High Density Energy Systems

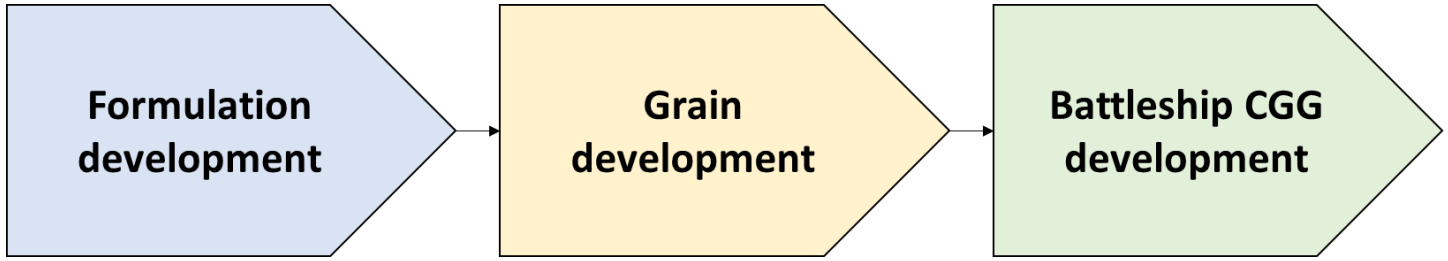
Final review

CGG for EP De-Risk project 6 September 2024

Agenda of the Final review

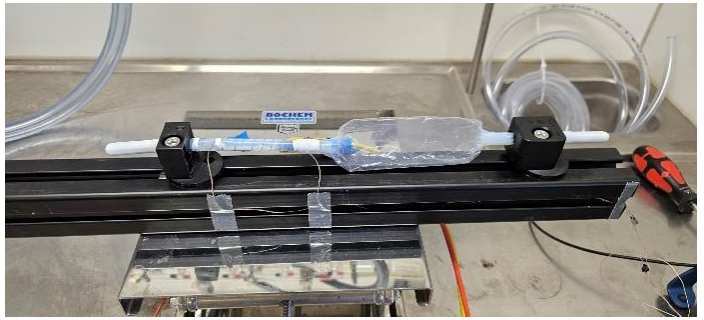
- 10.00 Opening
- 10:15 Presentation of the project results of the third and last phase
  - Introduction of the battleship development phase
  - Design of the improved test set-up
  - Experimental results and analysis
  - System study results
  - Questions / discussion
- 11:00 10 minute Break
- 11:10 Presentation of the follow on activities for the battleship phase
  - Development Plan
  - Technical Achievement Summary
  - Questions / discussion
- 11.30 Presentation to the Electric Propulsion Section of ESTEC
- 12.00 Lunch
- 13.00 Comments on the deliverables / technical data Packages
- 13:20 Contract Close out activities
- 13:40 Actions / Modifications of the documents
- 13:50 Any Other Business / Minutes of Meeting
- 14:00 Closing

Project overview



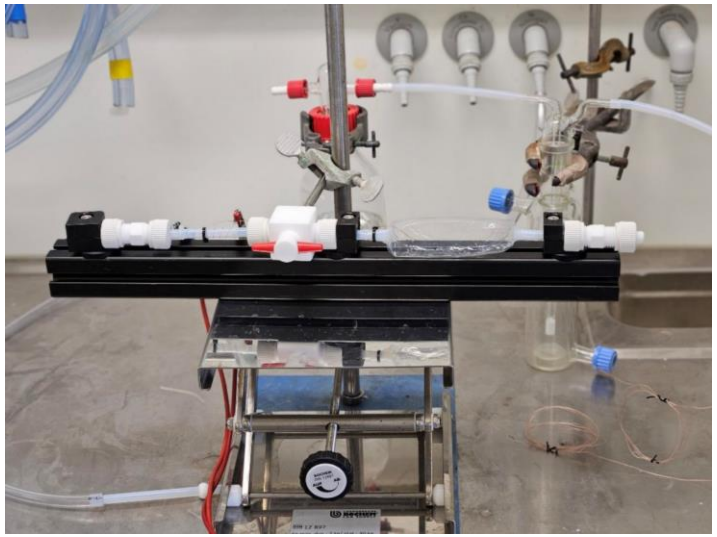
- Goal: to develop a xenon-producing cool gas generator
- WP 300 objectives:
  - To test the grain in a battleship CGG test setup

- The battleship was an improved version of the setup issued in the grain development phase.



Introduction of the battleship phase

- In the grain development phase, feasibility of the Xenon CGG was proven, however no independent working was realised
  - External heating
  - Hot nitrogen flow help the flow inside the test set-up
- The goal of the battleship phase was to improve the set-up used in the grain development phase.
- Main improvement was reduction in thermal inertia
- Main goals for the grain development phase:
  - Achieve independent xenon production
  - Test filters
  - Improve reaction chamber
- The first goal was achieved, the other two only partly



Improvements of the test set-up

- From a number of ideas for improvements, the following were selected

1) Remove the valves, as the reaction is slow there is minimal risk in removing the valves.
2) Reduce the mass and size of the setup to a large degree
3) Improve the use resistance wire configuration (more and better placed) and mount them up to the reaction chamber

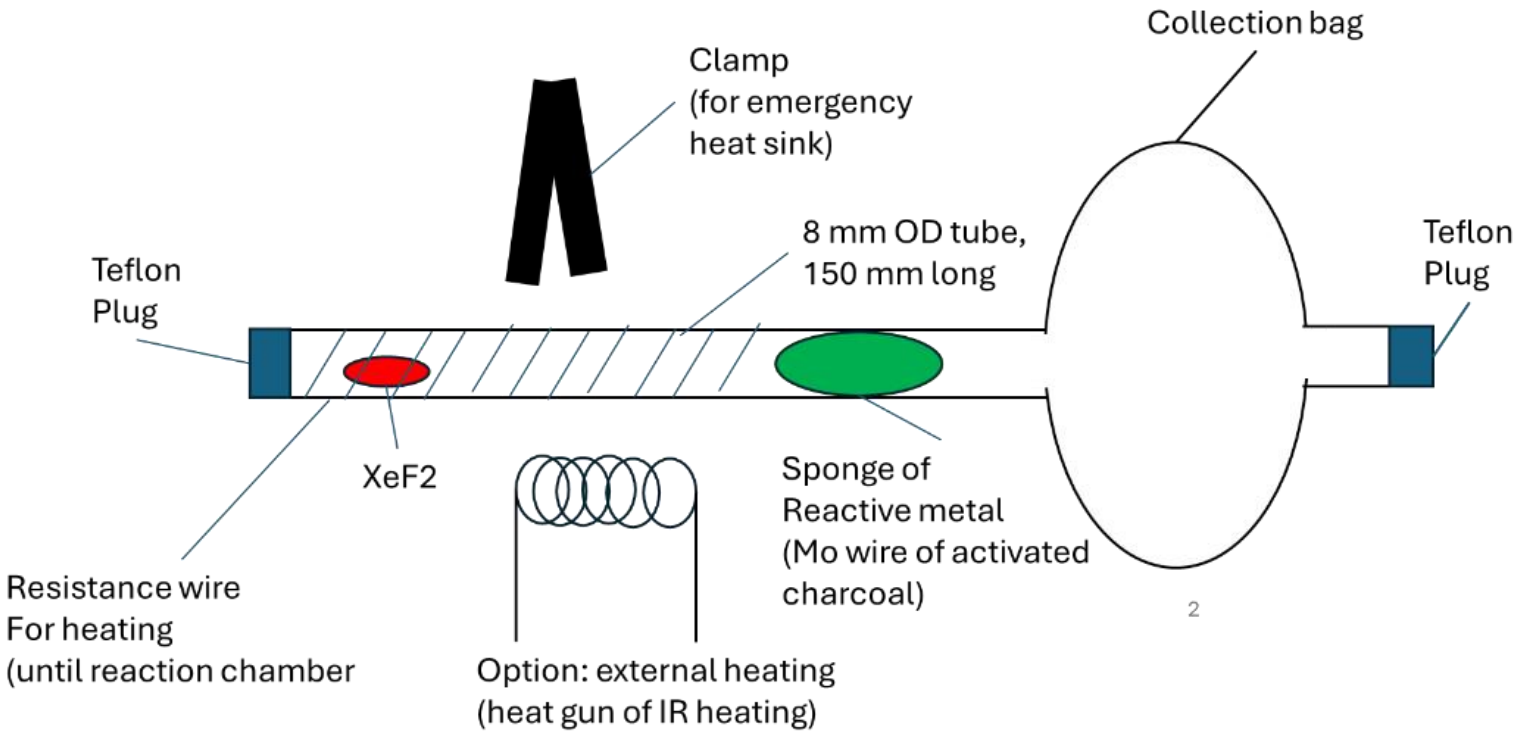
- Before the improvement were implemented, a thermal model was set-up to chain their effectiveness

