ECONOMIC ASPECTS OF ECOLOGICAL RISK DUE TO NUCLEAR AND COAL-FIRED ELECTRICITY PRODUCTION (General comparison Related to the USSR)

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Foreword

It is becoming increasingly important to alleviate the environmental and health impacts of primary energy generation. A comparison of the costs for different abatement measures can provide guidance for the policy makers. This paper provides such a comparison between nuclear and coal-fired electricity production with special application to the USSR. The study is the result of cooperative work between the I.V. Kurchatov Atomic Energy Institute in Moscow, USSR, and the Social and Environmental Dimensions of Technologies (SET) Project at IIASA. It makes use of the methodologies developed for similar studies at the OECD.

Peter de Jánosi
Director

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1 Introduction

This investigation was undertaken jointly between the International Institute for Applied Systems Analysis and the I.V. Kurchatov Institute of Atomic Energy. The main purpose of the study was to analyze the economic and ecological aspects of nuclear and coal-fired electricity production relating to specific conditions in the USSR [1, 2].

The calculations made in the mid-1980s on optimizating the energy balance for the period up to the year 2005, revealed that within this time frame the marginal energy resources in the USSR will be mainly provided by the Kamsko-Achinsk and Kuznetsk coal basis and nuclear power. These sources determine the main scheme of formating marginal costs for other fuel and energy types and their numerical values [3].

Use of natural gas at condensation power plants in the European part of the USSR is supposed only at steam-gas installations.

When estimating the prospects for electricity generation in the next 15–20 years, it is expected [4] that the residual fuel oil for the conventional power plants would be reduced several times. Stabilization of gas mining will result in reducing gas firing in the power plants as well as in the co-generation plants sited in large cities. Gas for new conventional power plants would be used only at the gas-mining regions. Thus the fraction of coal in the power plant balance will be increased. Therefore, at present, it may be considered that coal and nuclear power will remain the marginal energy resources.

It is expected that the specific weight of coal in total electricity generation at conventional power plants will rise to 50–60% [5]. At present about one third of the electricity output of the Soviet conventional power plants is generated at the coal base.

The goals of the present paper are as follows:

- to investigate the ecological problems which have arisen from electricity generation at nuclear power plants (NPP) and coal-fired power plants (CPP);
- to determine the economic efficiency of electricity generation at NPP and CPP in the European part of the USSR, taking into account additional expenditures required for accomplishing environmental protection measures;

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- using the same economic methodologies to compare the results obtained for the USSR with those for OECD countries [6]; and
- to estimate the economic reserve which could be spent on NPPs for enhanced and ultimate safety.

Environmental pollutions due to present-day CPPs in the USSR are examined in Section 2. Environmental pollutors include air and water pollutants, solid wastes and radioactive discharges from CPPs. The problems of the ozone layer and CO_2 discharge are also briefly discussed. Large scale environmental protection measures at USSR CPPs are considered which could help in bringing the CPP to a lower level of social acceptability. It is shown in Section 3 that in this case the specific capital cost of a CPP would reach a level of 330–500 rub/kW. These figures are mainly determined by the cost of widely used methods of sulphur and nitrogen cleaning and ash-suppression as applied to the conventional CPP with coal dust burning. In addition, some variants including the usage of water-coal suspension, CO_2 trapping by chemical absorbers, etc. are discussed.

The comparison of economic efficiency of NPPs and CPPs is investigated in Section 4. It was performed in the framework of levelized discounted electricity production costs, which permits the comparison of results obtained for the USSR with thos for OECD countries [6].

The reference calculations adopted in the study for the USSR assume a 30 year life time for both CPPs and NPPs and 74% levelized life time load factor. A reference discount rate of 10% per annum is adopted, in line with normal recommendations of official economic bodies of the USSR [24, 25] with sensitivity studies at 5% and 12% per annum. Generating costs are also presented for alternative assumptions of a higher and lower life time as well as for different construction times of power plants.

The reference calculations show that present day NPPs and CPPs possess equal efficiency in the Ural and Middle-Volga regions, but in the West-European part of the USSR there is approximately a 20% advantage for NPPs. Comparing NPPs with CPPs provided with environmental protection equipment gives a 15–40% advantage to the NPP in the Urals and 35–60% in the western part of the USSR. These figures correlate with those of for many OECD countries [6] and may be regarded as a reserve which could be spent for improving the NPP and its fuel cycle safety.

The levelized generation costs are most sensitive to the discount rate. Using 5% per annum instead of 10% leads to 12% increase in the ratio of coal/nuclear electricity production costs. Thus, it may be supposed that market economy conditions applied in the USSR give an additional reserve to NPPs.

The last two sections of the paper are devoted to the problems of environmental costs of the normal operation of NPPs and its fuel cycle facilities and that of accidental risk from off-reactor nuclear fuel cycles.

In Section 5 consumptions of natural resources and hazards to the biosphere due to NPPs with VVER-1000 and the corresponding nuclear fuel cycle (NFC) plants in normal operation are assessed in the natural and cost indices. It is understood, that at all NFC stages, including energy generation at NPPs, the following resources are consumed: land, water, various materials, heat, andelectricity. The land in NFCs is used for locating nuclear power factories as well as for storing ore and various wastes and spent fuel.

The largest areas of land are alienated during the mining and processing of uranium ore since a relatively large amount of uranium—containing ore (100,000–300,000 tons per 1 GW(e)*yr, with a uranium content of 0.2–0.1%) is extracted. About the same quantity, or somewhat more, of alienated land for NPPs depends strongly on the cooling method used. The NPP without its cooling system occupies an area of 30–60 ha. This land may then be considered mainly as temporarily alienated. Permanently alienated land should be considered land on which the reactor building has been constructed (about 0.5 ha). When cooling towers are used for cooling the NPP condensers, the land occupied by NPPs is insignificantly larger, but when a cooling pool is used, then the temporarily alienated land is larger by about an order of magnitude. For the open NFC the land alienated for spent fuel storage is rather small (about 0.1 ha per GW(e)*yr).

The consumption of water is primarily connected with the need of removing heat mainly from the NPP. Water is also used in various technological operations in ore concentration and processing as well as at other NFC stages. In some cases closed water supply systems are used, which reduces the water demand as well as the discharge of various hazardous products into the environment.

The environmental effect of NFCs in normal operations is determined by hazardous chemical products, radioactive materials, waste heat, water vapor and condensed moisture, released together with liquid and gaseous wastes. Changes also take place in the conditions of fish production in the cooling pool as well as mechanical traumas of fish and other hydrobionites in the cooling and water intake systems.

Table 5.7 summarizes the data on expentitures for "ecology and safety" in normal operations. The components of these expentitures depend essentially on plant location, chosen method for heat removal, etc. These account for a wide range of expenses for the compensation of natural resources (land, water) used in NFCs as well as for hazards from fog generation at NPPs.

The limiting value of hazards from fog generation was obtained for an extremely bad sited NPP in central Russia. The resettling of 10,000–20,000 inhabitants from nearby settlements was even considered. The maximum value of the damage of the flora and fauna of the cooling reservoir (loss of fish) was obtained by comparison with a NPP located near Leningrad.

The ecological factors of the NFC stages lead to increased expentitures for electricity generated by 2–20% depending on the method of cooling the NPP turbine condensers (the minimum estimate corresponds to cooling by cooling towers, and the maximum by cooling ponds). This corresponds to the well-chosen NPP site (with no damage from fog generation). A large difference in the values is mainly due to allowing for the ecological factor associated with use of land and water resources in different methods of cooling the NPP turbine condensers.

Estimations of accidental risk from off-reactor nuclear fuel cycles are presented in the last section. Earlier estimates [32] show that ecological risk from this part of the fuel cycle did not exceed 1% of that from NPP per se. However, the radical increase in NPP safety (for instance reduction of beyond design accident probability by two orders of magnitude, which is being discussed now) may lead to the risk from off-reactor NFCs becoming comparable, or even higher, to that from NPPs. For valid progress in nuclear power development it would be necessary to invest in safety improvements of the former. The following stages of the off-reactor fuel cycle were examined: uranium mining, uranium enrichment, fuel elements manufacturing, spent fuel storage, transportation of irradiated fuel, chemical reprocessing, underground storage of nuclear wastes.

