IAEA-TECDOC-1189

Radiation processing of flue gases: Guidelines for feasibility studies

IAEA

December 2000

IAEA-TECDOC-1189

Radiation processing of flue gases: Guidelines for feasibility studies

INTERNATIONAL ATOMIC ENERGY AGENCY IAEA

December 2000

The originating Section of this publication in the IAEA was:

Industrial Applications and Chemistry Section
International Atomic Energy Agency
Wagramer Strasse 5
P.O. Box 100
A-1400 Vienna, Austria

RADIATION PROCESSING OF FLUE GASES: GUIDELINES FOR FEASIBILITY STUDIES
IAEA, VIENNA, 2000
IAEA-TECDOC-1189
ISSN 1011–4289

Printed by the IAEA in Austria
December 2000

FOREWORD

The emission of toxic gases, sulphur dioxide (SO_2) and nitrogen oxide (NO_x) into the atmosphere from coal and oil fired boilers in power plants and industrial installations has long been recognized as the main source of environmental pollution on a large geographical scale. Reactions in the atmosphere result in an "acid rain" effect with devastating consequences to the green covering of the earth. The situation is becoming more serious due to increasing use of low quality, high sulphur content coal for power production.

There are conventional and emerging techniques to remove toxic components from the gas effluents, i.e. chemical and radiation techniques. Among conventional methods, a combined technology of selective catalytic reduction of NO_x by ammonia and neutralization of SO_2 by $Ca(OH)_2$ is most frequently used. The potential of using radiation to initiate the process aimed at the removal of the toxic gases SO_2 and NO_x using accelerated electron beams (EB) was first investigated in 1971 in a joint research of the Japan Atomic Energy Research Institute (JAERI) and Ebara Corporation. The method has subsequently been developed — from laboratory scale to pilot and large demonstration scale — by research, development and implementation projects in Germany, Japan, Poland and the United States of America.

Considering the important role of radiation technology in environmental cleanup — and in response to the increasing interest of Member States of the International Atomic Energy Agency (IAEA) for this technology — the IAEA has organized several scientific activities on the subject:

- A Consultants Meeting on Electron Beam Processing of Combustion Flue Gases, held in Karlsruhe, Germany, 27–29 October 1986 (IAEA-TECDOC-428).
- A Co-ordinated Research Project (CRP) on Radiation Processing of Combustion Flue Gases:
  - Results of the first co-ordination meeting held in Warsaw, Poland, 29–31 March 1991, were published as a special issue of the journal Radiation Physics and Chemistry **40** 4 (1992).
  - Results of the second research co-ordination meeting held in Zakopane, Poland, 24–28 May 1993, were published as a special issue of the journal Radiation Physics and Chemistry **45** 6 (1995).
- An International Symposium on Radiation Technology for Conservation of the Environment, held in Zakopane, Poland, 8–12 September 1997. The proceedings were published as IAEA-TECDOC-1023.

This publication is based on expert contributions by the participants of a consultants meeting held in Vienna from 28–30 October 1997. It is hoped that it will facilitate the implementation of feasibility studies for EB flue gas cleaning projects by providing guidelines and information on the state of the art. The IAEA gratefully acknowledges the work and efforts of all contributors and the preparation of the manuscript by H.R. Paur. The IAEA officer responsible for this publication was O. Güven of the Division of Physical and Chemical Sciences.

EDITORIAL NOTE

CONTENTS

1. INTRODUCTION

The emission of the toxic gases SO_2 and NO_x into the atmosphere from coal and oil fired power plants and industrial installations has long been recognized as the main source of environmental pollution on a large geographical scale. Reactions in the atmosphere result in the "acid rain" effect with devastating consequences to the environment. The situation has become more serious due to a further increase in the use of coal for power production and to increasing use of low quality, high sulphur containing coal.

There are conventional and emerging techniques to remove toxic components from flue gas effluents, i.e. chemical and radiation techniques. Among conventional methods, a combined technology of selective catalytic reduction of NO_x by ammonia, NH_3, and neutralization of SO_2 by lime/limestone is most frequently used. The potential of using radiation to initiate the process aimed at removal of the toxic gases SO_2 and NO_x using accelerated electron beams (EB) was first investigated by Japanese institutes in the 1970s. The method has subsequently been developed, from laboratory scale to pilot and large demonstration scale, by research and development projects in Germany, Japan, Poland and the United States of America.

This flue gas treatment consists of adding small amounts of ammonia and irradiation by EB. Irradiation of the flue gas produces radicals which react with SO_2 and NO_x to form their respective acids. In the presence of ammonia, these acids are converted to ammonium sulphate ($(NH_4)_2SO_4$) and ammonium nitrate (NH_4NO_3). These salts may be collected from the flue gas by conventional collectors like electrostatic precipitators.

The process has numerous advantages over currently used conventional ones:

— it simultaneously removes SO_2 and NO_x at high efficiency levels,

— it is a dry process which is easily controlled and has excellent load-following capability,

— the pollutants are converted into saleable agricultural fertilizers,

— the process has low capital and operating cost requirements.

The aim of this publication is to facilitate the performance of feasibility studies for EB flue gas cleaning projects by providing guidelines to conduct these studies and compiling information on the state of the art.

The process consists of three main steps: (a) flue gas humidification and ammonia addition, (b) EB treatment of the flue gas, and (c) precipitation of the fertilizer product. The history of process development and the main R&D tasks are outlined.

In the generalized study the design of an industrial scale EB process for a 350 MW(e) power plant treating a flue gas flow of 1 500 000 m^3h^{-1} (NTP) is shown. The flow sheet of the process is described in some detail and the required utilities and amounts of by-product are calculated. The layout of such a plant and its space requirements are presented. An estimation of construction and operation costs of the EB process is compared with its nearest competitors such as wet limestone flue gas desulphurization (FGD), Wellmann Lord FGD and wet ammonia FGD. Significant savings in construction and operation are calculated for the EB process. The agricultural use of the fertilizer by-product and the market for nitrogenous fertilizers are discussed.

The contents of a feasibility study for the EB process are summarized comprehensively. The main items to be discussed in plant construction, measurement and control systems, radiation safety and building construction are compiled. The cost analysis lists the required economic data for international funded projects. The main considerations in implementation planning of an EB project are discussed.

The final section outlines the economic and environmental benefits of the EB process according to actual feasibility studies which were conducted previously for specific conditions in Bulgaria and the USA.

2. PROJECT BACKGROUND

Pollutants emitted from industrial activities, such as power plants, production facilities and traffic are transformed by photo-chemical reactions in the atmosphere, yielding oxidized products species, which are gaseous or particulate matter. By irradiation with accelerated electrons high concentrations of hydroxyl radicals (OH) are formed in the emitted gases and atmospheric reactions may be applied already at the source for the removal of the pollutants. In recent years, flue gas cleaning by EB dry scrubbing was investigated by several research groups worldwide [1–3].

This section summarizes the history of process development since 1970. The present state of the art of EB process research and development is described. The process principles are outlined and the experimental and theoretical capabilities are discussed.

Presently, the main areas of research are:

- Improvement of energy efficiency by multiple irradiation
- Computer modelling of gas-phase chemistry and aerosol formation
- Decomposition of organic trace compounds (e.g. VOC, CHCs, PCDD/F).

The main tasks of development are:

- Demonstration of the technology in large scale installations
- Application to high sulphur flue gas
- Development of large accelerators.

EB process removes SO_2 and NO_x simultaneously from flue gas. By irradiation with accelerated electrons, SO_2 and NO_x are oxidized to yield sulphuric acid (H_2SO_4) and nitric acid (HNO_3). These acids are neutralized by ammonia, and a submicron aerosol consisting of ammonium sulphate and nitrate is formed. The product is collected by suitable filters and may be used for the production of agricultural fertilizers.

The EB process consists of three steps:

(1) **Flue gas conditioning**. Humidification and cooling of the flue gas is performed by spraying water into the hot flue gas. Eventually low enthalpy steam can be used additionally to enhance the humidification process and reduce spray cooler size. Ammonia is added to the flue gas in substoichiometric quantities.

(2) **Irradiation by accelerated electrons.** In this step oxidation of NO_x and of SO_2 is performed simultaneously. Aerosol formation occurs instantaneously due to the nucleation of sulphuric acid droplets, which are immediately neutralized by ammonia. In addition, ammonia and SO_2 react rapidly on the freshly formed particle surface (thermal reaction) yielding ammonium sulphate.

(3) **Precipitation of aerosol.** After leaving the reaction vessel the product is collected using electrostatic precipitators, bag filters or gravel bed filters.