Preliminary design for improved set-up

- From a number of ideas for improvements, the following were selected

1) Remove the valves, as the reaction is slow there is minimal risk in removing the valves.
2) Reduce the mass and size of the setup to a large degree
3) Improve the use resistance wire configuration (more and better placed) and mount them up to the reaction chamber

- Before the improvement were implemented, a thermal model was set-up to chain their effectiveness



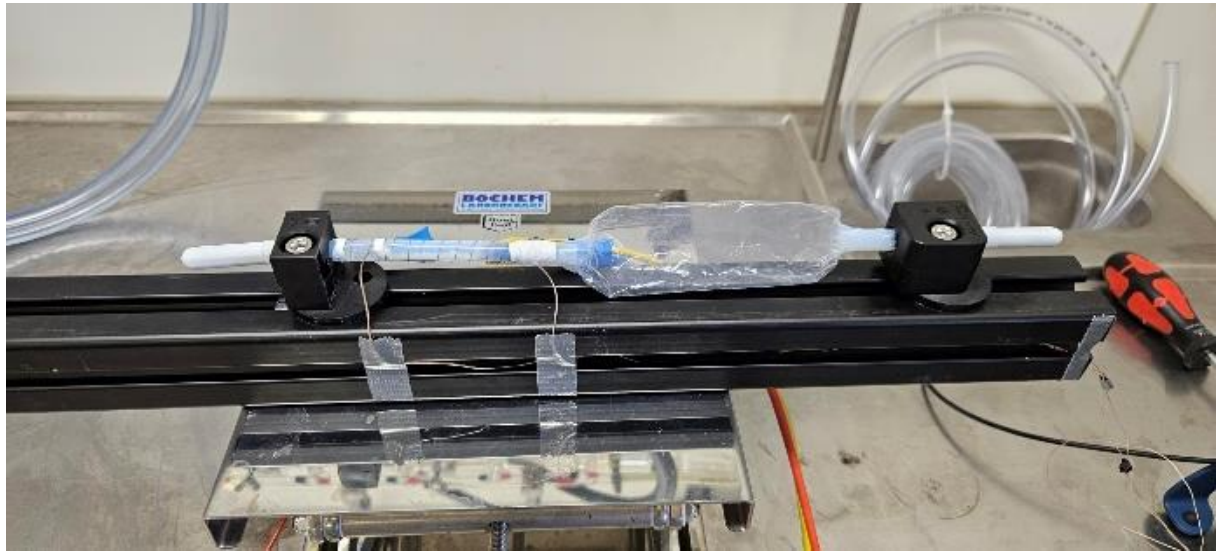
(simplified) thermal model

- Considers main parts as nodes with thermal properties
- Used to compute expected heating energies and times
- Confirmed the modifications of the set-up

simplified thermal model									Specific heat		heating the set-up from 1	
item	material	inner diameter (mm	outer diameter (mm)	length (mm)	volume (CC)	density (gr/cc)	mass		J/gr/K		T (degrees C)	E (J)
Tube	Teflon	7	8	150	1,767145868	2,2	3,887721		1,5		40	145,7895
XeF2						4,3	2	given	0,44		40	22
Teflon plug	Teflon	7	7,5	10	0,3848451	2,2	0,846659	left end	1,5		40	31,74972
Teflon plug	Teflon	7	7,5	10	0,3848451	2,2	0,846659	right end	1,5		15	0
Resistance wire	Ni-Chr steel	1	1	TBD		10,22	2				NA	
Reaction material	Molybdenum				0,2-0,8		2	25% porosity	4,18		NA	
Collection bag	PTFE	50	50,2	50	6,308351559	2,2	13,87837		1,5		NA	
						total mass	25,45941					199,5393
								sublimation energy of XeF2		304	J/gr	608

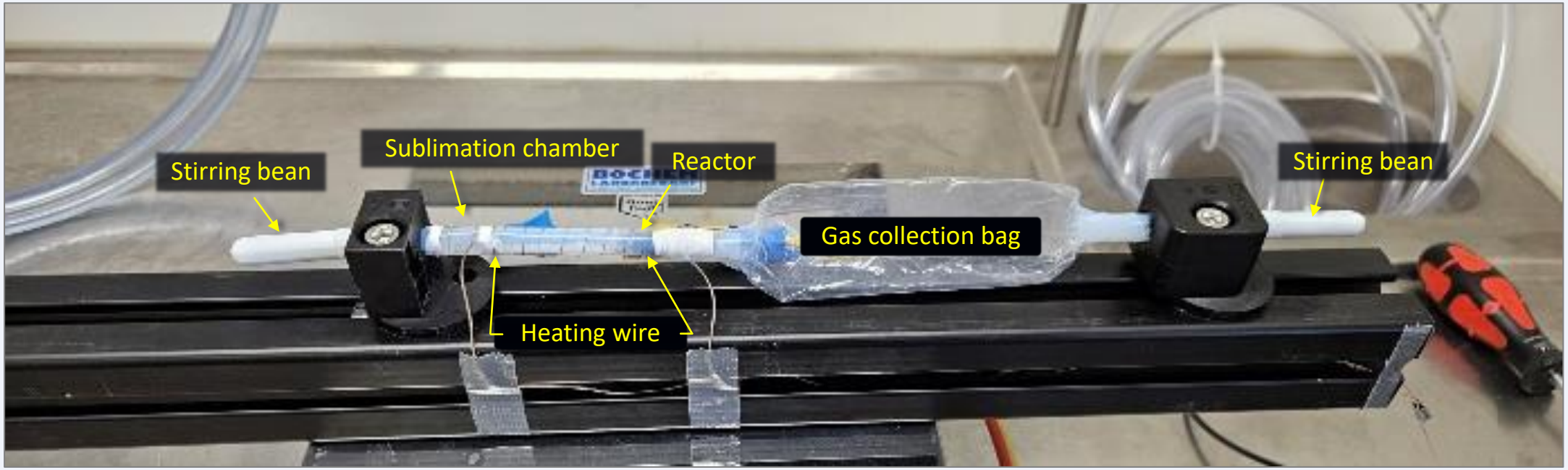
Modified test set-up

- TNO modified the test set-up on the basis of the design of HDES.
- HDES has produced a test plan based on the test set-up design. This plan is input for the TNO detailed experimental procedures
- Plan was to first test the improvements
- Then test different configurations of reaction chamber and filters



Battleship setup

- The sublimation chamber and the reaction chamber have been integrated into a single chamber made of a short PFTE tube.
- A resistance wire heats the complete tube, so both the sublimation and reaction chamber sections are heated.
- The gas collection bag is situated directly after the reaction chamber, thereby reducing all unnecessary thermal mass.

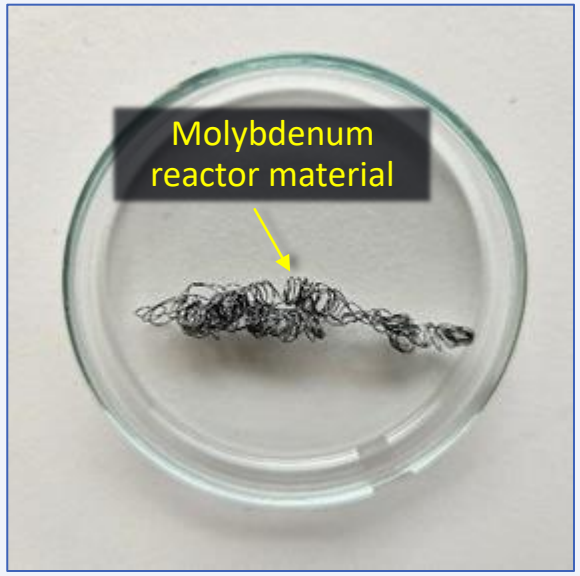


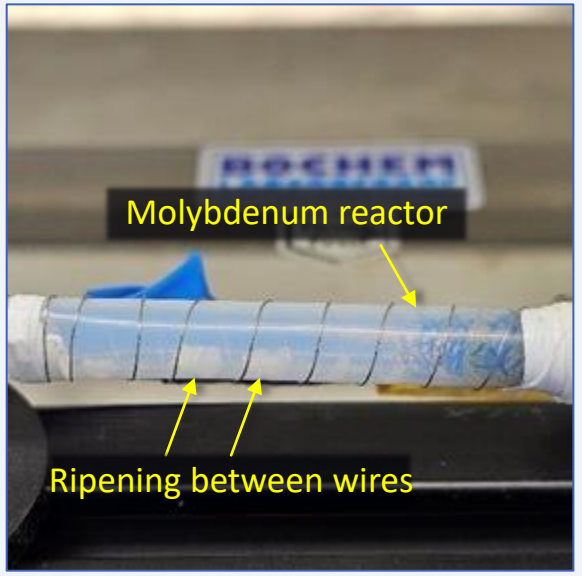
Molybdenum reactor test:

