^{\frac{2}{\gamma-1}}$$



  - **And from mass conservation**

$$A_p = \frac{u^* / 2u_{\lim}}{\int_0^{\theta_{\lim}} \left(\cos\left(\frac{\pi\theta}{2\theta_m}\right)\right)^{\frac{2}{\gamma-1}} \sin(\theta)d\theta}$$

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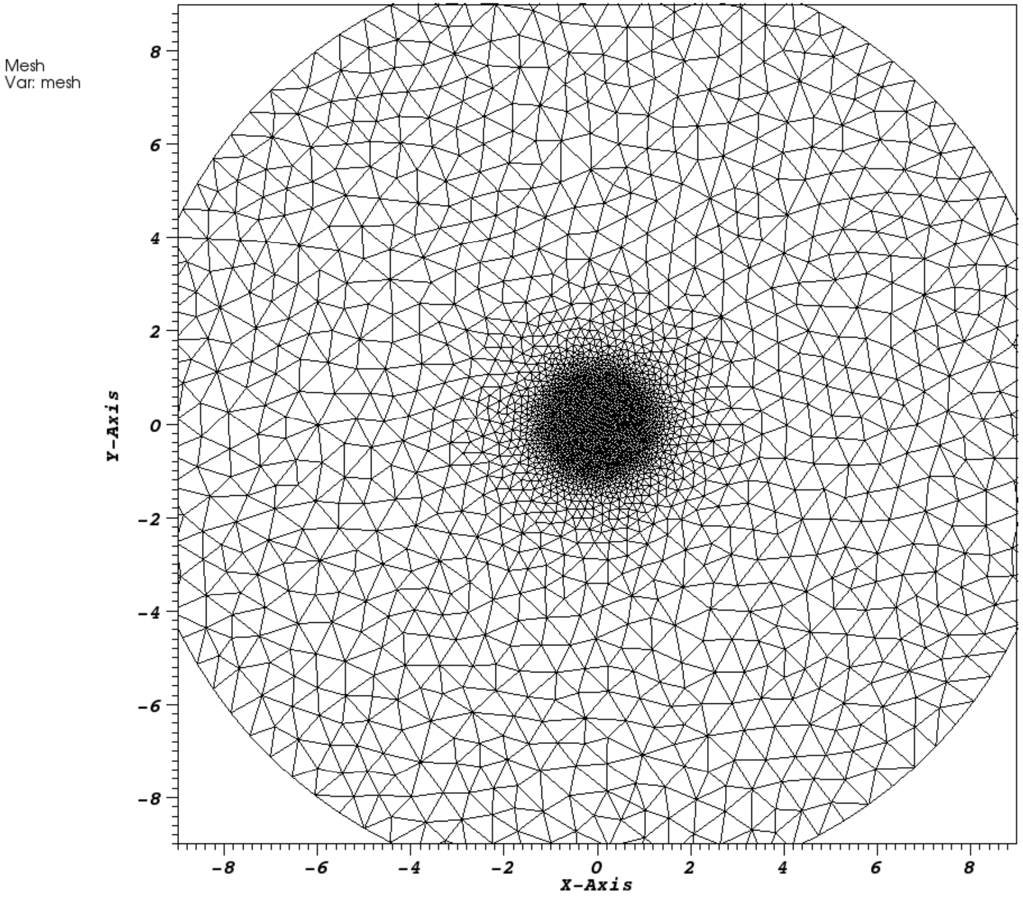
Example grid for incident mass flux



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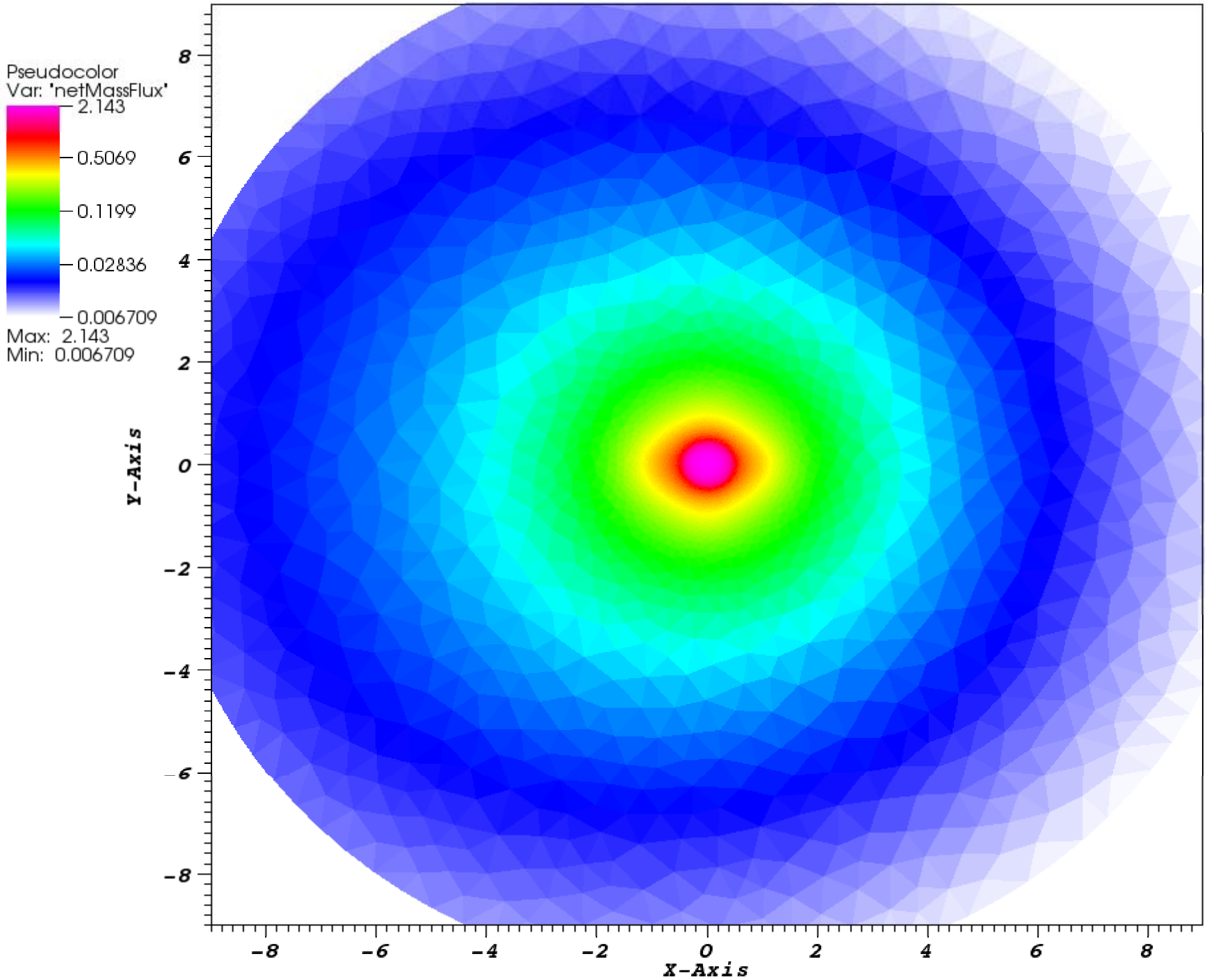
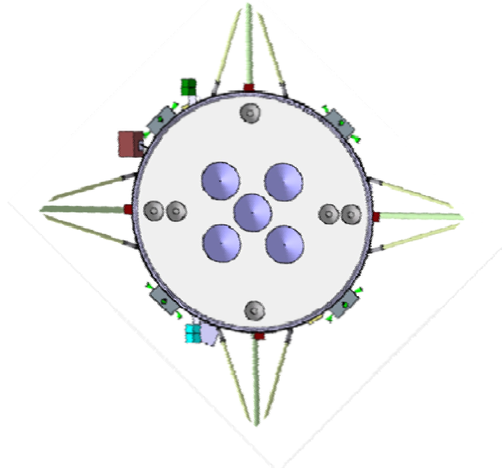
Incident Mass Flux Calculation: log scale





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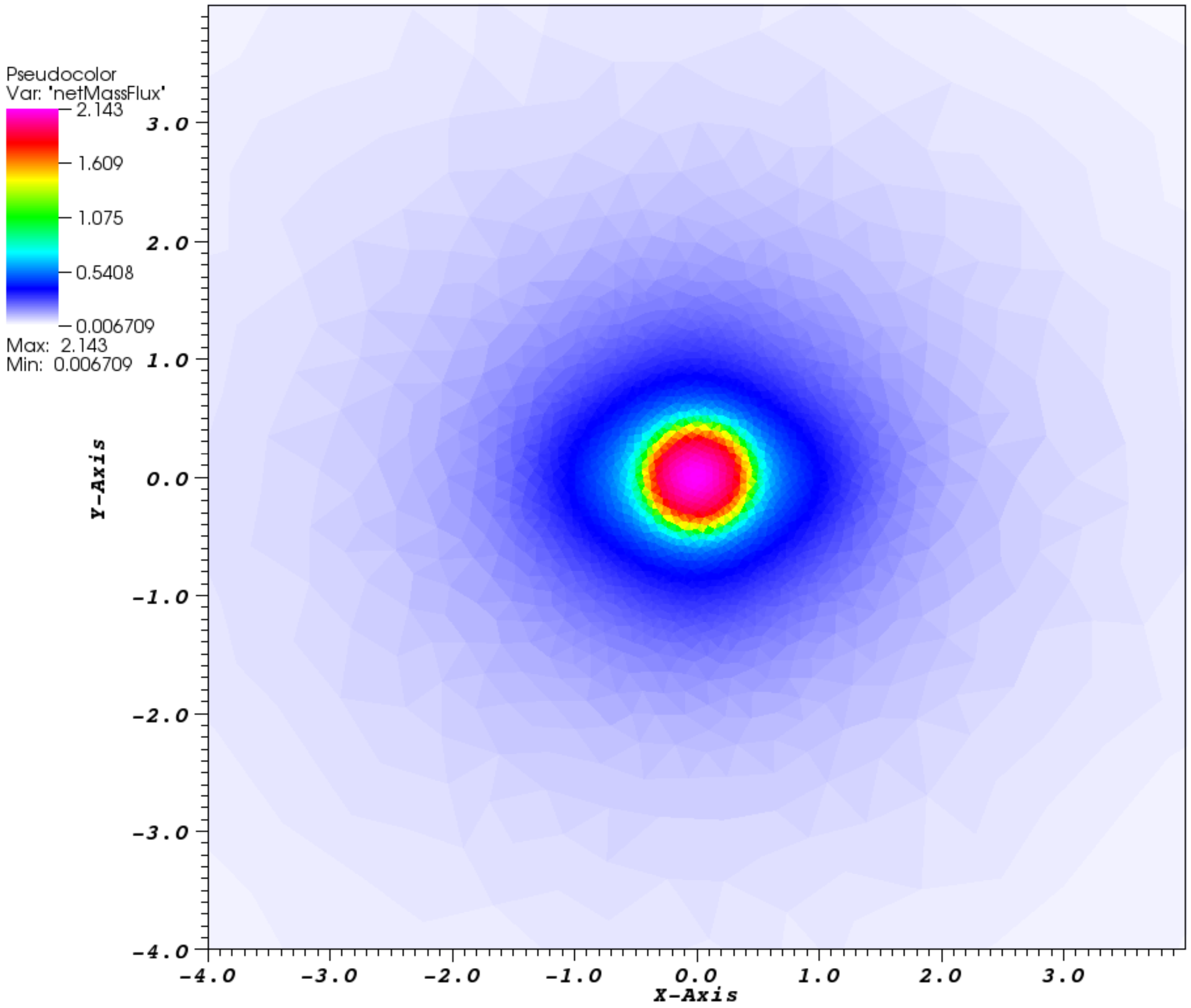
Incident Mass Flux Calculation: lin. scale



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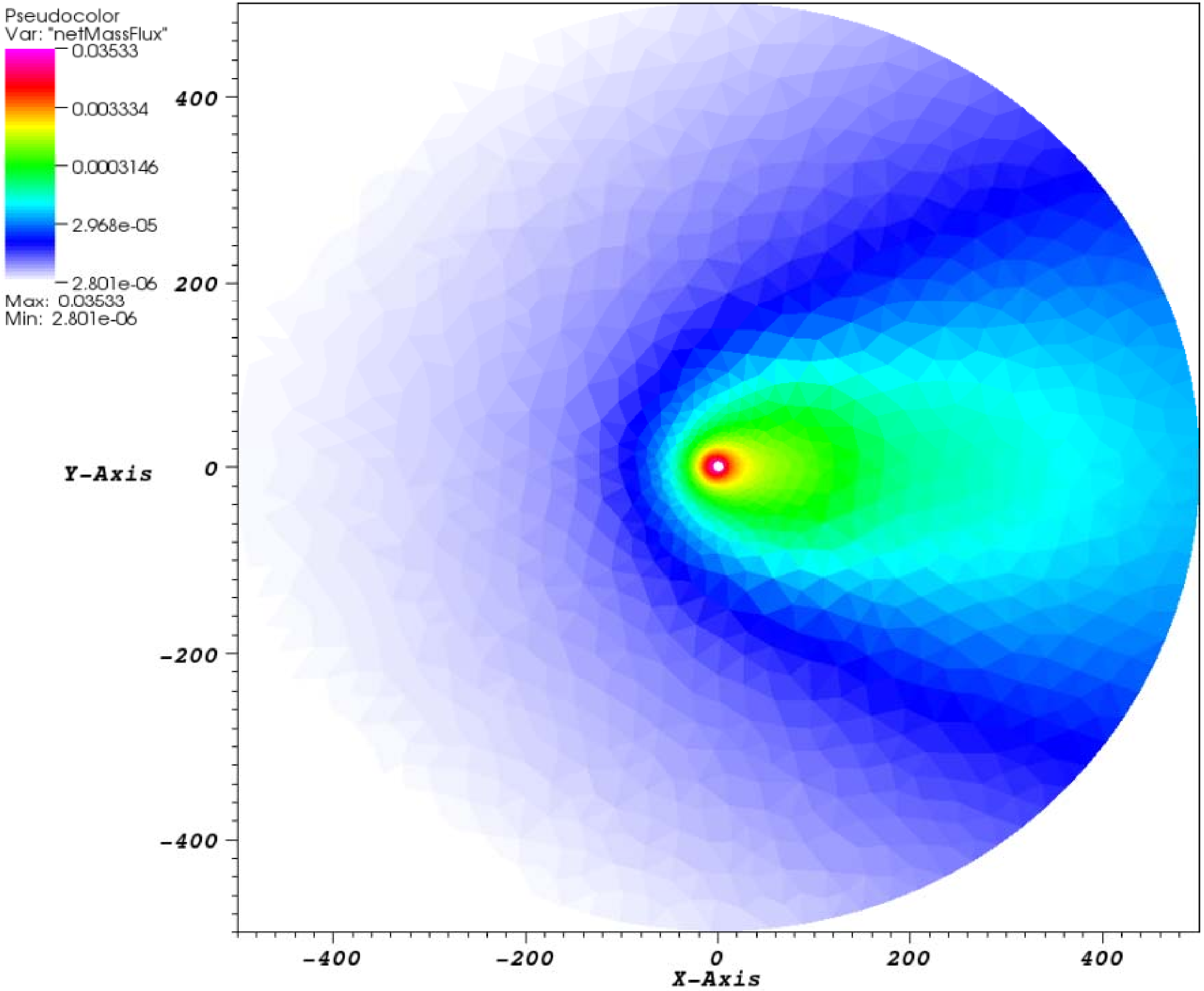
Incident Mass Flux Calculation: log scale, far field



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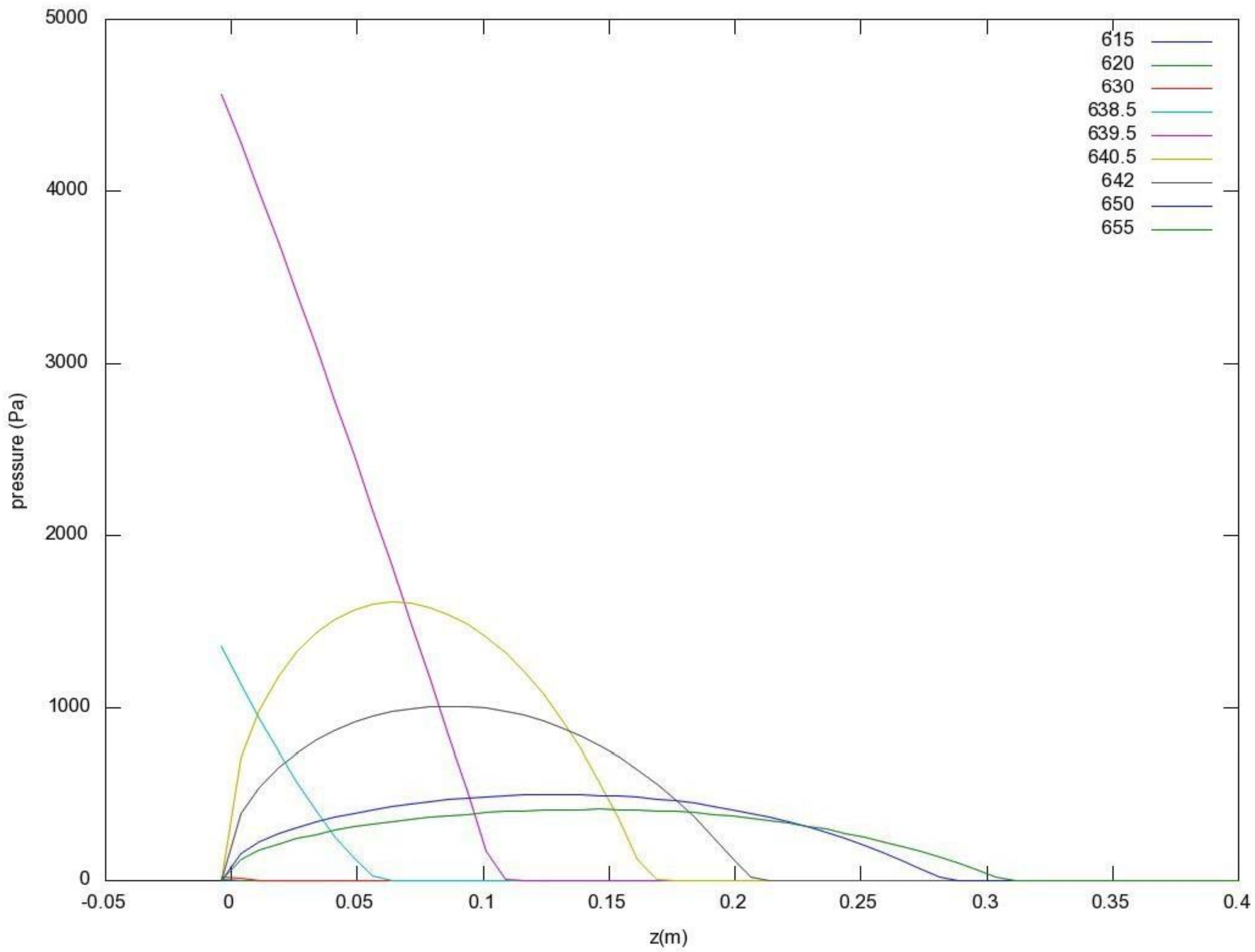
Stagnation point flow in-depth: pressure

$$q = -\frac{\kappa}{\mu}\,\nabla p$$



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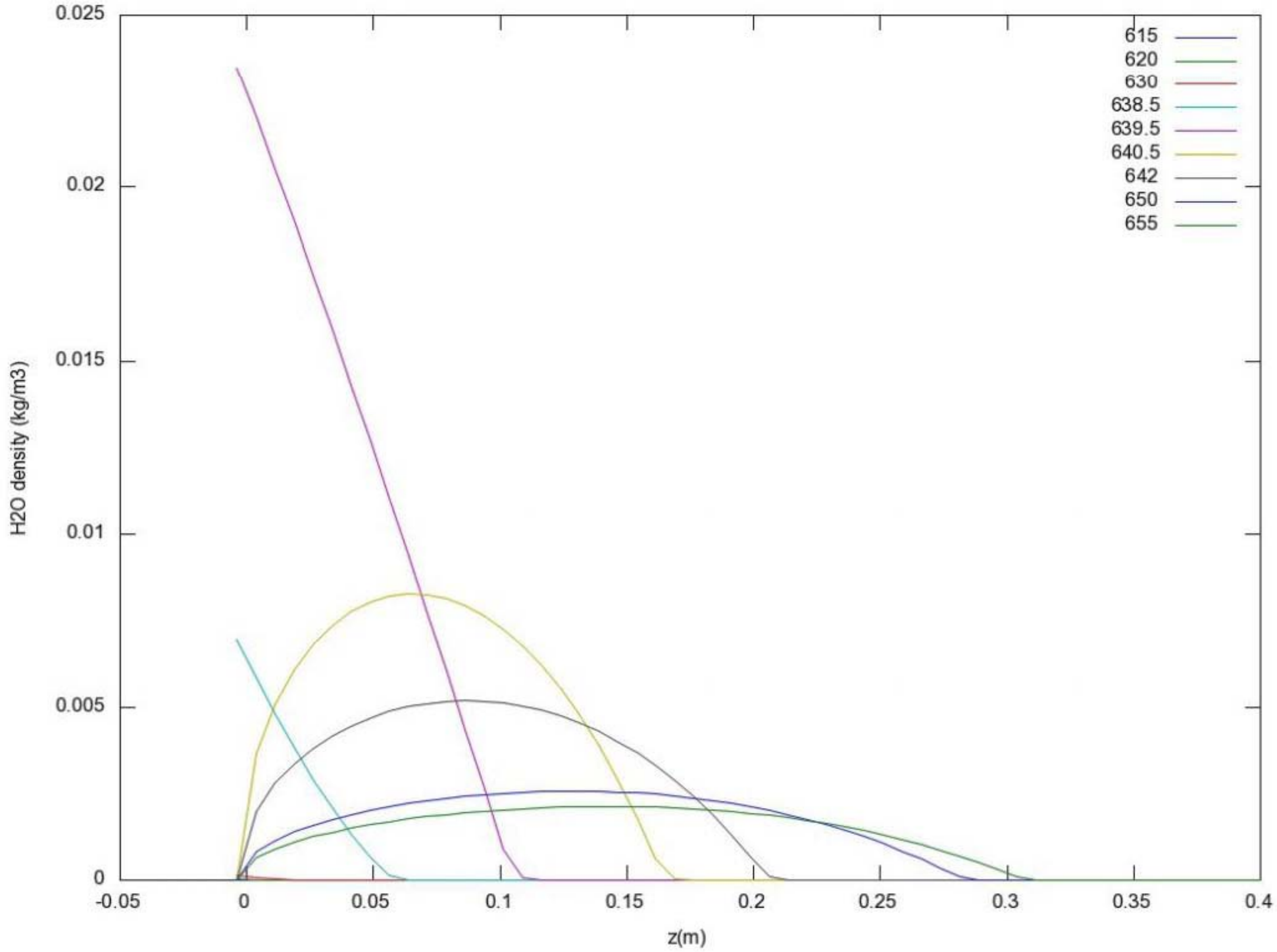
Stagnation point flow in-depth: water vapor density



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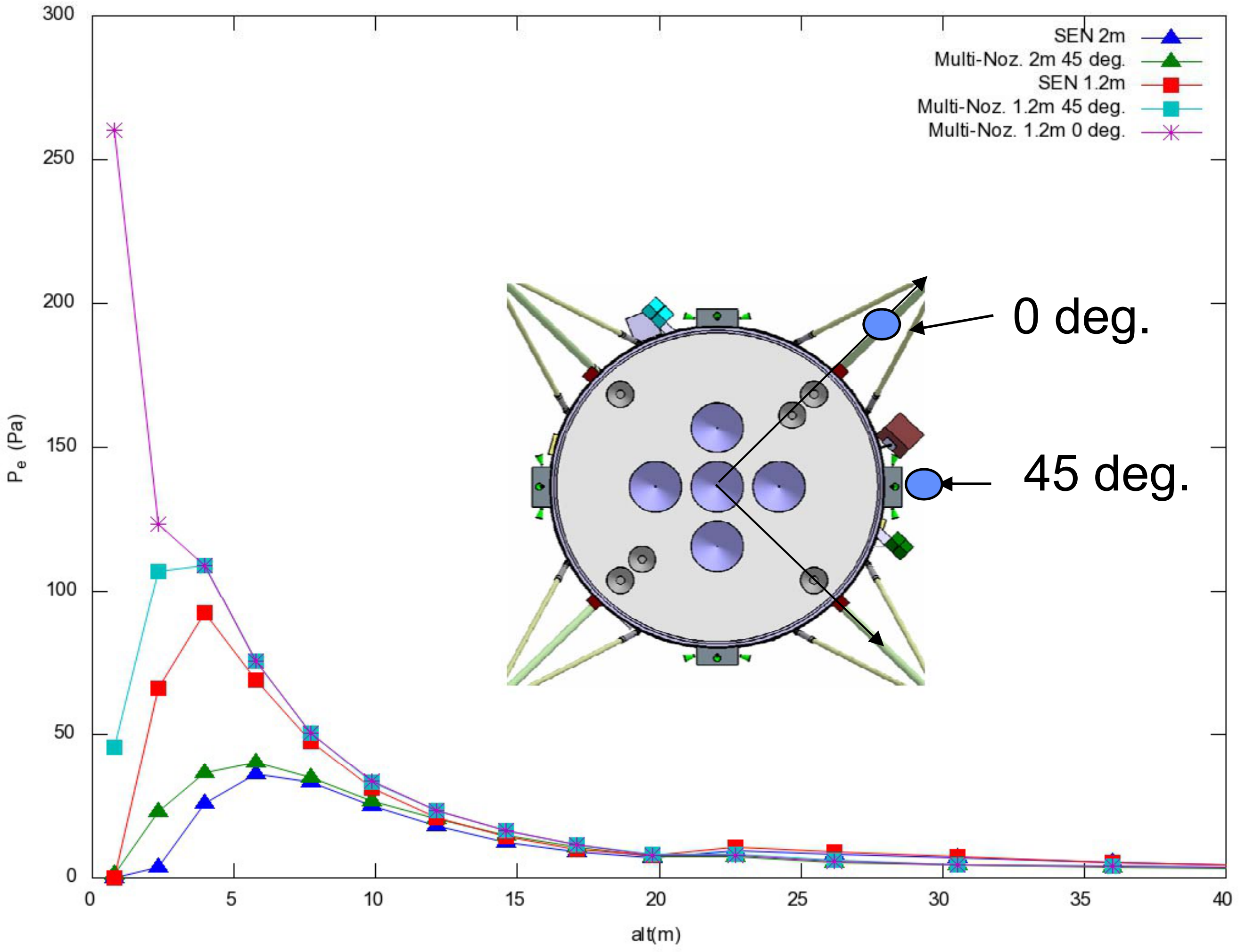
Multi-nozzle and Single Equivalent



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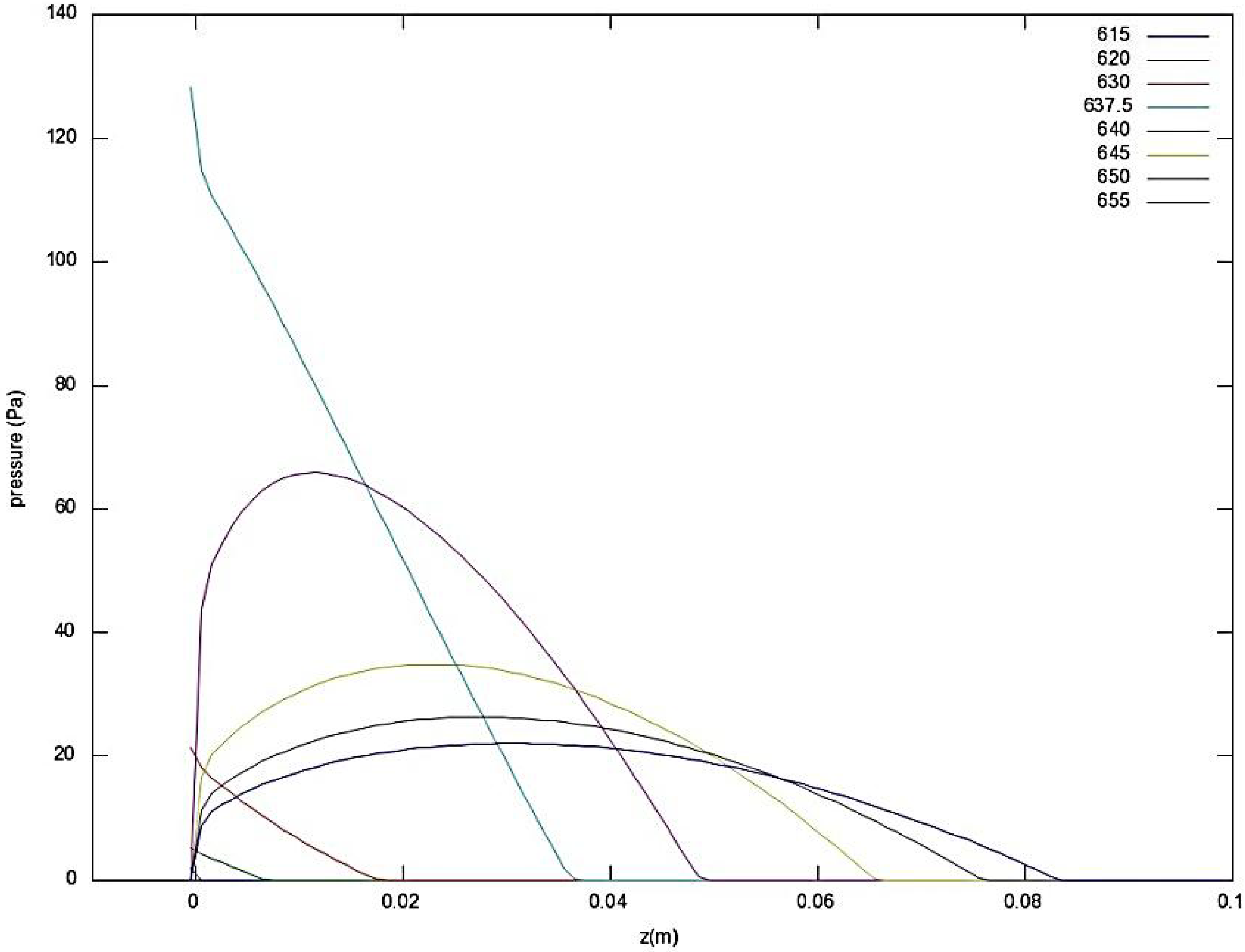
In-depth gas flow with rocket heating and deposition (1.2m, 45 deg.)



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Erosion calculation

- **Mass loss rate expressed as** $\dot{m} = \dfrac{2(\tau_0 - \tau^*)}{ua}$
  - **Parameter *a* is very important in determining the mass loss rate**
  - **Should expect significant uncertainty here …**

- **Analytic expression for *a* after Roberts**

$$a = \left[\frac{1}{2} + \sqrt{\frac{1}{4} + \frac{1}{\zeta}} \right]^{-1}$$

$$\zeta = \frac{18\mu_C h}{\sigma \sqrt{RT_C}\left(4 + k_{\text{hyper}}\right)} \left[\frac{1}{D^2} + \frac{1}{D} \cdot \frac{\left(4 + k_{\text{hyper}}\right) C_D}{72 e \sqrt{2RT_C}} \frac{F_{\text{Thrust}}}{\mu_C h^2} \right]$$

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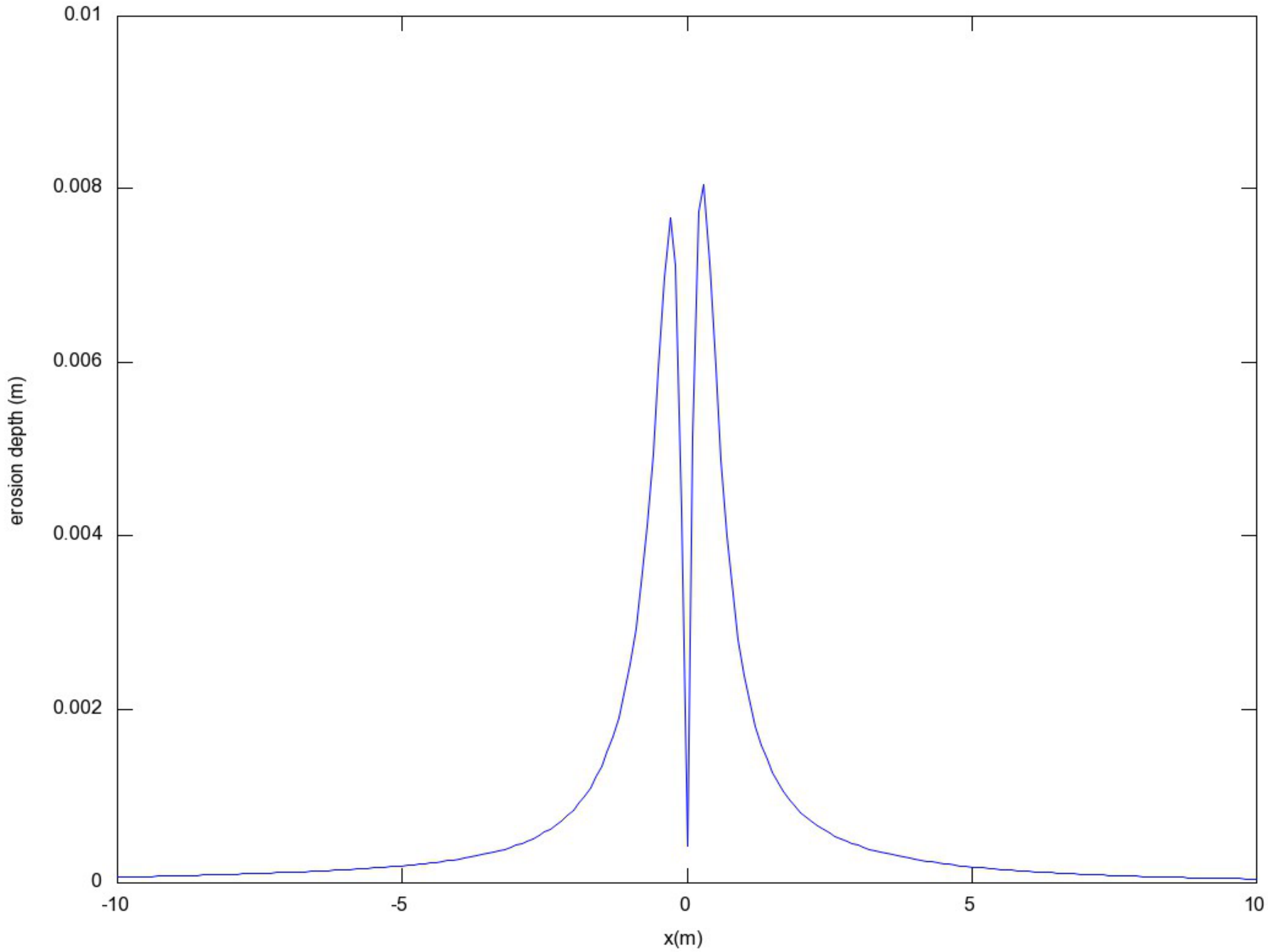
Erosion annulus predicted for present Lander
Minimal viscous erosion predicted



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Conclusion

- **Work Performed**
  - **Characterisation of the Lunar Lander's propulsion system**
  - **Calculation of the exhaust gas flowfield**
  - **Assessment of the surface fluxes (skin friction and heat transfer) resulting from the time varying flowfield**
  - **Calculation of in-depth flow solution resulting from rocket plume impingement (flow through a porous medium) and an assessment of the likely level of surface erosion**
- **Spot point studied (1.2m from Lander central axis)**
  - **Viscous erosion is likely to be low (order of mm)**
  - **Alternative erosion mechanisms deserve more attention**
  - **Gas penetration on the order of cm**
- **Further study**
  - **Higher fidelity analysis is required for experiment / mission design**
  - **Only so much progress can be made with numerical analysis: dedicated experimental programme is required to reduce uncertainties**
  - **Lead to reduction in uncertainties and consolidated margins policy**

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Further Study

- **CFD study of plume surface interaction**
  - **Compare with and tune point source methodology**
- **Test planning**
  - **Study along the lines of that pursued by Mehta et al.**
    - **Determined significance of pulsed mode operation re: diffuse gas explosive erosion (DGEE)**
  - **Study along the lines of LaMarche et al.**
    - **Gather data on permiability and chemical adsorption**
    - **Improve on past activity by testing under realistic pressures and temperatures**
    - **Support from OU required for chemical analysis**
    - **Look at feasibility of performing tests in real rocket plume or RF/Arc heated plasma facility with representative composition**
- **Test activities**
  - **Following on from planning stage**
- **DSMC/Hybrid calculations**
  - **Validate / update simple flow model in transitional region**
- **Synthesis of findings and margins**
  - **Generation of contamination / surface alternation database for nominal (and some off nominal) trajectories with application rules and margins**

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Driving requirements and constraints: scientific

High Priority Requirements:

RQ 1 Volatiles shall be liberated from lunar regolith.
RQ 2 The species of volatiles liberated shall be identified.
RQ 3 The quantities of volatiles extracted shall be determined.
RQ 4 The chemical and isotopic abundances and concentrations of those species in the lunar regolith shall be determined.
RQ 5 Concentrations of H_2O and OH on the surface shall be measured for concentrations greater than 10 ppm.

Medium Priority:

RQ 6 Measure the number density and composition of neutrals in the lunar exosphere (nominally to include the following species: Ne, Ar, H, He, Na, K, CH_4, H_2O, OH, CO_2, NH_3).
RQ 7 Measure the number density and composition of ions in the lunar exosphere (nominally to include the following species: Ne, Ar, H, He, Na, K, CH_4, H_2O, OH, CO_2, NH_3).

Driving requirements and constraints: scientific

- SoW requirements RQ1-5 (regolith) and RQ6-7 (exosphere) as developed in TN9 (Requirements List). These translate to:
- For regolith:
  - Extract volatiles from regolith samples obtained from known (and ideally, characterised) localities including from depth and from the surface (top ~1 mm)
  - Identify the volatiles released
  - Quantify the volatiles released
  - Isotopically characterise the volatiles released
  - Relate all of the above back to the original nature of the components in the regolith
- For exosphere:
  - identify and quantify and as far as possible isotopically characterise volatile **neutral** species (ions descoped)

Driving requirements and constraints: environmental

- Thermal environment
  - Wide temperature range day/night
  - Don’t fry at day when operational and don’t freeze at night when non-operational
  - Plus ideally, some operations at night
- Contamination
  - From Lunar lander motors during descent and landing
  - From pervasive Lunar (magnetic, abrasive…) dust
- Approach:
  - Measuring volatiles as a function of lateral distance from Lander (to investigate decline in alteration with distance)
  - Measuring volatiles as a function of depth
  - Being able to recognise contamination effects in acquired data

Driving requirements and constraints: system interface

- Uncertainties wrt accommodation on Lander and also eventual orientation (view factors, slope) after landing
- Solid Sample inlet
- A sampling campaign is a non-trivial undertaking to plan and implement

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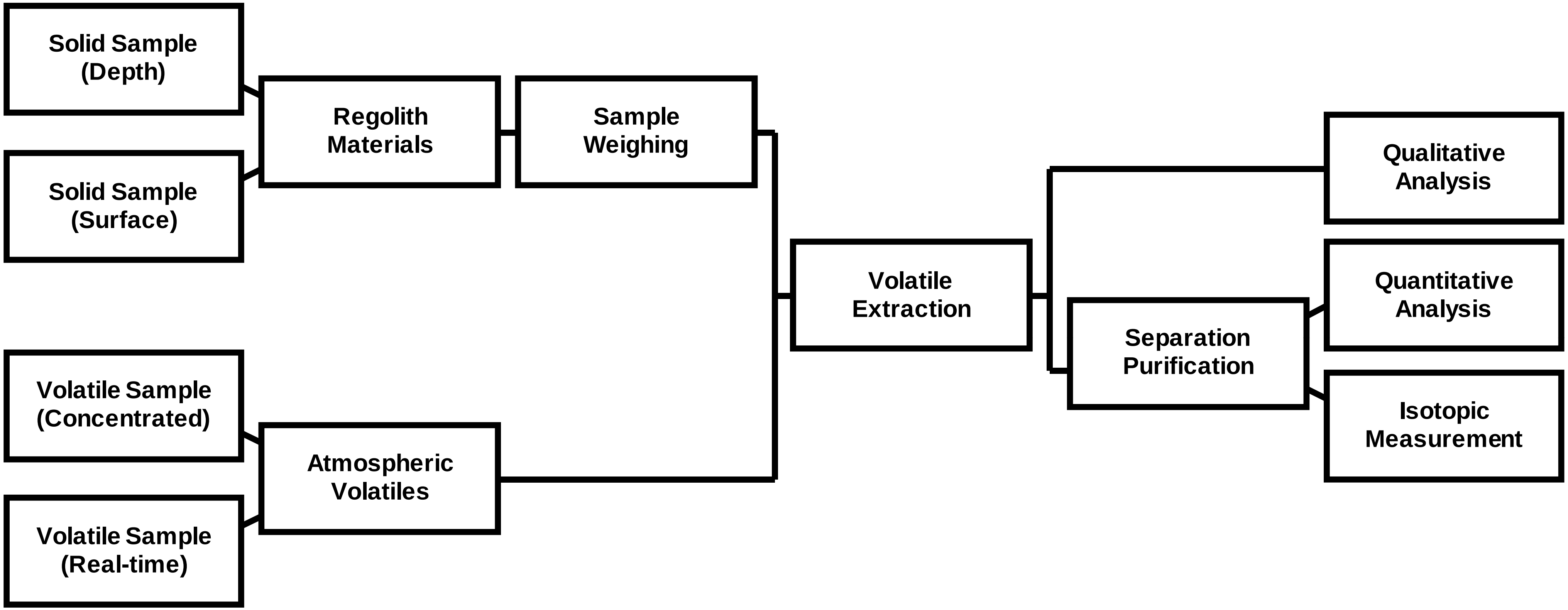
L-VRAP Concept for ESA IRR

- A concept for L-VRAP was presented to ESA for approval at IRR (T0+5 mo)
- L-VRAP requires the following:
  - Means for receiving regolith samples from Platform's robotic arm
  - Means for metering and/or determining mass of sample
  - Means for extracting volatiles from sample
  - Means for cleaning up/separating evolved gases
  - Means for qualitative, quantitative and isotopic analysis of volatiles
- Key driving requirements were identified as
  - RQ2/RQ3 identification/quantification of wide range of volatiles
    - Suggests mass spectrometer
  - RQ4 Chemical & Isotopic abundances in regolith
    - Requires means of determining sample size and isotopic capability to mass spectrometer
  - The effects of contamination from the Lunar Lander descent
- Alternative schemes were assessed and trade-offs performed

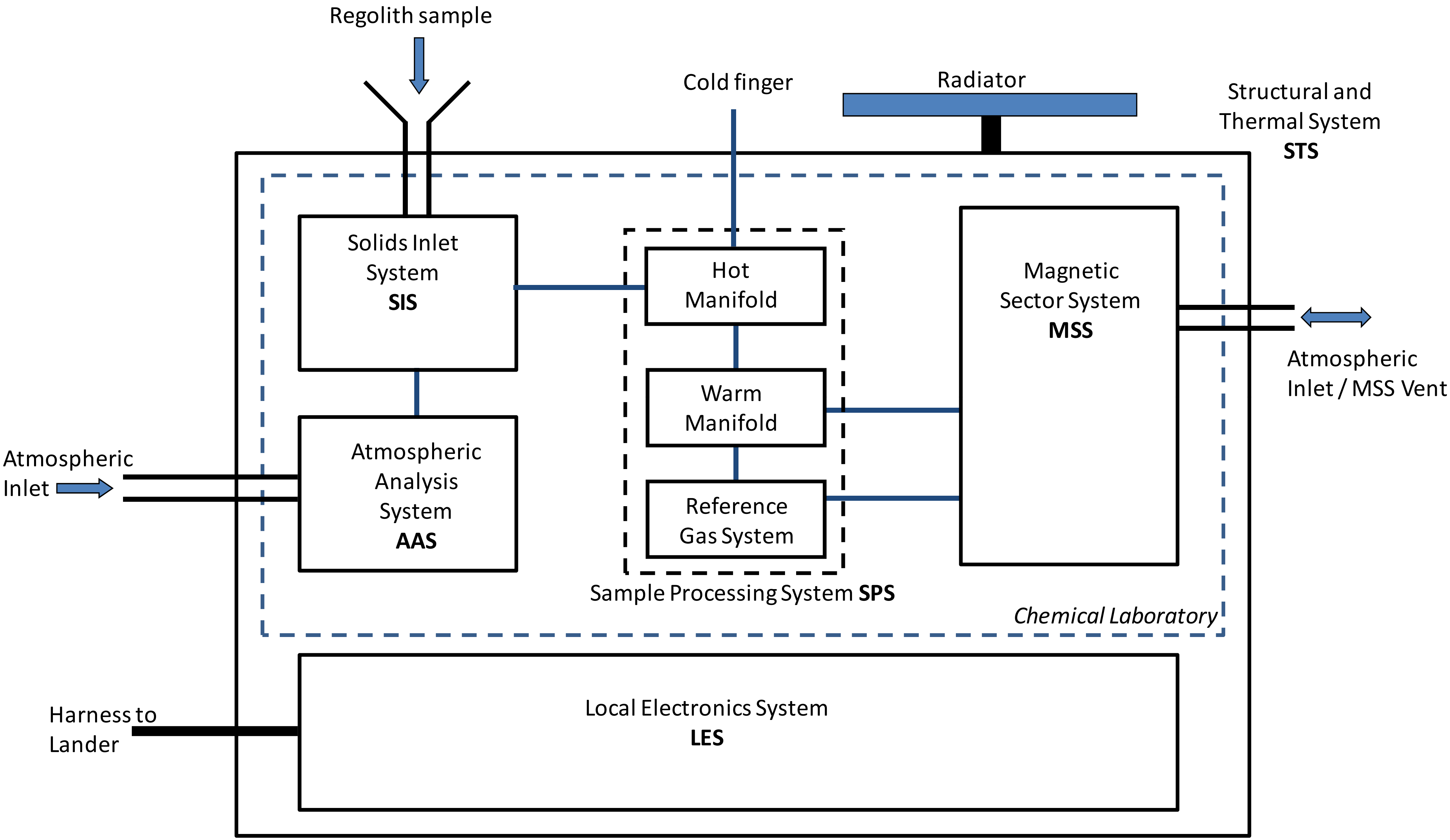
L-VRAP Concept

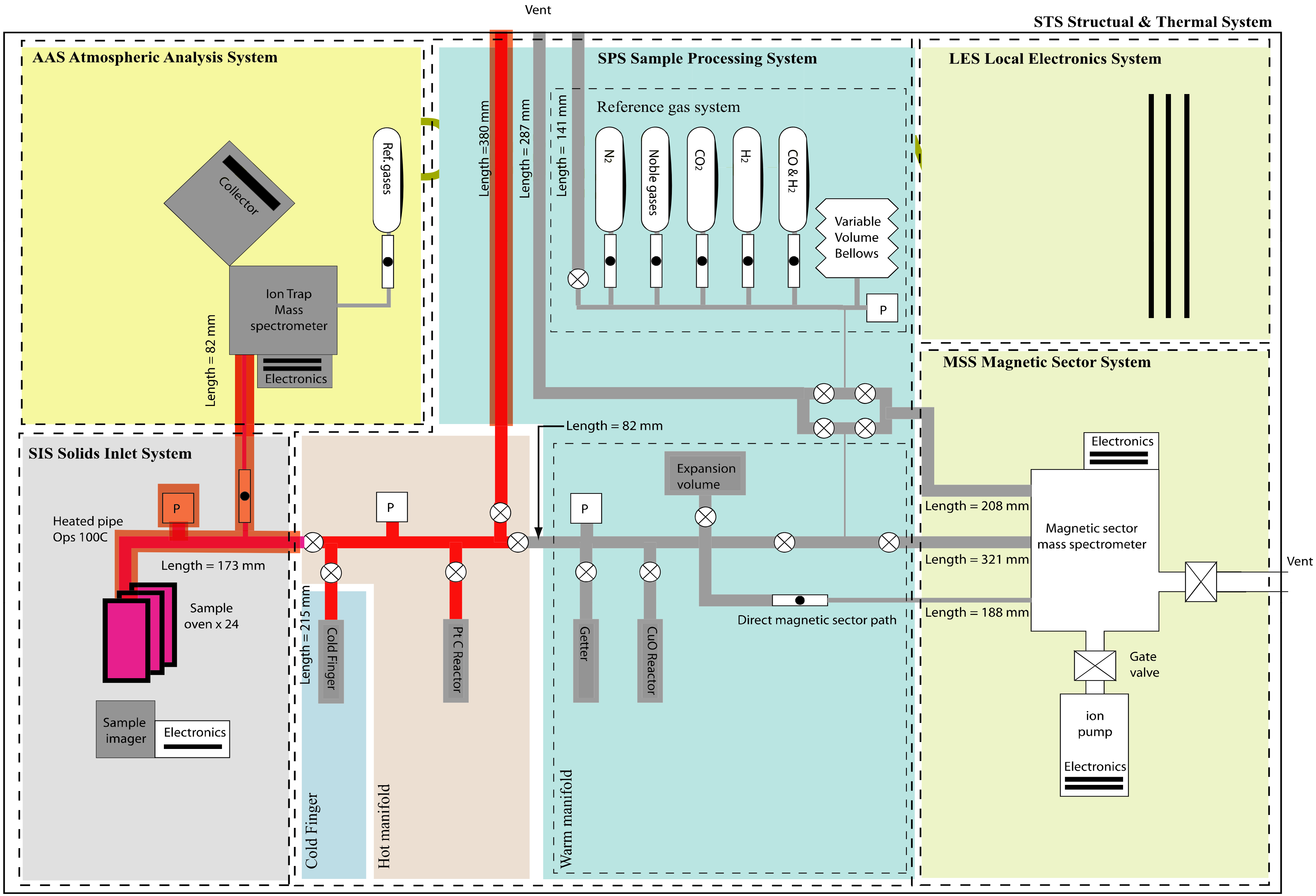
- Proposed concept



- functional process shown above is effective for
  - solids from any source (near to the lander, at distance) and
  - atmospheric volatiles either directly or extracted from an atmospheric collector / concentrator