These facilities possess an adequate safety mechanism for internally initiated accidents. But extraordinary external accidents like aircraft impacts, etc. may have ecological impacts which are comparable with those of high-hypothetical accidents in a NPP. This refers first of all to a fuel-reprocessing plant, to MOX fuel assembly fabrication and to enrichment. A way of increasing ecological safety is higher mechanical protection for the process areas where plutonium and concentrated fission products are handled. Development of more compact, non-aqueous methods of spent fuel reprocessing may also help. It was estimated that reinforced shields against external impacts in some process areas would result in rising costs for NPP electricity production by 2–3%. Therefore, costs for environmental protection for the normal operation of a complete nuclear fuel cycle and for accidental risks from an off-NPP fuel cycle may increase electricity production costs by 3–23%.

If these figures are compared with the possible reserves listed above, we see that for a radical improvement of safety of a NPP itself a margin still exists of about 25–55% of present day levelized discounted costs of electricity production from a NPP in the West European part of the USSR.

2 Environmental Problems Relating to the Coal-Fired Power Plants

2.1 Air Pollution

As known, in firing the fossil fuel (coal, gas, fuel oil) at the modern conventional power plant furnaces, a significant amount of substances, such as CO_2, CO, SO_2, NO_x etc., hazardous to the public health and the environment are produced. In the total amount of industrial contaminants discharged by conventional power plants amounts to around 30% [7].

In the industrial countries the problem of environmental protection against the hazardous effect of the conventional power plants has become so serious that sometimes their efficiency is considered as a much less important problem.

In addition to the atmospheric protection against discharges of solid particles, sulphur anhydride and nitrogen oxides, some other environmental protection problems connected with the operation of conventional power plants have to be solved.

Some industrial countries have reached encouraging results primarily due to the extensive development and production of various environment-protecting facilities and technologies. Special attention is being given to gas purification systems.

At present Soviet conventional power plants annually discharge about 6 million tons of ash (35% of discharges from all Soviet industrial productions), more than 8 million tons of sulphur dioxide (44%) and about 2 million tons of nitrogen oxides (60%) into the atmosphere [8]. Power plants are intense sources of air pollution in cities and industrial centers. They are the cause, to a significant degree, of so-called acid rain.

With the aim of improving the ecological situation, the governmental research and engineering program "Ecologically Safe Power Engineering" is being developed. One of the priority directions of this program is "Ecologically Safe Thermal Power Plant"[8].

This program envisages the development, creation, and mastering of the newest technologies and equipment for opencast collieries, concentrating mills, thermal power plants; ensuring environmentally safe burning of the solid fuel and complex utilization of CPP wastes.

At present, very strict standards for the amounts of air-polluting products and industrial wastes have been legislatively established nearly in all countries. This requires taking special measures to ensure lower concentrations of hazardous substances in gas releases, including various types of traps.

In the USA for instance, the national problem of reducing hazardous discharges by 6–12 million tons by 1995 has been set. Further strict requirements to limiting permissible discharges are expected [9].

It should be emphasized that at conventional power plants in the USSR there are no industrial sulphur-trapping equipment and until now only fly ash trapping systems are used for the purification of stack gases at the power plants. [10].

In accordance with estimations [10] in the USSR they produce the electrical filters for ash trapping, ensuring ash concentrations of 500–1500 mg/m^3 in the purified gases whereas the developed foreign firms supply various equipment for stack gas purification, ensuring ash concentration as low as 30–250 mg/m^3.

In the industrial countries the facilities for the purification of conventional power plant stack gases from sulphur oxides and nitrogen are being widely used.

In this country no necessary attention has been given to the introduction of similar facilities up to now.

However, in accordance with the USSR, obligations by the international convention of transboundary air transfer the discharges of sulphuric compounds in the European regions of this country will have been reduced by 1993 by 30% as compared with the level in 1980 [7].

In October of 1988 a protocol was signed committing the parties involved, including the Soviet Union, to fix discharges of nitrogen oxides at the 1987 level until 1994 and to subsequently reduce [11].

The government program being developed in the USSR of environmental preservation until 2005 envisages about a double reduction of discharges from USSR power plants [12].

2.2 Water Pollution and Solid Wastes

The CPP sewage water is also a contaminant. The major part of the discharge comes from water treatment and hydraulic ash handling systems. The purification facilities currently used at a CPP ensure sewage water purification by 95–98%. However, such purification is not sufficient and the protection of reservoirs from contamination is an important problem.

The other important problem of power plants using solid fuel is connected with ash handling systems. Deterioration of the quality of the fuel burned resulted in a sharp increase of ash released. At present the annual amount of ash from Soviet coal power plants exceeds 120 million tons. As the efficient use of ash (according to 1988 data) does not exceed 15% of their annual amount, the area of all ash dumps, operating and taken out of service, exceeds 3500 ha. It is known that the ash dumps are potential sources of contamination of the atmosphere, ground and surface water in the adjacent territories.

The ash dump is full after 5–6 years. To ensure the further operation of the CPP the ash dump has to be expanded, which may be by using additional areas, or increasing the capacity of the existing ash dumps. As there are few free areas it is decided, as a rule, to increase the ash dump capacity by raising the height of the dikes, which makes them less safe [13].

The state of most ash dumps is far from being satisfactory. Almost all of them have suffered accidents, including those with dike breaks, and the release of ash into the environment. At present, when attention on ecological problems is continuously growing, such a situation is intolerable. Even more so as accidents in the ash dumps may have catastrophical consequences and cause serious material losses which sometimes exceed the cost of the ash dump itself.

An illustration of this situation is the accident in the ash dump of the co-generating power plant, near Irkutsk, when the dikes, as low as 10 m, were broken and the pulp (mixture of ash, ice and water) flow "passed" more than 3.5 km over the flat countryside damaging some engineering and service buildings. All chemically contaminated water flowed into the Angara-river [13].

Ash blown by the wind from the surfaces of the ash dumps cause dust-storms which deteriorates the sanitary condition of the environment.

At present there are about 100 ash dumps over a total area of about 20,000 ha [13]. As a rule, dust-fighting in the operating ash dumps is reduced by the irrigation of the ash dump's surfaces with clarified water.

2.3 Problems of Ozone Layer and CO_2 Discharge

In accordance with the Montreal Protocol of 1988 the Soviet Union has taken over the responsibility of reducing the production of ozone-destroying materials by 50% during the next 10 years. The specialists consider that the role of the ozone-destroyer at altitudes of 15–30 km (the layer of maximum ozone concentration) belongs to nitrogen oxides [14,15]. In [15] it is noted that NO, NO_2 contained in flue gases from the boilers participate in:

- reactions causing exhaustion of the earth's ozone layer;
- creation of the green-house effect (just as CO_2).

It is also emphasized that the N_2O concentration in the atmosphere is continously growing.

The discharge of CO_2 produced at a CPP increases the real threat of dangerous changes in the climate, resulting in the green-house effect.

At the International Conference on changes in the atmosphere, held in June 1988 in Toronto, Canada, [16] a plan for the reduction of CO_2 discharges into the atmosphere was proposed. This plan suggests that by the year 2005 the developed countries should reduce CO_2 discharges by

20% of those of 1988. Half of this reduction has to be reached by increasing the efficiency of energy utilization and the introduction of other energy-saving systems. The other half might be reached due to the transition to fuels which produce lower CO_2 discharges or by choosing renewable sources or nuclear energy.

In addition to the products of complete fuel combustion and nitrogen oxide, hydrocarbonds, soot, having toxic and carcinogenic properties, are discharged into the atmosphere.

2.4 On Radioactive Discharges from CPP

It is not well known that the process of coal burning for electricity general and communal and industrial heating the air is being contaminated with radioactive products. In coal combustion some radionuclides are concentrated in ash. Therefore the thermal power plants may be a more serious source of irradiation of the population living at the adjacent areas than a normally operating NPP [17]. The estimates show that radioactive discharges from CPP form the effective equivalent irradiation dose higher by dozens of times than the technological discharges of a normally operating NPP.

Specialists have calculated that the average annual individual irradiation doses in the areas where a 1 GW(e) CPP is sited vary within the range 0.6–6 mrem depending on the factor of ash discharge purification, while those from the NPP discharges are from 0.004–0.08 (for VVER) to 0.015–0.13 (RBMK), i.e., by 1–3 orders of magnitude lower than the doses resulting from the CPP discharges which, in turn, constitute 0.3–3% of the natural background dose [17].