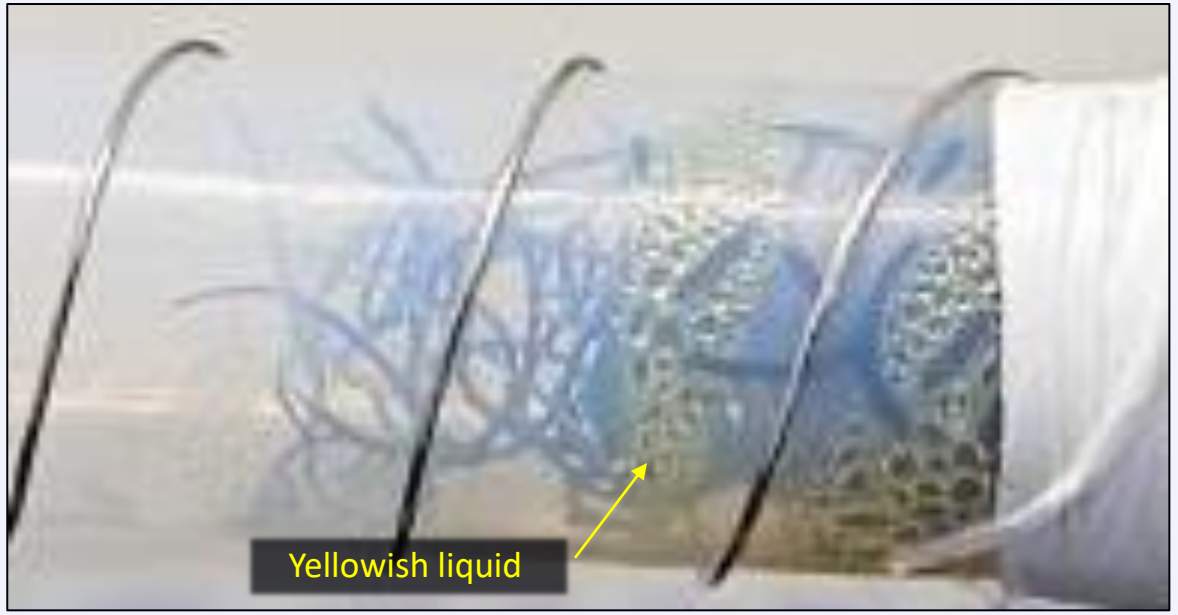
- Heating wire:
  - Ø: 0.25 mm, L: 37.0 cm, Power: 5.5 Volt & 0.5 Amp → T: 80 °C
- Reactor: Molybdenum
  - Ø: 0.20 mm, spiral form
- XeF_2:
  - 0.5 g

Observations:

- Slow sublimation of XeF_2
- Ripening of XeF_2 between the windings of the heater
- In reactor yellowish liquid formed
- No inflation of gas bag







Conclusions Molybdenum reactor test:

- Reaction takes place between XeF_2 and molybdenum
- No detectable formation of xenon observed

- Insufficient XeF_2 decomposed

  or

- Another Xe containing solid is formed
  - XeF_4
  - $[C_6F_5]_2Xe$, $C_6F_5–Xe–C\equiv N$, $C_6F_5–Xe–F$

Lit. THE CHEMISTRY OF XENON', J. Malm, H. Selig, J. Jortner. S. Rice, Sept. 1964:

'XeF_2 has been prepared by a variety of methods, nearly all of which depend on the rapid removal of XeF_2 from the reaction system to prevent its further reaction resulting in the production of XeF_4'

F comes from XeF_2 then: $2\ XeF_2 \rightarrow 2\ Xe + 2\ F_2 \rightarrow Xe\ (gas) + XeF_4\ (solid)$: Gaseous Xe formed however 50% yield

$12\ C + 5\ XeF_2 \rightarrow Xe + [C_6F_5]_2Xe\ (solid) + 4\ Xe\ (gas)$: Gaseous Xe formed however 80% yield

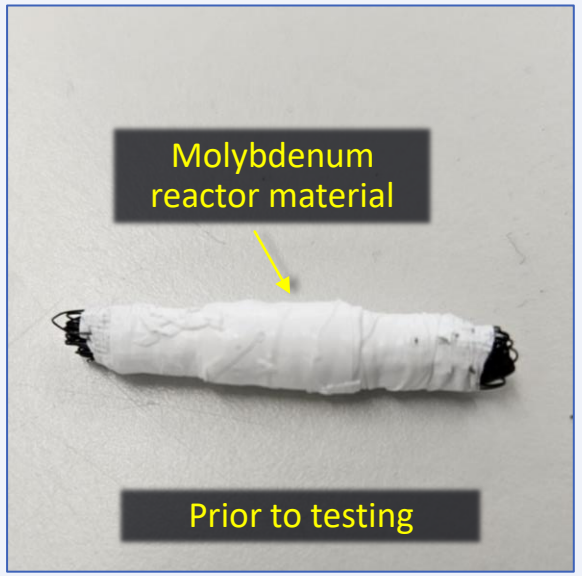
To form 'possible' Xe containing molecules always Xe is released from XeF_2 the Xe yield however is reduced

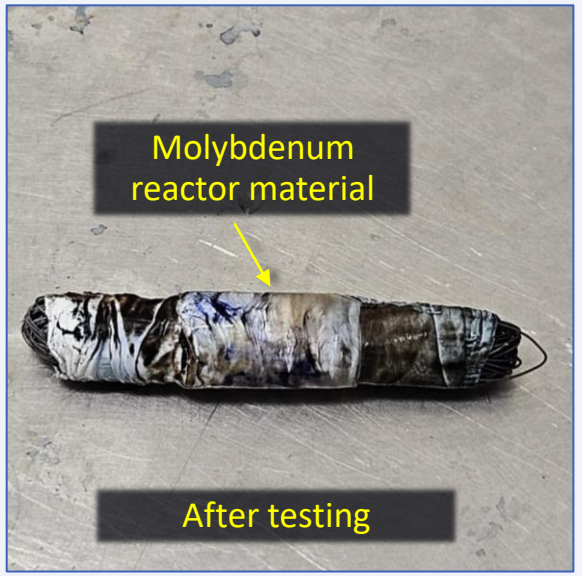
No detectable formation of xenon observed:

most likely insufficient XeF_2 is decomposed to noticeably inflate the gas collection bag

Molybdenum improved reactor test:

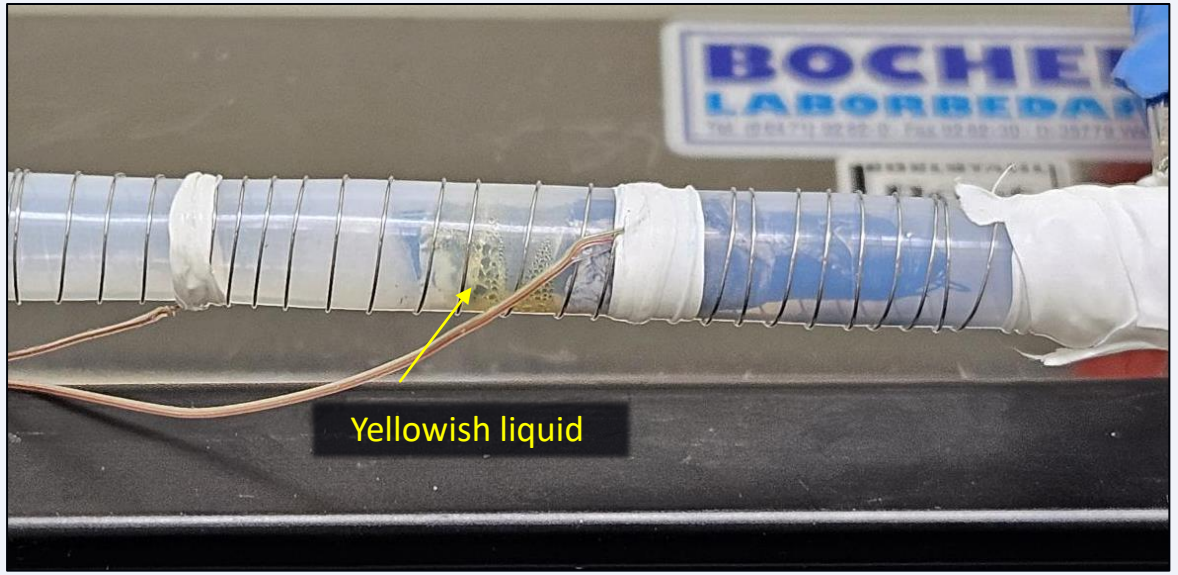
- Heating wire:
  - Ø: 0.25 mm, L: 95.0 cm, Power: 9.5 Volt & 0.4 Amp → T: 110 °C
- Reactor: Molybdenum
  - Ø: 0.20 mm, folded many times, hold together by Teflon tape
- XeF_2:
  - 0.5 g





Observations:

- Sublimation of XeF_2
- Tape of reactor turned black with some blueish spots
- In reactor yellowish liquid formed at the stream upward side
- No inflation of gas bag



Conclusions Molybdenum reactor test:

- Reaction takes place between XeF_2 and molybdenum
- No detectable formation of xenon observed

- Insufficient XeF_2 decomposed

  or

- Another Xe containing solid is formed
  - XeF_4
  - $[C_6F_5]_2Xe$, $C_6F_5–Xe–C\equiv N$, $C_6F_5–Xe–F$

To form 'possible' Xe containing molecules always Xe is released from XeF_2 the Xe yield however is reduced

No detectable formation of xenon observed however:

- yellowish liquid at the upstream side reactor, most likely MoF_5 → XeF_2 is decomposed, where is the Xe?

