Replacement of neutron absorbers in the spent fuel pool storage facility of the Tihange 3: An ALARA approach.

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1. Boraflex in storage racks for fuel elements

Boraflex is a neutron absorbing material used in spent fuel storage facilities to ensure control of criticality, and as such to make it possible to store a larger quantity of fuel assemblies per square metre. It is used in the following nuclear plants in Belgium: Doel 1-2 (some racks), Doel 3 (racks made of 50% boron steel, 50% Boraflex), Doel 4 (100% Boraflex), Tihange 1 (stainless steel racks), Tihange 2 (boron steel racks) Tihange 3 (100% Boraflex racks).

The fuel building at Tihange 3 houses three pools for fuel elements (annex 1 fig.1, 2 & 3) : pool D412 containing 1 rack of 3x4 cells (rack T), pool D421 containing 6 racks of 7x6 and 7x7 (racks M, N, P, Q, R and S) and pool D422 containing 12 racks of 6x6, 7x6 and 7x7 (racks A, B, C, D, E, F, G, H, I, J, K and L). A fourth pool D513 is a decontamination pool for inspecting and monitoring fuel assemblies, fitted out and used in this project for HP cleaning of racks, chipping of surrounding plates on four sides, and cutting of plates located in the inter-compartmental spaces.

Boraflex is a supple, composite material (similar to rubber) made by dispersing boron carbide B_4C in a silicone elastomer matrix. Composition by weight (in %): boron (31.5%), carbon (19%), oxygen (22%), hydrogen (3%), and silicon (24.5%). The Boraflex strip is 'sandwiched' between the external wall of the cell and a TIG spot-welded 8 mm stainless steel plate. (annex 1 fig.4) The material is therefore in permanent contact with the water in the pool containing boric acid.

2. Degradation of the BORAFLEX

The irradiated fuel assemblies placed in the racks subject the Boraflex to an intense gamma flux, which causes degradation of the Boraflex arising from the radiolysis reaction, and rupture and rearrangement of the chemical bonds by the gamma rays. These products include: gases (mainly CH_4 and H_2) of soluble silicon (H_2SiO_3), insoluble silicon (in amorphous form) SiO_2, organosilic compounds of (insoluble) boron carbide. It is assumed that the end degradation product of Boraflex is amorphous silicon, which generally occurs in solution in colloidal form (that is to say in grains of less than 1 micron), like activated corrosion products (Co58, Co60, Cr51).

3. Drawbacks of silicon release

The drawbacks of silicon are the following:

- The capacity of silicon to form gels in the presence of other elements (such as Ca, Mg and Al) results in the filters quickly becoming clogged, which reduces their capacity to effectively filter the radioactive corrosion products;
- The higher concentration in colloidal silicon also causes opacity in the spent fuel storage pool, and even in the reactor pool during servicing ;
- The complete removal of the Boraflex leads to an increase in the keff, without boron, of approximately 0.25 (from 0.093 to 1.18), with a 50% reduction in storage capacity. 1000 ppm of boron is enough to re-establish the margin: 0.97 (limit: 0.98);
- In the primary circuit, a higher silicon concentration in the presence of other elements such as Al, Ca or Mg can result in the formation of zeolites (complex molecules of aluminosilicates, calcium and magnesium) that can precipitate on the cladding of the fuel rods and limit heat transfer.

4. Technical solution

Having examined the various alternatives - including replacing the racks with new ones - the decision was taken to remove the Boraflex from the existing racks and reuse them with another neutron absorber, boron steel or Borated Stainless Steel (BSS). Consequently, all four sides of all the cells must be coated with borated steel to a thickness of 2 mm containing 5 mg/cm2 of B10. This modification would make it possible to load fresh fuel with an enrichment of up to 5%.