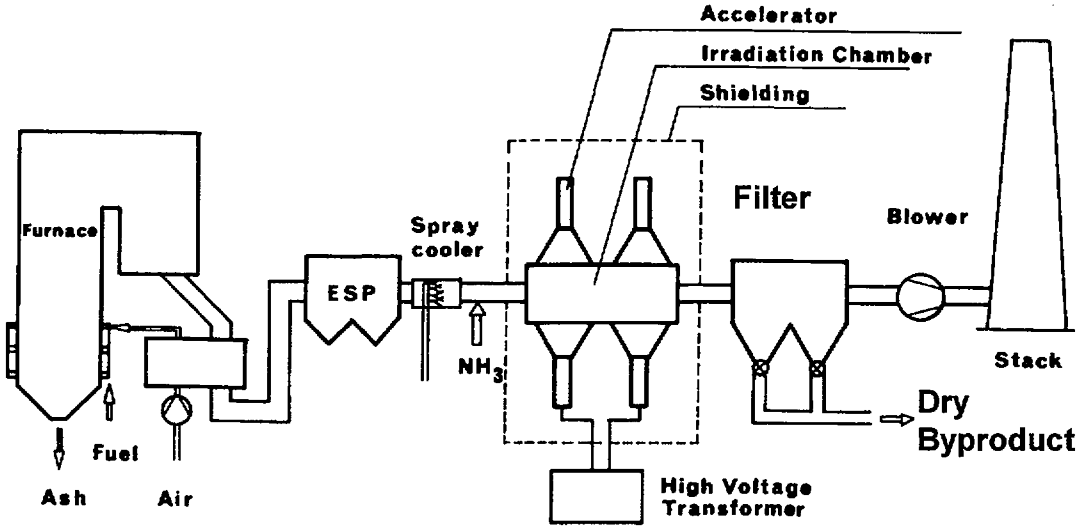


FIG. 1. Simplified flow sheet of the EB process.

The potential advantages of the process have triggered intensive R&D work on the EB process. Table I shows selected development steps of the EB processing of flue gases.

In **Phase 1** exploratory research was performed in Japan during the 1970s. In this phase work was performed by the Ebara Corporation, the Japan Atomic Energy Research Institute (JAERI) and the University of Tokyo. The development was mainly aimed at the purification of flue gas generated from an iron ore sintering plant [4]. Despite promising pilot plant results, further development was halted by the steel crisis in Japan at the end of the 1970s.

In **Phase 2** industrial scale pilot plants were built in the USA [5] and in Germany [7–9]. The goal of these tests was the development of a flue gas cleaning process for coal fired power plants. The main results of these studies showed that the process is viable, safe and provides high removal efficiencies for SO_2 and NO_x. Besides these favourable results, problems occurred regarding the energy consumption of the process and the filtration of the sticky aerosol. Therefore, a second optimization phase was started at the end of the 1980s which concentrated on the improvement of the energy efficiency of the process and the development of suitable aerosol filters [10].

TABLE I. SELECTED DEVELOPMENT STEPS OF THE EB TECHNOLOGY FOR FLUE GAS CLEANING

Organizations	Location/Countries	Max. flow rates [$m^3\ h^{-1}$]	Accelerators [keV kW^{-1}]	Typical applications	SO_2/NO_x [ppmV] others	Years of operation
JAERI	Takasaki, Japan	1	1 500–2 500	laboratory		since 1970
Ebara	Japan	10 000	750/2 × 45	iron ore sintering	200/180	1977–78
FZK	Karlsruhe, Germany	300 1200	300/12; 550/16.5	coal	300/300 3 000/500	1985–1995
ITS	Karlsruhe, Germany	1000	200/100	coal	50/500	1985–1991
FZK	Karlsruhe, Germany	1000	200/150	VOC/incinerator	VOC/dioxins	since 1994
JAERI/NKK	Matsudo, Japan	1000	900/15	waste incinerator	100/100/HCl 1000	1992
Ebara Corp.	Indianapolis, USA	24 000	800/2 × 80	coal	1000/400	1984–1988
Badenwerk	Karlsruhe, Germany	20 000	300/2 × 90	coal	50/500 and 300/500	1985–1989
EPS Kawezyn/INCT	Warsaw, Poland	20 000	700/2 × 50	coal	250/200	since 1990
Ebara Corp./EPA	Tokyo, Japan	50 000	500/2 × 12 5	tunnel offgas	$NO_x = 0–5$	1992
Ebara/JAERI	Chubu, Japan	12 000	800/3 × 36	coal	800–1000/150–300	1992
Ebara Corp.	Nishi-Nagoya, Japan	620 000		heavy oil (2.5% S)		from 1999
Ebara Corp.	Chengdu, China	300 000	800/2 × 300	coal	2000/400	from 1997
IAEA/EPS/INCT	Pomorzany, Poland	290 000	800/4 × 300	coal	450/300	from 2000

A pilot scale test for EB treatment of flue gas (12 000 m^3 h^{-1}) from a coal fired boiler was conducted by JAERI, Chubu Electric Power Company and Ebara Corporation at the site of Shin Nagoya Thermal Power Plant in Nagoya, Japan [11]. During 14 months of operation it was proven that the method is suitable for simultaneous removal of SO_2 and NO_x within a wide concentration range (SO_2: 250–2000 ppm, No_x: 140–240 ppm). At appropriate operation conditions (dose, temperature) the efficiency was higher than that of conventional methods. The pilot plant was operated with good controllability and durability without serious problems. The by-products, ammonium sulphate and ammonium nitrate, proved to be fertilizers of excellent quality.

A large pilot plant was built and has been in operation since 1990 by the Institute of Nuclear Chemistry and Technology (INCT) the Kaweczyn thermal power plant near Warsaw. This plant is equipped with two accelerators and treats a maximum flow of 20 000 m^3 h^{-1}. Two stages longitudinal gas irradiation was applied and different gas humidification methods were investigated (water recirculation, steam injection and high enthalpy water application). The by-products were collected using a bag filter and a wet gravel bed filter. The plant has been in operation since 1991 [12, 13] and has recently been furnished with an electrostatic precipitator (ESP). Several tonnes of by-products obtained were used for agricultural tests and nitrogen, phosphorous, potassium (NPK) fertilizer production. All reports from four independent agricultural research institutes and fertilizer manufacturers were positive. After several optimization steps the plant has reportedly produced satisfactory results and serves as model for the demonstration plant in Pomorzany, Poland.

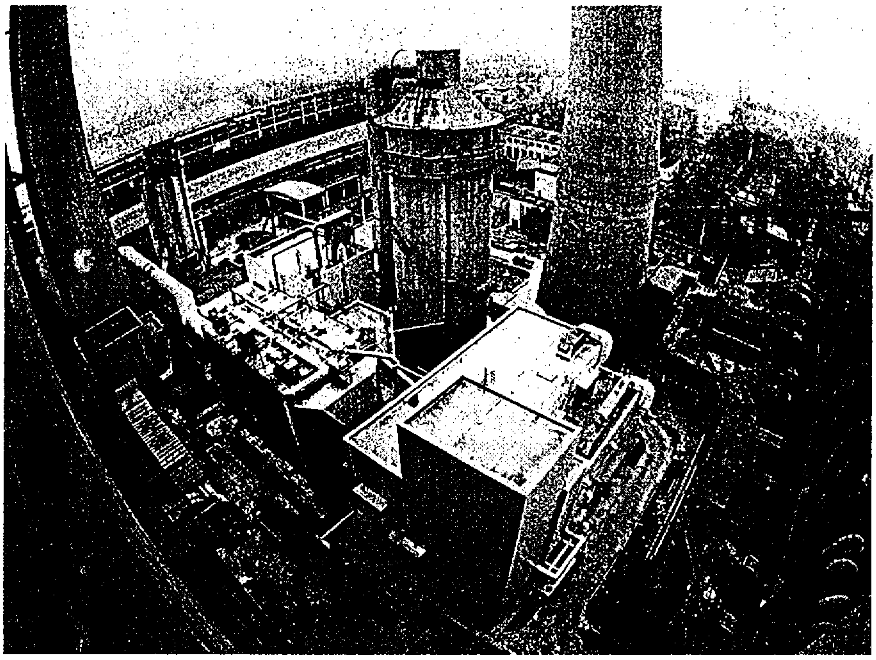


FIG. 2. Industrial scale EB process demonstration plant in Chengdu, China.

In **Phase 3**, large scale demonstration of the process and its industrial use are in progress. The IAEA and its counterparts in Poland have started the construction of a demonstration plant. The Ebara Corporation has recently completed installation of the process at a 100 MW(e)-power plant in China which aims at demonstrating the desulphurization process (see Fig. 2) [14]. A 220 MW(e) power plant in Japan was recently equipped by this EB process. Large scale demonstration projects have been announced in Bulgaria, the Republic of Korea and the USA.

The advantages of the EB process are:

- The process removes SO_2 and NO_x simultaneously in one process step.
- The process yields a usable and valuable product which is suitable for the production of agricultural fertilizer. The deposition of waste materials containing water soluble salts is avoided.
- Economic studies show that the operation and investment costs of the process are very competitive. In addition, the profit from product sale may lower the costs for flue gas cleaning significantly when compared to conventional technology.
- The process has low energy consumption for off gases with high SO_2 concentrations.
- The process operates depending on the required SO_2 removal efficiency in a quite broad temperature range (55–90°C), which is not possible in the case of wet gypsum process. Thus, in certain configurations, the energy consumption for re-heating of the flue gas is avoided or minimized.
- The process may be used not only for small and medium size plants, which supply peak load electricity, but also for large plants.