Mo fluorides	Physical form	mp (°C)	bp (°C)	Density (g/cm^3)	Vapor pressure (1kPa @ °C)
Mo	Gray cubic	2623	4639	10.2	
MoF_3	Brown hexagonal crystal	>600		4.64	
MoF_4	Green crystal	D			
MoF_5	Yellow monoclinic crystal	67	213	3.5	86.6
MoF_6	White cubic crystal Colorless liquid at RT	17.5	34	2.54	41.2
$MoOF_4$	Volatile solid	98			

mp: melting point, bp: boiling point, RT: room temperature, D: decomposes 1Pa = 7.5 mTorr

Hypothesises Molybdenum reactor test:

Most likely insufficient XeF_2 is decomposed to noticeably inflate the gas collection bag why?

- Test with syringe shows that from 1 ml gas insertion, the gas collection bag starts to show signs of inflation. From this it is calculated that less than 7.6 mg (<1.5% of the XeF_2) generated Xe why?

    - Molybdenum is oxidized at the surface area of the wire and for this not effective as reactor?:
        - Pro: Free metallic molybdenum does not occur naturally on Earth (Wikipedia) it is found only in oxidized states
        - Con: Oxidation of Molybdenum starts at 300 °C (Wikipedia)

    - The surface area of the reactor is too small or the residence time in the reactor is too short?
        - Con: no inflation of the bag, if the residence time was too short, the velocity at which XeF_2 travels through the reactor would have been high and unreacted XeF_2 should ripen after the experiment down stream of the reactor → this is not observed

Hypothesises Molybdenum reactor test:

- Within the reactor XeF_2 ripens and is blocking the flow through the reactor

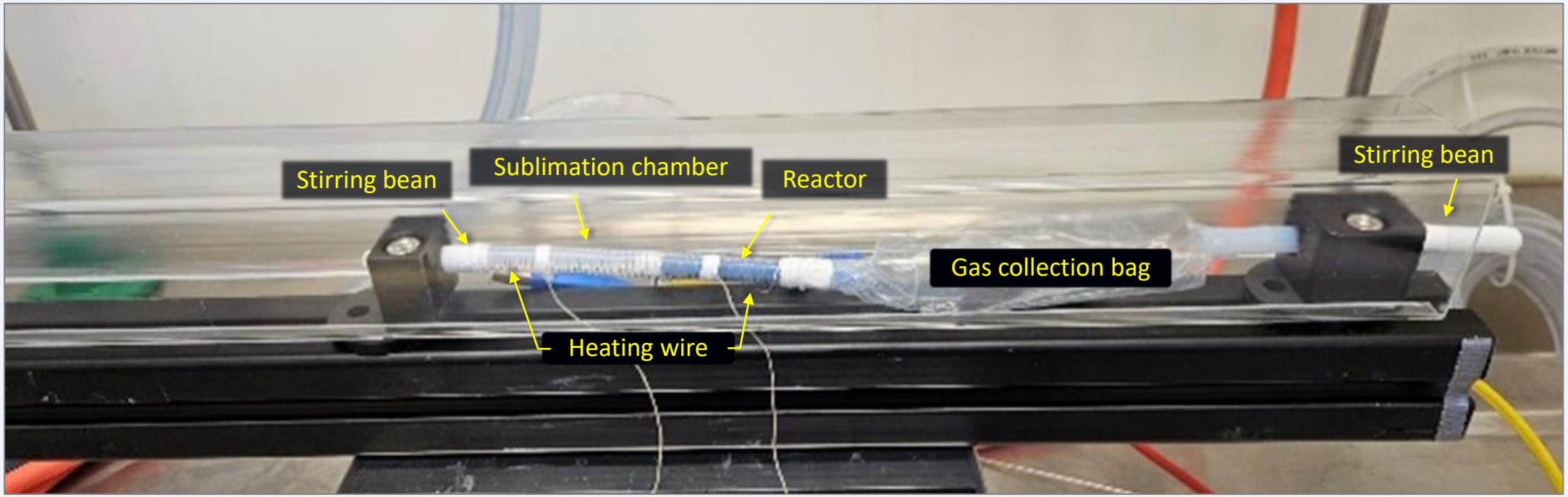
  - Pro: only a reaction is observed upstream of the reactor (formation yellow liquid) no reaction products or XeF_2 observed down stream of the reactor
  - Con: no XeF2 was found in the catalyst, but that is due to the passivation procedure before the setup could be taken apart
  - Con: the Teflon tape is changed from white to black over the total length of the test and coloration started upstream and traveled downstream in time (something flowing?)

  May be possible, the heat added to the reactor comes from the outside and has to be transferred to the core of the reactor, the contact surface between the wires is small. Significant heat is required to do heat the reactor down to its core. It is believed that only a very small part of the reactor is warm and capable decomposing XeF_2, the core of the reactor is cold and gaseous XeF_2 ripens between the Mo wires, and may there react very slowly.

  Note: no conclusive proof for any of the hypothesis

Activated charcoal reactor

- Fairly similar to the molybdenum setup, the only difference is that the activated charcoal version has a bit longer reaction chamber .
- The number of windings of the heating wire on the reaction chamber were increased to prevent the xenon difluoride from ripening between the windings of the heating wire
- To boost the sublimation reaction by increasing the temperature of the heating wire to 140°C.

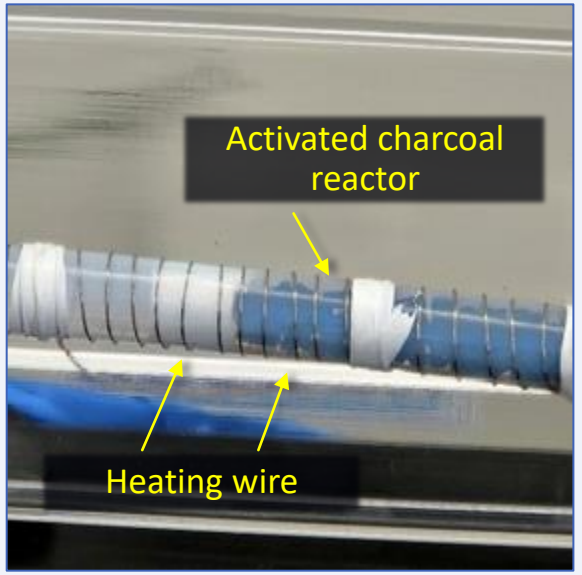


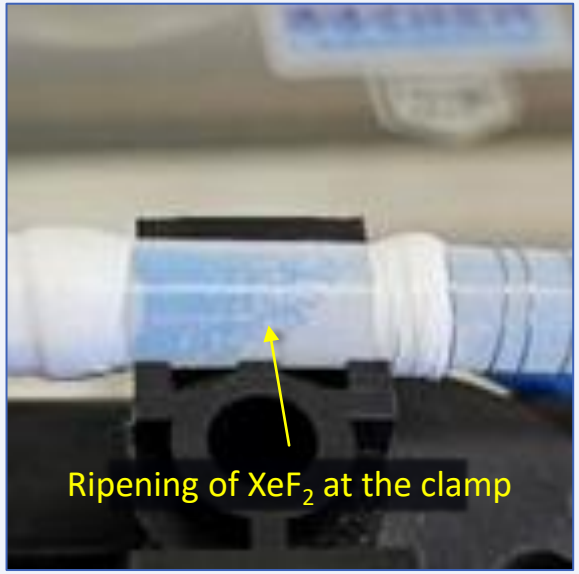
Activated charcoal reactor test A:

