TENEX
ROSATOM

Development of Technologies for scaling up Retrieval of Fuel Debris and Internal Structures (Development for Dust Collection System of Fuel Debris)

Final report for FY 2019 and 2020

Project Main Goals

1 Assessment of dust generation regularity, amount, content and distribution depend on several cutting methods and conditions

- ✓ Types of generated aerosols, vapor phase, solid particles
- ✓ Dust amount and particles size strongly depend on cutting methods and cutting conditions
- ✓ Dust distributes in space irregularly
- ✓ Particles with different sizes have a different penetrate capability
- ✓ Particles with different sizes have a different deposit rates

2 Assessment of separate filtering elements and integrate dust collection system efficiency

- ✓ Filtering units efficiency depends on types of generated types of aerosols, vapor phase.
- ✓ Filtering elements efficiency depends on them filtering principle and them position in the system
- ✓ Different filtering materials could change there properties depend on dose loading

3 Development of initial technical requirements and conceptual design of full scale dust collection system

"Dust"

- Aerosols (tenths to 10 µm)
  - Liquid
  - Solid
- Solid particles > 10µm (coarse dust)
- Vapor phase (molecule to tenths µm)

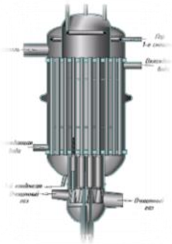
Based on ROSATOM experience

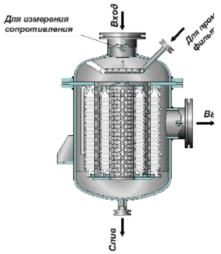
- **> 500 µm particles will deposit immediately**
- **<50 µm - cloud of long-term floating particles**
- **0.1 – 0.3 µm particles – most dangerous (have the most penetrate capability)**
- **< 0.1 µm particles – mostly stick together and generate large conglomerates**

Russian experience in the field of dust collection system development and operating review (1/2)

❖ **Report's content**

- real Russian experience in the operation of various gas cleaning systems at the enterprise of the nuclear industry.
- list of main devices of gas-aerosol cleaning systems used at the enterprises of the nuclear industry of Russia and MAYAK Plant and them technical description.
- summarizing data on all methods of localizing radioactive gaseous waste, both for normal operating conditions of equipment and for high-temperature processes.
- overview of methods and equipment for collecting sols (dust) from liquid media and the influence of the state of pollution on the choice of cleaning methods.
- Initial recommendations for dust collection system development.
- Explosion and Fire Safety aspects.





Citation:
"… The decontamination factors of sequentially installed filters are not equal to each other and they significantly decrease along the gas flow. Understanding how the cleaning factor changes with an increase in the number of filters in the gas cleaning system is of very practical importance and should be taken into account when developing and creating gas cleaning systems…"

Russian experience in the field of dust collection system development and operating review (2/2)

- **Analysis of causes of the formation of explosive and fire hazardous situations in the gas-aerosol treatment processes**

Based on ROSATOM experience

Flammability risk for Zr-Nb alloy (and metallic Zr the same):

- Particle size > 600 µm → combustion is impossible
- Particle size < 50 µm, concentration >20% → momentary local combustion points is possible
- Particle size < 50 µm, concentration >30% → low-flammable environment
- Particle size < 50 µm, concentration <20% → low-combustible environment
- Dewy particles with moisture mass content 3 – 7% → flammability risk (because of H2 generation)

Flammability risk for Uranium & Plutonium dioxide:

- Explosion and fire safety materials

Brief conclusions:

- All components of fuel contain material (FCM), except for zirconium are non-combustible and do not pose a fire hazard with any handling in the discussed technological processes.
- When the mass content of metallic Zr in the FCM is 10% or less during the cutting of FCM fragments, the formation of finely dispersed Zr with pyrophoric properties is possible. In this case, Zr particles will be phlegmatized by non-combustible components, the formation of combustible dust is excluded. **For the same reason, the accumulation of dust with combustible properties in the units of the gas cleaning system is unlikely.**

Sample types description

Type A

Components	mass,%
HfO_2	30
ZrO_2	16
Stainless steel	7
SiO_2	31
CaO	6
Al_2O_3	7
Fe_2O_3	3

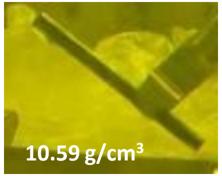
A-1: press force - 2 t, t°C =1400

A-2: press force - 2 t, t°C =1000, 2 hours exposition

[ON AIR]
- Diamond bit
- Carbide mill
- Disc cutter

[Cutting experiments implemented using of RIAR existing vacuum system]

Type B

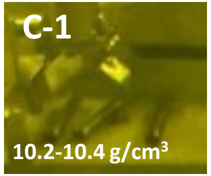


- Unirradiated MOX fuel placed in a Zr-Nb alloy
- U-Pu dioxides
- Pu content 2.7-5.3%

[ON AIR]
- Carbide mill
- Laser cutting

[IN WATER]
- Carbide mill

Type C

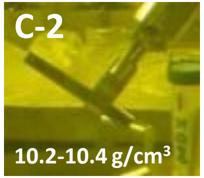


- SNF WWER placed in a tube Zr-Nb alloy
- ^{235}U – 4.4%,
- 46.31 MW/day×kg
- 9 years 6 month

1F SNF (U1-U2) properties:
- 45 MW/day×kg
- >10 years
- ^{235}U – 3,6 – 3,8%

[ON AIR]
- Carbide mill
- Laser cutting

[IN WATER]
- Carbide mill

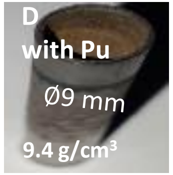


- MOX SNF placed in steel tube
- ^{235}U – 0.6%, U/Pu=5.68/1
- 47.39 MW/day×kg
- 3 years

1F SNF (U3) properties:
- 33 MW/day×kg
- >10 years

[ON AIR]
- Carbide mill

Type D

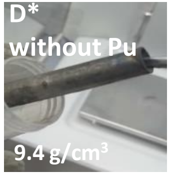


Comp.	mass,%
UO_2	50.93
ZrO_2	14.0
FeO	3.05
Cr_2O_3	0.91
NiO	0.47
SiO_2	16.82
CaO	3.14
Al_2O_3	4.24
Zr	0.98
Fe	0.97
PuO_2	3

Melting at t°C =1480

[ON AIR]
- Carbide mill
- Laser cutting

[IN WATER]
- Carbide mill



The same composition, but without Pu

[ON AIR]
- Carbide mill
- Laser cutting

[Cutting experiments implemented using of laboratory scale dust collection system inside the hot cell]

Laboratory scale dust collection system manufacturing, assembling and testing

Laboratory scale dust collection system main aims

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Due to the fact of many uncertain factors of dust generation during the real fuel debris (FD) retrieval on Fukushima-Daiichi (1F) site we provide the number of cutting experiments with laboratory scale dust collection system to study the following phenomena and aspects which should be taken into account on stage of full-scale system design development:

1. **Types of generated dust and their special properties (solid particles, solid/liquid aerosols, vapor phase).**
2. **Generated dust particles distribution throughout the cutting point – dust collection system's filtering units depending on cutting methods and conditions.**
3. **Determination of generated dust particles granulometric composition (particles size), mass and dust particles concentration and specific activity depending on cutting methods and conditions.**
4. **Different dust accumulation mechanisms examination as well as different filtering materials examination depending on cutting methods and conditions.**
5. **Influence of different types of generated dust (solid particles, aerosols, vapor phase) on filtering apparatus.**
6. **Examination of optimal air-flow rate in a suction unit and in laboratory scale dust collection system to remove as much dust particles from cutting point as possible and collect in Cyclone filter as much dust particles as possible.**

How our conservative cutting tests results could be useful on 1F site ?

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“Conservative” = the worst conditions than on 1F site.
Samples C cutting => huge dose rate + high α-nuclides concentration + high concentration of smallest dust particles (carbide mill 1000 rpm)

The number of samples with different properties:

Samples A → imitate the granulometric composition of cutting products of silicate phase of 1F corium
Samples D → imitate the granulometric composition of cutting products of 1F corium simulants
Samples C → provide the most **conservative** conditions (e.g. α-nuclides concentration) for dust collection system

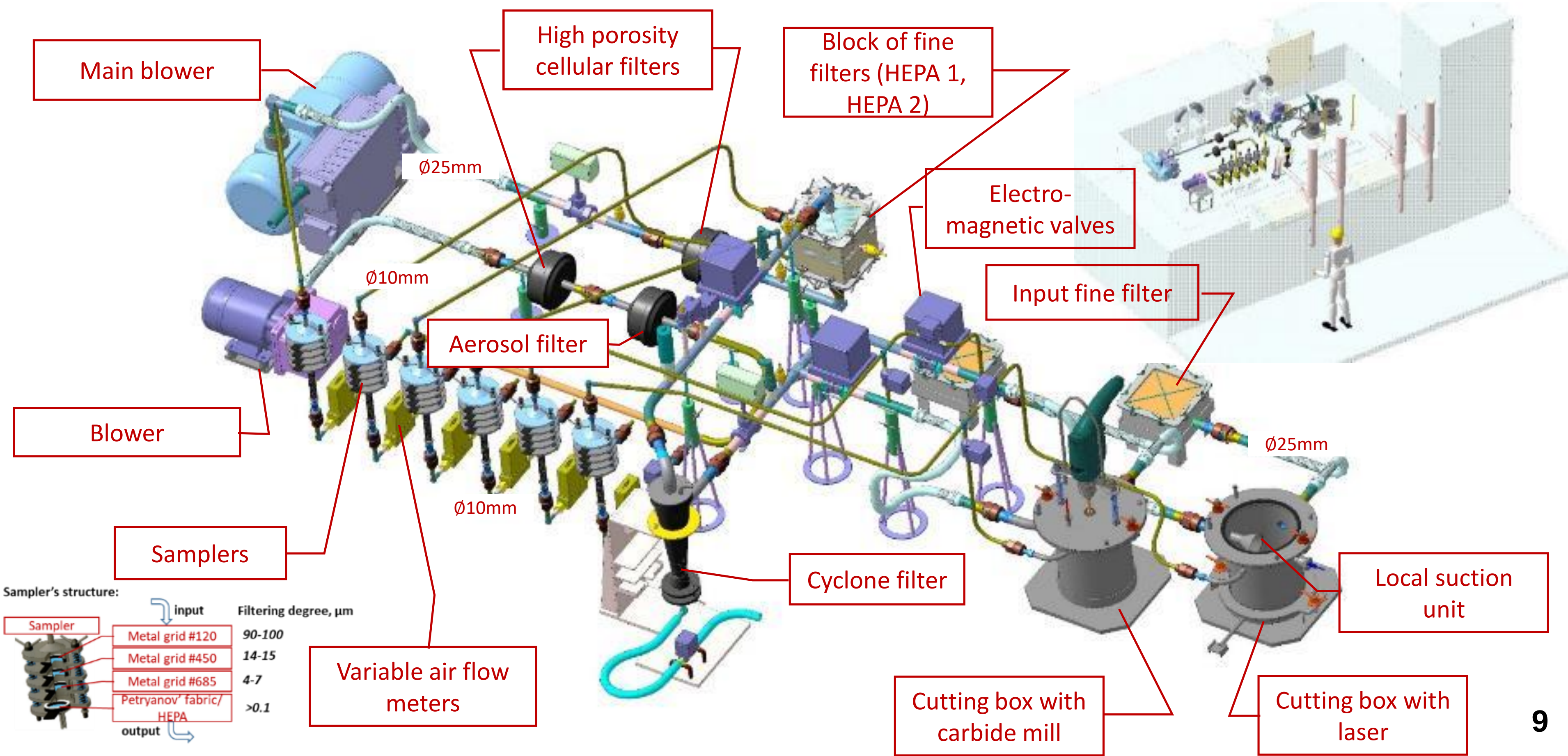
Different cutting methods:

Mechanical cutting → provide the high concentration of smallest dust particles (carbide mill 1000 rpm)
High temperature cutting→ provide the vapor gas fraction and smallest dust particles (like a molecule in some cases) (laser 2.4 kW)
On-air/ In-water cutting conditions

Useful Outputs:

- ✓ Results of comparison the dust particle granulometric composition dependent on samples type and cutting methods allows us to predict the potential 1F dust particles granulometric and specific activity diapasons.
- ✓ Confirmed the effectiveness of filtering materials and separate filtering units depend on dust particle size, mass and specific activity. These filtering materials and filtering mechanisms could be recommended for 1F full scale dust collection system. Necessary safety assessments could be provided to Japanese regulatory bodies.
- ✓ Recommendations for providing the fire, explosion safety and criticality control of full scale dust collection system operating.
- ✓ Recommendation for full scale dust collection maintenance and separate filters changing.