Concept Design: Overview

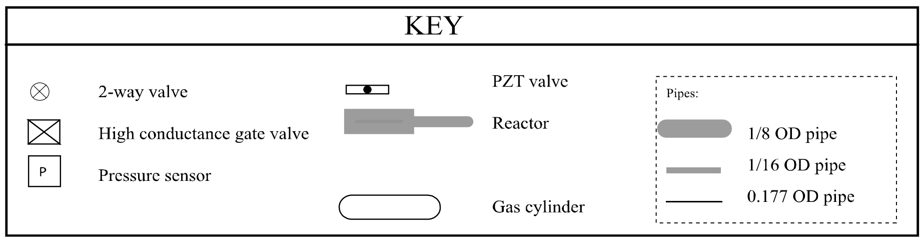




ISSUE	DATE	DRAWN BY	COMMENTS
	Feb 12	SS	**PROVISIONAL**

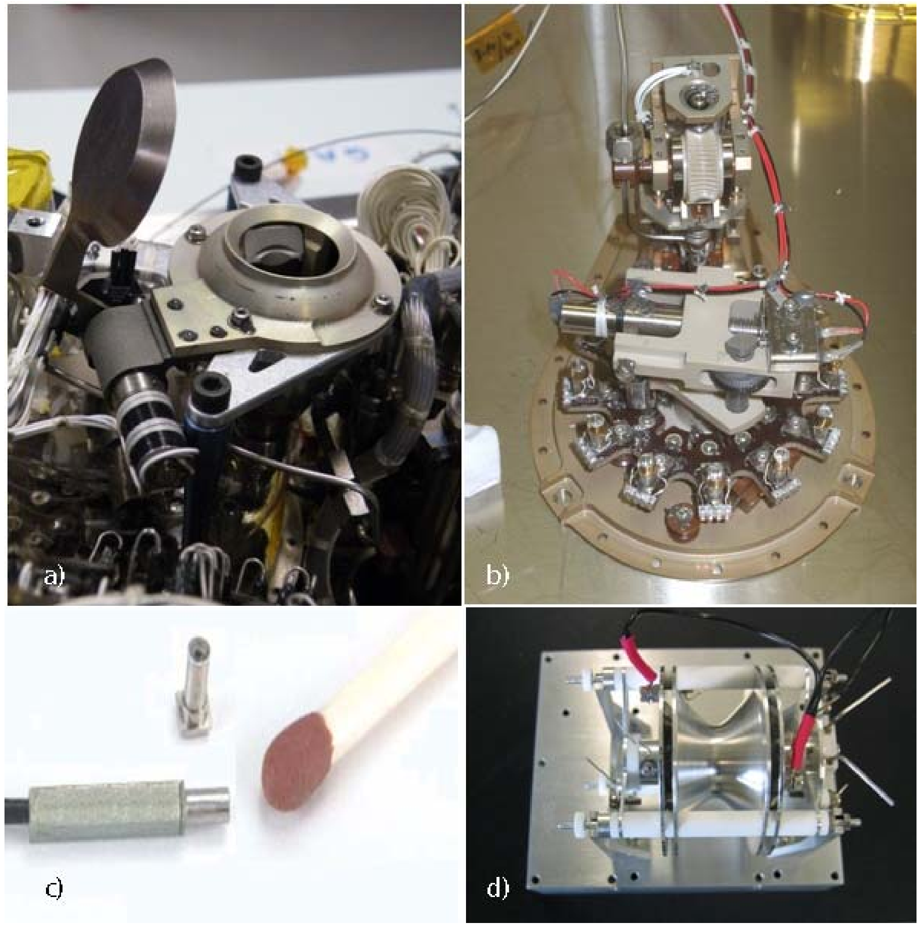
L-VRAP system diagram

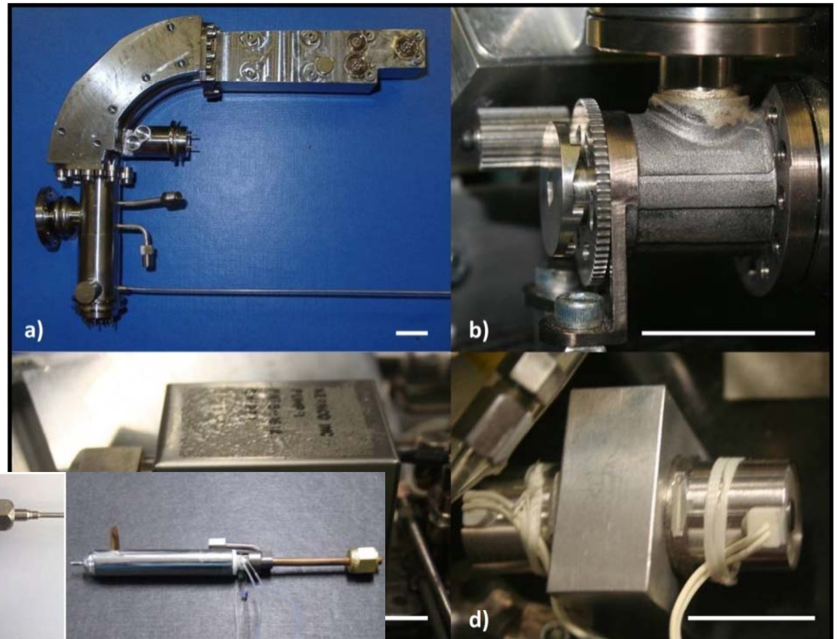
Drawing Number: AO6620-LVRAP-DW-001-Issue2-System_Diagram



L-VRAP Concept - Heritage

- Majority of subsystems and components draw heavily on flown technology
- Some areas will require incremental development/optimisation for Lunar lander context (valves, mass spectrometer…)
- Other areas may require more development (sample mass determination, …)





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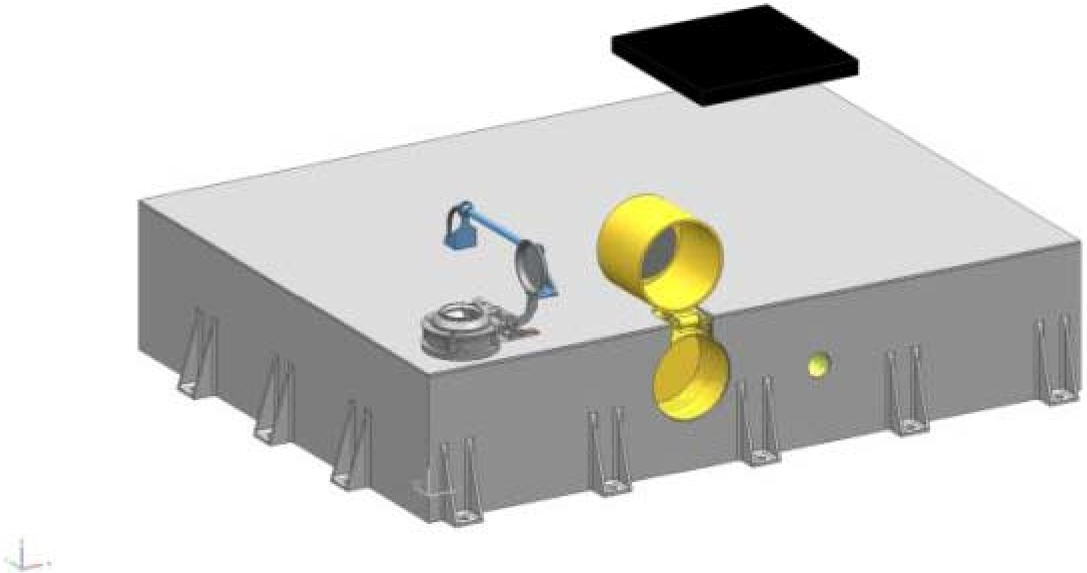

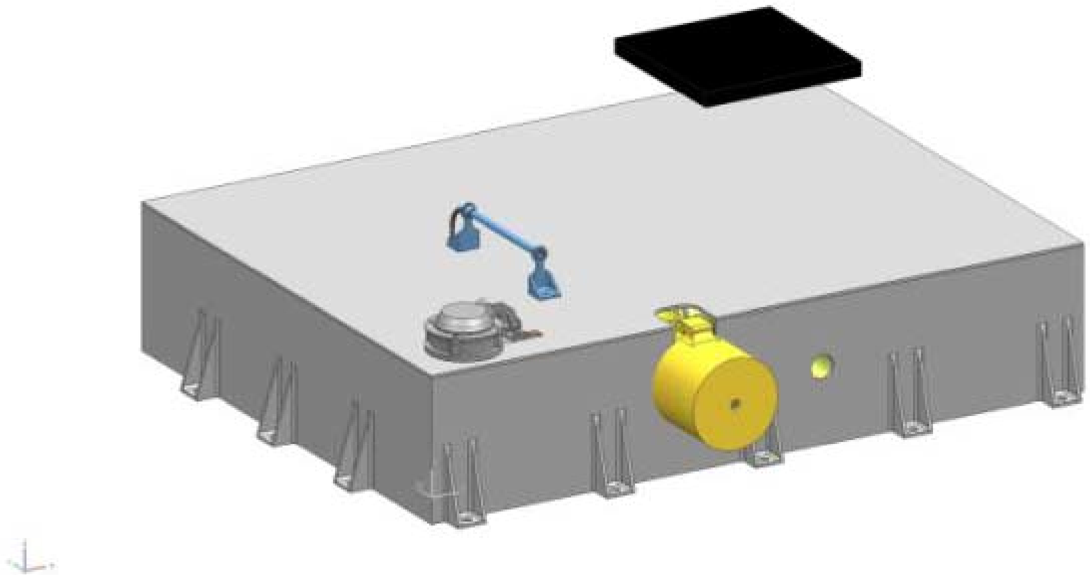

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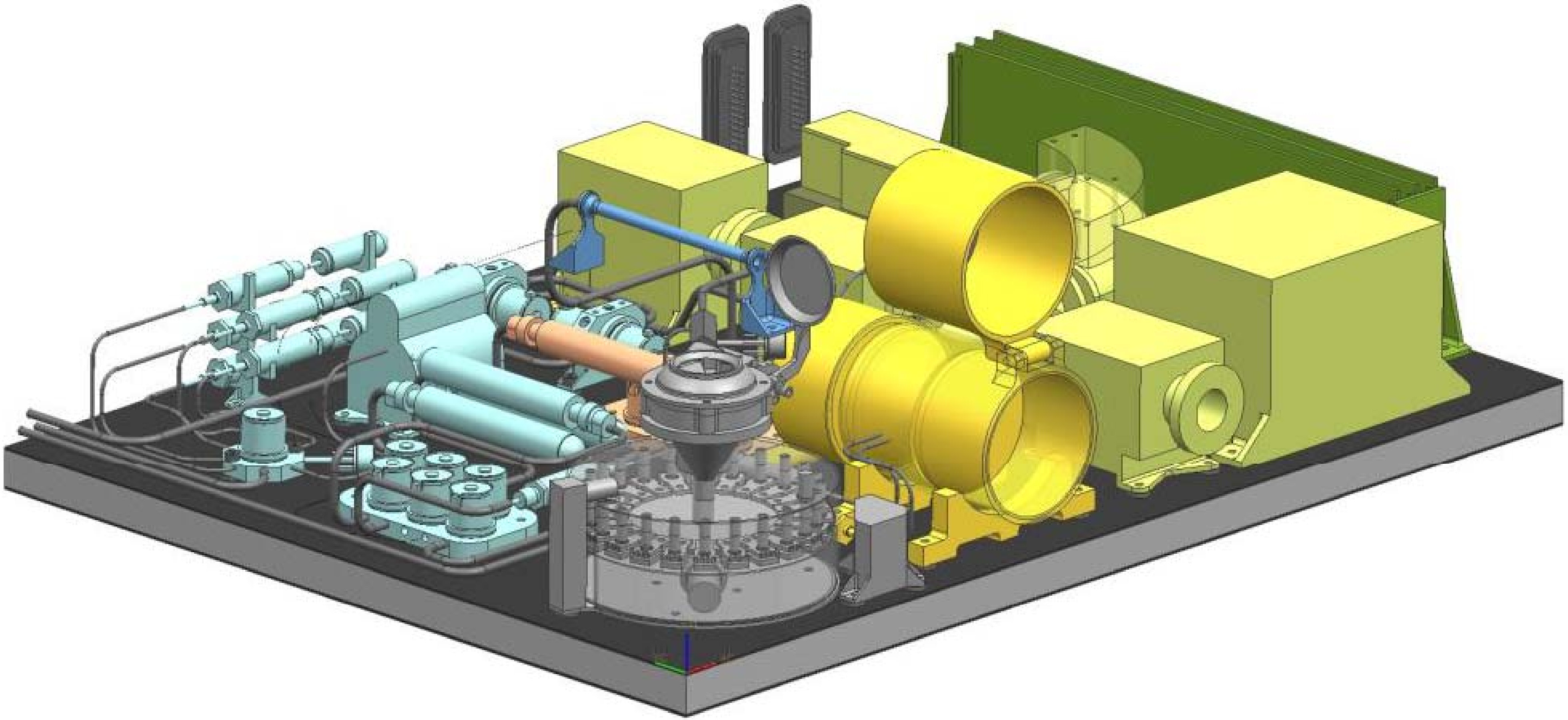

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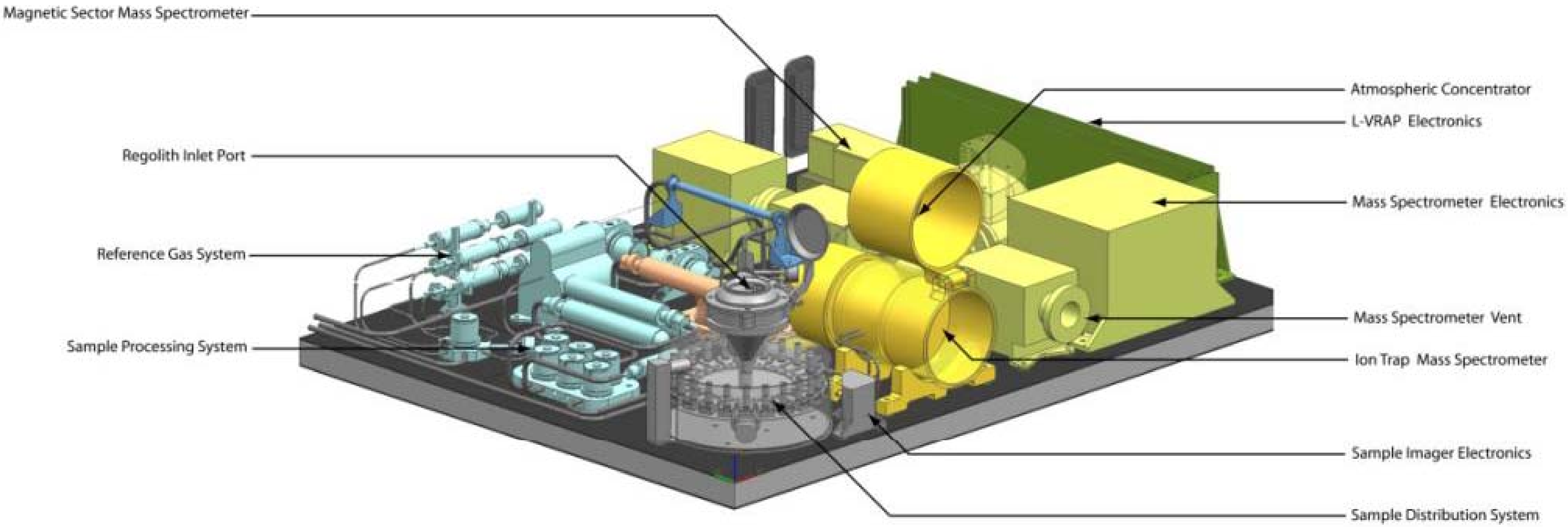


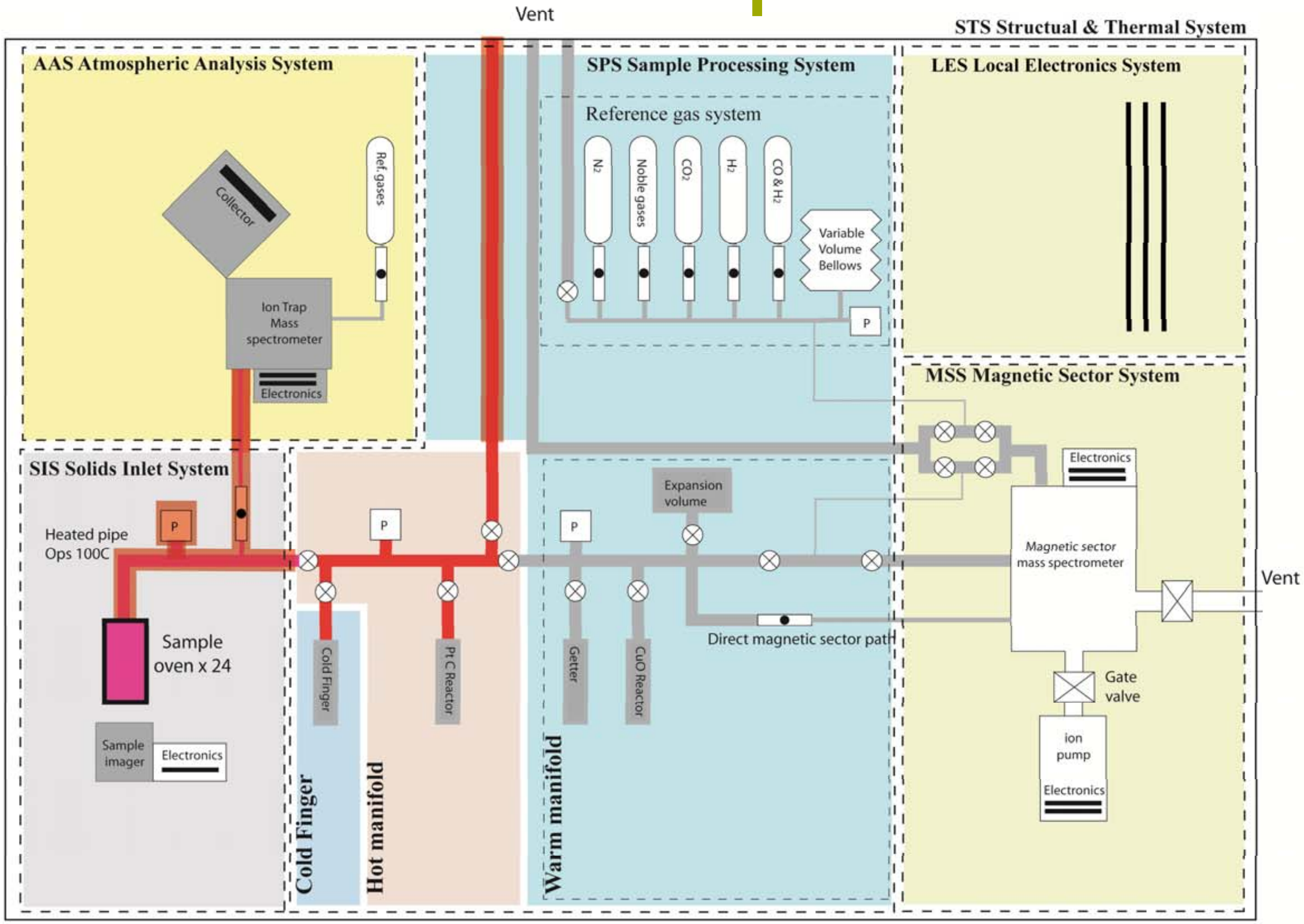
Agenda

- Introduction to L-VRAP Study [SB]
- Task 1: Literature & Requirements Review
  - Science Review [CTP]
  - Requirements Review [SB]
  - Technology Assessment [ADM]
- Task 2: Contamination & Surface Alteration Effects Analysis [JM]
- Task 3: L-VRAP Definition & Preliminary Design
  - Summary of driving requirements and constraints [SB]
  - L-VRAP Concept/Preliminary Design - overview [SB]
  - **L-VRAP sample analysis process [ADM]**
  - L-VRAP baseline operations planning [ADM]
  - L-VRAP Concept/Preliminary Design – by subsystem [SB]
  - Scientific performance assessment [SB]
  - Lander & environment interfaces [SB]
  - Resource requirements [SB]
- Task 4: L-VRAP Development Plan [SB]
- Summary and Conclusions [SB/CTP]

L-VRAP Sample Analysis Process

- The following slides show the processes involved in a typical analysis
- Note there are a range of processes, which would be pre-selected on Ground

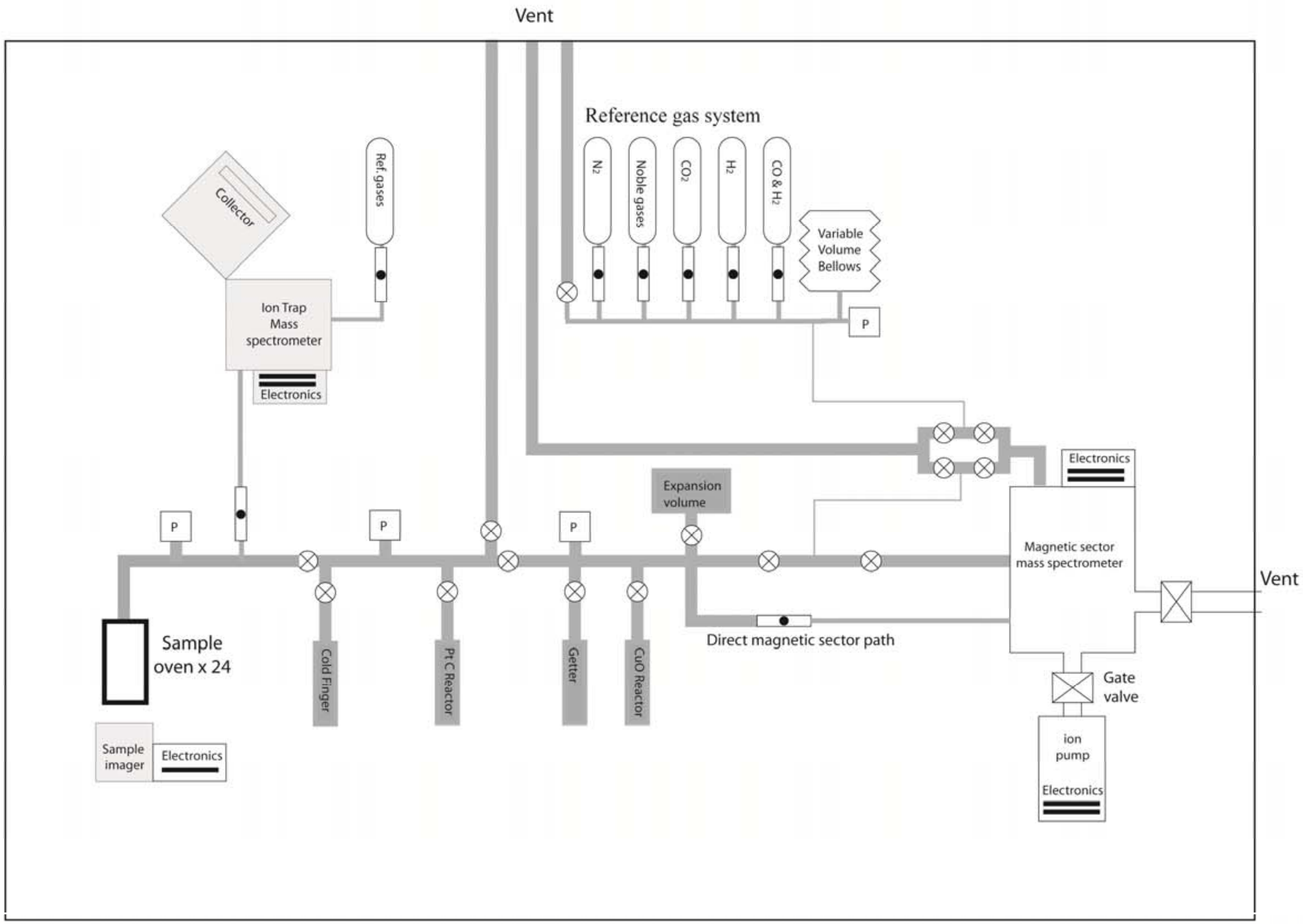
L-VRAP Sample Analysis Process – an example



Sample delivered and sealed in an oven

L-VRAP within operational temperature limits

Initial Choices

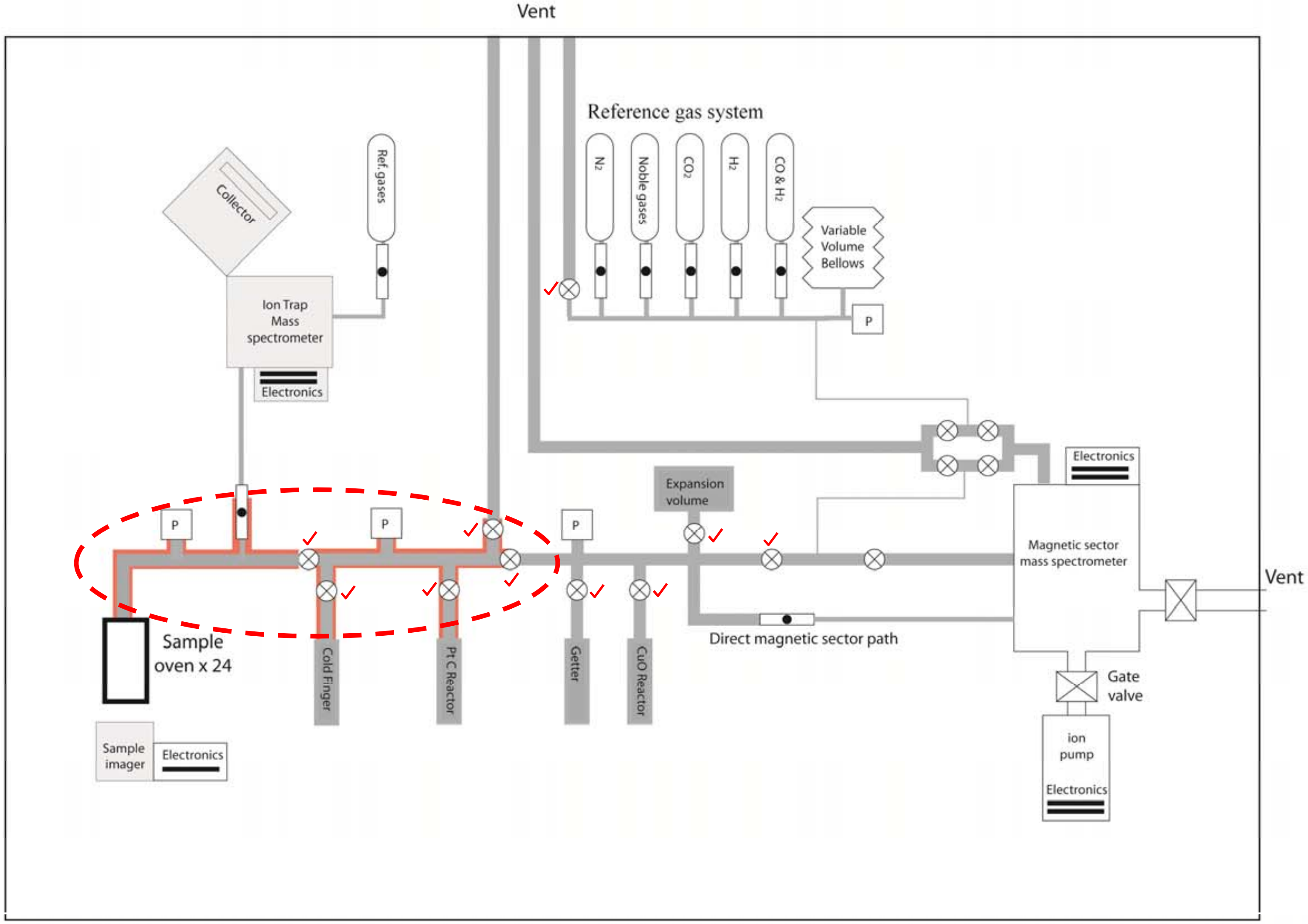


Temperature step? - Energy vs. detail
Combustion or Pyrolysis?
Which volatiles to analyse?
Which analysis method? - Static/Dynamic

Choices

Prepare manifolds
Prepare O_2
Heat sample
Quick analysis
Trap water & CO_2
Remove O_2
Dy. Analysis N_2
Remove N_2
St. Analysis Noble gas
Evacuate
Release CO_2
St. Analysis CO_2
Evacuate
Heat Manifold
Release H_2O
Convert to H
Dy. Analysis D/H
Evacuate

Prepare Manifolds



Water sticks in a vacuum system

Hot Manifold & Pipe +100ºC

Evacuate manifolds

Choices

Prepare manifolds

Prepare O_2

Heat sample

Quick analysis

Trap water & CO_2

Remove O_2

Dy. Analysis N_2

Remove N_2

St. Analysis Noble gas

Evacuate

Release CO_2

St. Analysis CO_2

Evacuate

Heat Manifold

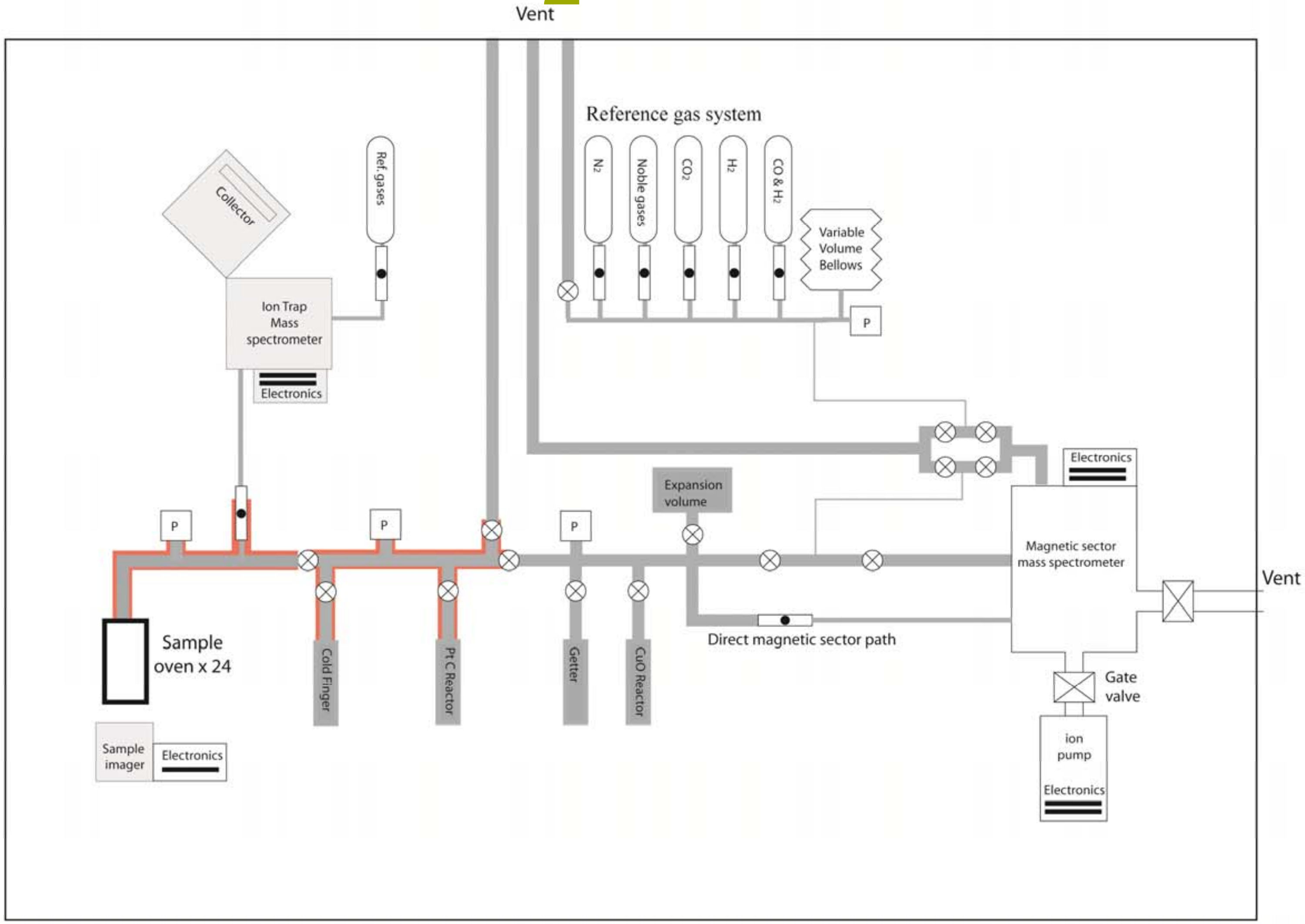
Release H_2O

Convert to H

Dy. Analysis D/H

Evacuate

Prepare O_2



Heat CuO reactor to +850°C
Expand O_2 gas to sample
Close hot/warm manifold valve
Reduce CuO temperature to +650°C

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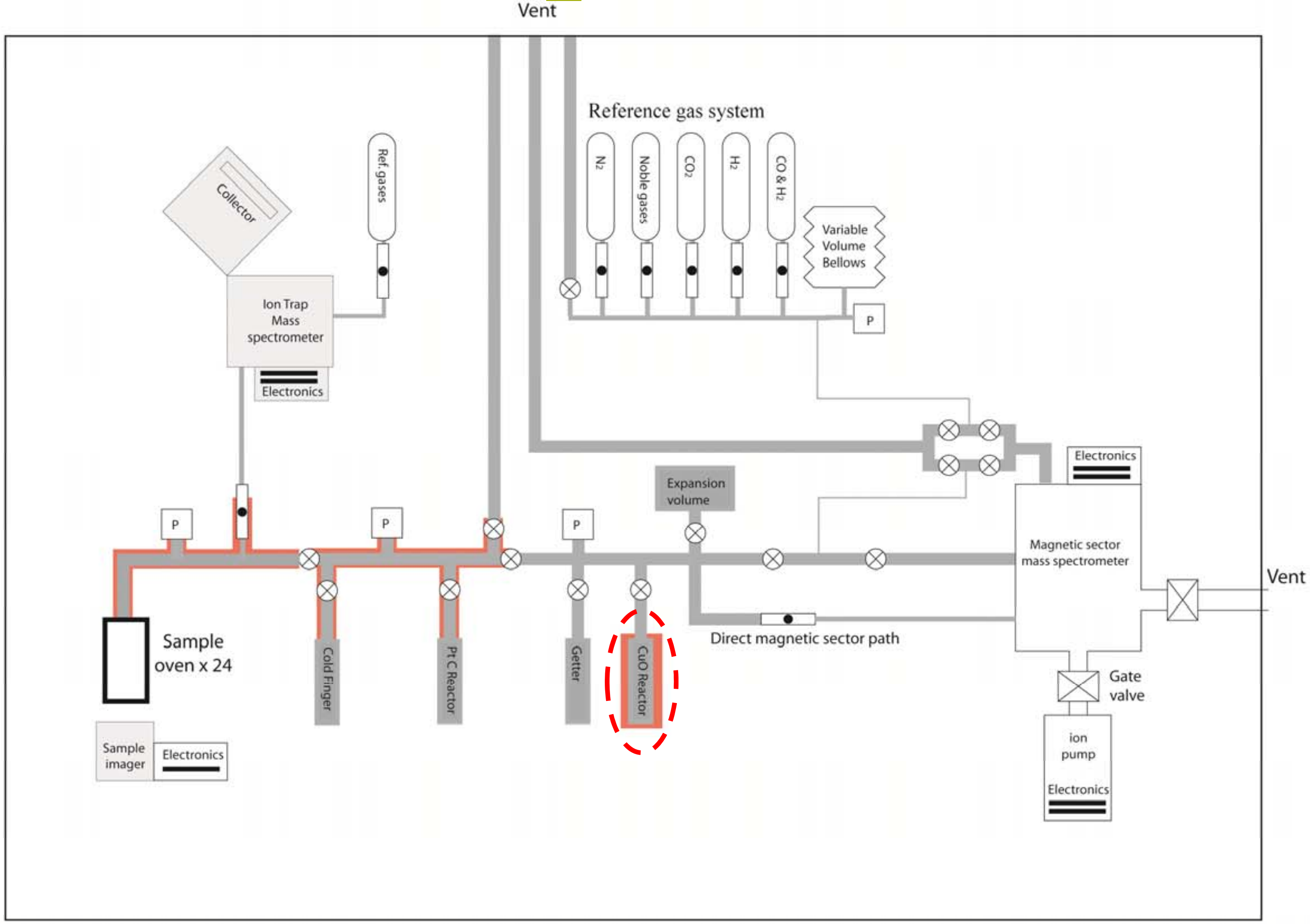

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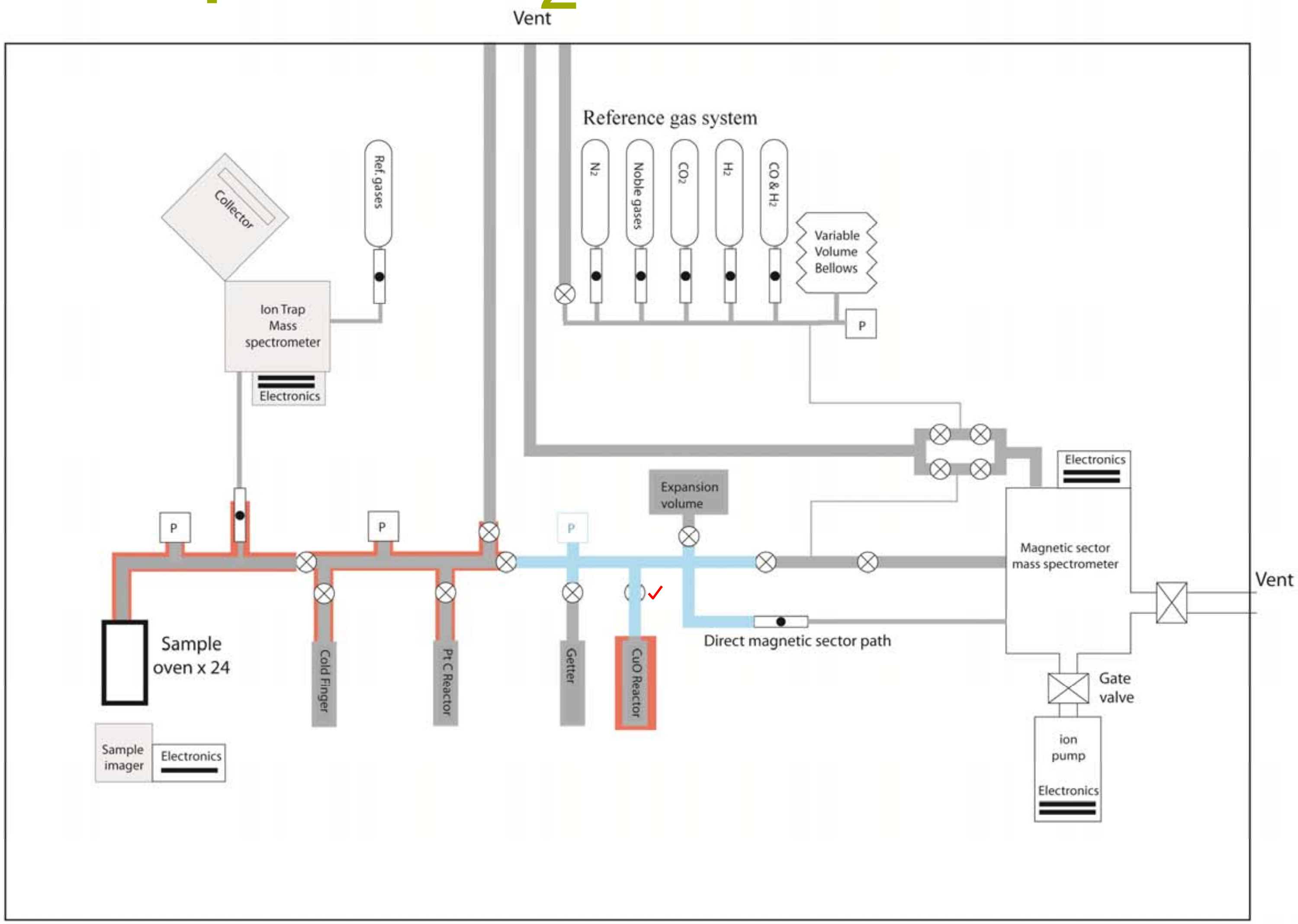

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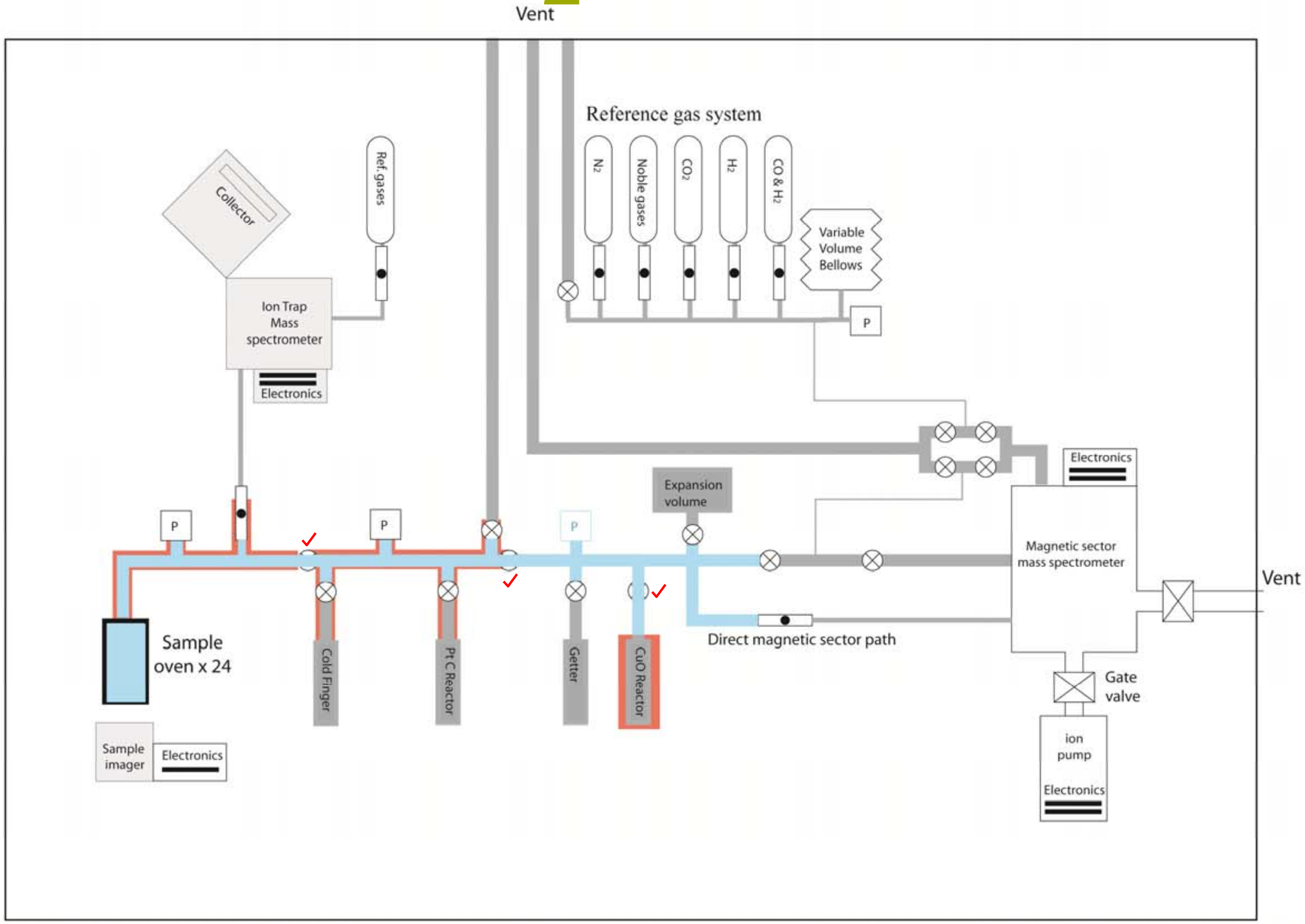

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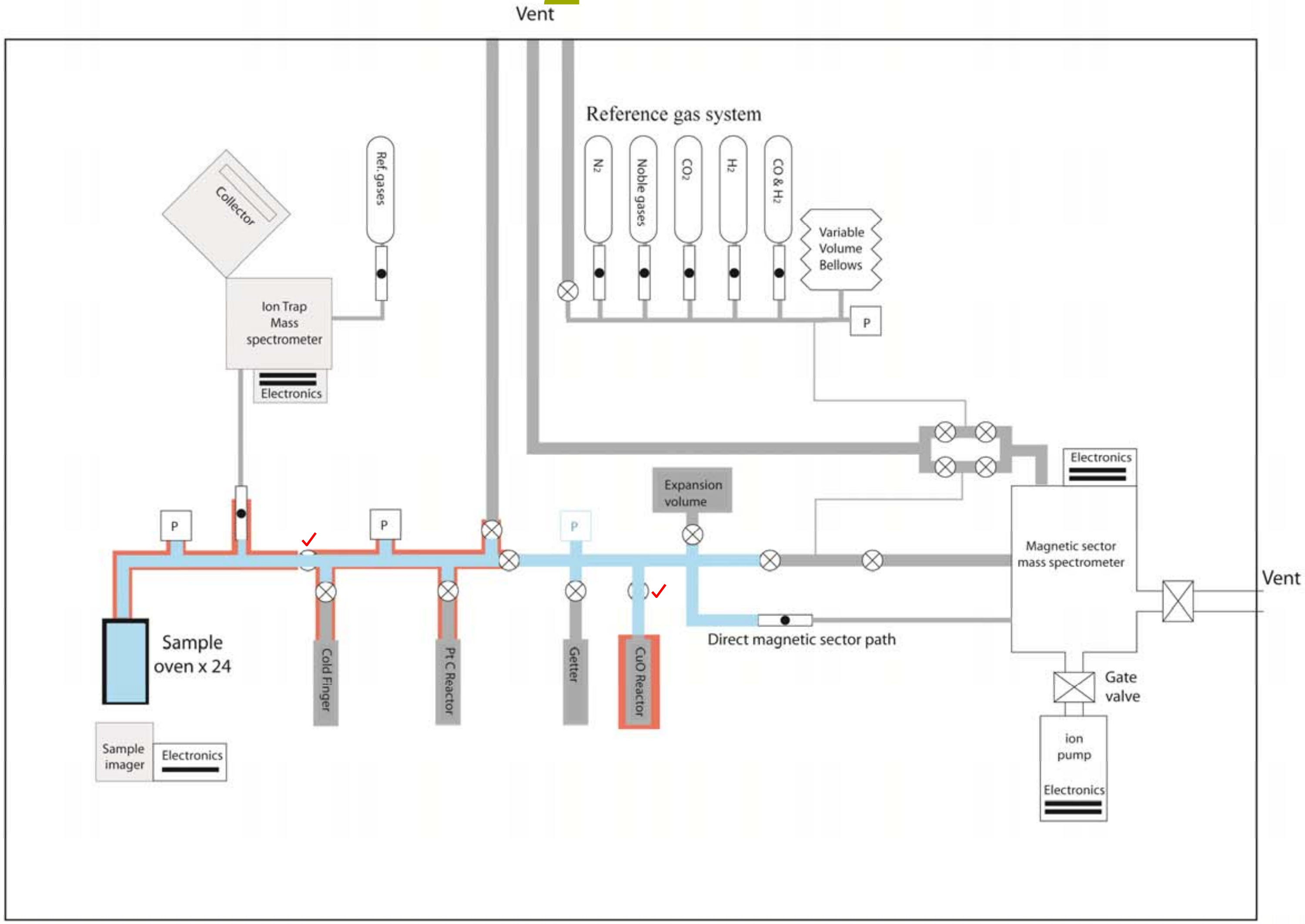