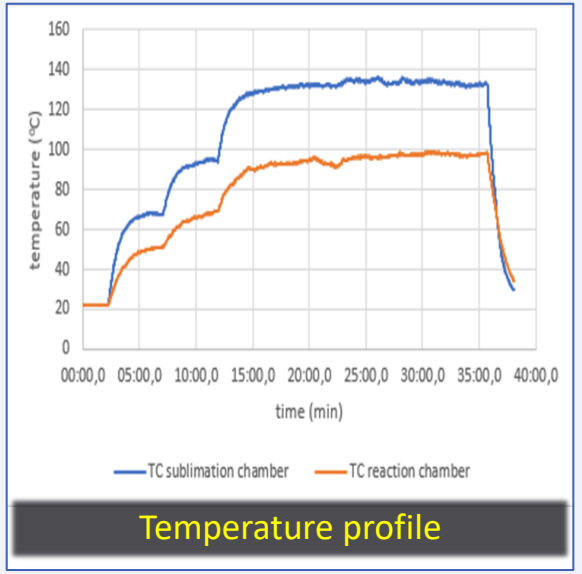
- Heating wire:
  - Ø: 0.25 mm, L: 74.0 cm, Power: 8.0 Volt & 0.4 Amp → T: 140 °C
- Reactor: activated charcoal
  - 0.56 g
  - thermo scientific Carbon, activated, -4+8 mesh, cat.no 043118.36 lot:Y13J028
- XeF_2:
  - 0.50 g

Observations:

- Sublimation of XeF_2 more quickly than previously
- Ripening of XeF_2 at the fixation clamp
- No inflation of gas bag





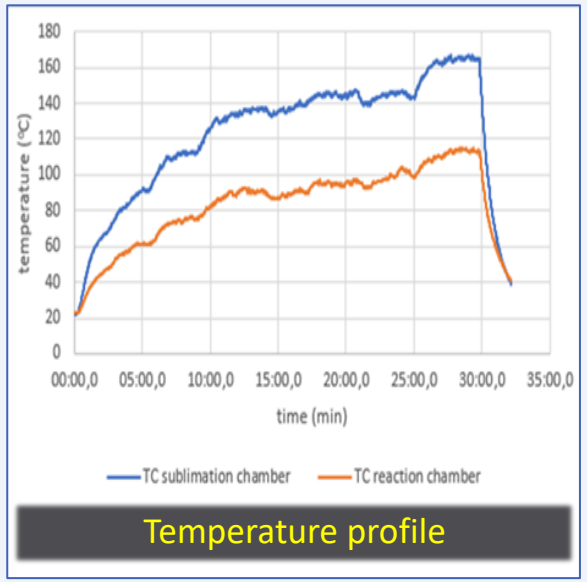


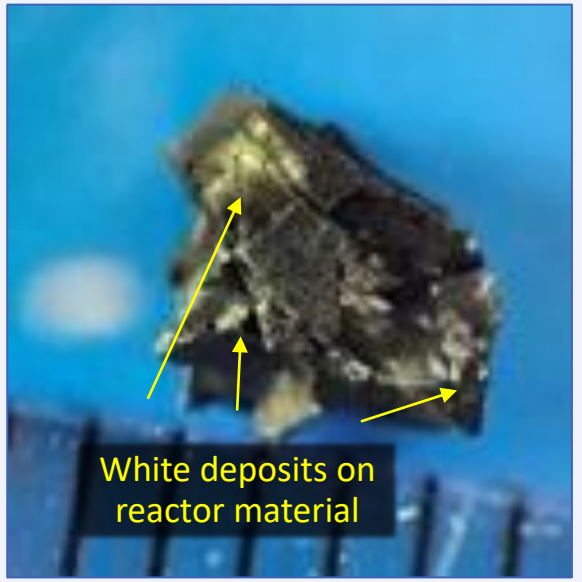
Activated charcoal reactor test B:

- Heating wire:
  - Ø: 0.25 mm, L: 115.0 cm, Power: 14.5 Volt & 0.5 Amp → T: 140 °C
- Reactor: activated charcoal
  - 0.56 g
  - thermo scientific Carbon, activated, -4+8 mesh, cat.no 043118.36 lot:Y13J028
- XeF_2:
  - 0.50 g

Observations:

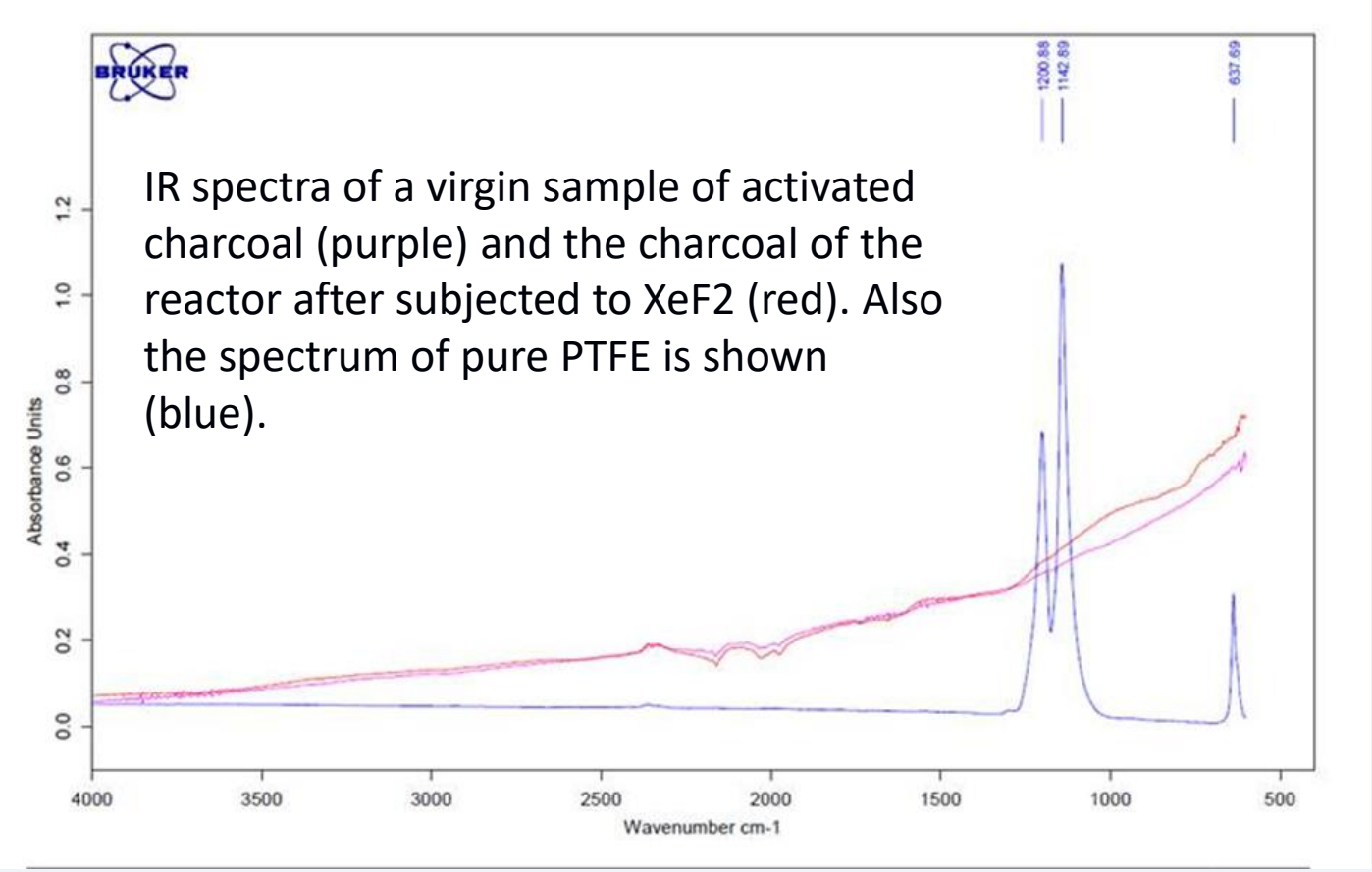
- Sublimation of XeF_2 , some ripening of XeF_2 at the steering bean
- No inflation of gas bag
- Mass reactor increased to 0.61 g
- White deposits on the activated charcoal





Decomposition of XeF_2 in the activated charcoal reactor:

- sample of the reactor was taken for analyses means of FTIR (Fourier-transform infrared spectroscopy



IR spectra of a virgin sample of activated charcoal (purple) and the charcoal of the reactor after subjected to XeF2 (red). Also the spectrum of pure PTFE is shown (blue).

- Because the concentration of the white residual is low, only small deviation in the spectra between before and after reaction is visible.
- Despite this, the deviation between both spectra's starts exactly at the location of the PTFE absorption peak

White residual is most likely PTFE, and is proof that decomposition of XeF_2 has taken place

Conclusions activated charcoal reactor test:

- Reaction takes place between XeF_2 and charcoal
- No detectable formation of xenon observed

- Insufficient XeF_2 decomposed

  or
- Another Xe containing solid is formed

  or
- Xe is adsorbed by the activated charcoal

Lit. Adsorbed xenon propellant storage: are nanoporous materials worth the weight? M. Huynh et all:

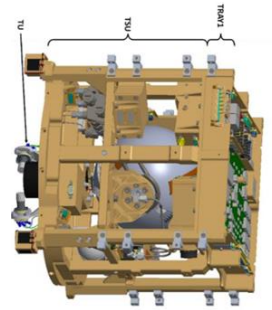
Activated Carbon is studied for Xe storage due to its ability to adsorb Xe

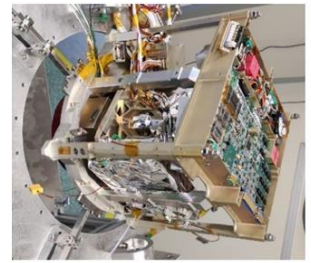
→ *Most likely, in the gas generator the gaseous Xe is trapped in the reactor*

The activated charcoal adsorbs the xenon that is being produced and for this, it is not a viable material for a xenon gas generator reactor.