Besides these advantages several limitations of the process have been addressed previously by research groups worldwide:

- The energy consumption of the process is relatively high, especially for application to flue gases with high NO_x and low SO_2 concentrations. Further reduction of energy consumption by process improvement is required.
- The filtration of the aerosol requires special attention, due to potential clogging of filters and its deposition in the flue gas ducts. This may be overcome by the use of electrostatic precipitators and mechanical scrapers.
- Investment costs of accelerators are rather high. Further reduction of accelerator is required and expected.

To solve these problems pilot plants were built as tools for experimental research; and computer codes were developed to analyse the gas phase chemistry of the process. The discussion of these results is beyond the scope of this publication.

3. GENERALIZED STUDY TO ADOPT THE EB PROCESS

In recent years, the output capacity of thermal power plants has steadily become larger, with 200 to 600 MW capacity now being the norm. This section outlines the application of EBs to the treatment of flue gases in power plants, using as a typical example a 350 MW coal fired thermal power plant outputting 1.5 million cubic meters of exhaust gas an hour (NTP), and examines such aspects as the economy of such an application and the use of the by-product.

3.1. DESIGN BASIS FOR A 350 MW PLANT

3.1.1. Flue gas conditions

Table II shows the flue gas conditions for the 350 MW coal fired thermal power plant used in this plan.

TABLE II. FLUE GAS CONDITIONS (INLET)

Gas flow rate	1 500 000 m^3h^{-1} (NTP) (Wet base)	
Temperature	140 °C	
Pressure	atmospheric	
Components		
N_2	balance	(dry base)
O_2	7.5 vol.%	(dry base)
CO_2	12.0 vol.%	(dry base)
H_2O	22.0 vol.%	(wet base)
So_x	5 500 ppm	(dry base)
NO_x	390 ppm	(dry base)
Fly ash	200 mgm^{-3} (NTP)	(dry base)*

*Less than 50 mg/Nm^3 is normally accepted.

3.1.2. Treated gas conditions

Table III shows SO_x, NO_x and particulate concentrations, and SO_x, NO_x removal efficiencies.

TABLE III. TREATED GAS CONDITIONS

SO_x	825 ppm (dry base) (SO_x removal efficiency 85%)
NO_x	156 ppm (Dry base) (NO_x removal efficiency 60%)
Particulates	50 mg/m^3 (NTP) (dry base)

3.2. FLOW SHEET

This is a dry process (no wastewater treatment required) that simultaneously performs desulphurization and denitration on flue gases and produces nitrogenous fertilizers (ammonium sulphate and ammonium nitrate). Figure 3 shows the simplified process flow.

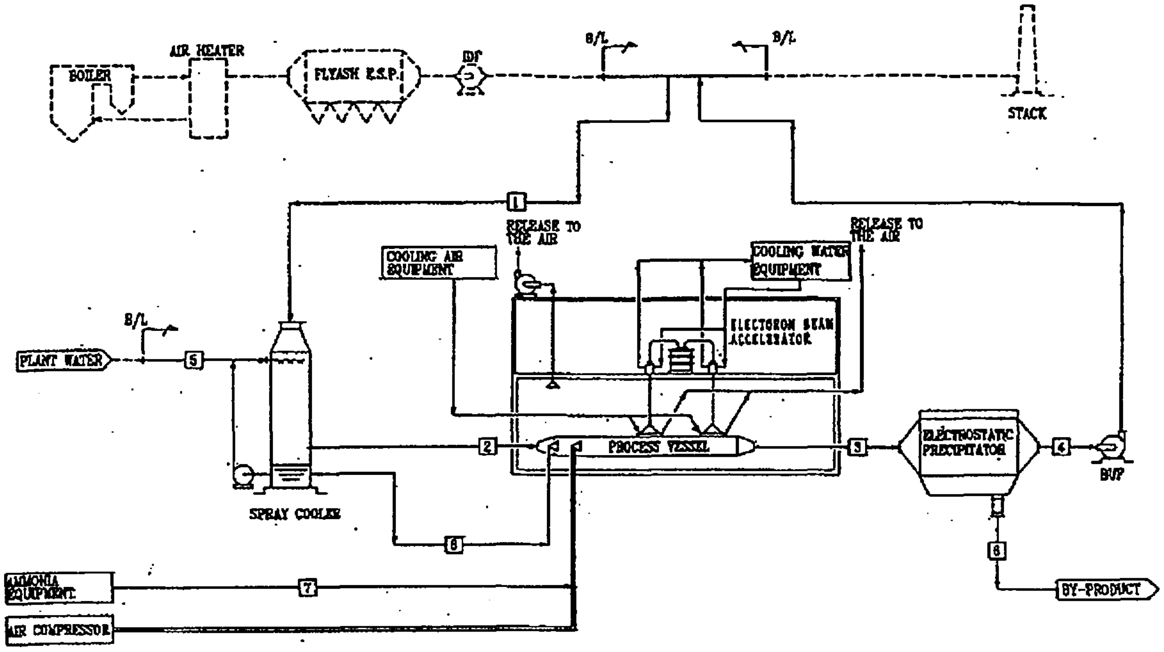


FIG. 3. Process flow diagram.

The principal stages of this process are the cooling of the exhaust gases, addition of ammonia, irradiation of gases by EB, and separation of by-products.

After most of the fly ash is removed using a fly ash dust collector, a spray cooler is used to cool the 140°C flue gases to 5–10 K above the flue gas dewpoint by water cycling method. The extracted water from the spray cooler is atomized at the process vessel inlet and completely evaporated within the flue gases.

Accordingly, waste liquids requiring treatment do not arise. The flue gases, to which a certain amount of ammonia has been added in accordance with the SO_x and NO_x concentrations, are fed into the process vessel and irradiated with an EB. The SO_x and NO_x in the flue gases are very rapidly oxidized by the EB into their respective intermediate products: H_2SO_4 and HNO_3. A neutralizing reaction with the coexistent ammonia then turns these into powder (ammonium sulphate $(NH_4)_2SO_4$ and ammonium nitrate NH_4NO_3 mixed powder). After these powders are separated and collected by a dry type electrostatic precipitator, the cleaned flue gas is dispersed from a stack into the atmosphere using a boost-up fan.

3.3. UTILITIES AND BY-PRODUCTS

Table IV shows the utilities required and quantities used by the process.

TABLE IV. UTILITIES

Utility	Quantity Used
Electric power	10 200 kW
Anhydrous ammonia	8 550 kg/h
Process water	110 t/h
Steam	9 t/h

Table V shows the composition and amounts of the by-products (nitrogenous fertilizers) produced. About 32.9 tonnes of fertilizer containing 21% nitrogen is produced per hour.

TABLE V. BY-PRODUCTS

Composition	Amount
Ammonium sulphate	32 200 kg/h
Ammonium nitrate	450 kg/h
Fly ash	230 kg/h
Total	32 880 kg/h

3.4. PLANT LAYOUT

Figure 4 is a horizontal layout showing the equipment used.

The total space is approximately 110 × 76 meters (87360 m^2) and includes storage facilities for storing seven days' supply of liquid ammonia and seven days' production of by-products.

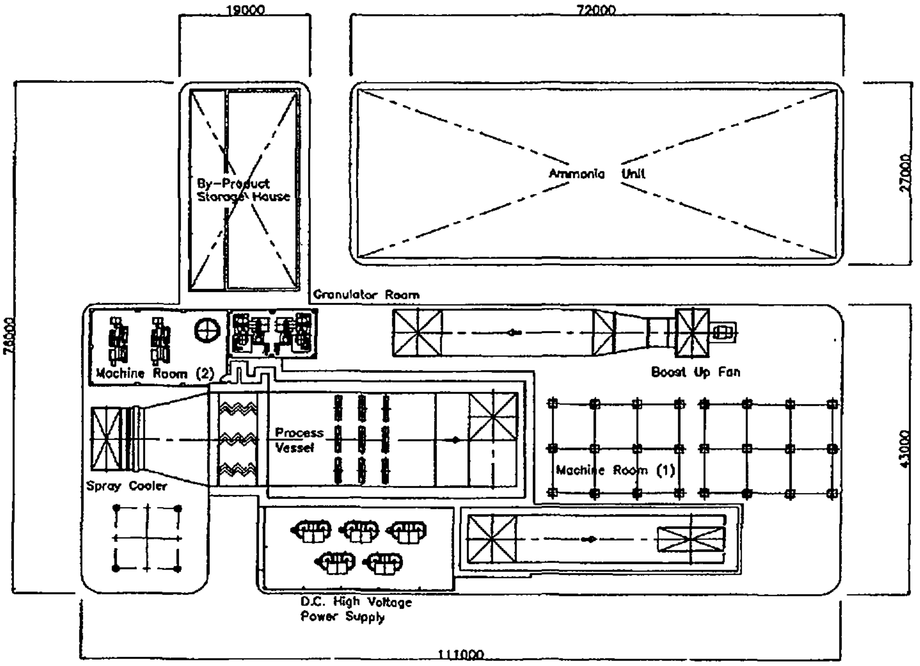


FIG. 4. Layout (by-product collector located above process vessel).