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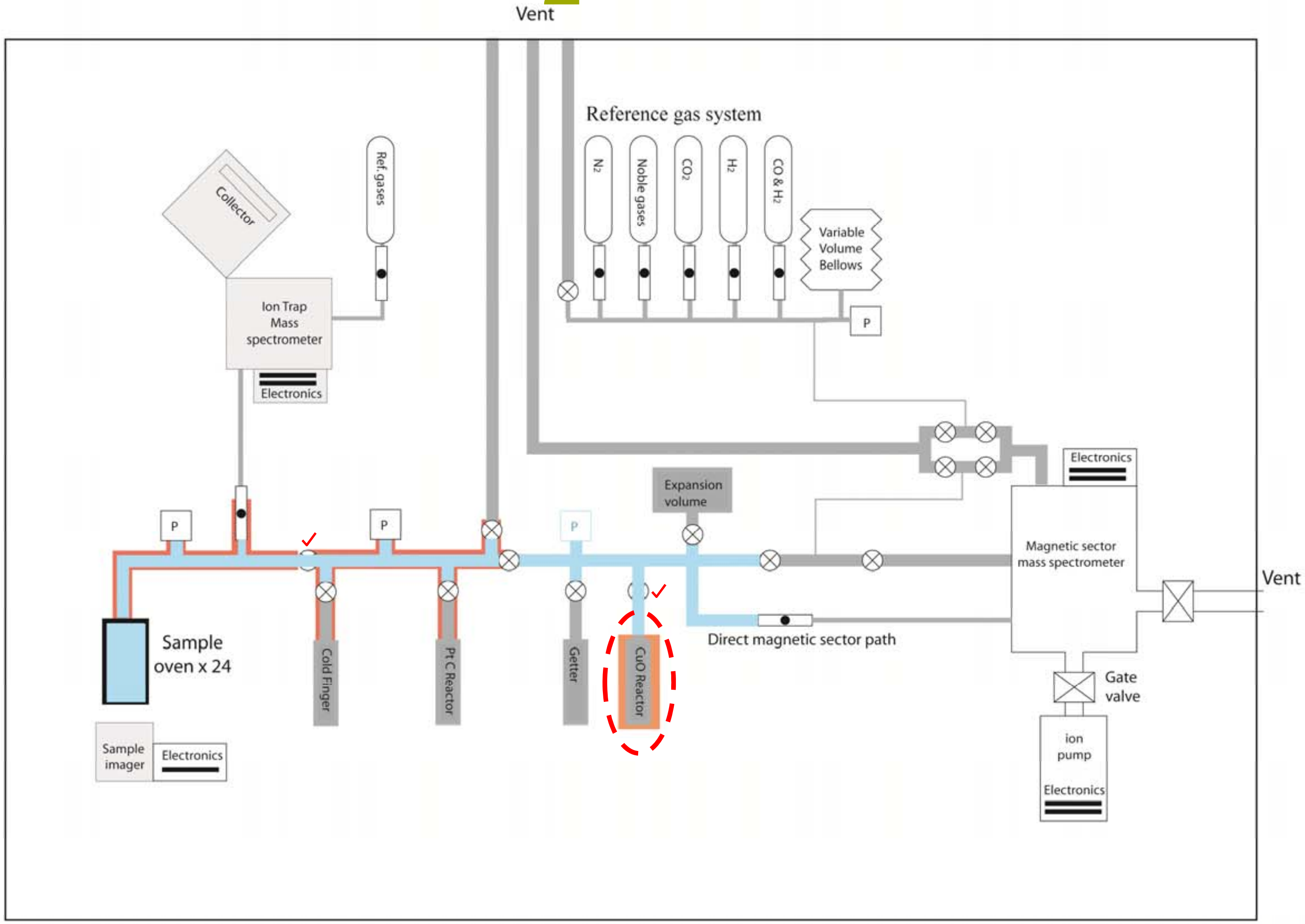

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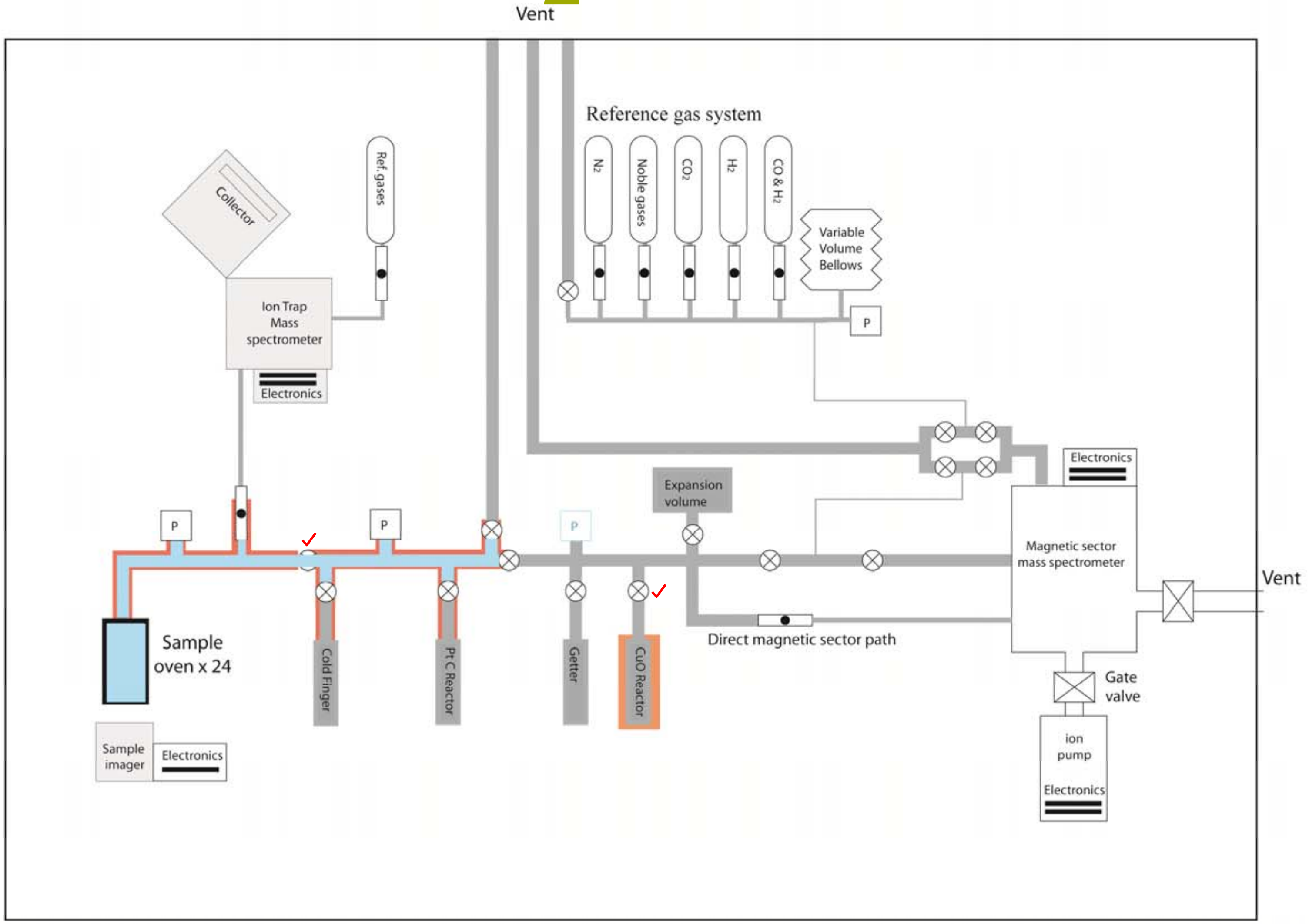

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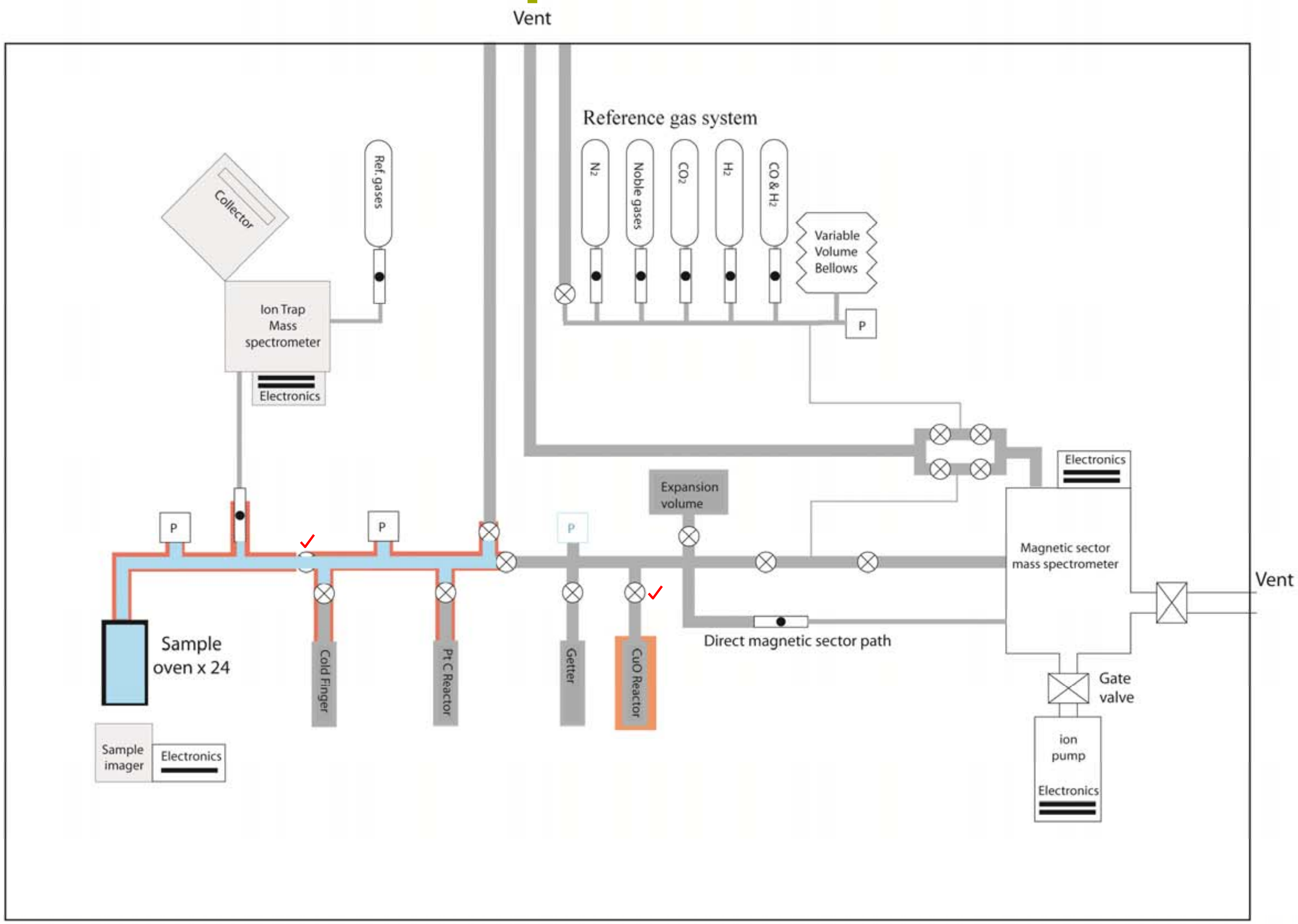

Heat sample to predetermined temperature

Volatiles released – H_2O, CO_2, N_2, noble gases + excess O_2

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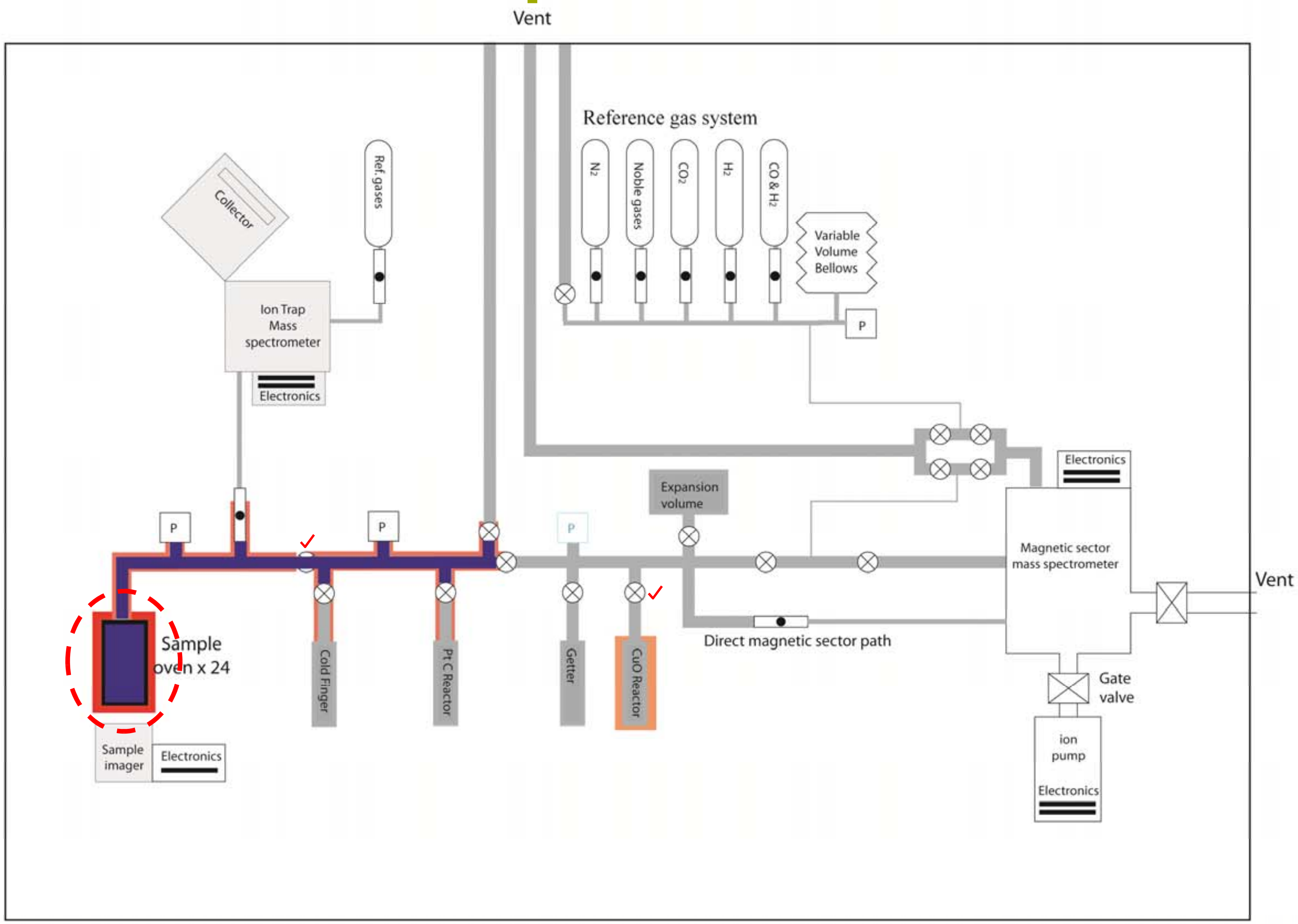

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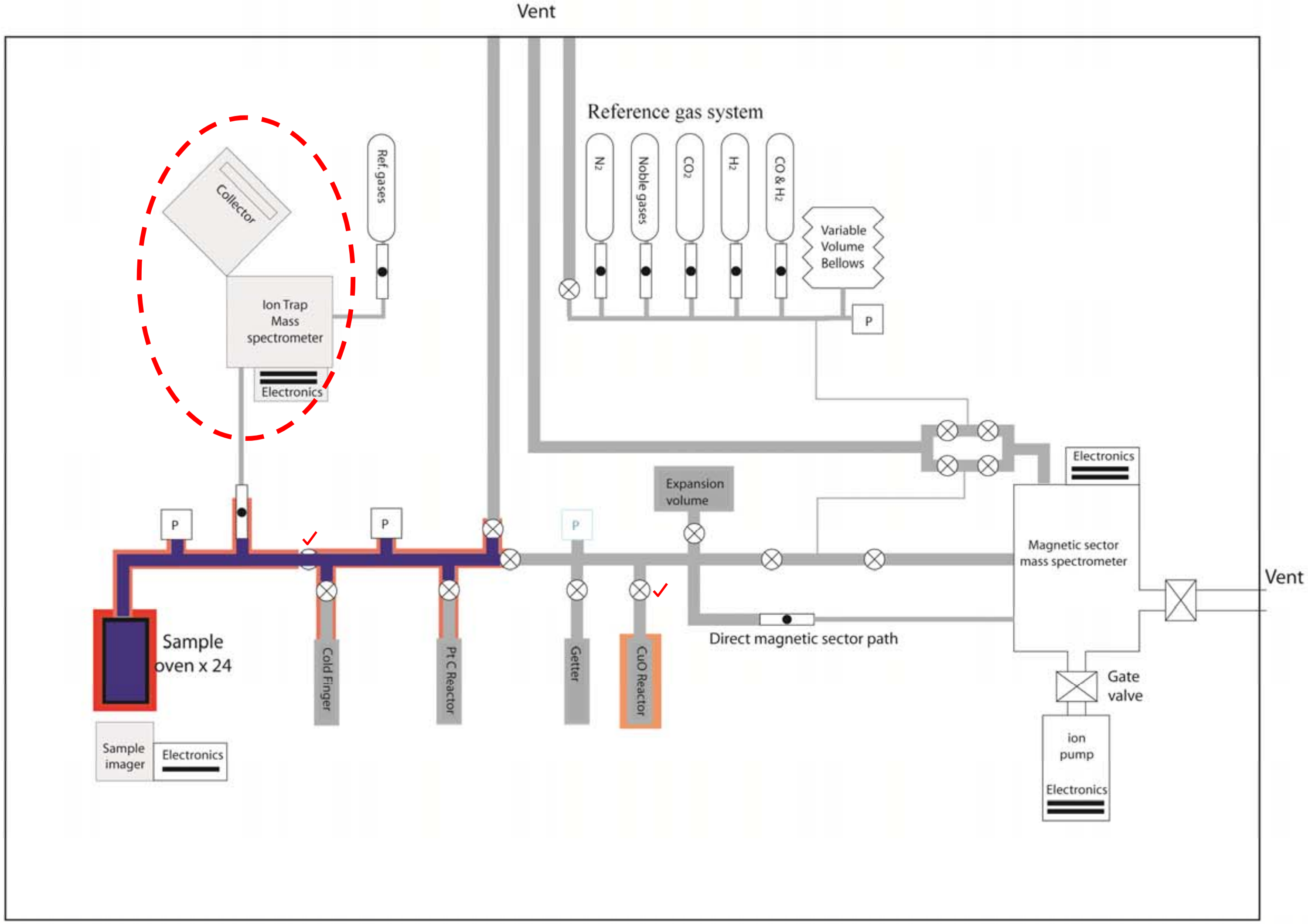

Analyse volatile concentration using Ion Trap MS

Choices
Prepare manifolds
Prepare O_2
Heat sample
Quick analysis
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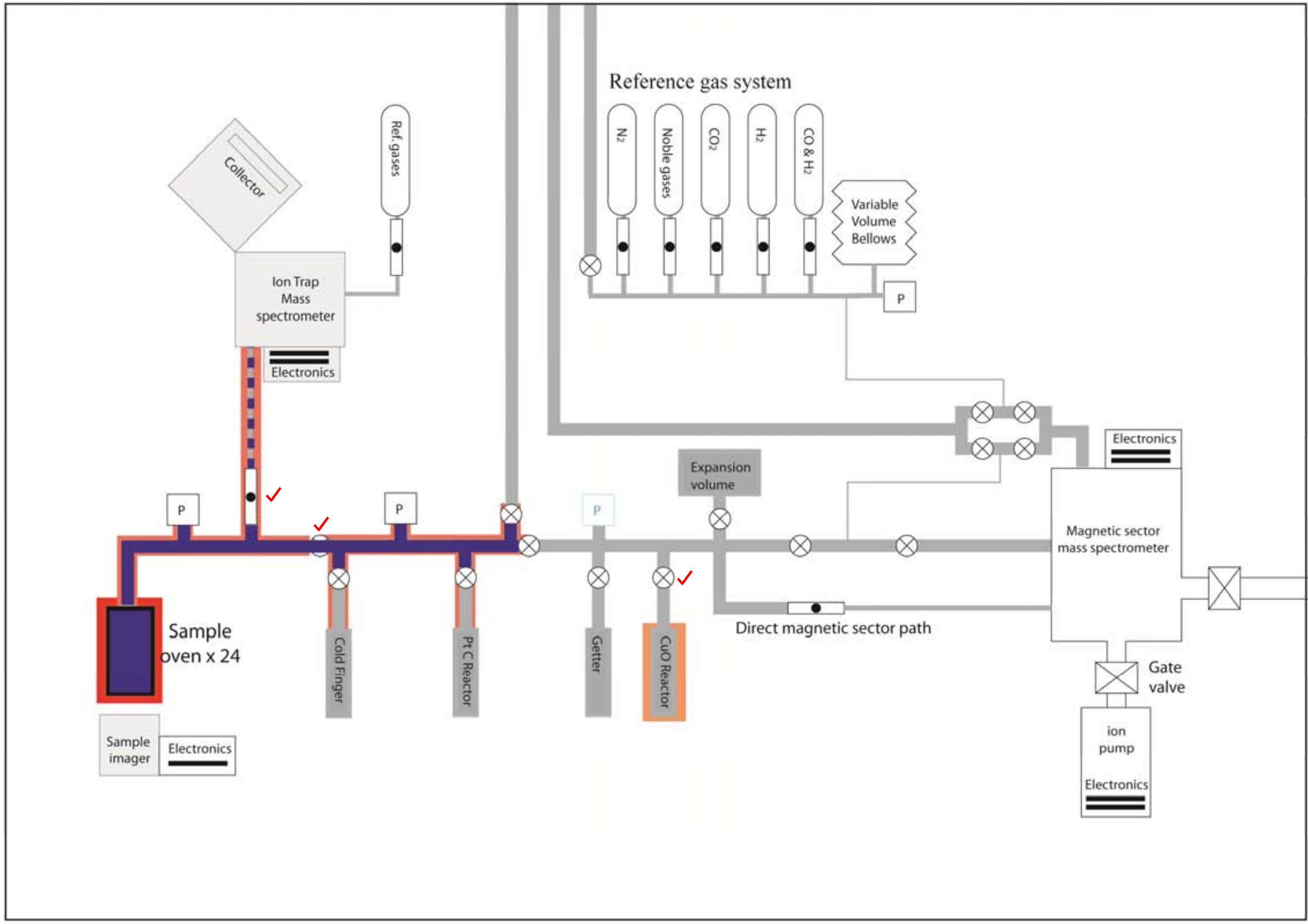

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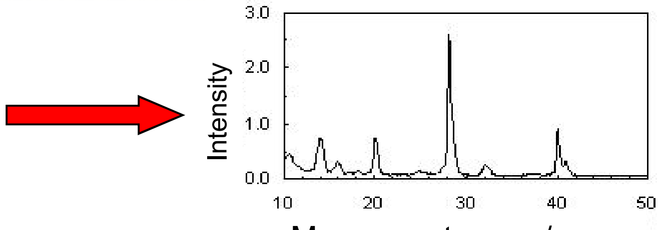

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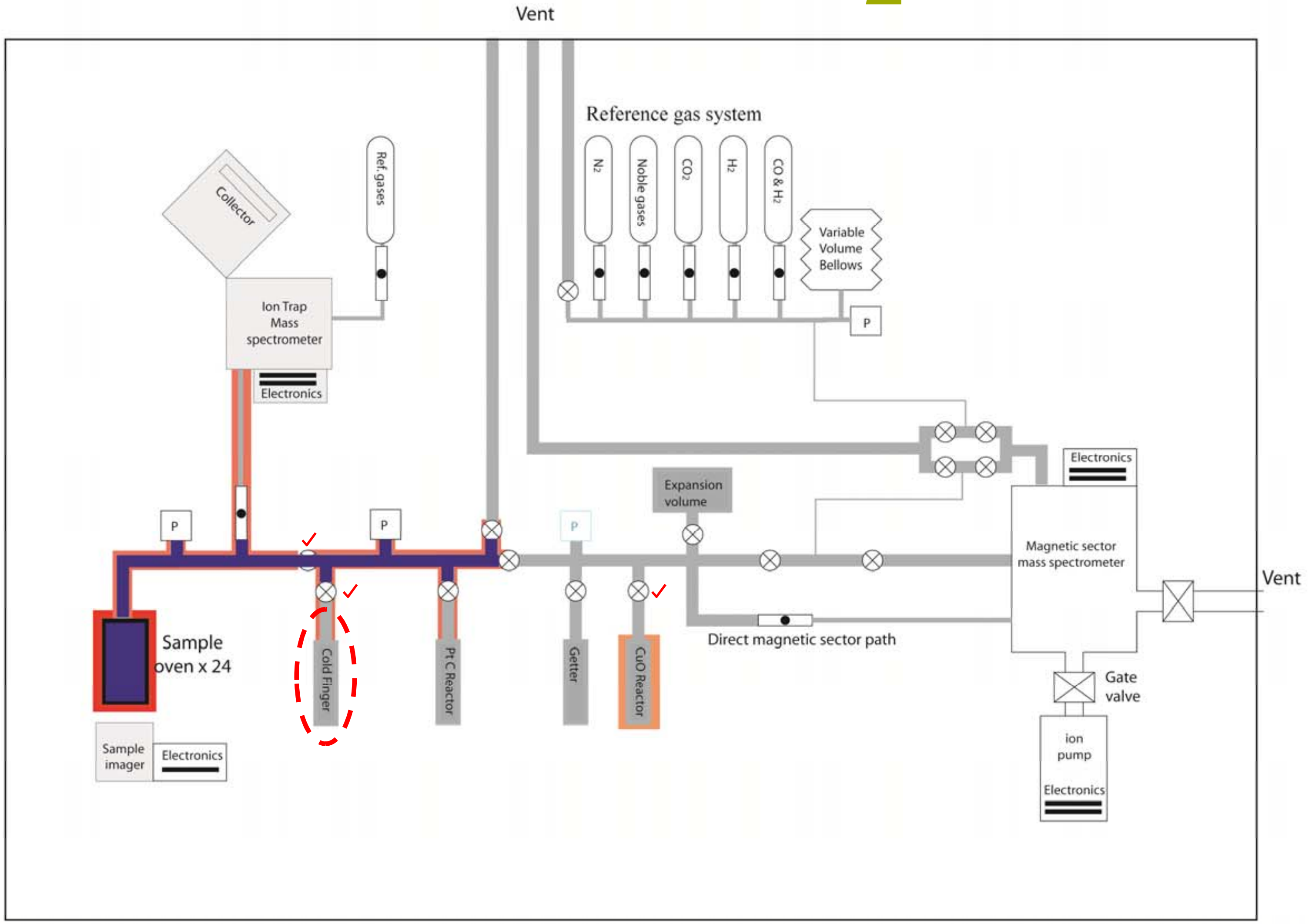
Trap water & CO_2



Close valve to CuO, open valves to cold finger
H_2O and CO_2 trapped
Volatiles remaining N_2, noble gases and excess O_2
Allow hot manifold to cool ~+20°C

Choices
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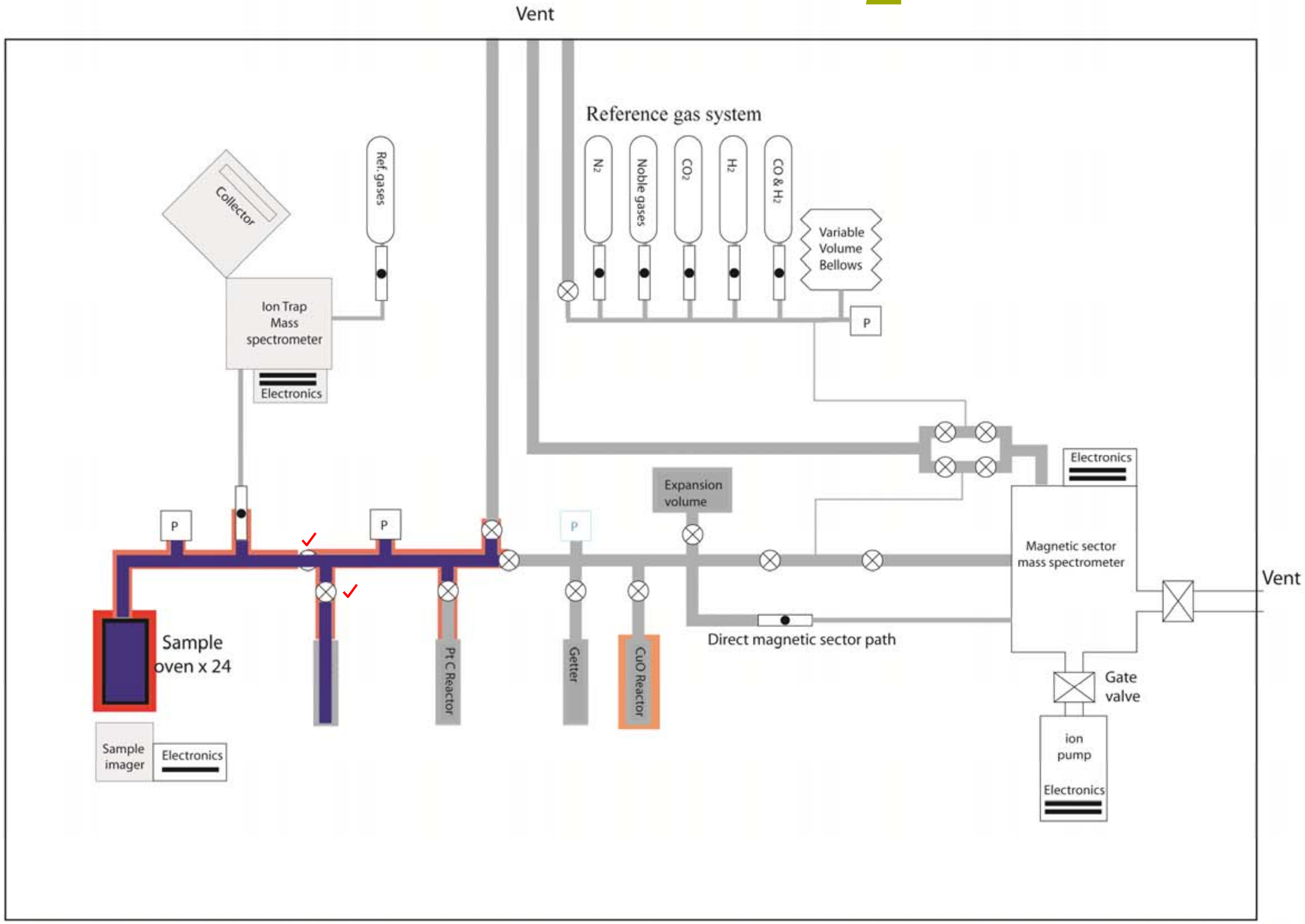

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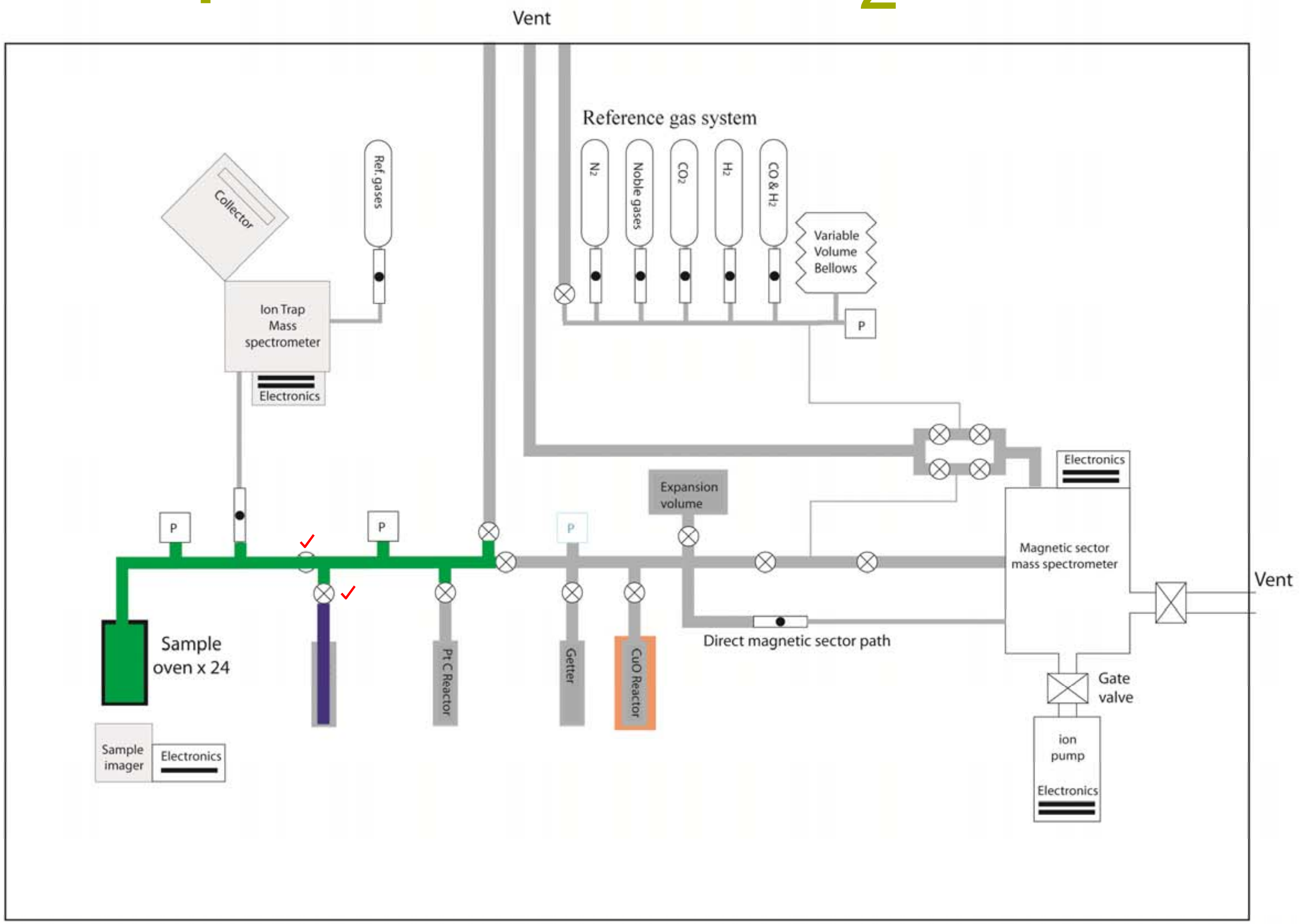

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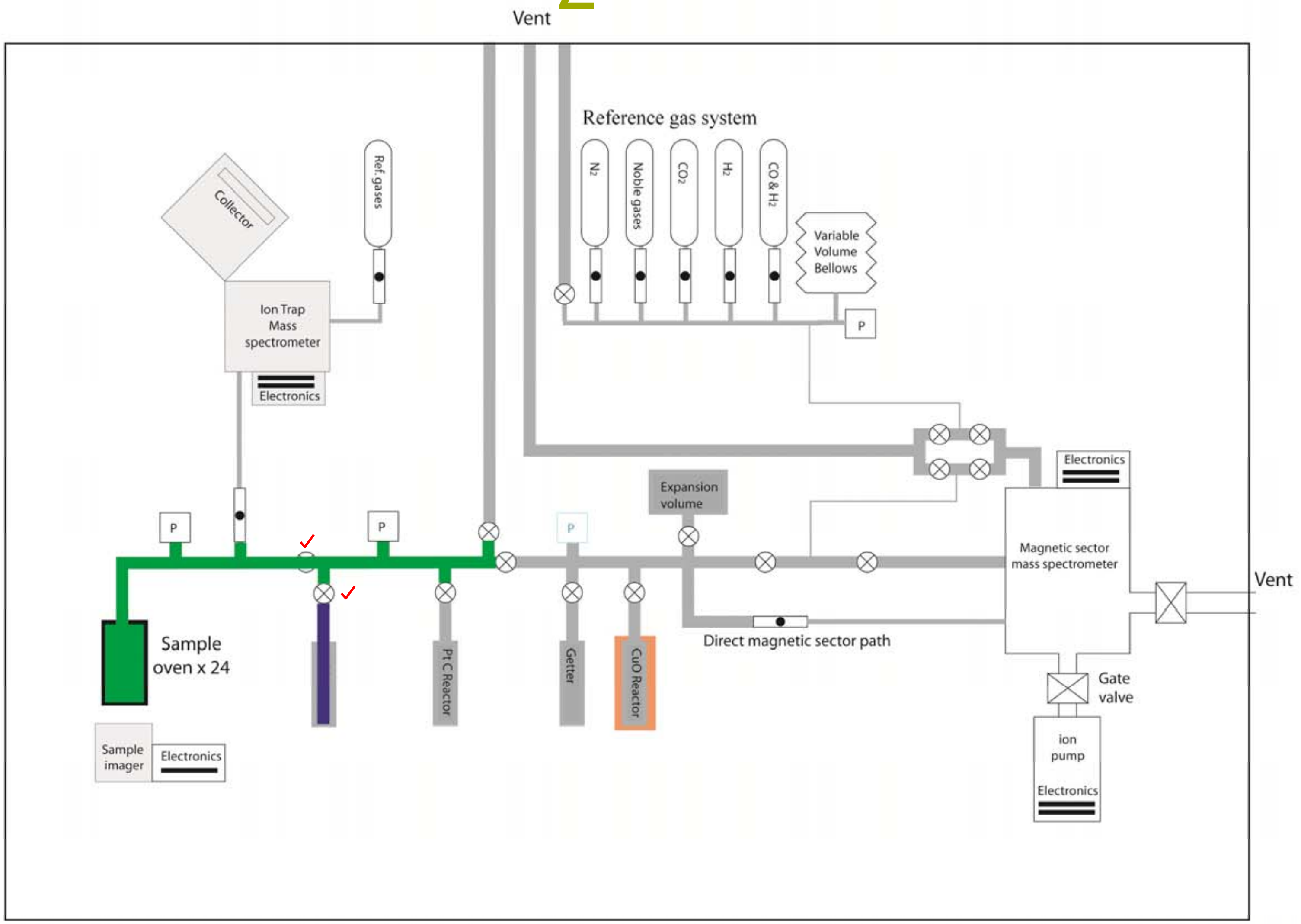

Open valves to CuO reactor
Wait 10 minutes
Reduce CuO reactor to +450°C
Wait 5 minutes
Volatiles remaining N_2 and noble gases

Choices
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Prepare O_2
Heat sample
Quick analysis
Trap water & CO_2
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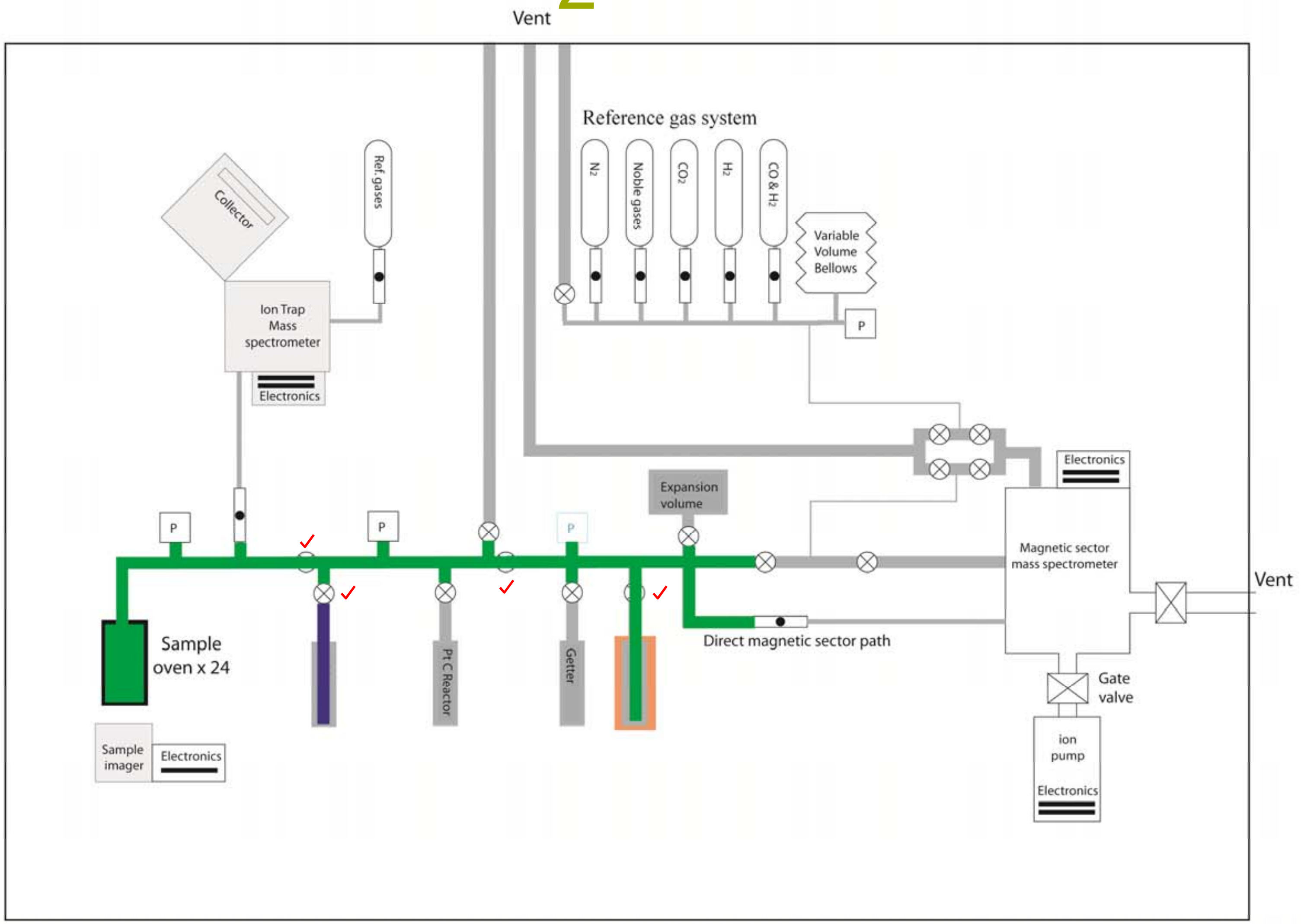

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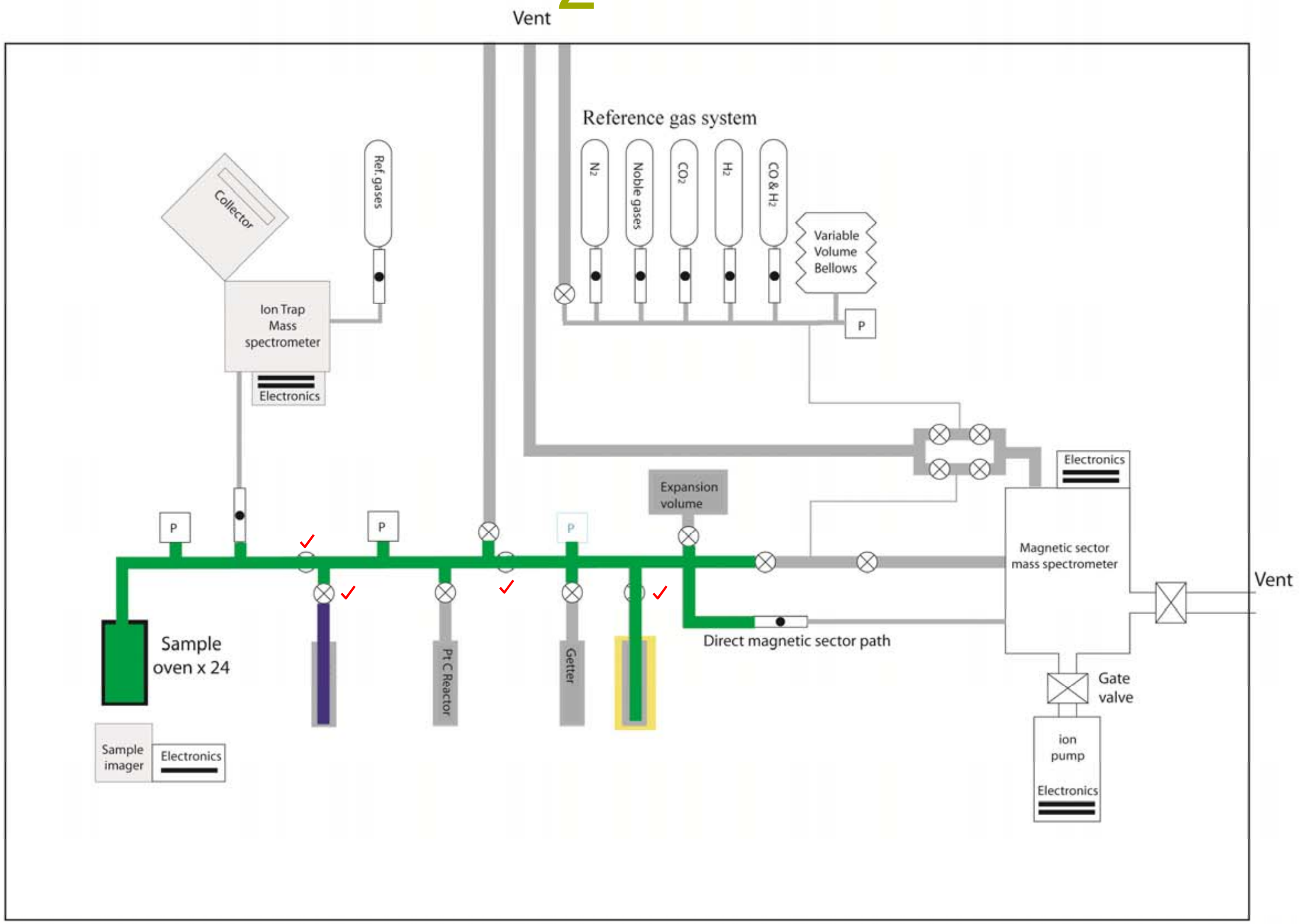