System study results

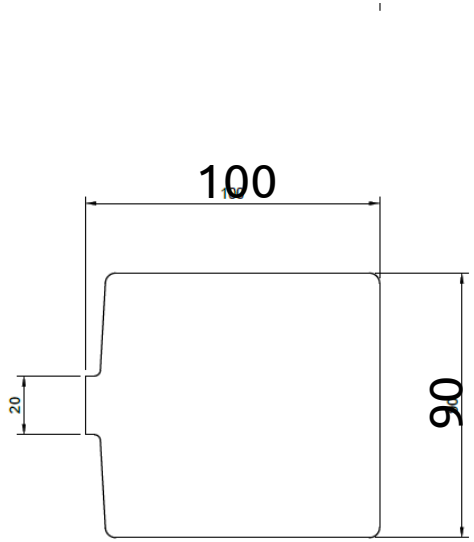
- In the system study the test results were used for a system design
  - Based on experience of the last
  - Realistic and conservative expectations
- Comparison with existing systems
- Analysis of the business case (market size and economics)

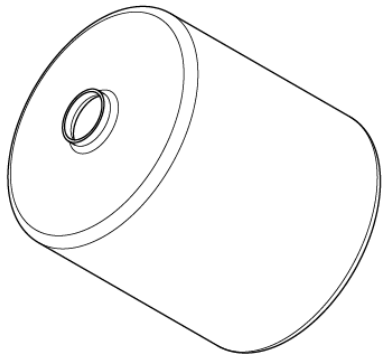


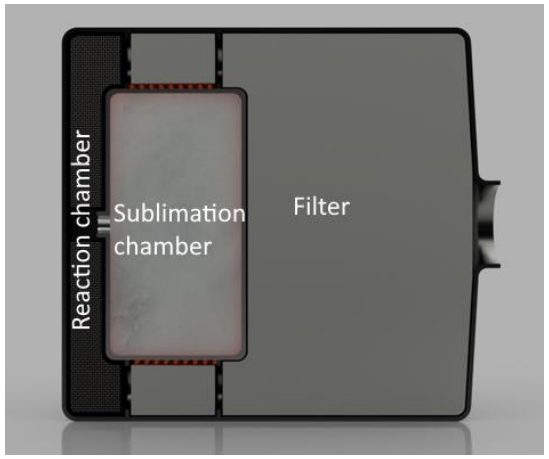


- Main results are:
- There are big advantages in mass and volume for xenon system with up to 5 kg Xe storage

System design

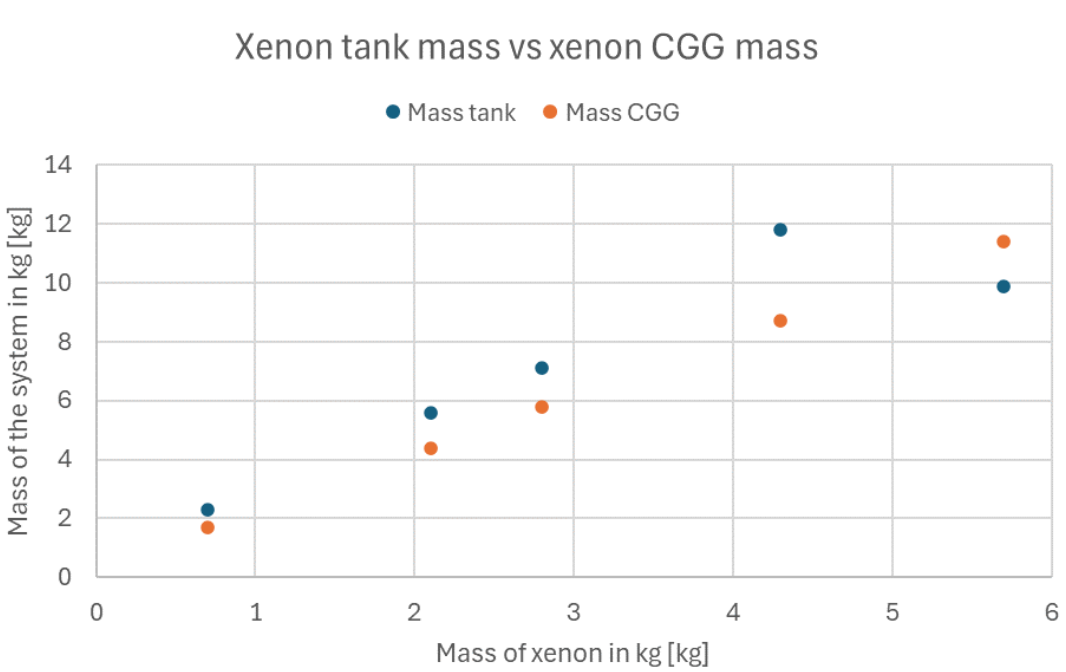


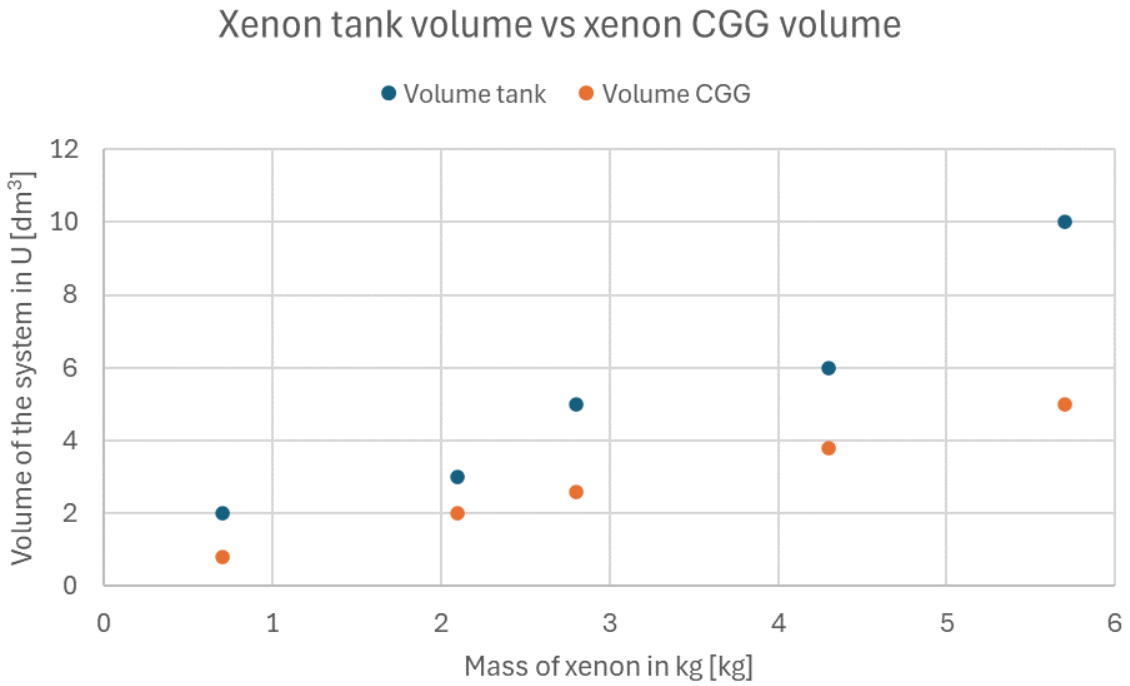




- Specifications:
- Xenon storage: 300 grams
- Mass: 0,7 kg
- Volume: 1 U
- Power: < 5 W
- Flow is controllable
- No filling before launch
- No mech parts

System study results

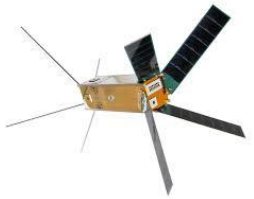




- Advantage in mass is up to 20% (realistic case)
- Advantage in volume is up to 60% (realistic case)
- Advantage in mass is up to 10% (conservative case)
- Advantage in volume is up to 30% (conservative case)
- Up to 5 kg of xenon storage

Business case xenon CGG system

- Market size is estimated to be between 10 and 30 systems/ yr
- A storage system may cost between 5 and 25 kEuro
- This price is achievable, but XeF_2 will be 25% of the price
- This assumes production of larger quantities at a lower price
- Total expect turn-over between 400 and 800 kEuro/yr



