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Article

Chernobyl – A solution for the clean up of highly contaminated forests and woodlands

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ABSTRACT **This study corresponds to a remediation action of contaminated woodlands and forests due to the fall out of radionuclides after the Chernobyl accident. This remediation action implies both incineration of contaminated wood products and foliage and the transformation of clean wood into paper pulp for the industry. Based on existing industrial products, this remediation action can be justified by the sale of by-products such as electricity and card board which can pay for the necessary industrial investment. The pay back return is estimated to be obtained in about five years.**

RÉSUMÉ **Cette étude se rapporte à une démarche de réhabilitation des forêts contaminées par les retombées dues à l'accident de la centrale nucléaire de Tchernobyl. La démarche de réhabilitation et d'assainissement radiologique préconise et implique à la fois l'incinération des parties de l'arbre contaminé et des branchages, et la transformation en pâte à papier de la partie faiblement contaminée du tronc. En utilisant des moyens industriels existants, l'action de réhabilitation peut se justifier et s'amortir grâce à la vente de sous-produits tels que la production d'électricité et de cartons. Le retour sur investissement des moyens industriels nécessaires à la réhabilitation radiologique est estimé à 5 ans.**

1. Introduction

The purpose of this study is to present an industrial demonstration unit able to process wood contaminated by the fallout of radionuclides, particularly ^{137}Cs (half-life 30 years) from the accident of Chernobyl nuclear power plant Unit 4.

• 50,000 km^2 of contaminated forests have to be cleaned up from cesium, strontium but also hot particles contamination ^{241}Pu and also ^{241}Am, which present a real danger for the environment,

• Contaminated woodland and forests would be cleaned up by cutting up and chipping the contaminated wood or bark, converting it into small-size waste (chips measuring three to five centimeters), and incinerating the conta-

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minated portion to generate steam and electricity in a waste heat recovery boiler associated with a fluidized bed incinerator,

• The sound portions of the wood could be converted into building materials or wood pulp by twins-crew extruders. These extruders are particularly economical in their use or energy and produce little secondary waste.

2. Assumptions taken into account concerning the contamination level in woods and forests

2.1. General

Using the data generated by Russian, Ukrainian and Bielorussian universities, more than 130,000 km^2 were contaminated as a result of the Chernobyl accident (See Tables I and II). Forests occupy about 50,000 km^2 and more than 20 million m^3 of industrial wood could be produced from this area.

In the Belarus forest soil, the condensed form of cesium and ruthenium is mainly present. In the southern part of the Gomel Province and in some regions of the Mogilev Province spots have been discovered where the contamination levels of strontium and plutonium are more than 3 Ci/km^2 and 0.1 Ci/km^2, respectively.

Cesium is found, as a rule, in the absorbed form. Strontium is mainly in the mobile, and soluble forms. Plutonium is found as dispersed particles and has mainly the insoluble form.

In the coniferous forest litter and in the foliage about 84% and 40% of the radioactive cesium are respectively concentrated.

More than 90% of the total activity is contained in a layer of 6 cm depth for ^{137}Cs and ^{134}Cs and 15 cm deep for ^{90}Sr.

TABLE I

Contamination area (1), km^2
Surfaces contaminées en km^2

Region	^{137}Cs Activity level, Ci/km^2				Total contaminated area	% of republic territory
	1-5	5-15	15-40	> 40		
Belarus	29,920	10,170	4,210	2,150	46,450	22.4
Ukraine	34,000	1,940	820	840	37,600	6.2
Russia	39,280	5,450	2,130	310	47,170	1.1 (2)

(1) Data at the end of 1990.
(2) European part.

TABLE II

Main figures showing the extent of contamination in Belarus (1)
Niveaux de contamination en République Biélorusse

Parameter	^{137}Cs Activity level, Ci/km^2				Total	
	1-5	5-15	15-40	≥ 40	Belarus	Ukraine (1)
Population, thousand (1985)	1,956	271	96	9.6	2,332.6	3,050.4
City amount	14	8	5	–	27	42
Village, amount	1,927	942	330	70	3,269	2,750
Arable lands, km^2	5,670	2,880	1,330	220	10,100	14,200
Meadows and pastures, km^2	4,400	1,920	960	140	7,420	3,640
Forests, km^2	{17,000}		1,880	290	19,170	12,500

(1) Data at the end of 1990.