Laboratory Scale Dust Collection System 3D View



Dust particles mass and activity balance determination

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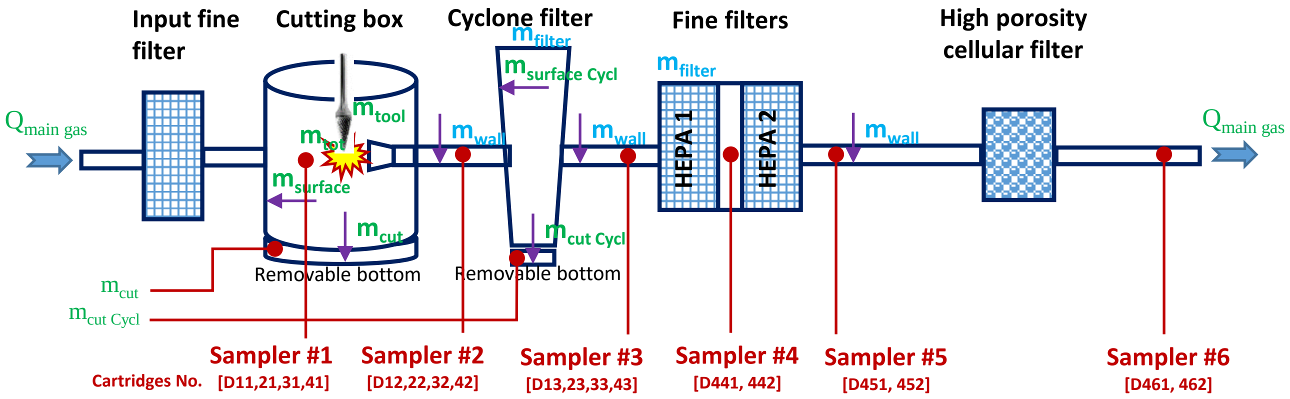


Measured parameters

Sampler #1	Sampler #2	Sampler #3	Sampler #4	Sampler #5	Sampler #6
$Q_{sampler\#1}$	$Q_{sampler\#2}$	$Q_{sampler\#3}$	$Q_{sampler\#4}$	$Q_{sampler\#5}$	$Q_{sampler\#6}$
$V_{sampler\#1}$	$V_{sampler\#2}$	$V_{sampler\#3}$	$V_{sampler\#4}$	$V_{sampler\#5}$	$V_{sampler\#6}$
$m_{sampler\#1}$	$m_{sampler\#2}$	$m_{sampler\#3}$			
$A_{sampler\#1}$	$A_{sampler\#2}$	$A_{sampler\#3}$	$A_{sampler\#4}$	$A_{sampler\#5}$	$A_{sampler\#6}$
$A_{sp\text{-}sampler\#1}$	$A_{sp\text{-}sampler\#2}$	$A_{sp\text{-}sampler\#3}$	$A_{sp\text{-}sampler\#4}$	$A_{sp\text{-}sampler\#5}$	$A_{sp\text{-}sampler\#6}$
	$P_{\#2}$	$P_{\#3}$	$P_{\#4}$	$P_{\#5}$	$P_{\#6}$
t, $\varphi_{\#1}$	t, $\varphi_{\#2}$	t, $\varphi_{\#3}$			

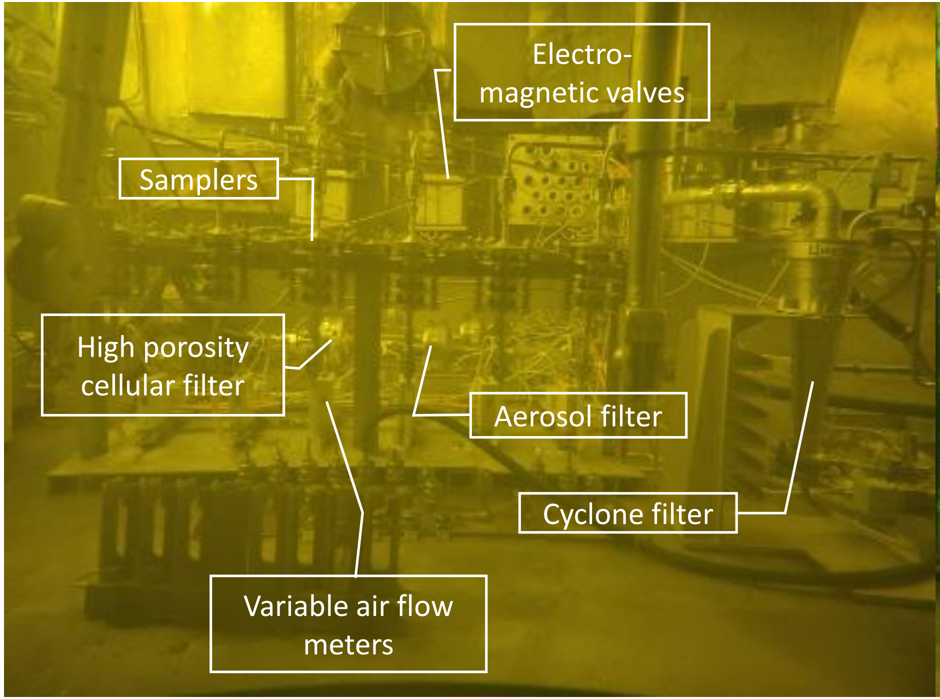
m_{tot} (mg or Bq) $= m_{sample\text{-}before\text{-}cut} - m_{sample\text{-}after\text{-}cut} = m_{tool} + m_{cut} + m_{surface} + m_{wall} + m_{filter}$

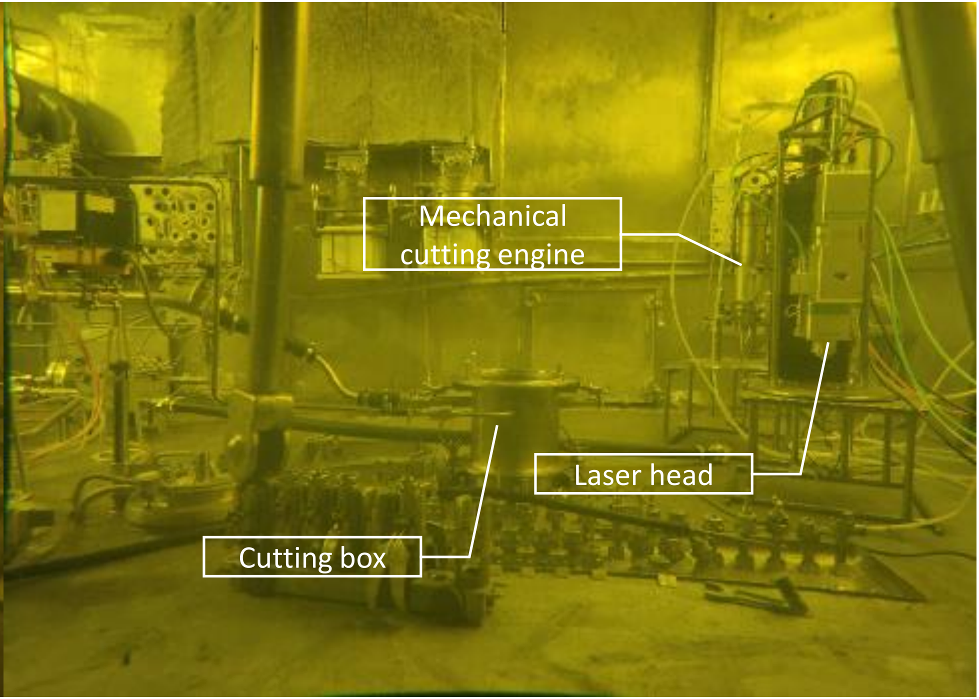
Transfer fraction in air = $m_{tot} / m_{sample\text{-}before\text{-}cut}$

Legend

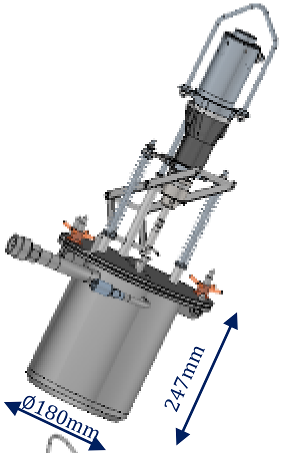
- Q – air consumption, dm^3/min
- T – cutting duration, min
- V – pumped air volume, dm^3
- A – activity, Bq
- A_{sp}- specific activity, Bq/dm^3
- $D=m_{sampler\#}/V_{sampler\#}$ – dustiness, mg/dm^3
- m – dust mass, mg
- P – pressure, kPa
- t- temperature, °C
- φ – humidity, %
- $m_{surfaceCycl}$ – mass of the dust accumulated on internal Cyclone filter surfaces
- $m_{cutCycl}$ – mass of the dust accumulated in Cyclone filter removable bottom
- $m_{tot}=m_{sample\text{-}before\text{-}cut}-m_{sample\text{-}after\text{-}cut}$
- $m_{cut}=m_{bottom\text{-}befor\text{-}cut}-m_{bottom\text{-}after\text{-}cut}$
- $m_{tool}= m_{tool\text{-}before\text{-}cut} - m_{tool\text{-}after\text{-}cut}$
- $m_{filter}= (D_{\#n}-D_{\#n-1})^{\times} Q_{main\ gas}{}^{\times} T$
- $m_{surface}$ - is determined by taking the number of smears.
- $m_{wall} = m_{tot} - m_{cut} - m_{surface} - m_{tool} - m_{filter}$
- Filter' aerosol effectiveness = $A_{sp\text{-}sampler\#n} / A_{sp\text{-}sampler\#n-1}$
- Integral dust collection system aerosols effectiveness = $A_{sp\text{-}sampler\#6} / A_{sp\text{-}sampler\#2}$

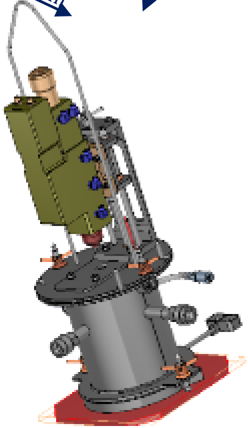
Laboratory scale dust collection on RIAR site inside the K-10 hot cell