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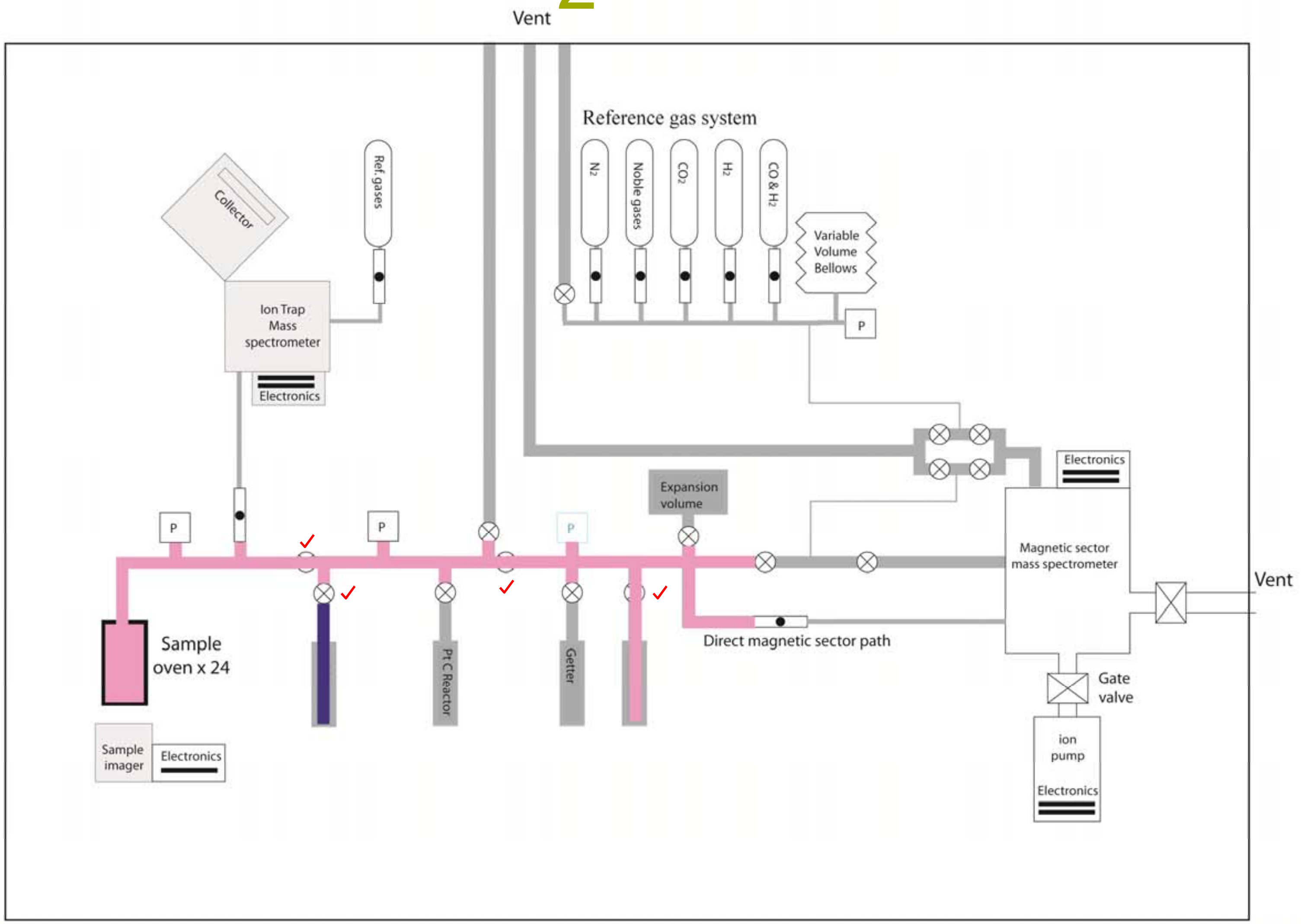

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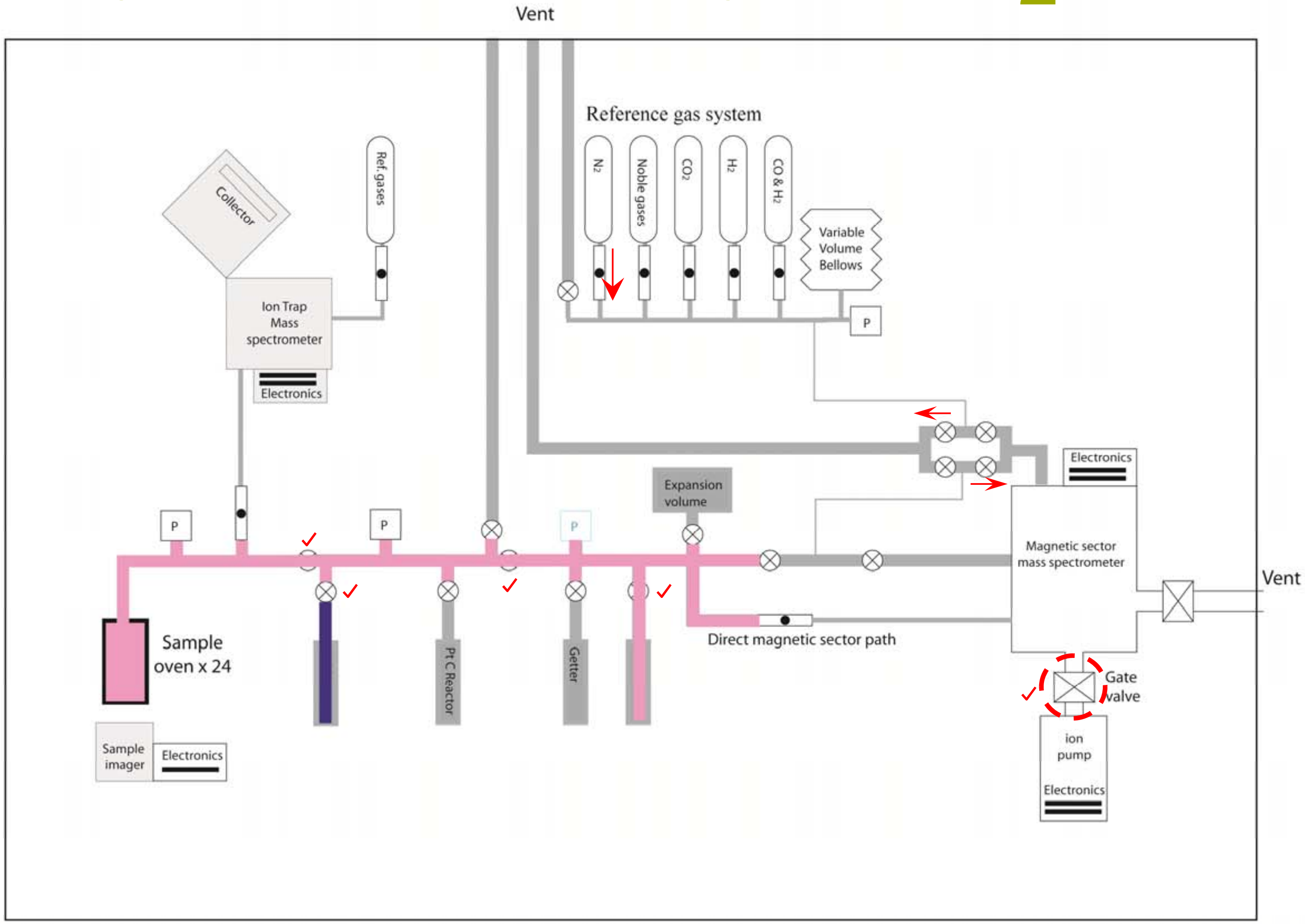
Dynamic Analysis N_2



Prepare N_2 reference gas
Open gate valve to ion pump
Sector MS set to m/z 28 & 29 on CNOS Faraday detectors
Ref/Sample comparison through change-over valve
– isotopic analysis $\delta^{15}N$

Choices
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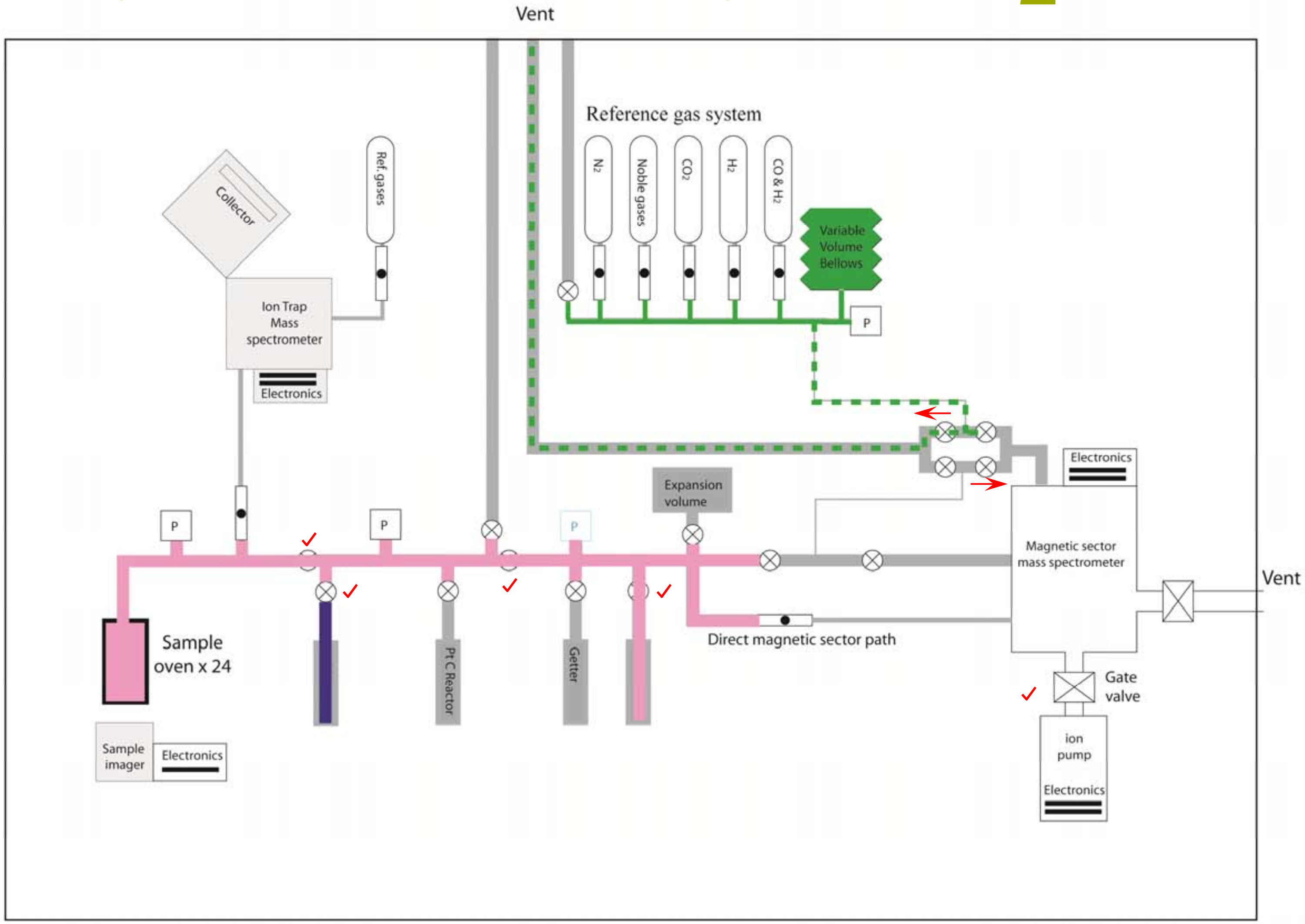

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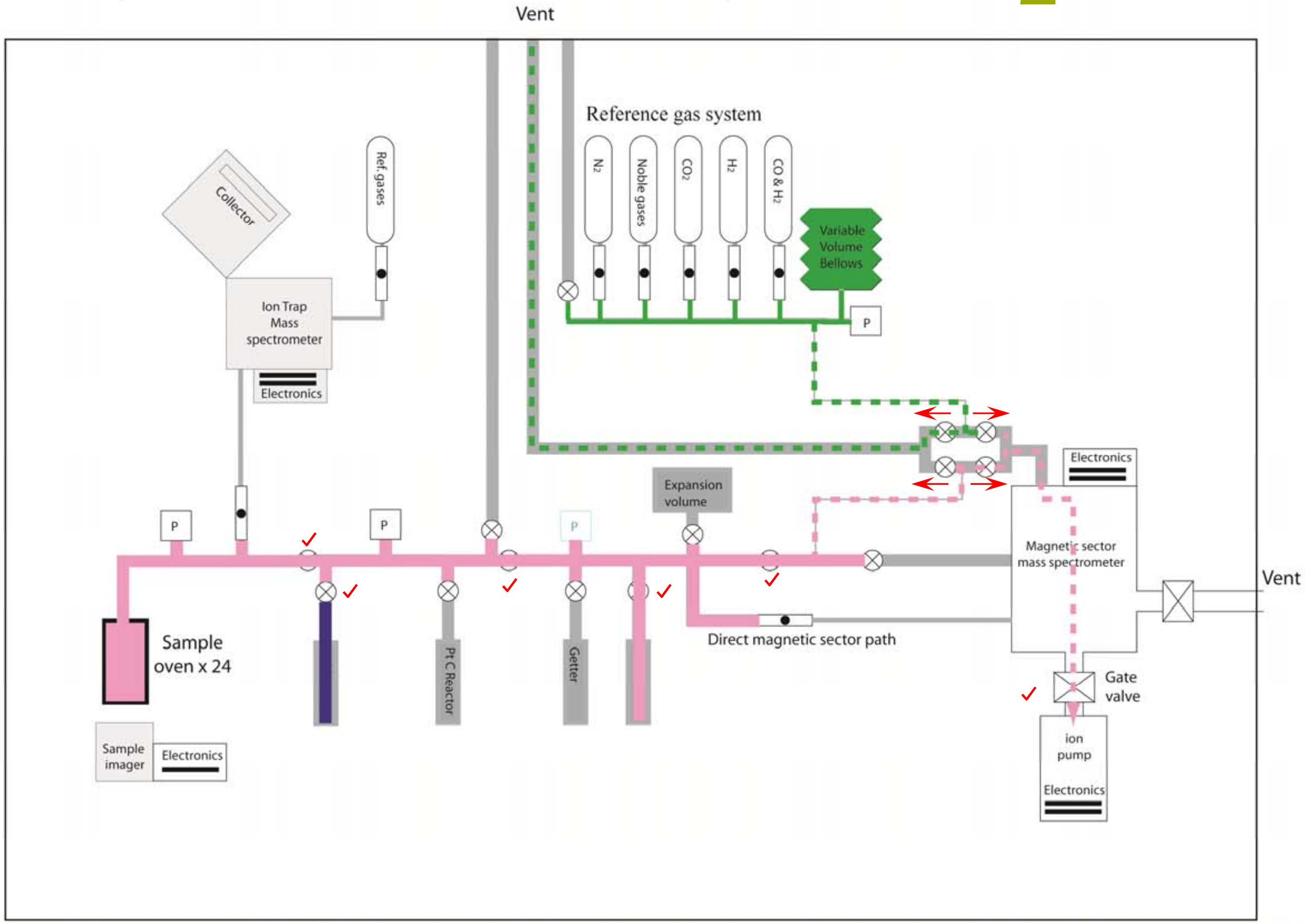

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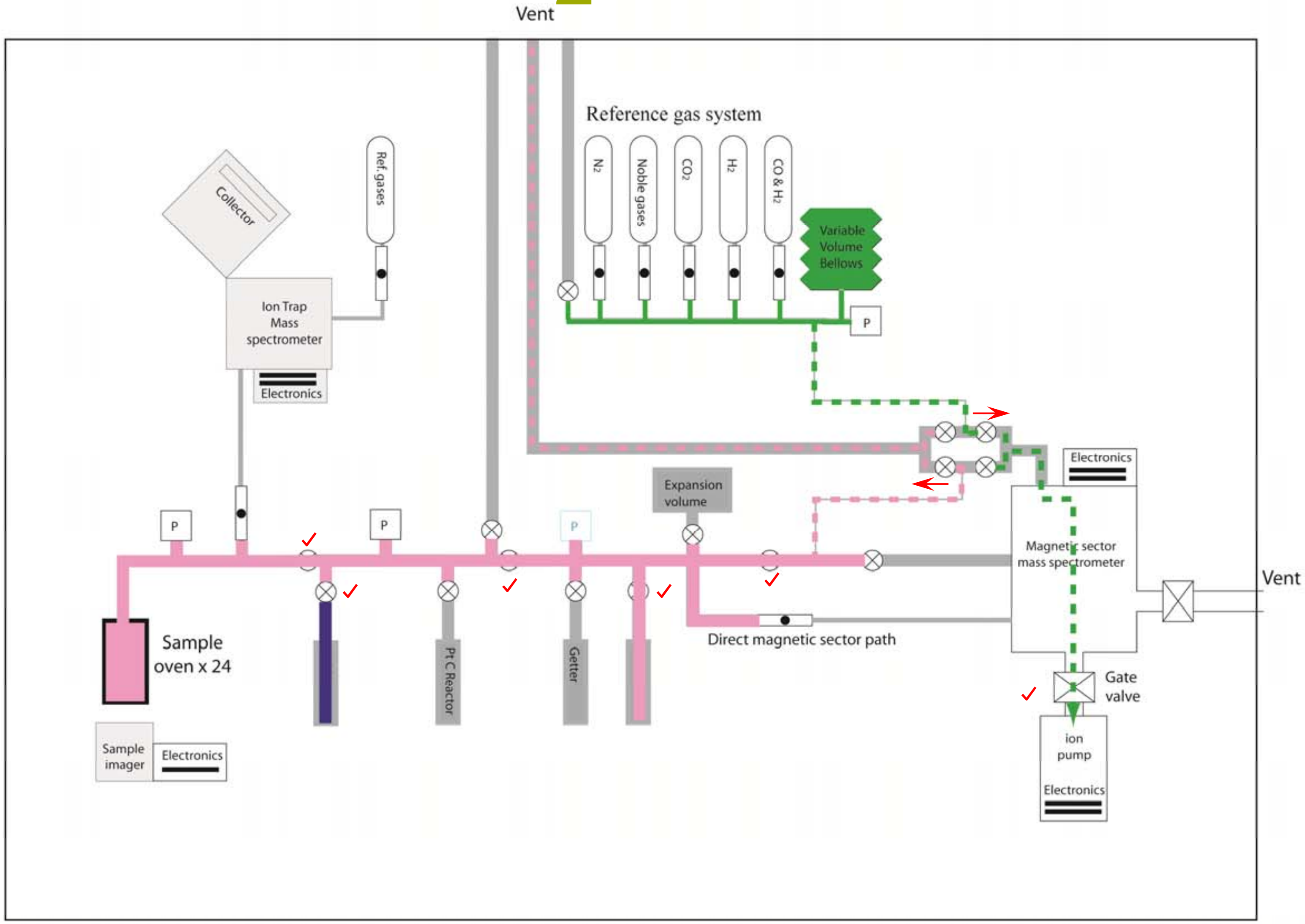

Close valve to magnetic sector MS
Open valve to getter
Volatiles remaining - noble gases

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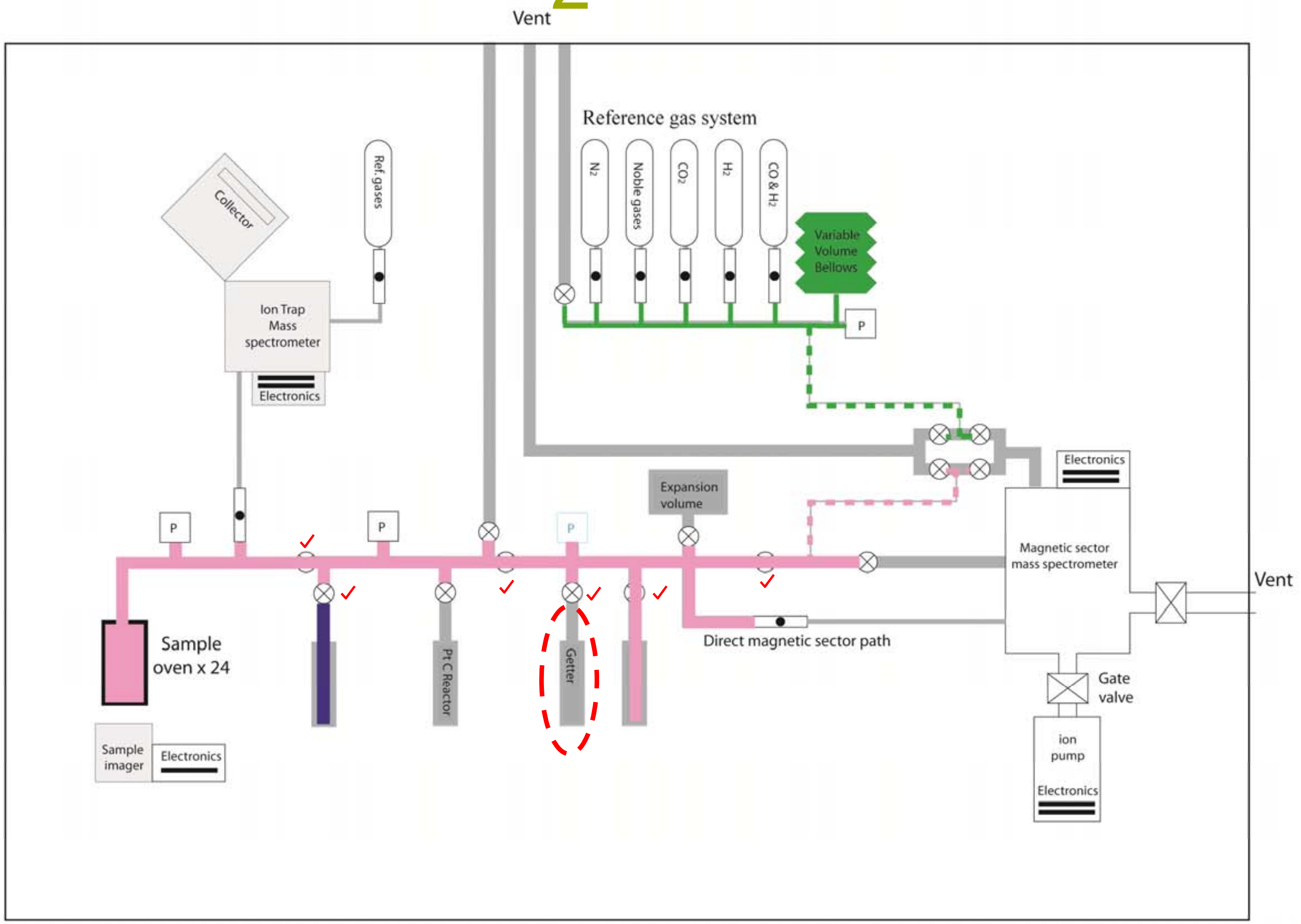

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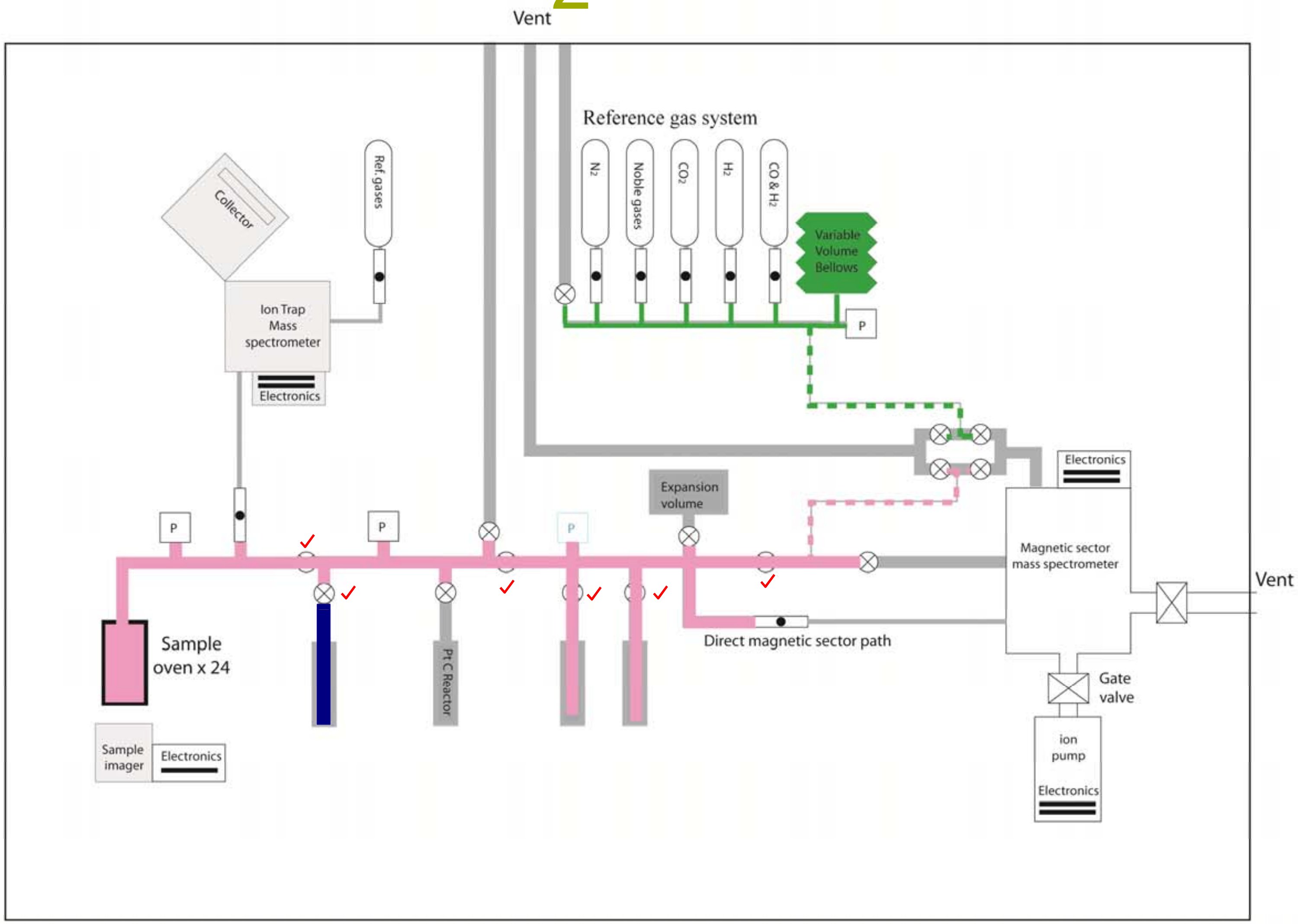

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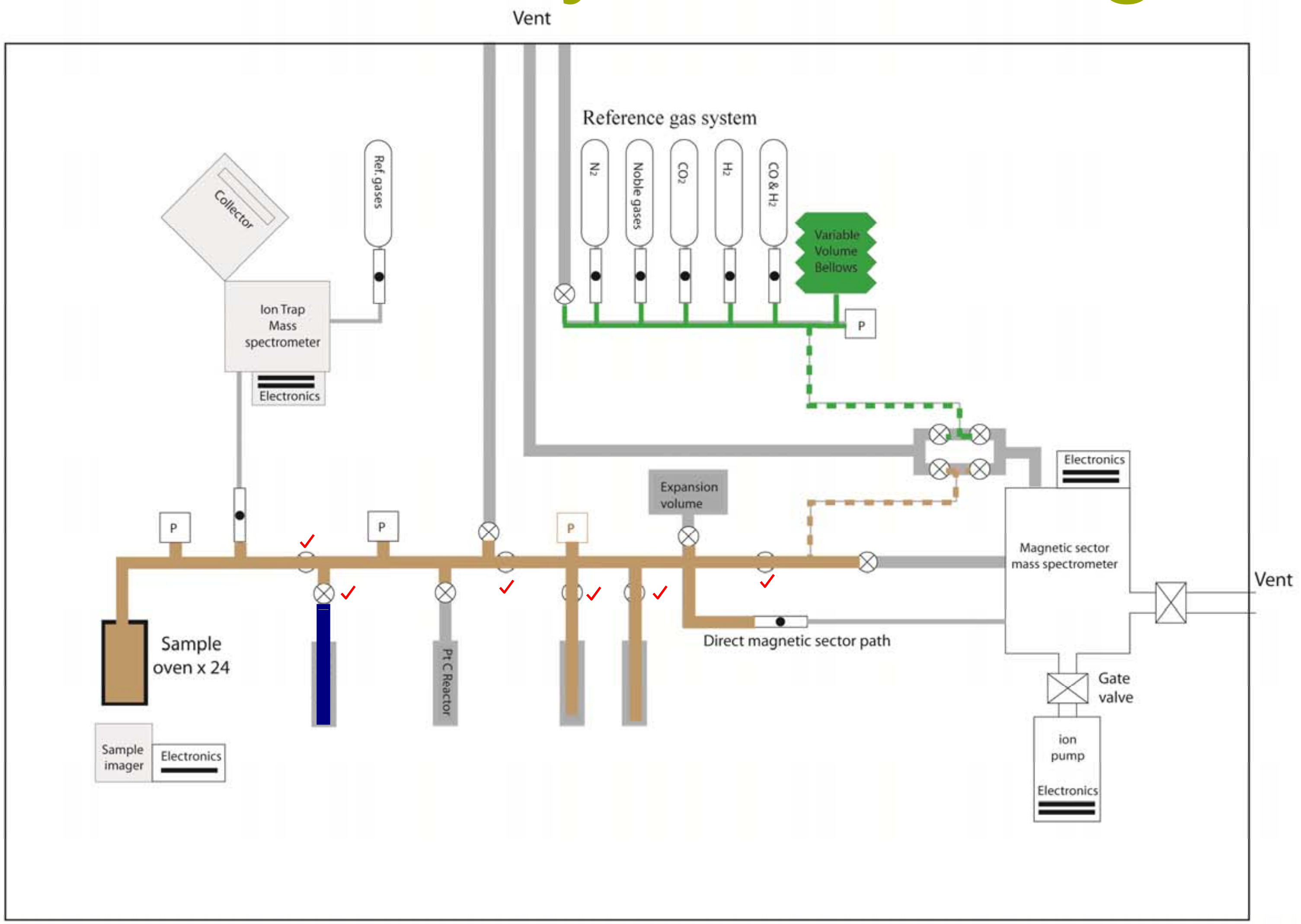
Static Analysis Noble gases



Close gate valve to ion pump
Admit all sample gas to magnetic sector mass spectrometer
Analyse noble gases on electron multiplier
-Ar m/z 36 – 40, Kr m/z 78 – 86 & Xe m/z 124 – 136
-He m/z 3-4 & Ne m/z 20-22 ?

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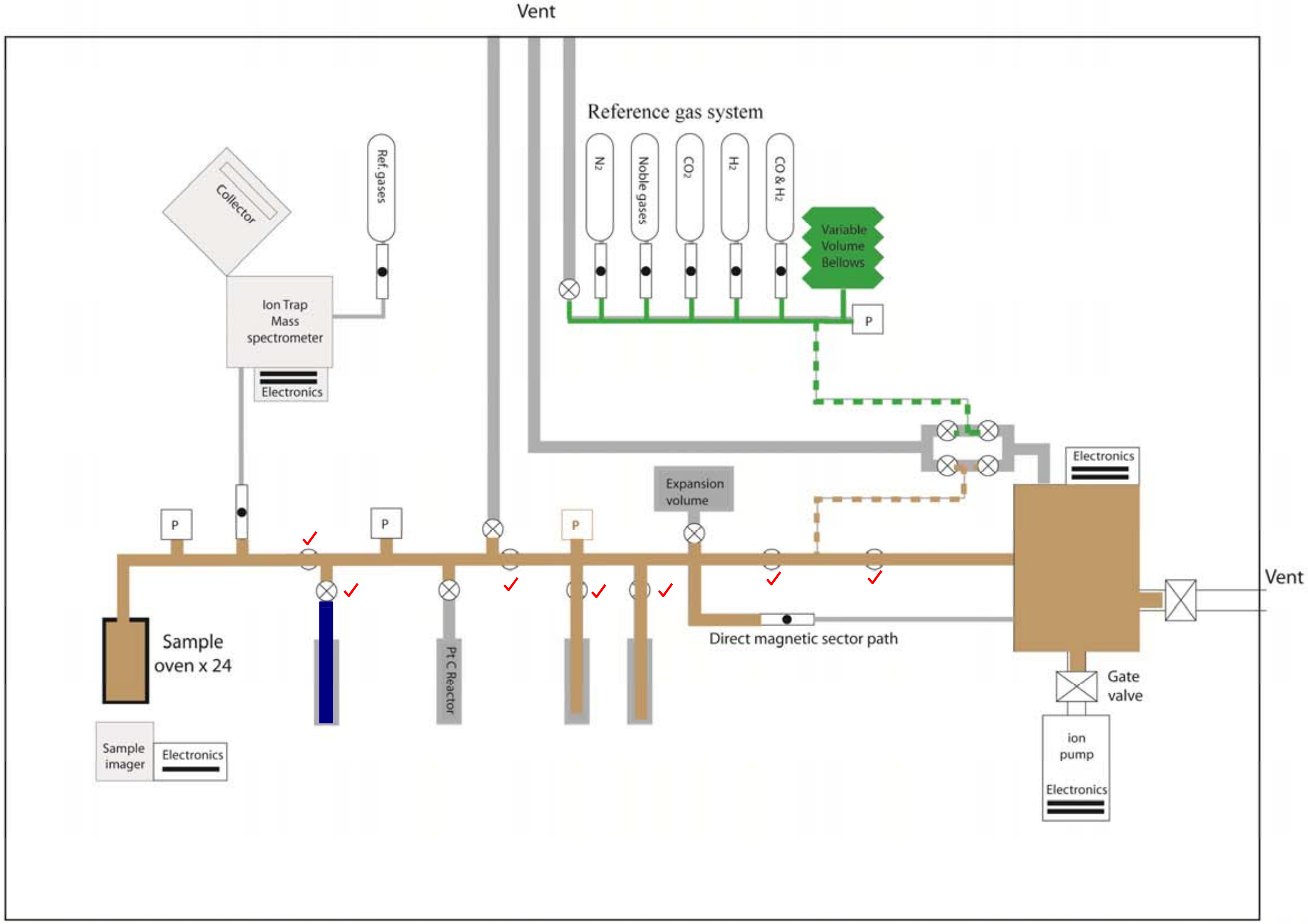

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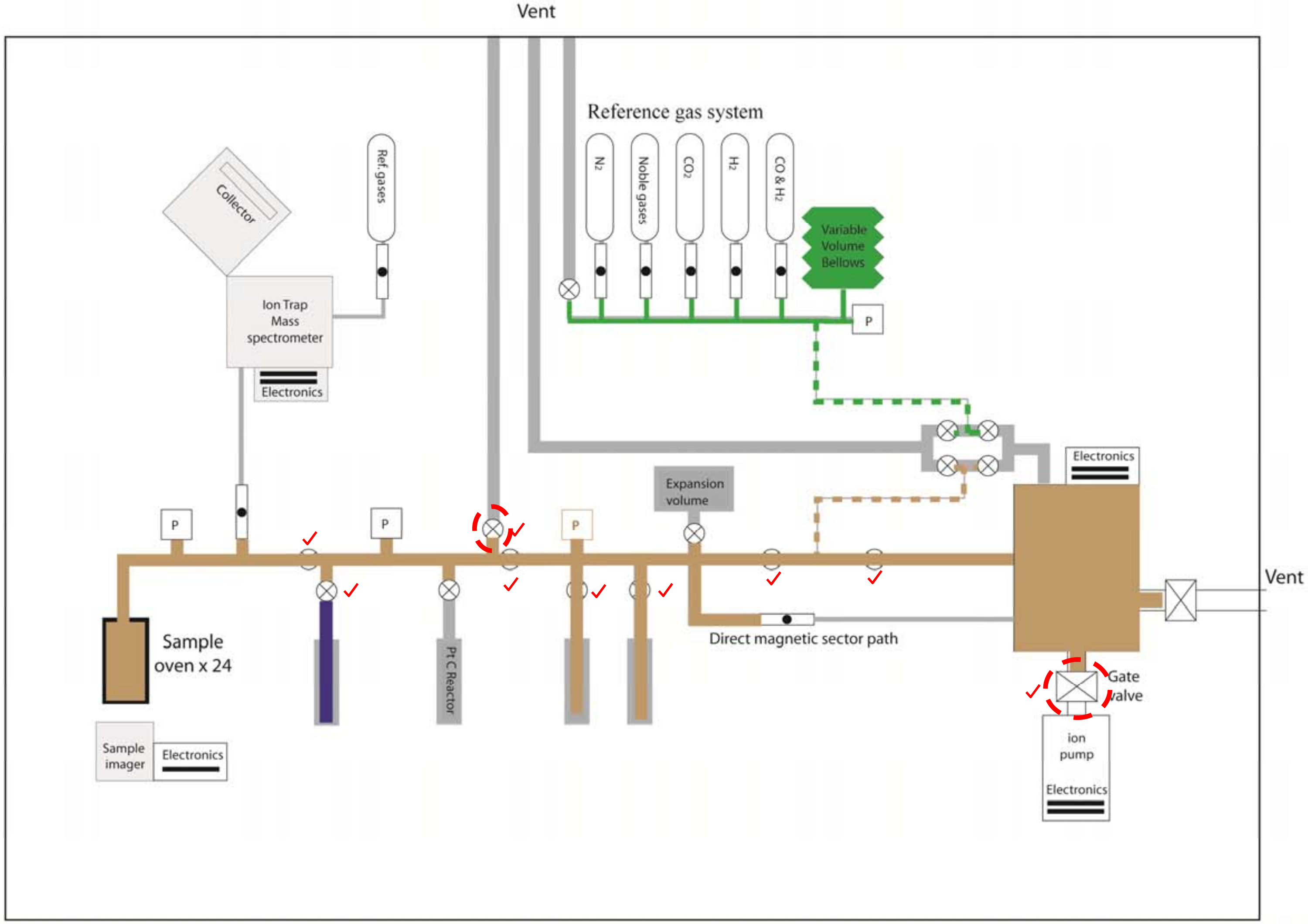
-He m/z 3-4 & Ne m/z 20-22 ?

Evacuate



Open gate valve to ion pump
Open Hot and Warm manifolds to vent
Open Reference gas manifolds to vent

Choices
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Prepare O_2
Heat sample
Quick analysis
Trap water & CO_2
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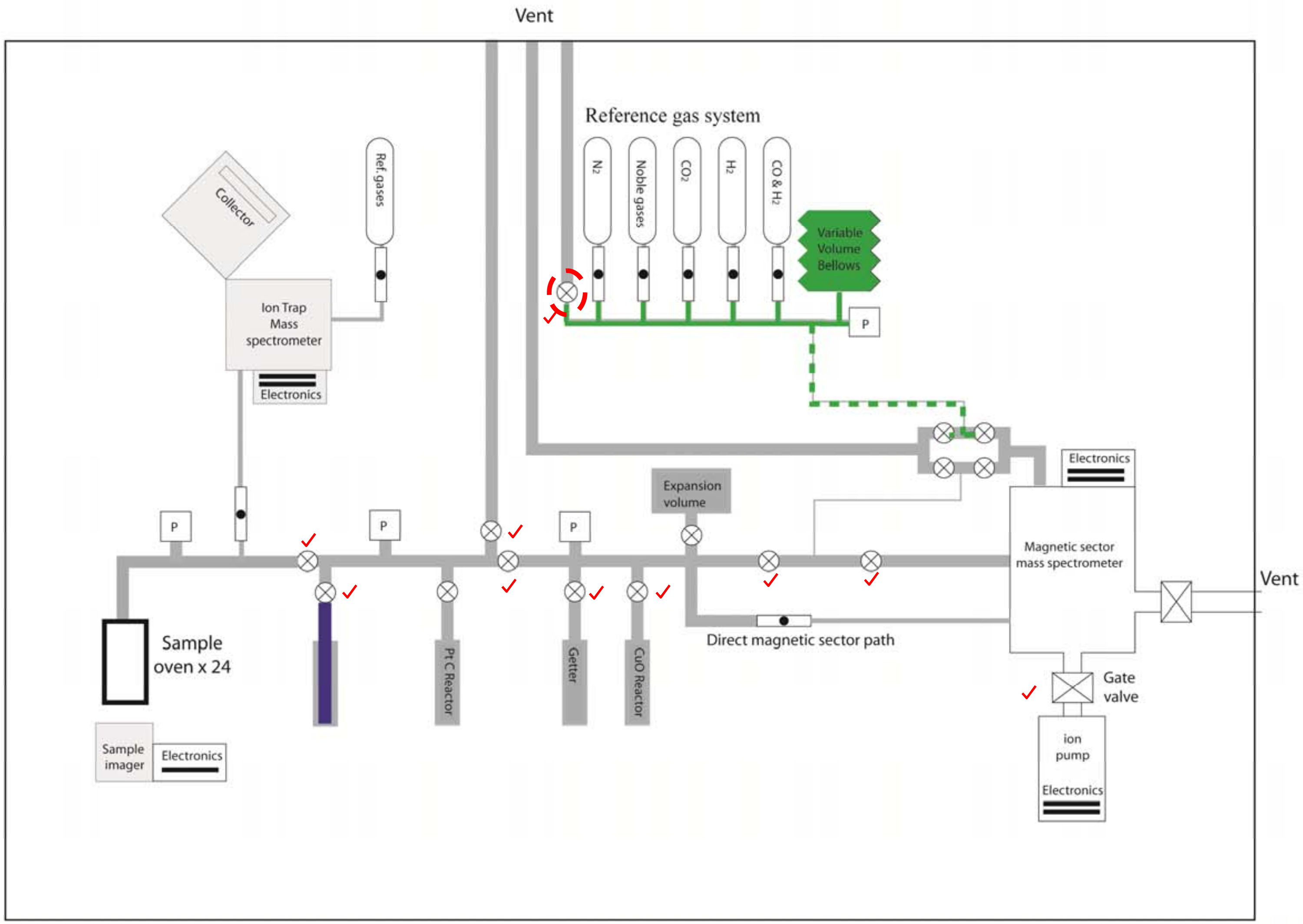
Remove N_2
St. Analysis Noble gas
Evacuate
Release CO_2
St. Analysis CO_2
Evacuate
Heat Manifold
Release H_2O
Convert to H
Dy. Analysis D/H
Evacuate

Evacuate



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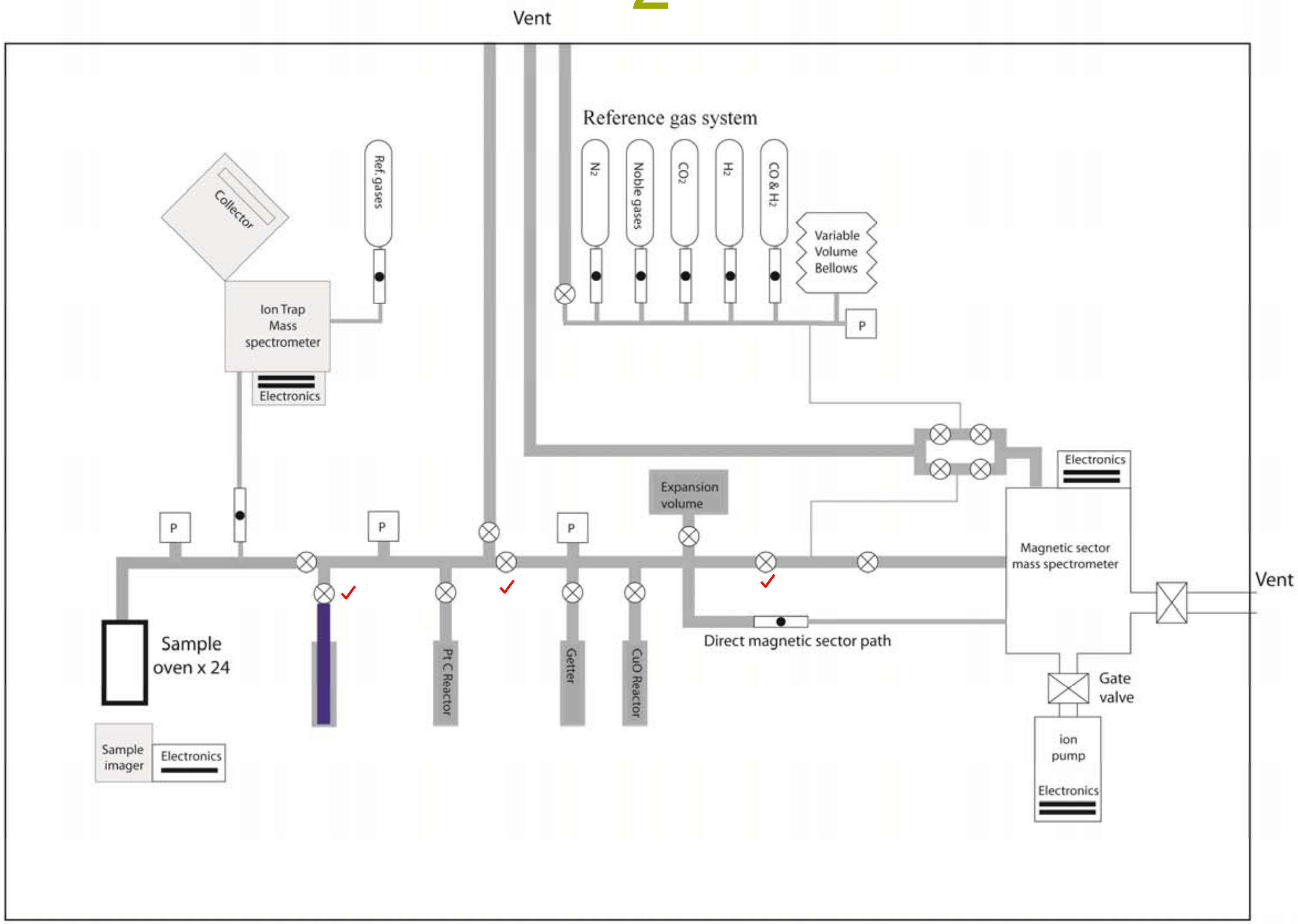
Release CO_2



Heat cold finger to -100°C

CO_2 released

- Choices
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- Prepare O_2
- Heat sample
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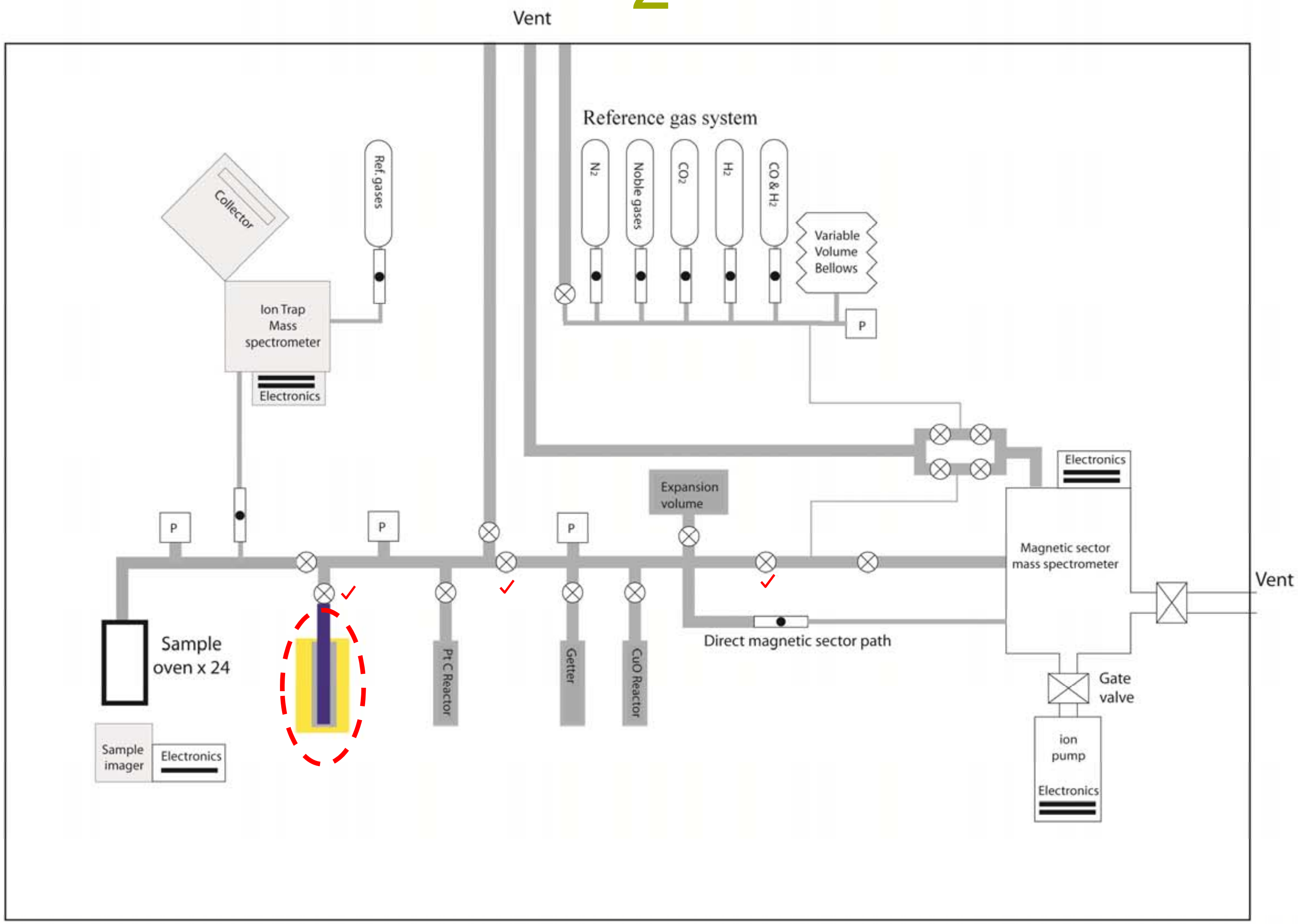
- Evacuate