The specific activity of wood with respect to the activity level of soil, the so-called transfer factor (TF), measured in 1991, is given in Table III. The average specific activity of different parts of the tree is shown in Table IV.

For contaminated land of 15 to 50 Ci/km^2 special technologies must be developed for the defoliation, litter layer removal and cutting down the mature trees forest and processing the wood for utilization of the wood by-products.

As seen from Table IV, tree trunks have a specific activity of about 2 to 5 Bq/g, which makes them suitable for wood pulp processing or for the timber industry.

However bark and external layers must be treated by incineration in order to concentrate the residual contamination in the ashes.

2.2. Contamination assumptions taken into account for the study

The purpose of designing a circulating fluidized bed incineratorwhich is able to treat and process contaminated wood and contaminated litter we have made the following umbrella assumptions:

Contamination : ^{137}Cs : 10 Bq/g ; ^{90}Sr: 10 Bq/g ; α : 1 Bq/g.

TABLE III

Average of ^{137}Cs in the 15-40 Ci/km² in (µCi/kg)/(Ci/km²) or in (Bq/kg)/(Bq/m²)
Contamination des arbres en ^{137}Cs
rapportée à la contamination surfacique des terres

Species	Trunk 1987	Trunk 1991	Crown (Twigs, leaves, needles)	Bark
Asp	0.0018	0.0054	0.005	0.0046
Birch	0.0013	0.0035	0.0043	0.0015
Oak	0.0012	0.0022	0.0042	0.0025
Pine	0.0012	0.0025	0.0022	0.0018
Alder	0.0012	0.0027	0.0021	0.0025
Crops	0.15	0.03		
Grass (1)	4.5	0.06		

(1) un-ploughed

For crops and grass, the data comes from R.M. Alexakhin, REACT, October 1991.

The lower table gives one more argument as radionuclide uptake by plants begins to increase in the deeper layers and the amount of ^{137}Cs in the upper part of soil becomes less concentrated.

TABLE IV

Average of specific activity of wood (kBq/kg)
Contamination spécifique des bois en kBq/kg

Activity level, Ci/km²	Tree trunk	Crown and external layers	Bark	Integrated byproduct ash
15-40	1.9	5.9	4.4	355
1-15	0.8	2.2	1.8	148

Figure 1 gives the cesium 137 contamination measurements by the Institut de protection et de sûreté nucléaire (IPSN) on contaminated trees in the Belarus forest.