Break and Coffee

Take-aways from the de-risk project

- The project went very well
- With a lot of flexibility, a working concept has been established
- Feasibility of a Xenon CGG has been shown
- System study confirmed the expected advantages

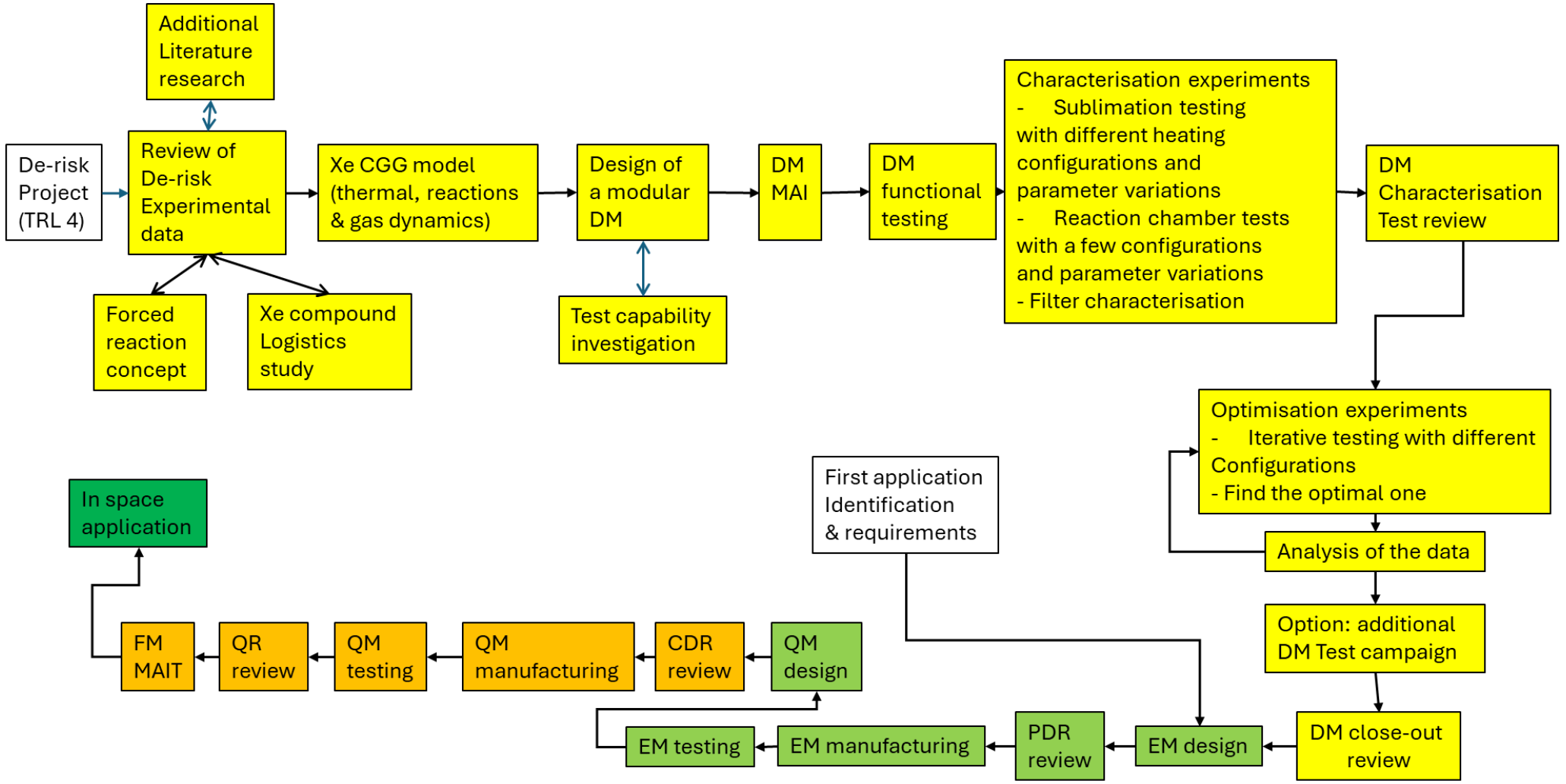
- However……

- Detailed interaction between the physical processes in a Xenon CGG are still poorly understood
- No design optimisation
- Xenon purity has not yet been proven

Development Plan

- On the basis of the successful De-risk a Development Plan has been made
- The plan addresses the problems identified during the de-risk
  - Better characterisation of physical processes and interaction
  - Design optimisation
  - Filtering
- This included budget estimation and planning.
- It uses the end point of the de-risk as the start
- Three phases: Demonstration Model, EM and QM

Proposed development logic

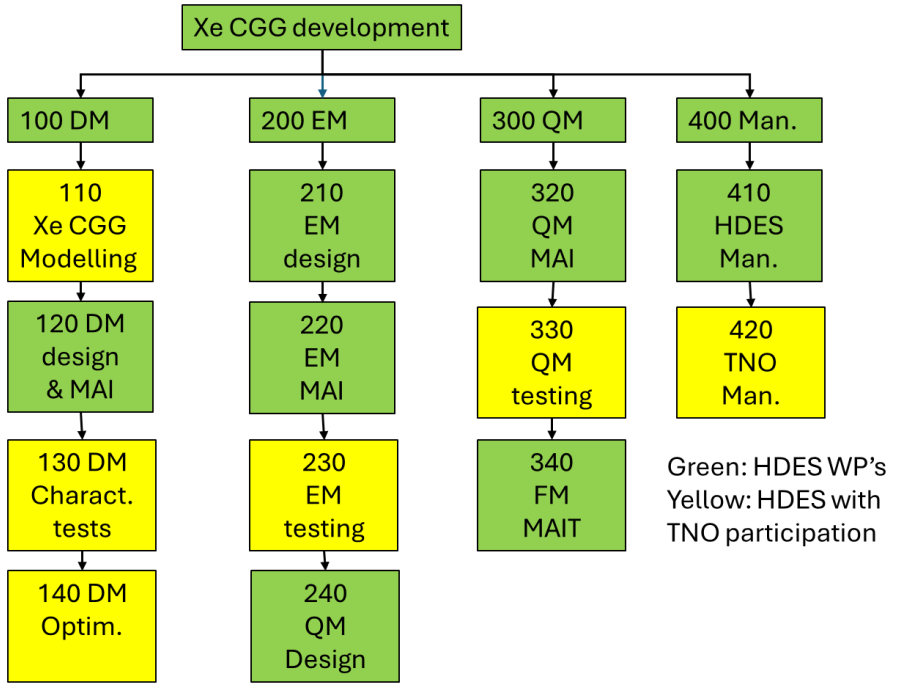


Development logic

- Demonstration Model phase is needed to perform an extended characterisation
  - Physical processes
  - Chemical processes
  - Thermal processes
- And their interaction
  - With a flexible and modular set-up
  - With up to 100-300 grams of XeF_2
  - Extensive tests with many variations
- Identification of a first flight opportunity / customer / mission
- EM and QM can be typical for ESA