Release CO_2



Heat cold finger to -100°C
CO_2 released

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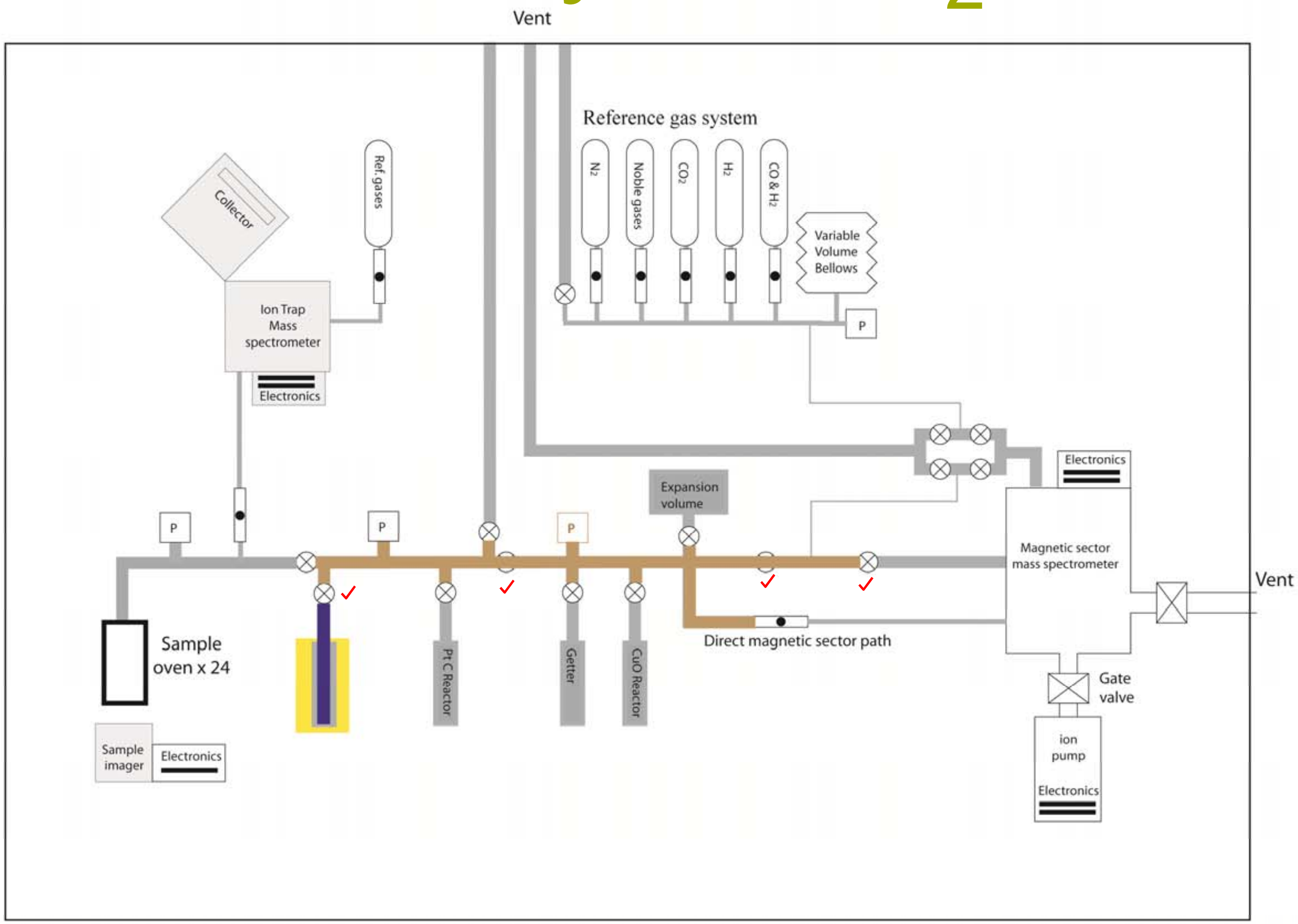
Convert to H
Dy. Analysis D/H
Evacuate

Static Analysis CO_2



Close gate valve to ion pump
Admit all sample gas to magnetic sector mass spectrometer
Analyse CO_2 sample gas on CNOS detector
Remove sample CO_2
Prepare and analyse CO_2 reference gas

Choices
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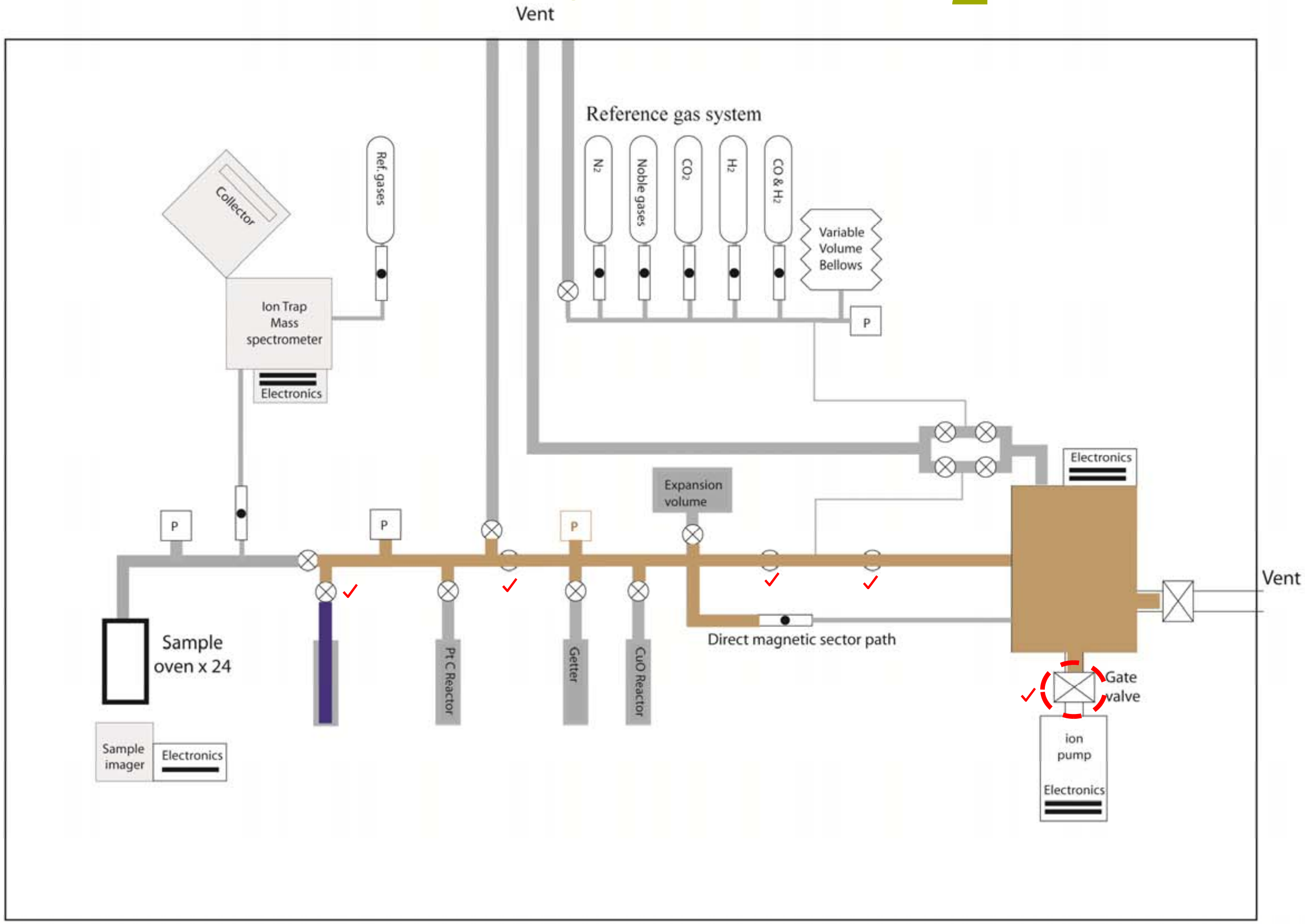

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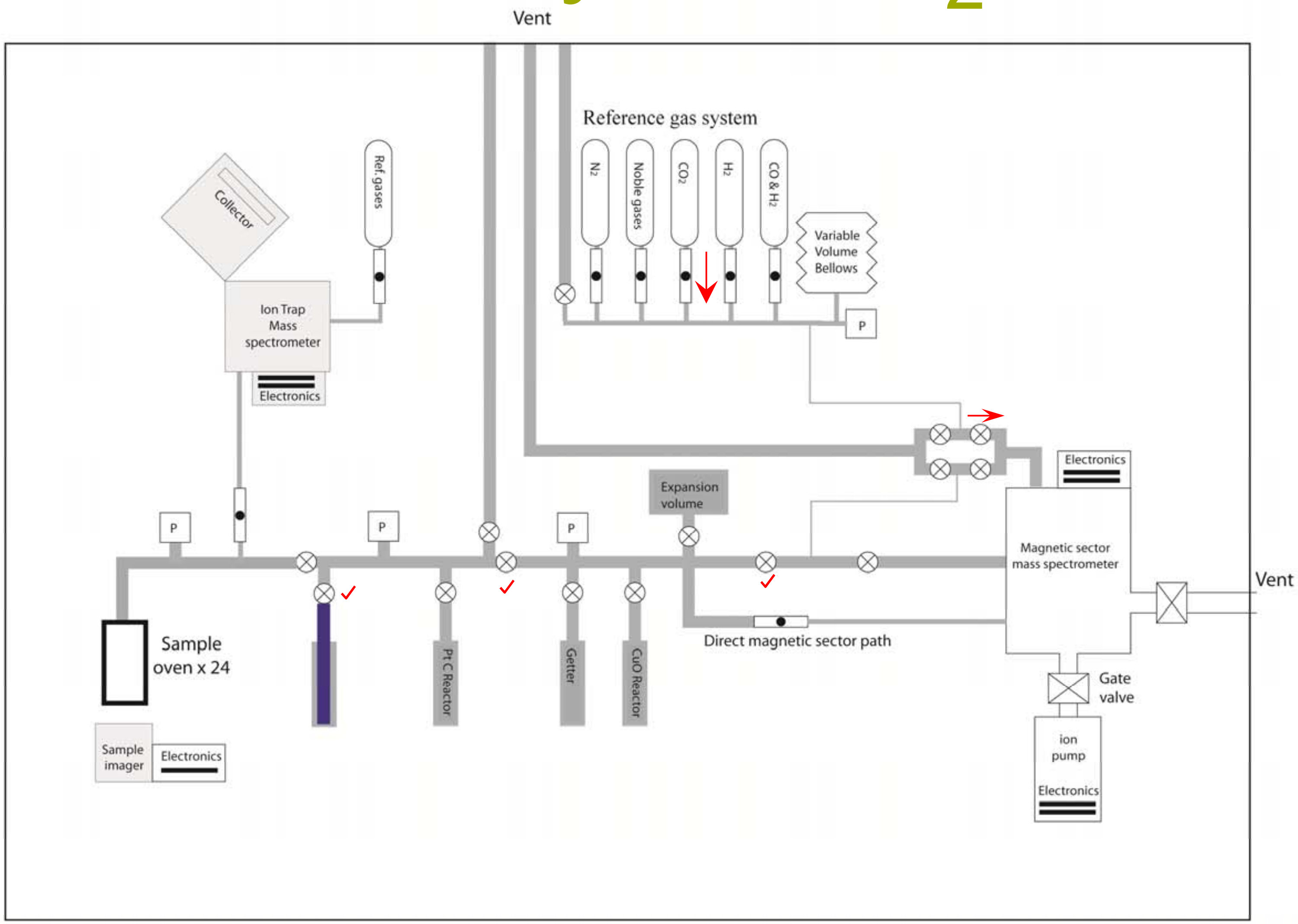

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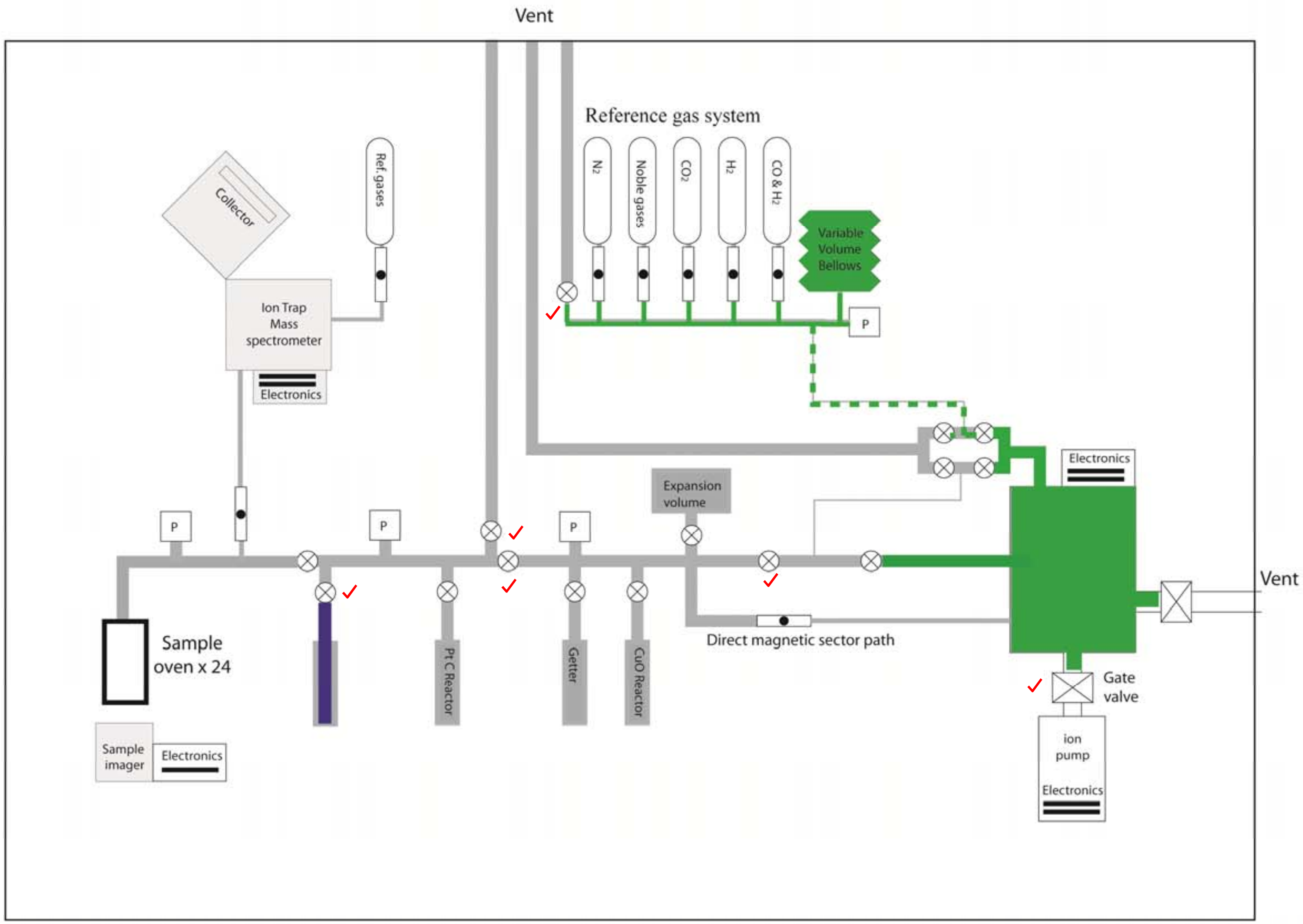
Evacuate



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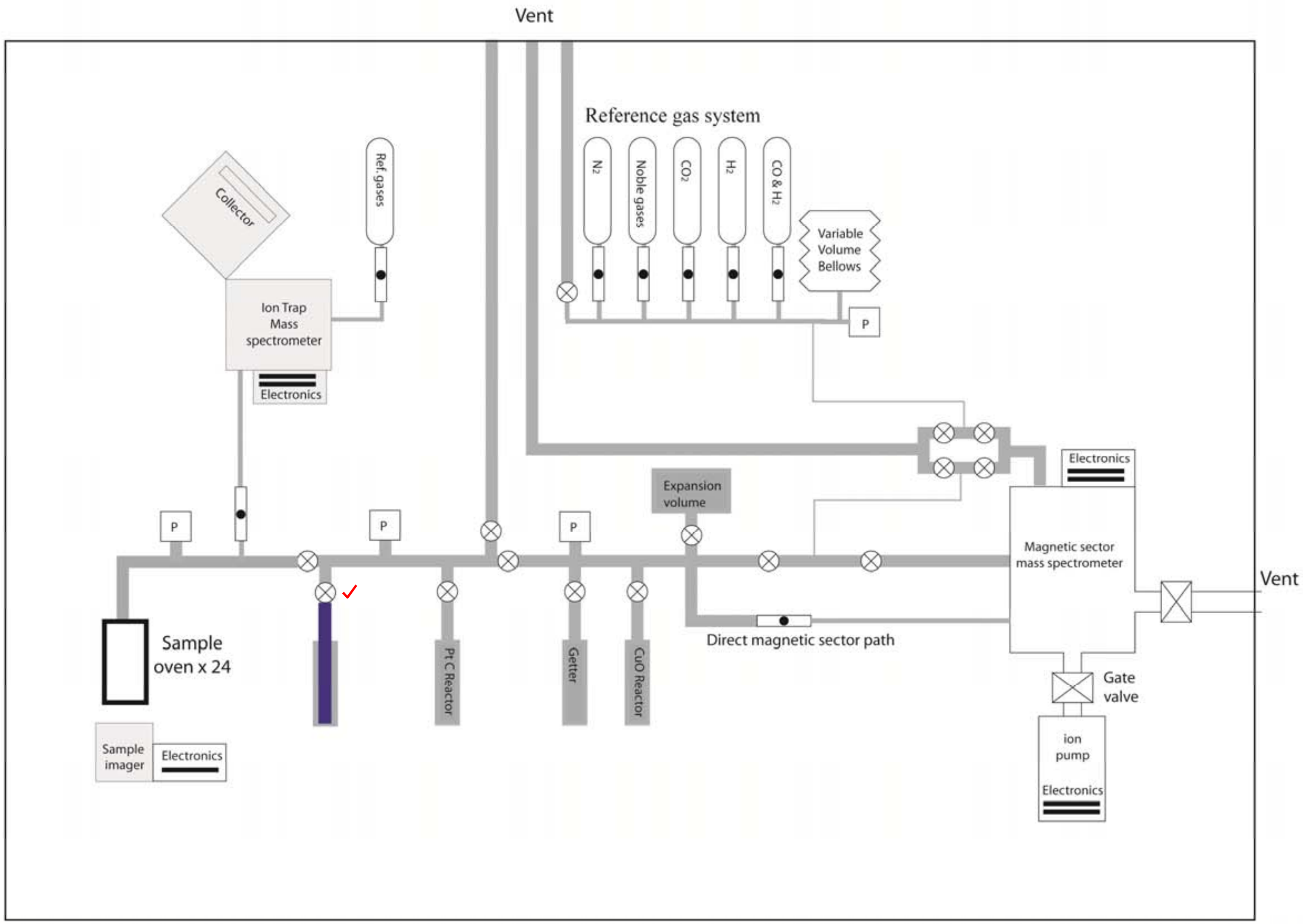
Heat Manifold



Water sticks
Heat hot manifold to +100°C

Choices
Prepare manifolds
Prepare O_2
Heat sample
Quick analysis
Trap water & CO_2
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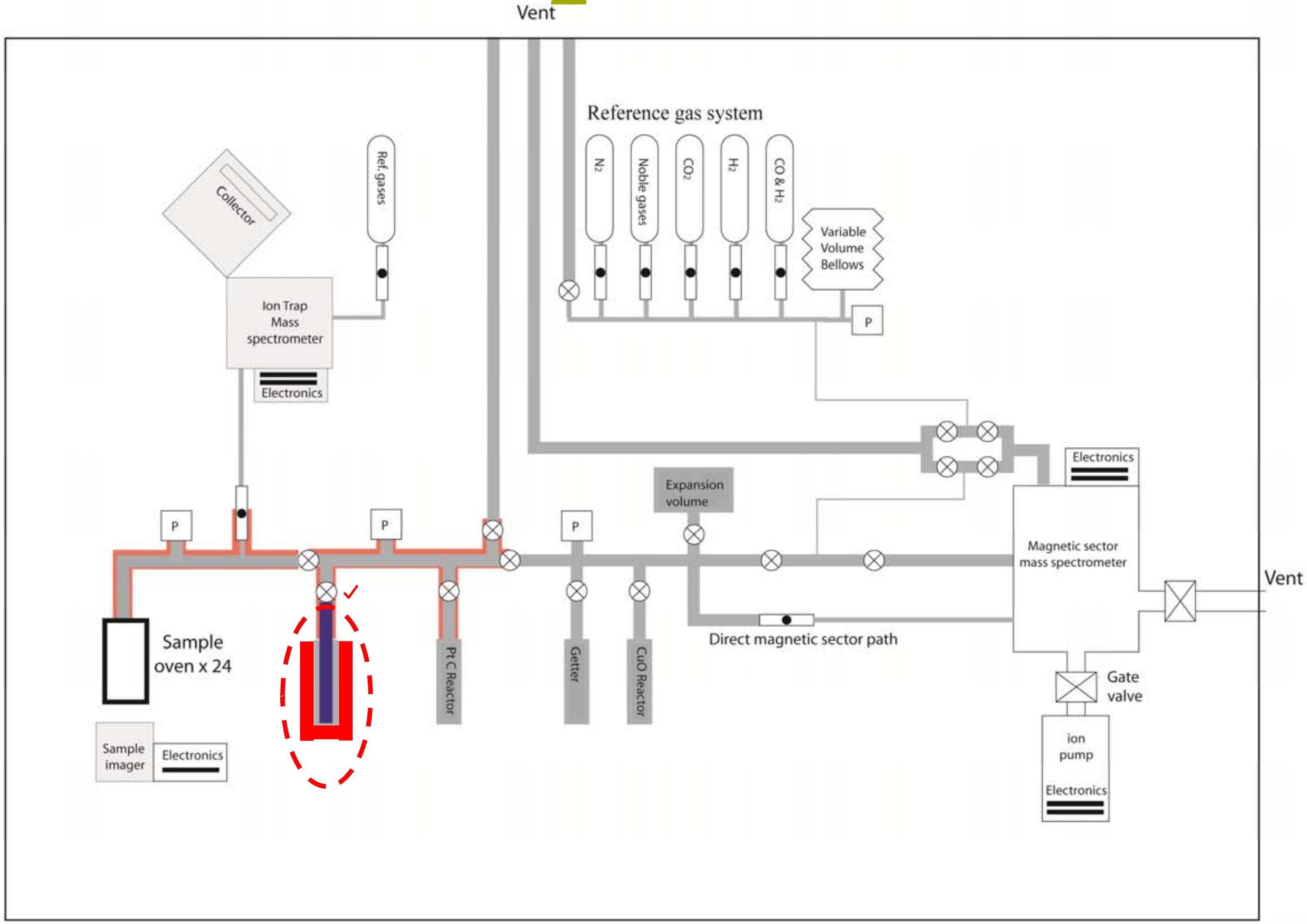
Release H_2O



Heat Cold finger to +100°C
Expand released water into hot manifold

Choices
Prepare manifolds
Prepare O_2
Heat sample
Quick analysis
Trap water & CO_2
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Dy. Analysis N_2
Remove N_2
St. Analysis Noble gas
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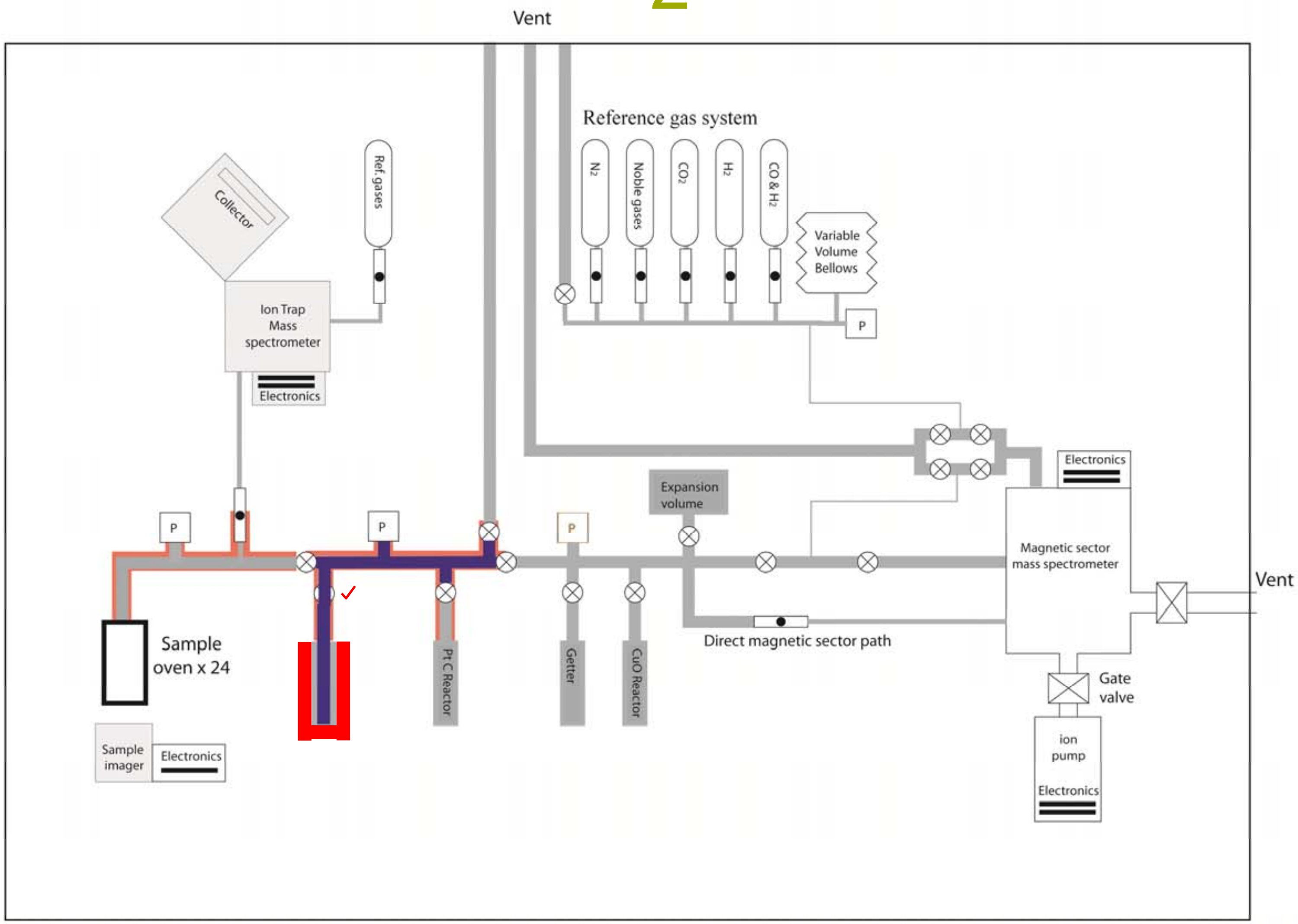
Evacuate

Convert to H_2



Heat Pt C reactor to +1000°C (alternative Zn +450°C)

$H_2O \rightarrow H_2 + CO$ ($H_2O + Zn \rightarrow H_2 + ZnO$)

Expand H_2 + CO into warm manifold

Allow Pt reactor and hot manifold to cool

Choices
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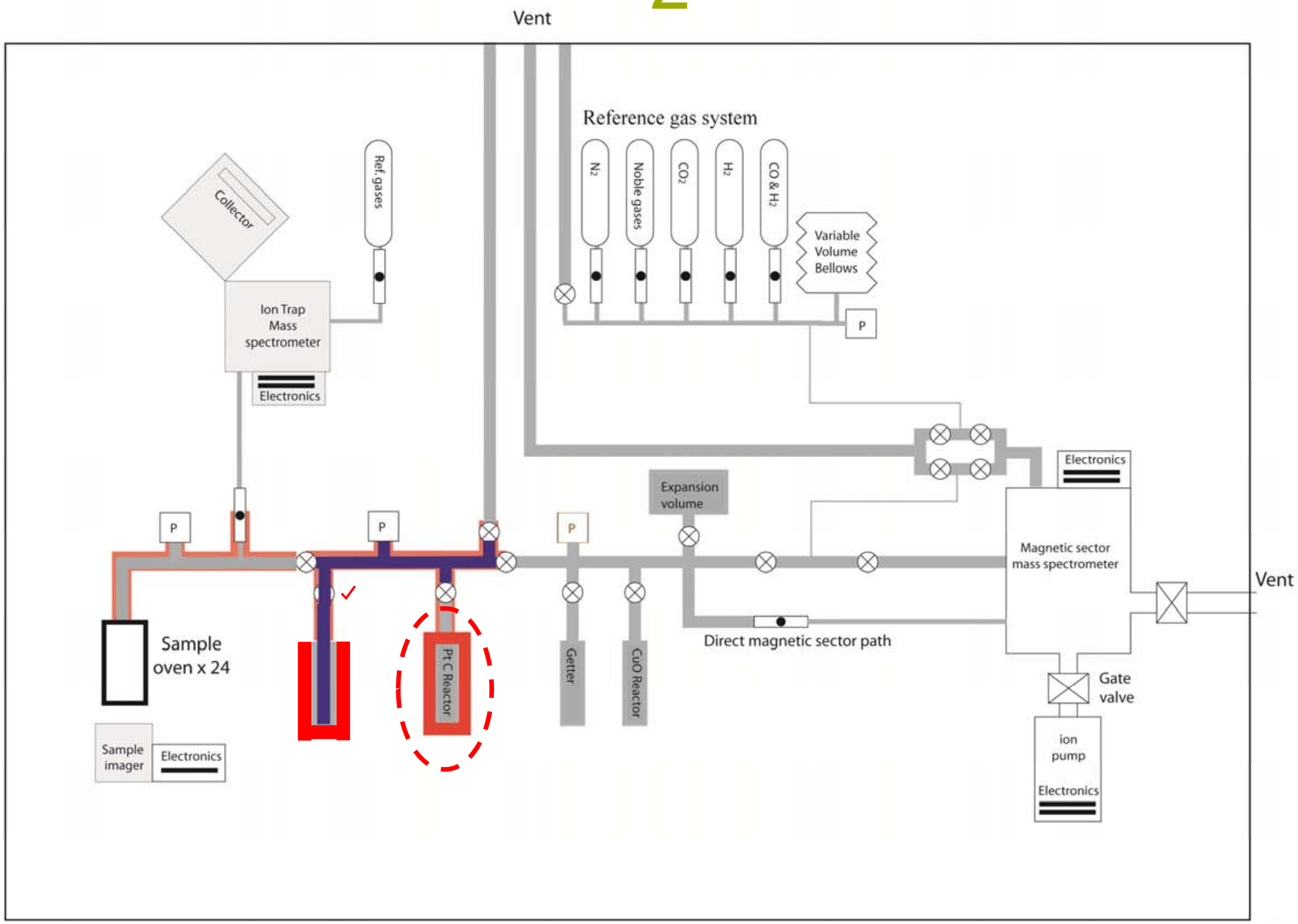
Convert to H_2



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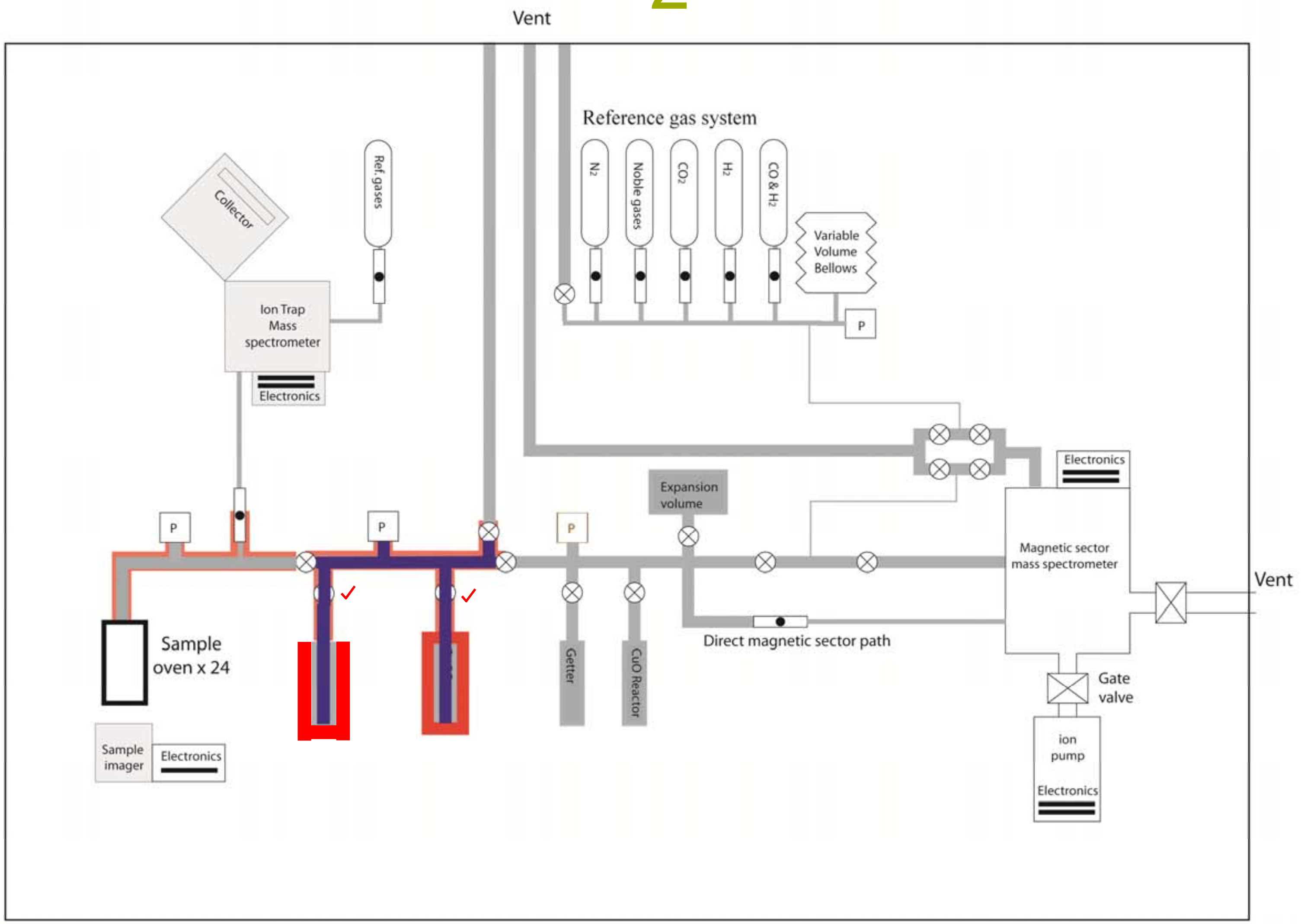
Convert to H_2



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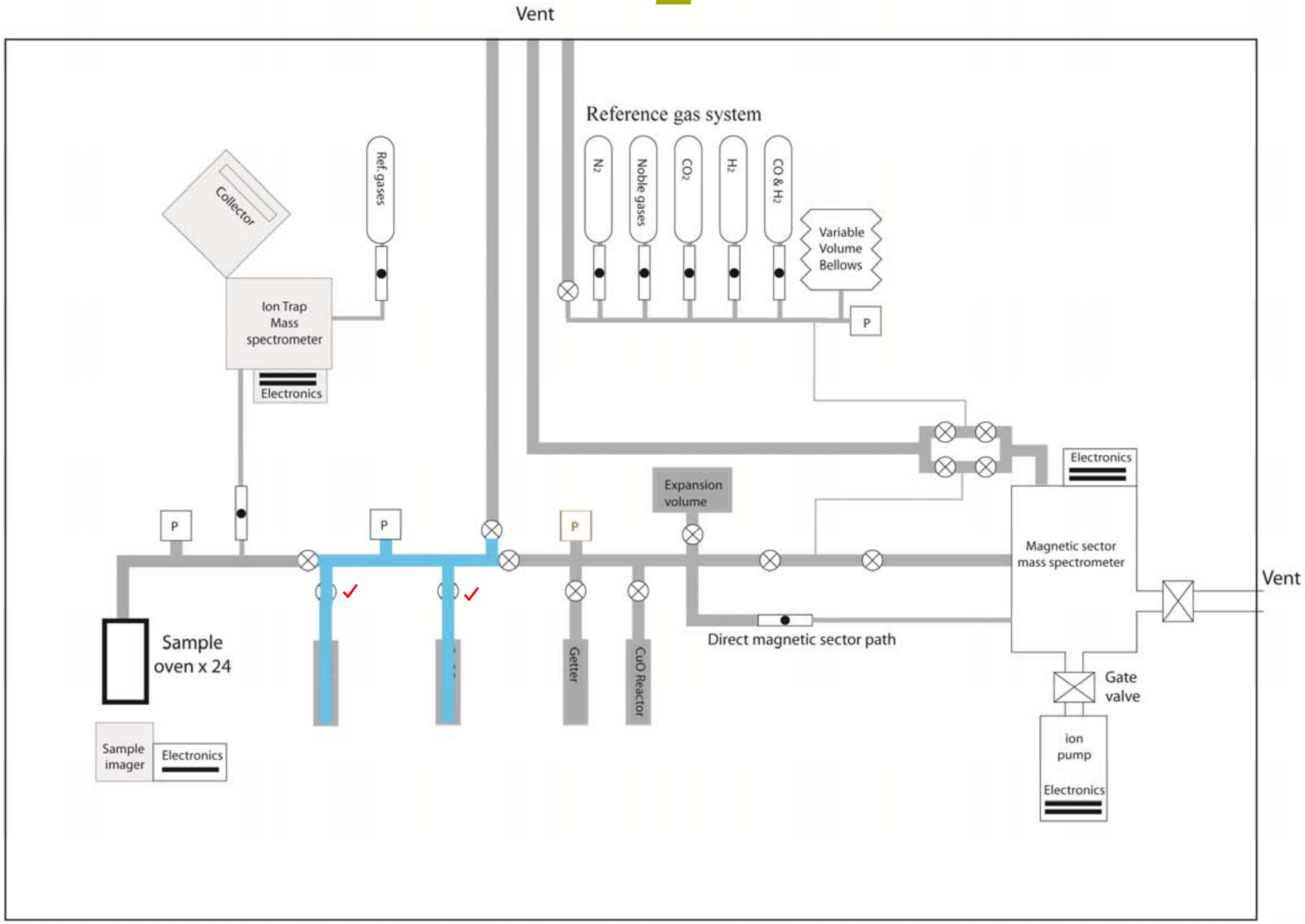
Convert to H_2



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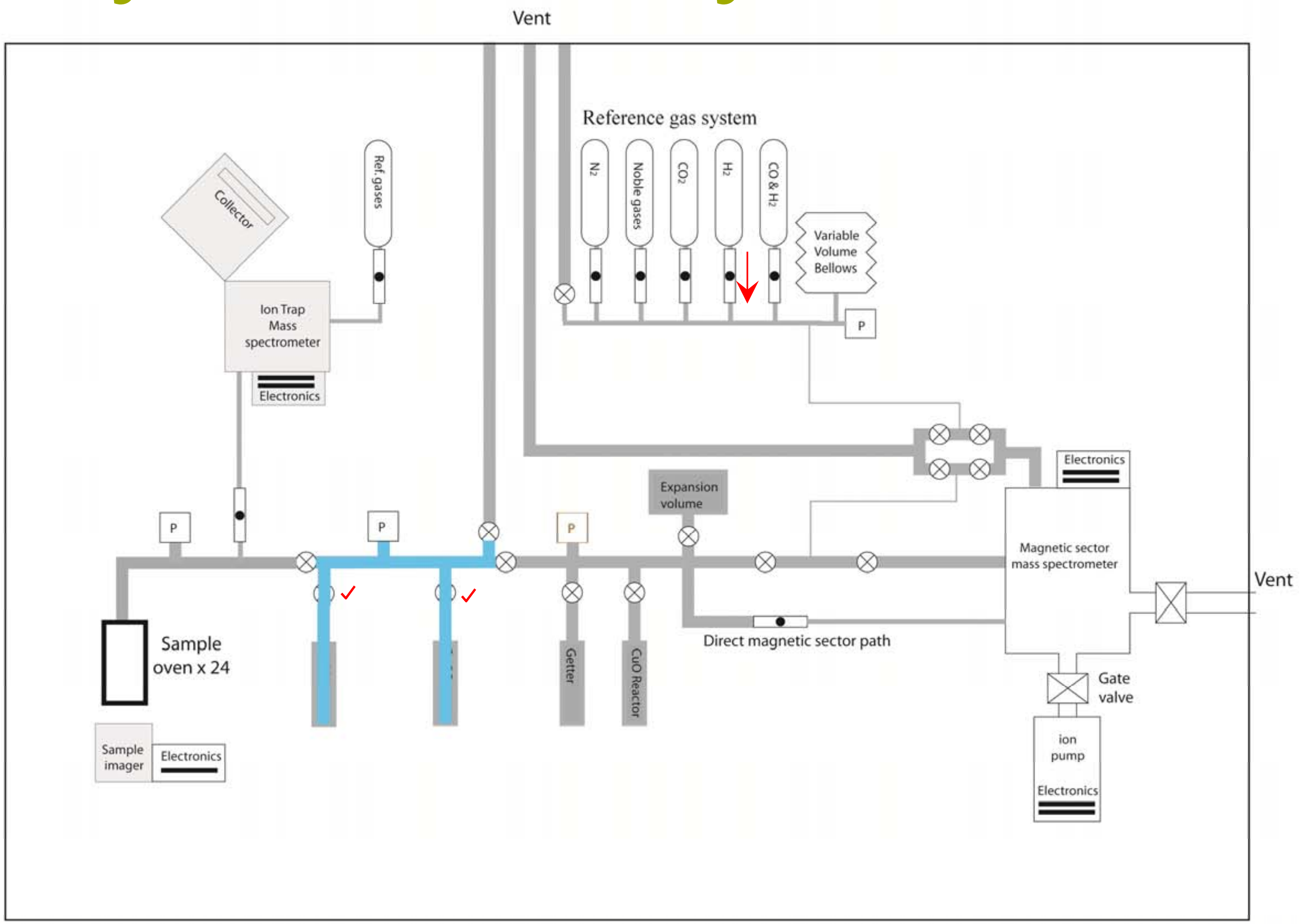
Dynamic Analysis D/H



Prepare H_2 reference gas
Open gate valve to ion pump
Sector MS set to m/z 2 & 3 on DH Faraday detectors
Ref/Sample comparison through change-over valve – isotopic analysis δD

Choices
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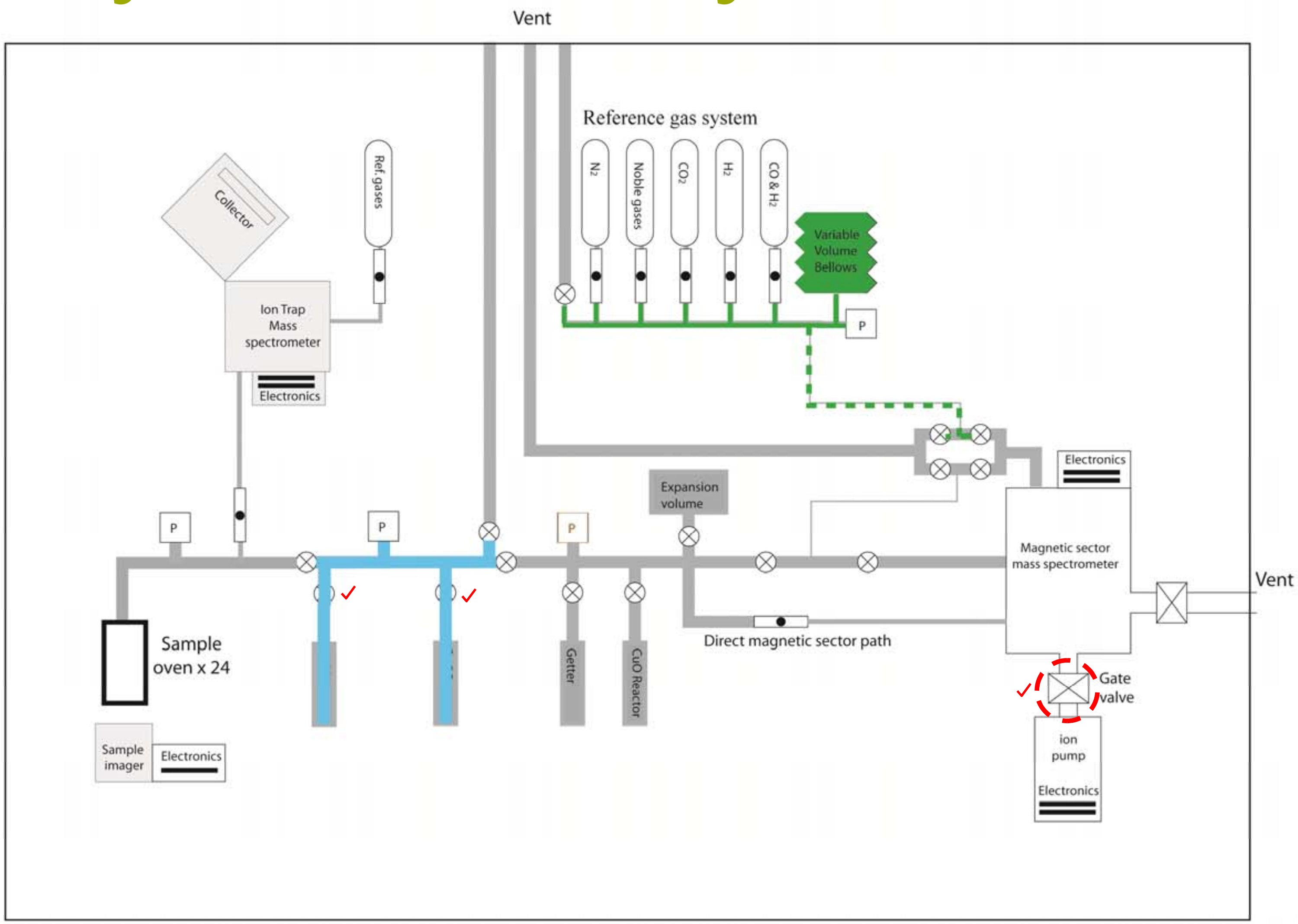