3.5. COST ESTIMATION AND COST COMPARISON WITH CONVENTIONAL FLUE GAS DESULPHURIZATION (FGD)/SELECTIVE CATALYTIC REDUCTION (SCR) TECHNOLOGY

The construction and operating costs of the EB treatment of flue gases were compared with the construction and operating costs of desulphurization and denitration treatment in which the three desulphurization technologies below were combined SCR of NO_x.

(1) Wet limestone FGD

A desulphurization technology using limestone as the desulphurization agent, producing gypsum as a by-product, and requiring wastewater treatment facilities.

(2) Wellman Lord FGD

A desulphurization technology using sodium carbonate as the desulphurization agent, producing SO_2 gas as a by-product, and requiring wastewater treatment facilities.

(3) Wet ammonia FGD

A technology using ammonia as the desulphurization agent, producing ammonium sulphate as a by-product, and not requiring wastewater treatment facilities.

3.5.1. Cost estimation conditions

The cost estimation is based on the following conditions:

(1) Location of plant: USA
(2) Cost/value of utilities, raw materials and by-products

a) Utilities and raw materials

Anhydrous ammonia	\$150/t
Limestone	\$15/t
Electric power	\$0.06/kw·h
Steam	\$6/t
Sodium carbonate	\$80/t
Fresh water	\$0.25/m^3

b) Marketable by-product yields

SO_2 tail gas (Wellman Lord)	\$15/t of contained SO_2
Gypsum	\$2/t
Granulated ammonium sulphate	\$100/t

3.5.2. Construction and operating costs

Table VI compares the capital costs, operating costs, and annual costs.

Table VII shows comparisons for desulphurization only. The operating costs include costs required for utilities, operators, and maintenance as well as the profits from marketing the by-products. Negative operating costs refer to profits from the by-products exceeding plant operation costs. Tables VI and VII demonstrate that EB treatment is the most economic technology.

TABLE VI. ECONOMIC COMPARISON (FOR SIMULTANEOUS REMOVAL OF SO_X AND NO_X)

	Capital cost	Operating cost	Annual cost
Wellman-Lord+SCR	*151 M$	1 372 $/h	34.9 M$
Wet ammonia+SCR	116 M$	– 911 $/h	15.6 M$
Wet limestone+SCR	*98 M$	1 378 $/h	25.4 M$
EB treatment	71 M$	–1 050 $/h	6.8 M$

*Wastewater treatment facilities not included.

TABLE VII. ECONOMIC COMPARISON (SO_X ONLY REMOVED)

	Capital cost	Operating cost	Annual cost
Wellman-Lord	*123 M$	1 109 $/h	28.4 M$
Wet ammonia	88 M$	–1 174 $/h	9.1 M$
Wet limestone	*70 M$	1 115 $/h	18.9 M$
EB treatment	71 M$	–1 050 $/h	6.8 M$

*Wastewater treatment facilities not included.

3.6. USE OF BY-PRODUCT FERTILIZERS (MAINLY AMMONIUM SULPHATE)

3.6.1. Characteristics of ammonium sulphate

Sulphur, which is found in ammonium sulphate, the main component of the EB flue gas treatment by-products, is a major plant growth nutrient along with nitrogen, phosphorous and potassium. The main effects of sulphur on plants are:

(1) Synthesizing the amino acids needed for protein formation

(2) Forming chlorophyll

(3) Creating the essential components of rape seed, mustard seed, and other vegetable oils

(4) Improving the quality of plants

(5) Improving the nutritional value of livestock feeds and feed grains.

The Food and Agriculture Organization of the United Nations (FAO) regards sulphur in ammonium sulphate as the fourth most important plant nutrient. The FAO conducts tests on the effects of sulphur on plants all over the world. Improvement in yields by 8–16% as a result of using ammonium sulphate fertilizer has been reported by FAO.

In addition, ammonium sulphate offers the following advantages, which exceed those of other nitrogenous fertilizers like urea:

(1) Low hygroscopicity, easy to store. As ammonium sulphate, characteristically, has a low hygroscopic molecular structure when mixed with other fertilizers or stored for a long period, it absorbs virtually no moisture.

(2) Quick acting. Ammonium sulphate is 100% water soluble and, when applied as a fertilizer, immediately separates into ammonia and sulphuric acid ions, facilitating absorption by plants.

(3) Long term storage of fertilizers. Ammonia nitrogen (NH_4) is absorbed into the soil particles, does not flow into the ground water, and remains in the soil until absorbed by the plant's roots.

Using only chemical fertilizers causes the soil to harden and acidify. These are attributes not only of ammonium sulphate but of chemical fertilizers in general. To prevent the soil from hardening and acidifying, chemical fertilizers such as ammonium sulphate should normally be used in conjunction with alkalis like lime and organic matter.

3.6.2. Nitrogenous fertilizer market

Table VIII shows the world and regional nitrogen supply and demand balance.

The worldwide consumption of nitrogenous fertilizers was around 79 million tonnes during the 1996–1997 period and has been predicted to increase at an average of 2% a year. The demand and supply balance varies according to region. Regions where consumption substantially exceeds production are East Asia, South Asia, western Europe, and South America and, in these regions, the EB treatment of flue gases is regarded as a more desirable technology.

4. PROJECT ENGINEERING AND DESIGN

This section summarizes the contents of a feasibility study for the EB flue gas cleaning process.

4.1. PLANT CONSTRUCTION

4.1.1. Process technology

- Short technology description, comparison with conventional technologies, process history, process upscaling, feasibility studies for industrial units
- General technological scheme, description of the units operation, dependence of NO_x, SO_2 removal efficiency on dose, humidity, temperature and ammonia stoichiometry
- Mass and heat balances, energy consumption, raw materials consumption, by-product production, by-product physico-chemical parameters
- Analyses of components location (new or retrofit installation)
- Design offices selection.

TABLE VIII. WORLD AND REGIONAL NITROGEN SUPPLY AND DEMAND BALANCE (10^3 T)

	1996/1997			1997/1998			1998/1999			1999/2000			2000/2001		
	Supply	Consumption	Surplus (Deficit)	Supply	Consumption	Surplus (Deficit)	Supply	Consumption	Surplus (Deficit)	Supply	Consumption	Surplus (Deficit)	Supply	Consumption	Surplus (Deficit)
World	80 631	78 910	1 721	83 526	80 759	2 767	85 624	82 437	3 187	87 985	83 868	4 117	90 709	85 746	4 963
Africa	2 324	2 416	(92)	2 346	2 610	(264)	2 346	2 722	(376)	2 545	2 827	(282)	2 768	2 920	(152)
North America	12 458	12 944	(486)	13 037	13 250	(213)	13 474	13 500	(26)	13 633	13 502	131	13 672	13 785	(113)
Central America	3 241	1 589	1 652	3 440	1 825	1 615	3 720	1 960	1 760	3 954	2 047	1 907	4 011	2 133	1 878
South America	1 298	2 320	(1 022)	1314	2 440	(1 126)	1 345	2 570	(1 225)	1 607	2 700	(1 093)	2 168	2 980	(612)
West Asia	4 247	2 835	1412	4 766	2 930	1 836	4 982	3 040	1 942	5 209	3 150	2 059	5 449	3 150	2 299
South Asia	10 095	13 145	(3 050)	10 794	13 517	(2 723)	11 513	13 974	(2 461)	11 804	14 421	(2 537)	12 787	15 124	(2 317)
East Asia	23 560	17 847	(4 287)	24 466	28 179	(3 713)	24 899	28 520	(3 621)	25 555	28 866	(3 311)	26 080	29 310	(3 230)
East Europe	2 997	2 380	1 617	4 175	2 510	1 665	4 247	2 650	1 597	4 258	2 800	1 458	4 304	2 950	1 354
West Europe	7 515	9 820	(2 305)	7 551	9 700	(2 149)	7 551	9 580	(2 029)	7 551	9 460	(1 909)	7 551	9 340	(1 789)
FSU	11 615	2 750	8 865	11 340	2 930	8 410	11 232	3 050	8 182	11 460	3 200	8 260	11 588	3350	8 238
Oceania	282	864	(582)	296	868	(572)	313	871	(558)	330	895	(565)	330	924	(594)

Source: Current World Fertilizer Situation and Outline, 1994/1945 ~ 2000/2001

4.1.2. Flue gas cooling humidification system

- Process requirements concerning gas parameters (inlet and outlet temperatures, humidity, water or steam demand)
- Flue gas composition and flow depending on boiler load
- Influence of solid particulate on humidification process (dust removal in ESP, multicyclone or Venturi scrubbers)
- Humidification and cooling system selection, water, water/air spray
- Hot water, steam
- Dry bottom or water recirculation
- Co-current or counter current phases flow
- Enthalpy graphs
- Balances
- Technical solutions, scheme with balances, drawings
- Humidification-cooling tower: diameter, height, materials, anticorrosion protection
- Nozzles: type (water or water/air), construction and manufacturer
- Gas outlet system: solid separation, water droplets separators (demisters)
- Data for detailed engineering
- Data for building construction
- Data for electrical system design
- Data for control and monitoring systems
- Control parameters (inlet and outlet gas temperature, gas humidity, water and/or steam, and air flows)
- Feedbacks with other system components
- Cost calculations.