2.5 Other Dangerous discharges

It must be also taken into account that besides the radioactivity of flying ash there are some other harmful chemical carcinogenic products, particularly benzopyrene, as well as non-carcinogenic components, such as sulphur dioxide, nitrogen oxides, mercury, lead, cadmium, etc., causing other serious illnesses. These discharges are apparently dependent on the type of coal used.

3 Costs of Environmental Protection for Coal-Fired Power Plants

3.1 Reference Case

Environmental contamination from coal-fired power plants, briefly discussed in the previous section, leads to social consequences such as human illnesses, damage to cultural values, irreversible processes in nature, damages to the agriculture, etc.

In the literature, the notion "damages from contamination" means the additional expenditures and losses which arise in the national economy as a result of an increase in environmental contamination. It is extremely difficult to estimate those damages. For example: the estimated damages from the discharges are [18]:

- non-toxic dust - 90 rubles (per ton)
- sulphur oxides - 85 rubles (per ton)
- and those from nitrogen oxides damages are 6–10 times higher.

It is easy to calculate that allowing for the scale of CPP discharges the total damage in the USSR from these three discharge components amounts to about 3 billion rubles per year. The combined effect of various discharge components increases the total damage compared to the damage caused where they to act independently.

In comparing NPP and CPP by their discharges, the heating of the water reservoirs must be taken into account. The parameters of the steam used at most NPPs are lower than those at CPPs. Therefore the specific steam generation and heat discharges from the NPP condensers are about 1.5 times higher compared to the most efficient current CPPs. However, at a CPP the heat discharged with fossil fuel combustion products is present, whereby it is absent at a NPP.

For the USSR, the expenditures for the main environmental protection equipment at the coal power plants can be evaluated as follows:

- for sulphur cleaning—up to 150 rubles/kW; [19]
- for ash suppression—up to 50 rubles/kW; [19]
- for water reservoir protection—about 20 rubles/kW;
- for ammonium-catalytic purification—up to 40 rubles/kW. [11]

In accordance with available data [12] the specific costs of various types of purification from sulphur ranges from 40 to 100 rubles per 1 kW of installed power for the USSR. The operation expenses increase by 10–15%. The capital investments for construction of 152 sulphur-trapping facilities are estimated to be 4–5 billion rubles.

It has been pointed out in the literature that the total expenditures for stack gas purification facilities in electricity engineering are estimated to be 6–7 billion rubles. The cost of ammonium-catalytic nitrogen purification facilities (the first of such facilities are expected to be introduced in the Soviet Union in 1991–92) will be 30–40 rubles/kW. [12] According to estimates [4] the specific capital costs for ecologically safe thermal power plants based on fossil fuel are expected to be 330–500 rubles/kW.

These capital investments for coal power plants account for the previously mentioned expenditures for environmental protection equipment. These evaluations of the specific capital investments refer to coal power plants with conventional pulverized coal fuel burning. Therefore we take as a reference case for a CPP the following values of specific capital cost (investment):

- 200 rub/kW for a present day coal-fired power plant without large environmental protection measures;
- 330–500 rub/kW for a coal-fired power plant with environmental protection measures as discussed.

3.2 Variants

In the above study the increase in the CPP cost was mainly determined by the cost of the widely used methods of sulphur and nitrogen cleaning and ash-suppression as applied to a conventional CPP with coal dust burning.

Now let us estimate how this situation could be changed if ecologically more acceptable methods of coal burning such as using steam boilers with a fluid-bed furnace and if water-coal suspension were applied. These approaches were discussed in detail at the 14th World Energy Conference (WEC). [21]

The fluid-bed furnace in burning coal in conjunction with limestone permits the discharge of sulphur and nitrogen oxides to be reduced. However, the current costs would then increase significantly due to the use of limestone, preparation of a limestone-coal mixture, and feeding the latter into the furnace. [22] Besides, it is only reasonable to apply this technology for boilers of small and medium sizes.

In accordance with US data, the use of water-coal suspension requires additional capital investments of 20–50 $/kW. Therefore the capability and efficiency of the coal power plant somewhat decreases and the electricity cost rises by 1.1–2.3 cent/kWh. In 1987 the cost of electricity generated at a US CPP was about 2.1 cent/kWh. [23] Hence the use of water-coal suspension at a CPP will lead to an increase in electricity cost by 1.5–2 times. These figures correlate with the UNO data reported at the 14th Energy Conference. It was stated in the UNO presentation that in allowing for damage caused to the environment (atmosphere pollution, acid rain, etc.) will double the cost of electricity produced by burning fossil fuel. This figure is significantly higher when compared to the reference case following.

Finally a few words about the "green-house effect". In the opinion of some specialists as much as 90% of the total amount of carbon dioxide, the main "green-house" gas produced in burning the pulverized coal fuel at a CPP, can be trapped from the vent stack by chemical absorbers. But then, the plant's efficiency would be reduced from 40% to 29.3% and the electricity production cost would increase by about 2/3. [21]

Taking these figures into account, it is easy to show that only these absorption processes of CO_2 trapping will increase electricity cost even more than in the case of using the environmental protection equipment for the cleaning gas from ash, sulphur and nitrogen oxides, and for cleaning of CPP sewage water.

4 Comparison of Economic Efficiency of Nuclear and Coal-Fired Power Plants

4.1 Method of Calculation

We perform a comparison of economic efficiency of nuclear and coal-fired power plants in terms of a levelised cost per kWh, which allocates life time production costs over life time output of electricity. This levelised cost can be calculated by the formula

$$E = \frac{\sum_{t=0}^{T} \Big(C(t) + m(t) + f(t)\Big) \times (1+p)^{-t}}{\sum_{t=0}^{T} e(t) \times (1+p)^{-t}} \tag{4.1}$$

where T–lifetime of the plant in years, t–time in years, $e(t)$-net electrical output, c, m, f–capital, operation and maintenance costs, and fuel cost respectively, p–discount rate for one year.

As a rule, a simplified expression is used in the USSR. [25]

$$E_s = p\frac{K}{T_0} + \bar{m} + \bar{f} \tag{4.2}$$

Here K–specific capital cost, ruble /kW; T_0-load time during one year, $\bar{m}$–specific operation and maintenance expenditures, in ruble/kWh; $\bar{f}$–specific fuel expenditures, in ruble/kWh. Expression (2) reduces to (1) under the simplifying conditions:

- life time is large enough, then $(1+p)^{-T} \to 0$;
- $c(t)$ differs from zero only for $t=0$;
- m, f, e are constant in time.

The experience of NPP and CPP operation in the USSR generalized in [25] shows that with good accuracy,

$$\bar{m} = 0.07\frac{K}{T_0} \text{ for NPP}$$

and

$$\bar{m} = 0.1\frac{K}{T_0} \text{ for CPP} \tag{4.3}$$

These values are officially introduced as normative ones. [24] For the USSR condition it can be shown that NPP fuel components are close to 30% of E_s [3], that is

$$\bar{f}_{\text{NPP}} = 0.3E_s^{\text{NPP}} \tag{4.4}$$

The CPP fuel cost can be written as

$$\bar{f} = b \times \Gamma \tag{4.5}$$

where b is specific fuel consumption; Γ–is the value of the marginal costs of coal. For further calculation we use the general formula (4.1) but with (4.3)–(4.5) conditions.

4.2 Data for Reference Case

The calculation of the levelised discounted electricity generation costs (specific discounted costs of electricity production) for the domestic PP and NPP is performed in this paper based on the following data:

- the numbers of hours using the CPP and NPP installed power are equal and amount to 6500 hr/year;

- the standard discount rate-p for NPP and CPP is taken to be equal 0.1 1/year. [24] It should be noted that normative recommendation [25] suggests using $p = 0.1$ for NPP and $p = 0.12$ for CPP, thus giving an advantage to NPP, which we do not use here.
- for a NPP specific capital cost K=510 ruble/kW, which includes 90 ruble/kW of first core loading;
- for a CPP specific capital cost is 200 ruble/kW without large environmental protection measures and 330 and 500 ruble/kW with the measures; the specific consumption of equivalent fuel is 336 g/(kWh); the coal cost is marginal cost for the particular economic regions of the USSR ranging from 39 to 58 ruble per ton of equivalent fuel. Table 4.1 presents the distribution of marginal costs over regions in the USSR. In the calculation it is supposed that K at a NPP and a CPP remains constant for the regions considered below.
- the life time of power plants of both types is chosen to be equal to 30 years.