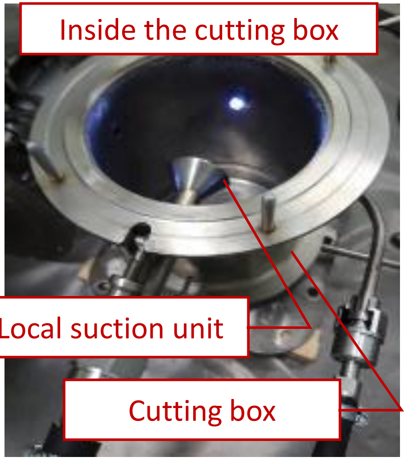


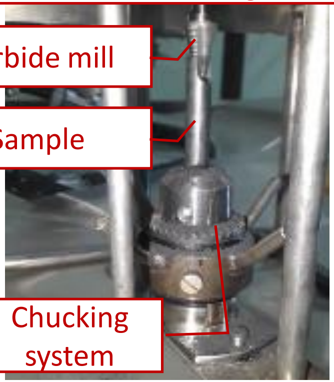


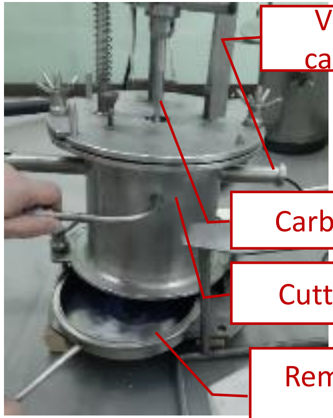
Cutting Boxes General View









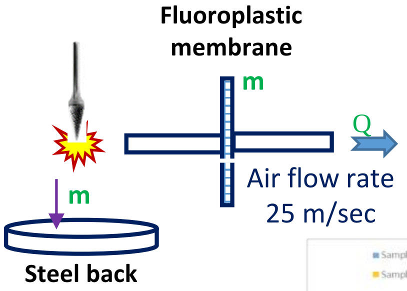


Cutting experiments results

Samples A cutting

Samples A cutting experiments results

Experimental cutting scheme



Disc cutter, 60 rpm

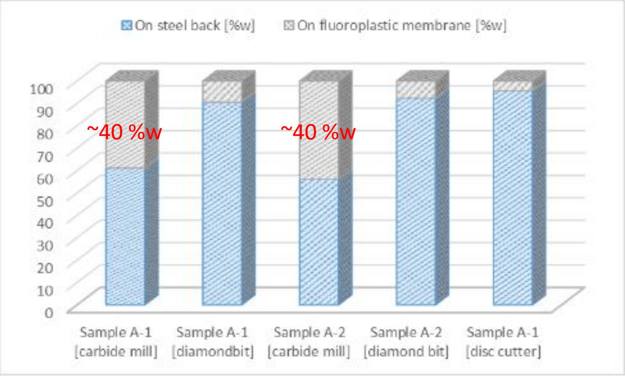
Diamond bit, 1000 rpm

Carbide mill, 1000 rpm

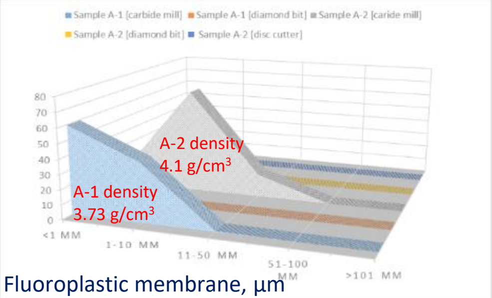
Samples A cutting reasons

- ✓ to develop initial technical requirements for laboratory scale dust collection system
- ✓ to select the most conservative mechanical cutting method

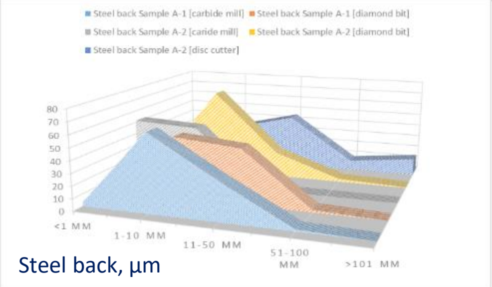
Cutting experiments conditions:
On-air, temperature 24-25 °C,
Humidity 26.4-27.3%



Comparison of results of dust distribution

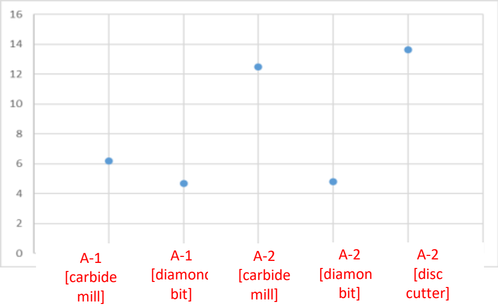


Fluoroplastic membrane, μm



Steel back, μm

Dust particles size distribution



Dust particles generation intensity, mg/sec

More details you could find in Appendix 1

Samples A cutting tests conclusions

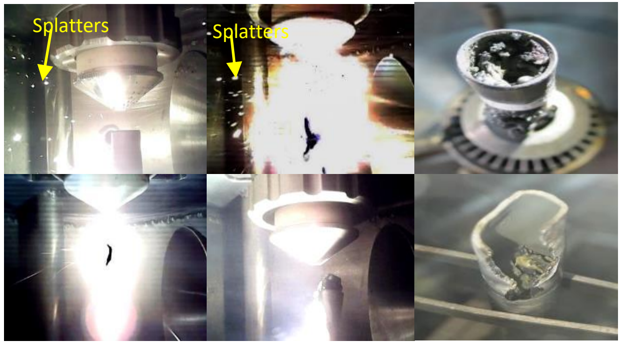
- Carbide mill 1000 rpm cutting generates the smallest solid dust particles, ~40 wt%. of such generated dust was collected with existing vacuum system (air flow rate 25 m/sec). Average size of solid dust particles generated with carbide mill was in diapason 0.34-50 µm.
- Disc cutter 60 rpm generates the biggest solid dust particles, most part of it (~90-95 wt%.) was accumulated on steel back. Average size of solid dust particles generated with disc cutter was in diapason 1-100 µm.
- Average dust particles size diapason was 0.34 – 800 µm.
- Thus, carbide mill 1000 rpm will be used as conservative mechanical cutting method in laboratory scale dust collection system for sample B, C, D cutting.

Cutting experiments results

Dust behavior phenomena and aspects during samples B, C, D, D* **laser cutting**

Dust behavior phenomena during laser cutting (1/2)

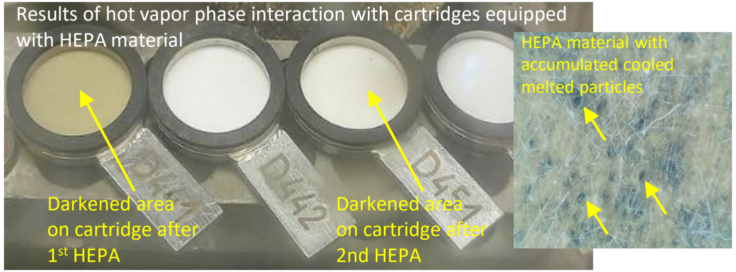
Laser cutting power was in diapason from 1.2 to 2.4 kW depending on cutting experiment



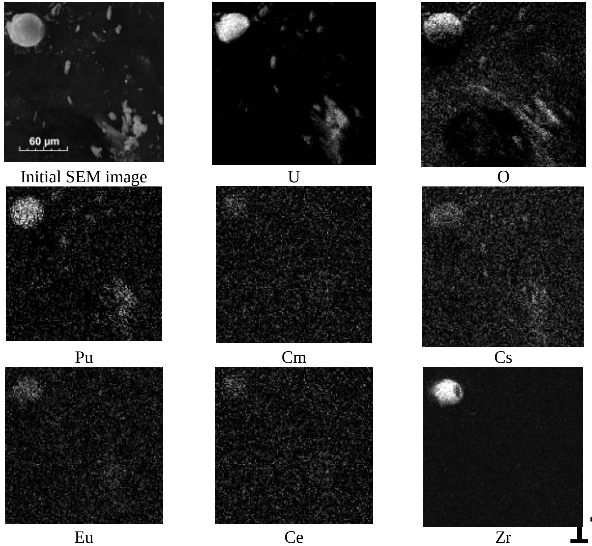
Laser cutting process and general view of sample after laser cutting

Laser cutting method provides:

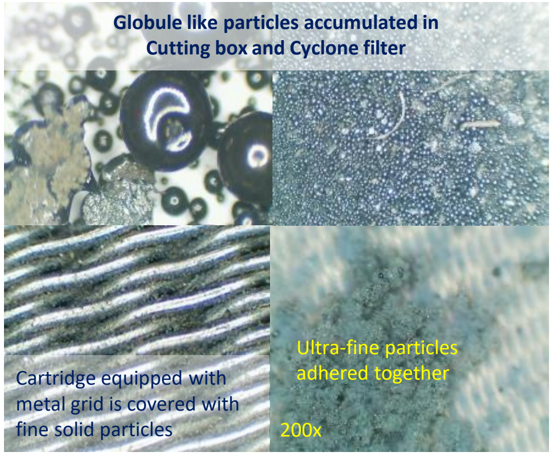
- Sample’s materials evaporation
- Hot vapor phase of sublimated materials generation
- High dust generation intensity
- Low efficiency of Cyclone filter
- HEPA material destruction due to the direct interaction
- Average temperature in cutting box – 50 °C during cutting, average humidity – 11%



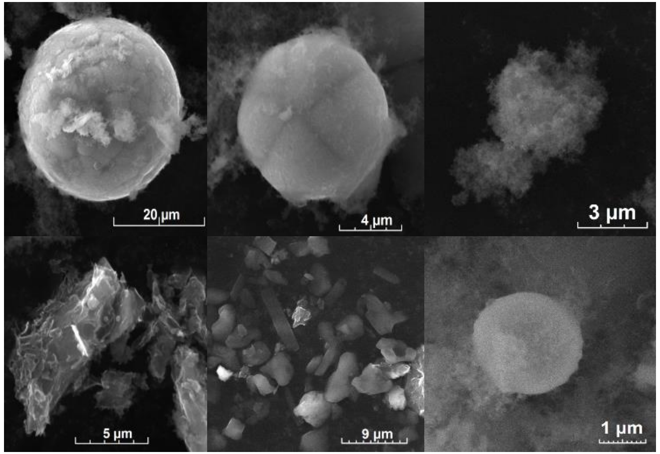
General view of HEPA material after laser cutting



Results of determination of dust particle element composition



General views of melted dust particles and ultra-fine dust particles



SEM-image of different dust particles types after laser cutting

Dust behavior phenomena during laser cutting (2/2)