4.1.3. Ammonia storage and dosage system

- Physico-chemical parameters of ammonia
- Conditions for supply, handling and storage according to the country regulations
- Reagent daily demand and size, and number of storage tanks
- Ammonia delivery to the installation, pressure reductions, pipes and valves
- Ammonia injection, gas distribution system
- Ammonia mass dosage control
- Analyses concerning possible ammonia water application
- Scheme of ammonia installation, mass and heat balances
- Blue prints of components of ammonia installation, dimensions of equipment, tanks, pipes, etc.

- Specification of special and commercial equipment, construction materials, anticorrosion protection
- Drawings of special equipment
- Data for building construction, electrical and safety system designs
- Cost calculation.

4.1.4. Process vessel

- Process kinetics, dose requirements (pollutants reduction, gas flow and density)
- Electrons penetration
- Irradiation mode (single or multiple gas irradiation one, both sides irradiation)
- Accelerators, power and energy requirements, dimensions, weights, cooling mode
- Type, high voltage supply accelerating section connections, windows, control, maintenance, installation
- Irradiation vessel: configuration and dimensions, materials and anticorrosion protection, window construction and its protection, deposits removal, additional water sprays,thermal compensators, blue prints
- Ozone exhaust system: ventilation, SF_6 storage and refilling system, cooling system, radiation protection
- Special and commercial equipment: data for building construction, electrical systems, supply systems, control systems, monitoring systems
- Cost calculation.

4.1.5. Aerosol filtration

- Physico-chemical characteristics of by-product aerosol
- Filter selection (e.g. ESP)
- ESP selection, ESP data
- Scheme of the unit
- Anticorrosion protection
- Measures against clogging and deposits (e.g. scrappers)
- Special equipment (e.g. conveyors)
- Data for building construction, electrical and control systems
- Cost calculation.

4.1.6. By-product handling system

- Physico-chemical characteristics of by-product
- Agricultural by-product applications, local and export
- By-product granulation and packing
- Storage scheme, special and commercial equipment

- Materials and anticorrosion protection
- Data for building construction, electrical and control systems
- Cost calculation.

4.1.7. Ducts and flue/clean gas discharge

- Dimension of ducts, thermal compensators, deposits removal systems
- I.D. fans
- Stack analysis
- Special and commercial equipment
- Materials and anticorrosion protection
- Building construction and electrical systems basic data
- Emission data stack
- Cost calculation.

4.1.8. Control and monitoring systems

- Systems selection, data acquisition, measurement points localization, requirements for technological units
- Functions and assumptions
- System of calibration
- Cost calculation.

4.1.9. Electricity supply system

- System description, power requirements, scheme possibility of EPS technological (6 kV) net usage
- Equipment specification
- Data for building-construction, interfacing with technological units and monitoring-control systems
- Cost calculation.

4.1.10. Complex documentation

- External installations for supply of technological and energetic media
- Land management plan
- Connections between technological units, operation parameters (media, pressure, temperature etc.)
- Pipe dimensions
- Drawings of overall plant
- Materials for piping

- Work co-ordination
- Technical acceptance conditions.

4.1.11. Balances

- Basic data (from unit description), total costs. Balances for unsteady-state conditions
- Electrical power demand (total)
- Heat (steam, hot water) demand (total)
- Annual data
- Costs: plant realization, O and M costs, income from by-product sale, tax reduction due to emission reduction
- Technical-economic plant parameters: media, parameters, data for environment protection, costs, manpower, by-product and wastes.

4.2. MONITORING AND CONTROL SYSTEMS

4.2.1. Process monitoring system

The main process monitoring system consists of the following measurement points:

INLET GASES
- flow rate
- temperature
- pressure
- fly ash concentration
- SO_2 concentration
- NO_x concentration
- O_2 concentration

OUTLET GASES
- temperature
- SO_2 concentration
- NO_x concentration
- particulate concentration
- ammonia concentration (slip)

Installation components such as the humidification tower, ammonia storage and dosage system, process vessel with accelerators, electrostatic precipitators, by-product handling system are equipped with adequate measurement control systems.

4.2.2. Process control system

The structure of the process control system is based on algorithms describing functional parameters dependence.

SO_2, NO_x removal efficiencies and ammonia slip are the main parameters. Water/steam, ammonia and power consumed by accelerators are the consumables to be optimized.

Adequate forward and feedbacks have to be arranged in the system.

4.3. RADIATION PROTECTION

The radiation protection measures depend partly on local condition and specific country regulations.

Requirements concerning this issue consist of the following items:

- radiation shielding
- ventilation systems
- electric supply systems
- signals and safety locks
- alarms.

Each country has specific regulations and laws which, in many cases, are based on IAEA guidelines.

The methodology and procedures concerning shielding calculation are published, e.g.

- DIN Standard 6847, Part 2, 1990
- NCPR Report No. 51 — Radiation Protection Design
- Accelerator manufacturer information regarding requirements on radiation protection connected with specific machine construction.

4.3.1. Assumption for shielding calculation

(a) accelerator parameters and time of operation
    - accelerator power and beam energy
    - scan dimensions number of accelerators and their localization
    - operational time.

(b) accelerator maintenance
    - operators of EB flue gas treatment plant have only access to accelerator rooms (when shut down)
    - employees of other departments of the power station can do maintenance works outside the accelerator rooms at any time.

4.3.2. Calculation of shielding walls thickness

In the feasibility study, calculations only for direct radiation (no scattering) should be performed. The exact calculations should be performed in the final phase.

4.3.3. Types of materials used for shielding protection against ionizing radiation

Depending on the kind of shielding used and the specifics of surface area and cubature requirements the following materials can be used:

- solid brick with density ? = 1.8 g/cm^3
- concrete brick with density ? = 2.3 g/cm^3
- monolithic concrete walls with density ? = 2.35 g/cm^3
- monolithic dense concrete walls with density ? = 3.2 g/cm^3 (admitting barite, hematite, magnetite)
- walls made of lead bricks

- local shielding made of lead sheet
- local shielding made of steel sheet.

4.3.4. Facilities to be supplied to ensure radiological safety

To ensure radiological safety, the following installations will be provided:

- mechanical supply
- exhaust ventilation
- mechanical ventilation to remove ozone
- accelerator aerial window cooling system
- reaction chamber window cooling water system
- sound signalling system
- visual signalling system
- mechanical blocking system
- electrical blocking system
- access control system.

(a) Ventilation of high voltage generators rooms. In a high voltage generators room, mechanical intake-exhaust ventilation providing six exchanges per hour should be applied.

(b) Ventilation of accelerators rooms. Accelerators room must be equipped with mechanical intake-exhaust ventilation providing six exchanges per hour.

(c) Shielded doors. Both accelerators and process vessel rooms should be equipped in shielded doors system.

(d) Safety control system. Safety locks and signals have to fulfill country regulations. The system consists of:
    - automatics of opening and closing shielded doors
    - automatics to turn on and off ventilation systems
    - signal devices for accelerators (to turn on and off)
    - signal devices for interlocks.

4.3.5. Building construction

Three components of installation should be located in the building, i.e. reaction vessel with accelerators and power supplies, control room for accelerators, and monitoring and control system. These units may be located in integrated or separate facilities, e.g. control room for monitoring and control system can be integrated with the main control system of a power plant.

Building for reaction vessel and accelerators:

(a) The main requirements concerning the facility construction due to radiological protection are given in Section 4.3.

(b) The additional ozone exhaust system should be applied. Local exhaust fans and ventilators for removal of ozone from the zone between the accelerator (primary) and process vessel (secondary) windows should be provided. Depending on the conditions, ozone will be discharged to the atmosphere (active coal reactor and stack) or directed to the flue gas duct.

(c) Ventilation systems have to be provided for:
- accelerator chamber
- reaction vessel room
- high voltage generator rooms.

(d) The intake-exhaust ventilation systems have to be applied. For reaction vessel rooms 10–20 and for others mentioned, six air exchanges per hour have to be secured.

(e) The control rooms have to be equipped with air conditioning with air dust purification system.

Commercially available accelerators consist of:

- power supply
- transformer
- accelerating section
- tube with the window
- control panel
- vacuum unit
- vacuum pump
- ozone removal unit.

The auxiliary equipment consists of:

- window cooling fans (or/and water cooling system)
- water pumps for the primary and secondary circulation loops
- heat exchangers.

The accelerator cooling system consists of tanks for demineralized water, piping, heat exchanger and pumps.

The heat exchangers can be located outside the building.

5. COST ANALYSIS

5.1. GENERAL

Cost analysis in this section of a feasibility study is expected to answer the question whether the investment project, with all the necessary investment and operational expenditures and with the proper way of financing, will generate enough net profit that, expressed in financial terms, would justify its realization. Production investment projects are characterized by the fact that net profits obtained are mainly of material character and thus easily expressed in financial categories and cause no trouble to prepare a reliable financial analysis.

When it comes to pro-ecological investment projects, however, such as flue gas treatment installation for removal of sulphur dioxide and nitrogen oxides with an EB, the matter is not as simple as that, especially if they are considered separately. The net profit generated in pro-ecological investment projects are non-material in character. If it is expressed in financial terms, it seems difficult to obtain any reliable results indicating profitability of such a project, even if this matter is of major importance to a project financial manager.