Either a pair of cutters and a chisel method is used as appropriate cutting system. There are two types of jacket. The outer jackets are easily accessible and can be removed manually. The inner jackets are less accessible, the available space being an intercellular channel of cross section is 220 mm x 43 mm or 220 x 50 mm (annex 1 fig.5) depending on the jackets and of the same length as that of the racks. First the spot welds are cut on the upper and lower sides with a pneumatic chisel and manual chisels. Then two parallel longitudinal cuts are made simultaneously with cutters fixed on a holder. The jacket and the Boraflex are released. This is the longest phase and is carried out semi-automatically and by remote control. Then the plate and the Boraflex are removed from the cellular channel.

5. ALARA plan and the replacement of Boraflex

Throughout the project, the ALARA principle has been applied in developing tools and choosing working methods. Each phase was then re-evaluated in terms of dosimetry cost in order to make improvements that would mean a reduction in the dosimetry of the operation.

<u>Devising methods and tools - some examples:</u>

- The cover of the decontamination unit acts as a screen for the operators nearby by increasing its thickness;
- The jackets are cut using a remote-controlled cutting tool, which means it is not always necessary to have an operator present near to the rack being processed;
- Due to their shape, material and surface condition the equipment and tools can easily be decontaminated;
- BSS is introduced using a table equipped with a crank system allowing the operator to remain at a distance of five metres from the rack being processed;
- Where possible tools are fitted with extensions enabling the operator to keep their distance from the contaminated article being treated;
- Televisual inspection is carried out semi-automatically, reducing the time taken and therefore operator exposure.

<u>Decontamination:</u> a complete decontamination of pool D513 (in which the decontamination unit is located), as well as underwater suction of the horizontal surfaces of pools D421 and D422, was carried out before starting the project. Each of the racks underwent a two-stage decontamination process:

- First, under water US decontamination is carried out prior to removal from the pool; this makes initial decontamination possible without exposing the operators to a level higher than that normally found at pool level;
- The rack is then decontaminated a second time in the decontamination unit using a high pressure jet of water to remove any transferable contamination. The accessible surfaces are decontaminated manually.

The decontamination unit is decontaminated each time a rack is removed. Other small tools such as chisels coming into contact with the rack are sent as necessary to the decontamination room. All objects coming out of the water are subjected to intensive rinsing: racks, lifting equipment, cameras, screws, long tools etc.

<u>Maximising distance between operator and source:</u> For each phase of the process, the distance between operator and source is evaluated. In order to calculate the maximum distances, all possible practical improvements are included in the study.

Screens: The existing elements in the building, notably concrete and the water in the pool, are used as much as possible to screen the sources of radiation. As far as possible, the racks are treated under water or in pool D513, rather than at pool floor level. Due to its shape and location, pool D513 offers additional protection through the thickness of its cover. Metallic structures equipped with lead plates are available should a rack need to be screened in a horizontal position, in the event that there are any hotspots.

Staff training: All employees receive training and carry out practical simulation exercises in small groups, to become acquainted with the procedures, tools, and work processes. Operations that are carried out in positions where the dosage rate is particularly high are simulated in advance during intensive training in small groups. This practical and theoretical training aims to reduce working time and the risk of confusion when carrying out procedures, which could lead to longer periods of exposure to radiation.

Dosimetric estimate and initial hypothesis: The estimated dosimetric cost for all the operations is presented in table form (annex 2), making it easier to pinpoint the operations subject to increased exposure. the values are given in man-millisievert. The initial hypotheses for estimating the dosimetric cost are based on information gained from reracking in China, the United States, France and Spain, along with information provided by Electrabel/Tractebel. Exposure times have been calculated on the basis of detailed schedules of treatment of the racks, as have the human resources required for the procedure (in terms of number and position). The values recorded during the treatment of the first rack S serve as a base projection for the treatment of other racks.

Dosimetric follow-up: Staff are equipped with an official dosimetry film and an electronic dosimeter giving a direct reading of the accumulated dose with an audible alarm in the event of the maximum dose rate or total dose being exceeded. The dosimetric reading is linked to a daily dosimetric monitoring system consisting of a dosimetric monitoring form (filled in by the team coordinator) corresponding to the various stages of the operation. Monitoring means that any discrepancies between the estimated values can be detected quickly and the appropriate measures taken.