The results of the calculations for this reference case are presented in Table 4.2

4.3 Sensitivity of the Results to Variation of Parameters

It is mentioned above that p=0.12 1/year is the USSR normative value for a CPP. [25] This value is twice as large as that used for West Europe. [6] It may be thought that the transition from a centrally planned to a market economy one would result in the necessity to reduce the discount rate.

Some technological achievements in nuclear engineering (vessel annealing, etc.) increase the possibility of prolonging a nuclear plant's life time by 50 years. At the same time, new equipment of a CPP for environmental protection may appear to be not reliable enough and result in reducing the life time of the plant. This is why we use two other values for a power plant's life time of 25 and 50 years. The variations performed for $p = 0.12$ and 0.05 1/year and two values for a plant's life time of 25 and 50 years are presented at Tables 4.2–4.10.

Besides, in comparing the economic efficiency of electricity production at a CPP and a NPP is made considering the investments made during the construction of the power plants. To take this into account, it is necessary to know the schedule of expenditures for this time. Particularly in equation (4.2) it is necessary to replace specific capital cost K for

$$\sum_{t=0}^{T_c} \frac{dK}{dt} \times (1+p)^t \times 1yr. \tag{4.6}$$

where T_c–construction time. A similar modification should be made in (4.1). For a NPP the modification (4.6) certainly does not refer to the cost of first core loading. The corresponding modification of levelized discounted costs are illustrated in Figure 1.

The schedule of introducing capital investments represents, as a rule, a monotonously growing function or exhibits a small peak by the end of construction. Therefore for an upper limit of estimating the discounting effect a uniform schedule of capital investment introduction may be taken. It appears that for a CPP such an estimation offers an additional advantage as it is a less capital intensive plant. If the construction time for a CPP and a NPP is taken to be the same and equal to 5 years, the discount rate is 0.1 1/year, the increase of capital investments is 1.3 times. The K for a CPP varies up to 260, 430 and 650 ruble/kW and for a NPP to 640 ruble/kW. To take into account the tendency of increasing NPP construction time we also investigated the case $T = 6$ years for a NPP. Table 4.11 presents the ratio of a CPP to a NPP electricity costs calculated allowing for equal construction times.

4.4 Discussion of the Results

The results of the calculations of levelised discounted costs of electricity generation in different regions of the USSR by coal-fired and nuclear power plants are presented in Tables 4.2–4.12. They permit the following conclusions to be made:

- Present NPPs and CPPs possess an equal efficiency of electricity production in Ural and Middle-Volga regions, but in the West European part of the USSR there is approximately 20% advantage for a NPP;

- In comparing a NPP with a CPP which has reliable, high-quality environmental protection equipment installed gives (15–40%) advantage to a NPP in the Urals and (35–60%) in the west part of the USSR.

- This advantage may be regarded as an economic reserve which can be used for environmental protection and the enhancement of NPP safety. Table 4.12 presents the upper permissible level of capital cost of a NPP corresponding to the equal-efficiency with that of CPP with a capital cost of 330 ruble/kW.

- The above figures correlate with those for some OECD countries. [6] For instance, the ratio coal/nuclear is 1.22 for France; 1.42 for Belgium; 1.11 for Japan (discount rate 0.1 1/year, life time 30 yr).

- The increase of a power plant's life time from 30 to 50 years, which is now being discussed, only slightly (1–2%) enlarges the ratio coal/nuclear.

- The results are rather sensitive to the discount rate. Using $p = 0.12$ 1/year manifests 5% reduction of the ratio, while $p = 0.05$ 1/year leads to (10–12%) increase. It may be supposed that market economy conditions applied in the USSR give an additional reserve to a NPP.

- Allowance for discounting capital cost during power plant construction is in favor of a CPP. Five years construction time means 3% reduction of the ratio coal/nuclear. The two years difference in construction time (4 years for a CPP and 6 years for a NPP) gives an additional 3–4% advantage to a CPP.

- The data obtained can be used for a preliminary evaluation of the economic expediency of new NPP designs with enhanced safety.

5 Cost of Environmental Protection for Normal Operation of a Nuclear Power Plant And Its Fuel Facilities

The conclusion from the previous section is that for apresent day NPP there is an economic reserve which could be used for the enhancement of safety and protection of the environment (SPE). The question is whether this reserve is large enough and how it can be used for SPE in order to reach a social acceptance of nuclear power. The problem could be expressed as follows. How much does environmental protection for the *normal operation* of a NPP and its fuel cycle facilities cost?

Estimating the economic factors associated with ensuring the safety and protection of the environment is complicated both by the common problems of the national economy as a whole and by some specific ones. The common problems arise from shortcomings in the development and the practical application of economic methods for national economy management in the USSR.

The specific problems in SPE economy estimations are primarily associated with the influence on public health and the environment, the possibility of accidents with serious consequences for the economy and the environment, the difficulties in separating the reliability and safety-relating functions of some NPP systems, etc.

The above problems in economic estimations manifest themselves in the deficiencies of the corresponding normative documents or the absence thereof. Therefore, in some cases the available scientific approaches are used (this is the case, in particular, in considering possible accidents).

When studying the SPE economy questions, it should also be taken into account that not only economic factors are important in designing, constructing and operating of nuclear fuel cycle (NFC) plants, in waste removal, etc. The role of non-economic problems such as radiation safety standards, sanitary requirements, NPP siting rules, and so on, are not less important. All these are contained in appropriate normative documents and constitute the current basis for taking decisions on all aspects of NFC development and ensuring SPE.

Most of these non-economic requirements should be considered as limitations on the economic estimate application or, in other words, the admissible changes in characteristics and parameters describing the conditions of SPE insurance at NFC plants. In some important cases there is a certain freedom in choosing the values of these characteristics. Then the optimal decision can be made based on more thorough economic studies such as cost-effectiveness or cost-benefit analyses. Any normative documents which could recommend these methods are still lacking.

In this section efforts are made to estimate SPE economy in terms of the current normative documentation for the normal operation of a present day NPP with VVER reactors and an open NFC (without reprocessing of spent nuclear fuel).

5.1 Consumption of Natural Resources

At all NFC stages, including electricity generation at a NPP, the natural resources are consumed which must be allowed for in the cost of electricity produced. These are the following: land; water; various materials; primary energy.

The last two items refer to the category of reprocessed resources, i.e., produced on an industrial basis. Some quantity of natural resources are consumed for their production, which must also be allowed for in the cost.

Land

The land is used for the siting of the NFC's main and auxiliary plants as well as for the storage of various wastes, ore, and spent fuel. Besides some restrictions can be imposed on the land when it is used for agricultural and other purposes.

The temporal character of land alienation should be distinguished from the permanent one. The temporarily occupied lands are those which can be restored through recultivation after production has stopped, and the permanently alienated lands are those where cultivation is impossible for a long time after production has ended and where recultivation is non-effective (for technical or economic reasons).

The data on the utilization of land territories in NFC are summarized in Table 5.1. They are divided into two groups: non-permanent and current consumption.

The first group includes land where the main and auxiliary buildings, equipment, etc., are located (e.g., this is the area occupied by a NPP and its pond, cooling water). As a rule, these lands are allocated for the object prior to its construction. The second group is the current alienation of lands for the disposal of barren rock, wastes and so on. The generalized data on the consumption of natural resources are listed in Table 5.1.

Considering the two components, the following must be taken into account. In comparing different productions by the occupation of land the amount of all current expenditures and their comparison (or summing) with non-permanent use has to be made only by taking into account the temporary factor-function of discounting (as is done in converting these values to the economic indices).

At the head-end of the NFC stage (before NPP) the largest land areas are alienated for mining and reprocessing of uranium, or during mining, a relatively large amount of uranium-containing ore (100,000–300,000 tons per GW(e)*year at uranium content of 0.2%–0.1%) and about the same quantity, or somewhat more, of barren rock. Land is required for the storage of barren rock, ore, and wastes. In open-cast mining a considerable part of the alienated land is occupied by collieries.

A large part of the land alienated for ore reprocessing is occupied by special tailing ponds where liquid wastes (tailing solutions containing sludge and some insoluble chemical reagents, as well as natural radionuclides) are held until water evaporation occurs and then the waste is buried with clay and earth and planted for fixing the soil. After such treatment the tailing pond becomes the head-end NFC stage waste burial.

At the stages of uranium-UF_6 conversions, isotope enrichment and manufacturing of fuel assemblies, land alienation is negligible amounting to about 0.3 ha per GW(e)*year.