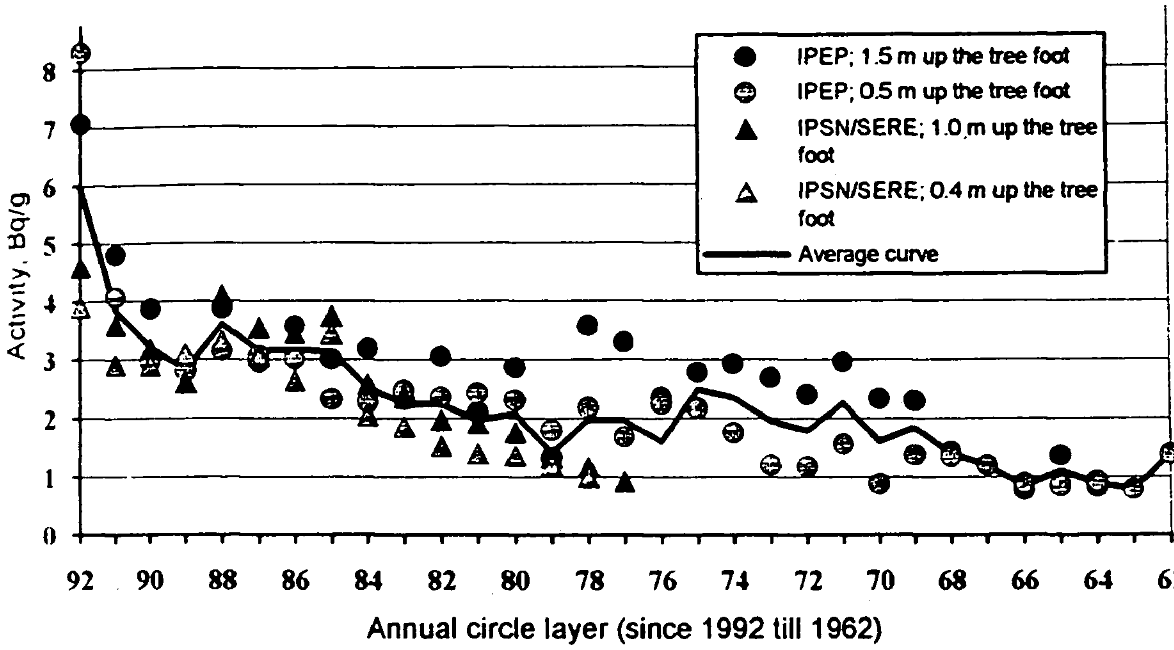

Fig. 1. - Radial distribution of ^{137}Cs radionuclide in the tree trunk.
Distribution radiale de la contamination en ^{137}Cs dans un tronc d'arbre en fonction des années de 1992 à 1962.

It can be seen that the maximum contamination is concentrated in the bark of the trees, and if the bark is removed from the tree and some outer rings, the rest of the tree can be considered as a non contaminated wood.

In the wood pulp industry, it also is possible to decontaminate the wood chips used to produce pulp with the twin screw extruders (bi-vis).

There are several solutions for treating wood chips and removing the residual contamination due to the ^{137}Cs.

3. Principle of wood treatment

The principles chosen for wood treatment will be according to the following main schemes:

A. Segregation of contaminated wood from non contaminated wood,
B. Cutting down contaminated trees
C. Removal of bark from clean wood
D. Incineration of contaminated bark
E. Transformation of clean wood into wood pulp

The contaminated portion of trees, foliage, branches and bark could be processed in a circulating fluidized bed incinerator designed to generate steam in an atmospheric fluidized bed incinerator in order to produce electricity. Secondary organic waste resulting from top soil decontaminating processes such as the RESSAC process developed by the French IPSN could also be collected and incinerated in a fluidized bed incinerator in order to produce steam for electricity generation.

The central portion of trunks which generally present low contamination will be chipped into small pieces in a sawmill and will be used as feed for producing wood pulp for the cardboard industry.

4. Fluidized bed incineration and steam production

The fluidized bed incinerator and the associated steam production unit include the following components (see Fig. 2).

