DE LA RECHERCHE À L'INDUSTRIE

Atalante Research Facility – Implementation of a rule of fractions for the management of reflecting materials in mass-limited units

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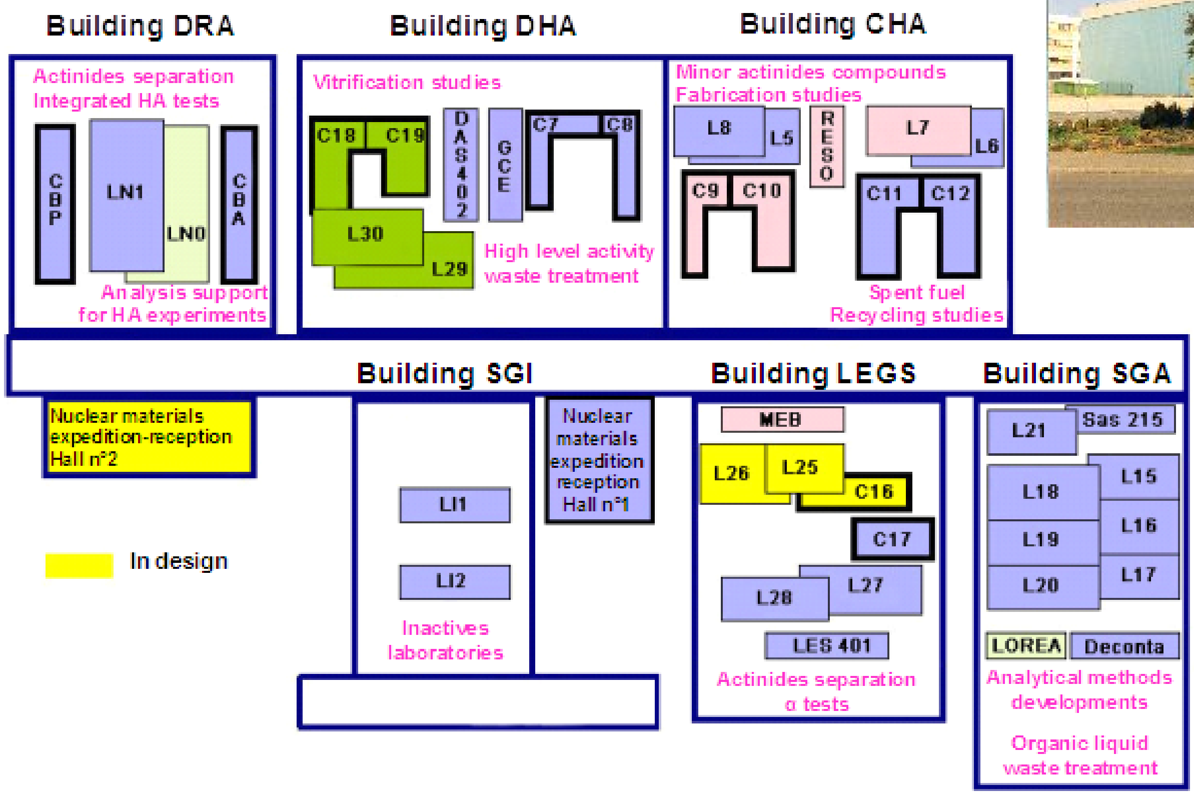
SUMMARY

1. ATALANTE FACILITY (1/2)



1. ATALANTE FACILITY (2/2)

The Atalante facility groups:

- **18 hot labs,**
- **11 shielded cells,**

devoted to fuel cycle research and development

For criticality risk prevention:

- **the facility is divided into about 30 work units,**
- **most of them are managed through a mass control mode.**

2. USUAL APPROACH TO CRITICALITY SAFETY IN ATLANTE

Reference fissile medium: $^{239}Pu - H_2O$

Limit for a mass-limited work unit: 350 g of fissile material

Fissile material = Pu + ^{233}U + ^{235}U (if $^{235}U/U_{total} > 1\%$)

This mass limit of 350 g:

- **was determined considering a reflection by 20 cm of water ("full water reflection"),**
- **was determined by multiplying the minimal critical mass by a safety factor of 0.7,**
- **leads to a maximum Keff lower than 0.93**

3. INITIAL CASE FOR REFLECTING MATERIALS (1/4)

Some neutronic reflectors are more efficient than water and are authorized only in limited quantities.