The area of alienated land for a NPP depends strongly on the condenser cooling method used. The proper NPP (one power unit) without the condenser cooling system occupies an area of 30–60 ha. This land may be considered primarily as temporarily alienated. Permanently alienated land should be considered as land occupied by the reactor building (about 0.5 ha per power unit). When cooling towers are used for cooling the NPP condensers, the territory occupied by NPP is somewhat larger but in the case of the ponds cooling water the temporary alienated land is larger by about an order of magnitude. For the open NFC, the land alienated for spent fuel storage is negligible ($\simeq$0.1 ha per GW(e)*year).

Water

The data on water consumption is listed in Table 5.1. Water consumption is primarily connected with the need of remove heat from some installations of NFC plants. The largest amount of water is spent for cooling the NPP condensers. In the direct flow cooling system, water consumption amounts to about 15 m^3/s and 50 m^3/s or $1.3*10^9$ m^3 and $2*10^9$ m^3 per GW(e)*year for VVER–440 and VVER–1000 respectively. Only a small part, about 2%, is completely lost (for evaporation and filtration through the ground for the ponds cooling water).

Besides, water is used in various technological operations in ore concentration and processing and at other NFC stages. In some cases, if permitted by the technology applied, closed water supply systems are used, which enables water demands as well as the discharge of various hazardous products to the environment to be reduced.

Materials and Energy Resources

The total consumption of materials, other than fuel, for all NFC stages is $16*10^3$t/(GW(e)*year). The main part of NFC electricity is consumed at the uranium enrichment stage.

5.2 Non-radiation Effects of NFC Facilities on the Environment

The negative effect of normally operating NFC plants on the biosphere is determined by: hazardous chemical products, radioactive materials, waste heat, water vapor and condensed moisture, released together with liquid and gaseous wastes, as well as by:

- deterioration of fish production in the ponds cooling water;
- mechanical traumas of fish and other hydrobionites in the cooling and other water intake systems.

The liquid wastes are formed in a NFC as a result of using water in various technological processes.

At the initial NFC stage, water is contaminated when it percolates through dumps of barren rock and stored ore. The largest amount of liquid wastes result from the hydrometallurgical treatment of ore. These are tailing solutions of about 150,000 m^3/(GW(e)*year) in volume.

Protection of the environment in handling liquid wastes consists either in the thorough decontamination of the wastes from hazardous impurities and the discharge of water decontaminated to the permissible levels to the water reservoirs, or in the use of reversible systems with water recycling.

The sources of gaseous wastes in a NFC are:

- dust production in ore mining and treatment;
- release of volatile products from various technological processes and the storage of solid wastes and materials;
- burning of fossil fuel (gas, residual fuel oil, coal) in engines, heaters, and other NFC facilities.

There is another indirect source of environmental contamination in a NFC: these are power plants generating the electricity required for NFC plants and burning, as a rule, coal or residual fuel oil. The electricity demands of a NFC does not exceed 4% of the total electricity produced at a NPP.

However, because of a great amount of waste discharged into the environment by the currently operating coal power plants, this source pollutes the biosphere much more than the main NFC production.

The effect on the flora and the fauna of the ponds cooling water in a NFC is only significant at the main stage of a NPP operation. Therefore, we consider only the NPP and the version of using natural water reservoirs (rivers, lakes, bays, and so on) for cooling. They also may be used for economic purposes as fishing areas with natural and/or artificial reproduction of fish.

A special ponds cooling water may become an object for consideration if it is used for artificial fish production where the heating of the water may be a positive factor. Such a case is not considered here.

Damage caused by the action considered manifests itself primarily in the reduction of fish in the water reservoir and, hence, in the amount of fish caught.

As a result of constructing an object and its operation, the hazard to the stock of fish may be caused by:

- total loss of fish production in the water reservoir or in a part of it;
- reduced fish production due to deteriorating conditions;

- direct destruction of feed organisms and fish at different stages of their development directly caused by heat generated from mechanical malfunctions in the water intake systems.

In this section the following data is used as the initial material:

- results of long observations and studies carried out in the Kopor Bay in the Baltic Sea (the water from this bay is used for cooling the power units of the Leningrad NPP (LNPP));
- normative documents and scientific approaches to estimate the hazard to hydrobionites of the ponds cooling water.

Direct Heat Effect

When the normative requirements to additionally heating water in the reservoir are fulfilled this factor itself does not play any significant role. However in combination with the chemical contamination the effect of waste heat may lead to noticeable ecological changes: growth of blue-and-green alga, a shift in the season fluctuations and in ecological equilibrium, etc.

These negative phenomena are observed actually in the Kopor Bay in the area of water dumping from the LNPP. It should be taken into account that the main source of chemical contamination of the Kopor Bay water is not the NPP but rather from the industrial and agricultural plants of the region.

With the current standards and rules observed for environmental protection, NPP is not a significant source of chemical contamination. This contamination cannot lead to any appreciable negative ecological effects either by itself or in combination with waste heat. The same can be said about the radioactive contamination of the natural pond with liquid wastes from a NPP. This is the reason why this is not considered in detail nor are any estimations made.

Mechanical Effect

Water intake from the pond may lead to the destruction of hydrobionites on the cleaning grids of water intake facilities (WIF). Plankton, spawn, young fish and larvae of invertebrates penetrate into cooling systems where they are killed or wounded. Larger hydrobionites, for example, fish of marketable sizes die directly in the water intake wells. Studies of mechanical malfunctioning of the fish population in LNPP, which have been carried out for many years, made it possible to make the following conclusions:

- in the absence of any fish protecting systems a great amount of fish is killed on WIF. This causes a significant damage to the fish catch and fishing industry, stopping the passage in the condenser tubes and WIF grids thus decreasing water supply, which in turn, results in NPP malfunction;
- every year, from dozens of thousands to dozens of millions, of various species of fish at different ages are killed on 1 GW(e) WIF of the NPP, which means that an annual loss in fish products increases from several dozens to hundreds of tons;
- the damage caused by destroying fish in a WIF may considerably exceed the amount of fish caught locally;
- the proper choice of water intake and/or use of relatively inexpensive advanced water intake facilities may greatly reduce the damage to the fish population, caused by malfunctioning in a WIF.

The main source of *moisture releases* to the atmosphere in a NFC is a NPP operation. This effect is associated with fog generated by the evaporation from the heated surfaces of the ponds cooling water or releases of steam and condensed moisture from the cooling towers.

Under some conditions favorable for fog generation (leakage of cold air onto the warmer water surface), fog may lift to a height of 10–100 m and spread to distances of 1–20 km depending upon wind. The intensity of evaporation from the pond cooling water surface may reach 0.8 t/s for a 1 GW(e) NPP.

As a result of the irrational siting of a NPP and its ponds cooling water, the population of the settlements and cities in the fog spread zone proves to be in uncomfortable conditions because of temperature disturbances and air moisture, especially in winter. Besides, great damage is caused by the formation of ice on roads, buildings, wires, and so on. Fog on roads increases the risk of transport accidents.

Until recently, this factor was not given much attention in designing and siting a NPP. As a result some operating NPPs experience serious difficulties associated with fog generation over the ponds cooling water. An especially complicated situation is at the site of the Kalinin NPP which uses the water from the lakes Udomlya and Pis'vo for cooling. There, the question is being discussed to evacuate the population from nearby settlements if measures are not taken to reduce the generation of fog.

At the operating NPP the problem of reducing the fog hazard can be solved either by evacuating the population from some of the nearer settlements, or by taking measures actively affecting the atmospheric processes, such as:

- the construction of cooling towers, if necessary, "dry" or "semi dry", which will affect NPP efficiency;
- the sowing of active materials enabling rapid condensation, coagulation and drop growth in clouds and fog;
- the use of surface-active films preventing evaporation from the water surface.

It appears that for a NPP under design the problem of the unfavorable effect of moisture release into the atmosphere could be removed. This might be ensured by the appropriate choice of a NPP siting and/or an appropriate method for turbine condenser cooling. The decision must be taken on the basis of a careful examination of economic and ecological factors using the methods for estimating the effect of moisture release into the air and effective measures for its reduction.

The data on chemical contamination of the biosphere in the normal operation of a NFC are presented in Table 5.2. The main sources of contamination are the enterprises at the first NFC stage.

It should be pointed out that the data presented in the Table 5.2 are indicative of a very low direct chemical contamination from NFC compared, for example, with the similar data on fossil fuel power engineering. However, contamination is much smaller than the chemical contamination from the source due to the use of non-nuclear energy in the NFC itself. In principle, this source can be eliminated if NFC energy demands will be satisfied by nuclear power stations.