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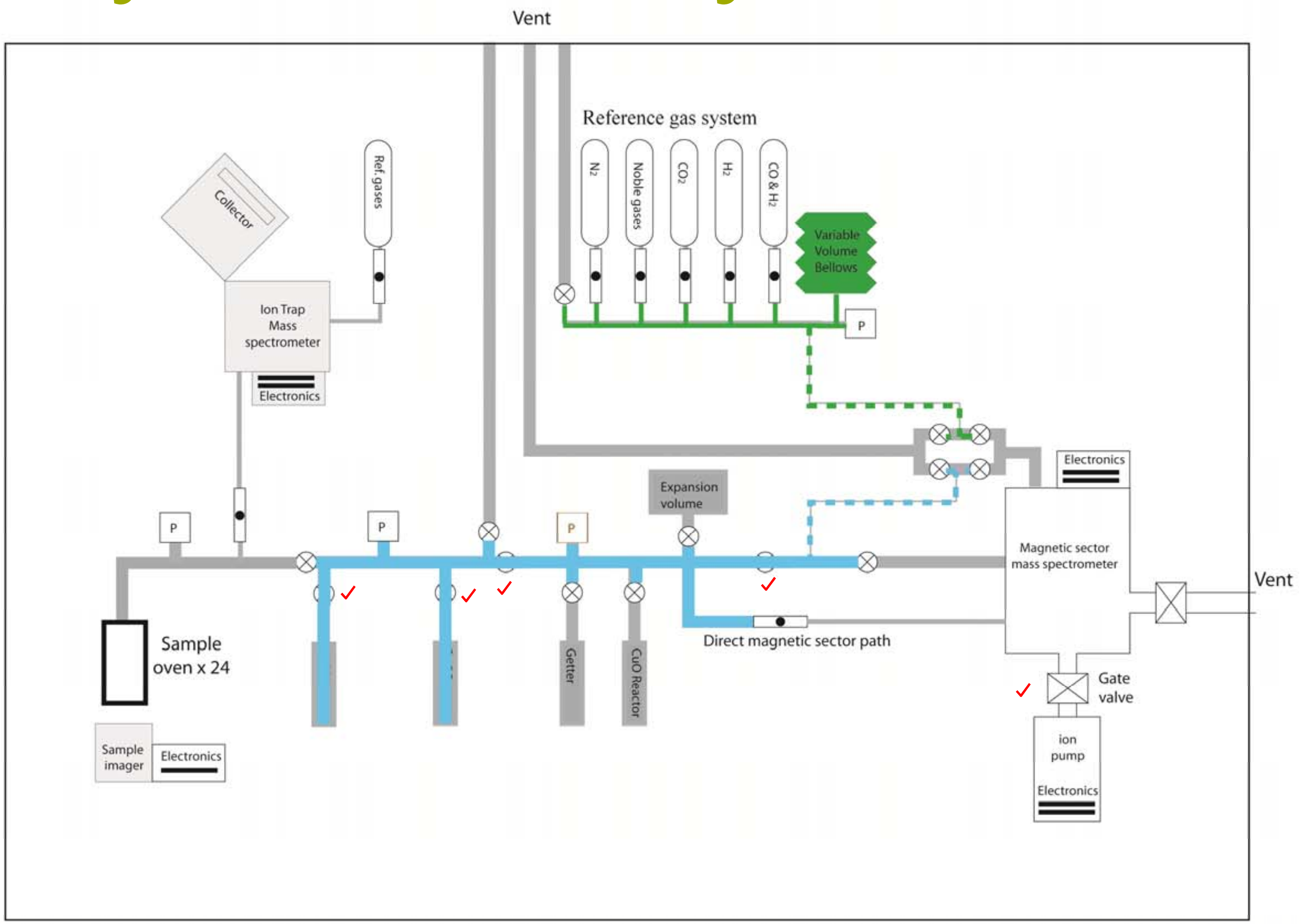

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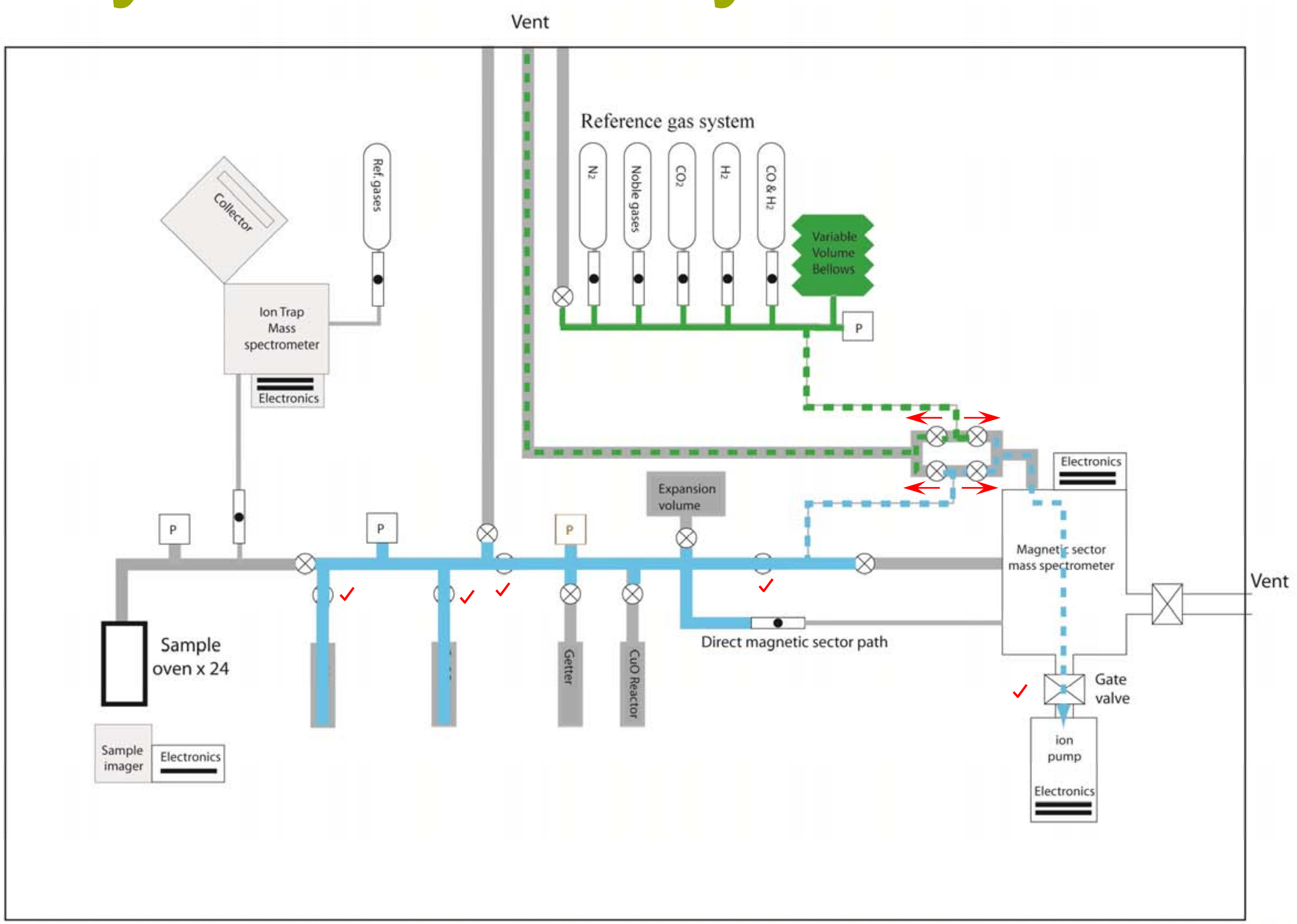

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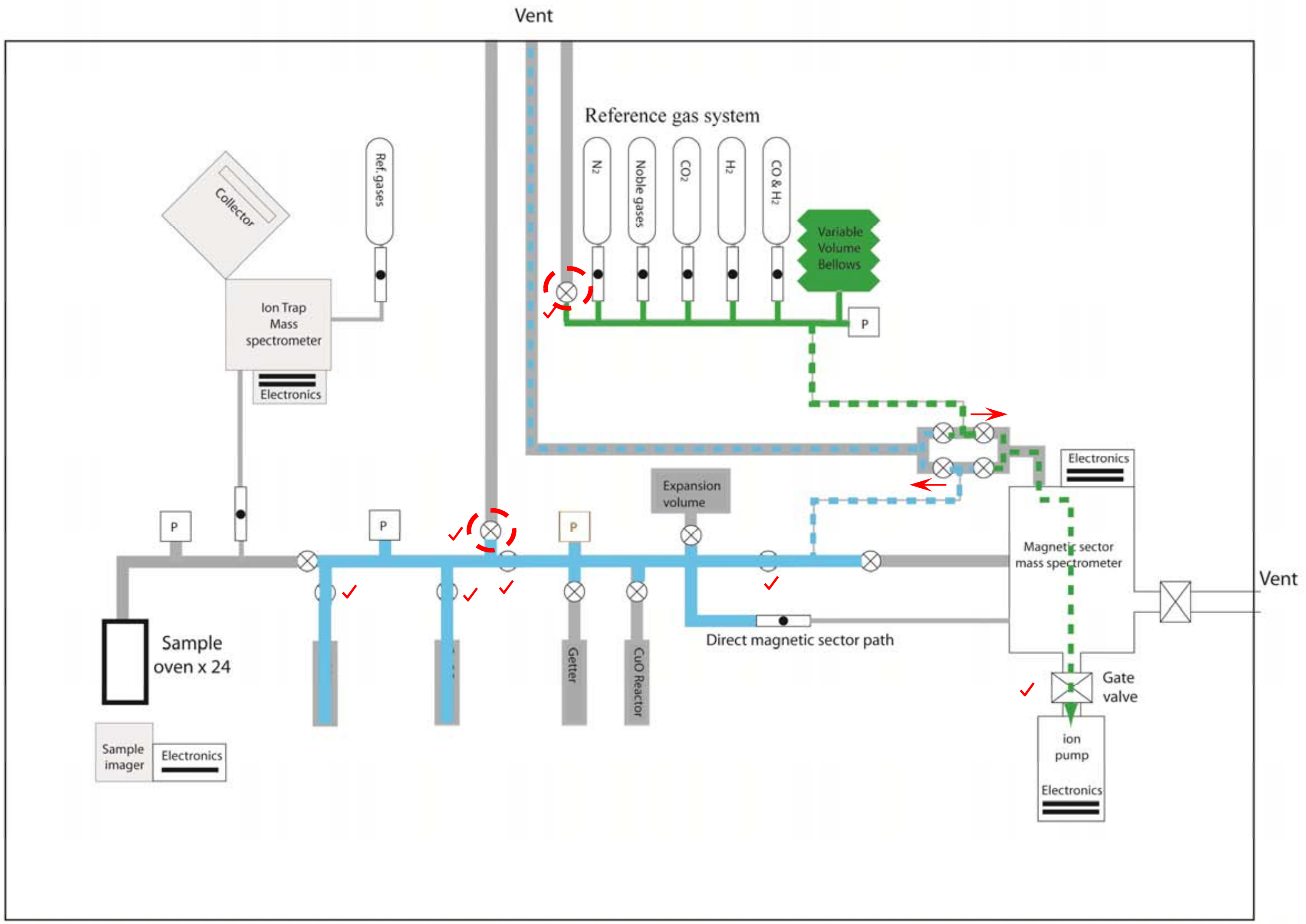

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Summary

Combustion to 400°C

Analysis volatile composition

Isotopic analysis μg N_2 ~0.1‰

Analysis noble gases

Isotopic analysis ng CO_2 ~1‰

H Isotopic analysis μg H_2O ~1‰

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  - Science Review [CTP]
  - Requirements Review [SB]
  - Technology Assessment [ADM]
- Task 2: Contamination & Surface Alteration Effects Analysis [JM]
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  - Summary of driving requirements and constraints [SB]
  - L-VRAP Concept/Preliminary Design - overview [SB]
  - L-VRAP sample analysis process [ADM]
  - **L-VRAP baseline operations planning [ADM]**
  - L-VRAP Concept/Preliminary Design – by subsystem [SB]
  - Scientific performance assessment [SB]
  - Lander & environment interfaces [SB]
  - Resource requirements [SB]
- Task 4: L-VRAP Development Plan [SB]
- Summary and Conclusions [SB/CTP]

L-VRAP Operations

Definitions:

- **L-VRAP Operational Sequence**

  Sequence of commands sent to L-VRAP from switch on to switch off

- **Experiment**

  Analysis of a single sample.
  This could require several L-VRAP Operational sequences
    e.g. collect sample, heat sample to 400°C, heat sample to 800°C
  Or several experiments may be done in one L-VRAP Operational Sequence
    e.g. Open passive collector, analyse regolith, analyse exosphere…

- **Scientific Measurement**

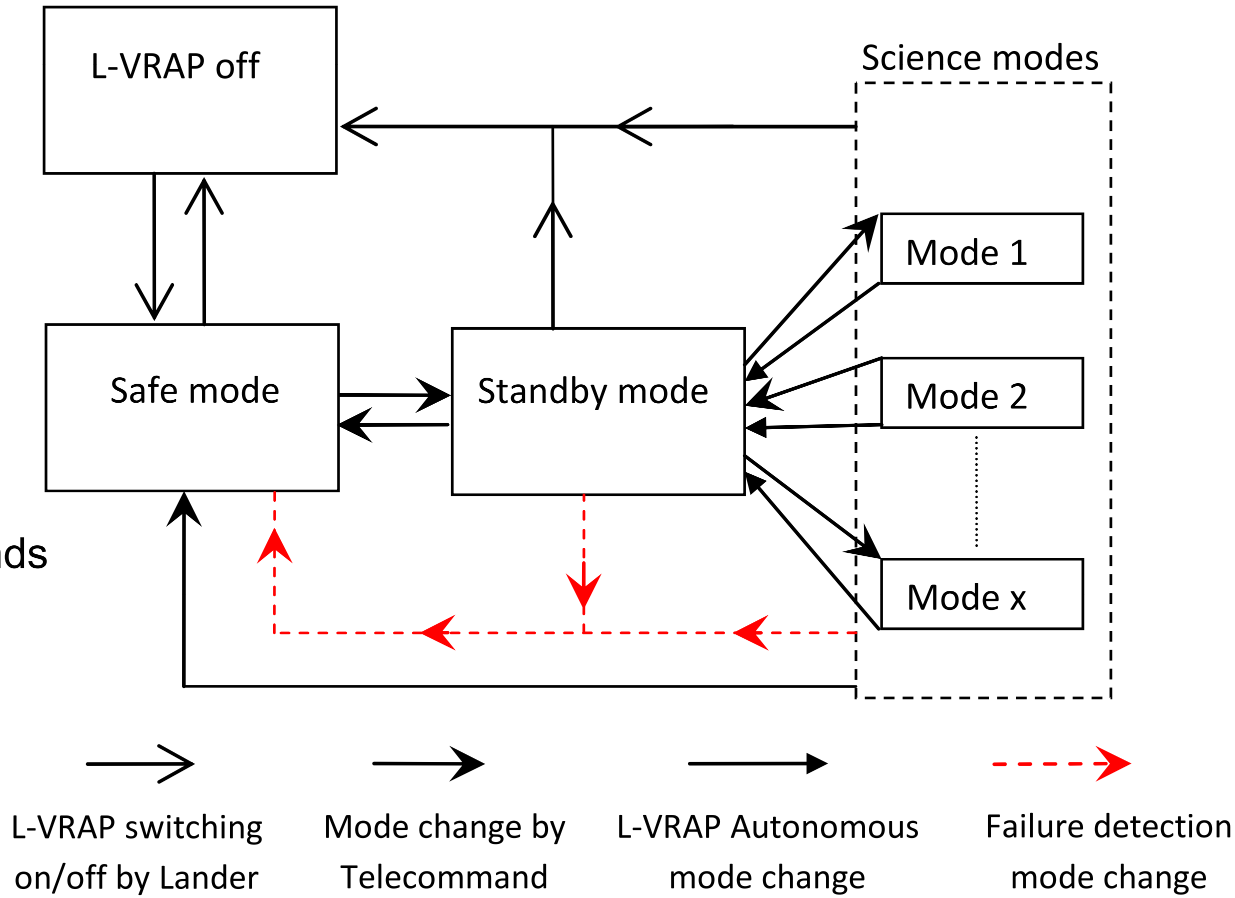
  One or more experiments to answer a science question
    e.g. depth profile using 5 experiments to analyse regolith at 2cm, 4cm,…

Operations Planning

- Functional Diagram

Safe mode:
    Memory management
Standby mode
    Enable L-VRAP components
Science mode
    Operate sequence of L-VRAP commands
    Generate science data

HK generated by all modes
    256 bytes every 30 seconds



From switch on to switch off is a single L-VRAP operational sequence
Many OBC's in a single operational sequence -
    Time tagged?
    requested by L-VRAP?
    L-VRAP state detected by Lander?

Operations Planning

- L-VRAP Failure Detection:
  - Watchdog timer 2 s (TBC)
  - Science mode fails to process L-VRAP command
  - Sensor outside safe operating range

- Failure puts L-VRAP in Safe mode
- Lander action?
  - No action
  - Monitor for 90 seconds then switch L-VRAP off
  - Transmit pre-loaded sequence of OBCs to L-VRAP

Operations Planning

- L-VRAP Experiments (TN-04 section 6.6)
  - Exosphere real time analysis
  - Exosphere collection / sample concentration
  - Regolith Quick Analysis
  - Regolith Detailed Analysis

  - Health check
  - MS bake
  - Commissioning 1 (motors & cameras)
  - Commissioning 2 (mass spectrometers)

Operations Planning

- Scientific measurements

A scientific measurement consists of 1 or more L-VRAP experiments to address a science question.

Exosphere measurements:

•Exo-0	Baseline measurement
•Exo-1	Time profile
•Exo-2	Measure as function of illumination
•Exo-blank	Characterisation of L-VRAP blank
•Exo-10	Opportunistic measuremnts (e.g. as SSS arm disturbs regolith)

Exosphere measurements use both real time monitoring and passive collecting experiments

Operations Planning

- Scientific measurements (2)

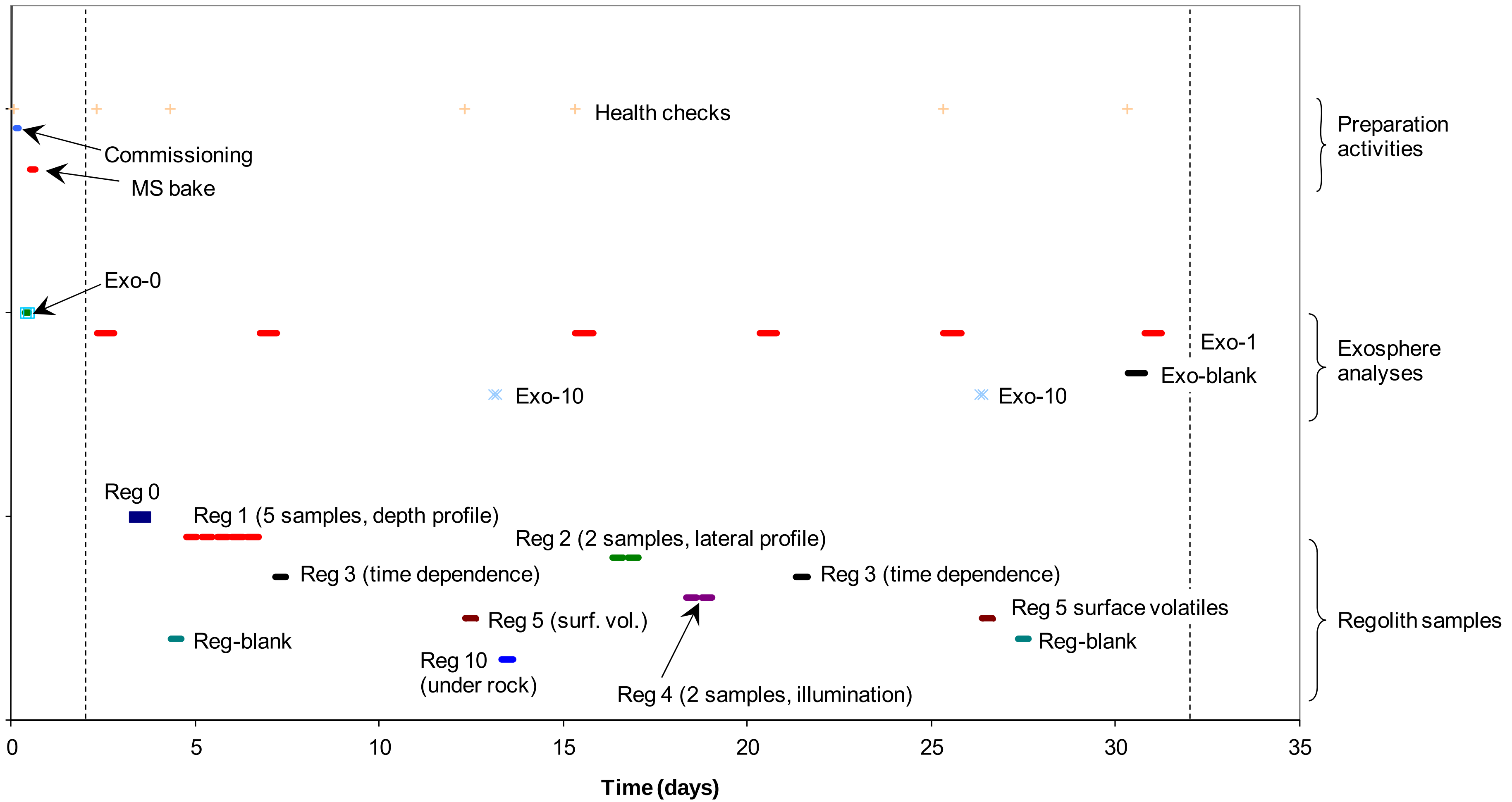
Regolith measurements:

•Reg-0	Baseline measurement
•Reg-1	Depth profile
•Reg-2	Lateral profile
•Reg-3	Time profile
•Reg-4	Illumination behaviour
•Reg-5	Volatiles in top 1mm (RQ5)
•Reg-blank	Characterisation of L-VRAP blank
•Reg-10	Opportunistic measurements (e.g. under rock)

Regolith measurements use “Regolith Detailed Analysis” experiment

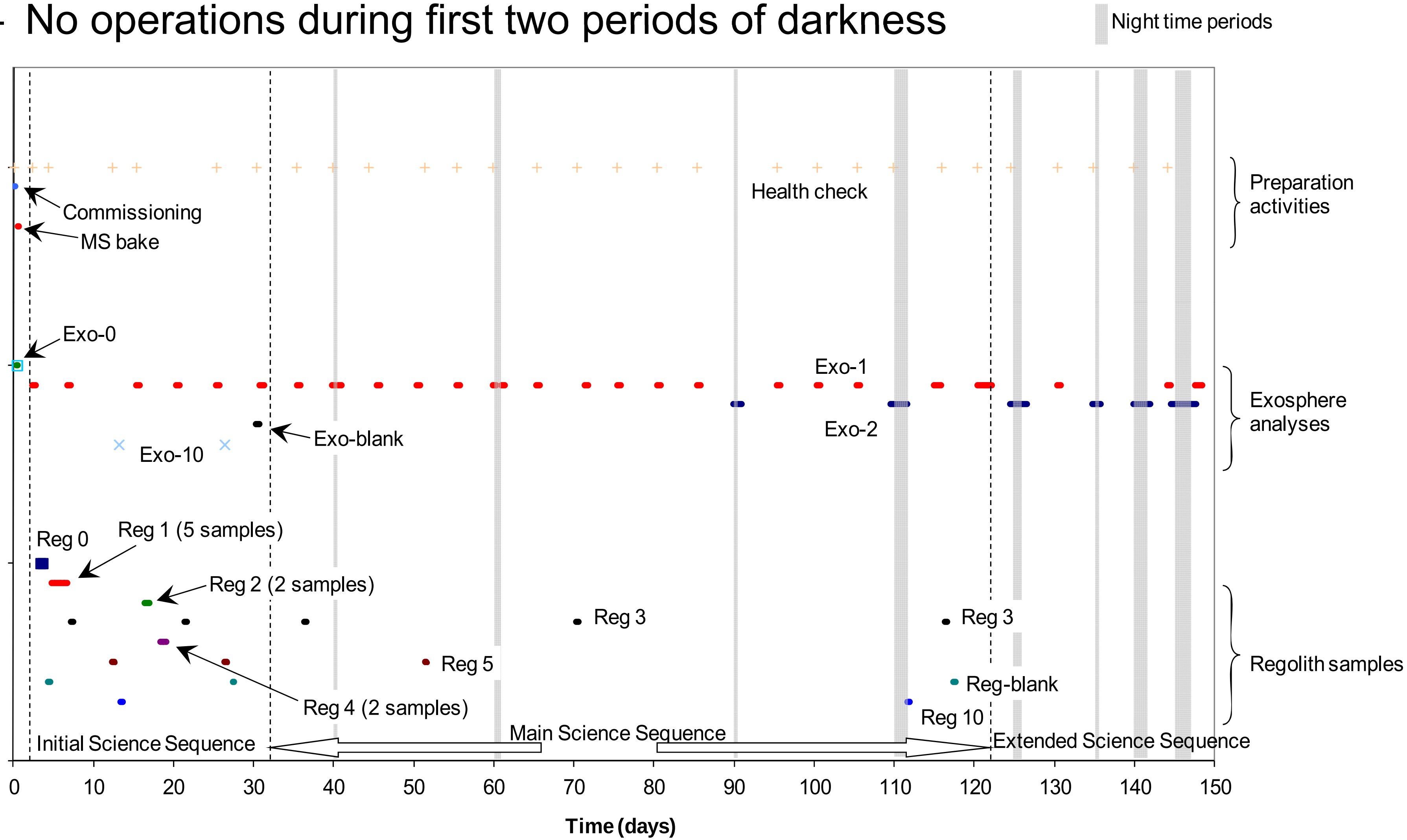
Operations Planning

- Baseline Operations plan constraints:
  - Limited measurements during Lander evaluation
  - Limit operations to average one experiment per day ~25% total time.
  - Complete science measurements as soon as practical (Initial Science Sequence)



Operations Planning

- Baseline Operations Long Term
  - Lander determines darkness periods during ISS
  - Limit operations to average ~25% total time.
  - No operations during first two periods of darkness



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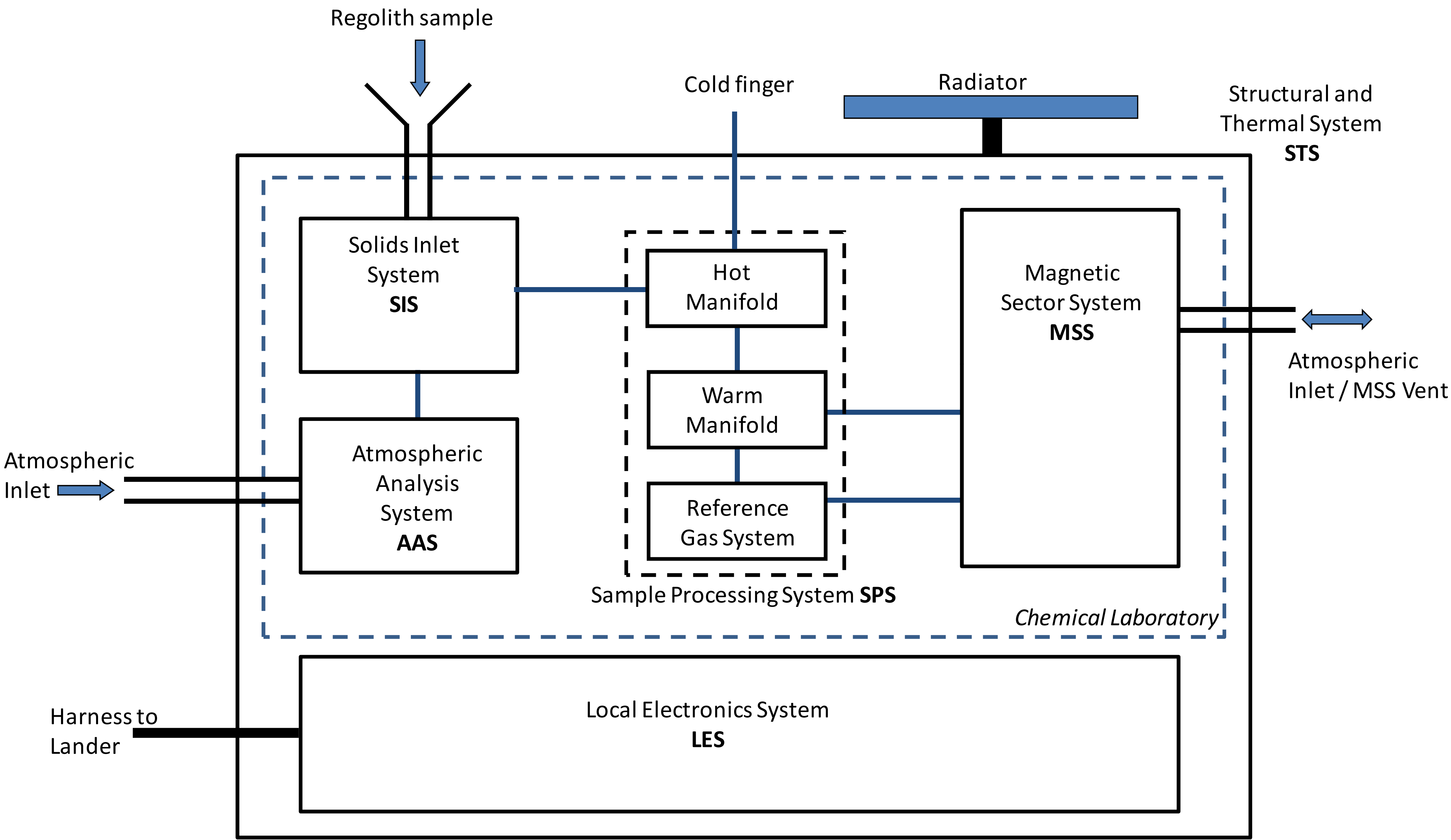
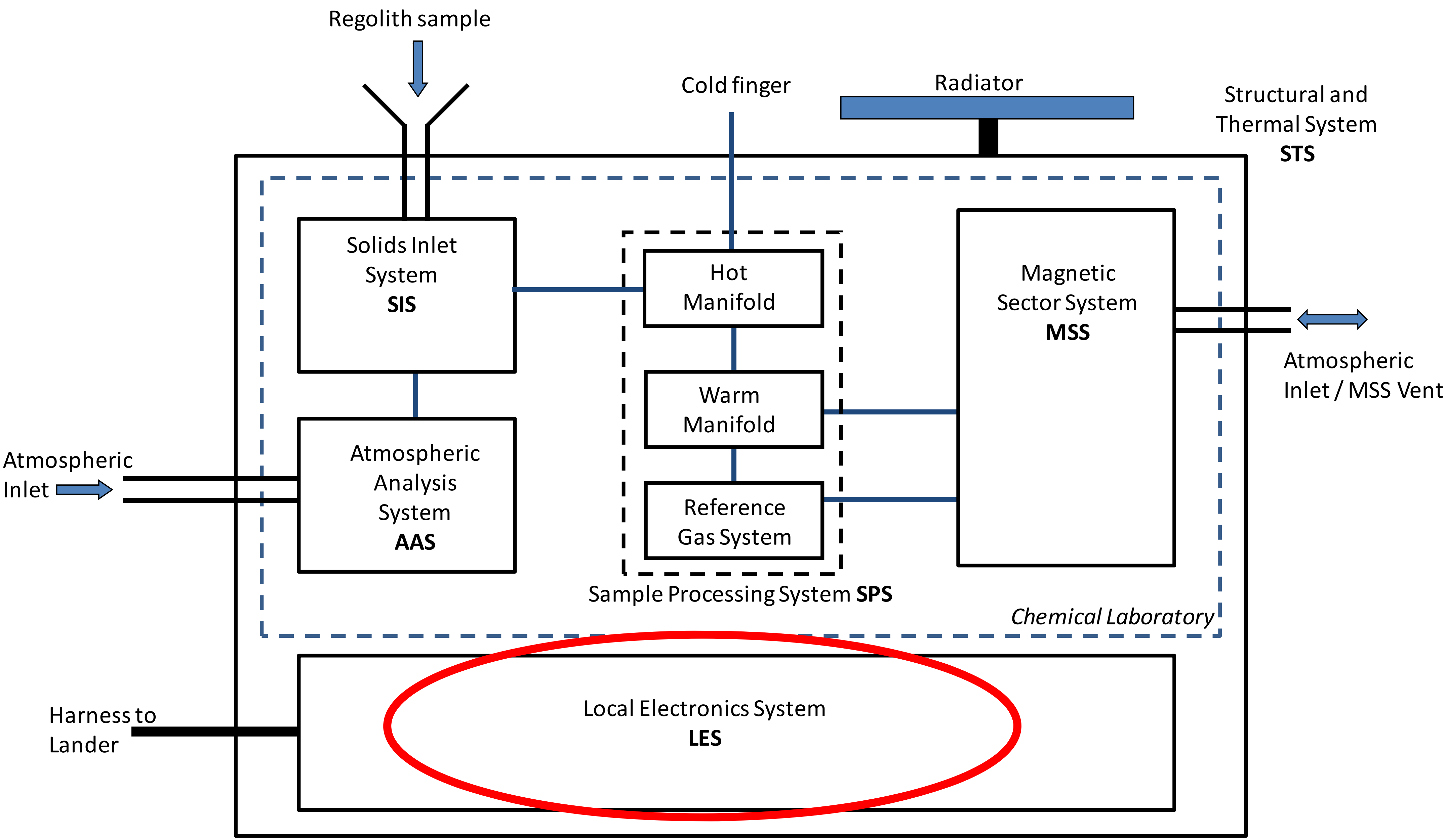
Concept design by subsystem



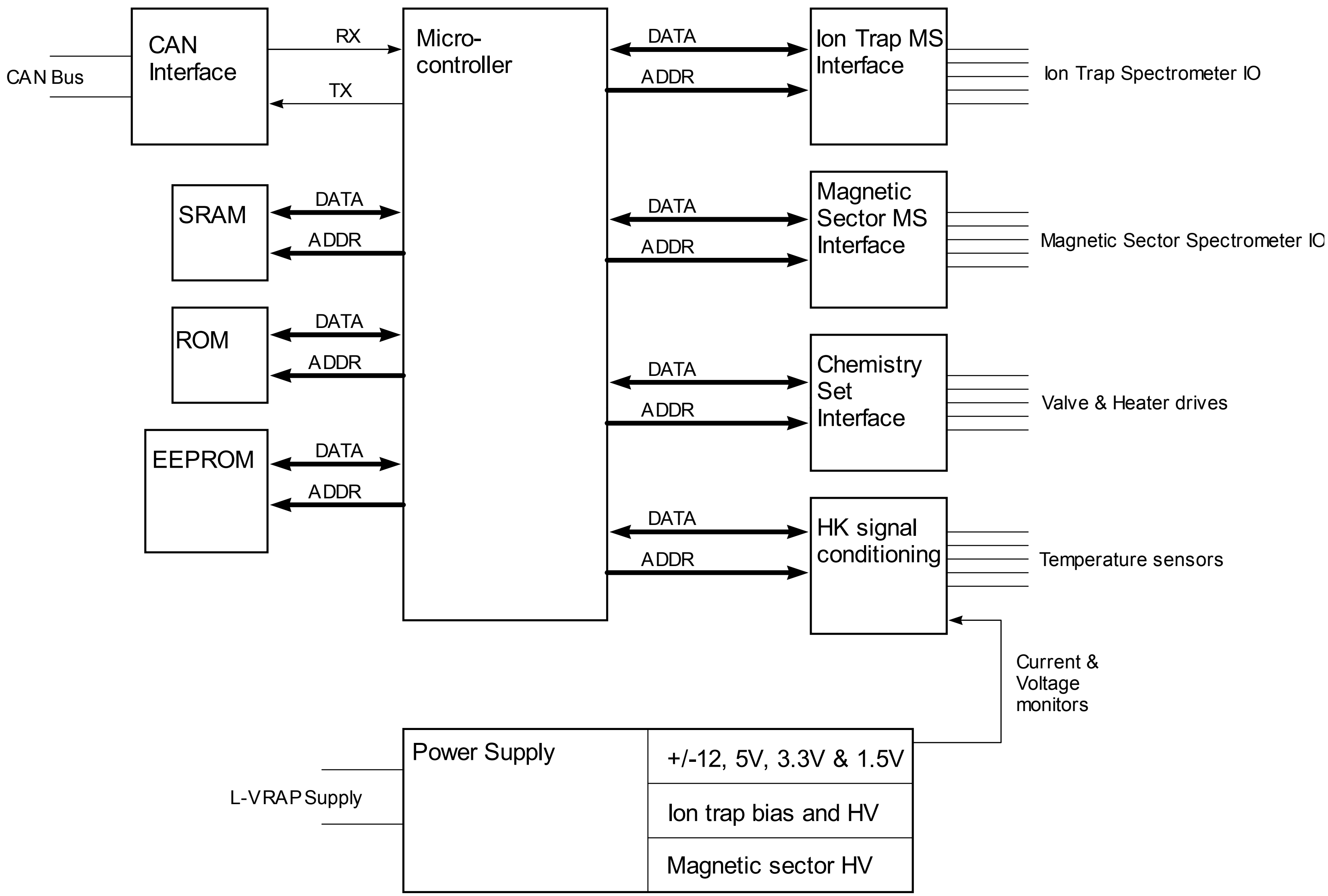
Concept Design: LES



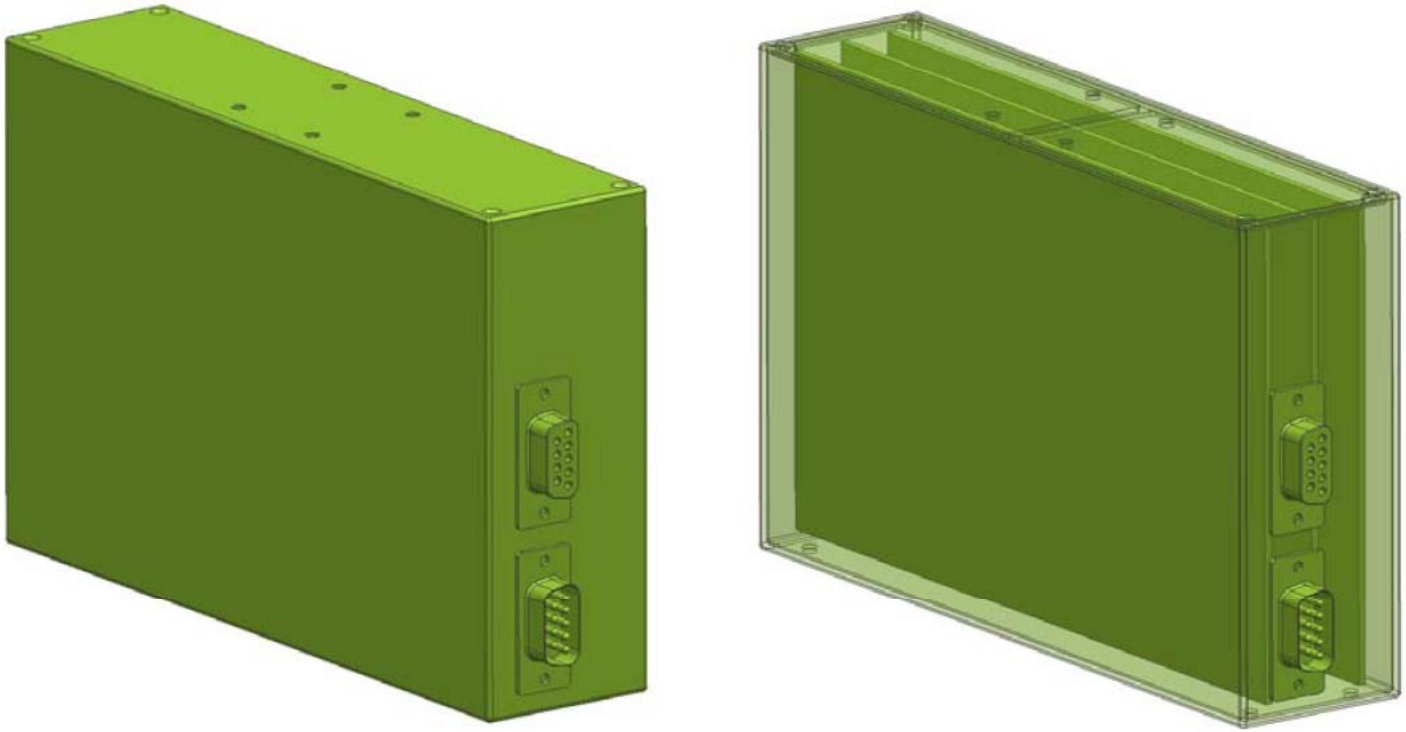
Concept Design: LES

- The LES performs the following functions:
  - Acts as the interface between the Lander and the two spectrometers
  - Generation of L-VRAP DC voltages from main 28V spacecraft voltage bus
  - Signal conditioning of sensor outputs within L-VRAP (Pressure, Temperature etc)
  - Control of components (Heater/gas processing valves/mass spectrometer)
  - Data collection
  - Store experimental sequences (EEPROM)
  - Autonomous control of experiments
  - Reporting experiment phase progression/status to lander.

Concept Design: LES



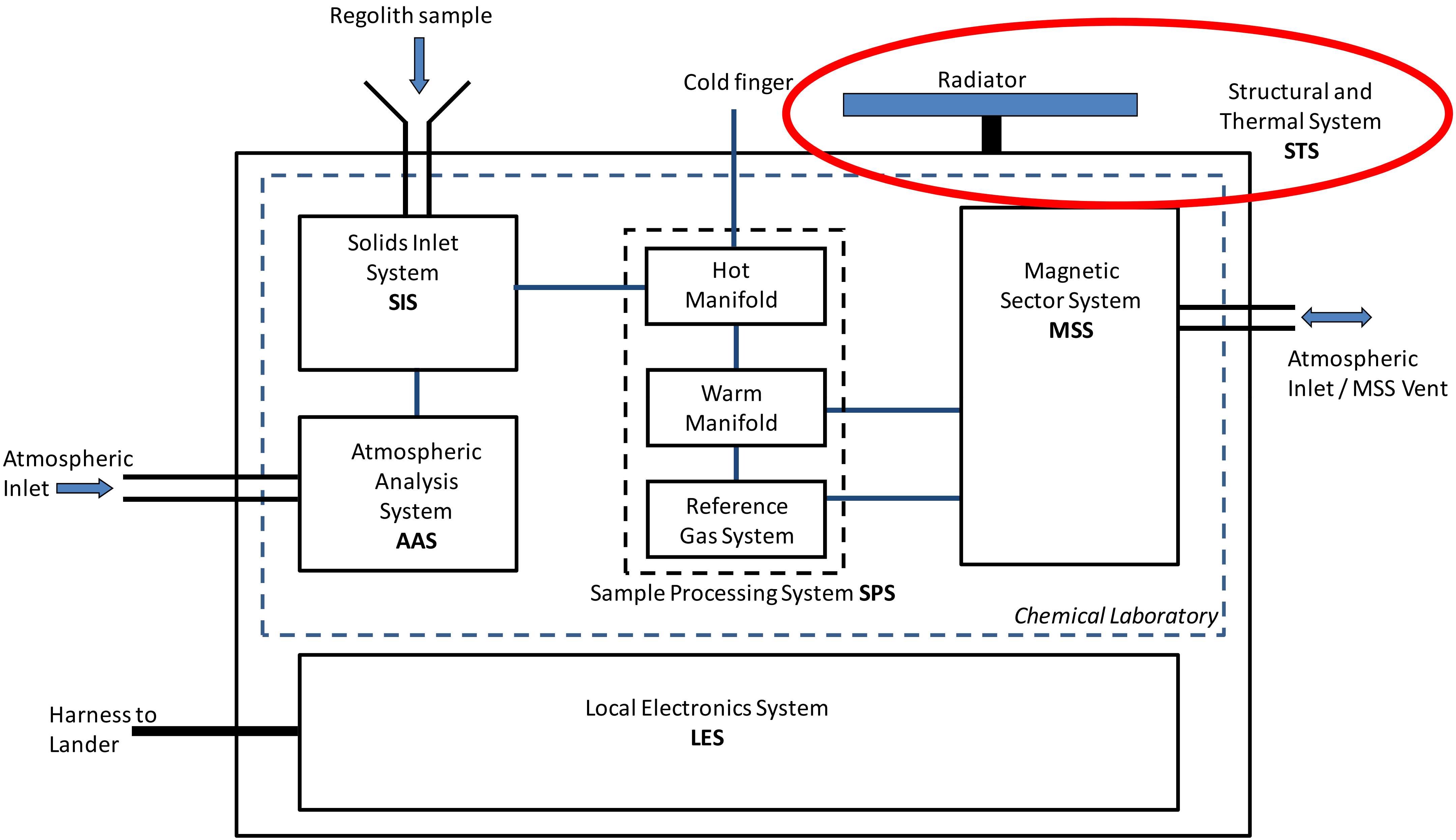
Concept Design: LES



Concept Design: LES

- Description
  - The LES comprises 3 main circuit boards
    - Instrument controller and space-craft interface
    - Control of valves, heaters, pressure sensors etc
    - Mass spectrometer control
  - Power electronics may be fitted close to high power actuators to reduce EMI
  - Ion trap: Possibility of new drive strategy compared to Ptolemy
  - Micro-controller selection
    - FPGA vs dedicated part
    - Type: ARM, LEON...
  - Memory selection, MRAM devices becoming available
    - ITAR
    - Could be used to save state while power removed
  - Power drive topology
    - Distributed: better EMI, harder to radiation shield
    - Dedicated power drive card

Concept Design: STS



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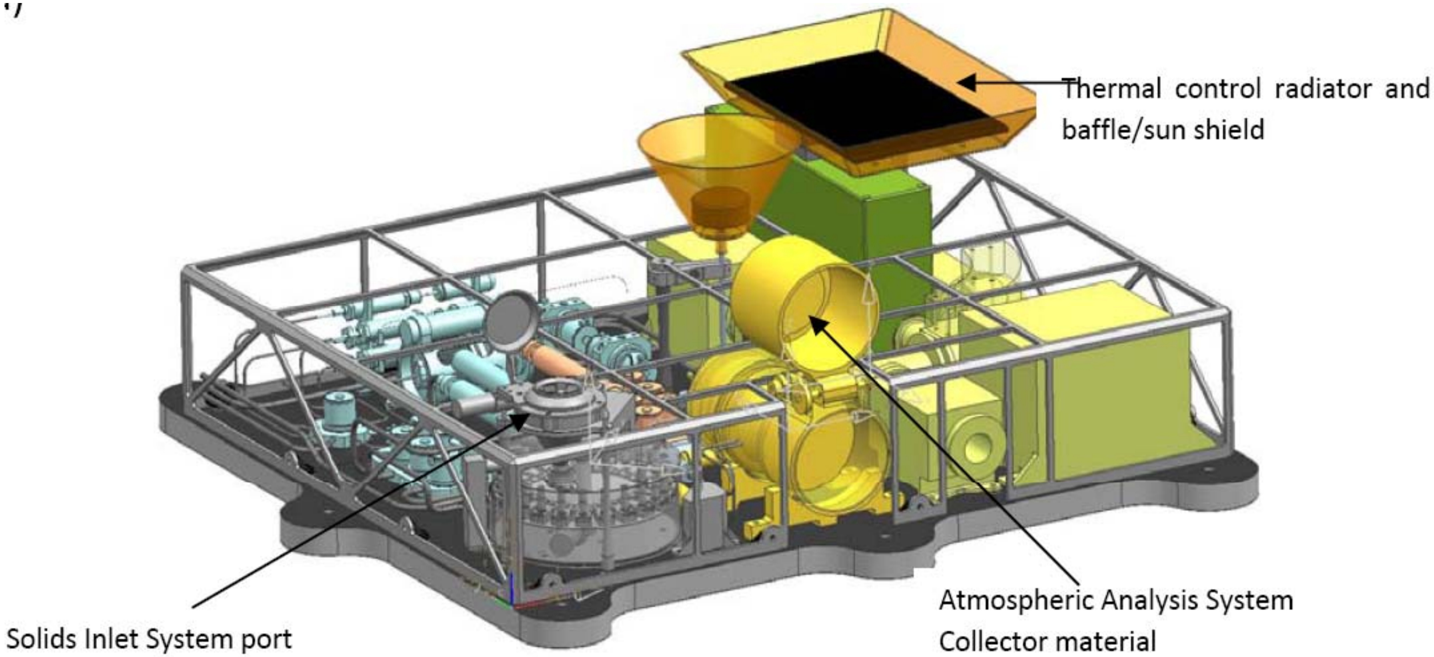
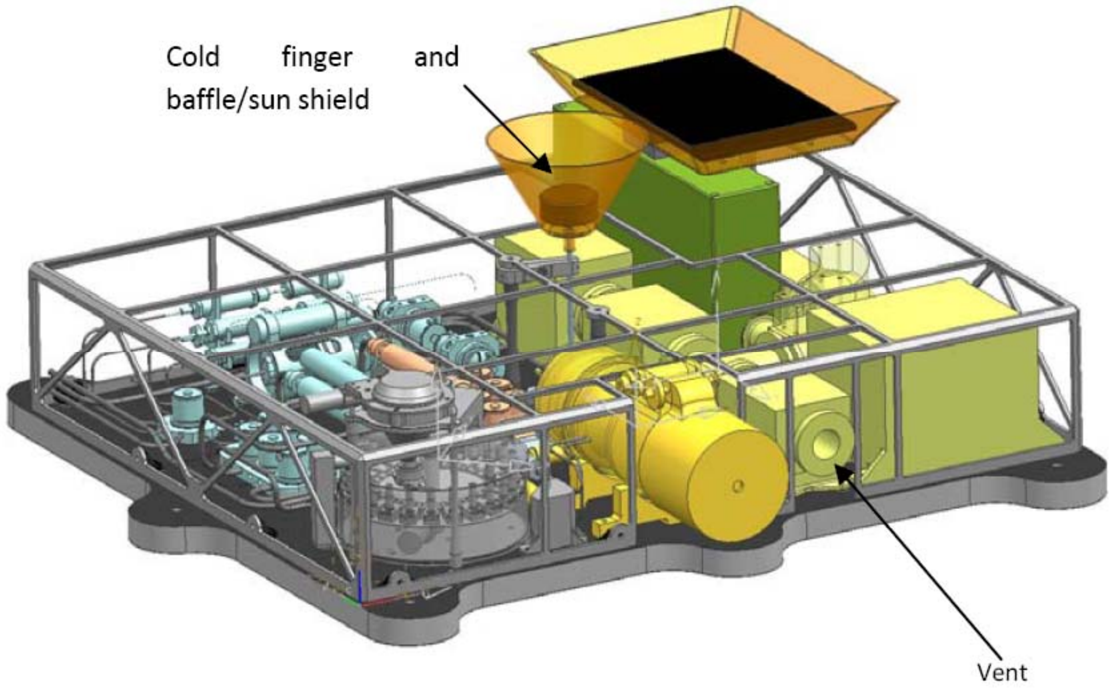