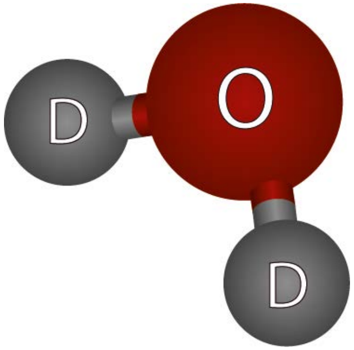
In ATALANTE the reflecting materials identified as requiring a specific form of management are:

Lead

Uranium
($^{235}U/U_t < 1\%$)

Graphite

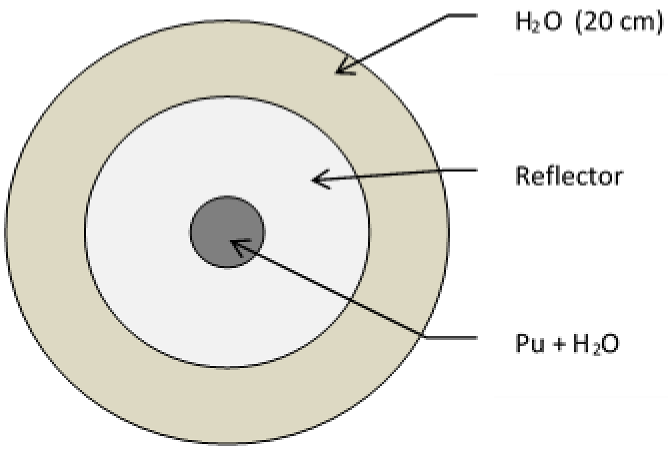
Heavy Water



Beryllium

3. INITIAL CASE FOR REFLECTING MATERIALS (2/4)

Initially a maximum permissible mass ($K_{eff} \leq 0.95$) was determined for each of the selected materials taken separately, considering 350 g of ^{239}Pu moderated by water and reflected by a variable mass of the reflecting material (+20 cm of water)



3. INITIAL CASE FOR REFLECTING MATERIALS (3/4)

The limits thus obtained (Keff = 0.95) are:

Lead

200 kg

Uranium

($^{235}U/U_t < 1\%$)

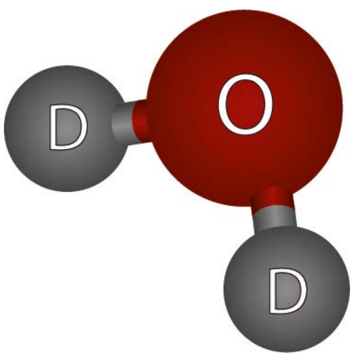
25 kg

Graphite

9 kg (density 1.8)
6.5 kg (density 2.3)

Heavy Water

5 kg



Beryllium

3 kg

3. INITIAL CASE FOR REFLECTING MATERIALS (4/4)

When only one single material is present in a work unit, this method is fairly satisfactory.

However, the method requires that when different reflectors are present simultaneously, the sum of the masses of all these reflectors must be less than the limit specified for the most penalizing of them.

For example, when lead (Mass limit = 200 kg) and beryllium (Mass limit = 3 kg) are both present, the total mass of beryllium AND lead must be limited to 3 kg.

-> too restrictive for the operators

4. RULE OF FRACTIONS

A new rule (rule of fractions) has therefore been implemented:

$$\boxed{\sum_i \left(\frac{m_{R_i}}{m_{R_i \,\mathrm{lim}}} \right) \leq 1}$$

With:

- m_{R_i} : mass of reflector i present in the unit,
- $m_{R_i \,\mathrm{lim}}$: maximum permissible mass of reflector i when considered alone (200 kg for lead, 25 kg for uranium, 9 or 6.5 kg for graphite, 5 kg for heavy water, 3 kg for Beryllium)

Relative mass of reflector i = m_{R_i} / $m_{R_i \,\mathrm{lim}}$

For example a relative mass of 50% means a mass of 1.5 kg for beryllium, or a mass of 100 kg for lead.