5.3 Assessment of Radiation Doses for Normal Operation of NFC Facilities

It should be noted that a reprocessing plant is, like a NPP, the source of continuous pollutant discharges of radionuclides (during a normal operation). Table 5.3 shows collective radiation doses received by the population of the USSR from continuous pollutant discharges of radioactive substances of NPPs and reprocessing plants into the air and water. [26] The mining and hydrometallurgy of uranium indicates the figure of local collective dose less two orders, and fuel fabrication by three orders of magnitude than a NPP. Let us compare the activity created by pollutions sited in Table 5.3 with a natural background. If it is assumed that the background is 10^{-5} rem/hr then the collective dose of the USSR population is 2.5×10^{7} man.rem/yr. Assuming the general power of USSR NPPs 100 GW(e), which is planned for the first decade after

2000 (it now constitutes 36 GW(e)), we obtain the global collective dose for the population of the country due to NPPs is 7×10^3 man.rem/yr and 1.2×10^4 man.rem/yr due to reprocessing plants. To calculate the upper limit of the local collective doses, let us assume that all reprocessing plants servicing 100 GW nuclear power are located in the same area with 100 km radius (this is the worst supposition). Then for the average population density of the country the local collective dose would constitute 4.4×10^3 man.rem/yr. Let us make the same supposition for the NPP's themselves. Then the local collective dose will constitute 1.1×10^3 man.rem/yr. The local collective dose from a natural background into the area with 100 km radius is 3.5×10^4 man.rem/yr. The local and global collective doses obtained by such a way are shown in Table 5.4 as the percentage of collective doses given by a natural background. It can be seen that the local collective doses are two orders higher than the global ones, although both local and global are very small parts of the natural background. This proves, once more, that sparsely populated areas are being preferred for the construction of NPPs and likewise reprocessing plants.

Depending on the field of application various characteristics of radioactive contamination are used: radioactive releases (dumping) from the plants per unit time, volume or surface densities of environmental contamination, man exposure dose. These characteristics are compared with the corresponding normative documents (PDV, PDK, dose limits, etc).

One of the objectives of this section is to assess the damage associated with the effect of radioactive contamination of the biosphere on public health. Therefore we use the effective equivalent dose S_E intended for such assessment. If the collective dose S_E is known, then damage G determined in lost man-days is written by a simple formula $G = g \times S_E$ where $g = 4.6$ man*day/man*rem. [27]

In the present study the quantity S_E or G are also used for assessing the economic damage. Therefore collective doses, different in time, are added allowing for the discounting function, i.e., in the above formula S_E denotes, as a rule, the discounted effective collective dose S_E^d reduced to the plant operation year considered.

In adding time-diversed economic quantities or in reducing them to a certain time instant, the discounting function $e^{-pt} \simeq (1+p)^{-t}$ (where p is the discount rate, t is the time) is used. In accordance with the decision taken above the value $p = 0.1$ is used.

In [28] and [29] the figures for collective doses which refer to VVER—based NPP and are slightly higher than in [26]. So, for further calculation, we take as representative, the data listed in Table 5.5. This data is expressed in $S_E^{(d)}$ values. The personnel exposure doses are not considered here.

5.4 Method of Cost-Damage Assessment in Economic Indices for Non-radiation Factors

In this section, brief descriptions are given of the methods for the assessment of:

- cost of resources used;
- damages to the flora and fauna of the ponds cooling water;
- damage from moisture discharged into the atmosphere;
- damage to the biosphere from chemical contamination.

The states of the above problems cannot be considered satisfactorily so far. The available set of methods, guidelines, or recommendations are being developed and improvement is not still acceptable for common use.

The methods of cost-damage assessment described here have been developed on the basis of expert analysis of the material available by the authors and [30].

Cost of Land Resources

The cost of the alienated land can be determined by some recent normative documents.

In Section 5.1 it was noted that the alienated lands are divided into two groups: permanently and temporarily occupied territories. The largest part of temporarily alienated land is occupied for a long time (>30 years). This time is longer than the characteristic economic time ($t_{\text{exp}} = 1/p = 10$ years) This means that the cost of the land to be recultivated and returned in the distant future, has been reduced and is close to zero. This is the reason why this land in economic assessment is conventionally referenced to the group of permanently occupied land. Assessment of the cost of alienated land was made based on the data of Table 5.6.

Cost of Water Resources

In this part of the cost only the water lost completely is taken into account. The water taken for cooling the plant components returns to the ponds. However, its quality may be deteriorated due to contamination. This is discussed in the next Sections.

The assessment of the cost of the water used is made in accordance with the recommendations of Goscomtsen of the USSR. [30] According to these recommendations tariffs of 1.15 copeck/m^3 and 2 copecks/m^3 for using surface and underground waters respectively, have been established. Besides depending on the particular region, additions or allowance to these tariffs have been introduced.

Effect on the Flora and the Fauna of the Ponds Cooling Water

In this section the damage to the fish economy, caused by injury to fish and other hydrobionites in the water intake facilities, is considered. The direct heat effect is insignificant if the current normatives are observed. Damage Y consists of two components:

$$Y = Y_1 + Y_2 \tag{5.1}$$

Y_1 is the damage caused by fish death, Y_2 is the damage caused by the loss of the posterity.

If any measures on fish protection are accomplished, the reduced damage (5.1) should be replaced by the generalized costs Z:

$$Z = \rho K + Z_C + Y_{res} \tag{5.2}$$

where K, Z_C are the capital and current cost of fish protection, Y_{res} – the residual damage. Fish protection measures are effective when

$$(\rho K + Z_C) < \Delta Y$$

Here ΔY is the damage reduced ($\Delta Y = Y - Y_{res}$) due to fish protection measures taken. In this case $Z < Y$.

Moisture Discharge to the Environment

The damage should be considered as the generalized costs Z calculated by formula (5.2), where K, Z_C are the capital and current cost of the protection measures, Y_{res} is the residual damage caused by the factor considered here $Y_{res} = Y_1 + Y_2$ where Y_1 is the damage caused by the formation of ice on roads, buildings, power lines etc.; Y_2 is the social damage caused by the hazardous effect on the living conditions of the population. All these values strongly depend on the choice of the NPP site and the method of cooling the NPP condensers.

Chemical Pollution of the Biosphere

In the first approximation the economic damage from chemical pollution of the biosphere in determined by the formulas:

$$Y = Y_a + Y_b \tag{5.3}$$

where Y is the total damage, Y_a and Y_b are the damage caused by the atmosphere and water pollution

$$Y_a = \gamma_a s f M_a \tag{5.4}$$

$$Y_b = \gamma_a s_\kappa M_b \tag{5.5}$$

$\gamma_a = 2.4$ ruble/equivalent ton is the normalizing constant, s is the index characterizing the relative hazard of the atmosphere pollution depending upon the type of the territory, s_κ is the constant depending upon the type of the water reservoir, f is the coefficient taking into account dispersion of the impurity into the atmosphere, M_a and M_b are the reduced masses of the annual discharge of the contaminant from the source into the atmosphere and water:

$$M_x = \sum_{i=1}^{N} A_i^{(x)} m_i^{(x)}$$

$x = a, b$; $A_i^{(x)}$ is the index of the relative aggressiveness of the $i - th$ kind impurity; $m_i^{(x)}$ is the mass of the annual discharge to the atmosphere or water, t/yr; N is the total number of hazardous impurities.

5.5 Method of Assessment of Economic Damage due to Radiation Factor

There are two groups of problems in assessing damage to public health caused by radiation exposure. The problems of the first group are associated with assessing this damage in natural indices or, in other words, assessing the radiation risk. The problems of the second group are associated with assessing the damage in economic indices. In the normal operation of NPP and other NFC plants the radiation exposure of the population does not exceed a few millirem per year (in most cases significantly lower) or 1 rem per life. These doses belong to the so-called "low exposures". At these exposures the manifestation of possible radiation effects (carcinogenic or genetic) hazardous to human health is of a probabilistic (stochastic) character.

One of the key problems of assessing radiation risk is associated with determining the exposure-effect dependence for "low exposures". This problem has not yet been completely solved, either experimentally or theoretically. Only working hypotheses are available, in particular, the hypothesis (model) of linear exposure-effect dependence recommended by the International Radiation Protection Commission (IRPC) for use in the assessment and rate setting of the radiation risk.