Thus, the implementation of a pro-ecological investment project would be decided upon taking into consideration the public interest represented by public institutions, and not only the net profit. State and municipal authorities, frequently inspired by international institutions, establish limits for pollutants discharged to the natural environment by various economic units, in the form of regulations in force. Such limits are often a condition of existence (to be or not to be) for a production investment project.

If there arises a necessity to build a pro-ecological installation, the related financial analysis has to be performed for the entire facility to be provided with such an installation. This is valid for both existing facilities and new projects. In practice, during preparation of such analyses, there are discounting methods that can be used which are promoted by the United Nations Industrial Development Organization (UNIDO) and recommended by the World Bank and the International Monetary Fund [15]. These methods are accepted also by the national banks granting investment credits. The Computer Model for Feasibility Analysis and Reporting (COMFAR) prepared by UNIDO [16] is a great help in producing cost analysis.

Calculations require a precise determination of components counted into revenues and expenses, followed by a forecast of their expected level over the subsequent years in the time span under consideration (calculation period). The basic condition for obtaining reliable results of such an economic calculation is to what extent such a forecast is reasonable.

5.2. CALCULATED RATIOS OF ECONOMIC PROFITABILITY

Economic calculations enable computation of economic profitability ratios as:

- Net present value (NPV)
- NPV for total investment expenditures
- NPV of a net value (equity + accumulated profits) related to the net cash flow
- NPV of equity in relation to the net profit
- Internal rate of return (IRR)
- IRR for total investment expenditures
- IRR of a net value (equity + accumulated profits) related to the net cash flow
- IRR of equity in relation to the net profit.

and preparation of financial statements as:

- Total initial investment expenditures
- Total investment expenditures during the production period

- Total production costs
- Net working capital
- Cash flow
- Balance sheet forecast
- Net income statement (profit and loss account)
- Sources of financing.

5.3. COMPONENTS THAT HAVE TO BE DETERMINED IN ORDER TO PREPARE AN ECONOMIC CALCULATION

5.3.1. Total investment expenditures

5.3.1.1. Fixed investment costs

- ***Total initial investment***
- Land, site preparation
- Buildings, structures and civil works
- Machinery and production facilities
- Other incorporated fixed assets, such as acquired property rights (licenses, patents, trademarks, etc.).

- ***Expenditures for reconstruction***

5.3.1.2. Pre-production capital expenditures

- Cost of establishing share capital, registration fees, advertisements
- Pre-investment studies
- Pre-production service fees
- Accompanying investment projects
- Interests on credit during the construction period
- Trial run, start-up
- Travel costs.

5.3.1.3. Expenditures for creation of a necessary working capital.

5.3.2. Investment realization schedule

See Section 6.

5.3.3. Sources of financing for the project

- Equity
- Bank credits
- Suppliers' credits.

5.3.4. Conditions of servicing the foreign financing sources

- Credit interest rate
- Credit payment period
- Method of credit payment.

5.3.5. Total O&M costs

5.3.5.1. Operating costs

- ***Factory costs***
  - Basic raw materials
  - Auxiliary raw materials
  - Environment protection costs (environmental protection costs)
  - Energy consumption
  - Direct labour
  - Repairs
  - Maintenance and spare parts
  - Factory overheads.

- ***Administration costs (salaries, office material, communication, rent).***

- ***Sales costs (advertisements, travels).***

- ***Distribution costs (packing, commissions).***

5.3.5.2. Financial costs (interests)

5.3.5.3. Depreciation

5.3.6. Working capital — Demand (minimum days of coverage)

5.3.6.1. Current assets

- ***Accounts receivable***
- ***Inventories***
  - Raw materials
  - Spare parts
  - Work in progress
  - Finished products
  - Cash in hand.

- ***Current liabilities***
  - Current accounts payable.

5.3.7. Revenues from sale of goods

- Product sales amount
- Product price per unit.

5.3.8. Other expenses

- Income tax
- Income tax for the budget, calculated from the net profit in the case of a State enterprise or dividend in the case of a private enterprise.

5.3.9. Other components

- Discount rate
- Depreciation rate
- Depreciation period
- Scrap value of the initial investment.

5.3.10. Value of the existing fixed assets

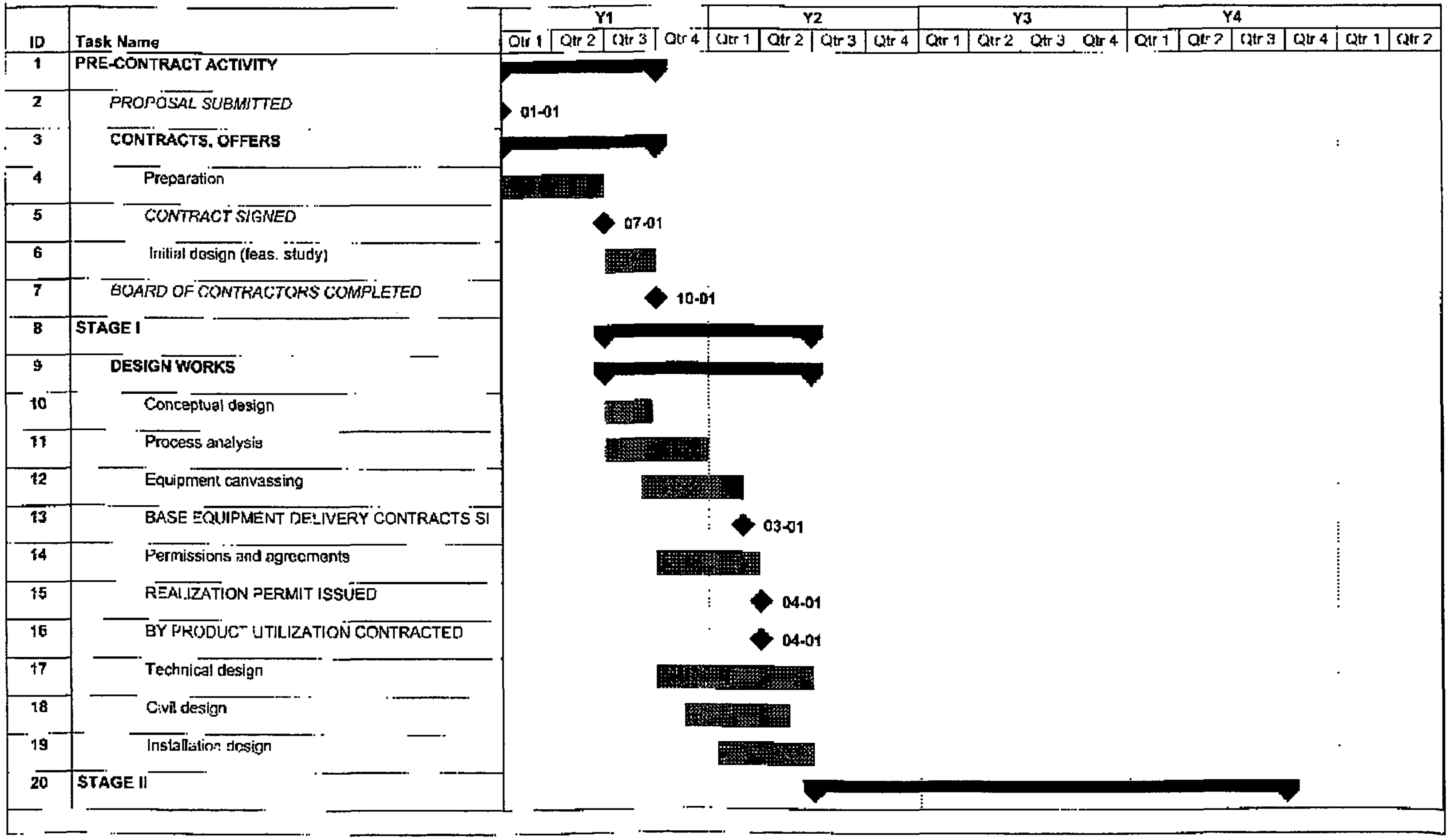
6. IMPLEMENTATION PLANNING

The purpose of implementation planning is to determine technical and organizational circumstances of each phase of implementation from moment of making the decision about an investment until the operational phase. Such plan should include scope of all tasks, time necessary to perform them and their sequence while taking into account tasks that are either interdependent or simultaneous.

Among several methods of preparation of the implementation plan, the best way to represent an implementation schedule for the purpose of a feasibility study is by a bar chart. It is a record of all tasks with their beginning and completion time marked on the time scale. An example of such a schedule is Project Milestone Schedule EPS Pomorzany Szczecin [17] and shown on Tables IX and X.