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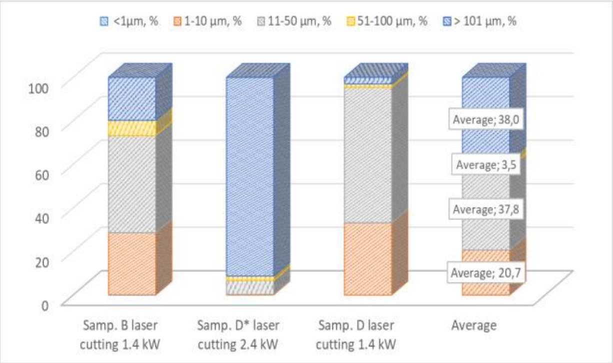
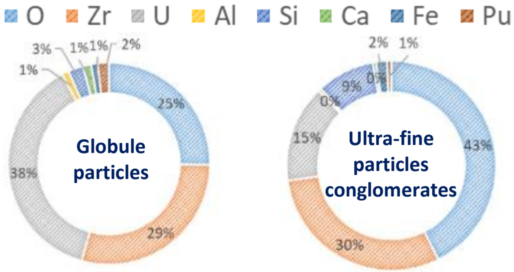
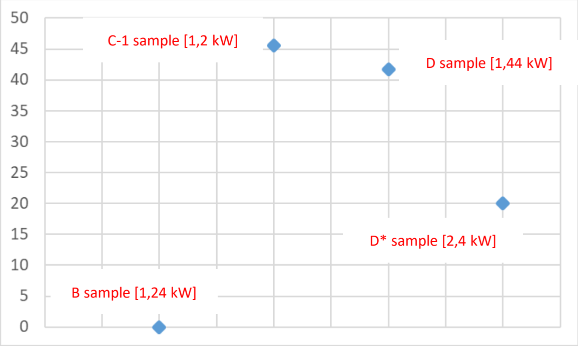


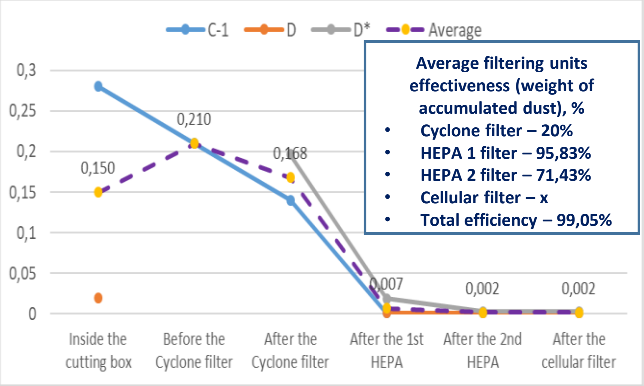
Solid dust particles granulometric composition determination results



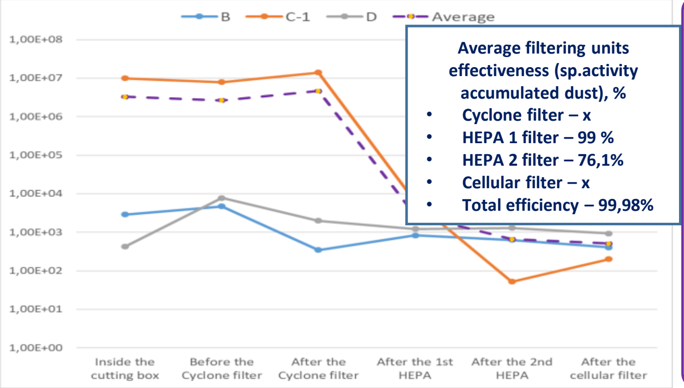
Dust particles elements composition



Dust mass generation intensity in cutting point, mg/sec



Dust particles concentration distribution, mg/dm³



Dust particles β,γ specific activity distribution, Bq/dm³ (logarithmic scale)

CONCLUSIONS

- Laser cutting provides high dust mass generation intensity up to 46 mg/sec
- Laser cutting provides hot and highly penetrated vapor phase generation
- Cooled and adhered particles average size → 1-50 µm - 58%, >101 µm – 38%
- Melted dust particles contains mostly U and Zr dioxides
- Approx. 40-50 wt% of generated dust were collected by dust collection system

Fine filters degradation after B, D, D* samples

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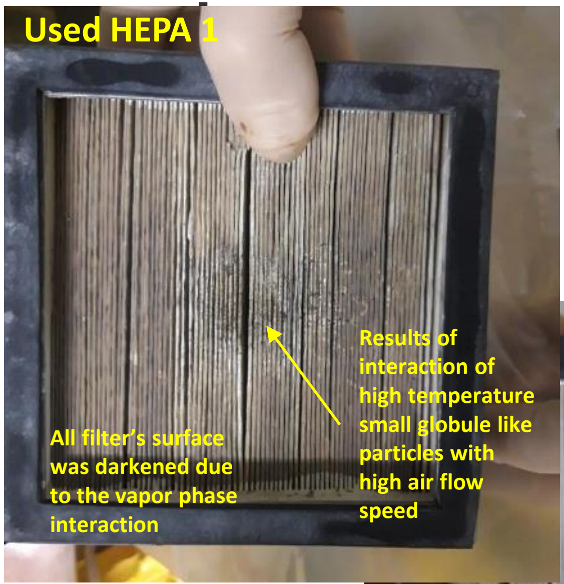
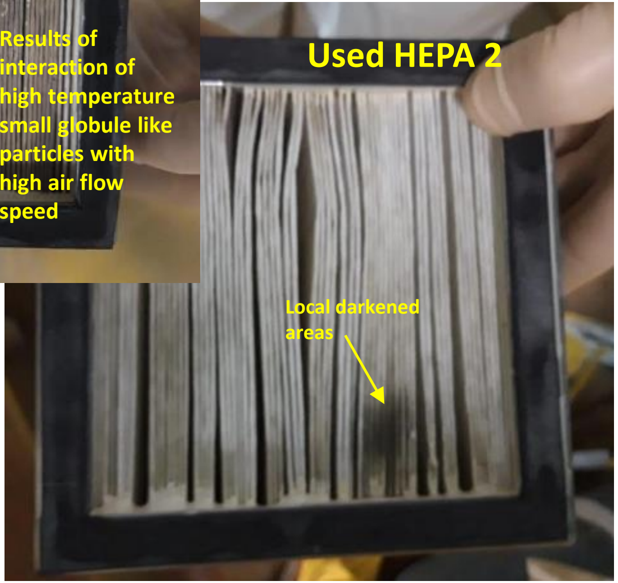


Before the Samples C cutting we changed the both fine filters in a main gas duct



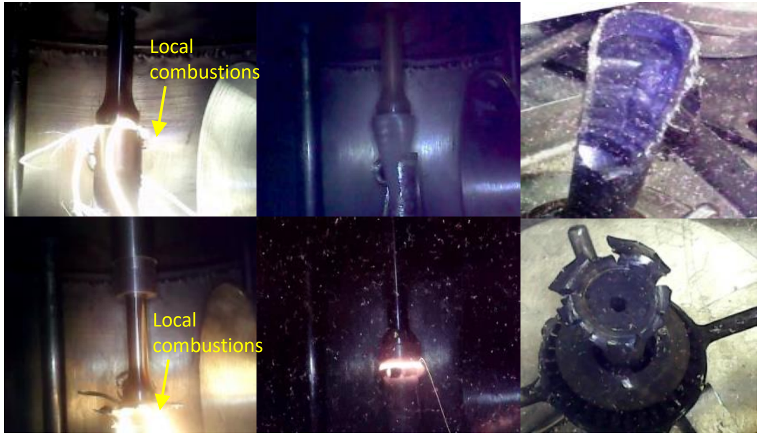
- As a result of high temperature laser cutting vapor phase and melted hot particles were generated and collected with dust collection system.
- Limited space in K-10 hot cell has restricted the dimensions of laboratory scale system and as a result hot particles and vapor phase did not have enough time to cool down before fine filters.
- Due to the hot vapor phase and hot particles influence, the filtering material was partially damaged, effectiveness of fine filters was reduced.
- We recommend to use preliminary enlarging and air cooling stages in a full-scale dust collection system to enlarge ultra fine solid particles, aerosols and vapor phase and to protect the following cleaning stages and safe its efficiency for a long period.

Cutting experiments results

Dust behavior phenomena and aspects during samples B, C, D, D* **mechanical cutting on-air**

Dust behavior phenomena during carbide mill cutting (1/2)

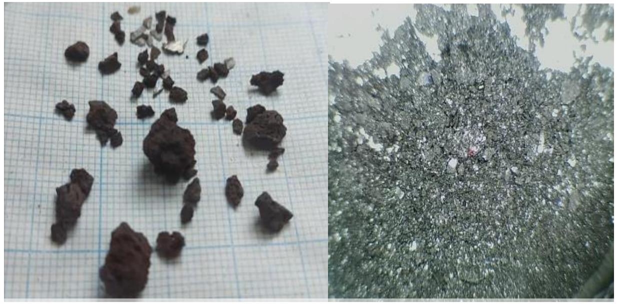
Carbide mill cutting 1000 rpm



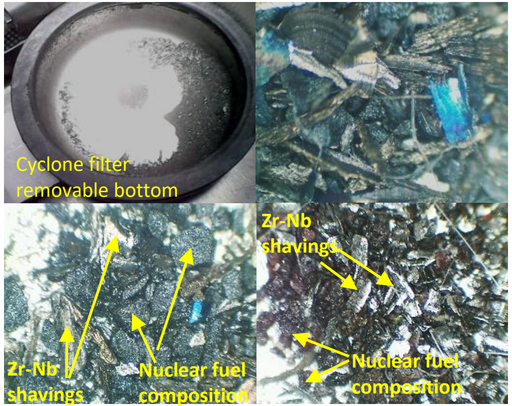
Mechanical cutting on-air process and general view of sample after mechanical cutting on-air

Carbide mill on-air cutting method provides:

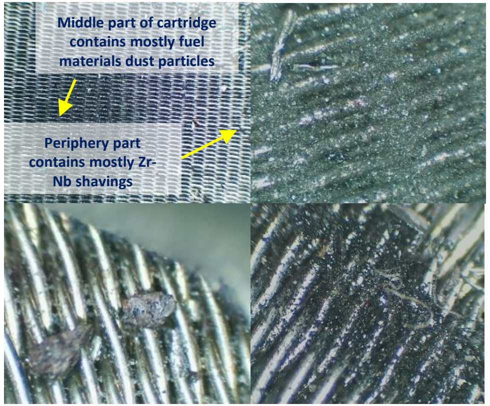
- Local combustions during the cutting (due to the friction between mill and Zr-Nb sample's tube)
- Ultra-fine solid aerosols generation
- High filtering efficiency of Cyclone filter and HEPA filters



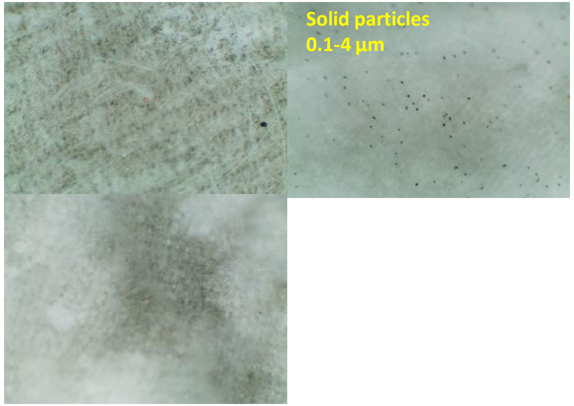
Dust particles and huge fragments accumulated in removable bottom of Cutting box