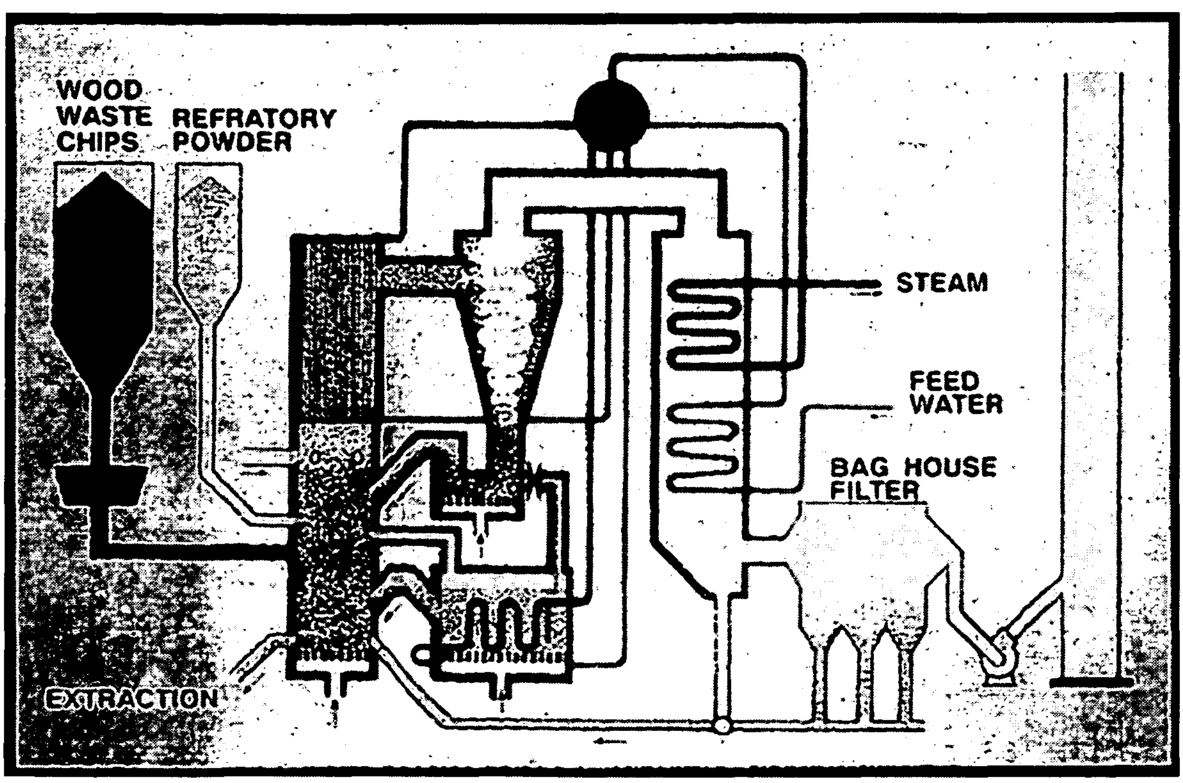

Fig. 2. – Fluidized bed incinerator for contaminated wood.
Schéma d'un incinérateur à lit fluidisé adapté au bois contaminé.

• A fluidized bed incinerator into which are injected the wood waste chips, the bark and the contaminated litter and also some refractory powder for the fluidized bed support.

• A solids separating cyclone, installed at the furnace outlet in the high temperature gas (870 °C) permits reinjecting most of the solid particles leaving the reaction chamber into the system, with only a very small fraction of the ash produced released with the smoke. This limits erosion constraints in the down-steam lines.

• The recovery boiler where the heat of the off gas stream coming from the cyclone is removed.

• An external heat exchanger feed with fluidized solids removed from the bottom of the solids collected from the cyclone and cools it before their reinjection into the furnace. The distribution between hot and cooled recycled solids permits maintaining the desired temperature in the furnace.

The stability of the circulating bed implies maintaining a large quantity of solids recirculating. The quantity recirculated affects the differential pressure between the top and the bottom of the furnace. Controlling this recirculation is obtained either by regulating the rate of removal of the dusty ash or by regulating the wood injection.

For the incineration of contaminated wood and organic wastes, it is assumed that a large scale fluidized bed incinerator (6 tons/hour of contaminated wastes) is necessary.

This incinerator, as defined in figure 2, is coupled to a waste heat recovery boiler for superheated steam production which could be used in a steam turbine for electricity generation.

Protection against the dispersal of radionuclides is provided by a bag house filter located on the off gas stream at the outlet of the waste heat recovery boiler.

The bag house filter is equipped with high retention efficiency bags made of Gore-Tex material having an efficiency of 99.8% for particles of 0.2 to 0.3 μ. The Gore-Tex felt is able to operate at 240 °C and the bags are periodically cleaned by pulsed air.

The incinerator operates a slightly negative pressure which is an additional safety feature. An environmental radiological assessment of the offgas treatment is given in Table V; this table indicates large safety factor regarding to the emission releases.

5. Wood pulp process for clean wood

The twin-extruder contains two intermeshing and corotating screws are identical and consist of a series of modules each module having a conveying section (right-hand thread) and reverse thread (left-hand thread) section retaining the fibrous matter.

TABLE V

Environmental assessment of contaminated wood incineration
Impact sur l'environnement et rejets radiologiques dus à l'incinération en fonction de la contamination massique

Incineration of contaminated wood and bark Level of activity 15 to 50 Ci / km^2
Radiological and environmental impact

Input: Feed: 6 T/h wood waste pine and birch

Contamination of wood waste

- Cesium 137: 10 Bq/g (Maximal value)
- Strontium 90: Bq/g (Maximal value)
- α : 0.5 Bq/g (Maximal value)

Overall in one year

- Contaminated wood processed: 42,000 ton
- Overall β, γ activity: 23 curies or 0.84 TBq
- Overall α activity: 0.56 curie or 20 GBq

Output

Ashes: 2,000 ton/year

Average activity of ashes 400 Bq/g

Flue gas activity at the stack
Volumic flow: 60,000 m^3/h at 150 °C

Radionuclides	Half-life years	Flue Gas* activity Bq/m^3	Allowable limits Bq/m^3	Safety ratio
Cesium: 137	30	2.4	185	77
Strontium: 90	28	2.4	74	30
α	24,000**	0.06	0.37**	6

* Assuming high efficiency filtration with Gore-Tex bags E = 99.7%
** Assuming the source corresponds to Pu 239

Slots and windows are cut into these latter sections. The modules are added, one after the other, on two splined shafts which provide the necessary rigidity.