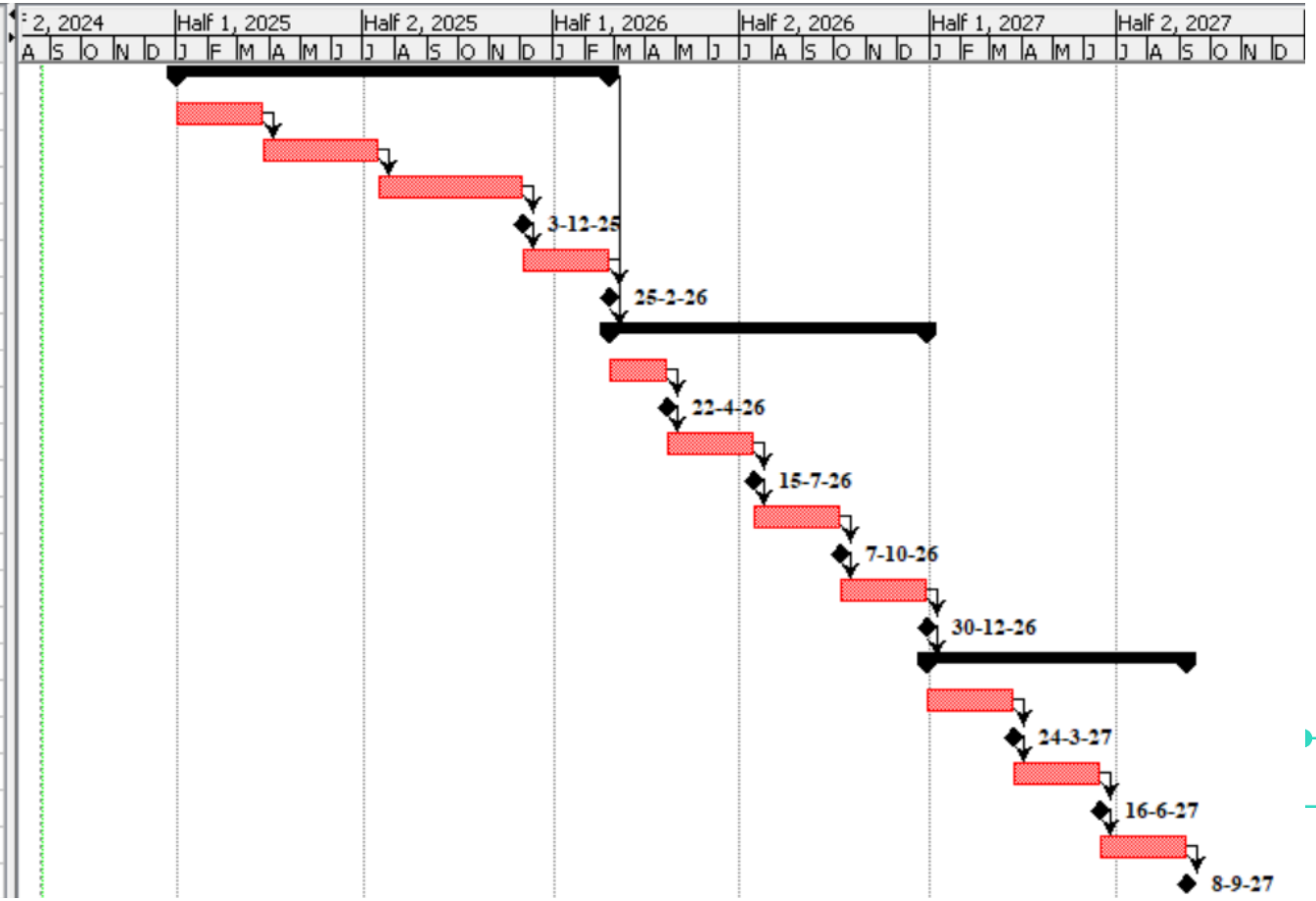
Development programme

- Three phases DM, EM and QM
- 2,5 to 3 year development until flight
- Estimated costs
  - DM phase: 445,5 kEuro (to TRL 4/5)
  - EM phase: 178,3 kEuro (to TRL 6)
  - QM phase: 267,3 kEuro (to TRL 7-8)
- Total: 891,1 kEuro
- Programme could start early 2025



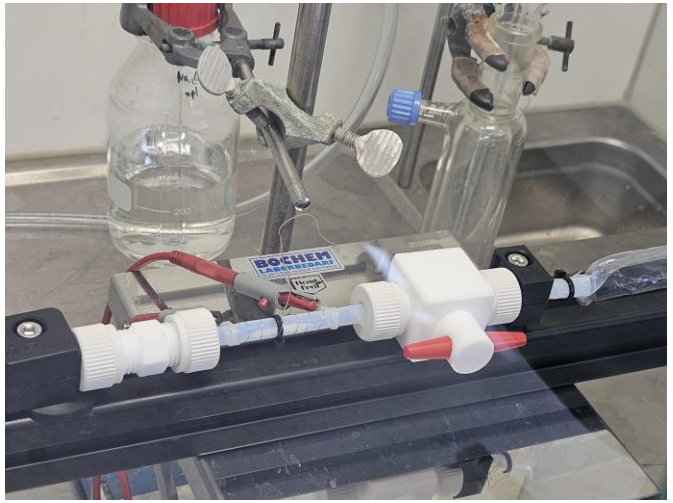
Follow-on planning

Naam	Duur	Begin
100 demonstration Mod	300 dagen	**1-1-25 9:00**
110 Xe CGG modelleing	60 dagen	1-1-25 9:00
120 DM design	80 dagen	26-3-25 9:00
130 DM Characterisation te	100 dagen	16-7-25 9:00
DM charcterisation test rev	0 dagen	3-12-25 9:00
140 DM Optimisation	60 dagen	3-12-25 9:00
DM Close out review	0 dagen	25-2-26 9:00
200 Engineering Model	220 dagen	**25-2-26 9:00**
210 EM design	40 dagen	25-2-26 9:00
PDR	0 dagen	22-4-26 9:00
220 EM MAI	60 dagen	22-4-26 9:00
EM pre-test review	0 dagen	15-7-26 9:00
230 EM testing	60 dagen	15-7-26 9:00
EM post test review	0 dagen	7-10-26 9:00
240 QM design	60 dagen	7-10-26 9:00
CDR	0 dagen	30-12-26 9:00
300 Qualification Model	180 dagen?	**30-12-26 9:00**
310 QM MAI	60 dagen	30-12-26 9:00
QM pre-test review	0 dagen	24-3-27 9:00
320 QM testing	60 dagen?	24-3-27 9:00
QR	0 dagen	16-6-27 9:00
330 FM MAIT	60 dagen	16-6-27 9:00
FM delivery	0 dagen	8-9-27 9:00



Technical achievement summary

- The feasibility of a xenon CGG has been established
- Independent working has been shown
- A large body of knowledge on XeF_2 has been gathered
- XeF_2 is much more benign than expected and good to work with
- System study confirmed the potential gains in mass and volume
- A development plan has been made up to applications
- Benefits
  - Up to 20 % reduction in mass, up to 40% in volume
  - No high pressure, limited mechanical parts
  - Can be filled and prepared in Europe, not pressurised during launch
  - No extensive temperature and pressure control needed



Requirements status

#	Requirement	Verification Method	Status
1	The compound has to be chemically stable (limited or no degradation over time)	Test	Verified by experiment
2	The compound has to be compatible with other ingredients of the CGG grain	Test	Verified by experiment
3	The xenon yield of the CGG grain composition has to be at least 40% (so 40 % of the grain mass needs to exit as xenon)	Test	Verified by analysis,
4	The CGG grain has to be mechanically stable (before and after firing), that is it should stay in one piece during removal from the mould and handling	Test	Verified by experiment
5	The overall volumetric yield has to exceed 80 liters of xenon per liter of gas generator	Analysis	Verified 85 nl/l estimated
6	The overall mass yield has to exceed 80 liters of xenon per kg of gas generator	Analysis	Not yet met: 72 nl/kg estimated
7	The xenon purity should be > 99%	Test	Not yet measured

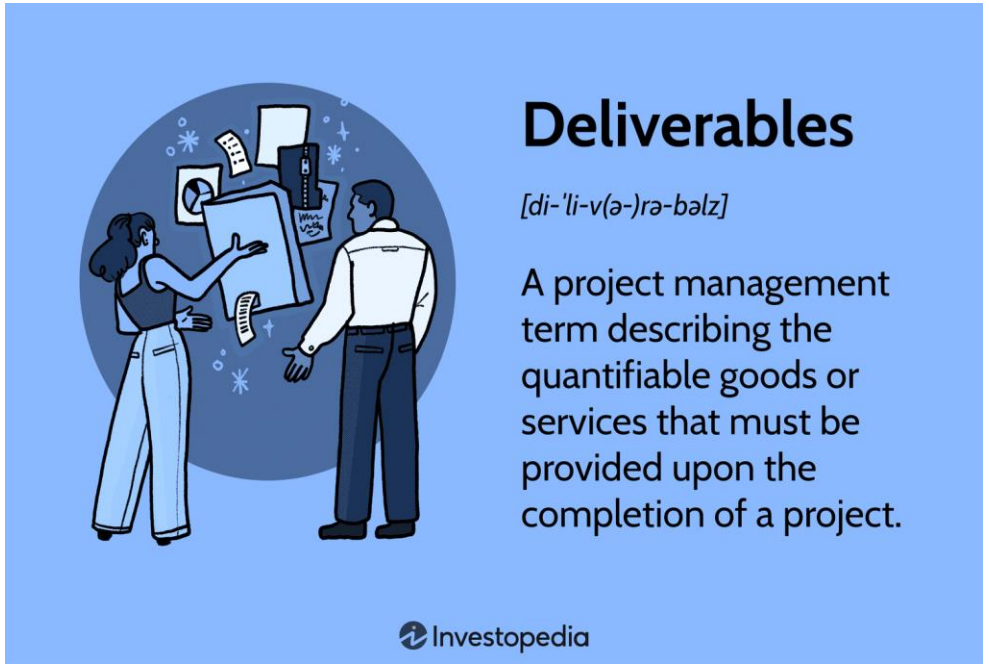
Presentation to ESA Electric propulsion Group

- Separate presentation (CEP-HDS-PT-05)

Lunch break

Comments on the deliverables

- Comments of ESA
- Comments of the team
- RIDs
- Actions



Contract close out

- What needs to be done before contract close-out?
- MoM of this meeting
- Invoice
- How to jointly working on a continuation?
- Any last points?