Enlarged view of dust particles collected in Cyclone filter

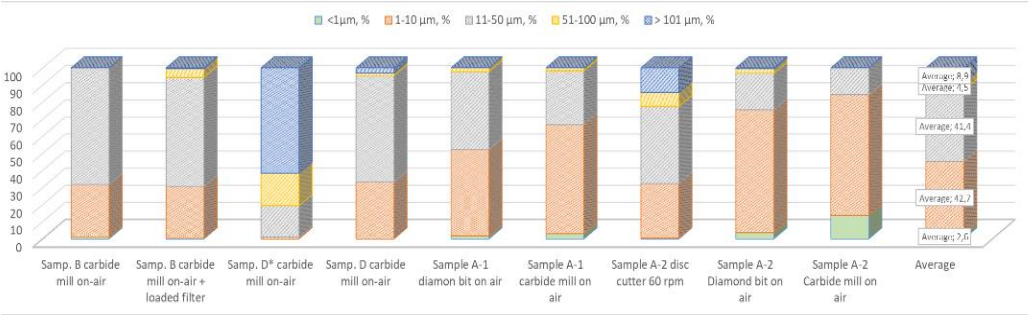


Enlarged view of dust particles collected in samplers on metal grid

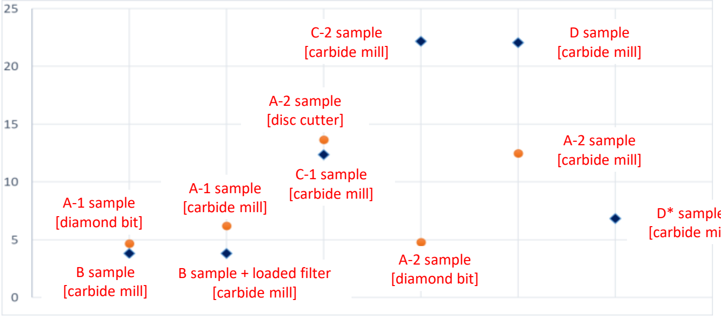


Enlarged view of dust particles collected in samplers on HEPA material

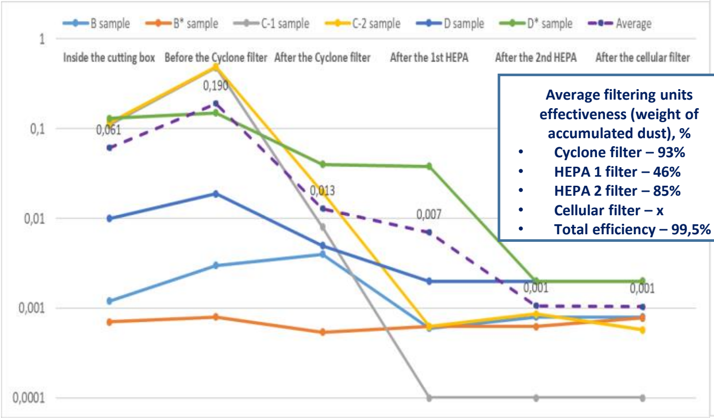
Dust behavior phenomena during mechanical cutting (2/2)



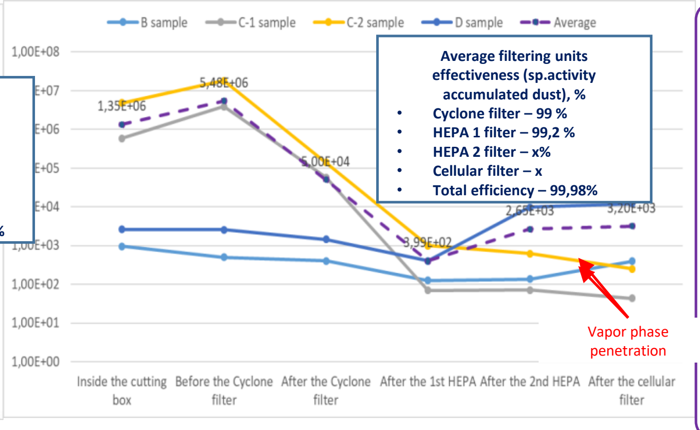
Solid dust particles granulometric composition determination results



Dust mass generation intensity in cutting point, mg/sec



Dust particles concentration distribution, mg/dm³ (logarithmic scale)



Dust particles β,γ specific activity distribution, Bq/dm³ (logarithmic scale)

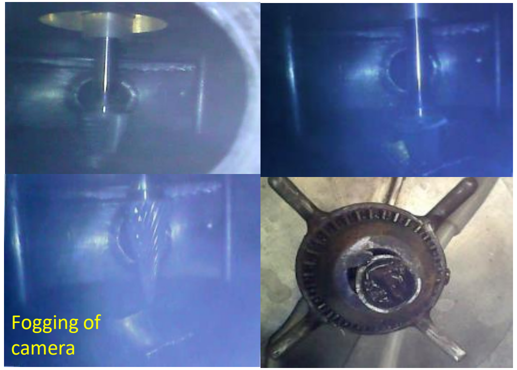
CONCLUSIONS

- Mechanical cutting provides dust mass generation intensity up to 22 mg/sec (twice lower than laser cutting)
- 85 wt% of dust particles have a size from 1 to 50 µm, 2.6% - <1 µm
- Due to the local short term combustions vapor phase was generated as well
- Approx. 30-40 wt% of generated dust were collected by dust collection system

Cutting experiments results

Dust behavior phenomena and aspects during samples B, C, D **carbide mill cutting in-water**

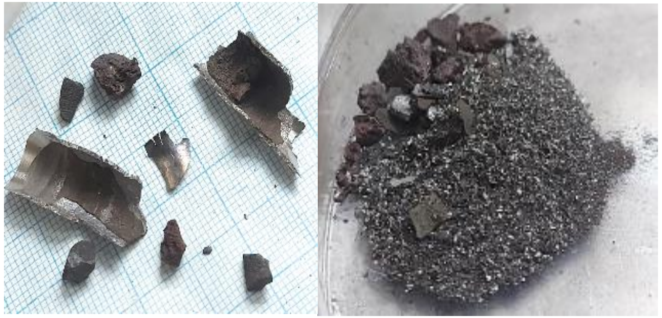
Dust behavior phenomena during cutting in-water (1/2)

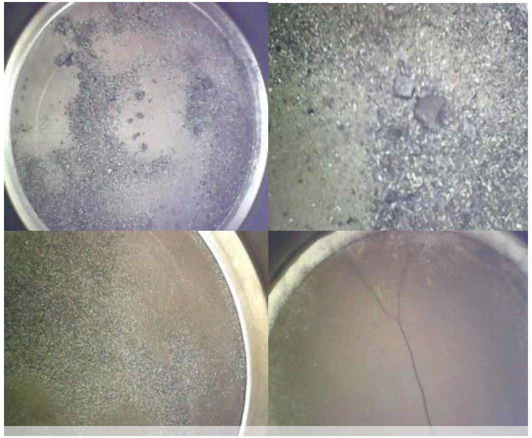


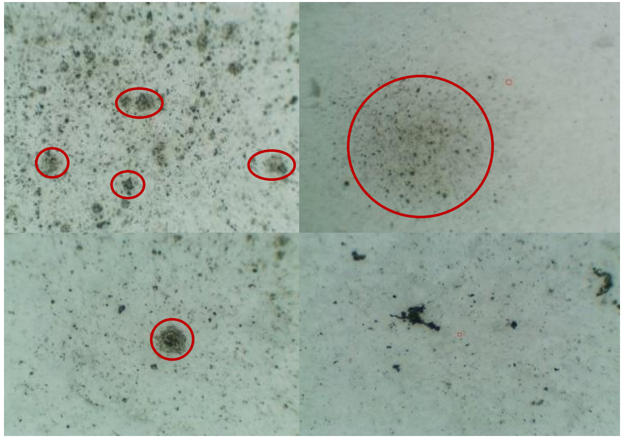
Mechanical cutting in-water process and general view of sample after mechanical cutting in-water

Carbide mill in-water cutting method provides:
- Generation liquid aerosols
- Negative influence on HEPA filters efficiency [mostly due to the changing of fiberglass properties in wet condition]


General view of cutting box for in-water cutting (with bubbling system)


Dust particles and huge fragments accumulated in removable bottom of Cutting box


Sifting of the dust particles accumulated in removable bottom of cutting box


Liquid aerosols tracks on cartridges equipped with HEPA material

Dust behavior phenomena during cutting in-water (2/2)

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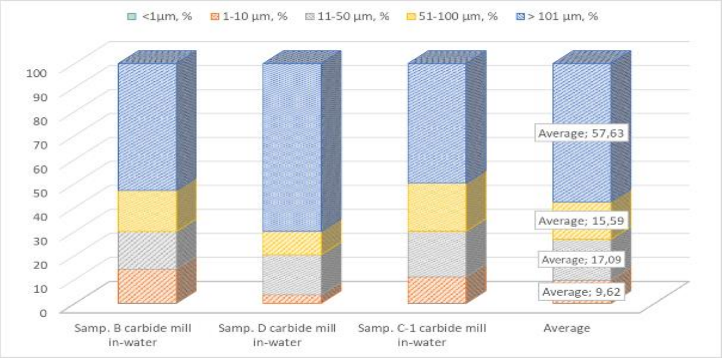
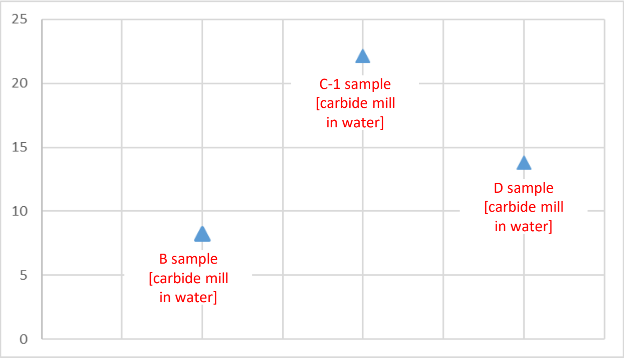
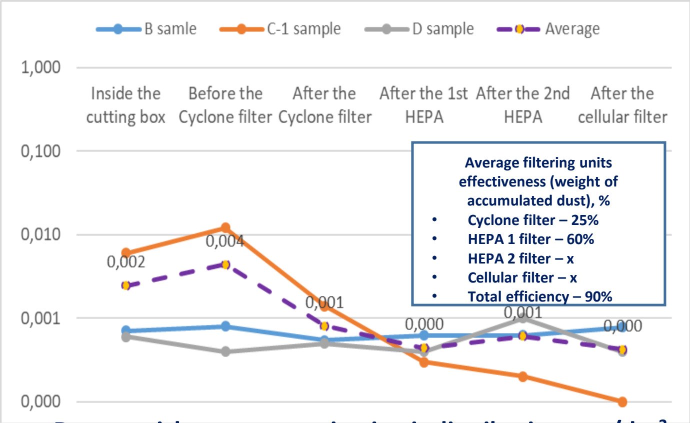


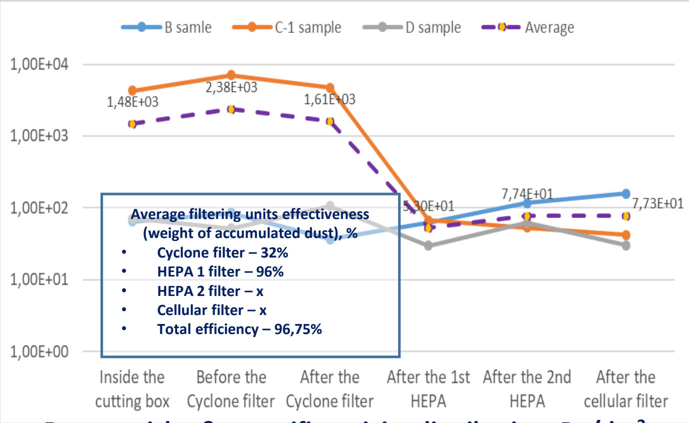
Solid dust particles granulometric composition determination results



Dust mass generation intensity in cutting point, mg/sec



Dust particles concentration in air distribution, mg/dm^3 (logarithmic scale)



Dust particles β,γ specific activity distribution, Bq/dm^3 (logarithmic scale)