The thread profile, the right and left hand thread pitches, and the number and which of the reverse thread windows are determined in order to achieve gradual defiberization of the chips and to obtain the required pulp consistency.

The chips fed into the extruder are picked up by the first conveying section of the first module. At the first left-hand thread, a "plug" forms which is forced through the windows. The pressure and induced heating involved in this operation cause the defiberization to begin.

For deciduous and coniferous wood chips there are already two units in operation the most recent started up in February 1992 at the Jacquemin cardboard factory in the Vosges, France. This twin-screw extruder has a capacity of 5 tons/h of wood waste for cardboard pulp as shown on figure 3.

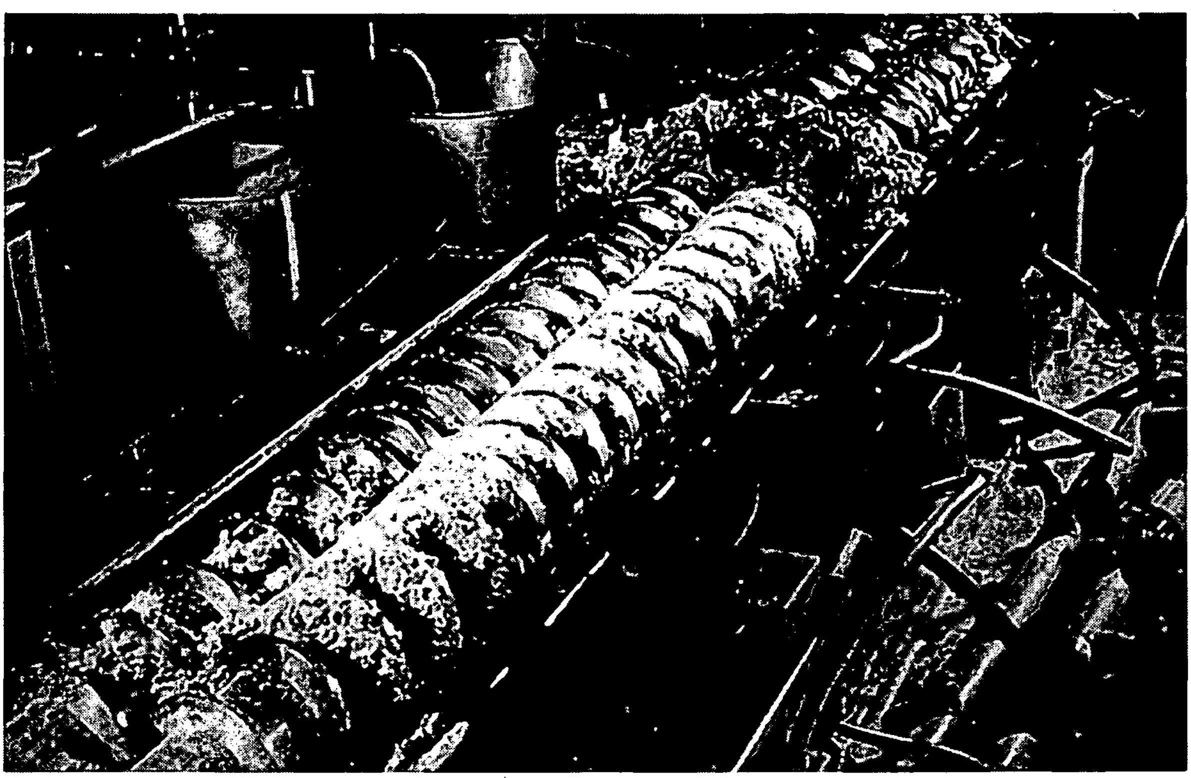

*Fig. 3. – **Extruder for paper pulps production.***
Extrudeur bi-vis pour la production de pâte à papier à partir de copeaux de bois.