Concept Design: STS

- The STS performs the following functions:
  - Provides overall structural basis for the L-VRAP hardware
  - Provides protection from dust and micrometeorites
  - Provides a barrier against chemical contamination from the lander and environment (including residual fuel vented by the lander)
  - Affords thermal control of overall instrument box (local control is also effected within the various subsystems/components)

Concept Design: STS - Structural

- Baseplate: CFRP-aluminium honeycomb-CFRP sandwich sheet
  - Light, stiff, good thermal isolation of sub-assemblies (isolating mounts)
  - Attached to Lander via 8off M6 threaded fasteners and isolating washers
- Lightweight aluminium alloy frame to support external MLI tent

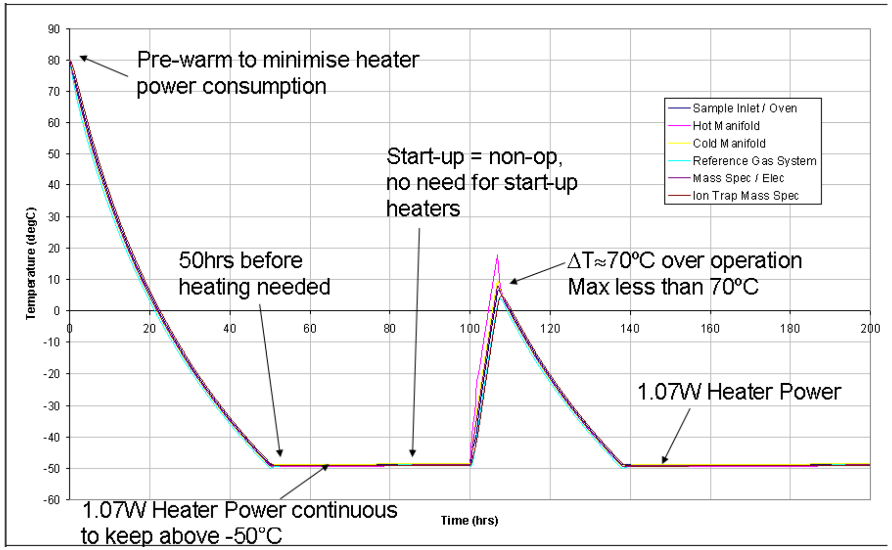
Concept Design: STS - Thermal

- Crucial to the successful operation of instrument on the Lunar surface
- The key design drivers:
  - Survive the extreme Lunar surface environment thermal range
  - Minimise power demand on the Lander during the lunar night
  - Control a variety of thermal interfaces within allowable temp ranges

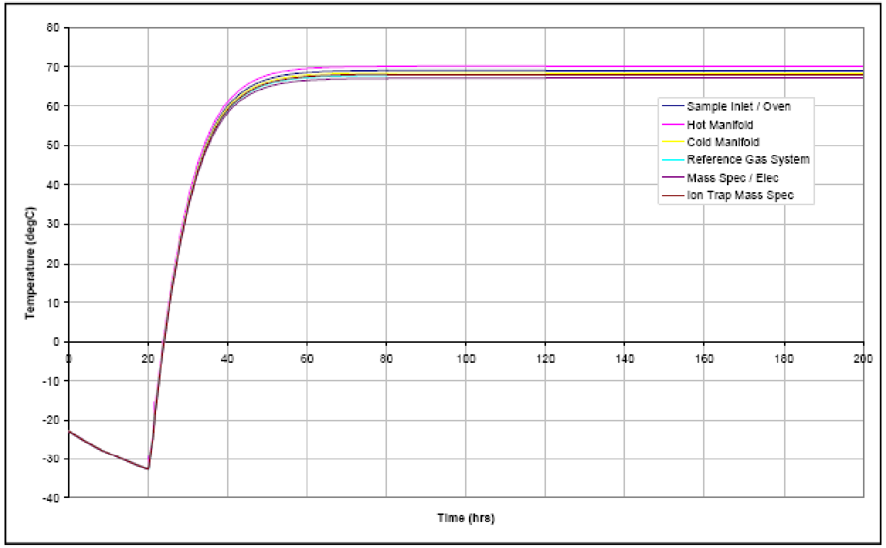
- Thermal control approach :
  - Insulation (MLI)
    - Isolates L-VRAP from external environment
    - Isolates regions within instrument to ensure efficient application of heat where needed.
  - Radiators
    - reject excess heat rejection to space during operations
    - decoupled during night to minimise heat loss (heat switch)

Concept Design: STS - Thermal

- Option 1: Fully insulated L-VRAP
- No radiator required
- But significant constraints on operations – e.g. introduce pauses
- Not robust solution (tilt etc)



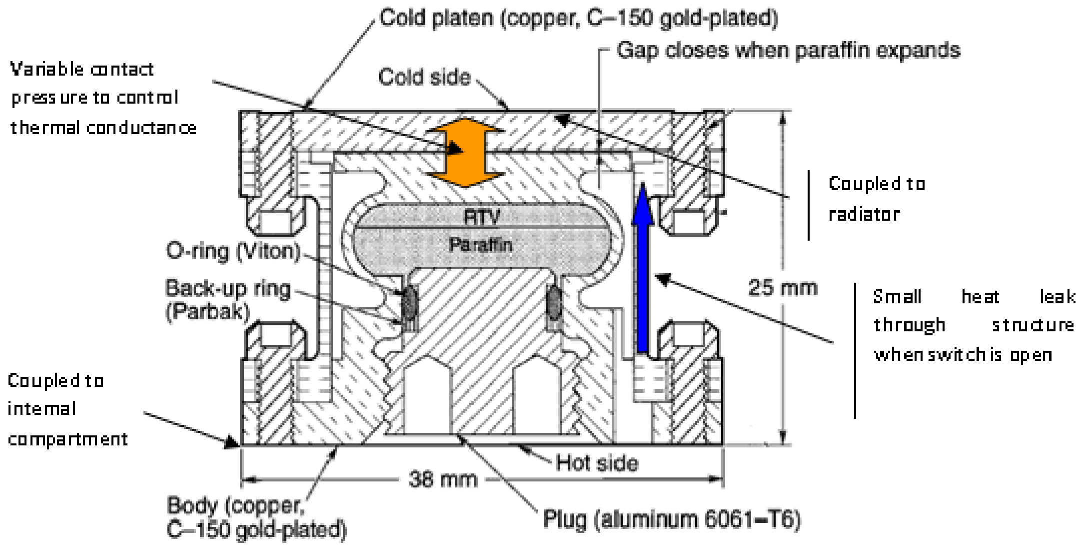
- Option 2: Size radiator (11cm x 11cm) to allow constant L-VRAP operation
- Heat switch to minimise cooling at night
- Mil-Spec parts for wide temp. range



Steady State Temperatures assuming constant 9.4W dissipation, sun angle 15°

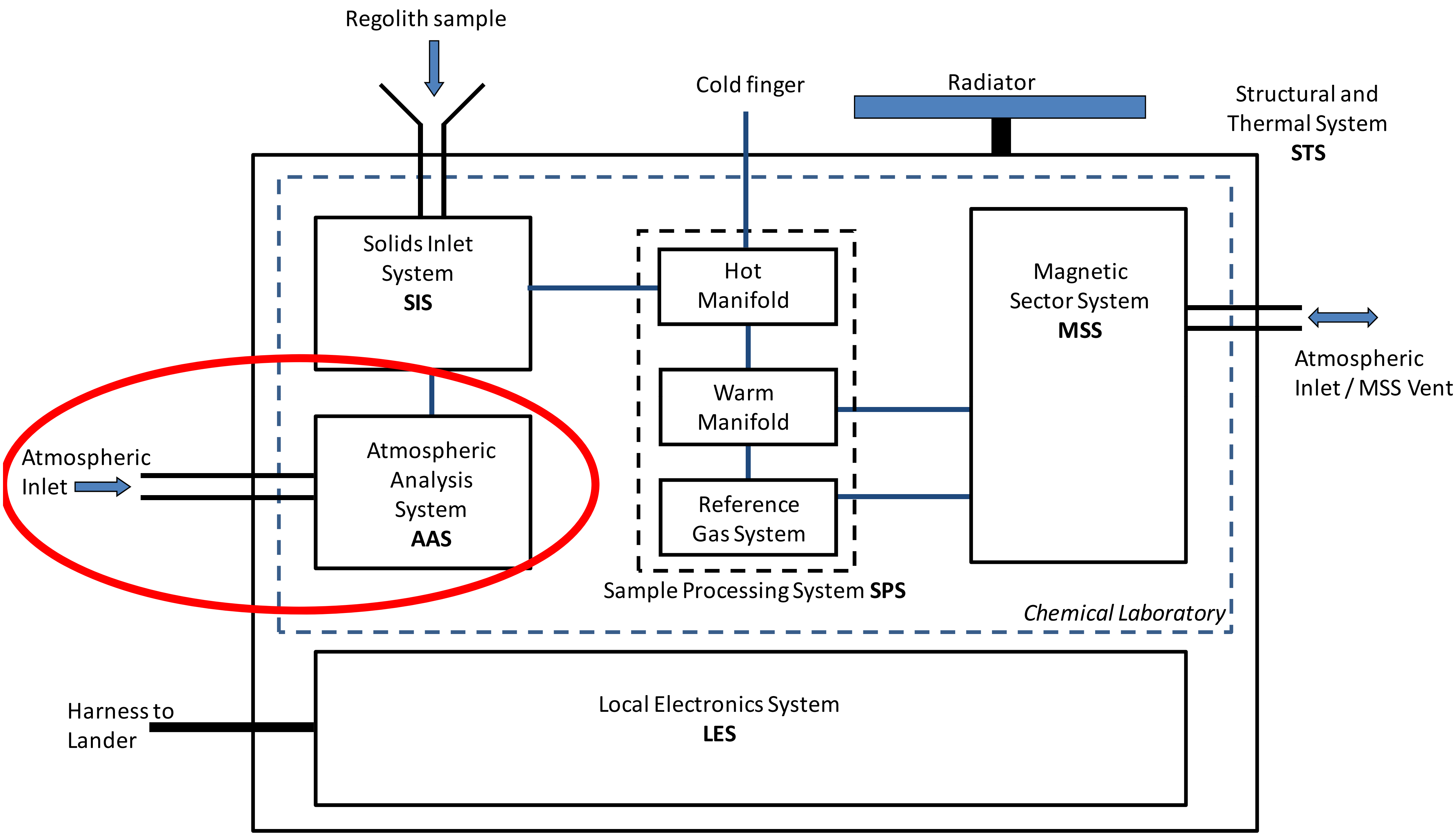
Concept Design: STS - Thermal

- Preferred configuration
  - Paraffin Heat Switch assumed
    - lower thermal performance but less complex than loop heat pipe
- Use pre-heat before night
  - L-VRAP ok for 38 hours
  - Survival heating 1.5 W after 38 hours
- Future work:
  - Reduce power dissipation during operations (mass spectrometer) → smaller radiator → slower cooling at night)



Paraffin Heat Switch

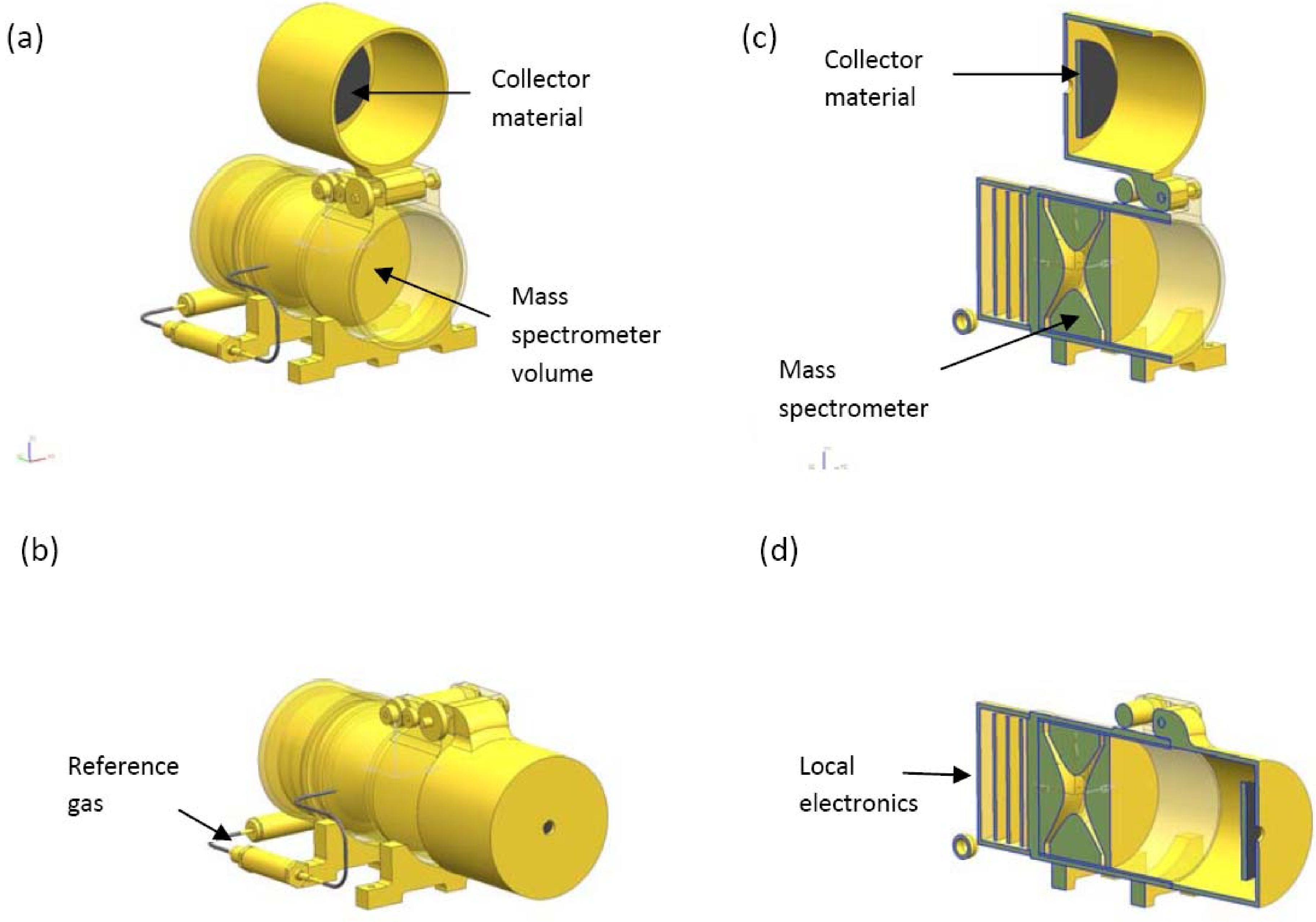
Concept Design: AAS



Concept Design: AAS

- The Atmospheric Analysis System (AAS) operates in two distinct modes:
  - Direct analysis mode (sometimes referred to as real-time analysis mode)
  - Atmosphere trapping mode in which gas molecules are collected and concentrated for a period of time before analysis
- AAS consists of:
  - Sample collector / concentrator
  - Mechanism to expose concentrator to exosphere
  - Thermal system to cool collector / concentrator
    - Thermal switch / link to cooling radiator
  - Mass spectrometer analyser
    - Ion trap
    - Magnetic Sector System

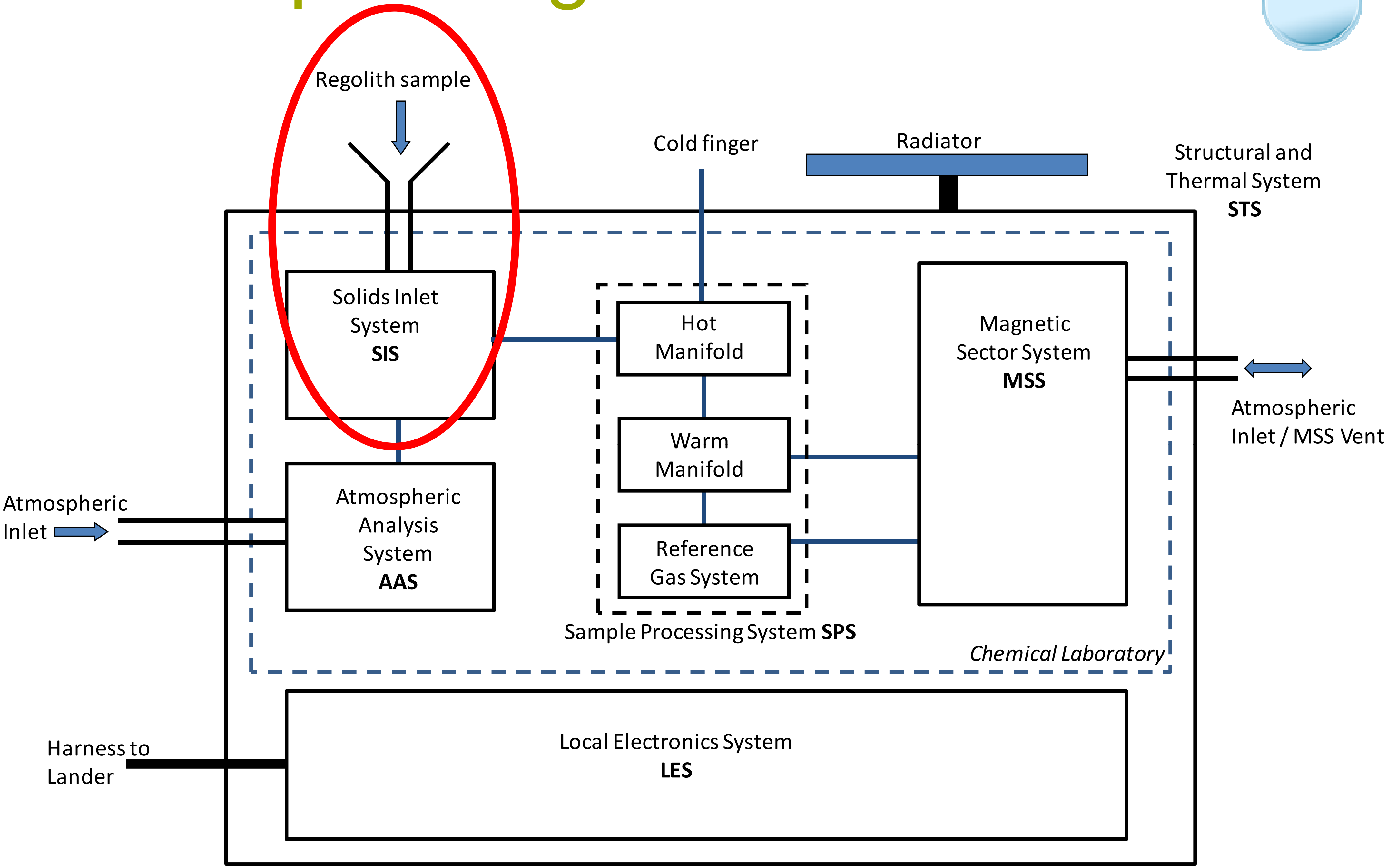
Concept Design: AAS



Concept Design: AAS

- Neutrals in exosphere are passively trapped onto an adsorbent material
  - Collector / concentrator removed from exosphere, sealed and heated to liberate trapped neutrals
  - Primary analysis performed by an ion trap mass spectrometer
    - Rapid identification of volatiles
    - Direct analysis of low concentration of water
    - Removes requirement of passing water into MSS
- Secondary option of analysis by Magnetic Sector System MSS
  - Valve to isolate exosphere from ion source of mass spectrometer

Concept Design: SIS

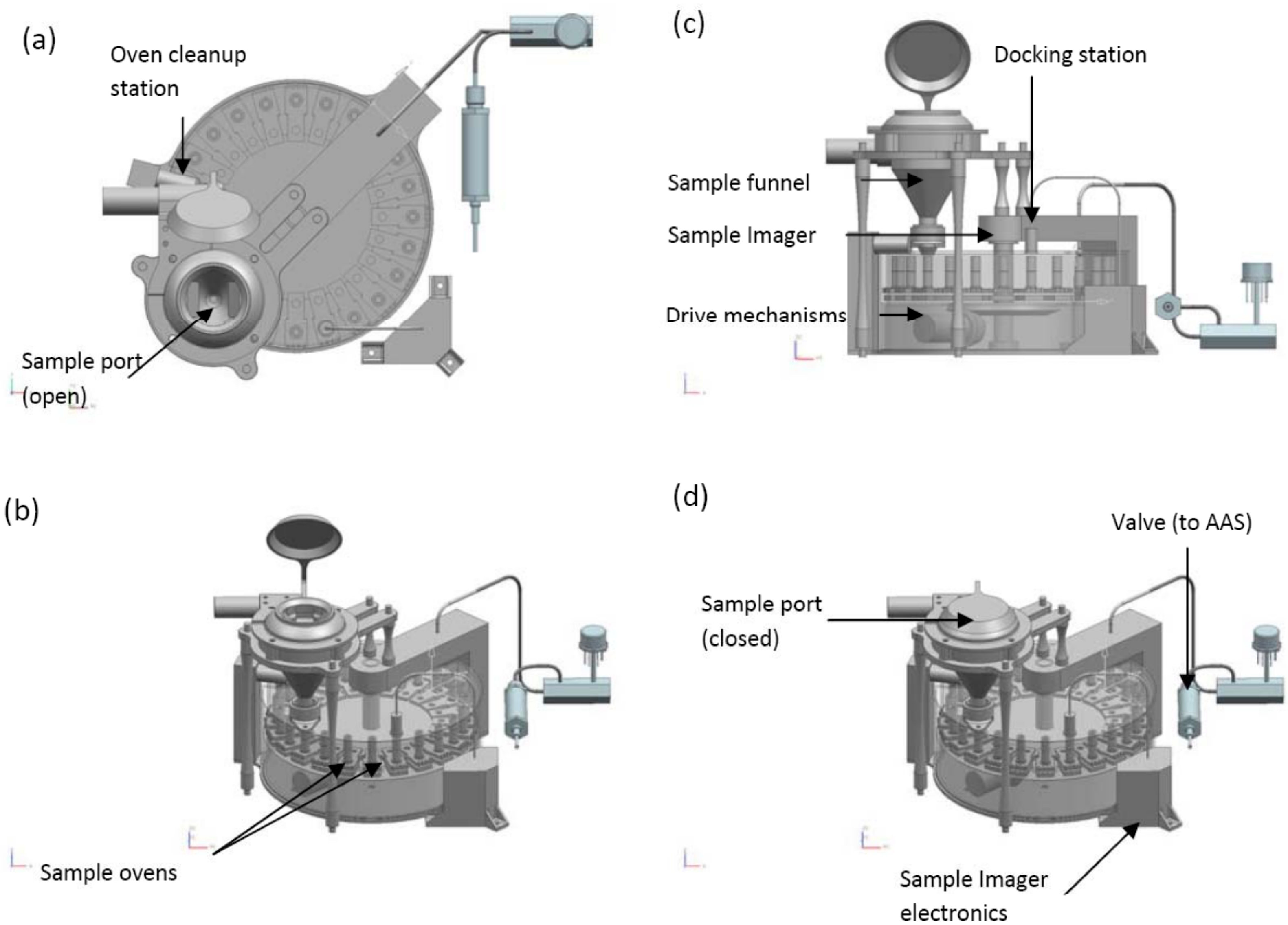


Concept Design: SIS

- The SIS performs the following functions:
  - Accepts samples
    - Solid (regolith) samples delivered by the robotic arm and associated sampling devices (e.g. scoop, mole)*
  - Characterise samples
    - For solid samples this includes visual appearance, verification of sample acquisition, estimation of mass / volume
  - Volatiles extraction
    - For solid samples for instance by heating
  - Deliver gases resulting from above processing on to the Sample Processing System

*current design does not address requirement to subsample from a larger sample delivered by SSS

Concept Design: SIS



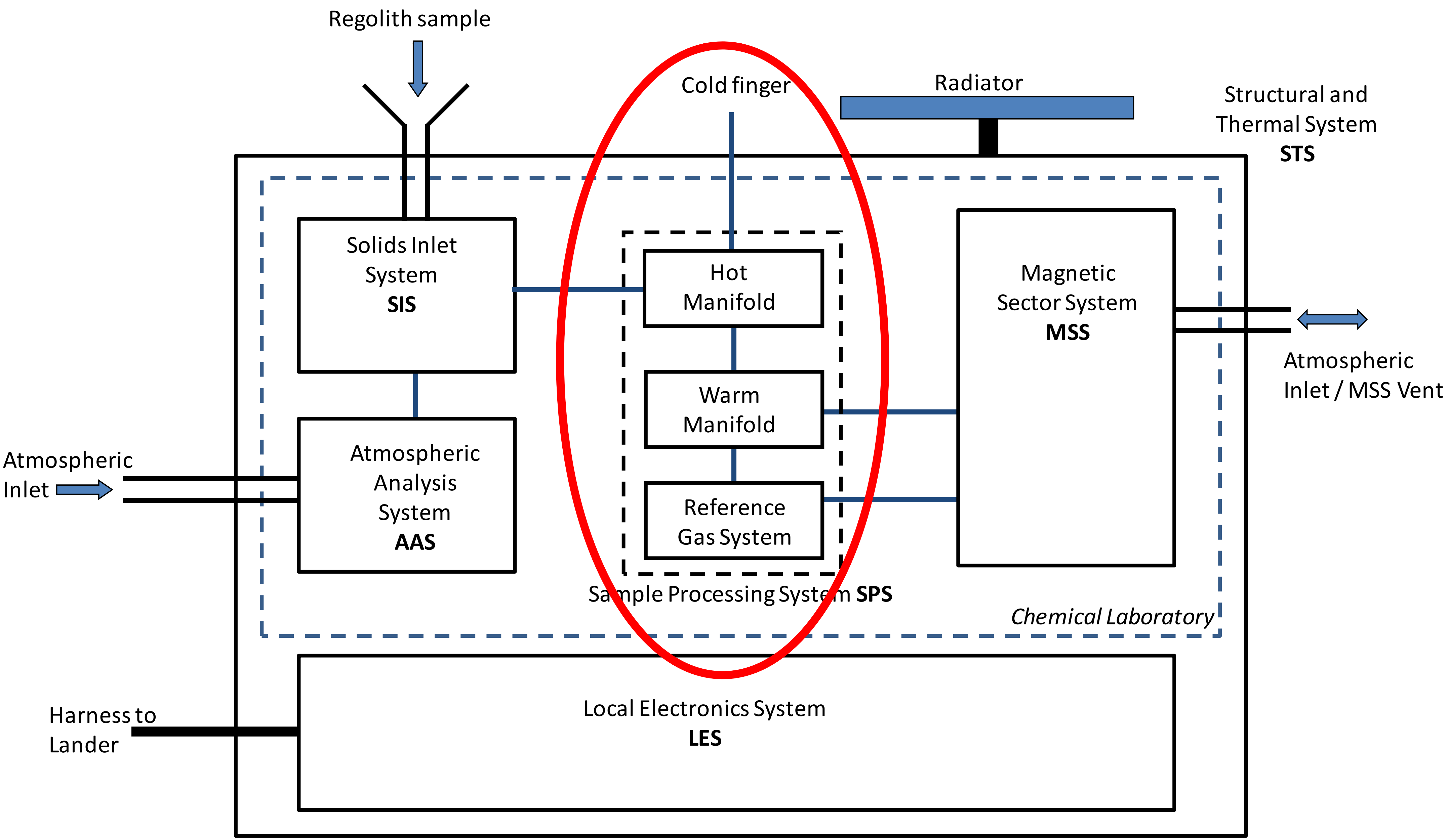
Concept Design: SIS

- Current concept does not perform sub-sampling of a larger sample delivered by SSS (new requirement from Sampling workshop)
- Interface is Sample Inlet Port (Beagle 2)
- cantilever sample retention and inspection platform allows direct imaging of deposited sample if imager available on SSS
- Piezoelectric shaker and charge neutraliser (TBC) to aid transit through funnel
- 24 “one-use” ovens
- Rotary carousel, drive and mechanisms below platform for isolation
- 3 (TBC) functional stations
  - Sample imaging station (sample characterisation & volume)
  - Oven clean-up station (to clean sealing surfaces)
  - Oven docking station (with TBD high force actuator for good seal)

Concept Design: SIS

- The SIS is a critical technology area
- The final design of the SSS will impact greatly on SIS (and potentially vice-versa)
- The performance of L-VRAP will depend upon SIS and its interface to SSS
- A new iteration loop is now required to assess the impact of the requirement to sub-sample
- There are radically different approaches to SIS e.g.
  - containment of samples in platinum foil parcels
  - Pelletisation
  - Sample acquisition in a manner more able than a simple scoop to fix sample volumes
- Bread boarding would doubtless be beneficial but needs to be considered at system level with SSS involvement

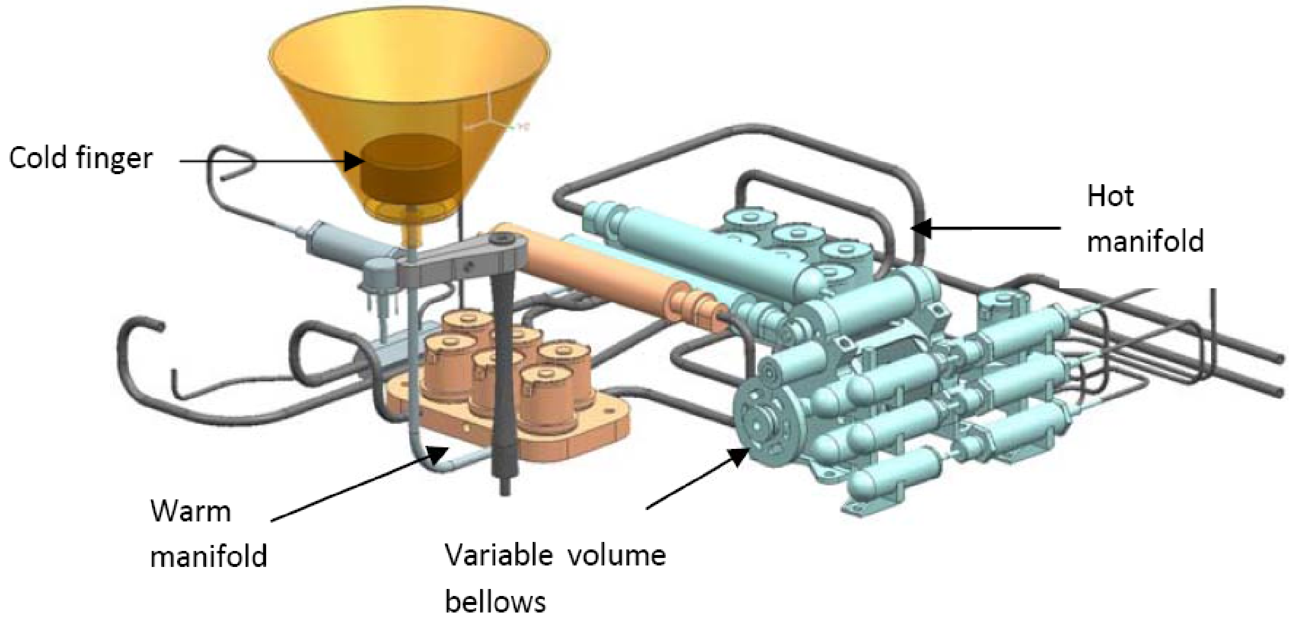
Concept Design: SPS

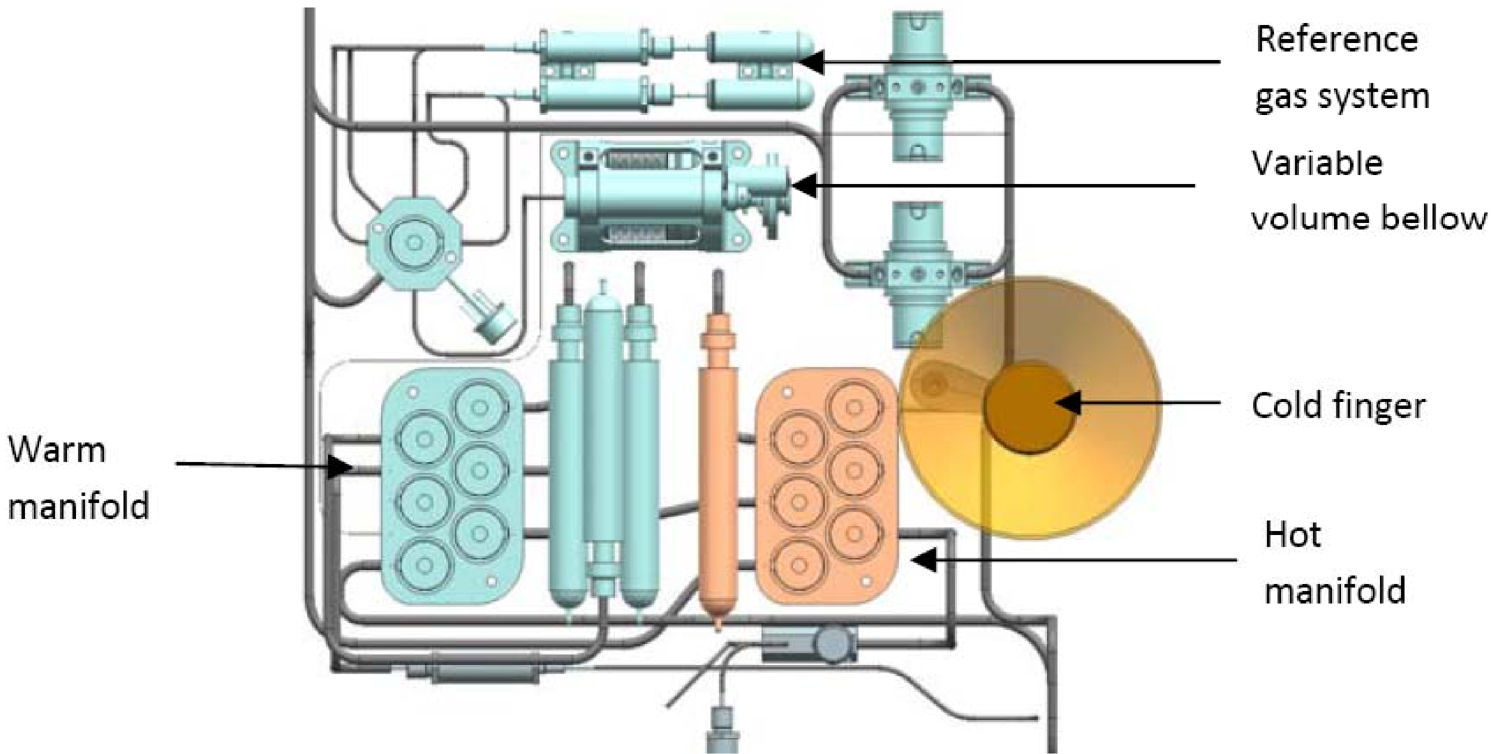


Concept Design: SPS

- The SPS performs the following functions:
  - Receive sample gases from SIS and/or AAS
  - Purify and process sample gases using chemistry and physical properties
  - Prepare and process reference gases for introduction into Magnetic Sector System
  - Deliver sample and reference into Magnetic Sector System
- Main subsystems of SPS are:
  - Hot Manifold
  - Warm Manifold
  - Reference Gas System
  - Cold Finger Assembly

Concept Design: SPS



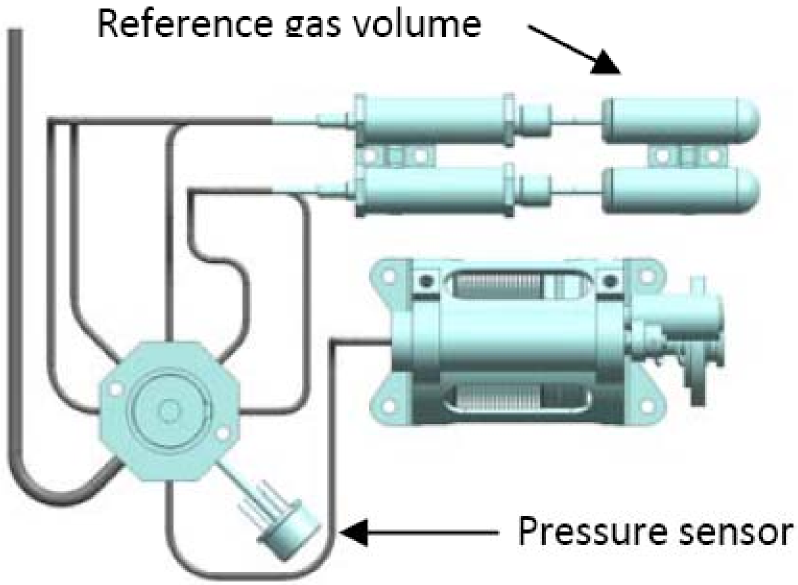


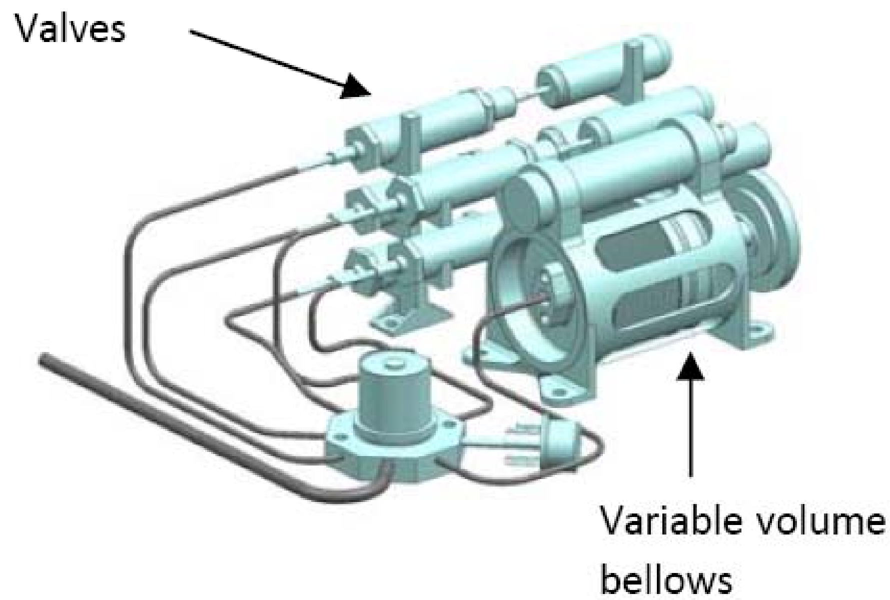
Concept Design: SPS Manifolds

- Manifold assemblies:
  - Hot Manifold
    - Process and purify volatiles which may contain high concentrations of water – High temperature
    - Removal of water vapour by drying agent
    - Cold finger for cryogenic separation
  - Warm Manifold
    - Volatiles processed by Hot Manifold
      - ‘Dry’ i.e. water vapour removed or chemically converted
      - Operate at lower temperature than Hot Manifold

Concept Design: SPS Ref Gas

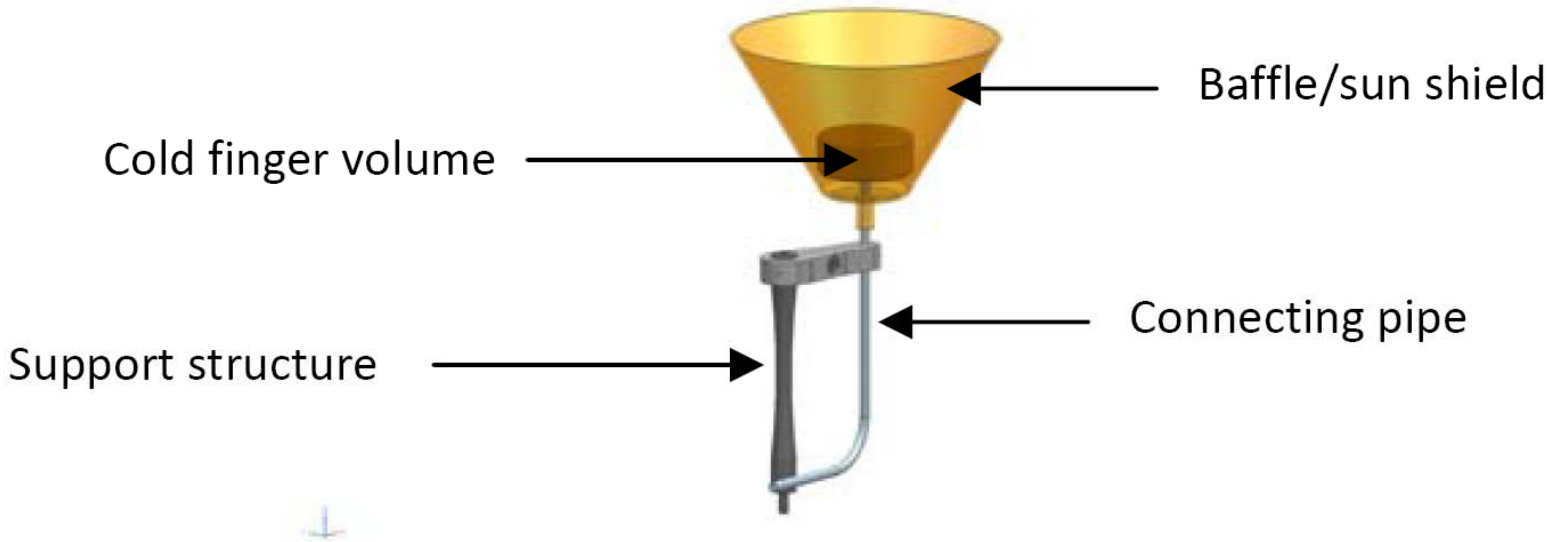
- Reference gas system
  - To store and release precise amounts of reference gases into the SPS and AAS
  - Gases stored at high pressure in miniature pressure vessels
  - Gas flow controlled by miniature proportional control valves and feedback loop with pressure sensors
  - Variable volume bellows to match pressure of sample and reference gas



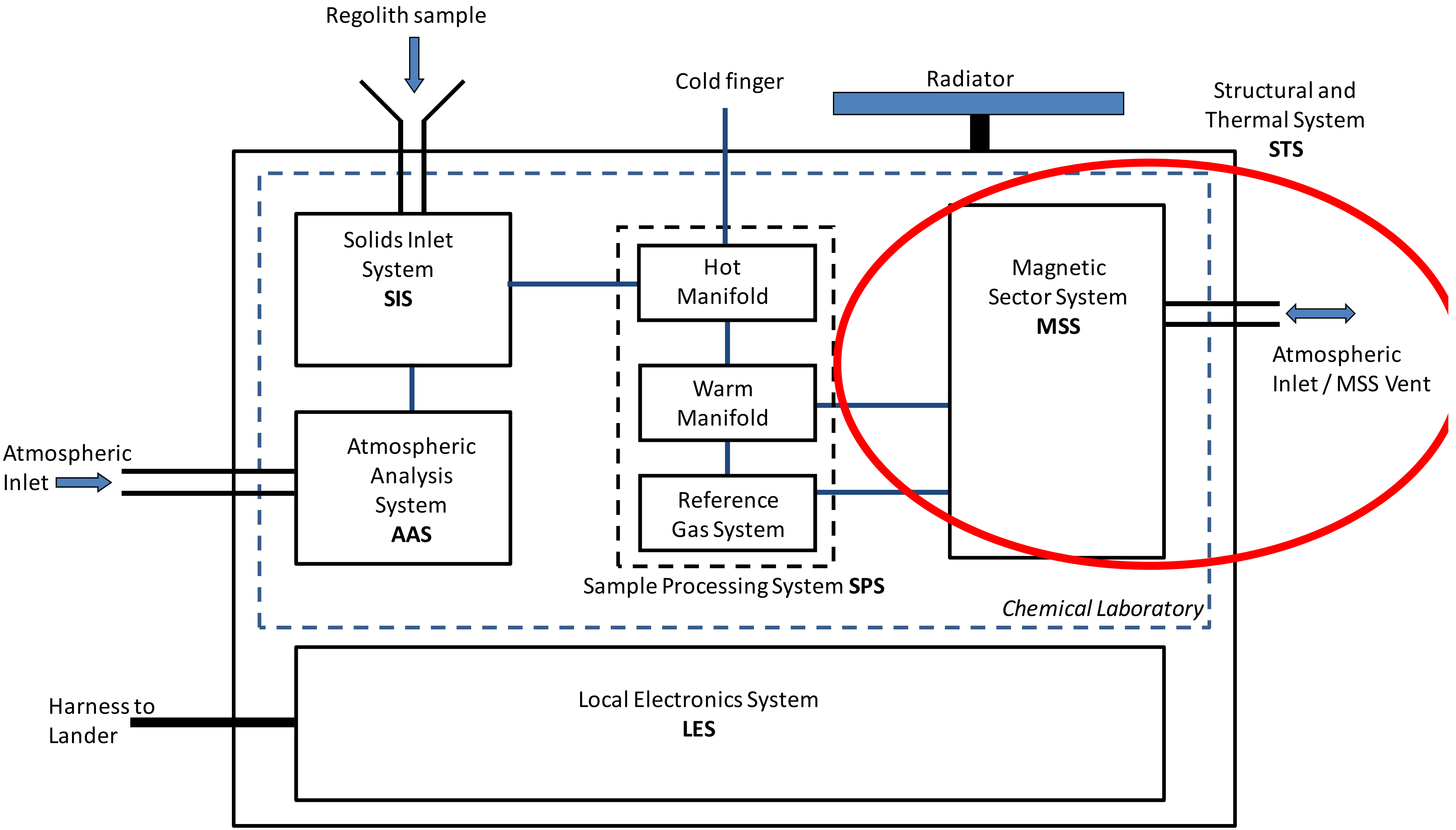


Concept Design: SPS Cold finger

- Cold finger assembly
  - to separate volatiles using cryogenic focusing techniques
  - thermally isolated volume
  - volume is exposed to deep space to allow it to cool
  - target volatiles will be trapped
  - Other volatiles ‘pumped’ away
  - Heating will liberate trapped volatiles for analysis



Concept Design: MSS



Concept Design: MSS

- The MSS performs the following functions:
  - Receive sample and reference gases from the SPS
    - Direct from SPS
    - Through change-over valve
  - Receive atmospheric samples from AAS via SPS and/or direct from lunar atmosphere
  - Perform qualitative, quantitative and isotopic characterisation of reference and sample gases

Concept Design: MSS

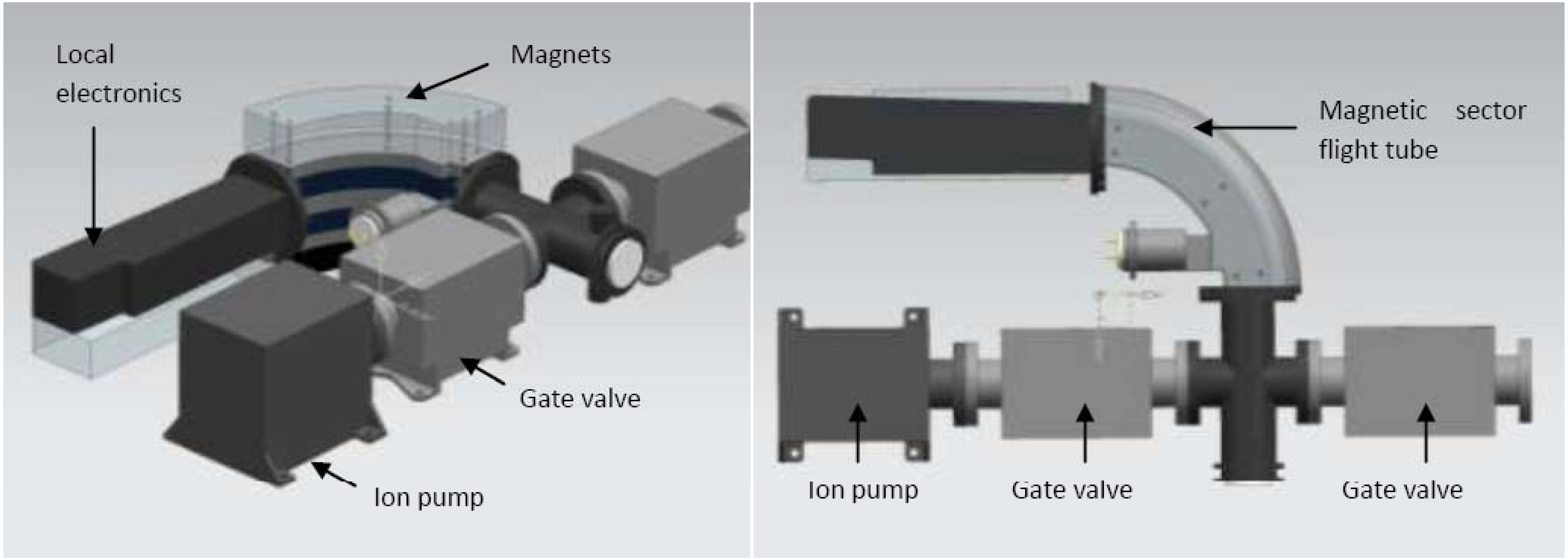
- Sample Inlets
  - Change-over valve – sample ref comparison
  - Direct inlet to SPS
    - Static gas analysis
    - Exosphere collected by AAS
  - Gate valve
    - Sample removal
    - Direct sampling of lunar exosphere

- key technology Critical/Open design issues and bread-boarding activities
  - In-line gate valve (required for atmospheric inlet)
  - Mass range 10 – 24 sufficient res? (extra collector?)
  - Low power ion source (as Ion Trap Ion source)?