CONCLUSIONS

- Mechanical cutting provides high dust mass generation intensity up to 22 mg/sec (same as mechanical cutting on air)
- 60 wt% of dust particles have a size more than 100 µm
- Up to 4 wt% of generated dust amount were collected by dust collection system
- Liquid aerosols were generated and it was a reason of HEPA filters efficiency reduction

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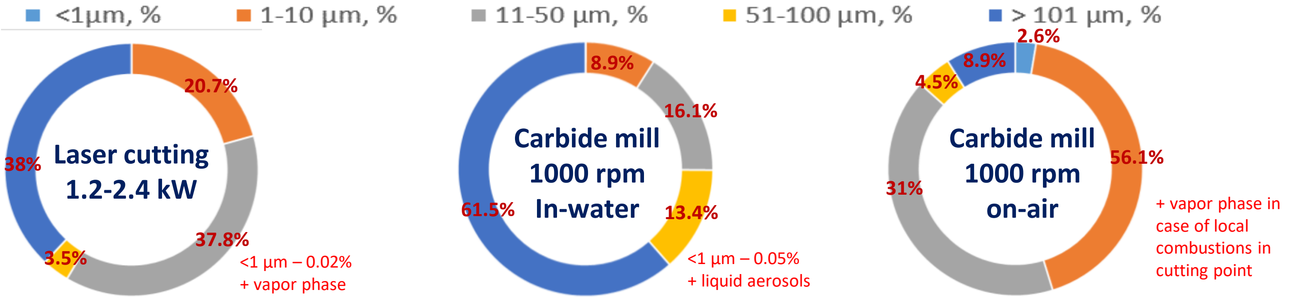
Cutting experiments conclusions

Cutting tests summary infographic (1/2)



Dust particles granulometric composition in cutting point, %w

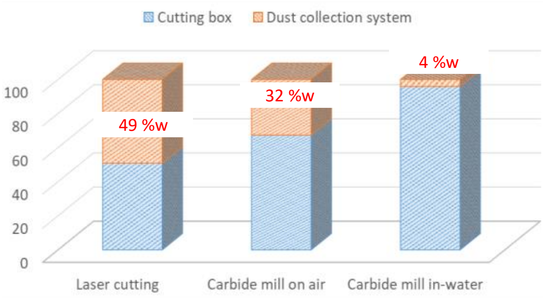
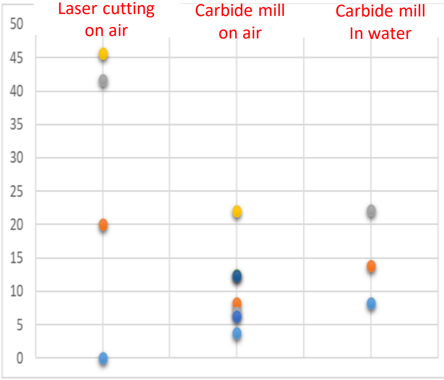
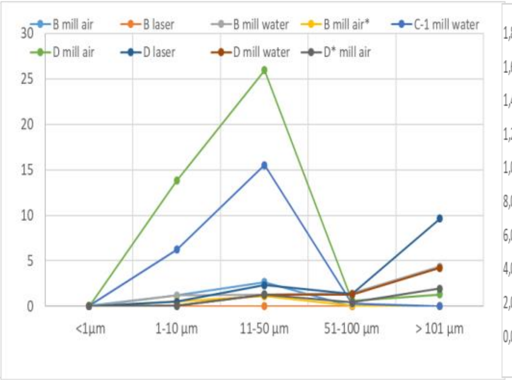


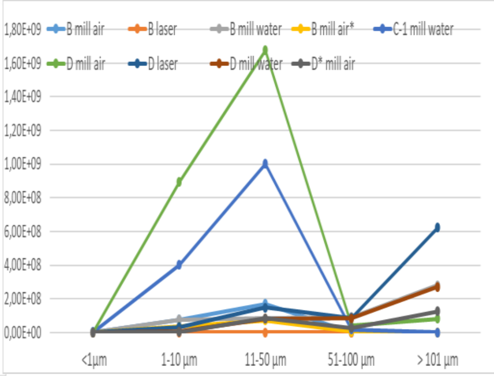
Diagram of generated dust mass distribution, %w



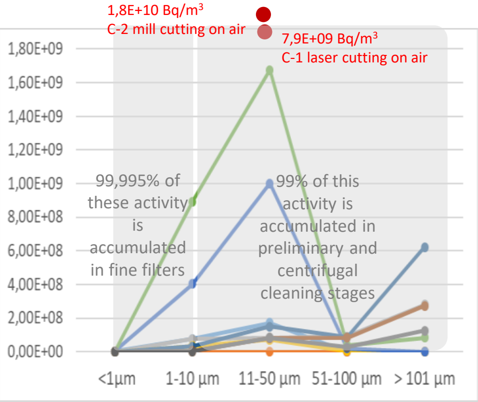
Dust mass generation intensity in cutting point, mg/sec



Dust mass generation intensity in cutting point, dust particle size vs mg/sec



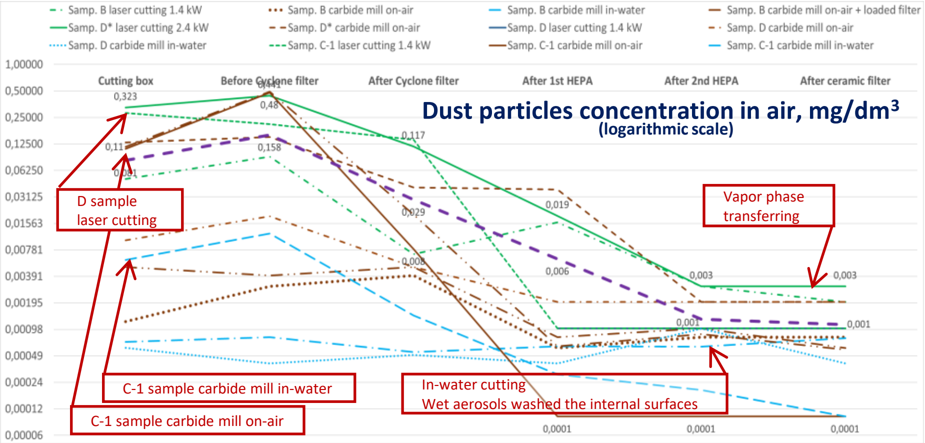
Dust specific activity intensity in local suction unit of full-scale system system adopted for 1F*, Bq/sec

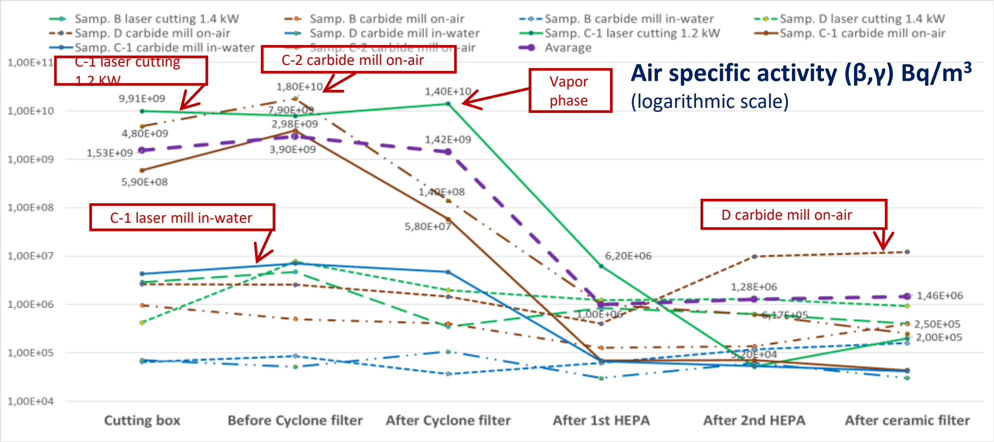


Dust specific activity in a local suction unit of full-scale system system adopted for 1F*, Bq/m^3

*Based on JAEA-Data/Code 2012-018 "Estimation of Fuel Composition in 1F NPP" modeled and calculated average 1F corium specific activity was up to 6,3E+09 Bq/g and planned air consumption in a full-scale system 350 m^3/h

Cutting tests summary infographic (2/2)





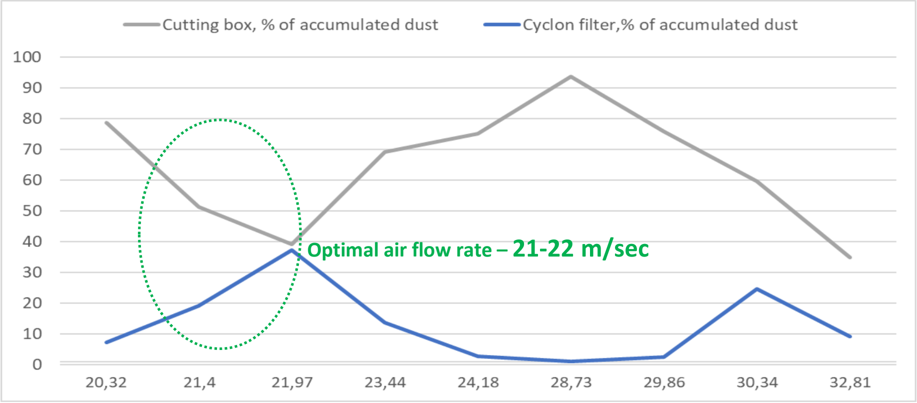


Diagram of %w dust distribution depending on air flow rate value

- More powerful laser provides higher dust particles concentration in air.
- Air flow rate higher than 22 m/sec reduces of collected amount of dust particles from cutting zone and amount of dust particles accumulated in Cyclone filter.
- Optimal air flow rate (~22 m/sec) and low air flow resistance of fine filters provide better dust collection process isokineticity.
- Lots of cutting operations provide the accumulation of dust particles on fine filters and increase its air flow resistance, thus isokineticity is changed and low dust amount is collected by dust collection system.
- Laser cutting as a high speed carbide mill cutting provide the generation of highly penetrated vapor phase.

Cutting experiments main conclusions (1/3)

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Common conclusions

1. Using "hot" samples with nuclear materials and fission products allowed us to detect dust penetration through the filters in case where we were unable to detect an increase in the dust mass on filters. Also, "hot" samples allowed us to determine the conservative (worst) values of assumed contaminated air specific activity in cutting point.
2. The particles which penetrated the filters in the largest volume have a size of 0.1-0.3 µm. Russian and worldwide experience review shown that most part of gas cleaning systems efficiency are examined with fogs with same particle size.
3. Approx. 40-50% of generated dust particles were successfully collected as contaminated air be the dust collection system in case of laser cutting, 30-40% in case of mechanical cutting on air and up to 4-5% in case of mechanical cutting in-water.
4. Approx.70% of accumulated dust particles have a size from 1 to 50 µm, 23% - more than 100 µm and up to 2% - less than 1 µm. It should be noted that ultra-fine particles as well as particles less than 5 µm mostly stick together during the interaction and form large conglomerates.
5. Dust solid particle's generation intensity close to the cutting point was up to 46 mg/sec in case of laser cutting and up to 22 mg/sec in case of carbide mill cutting on air and in-water.
6. Solid dust particles concentration close to cutting point was ~0.3 g/m^3 in case of laser cutting, ~0.11 g/m^3 in case of carbide mill cutting on-air and ~0.014 g/m^3 in case of carbide mill cutting in-water.
7. Upper worst contaminated air specific activities close to cutting point are up to (β,γ) 9.91E+09 / (α)8.02E+07 Bq/m^3 (for case of Unit 1,2 1F) and up to (β,γ) 1.8E+10 / (α)2.9E+08 Bq/m^3 (for case of Unit 3 1F).* We assume that real 1F contaminated air specific activity during FD cutting will be less than mentioned values due to the more than 10 years "storage" period.