Plan for remedial action: In the event of the estimated doses being significantly exceeded, a reevaluation of the risks is carried out on the basis of intervention times, positions and actual dose rates. Rack S, used for labelling tools and procedures, has provided actual values, making it possible to revise the estimate of the dosimetric cost, not so much on hypotheses linked to similar activities carried out on other sites, but on the basis of actual values recorded at Tihange 3.

6. VISIPLAN software

VISIPLAN software, used for this project, is an ALARA planning tool that makes it possible to predict the dose equivalents to which staff in a nuclear environment will be exposed whilst carrying out specified operations.

The initial stage of using VISIPLAN involves creating a geometric model of the materials able to absorb gamma radiation, form secondary radiation, and of radioactive sources.

The second stage involves analysis, following calculations, of the dose rate fields in grids (XY, YZ and ZX). These fields can be visualised by means of isodoses. Several dose rate fields can be obtained by speculating on the activity of the sources.

The third stage involves the detailed planning of tasks. Trajectories are defined as a sequence of tasks to be performed in a fixed geometry based on position, duration and description. A scenario is a collection of trajectories to which one or more operators is assigned. The calculation, of a trajectory and a scenario provides a collective equivalent dose value.

The fourth stage is that of dosimetric monitoring when work is being been carried out on the rack, followed by modification of the model once work is completed.

VISIPLAN is used interactively. Following many simulations, a collective dose of 13 man-mSv pro racks has been estimated.

7. Replacement of Boraflex with BSS

The different activities will be analysed under the ALARA principle (annex 2):

7.1 Identification of the rack by means of an ITV camera: The high-resolution auto focus camera whit a powerful zoom has been mounted on a pole made up of screwable carbon tubes that are of course very lightweight. The direction of the camera is altered by means of a joystick. There is also a printer and a video recorder. Dosimetric cost: 6 man-µSv/h.

7.2 Decontamination via ultrasound: The US cleaning system includes a generator and a transducer or resonator. The generator produces an alternating current of frequencies varying between 20 Hz and 40 Hz. The transducer then changes this current into mechanical vibrations. Two resonators function simultaneously. The water containing contaminated particles is sucked up and then filtered before being piped back into the pool. This operation is controlled visually by the camera. Dosimetric cost: 30 man-µSv/h.

7.3 Suction: Following US decontamination, the compartments are cleaned using the Balduf system, which is equipped with a booster designed to suck up any particles remaining after US decontamination. Dosimetric cost: 48 man-µSv/h.

7.4 Unscrewing: Each rack in the pool is fixed on a frame at the bottom of the pool by eight anchor points each consisting of a screw, grommets and an anchoring pin. First two sets are pulled out so that guiding columns can be introduced, then the remaining six are removed. Dosimetric cost: 20 man-µSv/h(rack S) and 40 man-µSv (rack P).

7.5 Transfer of the rack to the decontamination unit: To raise a rack out of the water in the pool, there are two stages. The first involves moving the rack onto a submerged platform located near to that being removed. The second stage involves pulling out a sling so as to raise the rack out of the water. Once removed from the water, it is then rinsed thoroughly and then let to drain. Next the dose rates in the vicinity of the raised rack are measured, and any hotspots identified. There is an average dose rate for rack S of approximately 300 µSv/h with hotspots reaching 11500 µSv/h, sometimes even 20000 µSv/h, at the bottom of the rack. Rack P approximately 250 µSv/h with hotspots reaching 1200 to 1500 µSv/h, at the bottom of the rack. Dosimetric cost: 303 man-µSv (rack S) and 101 man-µSv (rack P).