The present expert assessment is based on this hypothesis. Note that recently IRPC and other organizations accomplished a reevaluation of the parameters (risk coefficients) of the linear dependence model, based on the new data on radiation risk (including review of the data on Hiroshima and Nagasaki). This reevaluation had not been completed up to now. Therefore, the IRPC recommendations currently in force are used in this paper.

Another problem in assessing the radiation risk is the determination and use of radiation risk characteristics. The following factors make it difficult to solve this problem:

- dependence of harmful effects on age and sex;
- delay between a harmful action and its manifestation;
- variability of detriment, death or diseases of different types and severity;
- competition between the effect of harmful factors under study and other causes, including natural ones.

The generalized characteristics of radiation risk taken from various scientific works are now described. There are no recommendations of any regulatory organizations so far.

Generalized Natural Indices of Radiation Risk

The notion "generalized" is primarily connected with the attempt to describe a variety of detriments by a single index. On the basis of domestic and world experience gained in studies of the radiation risk, two natural indices are proposed:

- generalized individual life-long risk R (probability of losing life or health because of radiation);
- generalized detriment to health G (mathematical expectation of reducing life-span due to radiation exposure measured in man-years).

The main fields for using these indices are, respectively:

- normalization of radiation risk;
- assessing the damage caused by radiation exposure of a group of people and a comparison with other sources.

In accordance with the linear hypothesis:

$$R = r \times D$$

$$G = g \times D$$

where D is the dose-equivalent, r and g are the constants depending on age, sex, organ, tissue. In the equal exposure of the whole body the average values of these coefficients are: $r = 7.5 \times 10^{-4}$/rem; $g = 4.6$ man*day/rem. [27]

The IRPC recommendation uses another radiation risk index. This is the effective dose-equivalent D_E (the dose-equivalent of the whole body having the same risk of causing biological harm as an exposed part of the body):

$$D_E = \sum_i \omega_i D_i$$

where D_i is the dose-equivalent to organ or tissue $i; \omega_i$ is the corresponding weighing factor.

At the I.V. Kurchatov Institute of Atomic Energy two modifications of the effective dose D_E are proposed: for normalizing the radiation risk and for assessing the damage. The latter is used in the present work. It is determined by the following set of parameters:

$$\omega_i = \frac{g_i}{\sum_i g_i}$$

where g_i is the detriment in $i - th$ organ or tissue exposure, $g = \sum_i g_i = 4.6$ man*day/rem.

Economic Indices of Radiation Risk

The economic indices imply the socio-economic damage Y which is determined as:

$$Y = \alpha \times G$$

where α is the price of the damage (ruble/(man*day)). The quantity α consists of two components:

$$\alpha = \alpha_o + \alpha_s$$

where α_o and α_s are the objective and subjective prices of damage.

Component α_o characterizes the direct economic damage to society, caused by death or disease of an individual as a producer of the national product. The average value of α_o is 5–10 ruble/man*day. [31]

Component α_s shows the subjective attitude of the individual to the risk. It may be called the social component which is much larger than α_o. It is recommended to use the following value for $\alpha_s : \alpha_s = 200$ rubles/man*day. [31] Then $\alpha \simeq 210$ rubles/man*day.

Allowance for the time factor should be made taking into account the discounting function (see Section 5.3).

$$F(t) = e^{-pt} \simeq (1+p)^{-t}$$

For example, $\dot{Y}(t)$ is the intensity of the damage (annual damage) at time t. Then the total damage reduced to time $t = 0$ is

$$Y = \int_o^\infty \dot{Y}(t) e^{-pt} dt$$

The total collective dose, total natural damage has to be calculated in a similar way.

5.6 Summary Data

The summary data on the generalized costs (costs + damage) of electricity production in a NFC are presented in the discounted form: they are reduced to the current year of NPP operation and normalized to the unit of electricity produced. Recalculation of the capital costs K into the current ones is made by the formula $Z = pK$ and the same load factor of NPP as in Section 4. The summary data on the discounted generalized data is listed in Table 5.7.

Many components of the generalized data depend essentially on the plant's location, chosen method of heat removal, and so on. As are, for example, the costs of alienated land, water intake, etc. This is why there is a large difference in their values.

The maximum value of the discounted damage from the radiation effect on the flora and fauna of the water reservoir (Table 5.7) is obtained on the basis of studies by the Leningrad NPP. The final representative data on damage caused by fog cannot be obtained at present because of the lack of the initial economic assessment of the costs of measures for preventing this phenomenon. The limiting value of damage has been obtained for an extremely unfavourable siting of a NPP and for the case of taking decisions on the evacuation of the population of nearby settlements (10,000–20,000 people). Therefore, it is reasonable to take $Z \simeq 0$ as the representative value for this damage.

Comparing the figures in Table 5.7 with those in Table 4.3 one can conclude that the ecological factors of NFC stages leads to increased expenses for electricity generation by 2–20% depending on the method of cooling the NPP turbine condensers (the minimum estimate corresponds to cooling by cooling towers, and the maximum by cooling ponds).

This corresponds to the fortunately chosen NPP site (with no damage from fog). A large difference in the values is mainly due to allowing for the ecological factor associated with use of land and water resources in different methods of cooling the NPP turbine condensers.

6 Accidental Risk From Off-Reactor Nuclear Fuel Cycle Facilities

Unlike coal power plants, NPPs and their nuclear fuel cycle (NFC) facilities produce practically no harmful emissions under normal operating conditions. But in abnormal, accident situations the hazardous impact from a single case of radioactivity release can turn out to be more harmful than the total effects of emissions of coal-burning power plants over a long time. The accidental releases in NPPs and NFC facilities occurred in 1957, 1979 and 1986; their modeling on test facilities and mock-ups seems impossible for the present. The estimates of risk from NPPs and NFC facilities can only be probabilistic. As in the case of fossil-fired power plants, the estimates must determine the cost of the whole set of measures to mitigate the probability of an accident to an acceptable level.

The estimates of such a kind were used in [25] to establish the competitivity limits of an enhanced-safety NPP. It was assumed that all efforts on increasing the safety should be concentrated to an NPP per se. This can be justified, for example, by the earlier estimates [32] according to which the ecological risk from NFC facilities does not exceed 1% of that from NPPs. However, it is not difficult to see that the radical increase in NPP safety (for example, reduction of the probability of high-hypothetical accidents by two orders of magnitude) can lead to the risk from NFC facilities becoming comparable with that from NPPs. Under these conditions the further improvement of nuclear power safety has to be also extended over the off-reactor NFC part. Bearing this in mind we have attempted to represent the ways of increasing the reliability of "ecologically weak" points in a NFC and to estimate the scale of increase in the NFC cost affecting the competitiveness of nuclear power. This section also provides brief information about the structure and present day status of NFC facilities.

6.1 Structure of a NFC

Operation of the nuclear power reactors is ensured by a network of industrial enterprises of NFC including uranium mines, uranium concentrate production plants, uranium isotopic enrichment plants (including production of fluorine and uranium hexafluoride) and automated enterprises for manufacturing fuel assemblies (preliminary uranium dioxide is produced chemically from uranium hexafluoride).

All of the above mentioned facilities are designed to supply nuclear reactors with a natural fuel form the so-called head-end of a NFC. The back-end of a NFC deals with fuel discharged from the reactor at the end of the campaign. The main purpose of this final part of a NFC is to isolate highly active products of uranium decay from the biosphere for a period required for their natural decay. Moreover, the back-end facilities may be arranged so as to deliver to the nuclear reactors the secondary fuel (plutonium and transplutonium elements) produced in "burning" natural uranium. Such fuel recycling is a necessary condition for the operation of breeders. All the same, in traditional thermal power reactors the burnt fuel contains a sufficient quantity of plutonium. The composition of fresh and spent nuclear fuel is illustrated in Table 6.1 for VVER-1000 Reactor. [33]

Unlike the head-end of a NFC all back-end technological operations are performed inside a powerful biological shield. The radioactivity of the fuel assembly just withdrawn from the VVER-1000 core is 125 million curies and decreases to 3,5 million curies in 4 months after being discharged. The relatively short-term storage (for 3–5 and sometimes to 10 years) of spent fuel is made in a near-reactor pool.