Cutting experiments main conclusions (2/3)

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Common conclusions

8. Results of dust solid particles distribution demonstrate that optimal air flow rate for suction unit and main gas duct should be 21 – 22 m/sec during the FD cutting operations. Depend on real distance between cutting point and local suction unit it will be necessary to recalculate airflow rate and/or air consumption in a main gas duct.
9. Cyclone filter (imitation of centrifugal dust collection principle) allows to accumulate up to 60-70% of dust particles with a size of more than 10 μm collected with the dust collection system. Wherein we determine the effect of abrasive solid particles interaction between each other and the Cyclone filter internal walls, smallest particles are also generated after it.
10. Our experiments have shown than approx. 2-3% of the mass of collected dust could precipitate on internal walls of the main gas duct, sampling ducts and filters. After the accumulation of the significant dust layer on internal walls and the input liquid aerosols, it could be possible to wash a high concentration of dust particles onto the following filters instantly.
11. Our experiments have shown that total effectiveness of two consecutive HEPA filters is not equal to the sum of the effectiveness of each separate filter. It’s reasonable to consider the effectiveness of both filters as 10^5 in total.
12. Our experiments have shown that HEPA material safes its efficiency even under total alpha activity 5E+07 Gy loading.
13. Our experiments have shown that in case of mostly metal oxides corium phase mechanical cutting on air with high cutting speed there are local flammable risk in cutting point and risk of accumulation of flammable Zr concentration on filters. Special prevention countermeasures should be provided.

Cutting experiments main conclusions (3/3)

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Laser cutting aspects

1. Generation of ultra-fine aerosols (< 1µm) and highly penetrated vapor phase of sublimated materials.
2. Generation twice higher concentration of 1-50 µm solid particles concentration in cutting point and before first cleaning stage than carbide mill cutting on air.
3. Fiberglass/HEPA materials could be partially destructed after the interaction of hot melted particles of sublimated materials.
4. It should be noted, that the risks of challengeable vapor phase of Cs and I generation during laser (or any other high temperature) cutting of FD should be taken into account.
5. Cyclone filter partially could not allow to accumulate the hot vapor phase of sublimated materials.

Mechanical cutting aspects

1. High speed mechanical cutting could provide the local combustions in cutting point and generation of ultra-fine aerosols and vapor phase as well.
2. Mechanical cutting in water generates liquid aerosols and reduce the efficiency of fiber glass materials on the following cleaning stages as well as reduce the visibility of video control system.
3. Wet (in case of in-water cutting) fiberglass/HEPA materials irreversibly changed its properties such as the distance between fibers and fiberglass density, such materials effectiveness is reduced. Such filters should be replaced after wetting.
4. Cyclone filter partially could not allow to separate of total amount of generated liquid aerosols from contaminated air.

Recommendations for full-scale system based on cutting experiments results

Based on cutting experiments results we could strongly recommend for full-scale system the following:

1. To **use preliminary cleaning stage** (cooling and enlarging) for:

- cooling of input contaminated air and prevention of the finer filter's filtering material (fiberglass, fiber mats, HEPA) destruction as result of hot particles interaction in case of high temperature cutting,
- partially reduction of input dust particles, aerosols (and vapor phase in case of high temperature cutting) concentration/specific activity in contaminated air before the following filtering stages,
- partially reduction of input Zr-contained dust particles concentration and same particles enlarging to prevent the accumulation of flammable concentrations on the following filters. **Also, we recommend to replace fine filters before the FD retrieval operation suspension or long works stoppage.*

2. To **use centrifugal dust accumulation mechanism (Cyclone like filters)** for accumulation of most part of enlarged aerosols and solid particles with size more 10 µm with efficiency up to 60%. ** Also, we recommend to use of improved version of centrifugal filter (e.g. SOTAR) with possibility of forced dust particles and aerosols enlarging within mixing with wet steam to increase the filtering efficiency up to 90%.*

3. To **use the remotely decontaminated fine filter (e.g. FARTOS)** before the HEPA filters to increase the HEPA filters lifetime.

4. To **use two consecutive last fine filters** to provide guarantee total filtering efficiency in case of unforeseen penetration of ultra-fine dust particles.

5. To **use special vapor Cs, I cleaning stages** to prevent of risk of mentioned nuclides discharging in atmosphere.

6. To provide the possibility of first cleaning stages remotely decontamination to prevent of accumulation the significant dust layer inside.

Initial technical requirements for full-scale dust collection system

Initial technical requirements for full-scale dust collection system (1/2)

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Current environmental conditions inside the PCV/RPV

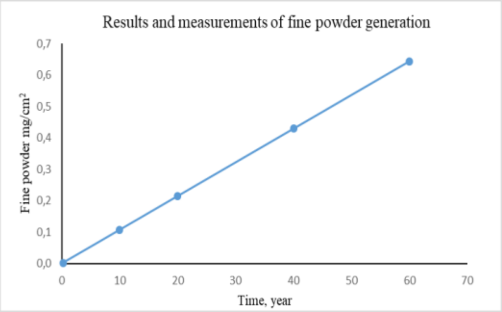
Air conditions

Unit #	Radioactive concentration inside the Units	Average temperature inside	Average humidity inside	Water injection capacity
1	7.1E-01 to1.4 Bq/dm^3	15.3 °C (inside RPV) 21.7°C (closed to the PCV bottom)	Up to 99,9%	3 m^3/h
2	100 Bq/dm^3	18.6 °C (inside RPV) 19.5°C (closed to the PCV bottom)		2.8 m^3/h
3	ND	19 °C (inside RPV) 20°C (closed to the PCV bottom)		2.9 m^3/h

Water conditions

Nuclide	Cs-134	Cs-137	I-131	Co-60	Mn-54	Sb-125	Ru-106
Specific activity, Bq/dm^3	8.5E+04 to 9.1E+04	1.7E+07	4.3E+03 to 6.3E+03	9E+03	8E+03 to 11E+03	1.3E+04 to 1.8E+04	2.4E+04 to 3.3E+04

Forecast of dry FD's surface dust generation



Expected environmental conditions inside the PCV/RPV during the FD retrieval operations

Parameter	(1) Gas-vapour phase (high temperature cutting, high speed mechanical cutting)	(2) Solid particles (mechanical cutting)	(3) Aerosol particles (underwater cutting, high humidity etc)	(4) exfoliation of adherent dust particles
Particles size diapason	Molecule size to 0.5 µm. *Dust collection system mostly accumulate dust particles with size from 0.8 to 300 µm. However approx. 10% of all particles has a sub-micron size*	1-2000 µm. *75% of dust particles collected by dust collection system have a size from 10 to 300 µm. However approx. 1% of all particles has a sub-micron size*	Different sizes	ND
Particles distribution aspects	Vapour phase could easily transfer and penetrate through the all filters in case of absence of special treatment stages.	Up to 50% of generated dust particles amount could be collected by dust collection system. Up to 58-95% of generated dust particles amount sediment close to cutting point.	Could provide the negative influence on fibre-glass filters	
Dust particles intensity generation in a cutting point	Up to 46 mg/sec			
Dust particles specific activity (β, γ) in cutting point	Up to 1.8E+10 Bq/m^3 (based on SNF cutting experiments, C-2 sample) Up to 2.69E+09 Bq/m^3 (based on assumed 1F corium specific activity)			
Other aspects	Vapour phase of Cs is generated. I, Rh gaseous are generated as well.	-	-	

Initial technical requirements for full-scale dust collection system (2/2)

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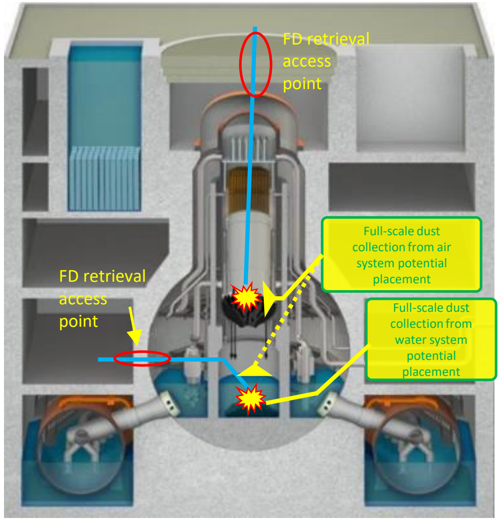
The list of initial technical requirements for full-scale dust collection system

#	Parameter	Value	Remark
1	Dust particles size diapason before first cleaning stage	Molecule size to 500 µm (vapour phase + solid particles + aerosols)	High temperature cutting, mechanical cutting
2	Contaminated air specific activity (β, γ) in cutting point	Up to 1.8E+10 Bq/m^3	**Conservative estimations** based on SNF cutting tests results. Also, it could be possible to generate Cs vapour phase as well as Rh and I during the high temperature cutting.
3	Contaminated air specific activity (β, γ) in a local suction unit	Up to 4E+08 Bq/m^3	Based on recommended air consumption 350 m^3/h Adopted to 1F conditions (Average sp.activity of corium is up to 6,3E+09 Bq/g)
4	Dust generation intensity in a cutting point	Up to 46 mg/sec	Conservative estimation based on cutting experiments
5	Dust specific activity intensity in a local suction unit	Up to 1,63E+08 Bq/sec	Based on recommended air consumption 350 m^3/h Adopted to 1F conditions (Average sp.activity of corium is up to 6,3E+09 Bq/g)
4	Humidity before the first cleaning stage	Up to 99%	Due to the existing stagnant water and continued FD cooling with water (up to 3 m^3/h)
5	Contaminated air temperature diapason before the first cleaning stage	Up to 100 °C	During the high temperature cutting
7	Main gas track diameter	50 – 100 mm	To satisfy optimal air flow rate
8	Air flow rate in full-scale dust collection system	19-22 m/sec	Based on results of experimental cutting tests
9	Air consumption	Up to 400 m^3/h	

Principal of placement of full-scale system



Required cleaning stages (for all types of cutting methods)

Preliminary cleaning stage Reduction of solid dust particle concentration, particles enlarging, air cooling ⇨ **1st cleaning stage** 99% of vapor phase treatment, aerosols enlarging, reduction of solid particles concentration ⇨ **2nd cleaning stage** Accumulation of fine solid particles and aerosols. Should be self-regenerated ⇨ **3d cleaning stage** Accumulation of ultra-fine solid particles and aerosols ⇨ **4th cleaning stage** Sanitary cleaning ⇨ **Adsorption tower** I-gas treatment ⇨ **Ceramic filter** Cs gaseous treatment

These clearing stages are required just in case of high temperature cutting

Full scale dust collection system

Preliminary conceptual design

Full-scale system conceptual flow-chart (air treatment)