7.6 HP decontamination: cover is placed on the decontamination unit, HP decontamination is then carried out to remove transferable contamination and contamination on the cover of the monitoring platform. Internal dose rate after HP decontamination100 to 300 µSv/h. Dosimetric cost: 138 man-µSv (rack S) and 171 man-µSv (rack P).

7.7 Decontamination of external surfaces: this operation is carried out manually with cloths. Exteral dose rate after decontamination: +- 50 µSv/h C Dosimetric cost: 140 man-µSv (rack S) and 112 man-µSv (rack P).

7.8 Removal of surrounding jackets and Boraflex: manual chisels are used to break the solder points and the surfaces are finally cleaned by grinding the residual solder points until they are completely smooth. Dosimetric cost: 699 man-µSv (rack S) and 451 man-µSv (rack P).

7.9 Preparing the rack before cutting:

- The rack is taken and placed on a tipper. The tipper is used for returning racks since access to the inter-compartmental spaces is easier from below. The racks must be returned in order to begin cutting the internal jackets;
- The rack is turned horizontal, the plates and the rack are inspected visually. The spot welds top and bottom are chiselled, and the indentations are increased at the foot of the racks to make room for knives to be inserted into the inter-compartmental space;
- The rack is turned upside down and placed in the decontamination unit;
- Positioning the holder for the cutting tool.

Dosimetric cost (intervention time): 4857 man-µSv/110 h (rack S) and 3393 man-µSv/47 h (rack P).

7.10 Cutting with a holder: With the help of cameras, the cutting head is positioned above an inter-cellular space. As the cut is made, the load is monitored. The holder is removed. The cut plates and the Boraflex are removed. Dosimetric cost/intervention time: 3499 man-µSv/195 h (rack S) and 1916 man-µSv/108 h (rack P).

7.11 Uniform cutting: Dosimetric cost: 652 man-µSv (rack S) and 577 man-µSv (rack P).

7.12 Chemical Cleaning: this stage will become obsolete with the use of non-ferrous chisels. Dosimetric cost: 307 man-µSv (rack S) and 163 man-µSv (rack P).

7.13 HP Cleaning: to remove any remaining traces of Boraflex. Dosimetric cost: 290 man-µSv (rack S) and 94 man-µSv (rack P).

7.14 Visual ITV inspection: this applies to all channels. Dosimetric cost: 356 man-µSv (rack S) and 110 man-µSv (rack P).

7.15 Insertion of the BSS plates: The rack is taken, placed on the tipper and turned horizontal. The BSS plates are introduced two at a time into the inter-cellular channels, forming a sandwich. A horizontal guide at each end, a medium length retractor, and a locking mechanism at the very bottom are soldered onto one of the plates. As well as the two horizontal guides, retractor and locking mechanism, six malleable locks are soldered onto the other plate. Once the sandwich is positioned in the inter-cellular space, a spacing tool is introduced between the two BSS plates and shapes the malleable locks by sticking the BSS plates onto the inner walls of the compartments. The locking mechanism is soldered onto the inner compartment wall. Dosimetric cost:/intervention time: 2510 man-µSv/77 h (rack S) and 1709 man-48 h (rack P)

7.16 Insertion of dummy into cells: the rack is turned upside down, placed in the decontamination unit and a mannequin is passed into each of the cells. Dosimetric cost: 72 man-µSv (rack S) and 79 man-µSv (rack P).

7.17 Screwing the rack to the pool: the rack is taken and placed on the bottom of the pool. Dosimetric cost: 80 man-µSv (rack S) and 21 man-µSv (rack P).

8. Dosimetry

Critical comparison of the key dosimetric phases (> 1000 man-µSv)

Operation		Rack S			Rack P		
		Maximum individual dose (µSv)	Total dose (man-µSv)	Time taken (h)	Maximum individual dose (µSv)	Total dose (man-µSv)	Time taken (h)
9	Preparing the rack	1349	4857	110	940	3393	47
10	Cutting	1247	3499	195	650	1916	108
15	Inserting BSS	479	2510	77	398	1709	48

The doses registered for rack P are lower than those registered for rack S. There are several reasons for this:

- The time taken for the most high-exposure operations is less (due to better knowledge of the operations to be carried out and stricter compliance with instructions), and so in particular is the time taken to prepare the rack, cut and insert the BSS;
- The operators, knowing that the dosage rate was higher for certain operations, subconsciously worked more quickly.