This wood pulp obtained from twin screw extruders is then transformed into high quality calibrated cardboard for the wrapping industry by means of standardized equipment used in this industry such as: high speed refiners, steam dryers and rollers.

The significant advantage of using twin-screw extruders for paper pulp processing is less energy consumption: 400 kWh saving per ton of paper pulp and a possible recycling of liquid effluent generated. Various low pollution of bleaching agent can be used such as ozone for obtaining high quality paper pulp.

6. Economical justifications

The aim of this paragraph is to give some preliminary economical justifications for a combined investment of:

- a fluidized bed incinerator having an overall output of 6 to 8 MWe of electricity generation.
- a wood pulp and Cardboard factory built on the same site and close to electricity generating equipment and having an output of 18,500 t/yr of cardboard for the wrapping industry.

The economical justifications will be based on the sale of cardboard produced by the paper pulp factory and the sale of electricity generated by the fluidized bed incinerator coupled with an heat recovery boiler and a steam turbine.

6.1 Main economical assumptions

The main economical assumptions taken into account are the following:

Sale of electricity: 27 c kWh^{-1} or 40 ECU MWh^{-1}

Sale of cardboard: 4,000 FF ton^{-1} or 600 ECU ton^{-1}

(taken into account an exchange rate of 6.7 FF for 1 ECU)

6.2 Operating assumptions

The following operating assumptions for the both industries have been into account based on the existing experience in France.

a) Paper pulp and cardboard industry

It is reasonable to anticipate based on the "Paul Jacquemin" factory that the paper pulp and cardboard industry can operate 5 full days a week at 24 h/day in continuous operation. The remaining two days in the week will be used for performing the light maintenance of the equipment. Consequently the cardboard factory will operate with 3 working shifts during 5 days a week.

The average output of the "Paul Jacquemin factory" is able to produce 3.5 tons of cardboard per hour so if we consider 44 operating weeks in the year, the overall production of cardboard will be:

$$44 \times 120 \text{ h} \times 3.5 = 18{,}400 \text{ ton yr}^{-1}$$

The energy consumption needed to produce this amount of cardboard will be about 5 MWe of electricity and 1.5 MWth of steam which will be provided by the incinerator and the heat recovery system.

b) Incinerator and electricity generation

The incinerator and the electricity generation, which means an heat recovery boiler and a steam turbine generator can operate continuously at nominal output with a load factor of about 75% i.e.: 6,570 hours of annual production.

During the normal operation of the paper pulp and cardboard factory the electrical output will be approximately 2.45 MWe and during the week-end or the shut down periods of the cardboard factory the electrical output would be approximately 6 MWe.

6.3 Overall revenues

The overall revenues computed on an annual basis are based on the sale of electricity to the distribution grid and the sale of cardboard on the market for the packaging and wrapping industries.

Taking into account of both operating assumptions and economical assumptions the following Table VI summarizes the overall revenues computed on an annual basis.

The sale of cardboard represents a fraction of about 90% of the annual revenues, however 2/3 of the electricity generation is self consumed by the paper pulp and cardboard factory. The entire complex will be able to treat annually:

TABLE VI

Overall revenues
Revenus financiers globaux

Sales	Economical index	Output	Annual operating hours	Total production	Annual sales
Electricity	27 c/kWh	2 MWe	5,280 h	20,680 MWe	5.58 MF
Generation	40 ECU/MWh	6 MWe	1,280 h		0.85 M ECU
Paper pulp	4,000 F/ton	3.5 T/h	5,280 h	18,480 ton	73.92 MF
and cardboard	600 ECU/ton				11 M ECU
	Total annual sales in MF			79.50	
	Total annual sales in M ECU			11.85	

• 40,000 tons of contaminated barks, litter or woods
• 20,000 tons of wood chips in the form of paper pulp
and to dispose of about 1,600 tons of contaminated ashes.

6.4 Investment

The total investment for the complex is estimated to be 150 MF respectively 70 MF for the fluidized bed incinerator, 40 MF for the electricity generation (Steam turbine and alternators) and about 40 MF for the cardboard factory.