Concept Design: MSS

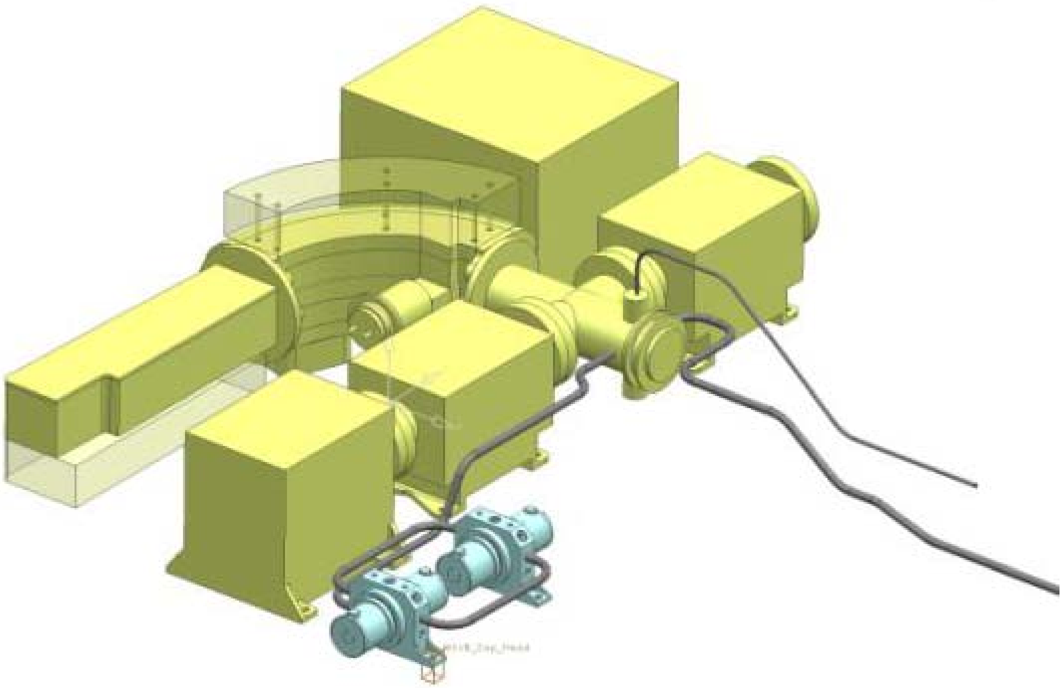
- MS 6cm radius magnetic sector - GAP heritage
  - Dynamic analysis   μmol sample, isotopic ~ 0.1‰
  - Static analysis   nmol sample, isotopic ~ 1‰
  - Mass range   2-150 amu
  - Mass resolution $M/\Delta M$ ~65
  - Filament electron source – heritage
- Ion Detection, 6 collectors - GAP heritage
  - Triple Faraday Cup– CNOS isotopes
  - Double Faraday Cup – DH isotopes
  - Electron Multiplier Detector – m/z 28 – 150, noble gas
- Ion Pump 2 $L.s^{-1}$ - GAP heritage

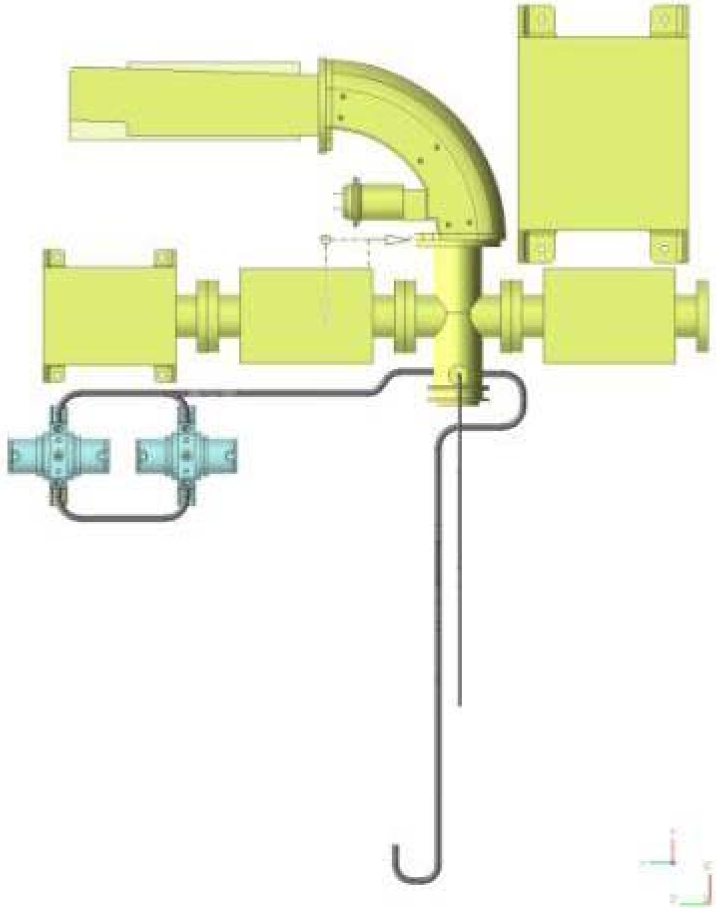
Concept Design: MSS



MSS High voltage electronics and change-over valve not shown

Concept Design: MSS





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  - Lander & environment interfaces [SB]
  - Resource requirements [SB]
- Task 4: L-VRAP Development Plan [SB]
- Summary and Conclusions [SB/CTP]

L-VRAP Scientific Performance

- Overall assessment of L-VRAP instrument concept
  - Requirements RQ1 to RQ6 can be met*
  - Requirement RQ7 not possible as things stand
- Overall assessment of contamination issues
  - Optimism regarding RQ8
  - Concept driven by a desire to characterise contamination
- Overall assessment of lunar volatiles investigation
  - May be constrained by landing site (e.g. no rocks!)
  - Ultimately limited by performance of sampling devices
  - Interface between sampling device and L-VRAP critical
  - The notion of sub-sampling an open issue
- Overall assessment of resources investigation
  - The use of a small-scale (sealed) heating device investigated
  - Possibilities of trapping also investigated

* Except Oxygen Isotopes (see following)

L-VRAP Scientific Performance

- Volatile identification
  - All requirements can be met

Species	Chemical symbol	Main mass(es)
Hydrogen	H_2	2
Helium	He	4
Methane	CH_4	16 (15)
Ammonia	NH_3	17
Water	H_2O	18 (17)
Carbon monoxide	CO	28
Nitrogen	N_2	28
Argon	Ar	36 and 40
Carbon dioxide	CO_2	44
Kyrpton	Kr	78 to 86
Xenon	Xe	124 to 136
C2 to C4 organics	e.g. C_2H_4	26 to 58

L-VRAP Scientific Performance

- Abundance Measurement (of volatiles in the regolith)
  - Currently estimated at ± 40%
    - Driven by error in determining mass of the sample
    - Current concept, based on high TRL, uses an imaging approach to determine sample size (volume measurement and assumed density)
    - Through further/additional work (phase 2), could consider a means for direct sample mass determination

L-VRAP Scientific Performance

- Isotopic analysis
  - All requirements can be met except $\delta^{17}O$

Isotope	Species	Analyser mode	Sample size	Precision (‰)
δD	H_2	dynamic	1 μmol	± 10
$\delta^{13}C$	CO_2	dynamic	1 μmol	± 0.1
		static	1 nmol	± 1
$\delta^{15}N$	N_2	dynamic	1 μmol	± 0.1
		static	1 nmol	± 1
$\delta^{18}O$	CO_2	dynamic	1 μmol	± 0.1
$\delta^{17}O$	CO_2	dynamic	1 μmol	± 2.2

Summary

- L-VRAP concept as defined is a flexible instrument with the potential to meet all major science requirements
- L-VRAP relies upon an effective SSS for best results
- L-VRAP operations can be tailored in light of previous results and to take into account real time constraints e.g. time, energy

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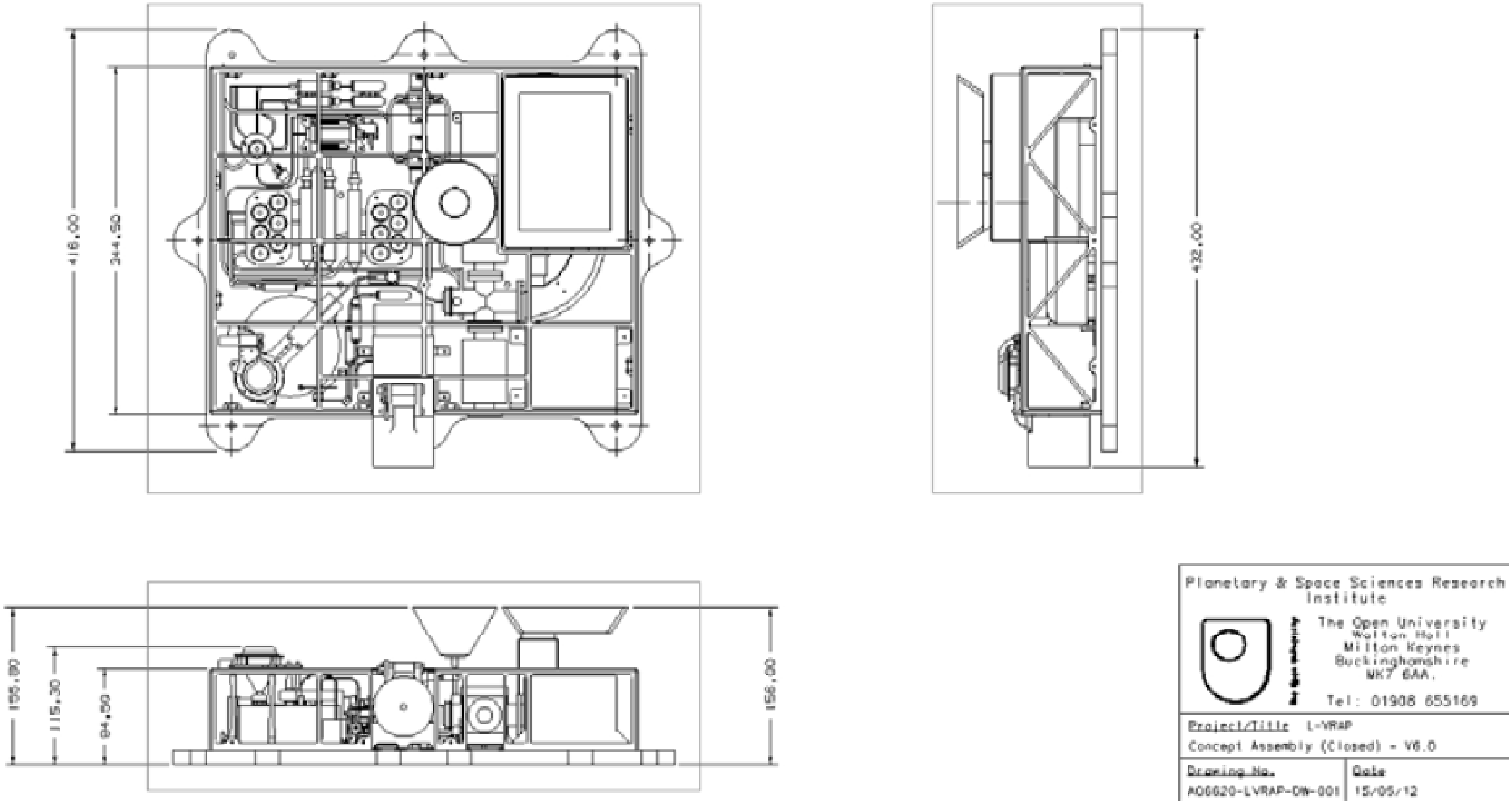
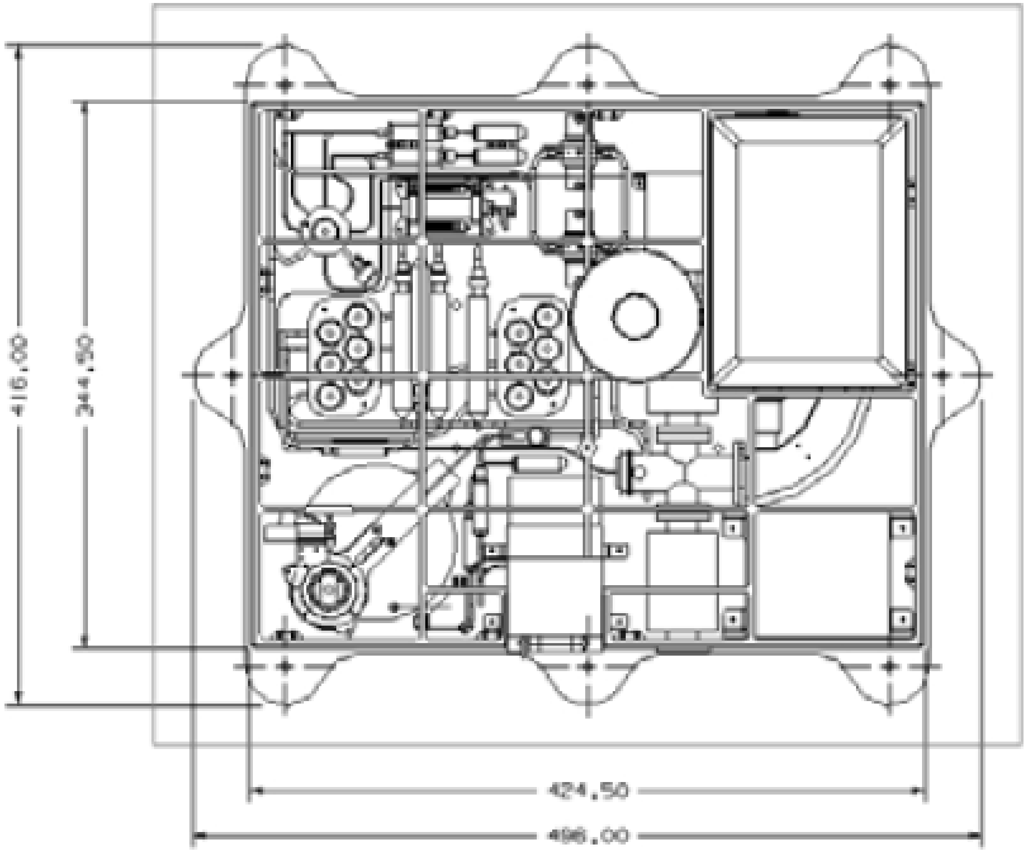
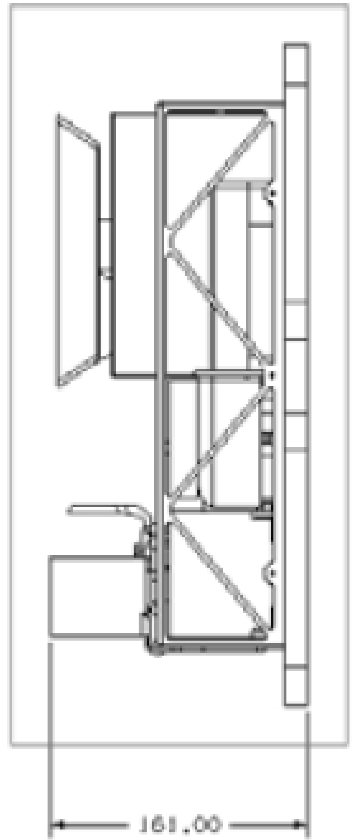
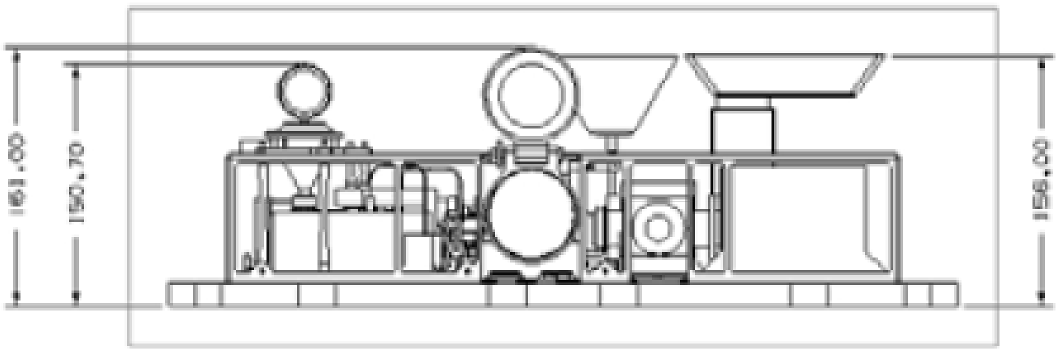
Interfaces: Mechanical



Interfaces: Mechanical

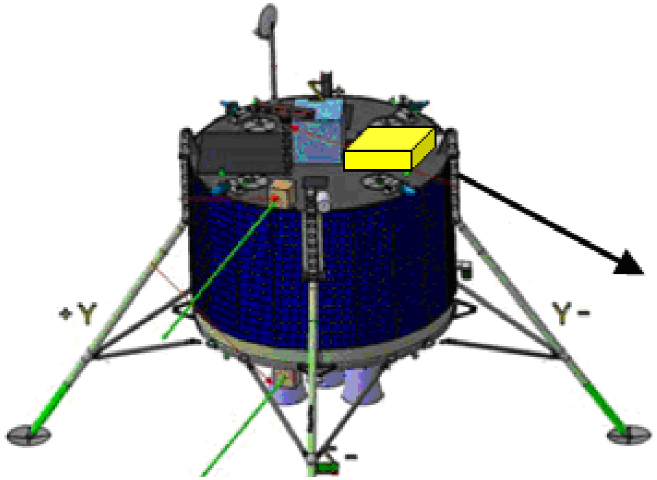


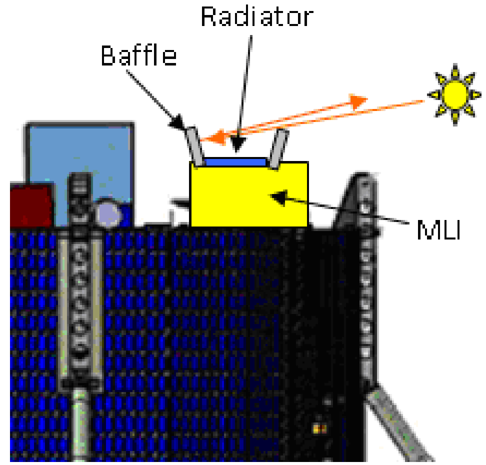




Interfaces: Thermal

- Interface with Spacecraft:





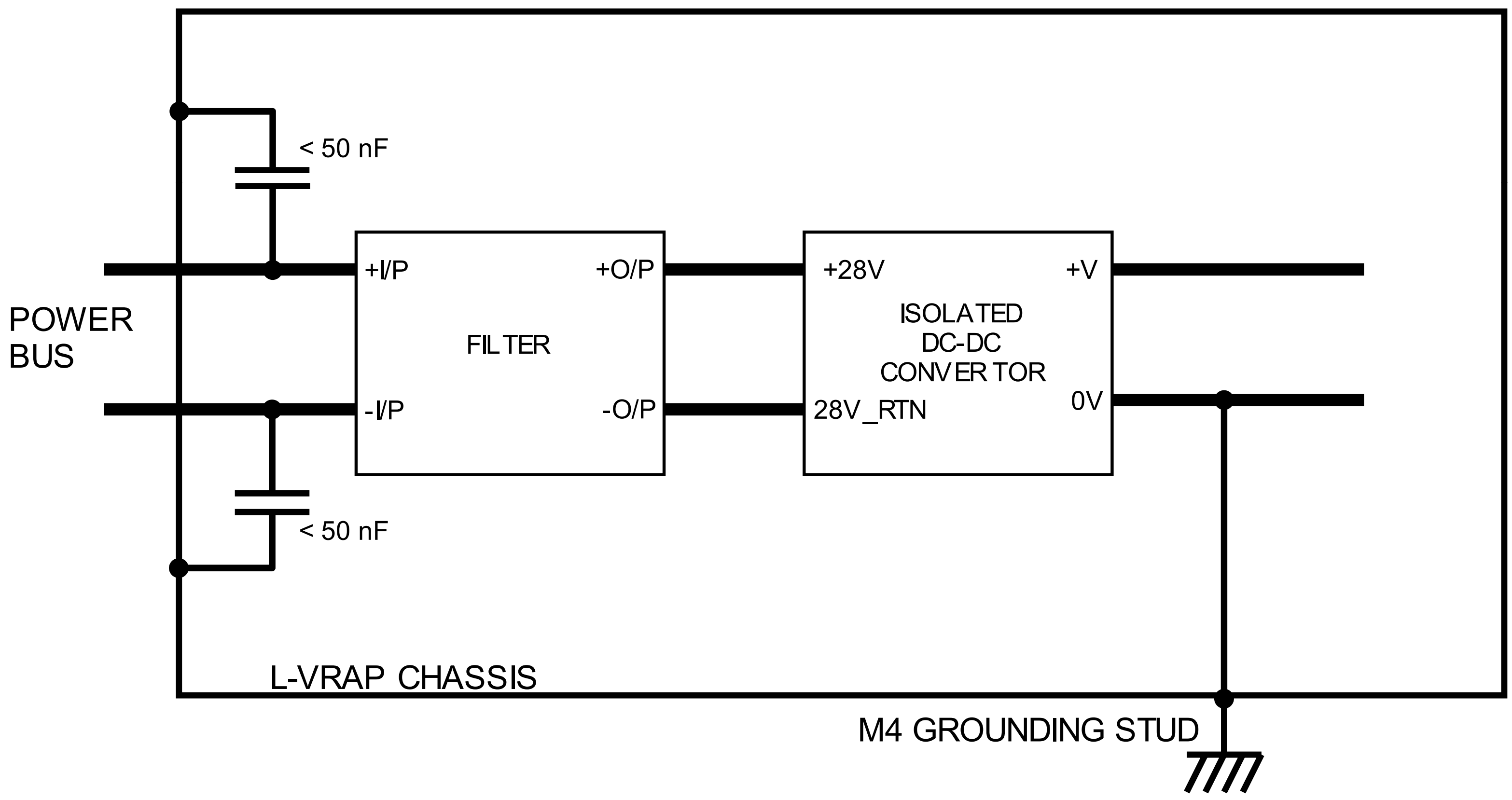
Interface	Configuration
Location on Lander	On the top surface of the lander.
Heat Rejection	110 mm x 110 mm (TBC) radiator with an unobstructed view to space
Heater Power of non-operations	Total of 1.4 W distributed throughout the instrument (Assuming allowable temperature range -50°C to +80°C Non-Op and -50°C to +70°C Op – see section 11.3.6)
Heater Power for Pre-Warm before entering Night	16W over 10hrs needed for entering night. Time can be reduced with bigger heaters for the same net energy input. Pre-warm effective for 38 hours after nightfall – i.e. survival heaters not needed for 38 hours.
Cold Finger	Unobstructed view to space.
Connection to Lander	Thermal decoupled using low conductance mounts and MLI to minimise the uncontrolled energy demand on the lander. Low conductivity materials such as Vetronite or PEEK are anticipated.

Interfaces: Electrical

- Power
  - 28V (nominal), 20 to 34V
  - Power switching performed by the lander (no relay in L-VRAP)
  - Two connector pins for supply and return
  - Standard density 9 way D-type plug
- Data
  - Prime and redundant CAN bus
  - 500 kbit/sec
  - Standard density 9 way D-type socket
- Dis-arming plug
  - Used to prevent operation of instrument HV supplies
  - Red tag item
  - Standard density 15 way D-type socket
  - EMC cover for flight

Interfaces: Grounding

- L-VRAP secondary supplies connected to chassis
- 28 V supply and return isolated from chassis at L-VRAP
- The 28V supply may be used directly for actuating high power devices, control via an isolation barrier.



Interfaces: Software

- All the Telemetry and Telecommand Packets exchanged will use the applicable parts of:
  - Telemetry and telecommand packet utilization (ECSS-E-70-41A),
  - Space data links - Telemetry transfer frame protocol standard (ECSS-E-ST-50-03C)
  - Space data links - Telecommand protocols, synchronization and channel coding (ECSS-E-ST-50-04C).
  - Lunar Lander Data handling document TBD
- L-VRAP and the on-board computer will exchange telemetry packets, telecommand packets and Time Distribution Messages.
- The way of transporting the data items on the CAN bus is currently undefined. A draft ECSS is available.

Interfaces: Software

- Telecommand Summary
  - Dummy command
  - Safe Mode
  - Standby Mode
  - Operational Mode
  - Request mode Status
  - Run module
  - Abort module
  - Shutdown
  - Save context
  - Load Memory
  - Dump Memory
  - Check Memory
  - Copy Memory

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Resource Requirements

- Mass
- Power
  - Ops power
  - Non-ops
- Energy and Data

Resources: Mass

L-VRAP MASTER EQUIPMENT LIST			
Indent ure	Item	CBE Total Flight Mass (g)	Max Exp. Mass [g]
	L-VRAP	**7170**	**7994**
1	**STS Structural & Thermal System**	1223	1363
1	**LES Local Electronics System**	900	990
1	**AAS Atmospheric Analysis System**	761	880
1	**SIS Solids Inlet System**	546	644
1	**SPS Sample Processing System**	1426	1596
1	**MSS Magnetic Sector System**	2314	2522

Resources: Mass

L-VRAP MASTER EQUIPMENT LIST			
Indenture	Item	CBE Total Flight Mass (g)	Max Exp. Mass [g]
	L-VRAP	**7170**	**7994**
1	STS Structural & Thermal System	1223	1363
2	Structure	881	986
2	Thermal	342	376
1	LES Local Electronics System	900	990
2	Local Electronics	900	990
1	AAS Atmospheric Analysis System	761	880
2	Atmosphere Collector System	526	621
2	Collector	40	44
2	QIT Mass Spectrometer	195	215
1	SIS Solids Inlet System	546	644
2	Solid Sample Inlet	68	75
2	Visual/Solid Characterisation	130	156
2	Volatiles Extraction	348	413
1	SPS Sample Processing System	1426	1596
2	Hot Manifold - for water	441	492
2	Warm Manifold - for other volatiles	450	502
2	Reference gas system	480	536
2	Cold Finger assembly	55	66
1	MSS Magnetic Sector System	2314	2522
2	Magnetic Sector Inlet	130	142
2	Magnetic Sector Analyser	1236	1360
2	Magnetic Sector Pumps	678	724
2	Magnetic Sector Electronics	270	297

Resources: Mass

Indenture	Item	CBE Total Flight Mass (g)	Maturity Code	Mass Growth Allow.%	Max Exp. Mass [g]
L-VRAP MASTER EQUIPMENT LIST					
		Launch Mass Tally			
	L-VRAP	**7170**			**7994**
1	STS Structural & Thermal System	1223			1363
1	LES Local Electronics System	900			990
1	AAS Atmospheric Analysis System	761			880
2	Atmosphere Collector System	526			621
3	Housing and Mechanism	400	new dev.	20%	480
3	PZT valve	35	new dev.	20%	42
3	Gas cylinder	5	modified	10%	6
3	Pipework	20	modified	10%	22
3	2 VCR Fittings	10	recurrent	5%	11
3	1 VCR fittings	6	recurrent	5%	6
3	Heater, PRT, Pipe, Valve	50	modified	10%	55
2	Collector	40			44
3	Collector	20	modified	10%	22
3	Heater, PRT	20	modified	10%	22
2	QIT Mass Spectrometer	195			215
3	Ion Trap Electrodes	40	modified	10%	44
3	Ion Trap Housing	50	modified	10%	55
3	Ion Trap Electronics	100	modified	10%	110
3	Ion Trap Heater, PRT	5	modified	10%	6
1	SIS Solids Inlet System	546			644
1	SPS Sample Processing System	1426			1596
1	MSS Magnetic Sector System	2314			2522

Resources: Mass

L-VRAP MASTER EQUIPMENT LIST					
		Launch Mass Tally			
Indenture	Item	CBE Total Flight Mass (g)	Maturity Code	Mass Growth Allow.%	Max Exp. Mass [g]
	L-VRAP	**7646**			**8751**
1	**STS Structural & Thermal System**	1300			1560
1	**LES Local Electronics System**	1000			1200
1	**AAS Atmospheric Analysis System**	871			1011
1	**SIS Solids Inlet System**	616			728
2	**Solid Sample Inlet**	68			75
3	**Sample Inlet Port (motor, Hall sensor)**	59	modified	10%	65
3	**Funnel (PZT)**	9	modified	10%	10
2	**Visual/Solid Characterisation**	200			240
3	**Camera structure, optics etc**	100	new dev.	20%	120
3	**Camera electronics**	100	new dev.	20%	120
2	**Volatiles Extraction**	348			413
3	**Oven(s)**	48	modified	10%	53
3	**Carousel subass'y inc structure, motors, heater, PRT**	300	new dev.	20%	360
1	**SPS Sample Processing System**	1425			1599
1	**MSS Magnetic Sector System**	2434			2654

Resources: Power

- Ops power:

  Peak power 56 W (TBC) – could be lower if required

  Power budget is flexible – low/slow vs high/fast (energy considerations)

Experiment	Average Power	Duration (minutes)	Data Volume (kBytes)	
			Science	Housekeeping
Exosphere real time analysis	Medium (7.9W)	611	242	306
Exosphere Passive Collection (NB L-VRAP on for only 59 minutes)	Low (0.015W)	659	63	30
Regolith Quick Analysis	Medium (8.0W)	74	553	37
Regolith Detailed Analysis	Medium (9.3W)	412	2258	206

- Non-ops:

  Pre-heat at dusk 16 W over 10 hr is effective for 38 hours darkness

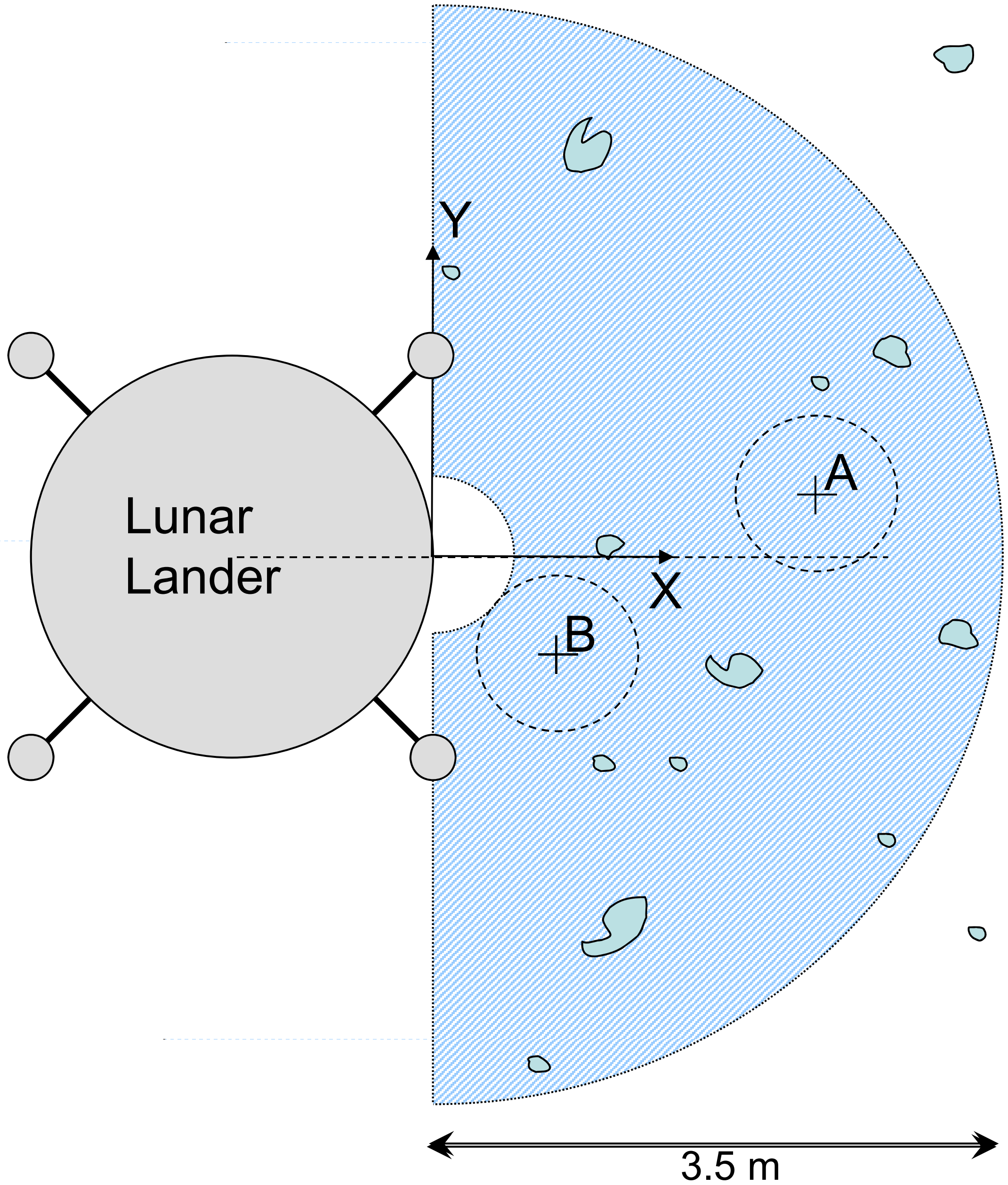
  1.5 W (TBC) for "keep-alive" after 38 hours

Resources: Energy and Data

- Energy and data budget quite flexible
- Table shows estimates for baseline operational scenario (no MPE)
- With MPE, figures are broadly similar

Mission Phase	Duration	L-VRAP Operational Resources				
		Duration		Energy	Data vol.	Ovens
	(days)	(hours)	(%)	(Wh)	(kBytes)	(#)
Descent and Landing	0.042 (1 hour)	0	0.0	0.0	0	0
Lander Checkout	2	9.3	19.3	109.3	3247	0
Initial SS	30	199.6	27.8	1754.8	41947	17
Main SS	90	381.6	17.7	3166.0	26204	6
Extended SS	28	245.5	36.5	1991.1	9496	0
Total	**150**	**836.0**	**23.2**	**7021.2**	**80894**	**23**

Sample Requirements



Assumptions:

- Slope <15°
- SSS has working zone
- Some cobbles in working zone (64 – 256mm)
- Clear areas > 500mm radius
- SIS has 24 ovens
- There is a model of surface

Define co-ordinates rel to SSS attachment point

X-Y plane = plane Lander baseplate

X direction through Lander centre

Z is relative to lunar surface

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- Summary and Conclusions [SB/CTP]

Open design issues

- Approach taken through study has been to achieve high TRL, low development risk design
- L-VRAP as described is flexible and robust to changes in mission parameters (mission design, performance and Lunar environment)
- However in each area any open issues have been identified and in critical areas technology development activities have been (are being) elaborated
- Some of these concern areas that lie at the interface between instruments such as L-VRAP and the (at the time of the study not fully defined) Lunar Lander Solids Sampling System

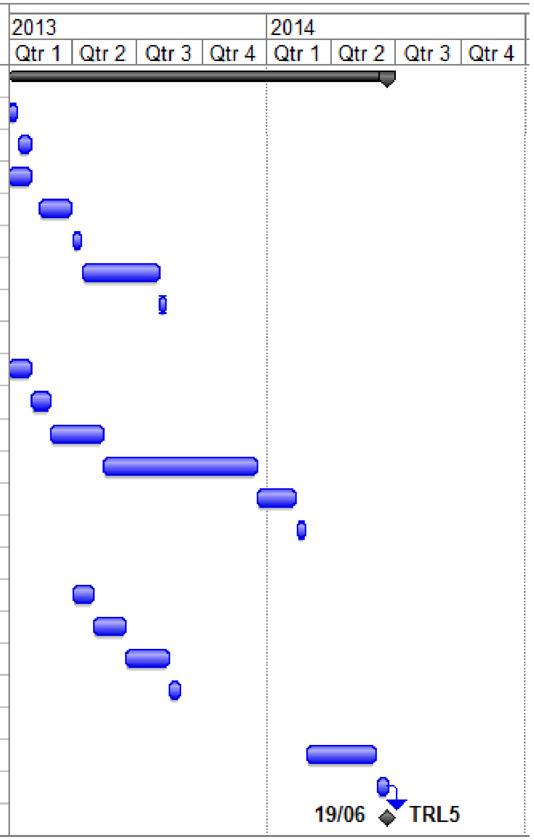
Task 4: L-VRAP Development Plan and Breadboarding Activities

- L-VRAP required to be TRL5 by mid-2014 assuming 2018 mission
- Baseline preliminary design utilises subsystems with heritage where possible to benefit TRL
- Some key areas have been identified where early development and/or development would be beneficial to derisk the instrument and mission concepts
- “Breadboarding” is defined broadly as encouraged by ESA to identify any activities that can move LL project forward in the timeframe to 2014/15

Task 4: L-VRAP Development Plan and Breadboarding Activities

- Breadboarding: SIS - Solid samples subdivision and sizing
  - Aim is to demonstrate ability to receive large sample from Lander SSS, perform subdivision, distribution and “weighing”

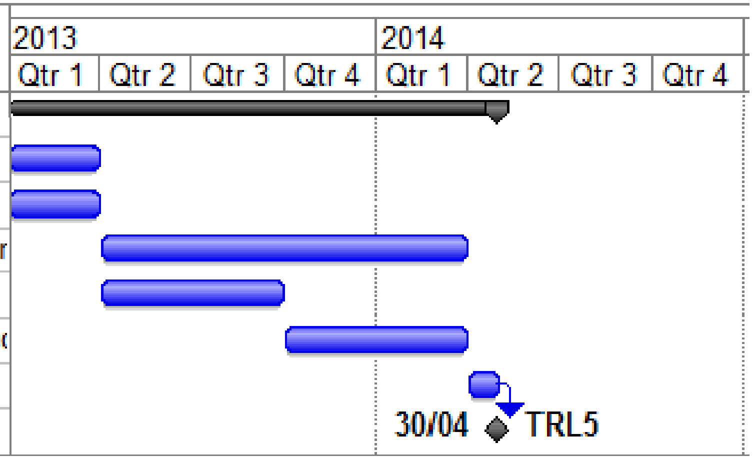
ID	Task Name
1	**SIS: Solid samples subdivision and sizing**
2	Design oven, heater and temperature system
3	Thermal modelling of oven designs
4	Design oven sealing mechanism
5	Manufacture oven and sealing breadboard
6	Build breadboard
7	Perform sealing, heating and lifetime test
8	Write report
9	
10	Design mechanical system for sample / oven transport
11	Produce CAD model for Breadboard system
12	Manufacture simple breadboard
13	Lifetime test of system in atm and in vacuum
14	Evaluate performance with oven design
15	Write report
16	
17	Design optical imaging system + CA
18	manufacture breadboard
19	Perform experiments with measured amounts of sample (Lunar simulant JSC)
20	Write report
21	
22	Perform integrated tests
23	Write full report
24	**TRL5**



Task 4: L-VRAP Development Plan and Breadboarding Activities

- Breadboarding: MSS Low power ionisation source
  - Aim is to reduce power dissipation of L-VRAP
  - To allow smaller radiator and reduce L-VRAP survival power demand
  - To reduce Lander energy demand at night (mass, power benefits)

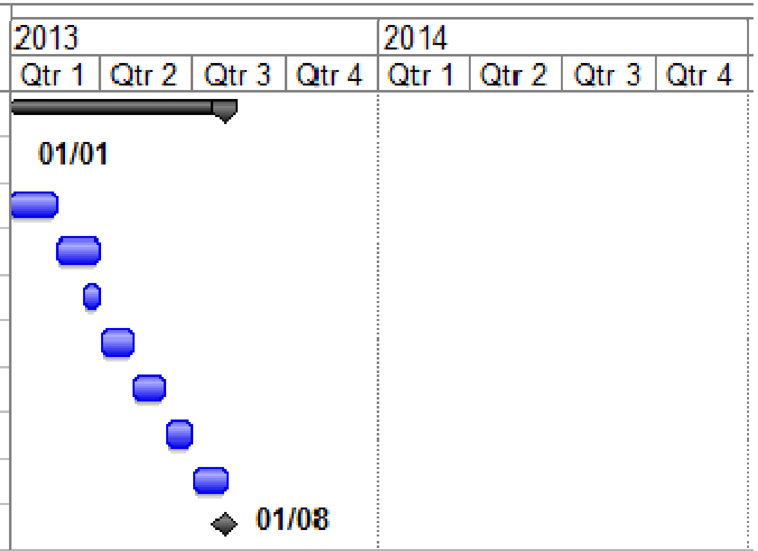
ID	Task Name
27	**MSS: Low power ionisation source for isotope mass spectrometer**
28	procure/manufacture FED source
29	build long term stability test rig
30	commence life time tests of FED sources under vacuum in relevant gaseous environment and der
31	procure & build test rig flexible magnetic sector instrument to allow FED subsitution into system
32	run FED sources under vacuum in relevant gaseous environment and demonstrate stability and co
33	write report on lifetime, stability and high voltage compatibility
34	TRL5



Task 4: L-VRAP Development Plan and Breadboarding Activities

- Breadboarding: ESS Distributed Power Switching
  - Aim is to reduce mass of L-VRAP harness to multiple valves

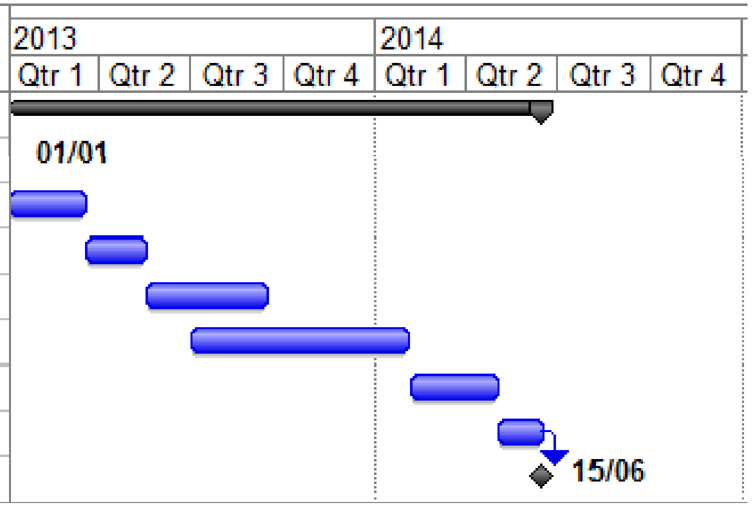
ID	Task Name
46	**Distributed Power Switching**
47	start
48	design study / trade
49	design and build prototype
50	define tests and associated equipment
51	Functional tests
52	Thermal test
53	Radiation test
54	Write test report
55	End



Task 4: L-VRAP Development Plan and Breadboarding Activities

- Breadboarding: Contamination modelling and measurement
  - To improve models, perform tests and validate model
  - Could take advantage of (collaborate with) any planned engine firing campaigns

ID	Task Name
36	**Contamination & Surface Alteration Modelling and Test Campaign**
37	Start (guideline calculations)
38	Higher fidelity computations
39	Test campaign planning
40	DSMC/Hybrid computations
41	Testing
42	Update engineering model
43	Synthesis and Margin
44	end (version 1 flight database)



Task 4: L-VRAP Development Plan / Model Philosophy

Term	Model	Deliverable?	Purpose	Build standard (general)	Build Standard (LES)
BB	Breadboard	N	technology development/demonstration of selected key subsystems	Prototypes of key components and subsystems	Prototype circuits using wirewrap/simple PCB to verify new circuit designs and support chemistry set prototypes.
EM	Engineering Model	N	demonstration of instrument performance in representative configuration	flight-respresentative in key areas	EM PCB, 4 off. Target flight design. Commercial components. Latest software version used and updated as required.
QM	Qualification Model	N	qualify design for flight (test to qual levels); after FM delivery is refurbished to become GRM	flight-identical	EM PCB design modified to take into account any design changes to produce an FM design. Prototype flight components fitted. FM Beta software used.
GRM	Ground Reference Model	N*	Allows on-ground rehearsal and simulation of operations planned for FM; enables characterisation and cross-calibration of experiments undertaken on Lunar surface	flight-identical	Existing QM PCBs modified to bring to same build standard as FM
FM	Flight Model	Y	Flight (test to Acceptance levels)	Flight Model	FM PCB design using flight parts (the intention is to use the EM board design provided there are no circuit changes required). FM final software.
FS	Flight Spares	n/a	Flight standard spare sub-assemblies available in event of failed FM hardware	flight-identical for selected sub-systems	FM PCB design using flight parts. FM final software installed when card required.
ES-1	Electrical Simulator 1	N	To allow dvelopment and testing of L-VRAP software	Will include dummy loads and indicators (resistors, sensors etc) for Chemistry Set to enable operation in atmosphere	Design based on EM circuit boards with additional heatsinks, wiring, indicators, sensor simulators and loads. Latest software build used and updated throughout the project
ES-2	Electrical Simulator 2	Y (TBC by LL)*	For integration into Lunar Lander Ground Reference Model for operations planning and rehearsals	Will include dummy loads and indicators (resistors, sensors etc) for Chemistry Set to enable operation in atmosphere	As ES-1 with representative loads and forced air cooling as required. Sensors used to 'close the loop' round the controlled items. FM software used.

*Model Philosophy (TBC): includes GRM and Simulator for operations planning/rehearsals

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Summary and Conclusions

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- It meets the science requirements as provided by ESA with a couple of exceptions (exospheric ions; regolith $\delta^{17}O$)
- Requires Solids Sampling System capable of delivering samples from depth (>~10 cm; ideally 40 cm) with little/known alteration
- Particular attention has been paid to high TRL and minimal development needs
- Development beneficial on:
  - Contamination modelling; Low power ionisiation
  - Sample inlet, distribution and imaging system; Multiplex valve control
- Significant attention paid to minimising night-time heating requirement
- Currently predicted 8 kg inc. margins (target 6 kg); descopes possible but at cost of reduced robustness/performance
- L-VRAP directly addresses the key questions that will be asked of a Lunar **Polar** Lander:
  - Concentrations, nature and sources of water and other volatiles in regolith around landing site and from more distant locations via exosphere

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- **L-VRAP performs vital science to enable exploration**

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