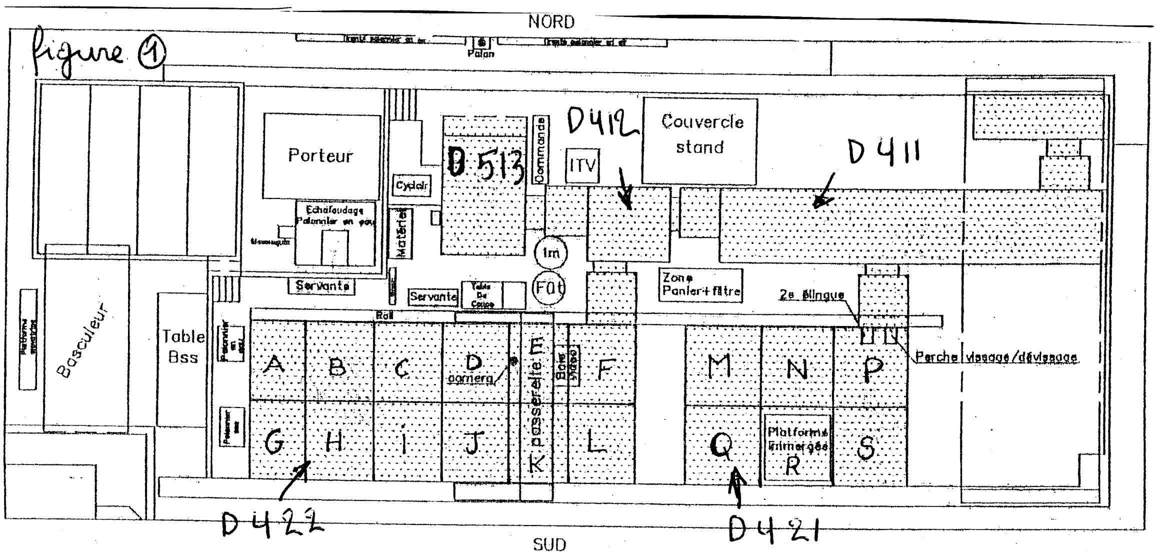
Improvement for the next racks

- When removing the rack out of the water, precise localisation of the hot spots, followed by efficient local decontamination.
- Optimising screens.

References:

- Projet Boraflex Tihange 3: Dossier ALARA. (TECHNUBEL : X. Bairiot)
- VISIPLAN ALARA Planning Tool. (SCK-CEN – Belgium: F. Vermeersch)
- Le remplacement du Boraflex dans les râteliers de stockage de Tihange 3. (GRAMME : F. Migeot)
- Application et évaluation du logiciel VISIPLAN sur le site nucléaire de Tihange lors du chantier Boraflex. (UCL-Louvain – Belgium : N. Druet)