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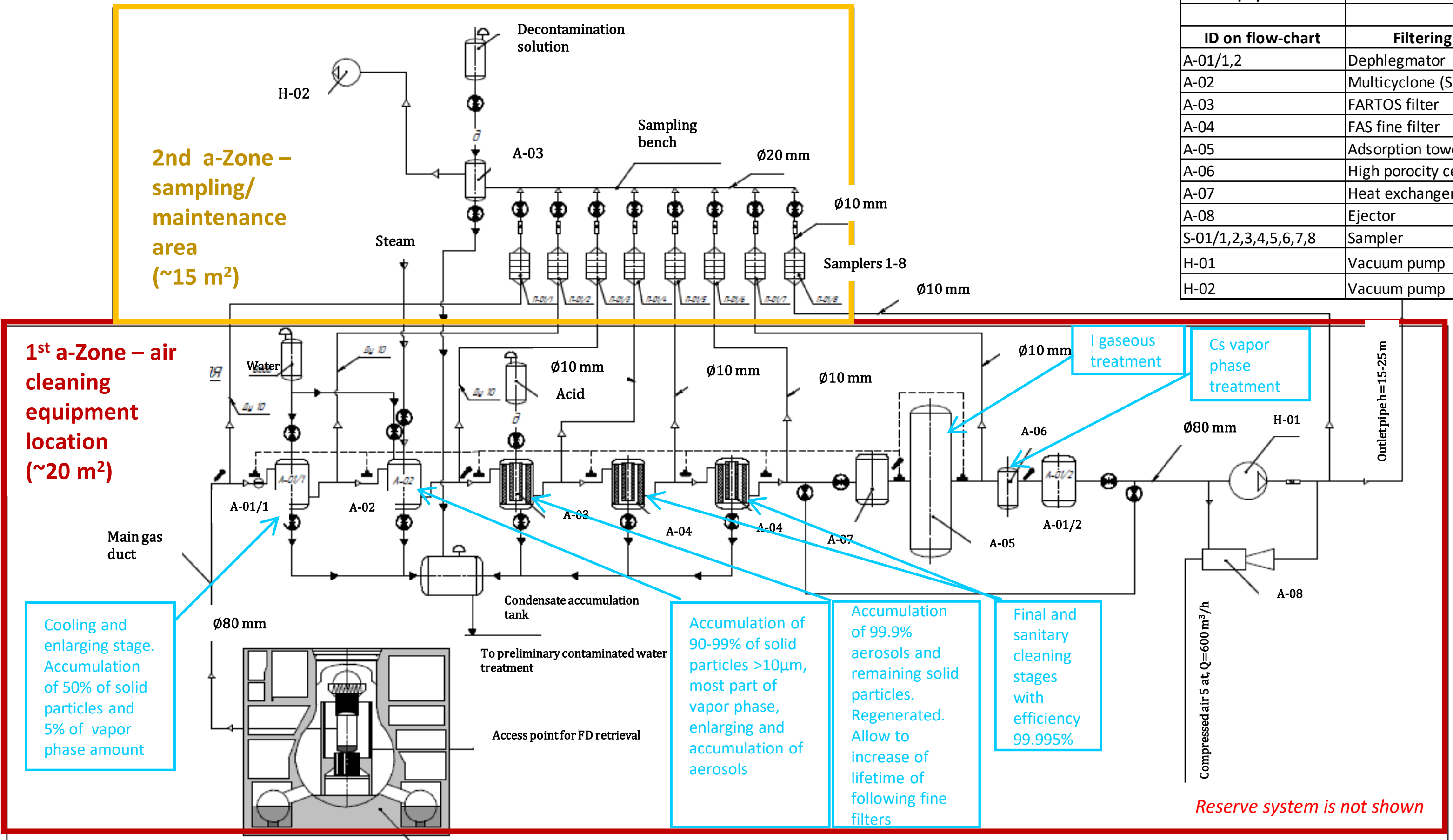
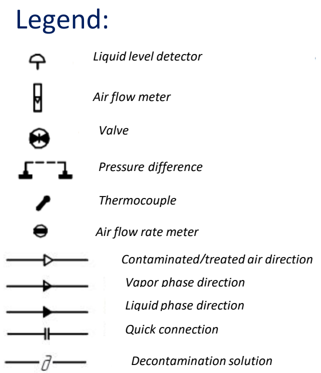
Main equipment			
ID on flow-chart	Filtering apparatus	Quantity	Parametres
A-01/1,2	Dephlegmator	2	x
A-02	Multicyclone (SOTAR)	1	x
A-03	FARTOS filter	1	x
A-04	FAS fine filter	2	x
A-05	Adsorption tower (for I collection)	1	x
A-06	High porocity ceramic filter	1	x
A-07	Heat exchanger (heater)	1	x
A-08	Ejector	1	x
S-01/1,2,3,4,5,6,7,8	Sampler	8	x
H-01	Vacuum pump	1	Q=280 m^3/h
H-02	Vacuum pump	1	Q=60 m^3/h



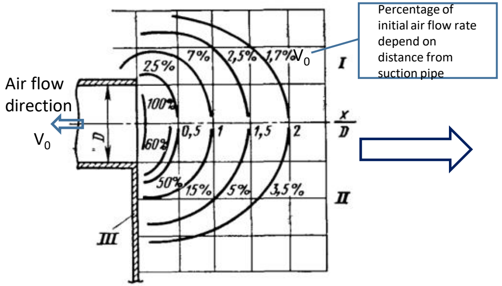


Conceptual proposals for full-scale local suction unit

We believe that full-scale dust collection system should mainly provide the following aims:

1. **To localize the generated dust particles and aerosols close to cutting point to prevent its uncontrolled transfer out of PCV/RPV**
2. **To reduce dust particles and aerosols concentration around the cutting point to provide the effective video control system operation**

Air flow rates in a suction zone of local suction pipe on a distance x[1]

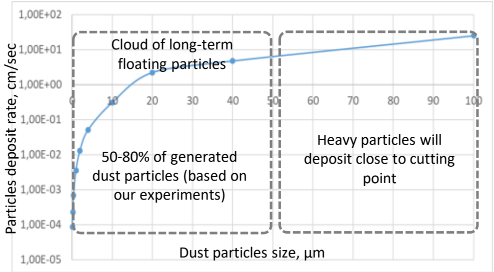


I – air flow rates fields in a suction specter without any shields
II – air flow rater fields in a suction specter with flat shield
III – flat shield to localize the dust particles and aerosols

Based on this diagram we could assume that the optimal air flow rate on a far distance of cutting point requires very huge air consumption, huge gas cleaning apparatus etc.

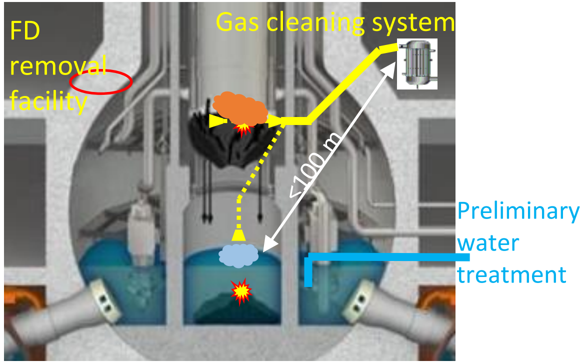
Thus we recommend to collect the surround floating dust particles cloud mostly than dust particles in cutting point

Dust particles deposit rate depending on size (logarithmic scale)[2]

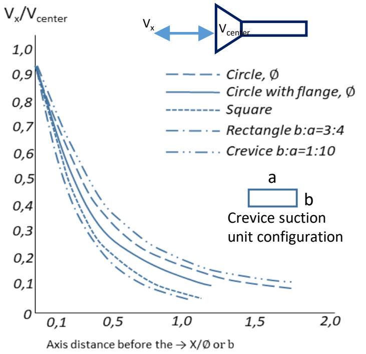


[1] V.Pisarenko, M.Roginsky "Ventilation of industrial working place"
[2] H.Green, W. Lane "Particulate clouds: Dust, Smokes and Mists"

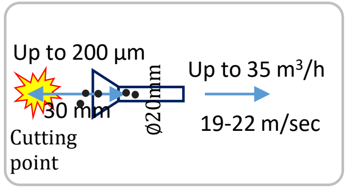
Dust collection system access point should be opposite to FD removal access point



Local suction unit configuration

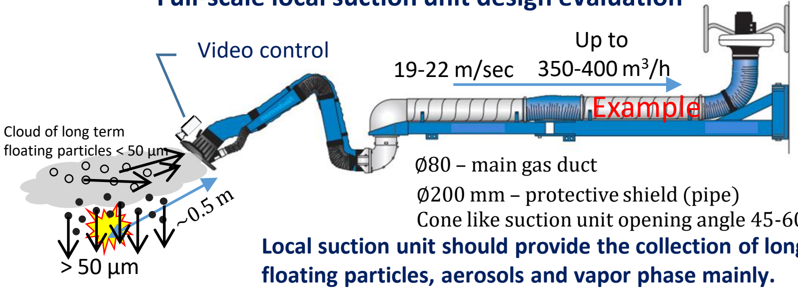


Laboratory scale system



To provide the same air flow rate we propose to use Ø80mm main gas duct and 350 m³/h air consumption.

Full-scale local suction unit design evaluation



Ø80 – main gas duct
Ø200 mm – protective shield (pipe)
Cone like suction unit opening angle 45-60°

Local suction unit should provide the collection of long term floating particles, aerosols and vapor phase mainly.

In case of increasing the distance to the cutting point to safe the optimal airflow rate, air consumption should be increased as well.
To provide the optimal design of local suction unit it's strongly required to know (or to simulate) the structure of air flows around local suction unit.

Full-scale system conceptual flow-chart (water treatment)

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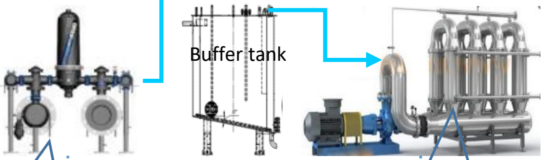
Priority proposed preliminary water treatment option

Phlegm from air cleaning 0.3m³/h

Preliminary filtration (coarse discs filter)

Buffer tank

Ultrafiltration unit (tangential filters)



Sludge/slurry

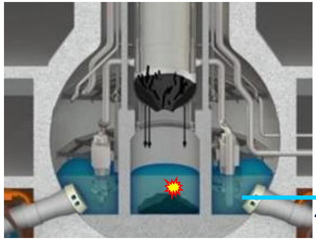
KURION/SARRY/ALPS requirements for input contaminated water :

•Solid particles concentration

•Specific activity

•Nuclear materials concentration

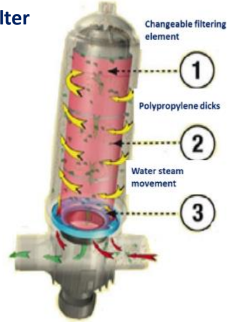
Existing water treatment system (KURION/SARRY/ALPS)



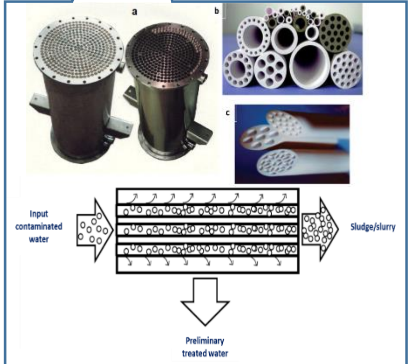
3m³/h

~38% of generated dust particles could have a size <50μm

Coarse disc filter



Filtration rate: 5-200 μm
Low energy consumption: 0.1-0.3 kW/m³
Fast self washing: 10 sec
Filtration capacity: 3-50 m³/h
Secondary RW amount reduction



Hydro-Cyclone filter applicability

- Cutting experiments shown that approx. 20-35% of generated solid dust particles during in-water cutting have a size less than 50 μm
- In this case it should be necessary to use hydro-cyclone filter + microfiltration –> a lot of secondary waste (spent microfiltration cartridges)

Disc filter is more suitable