5. CALCULATIONS PERFORMED AND RESULTS

Reflecting materials considered and calculation model

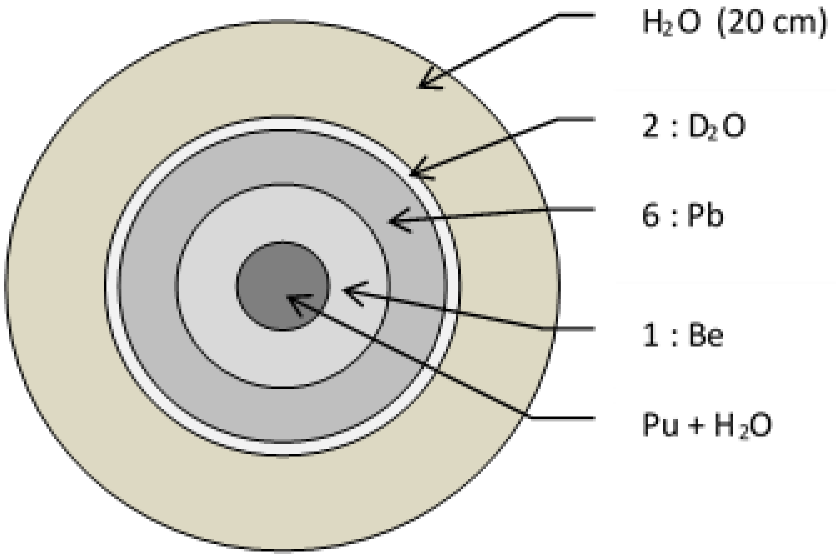
Reflector	Material	Density (g.cm^{-1})	Mass limit (kg)	Ranking Number
H_2O	Water	0.9979	/	7
Pb	Lead	11.35	200	6
U	Uranium (^{235}U =1%)	19.159	25	5
Gr1.8	Graphite 1.8	1.8	9	4
Gr2.3	Graphite 2.3	2.3	6.5	3
D_2O	Heavy Water	1.1055	5	2
Be	Beryllium	1.848	3	1

Calculation Tools: APOLLO2-MORET4
(Standard route of the CRISTAL V1.2 package)

Geometric configurations: 350 g spheres of ^{239}Pu moderated by water and reflected by 2 to 6 reflectors (successions of concentric shells) + 20 cm of water.

5. CALCULATIONS PERFORMED AND RESULTS

Example of configuration studied with several reflectors



In configuration 1-6-2, as shown above, plutonium is reflected by beryllium (1), then lead (6), then heavy water (2).

5. CALCULATIONS PERFORMED AND RESULTS

1 Calculations with two reflecting materials

The 30 combinations of 2 reflectors among the 6, with 2 different sequences, were all studied (1-2, 2-1, 1-3, 3-1, ……..5-6, 6-5)

For each combination, different relative masses of the two reflectors were considered: 0% -100%, 20%-80%, 40%-60%, 50%-50%, 60%-40%, 80%-20%, and 100%-0%.

One of the aims of this first step was to define the most penalizing sequence for the 6 reflectors.

5. CALCULATIONS PERFORMED AND RESULTS

Calculation results with two reflecting materials

	Direct sequence		Reverse sequence	
Couple	Optimal Relative Masses [% of mass limit]	k_{eff} +3σ	Optimal Relative Masses [% of mass limit]	k_{eff} +3σ
1 - 2	Be (20%) - D_2O (80%)	**0.952**		**0.951**
1 - 3	Be (40%) - Gr2.3 (60%)	**0.951**		**0.950**
1 - 4	Be (40%) - Gr1.8 (60%)	**0.951**		**0.950**
1 - 5	Be (0%) – U (100%)	**0.949**		**0.949**
1 - 6	Be (50%) – Pb (50%)	**0.951**		**0.949**
2 - 3	D_2O (60%) - Gr2.3 (40%)	**0.952**	Gr2.3 (60%) - D_2O (40%)	**0.951**
2 - 4	D_2O (80%) - Gr1.8 (20%)	**0.952**		**0.951**
2 - 5	D_2O (100%) – U (0%)	**0.951**		**0.953**
2 - 6	D_2O (50%) – Pb (50%)	**0.952**		**0.951**
3 - 4	Gr2.3 (50%) - Gr1.8(50%)	**0.952**		**0.950**
3 - 5	Gr2.3 (100%) – U (0%)	**0.950**		**0.952**
3 - 6	Gr2.3 (40%) – Pb (60%)	**0.952**		**0.950**
4 - 5	Gr1.8 (100%) – U (0%)	**0.950**		**0.952**
4 - 6	Gr1.8 (80%) – Pb (20%)	**0.951**		**0.950**
~~**5 - 6**~~	~~U (50%) – Pb (50%)~~	~~**0.959**~~		~~**0.949**~~

Except for the uranium-lead couple, direct and reverse sequences give similar results (max. difference = 0.02).