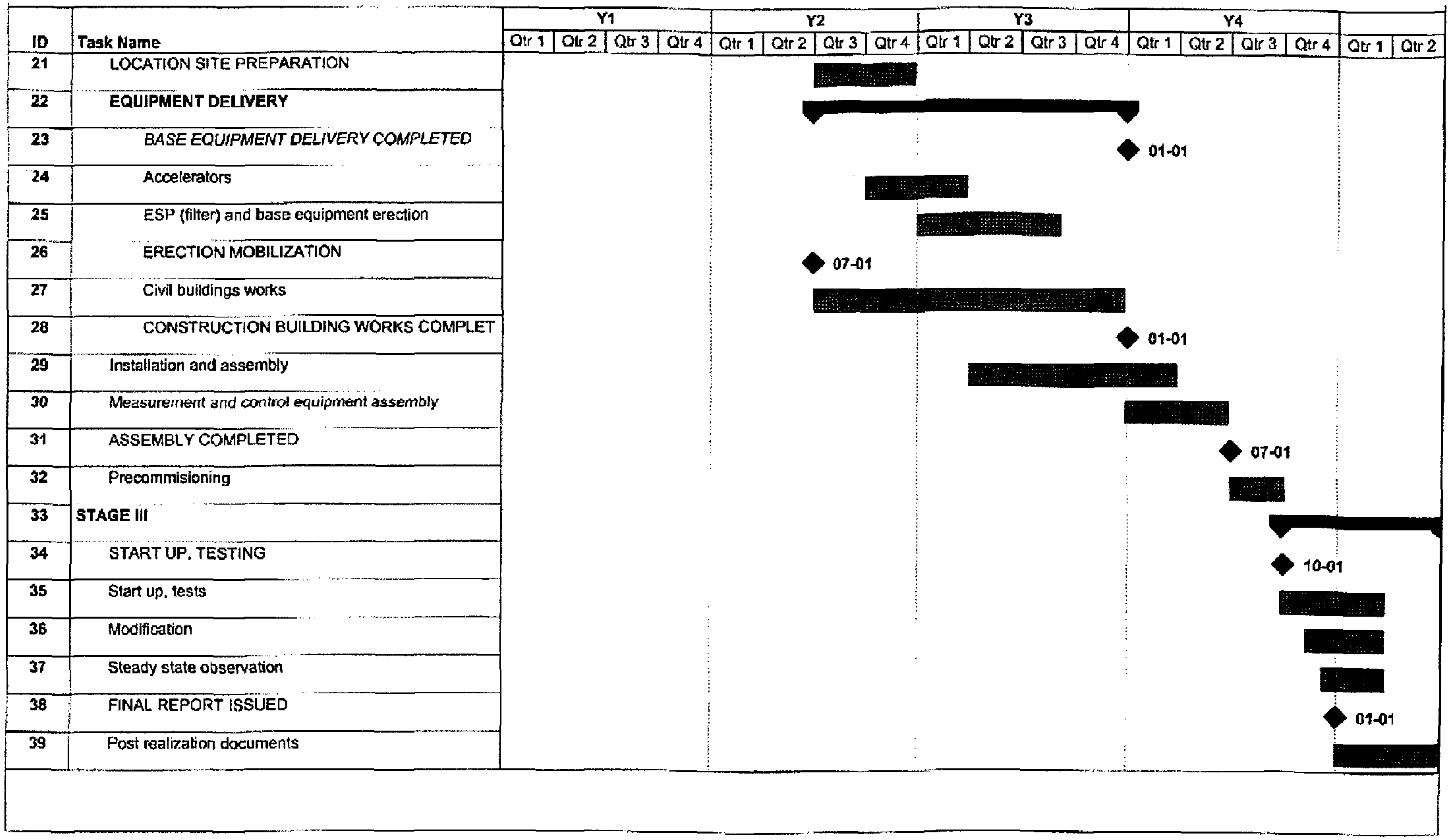
An implementation schedule constitutes the basis for preparation of a cash flow forecast and for follow-up and supervision of implementation of a project. As earlier indicated, the installation for removal of sulphur dioxide and nitrogen oxides from flue gas with application of an EB is never a stand alone installation, but always appears in connection with a site producing this polluted flue gas. This is valid both for the existing sites to be supplemented with such a pro-ecological installation and the newly designed ones. Thus, during preparation of an implementation plan for such an investment project it is necessary to also take into account the conditions relating to the features of the site being provided for such a flue gas treatment installation.

TABLE IX. PROJECT MILESTONE SCHEDULE (A)



ID	Task Name
1	**PRE-CONTRACT ACTIVITY**
2	*PROPOSAL SUBMITTED*
3	**CONTRACTS, OFFERS**
4	Preparation
5	*CONTRACT SIGNED*
6	Initial design (feas. study)
7	*BOARD OF CONTRACTORS COMPLETED*
8	**STAGE I**
9	**DESIGN WORKS**
10	Conceptual design
11	Process analysis
12	Equipment canvassing
13	BASE EQUIPMENT DELIVERY CONTRACTS SI
14	Permissions and agreements
15	REALIZATION PERMIT ISSUED
16	BY PRODUCT UTILIZATION CONTRACTED
17	Technical design
18	Civil design
19	Installation design
20	**STAGE II**

TABLE X. PROJECT MILESTONE SCHEDULE (B)



ID	Task Name
21	LOCATION SITE PREPARATION
22	**EQUIPMENT DELIVERY**
23	*BASE EQUIPMENT DELIVERY COMPLETED*
24	Accelerators
25	ESP (filter) and base equipment erection
26	ERECTION MOBILIZATION
27	Civil buildings works
28	CONSTRUCTION BUILDING WORKS COMPLET
29	Installation and assembly
30	*Measurement and control equipment assembly*
31	ASSEMBLY COMPLETED
32	Precommisioning
33	**STAGE III**
34	START UP, TESTING
35	Start up, tests
36	Modification
37	Steady state observation
38	FINAL REPORT ISSUED
39	Post realization documents

7. ECONOMIC AND ENVIRONMENTAL BENEFITS

In a comprehensive engineering and cost study on the large scale power plant application of the EB process, a representative wall fired, pulverized coal fired power plant was selected and defined [18]. This 300 MW(e) plant is similar in size and performance to base case units used in Electric Power Research Institute (EPRI) cost studies. An EB process was designed to consist of:

(1) Irradiation facility (building, EB generators/power conditioning components, concrete shielding).

(2) Flue gas handling (ductwork, dampers and expansion joints, fans, and appropriate ductwork shielding).

(3) Flue gas conditioning (humidifier, water injection system, and NH_3, transfer, storage and injection system).

(4) By-product removal/handling/processing (gravel bed filter, by-product compaction system, by-product storage).

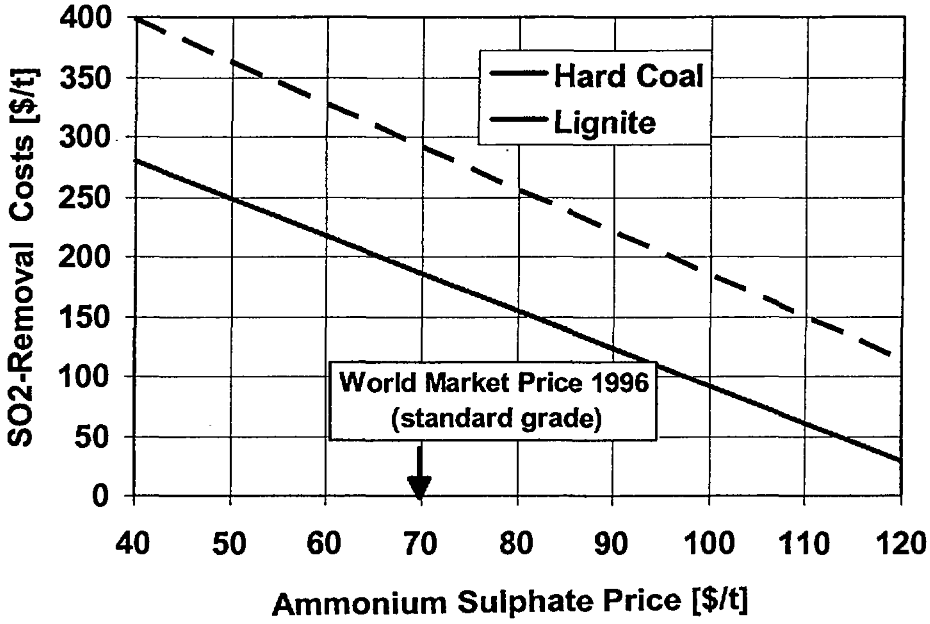


FIG. 5. Calculated specific cost for SO_2 removal [$/t]
(hard coal/upper curve [18]; lignite/lower curve [19].

According to the cost study using the EPRI methodology, the 30 year levelled costs will effect $100–$200/t of SO_2 and NO_x removed (see Fig. 5). This is rather competitive compared to other SO_2/NO_x control technologies which have been evaluated by the same EPRI method [20].

In a second study, the EB process was evaluated for the SO_2 removal at power plants fired with high sulphur lignite (5%) in Bulgaria [19]. The combustion of this fuel generates a flue gas which has high SO_x concentrations (SO_2 = 5600 ppmV and SO_3 = 140 ppmV) and lower NO_x concentrations (390 ppmV). In agreement with experimental data from Japanese groups it was found by theoretical calculations that the SO_2 removals will be above 90%. NO_x

removals of 60–80% are predicted at a dose of 5–10 kGy. In a preliminary economic evaluation of an industrial plant, it was found that the specific SO_2 removal costs will be even lower for the Bulgarian condition than calculated previously for the US condition (Fig. 5). This is due to rather high by-product credits and favourable transport conditions to a nearby ammonia producer. Presently a large pilot plant (10 000 $m_N^3h^{-1}$) is under construction at the Maritsa East power plant in Bulgaria.