Annexe 1



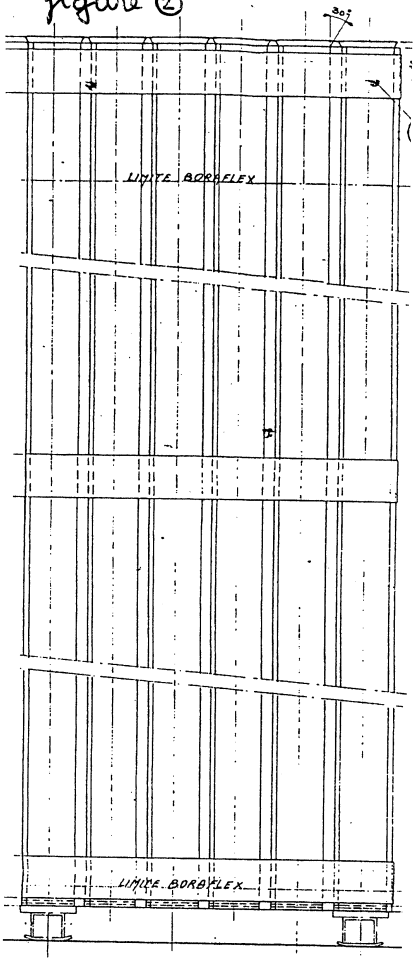


fig 3

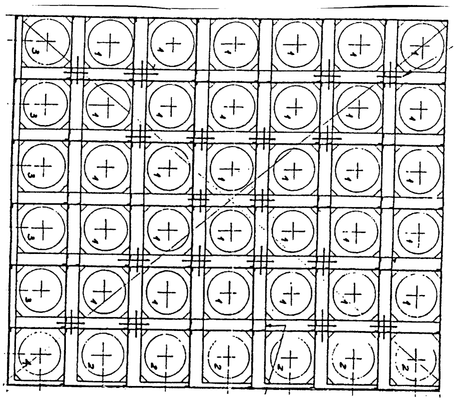


fig 4

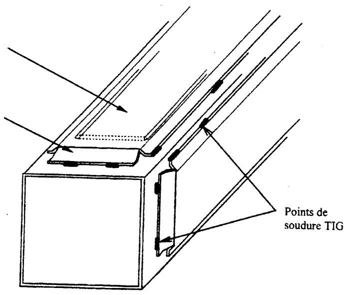
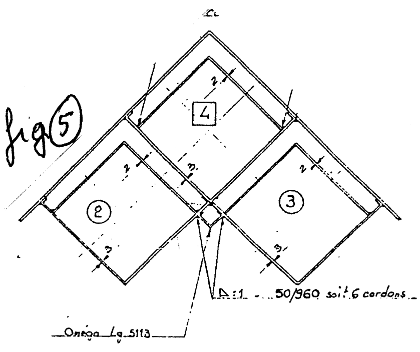


Figure 8 : principe de montage du Boraflex sur une cellule d'un râtelier

fig 5



VISIPLAN: estimation of the doses

N°	Activity	Dose Tot. M.µSv	(Fig.1)
1	US decontamination & preparation	469	469
2	Transfert of the rack to the deconta. unit	934	1403
3	Dimensional contrôle	1718	3121
4	HP decontamination	788	3909
5	Moving the HP cleaning cover	47	3956
6	Putting the rack into the tipper	746	4702
7	Rotation and chipping high and low spot welds	904	5606
8	Putting the rack into the decontamination pool	191	5797
9	Removing the esternal jackets	361	6158
10	Rotation of 90°	53	6211
11	Cutting and removing the internal jackets	1600	7811
12	HP cleaning	412	8223
13	Moving the HP cleaning cover	778	9001
14	Putting the rack into the tipper	246	9247
15	Rotation and insertion of the BSS plates	3179	12426
16	Transfert of the rack to the deconta. unit	198	12624
17	Dimensional contrôle with dummy	424	13048
18	Replacing the rack in the pool	119	13167
19	Screwing the rack to the pool	252	13419
	Total	**13419**	