Detailed results :

again except for the uranium-lead couple, when the rule of fractions is respected, the reactivity has only limited variations if the reflectors, their sequence or their relative masses are modified:

0.945 ≤ keff+3σ ≤ 0.953

5. CALCULATIONS PERFORMED AND RESULTS

Calculation results with two reflecting materials

	Direct sequence		Reverse sequence	
Couple	Optimal Relative Masses [% of mass limit]	k_{eff} +3σ	Optimal Relative Masses [% of mass limit]	k_{eff} +3σ
1 - 2	Be (20%) - D_2O (80%)	**0.952**	D_2O (100%) – Be (0%)	**0.951**
1 - 3	Be (40%) - Gr2.3 (60%)	**0.951**	Gr2.3 (100%) – Be (0%)	**0.950**
1 - 4	Be (40%) - Gr1.8 (60%)	**0.951**	Gr1.8 (100%) – Be (0%)	**0.950**
1 - 5	Be (0%) –		U (60%) – Be (40%)	**0.949**
1 - 6	Be (50%) -		Pb (100%) – Be (0%)	**0.949**
2 - 3	D_2O (60%) -		Gr2.3 (60%) - D_2O (40%)	**0.951**
2 - 4	D_2O (80%) -		Gr1.8 (0%) - D_2O (100%)	**0.951**
2 - 5	D_2O (100%		U (50%) - D_2O (50%)	**0.953**
2 - 6	D_2O (50%)		Pb (0%) - D_2O (100%)	**0.951**
3 - 4	Gr2.3 (50 (50		Gr1.8 (0%) - Gr2.3 (100%)	**0.950**
3 - 5	Gr2.3 (100%) – U (0%)	**0.950**	U (40%) - Gr2.3 (60%)	**0.952**
3 - 6	Gr2.3 (40%) – Pb (60%)	**0.952**	Pb (0%) - Gr2.3 (100%)	**0.950**
4 - 5	Gr1.8 (100%) – U (0%)	**0.950**	U (50%) - Gr1.8 (50%)	**0.952**
4 - 6	Gr1.8 (80%) – Pb (20%)	**0.951**	Pb (0%) - Gr1.8 (100%)	**0.950**
5 - 6	U (50%) – Pb (50%)	**0.959**	Pb (100%) – U (0%)	**0.949**

The uranium-lead couple gives special results, as the difference between direct and reverse sequence is about 0.1, and the maximum value of keff+3σ is 0.959.

5. CALCULATIONS PERFORMED AND RESULTS

Calculation results with two reflecting materials

	Direct sequence		Reverse sequence	
Couple	Optimal Relative Masses [% of mass limit]	k_{eff} +3σ	Optimal Relative Masses [% of mass limit]	k_{eff} +3σ
1 - 2	Be (20%) - D_2O (80%)	**0.952**		**0.951**
1 - 3	Be (40%) - Gr2.3 (60%)	**0.951**		**0.950**
1 - 4	Be (40%) - Gr1.8 (60%)	**0.951**		**0.950**
1 - 5	Be (0%) – U (100%)	**0.949**		**0.949**
1 - 6	Be (50%) – Pb (50%)	**0.951**		**0.949**
2 - 3	D_2O (60%) - Gr2.3 (40%)	**0.952**	Gr2.3 (60%) - D_2O (40%)	**0.951**
2 - 4	D_2O (80%) - Gr1.8 (20%)	**0.952**	Gr1.8 (0%) - D_2O (100%)	**0.951**
2 - 5	D_2O (100%) – U (0%)	**0.951**	U (50%) - D_2O (50%)	**0.953**
2 - 6	D_2O (50%) – Pb (50%)	**0.952**	Pb (0%) - D_2O (100%)	**0.951**
3 - 4	Gr2.3 (50%) - Gr1.8(50%)	**0.952**	Gr1.8 (0%) - Gr2.3 (100%)	**0.950**
3 - 5	Gr2.3 (100%) – U (0%)	**0.950**	U (40%) - Gr2.3 (60%)	**0.952**
3 - 6	Gr2.3 (40%) – Pb (60%)	**0.952**	Pb (0%) - Gr2.3 (100%)	**0.950**
4 - 5	Gr1.8 (100%) – U (0%)	**0.950**	U (50%) - Gr1.8 (50%)	**0.952**
4 - 6	Gr1.8 (80%) – Pb (20%)	**0.951**	Pb (0%) - Gr1.8 (100%)	**0.950**
5 - 6	U (50%) – Pb (50%)	**0.959**	Pb (100%) – U (0%)	**0.949**