7. Conclusions

The main conclusions of this study are that solutions for the clean up of contaminated woods and organic wastes exist:

• Incineration of contaminated wood can generate heat recovery and steam production with environmental protection,

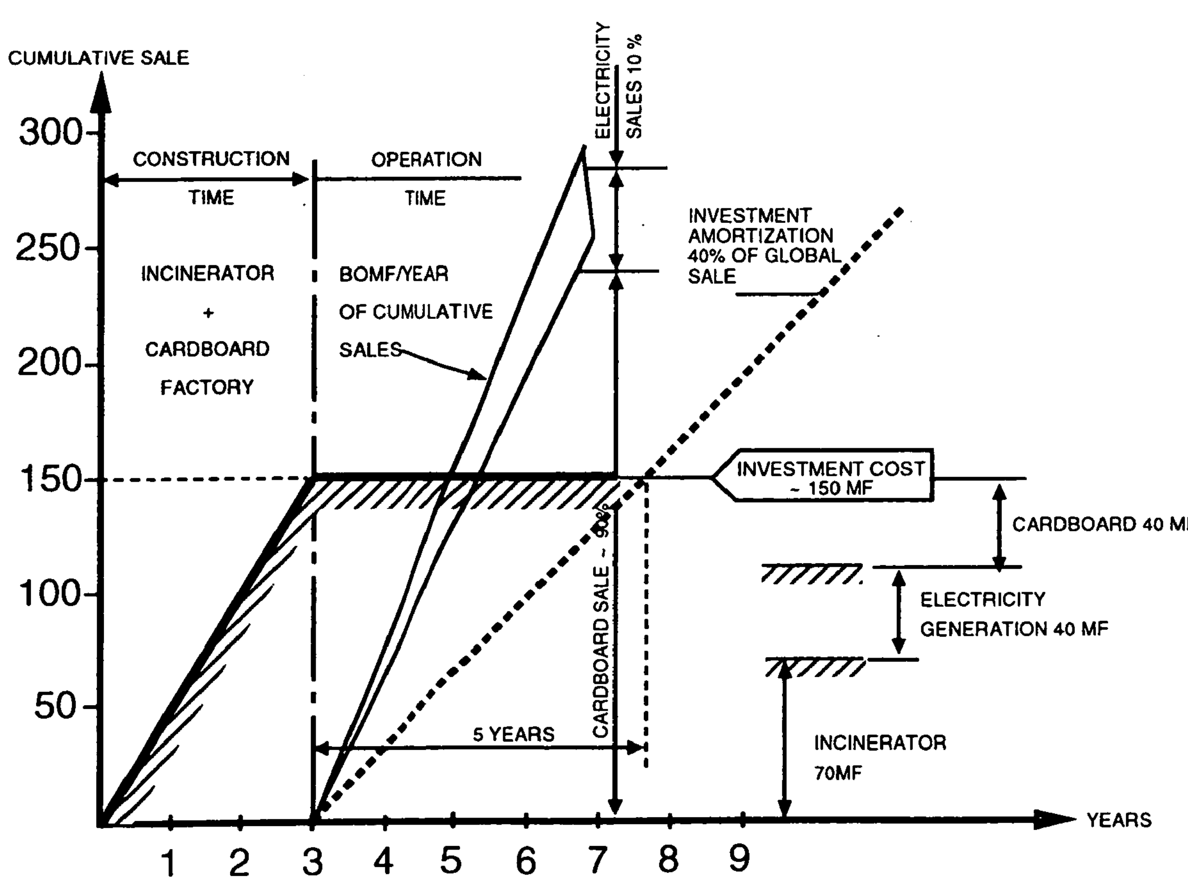

Fig. 4. – Economical justification of the clean up process
Justification économique du procédé d'assainissement pour une unité de traitement de 60 000 tonnes/an de bois contaminé.

• Off gas filtration can be achieved with a high degree of environmental protection. Even with high levels of contamination the emission releases are within the authorized limits.

• Clean wood or low contaminated wood can be processed into wood pulp with appropriate decontamination and effluent treatment.

• Sounds wood can be used also for construction timber.

• Generated energy and wood pulp production can solve economic problems.

• It seems that using fluidized bed incineration the wood pulp and timber industries can provide substantial benefit and revenues allowing the possibility of investing in equipment for the cleanup of Chernobyl contaminated areas (see Fig. 4). ■

Acknowledgements

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