An important parameter for the investment costs of the EB process is the specific price of the electron accelerators. Several market surveys have been conducted during the last 20 years among the main producers of industrial accelerators in Japan, Russia and the USA. About 1000 accelerators are meanwhile used in industry worldwide for the production of cable and wire, surface curing, sterilization, tire production, polyethylene (PE) tubes, etc. Nevertheless, for the environmental applications, even higher beam power (e.g. 10 MW) is required at a moderate electron energy (800 keV). Figure 6 shows on the left axis the flow rates of EB plants, which have been constructed between 1970–2000, for off gas cleaning. A rather slow development with flow rates of 1000–10 000 $m_N^3 \cdot h^{-1}$ occurred in Japan, Germany and the USA. during the period from 1970 to 1990 experiencing several interruptions due to market problems and technological setbacks. In the period from 1995 to 2000, large scale demonstration plants with flow rates of 300 000–600 000 $m_N^3 \cdot h^{-1}$ have been under construction in China, Japan and Poland. For comparison, a 5% market share (in Germany, Japan, the USA) for the time after the year 2000 is included in the diagram. On the right axis the specific EB costs (DM/W) are plotted in Fig. 6. The economy of scale clearly works for the EB process. With increasing plant size the specific investment costs of beam power decreased from about 25 DM/W in the 1980s to 3.5 DM/W in 1995. It is expected that the specific costs of EB equipment will decrease to some extent after the year 2000 due to new acceleration technologies and to standardization of equipment for environmental applications.

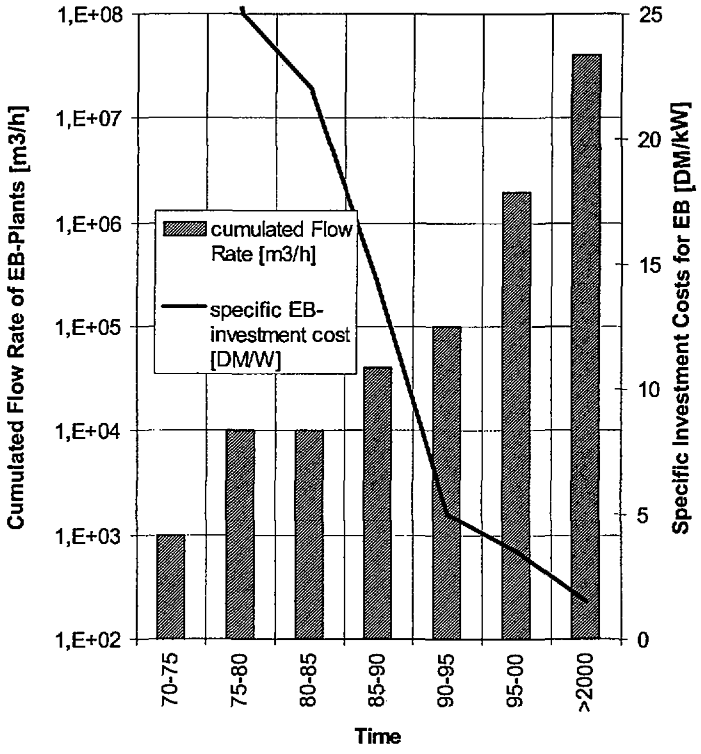


FIG. 6. EB plant flow rates and specific EB costs during the period from 1970 to 2000.

The economic and environmental benefits of the EB process as outlined above may be summarized as follows:

- Large scale EB plants for flue gas cleaning have cost advantages over conventional technologies for flue gas cleaning.
- These savings become more pronounced for the EB treatment of high sulphur flue gas, where high amounts of valuable fertilizer are produced.
- EB process avoids the production of waste such as wastewater and contaminated gypsum; therefore, expensive water treatment facilities and disposal sites for solid wastes are not required.

The simultaneous production of electrical energy and fertilizer in a power plant equipped with the EB process is a step towards sustainable development.

REFERENCES

[1] PENETRATNE, B.M., SCHULTHEIS, S.E., (Ed.), Non-thermal Plasma Techniques for Pollution Control, NATO ASI Series, Series G: Ecological Sciences 34 Part B, Springer-Verlag, Berlin, Heidelberg (1993).

[2] INTERNATIONAL ATOMIC ENERGY AGENCY, Electron Beam Processing of Combustion Flue Gases, IAEA-TECDOC-428, Vienna (1987).

[3] COOPER, W.J., CURRY, R.D., O'SHEA, K.E., Environmental Applications of Ionizing Radiation, John Wiley & Sons, Inc., New York (1998).

[4] KAWAMURA, K., et al., On the removal of NO_x and So_x in exhaust gas from the sintering machine by electron beam irradiation, Radiat. Phys. Chem. **16** (1980) 133–138.

[5] FRANK, N., KAWAMURA, K., Ebara Electron Beam Flue Gas Treatment Process, Indianapolis, Indiana Demonstration Unit, Final Report of DOE Contract #AE 22-830 PC60259 (1988).

[6] HELFRITCH, D.J., FELDMAN, P.L., Flue gas SO_2/NO_x control by combination of dry scrubber and electron beam, Radiat. Phys. Chem. **24** (1984) 129–143.

[7] FUCHS, P., ROTH, B., SCHWING, U., ANGELE, H., Removal of NO_x and SO_2 by electron beam process, Radiat. Phys. Chem. **31** (1988) 45–56.

[8] PAUR, H.R., JORDAN, S., Aerosol formation in the electron beam dry scrubbing process (ES-Verfahren), Radiat. Phys. Chem. **31** (1988) 9–13.

[9] WITTIG, S., SPIEGEL, G., PLATZER, K.H., WILLIBALD, U., The performance characteristics of the electron beam technique: detailed studies at the (ITS) flue gas facility, Radiat. Phys. Chem. **31** (1988) 83–93.

[10] PAUR, H.R., BAUMANN, W., LINDNER, W., MAETZING, H., "Improvement of energy efficiency and filter technology in the electron beam dry scrubber process, Radiat. Phys. Chem. **40** (1992) 273–278.

[11] NAMBA, H., et al., Pilot-scale test for electron beam purification of flue gas from coal-combustion boiler, Radiat. Phys. Chem. **46** (1995) 1103–1106.

[12] CHMIELEWSKI, A.E., ILLER, E., ZIMEK, Z., LICKI, J., Pilot plant for electron beam flue gas treatment, Radiat. Phys. Chem. **40** (1992) 321–325.

[13] CHMIELEWSKI, A.E., et al, Pilot plant for flue gas treatment — Continuous operation test, Radiat. Phys. Chem. **46** (1995) 1067–1070.

[14] DERONG, T., "Present status and prospects of developing EB technology for flue gas treatment in China" (Proc. Workshop on Present Status of Electron Beam Technology in Developing Countries, Vienna, 1995), http:www.ebara.co.jp/exte/ar1998/arzeroe.html (27–29).

[15] BEHRENS W., HAWRANEK P.M., Manual for the Preparation of Industrial Feasibility Studies, newly revised and expanded edition, UNIDO, Vienna, 1993 (in Polish).

[16] UNIDO Computer Model for Feasibility Analysis and Reporting (COMFAR), Users guide and reference manual (draft), Release 2.1., UNIDO/IO/R143/Rev. 4 (1988).

[17] Feasibility Study for Industrial Demonstration Plant of Electron Beam Process for Flue Gas Treatment at the Electric Power Station Pomorzany Szczecin, Poland (1993).

[18] RATAFIA-BROWN, J.A., BRIGGS, D., PAUR, H.R., MAETZING, H., Advanced Electron Beam Dry Scrubbing for High Sulphur Coal-Fired Plant Applications — Process Engineering Study Results for Phase 1 of the e-Scrub Project (Proc. AIChe Summer National Mtg., 1995).

[19] PAUR, H.R. et al., Personal communication, 1996.
[20] FRANK, N.W., MARKOVIC, V., Electron beam processing of flue gases: clearing the air, IAEA Bulletin **1** (1994) 7–10.

ABBREVIATIONS

CHC	chlorohydrocarbon
COMFAR	Computer Model for Feasibility Analysis and Reporting (UNIDO)
EB	electron beam
EPS	electrical power station
ESP	electrostatic precipitator
FGD	flue gas desulphurization
IRR	internal rate of return
NPK	nitrogen, phosphorous, potassium
NPV	net present value
NTP	normal temperature and pressure
PCDD/F	polychlorinated diphenyl
PE	polyethylene
SCR	selective catalytic reduction
VOC	volatile organic compound

CONTRIBUTORS TO DRAFTING AND REVIEW

Aoki, S.	Ebara Corporation, Japan
Cebula, K.	Energoprojekt-Katowice S.A., Poland
Chmielewski, A.	Institute of Nuclear Chemistry and Technology, Poland
Güven, O.	International Atomic Energy Agency
Paur, H.R.	Forschungszentrum Karlsruhe GmbH, Germany

ISSN 1011–4289