All these results can also be compared with the maximum keff+3σ obtained with only one reflector, which is <u>0.951</u>

5. CALCULATIONS PERFORMED AND RESULTS

2 Calculations with 3 to 6 reflecting materials

Considering the keff+3σ obtained with the direct and reverse sequences for each couple of reflectors, the following sequence of reflectors was determined in order to maximize the reactivity:
U-Be-D2O-Gr2.3-Gr1.8-Pb (= A-B-C-D-E-F)

All the possible combinations of 3 to 6 reflectors respecting this sequence were then studied, with the same relative mass for each reflector (33.34 % for 3 reflectors, 25% for 4 reflectors, etc…)

5. CALCULATIONS PERFORMED AND RESULTS

Calculation results with 3 to 6 reflecting materials

Number of reflectors (relative mass for each reflector)							
3 (33.34%)		4 (25%)		5 (20%)		6 (16.67%)	
Seq.	**k_{eff} +3σ**	**Seq.**	**k_{eff} +3σ**	**Seq.**	**k_{eff} +3σ**	**Seq.**	**k_{eff} +3σ**
A-B-C	0.951	A-B-C-D	0.950	A-B-C-D-E	0.952	A-B-C-D-E-F	0.951
A-B-D	0.949	A-B-C-E	0.951	A-B-C-D-F	0.952		
A-B-E	0.950	A-B-C-F	0.954	A-B-C-E-F	0.952		
A-B-F	0.955	A-B-D-E	0.950	A-B-D-E-F	0.953		
A-C-D	0.952	A-B-D-F	0.954	A-C-D-E-F	0.953		
A-C-E	0.953	A-B-E-F	0.953	B-C-D-E-F	0.952		
A-C-F	**0.956**	A-C-D-E	0.952				
A-D-E	0.952	A-C-D-F	0.954				
A-D-F	0.955	A-C-E-F	0.954				
A-E-F	0.955	A-D-E-F	0.954				
B-C-D	0.951	B-C-D-E	0.951				
B-C-E	0.951	B-C-D-F	0.952				
B-C-F	0.951	B-C-E-F	0.951				
B-D-E	0.951	B-D-E-F	0.951				
B-D-F	0.951	C-D-E-F	0.952				
B-E-F	0.950						
C-D-E	0.952						
C-D-F	0.952						
C-E-F	0.951						
D-E-F	0.951						

The maximum value of keff+3σ obtained is 0.956, which is lower than the maximum value of keff+3σ obtained with only two reflectors (0.959).

A = U

B = Be

C = D2O

D = Gr2.3

E = Gr1.8

F = Pb

Calculation results with 3 to 6 reflecting materials

Number of reflectors (relative mass for each reflector)							
3 (33.34%)		4 (25%)		5 (20%)		6 (16.67%)	
Seq.	**k_{eff} +3σ**	**Seq.**	**k_{eff} +3σ**	**Seq.**	**k_{eff} +3σ**	**Seq.**	**k_{eff} +3σ**
A-B-C	0.951	A-B-C-D	0.950	A-B-C-D-E	0.952	A-B-C-D-E-F	0.951
A-B-D	0.949	A-B-C-E	0.951	A-B-C-D-F	0.952		
A-B-E	0.950	A-B-C-F	0.954	A-B-C-E-F	0.952		
A-B-F	0.955	A-B-D-E	0.950	A-B-D-E-F	0.953		
A-C-D	0.952	A-B-D-F	0.954	A-C-D-E-F	0.953		
A-C-E	0.953	A-B-E-F	0.953	B-C-D-E-F	0.952		
A-C-F	**0.956**	A-C-D-E	0.952				
A-D-E	0.952	A-C-D-F	0.954				
A-D-F	0.955	A-C-E-F	0.954				
A-E-F	0.955	A-D-E-F	0.954				
B-C-D	0.951	B-C-D-E	0.951				
B-C-E	0.951	B-C-D-F	0.952				
B-C-F	0.951	B-C-E-F	0.951				
B-D-E	0.951	B-D-E-F	0.951				
B-D-F	0.951	C-D-E-F	0.952				
B-E-F	0.950						
C-D-E	0.952						
C-D-F	0.952						
C-E-F	0.951						
D-E-F	0.951						

The 4 most penalizing configurations, with a keff+3σ of 0.955 or higher, are 3 reflector configurations including uranium (A) and lead (F).