Dosimetry of the first two racks

Annex 2

N°	Acitivity	Time of activity Houre S	P	P-S	Max. indiv. Dose Man.µSv S	P	P-S	Total dose Man.µSv S (Figure. 4)	P	P-S	Total dose integrated S (Figure. 3)	P
1	ITV	*1*	1	**0**	*3*	3	**0**	*6*	6	**0**	*6*	6
2	US	*5*	5	**0**	*15*	15	**0**	*30*	30	**0**	*36*	36
3	Suction	*8*	7	**-1**	*24*	24	**0**	*48*	48	**0**	*84*	84
4	Unscrewing	*2*	8	**6**	*10*	22	**12**	*20*	40	**20**	*104*	124
5	Transfert of the rack to the deconta. unit	*8*	8	**0**	*61*	43	**-18**	*303*	101	**-202**	*407*	225
6	HP decontamination	*24*	13	**-11**	*64*	88	**24**	*138*	171	**33**	*545*	396
7	Decontamination of external surfaces	*4*	4	**0**	*50*	56	**6**	*140*	112	**-28**	*685*	508
8	Removal of the surrounding jackets	*14*	14	**0**	*204*	132	**-72**	*699*	451	**-248**	*1384*	959
9	Preparing the rack for cutting	*110*	47	**-63**	*1349*	940	**-409**	*4857*	3393	**-1464**	*6241*	4352
10	Cutting with holder	*195*	108	**-87**	*1247*	650	**-597**	*3499*	1916	**-1583**	*9740*	6268
11	Uniform cutting	*33*	17	**-16**	*249*	202	**-47**	*652*	577	**-75**	*10392*	6845
12	Chemical cleaning	*32*	4	**-28**	*111*	65	**-46**	*307*	163	**-144**	*10699*	7008
13	HP cleaning	*26*	7	**-19**	*101*	35	**-66**	*290*	94	**-196**	*10989*	7102
14	Visual ITV inspection	*12*	7	**-5**	*167*	40	**-127**	*356*	110	**-246**	*11345*	7212
15	Insertion of the BSS plates	*77*	48	**-29**	*479*	398	**-81**	*2510*	1709	**-801**	*13855*	8921
16	Insertion of the dummy into the cells	*4*	6	**2**	*22*	31	**9**	*72*	79	**7**	*13927*	9000
17	Screwing the rack to the pool	*4*	5	**1**	*24*	7	**-17**	*80*	21	**-59**	*14007*	9021
	Total	*559*	309	**-250**				*14007*	9021	**-4986**		

Fig.1: Estimation - Visiplan

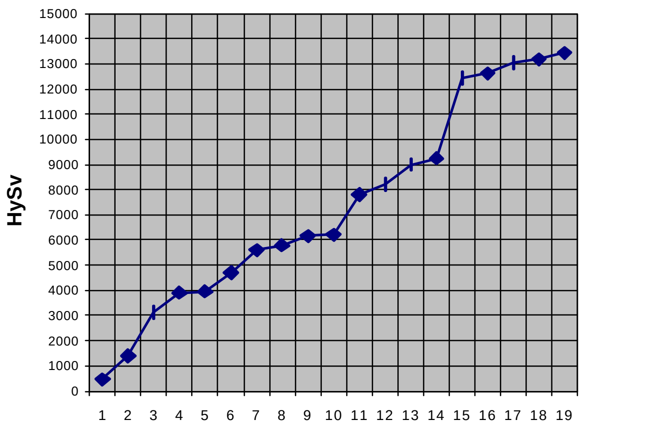


Fig.2: Racks S et P: doses pro acitivity

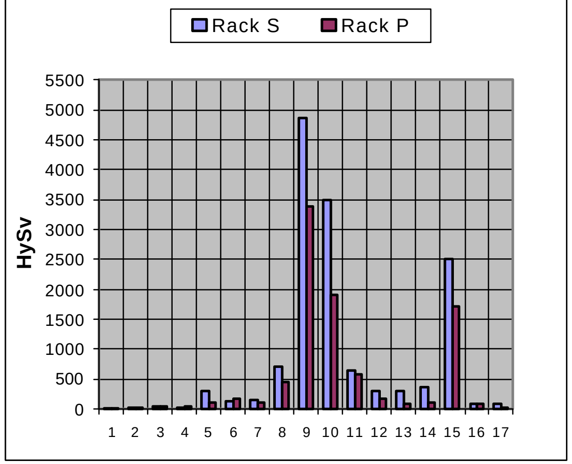


Fig.3: Racks S et P: integrated doses