All these results can also be compared with the maximum keff+3σ obtained with only one reflector, which is 0.951

A = U

B = Be

C = D2O

D = Gr2.3

E = Gr1.8

F = Pb

5. CALCULATIONS PERFORMED AND RESULTS

Conclusions reached based on the calculations

- **When the rule of fractions is respected, the calculations performed with 2 reflectors and with 3 to 6 reflectors lead to a maximum keff+3σ of 0.959 (about 0.01 above the max. keff+3σ with a single reflector).**
- **This result is regarded as acceptable, considering the highly penalizing model implemented.**

Additional calculations

- **A determination of the most penalizing proportions of reflectors was carried out using an optimization algorithm. The results confirmed the previous calculations: Maximum value of keff+3σ = 0.961 with 55% Uranium/ 45% Lead**
- **Validation calculations with the TRIPOLI-4.4 code, the reference route of the CRISTAL V1.2 package, were carried out on a few configurations.**

  -> <u>no significant difference in the results between the 2 routes</u>.

6. OPERATIONAL ASPECTS (1/2)

- Compliance with the new rule thus makes it possible to ensure criticality safety with different reflectors in the mass-limited work units of ATALANTE.
- The safety documentation now authorizes the use of the rule of fractions, and allows the handling of larger quantities of reflectors.

Some important points:

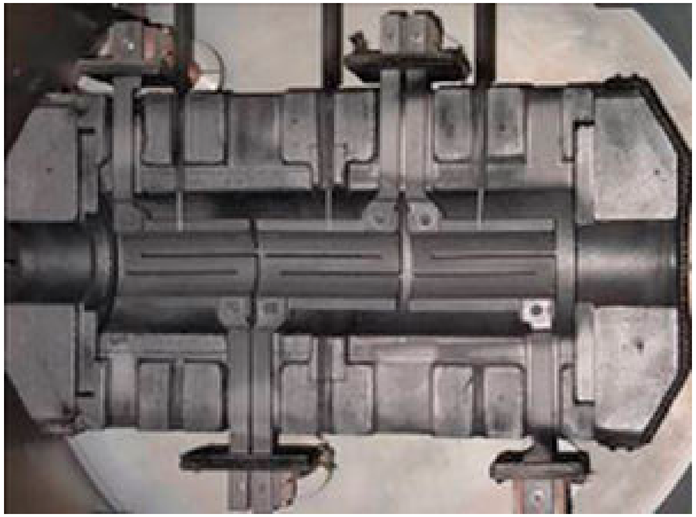
- With or without the rule of fractions, strict accounting of the masses of reflecting materials is necessary
  => requires a particular awareness level from operators,
  => requires specific training about the reflecting materials.

- In all cases, the entry of a new reflector has to be validated by a facility criticality specialist.

6. OPERATIONAL ASPECTS (2/2)

- Some situations have been identified where the accounting of some reflecting material is not necessary, for example if it cannot be located close to the fissile materials.

- The rule of fractions is useful for daily operations with small quantities of reflecting materials.
  But the presence, help and monitoring provided by the facility criticality specialists are always necessary to identify and evaluate specific situations, such as modifications with new apparatus including larger quantities of reflectors.



7. CONCLUSION

The calculations performed lead to a maximum keff+3σ of about 0.01 above the maximum keff+3σ in presence of a single reflector. This result is regarded as acceptable, considering the highly penalizing model implemented.

Some limitations in applicability should be noted:

- **The calculations performed only dealt with cases where the reflectors were all <u>concentric spheres</u>. This is considered a penalizing model compared to the real situations encountered in the facility. *Nevertheless some very specific arrangements could require additional verification.***

- **The calculations were limited to the reflectors widely used in ATALANTE.**

The use of the rule of fractions in ATALANTE can allow the operators to handle larger quantities of some reflecting materials.

THANK YOU FOR YOUR ATTENTION!

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