According the concept supported all over the world for the last decades after near-reactor cooling the spent fuel is transferred to a 40–60/year interim monitored storage facility. The delay in constructing radiochemical plants has been a main incentive to this procedure. The radiochemical capacities available in the world are far from sufficient to reprocess the whole of the fuel unloaded from NPPs.

Even though a sufficient number of radiochemical enterprises were constructed, it would anyway be impossible to direct the produced high-level waste immediately upon unloading to very long-term storage. For the first several decades after being discharged from a reactor the fission products have such a high specific heat release that it would be necessary to construct expensive systems to remove the heat from deep underground structures. Therefore, a temporary (for 40 to 60 years and possibly longer) controlled hold-up of fission products in near surface storage facilities is necessary whether they are "sealed" in the fuel assemblies or immobilized in a vitreous matrix after the chemical reprocessing of fuel and the extraction of uranium and plutonium.

6.2 Present-Day Status

Uranium Mining

The method of mining the uranium ores is determined by geological and engineering features and can be underground (rich ores, hard rocks, above 200 m in depth) or open-cast (uniform large-area deposits, small depth, sufficiently loose overlying rocks allowing the use of highly-efficient overburden machines).

Underground leaching (UL) for poor and run-of-the-mine ores (uranium content of 0.03–0.05%) in deposits with complex hydrogeological and mining engineering conditions of bedding (depth ranging from 40–80 to 450–600 m).

In addition to a considerable saving in equipment this method simplifies the solution of ecological problems. [34] In particular, the USSR produces 30% of uranium by the sulfuric-acid UL method; in the USA this figure is about 50% .

Uranium Enrichment

Production of enriched uranium is one of the capital-intensive links of a NFC. Table 6.2 [35] illustrates the potentialities of the greatest world producers of enriched uranium. At present industry uses both diffusion and centrifugal methods of enrichment. The great advantage of the centrifugal methods over diffusion consists of not only that its electricity consumption is 25 times less, but also that the stages of the centrifugal plant during work capture small quantities of uranium hexafluoride. This means that the ecological risk will be lower when an accidental external impact destroys the separation plants per se.

For the last 15 years, the USA and other countries have developed a laser method of isotope enrichment. By this method separation is not reached at the cost of molecular-kinetic effects as in the gas-diffusion or centrifugal method, but via selective excitation and photoionization of a chosen isotope by monochromatic light of a corresponding laser system. During isotope separation uranium is maintained in the vapor state by a special heater. The AVLIS (Atomic Vapor Laser Isotope Separation) method does not require the production of uranium hexafluoride and, hence, fluorine. This is an ecological advantage of the laser method as compared with the two methods now used in industry. The economic advantages of the laser enrichment of uranium isotopes are illustrated by Table 6.3.

Chemical Reprocessing of Irradiated Fuel

The total annual discharge of spent fuel at NPPs all over the world is about 7000 tons. The total quantity of spent fuel will be from 120 to 200 thousand tons by the year 2000.

The off-reactor part of a NFC may be arranged in two ways: the cycle can be open (without chemical reprocessing) or closed (with fuel reprocessing and waste conditioning). Different countries solve this problem in different ways. For example, France which is a densely-populated country, has at its disposal a sufficient reserve of natural uranium but nevertheless, since the sixties, spends considerable funds in constructing plants for reprocessing of power reactor fuels.

The French radiochemical capacities not only meet the needs of national nuclear power, but perform the orders of other countries (Sweden, Japan).

Japan, having serious seismic conditions in addition to being a high densely populated country, continues to construct NPPs and creates a second plant for reprocessing of spent fuel (using the French technology, 800 t/yr). Only recently, according to the Japan specialists' reports, the negative attitude of the population to the construction of this plant has arisen, whereby its start-up may be suspended.

Germany, in spite of taking the path of fuel reprocessing, periodically delays the construction of the plant, as it examines the possibility of reprocessing the fuel discharged from German NPPs in France or Britain.

The USA has decided, for the present, not to reprocess the fuel from power reactors; the radiochemical plants which have been constructed are not licensed because they do not meet the NRC safety standards.

Sweden is the convinced antagonist of fuel reprocessing on its own territory.

The USSR published (before the Chernobyl accident of 1986) the concept of a close cycle combined with breeder reactors. The concepts of safe breeders are heatedly debated now. [36] Development of the breeder program will mean the necessity of constructing new radiochemical enterprises producing plutonium for the breeder cores. The Soviet Union has an operating plant in Kyshtym to reprocess the spent fuel discharged from the VVER-440 reactors. It has a nominal capacity of about 400 MTHM (Metric Tonnes of Heavy Metal)/yr. The Kyshtym plant has recovered about 20 MT of plutonium from spent fuel discharged from PWRs (VVERs) since 1978 when it began reprocessing non-defense spent fuel. The second plant reprocessing 1500 tons of the VVER- 1000 fuel per year (annual discharge from about 80 power units of 1 GW) and the fuel of other reactors is at the 30% stage of construction near Krasnoyarsk, but its construction has now been suspended. [37]

At the present time the radiation-ecological factors are of decisive significance in choosing the strategy of spent fuel management.

Interim Storage of Irradiated Fuel

Development of interim storage facilities is based on over 40 years of world experience in spent fuel storage. Dry (in air or inert gas) and underwater storage of fuel assemblies exist. The dry storage facility is designed as regular rows of shallow dry wells (Nevada, USA; Japan), a concrete canyon (Britain, France, USA), a concrete surface container, called a "silo" (Canada, USA) and a two-purpose steel container in which the fuel assemblies are stored and transported (FRG, USA).

Use of the module methods (containers, dry wells, silos) does not cost much, since only minimum initial investments are required. However, the underwater storage of fuel elements is more reliable: it excludes overheating and thereby guarantees with a high probability the integrity of the claddings. The fuel storage racks in the pools are now more compact and equipped with neutron absorbers which enables almost double the initial fuel capacity. Another way of increasing the storage capacity is so-called rod consolidation (the fuel elements are removed from the assembly and packed more closely than during reactor service).

A CLAB facility in Sweden is an example of a structure for underwater storage. It has five (one in reserve) 3000 m^3 ponds made in rocks at a depth of 30 m. The total fuel capacity of the storage facility is 3000 t at an annual input of 300 t. The facility has been in service since 1985; the investments were $ 224 million (1985 dollars). The storage expense does not exceed 1,4% of the cost of nuclear-generated electricity or 20% of the total cost of the NFC back-end. [38]

The activity released into the air and water during the five first years of operation has been negligible, amounting to around 0.01% of the permissible release from a CLAB and the three colocated reactors together amounts to 0.1 m Sv/year.

The collective radiation dose to CLAB staff and contractors was between 6,5 and $7{,}0 \times 10^{-3}$

man.rem for 1986-88, which was about 25% of the expected values in the final safety analysis. In 1989 the dose increased to nearly 9,0 $\times$ 10^{-3} man.rem and for 1990 a further increase to 11 $\times$ 10^{-3} man.rem was expected. The rising tendency can be explained by a build-up of activity in plant systems, increased maintenance work, and more staff members passing the dose detection limit. [39]

The dry storage facility at Gorleben (Germany) disposed in a reinforced concrete building 200 $\times$ 38 $\times$ 20 m is designed for 1500 t of fuel achieved a burn-up of 35 GW∗d/t. The fuel is to be stored in 420 two-purpose containers with 0.4-m-thick walls for about 40 years.

The project of a 10,000-t dry well repository was developed in the USA. The repository will be constructed in Nevada to become one of several regional facilities which will store the fuel discharged from a third of PWRs and BWRs until the year 2010. The storage area will be extended as required and will be able to receive the assemblies (tightly welded inside thin-walled steel capsules) with a heat release of less than 1 kW. The time of monitored storage is as long as 100 years with subsequent removal. 23,500 wells will form a square lattice with a pitch of 3 m. The estimated cost of the facility is US$ 289 million. The initial capital investment required for the first year of service will not be more than US$ 35 million. [40]

Transportation of Irradiated Fuel. Transportation of spent fuel is an obligatory component of NFC as it is impossible to dispose all NPPs, interim storage facilities and radiochemical plants on the same site. Irradiated fuel is transported in massive steel casks by small portions which are ten times less than the reactor core loading and a hundred times less than the quantity of fuel in the regional storage facility. This excludes the risk of a global or regional catastrophe even in the case of a most serious transport incident.

Long-Term Storage of Nuclear Waste. Isolation of radioactive waste is the most important problem under study in many countries having NPPs. Underground disposal is recognized everywhere to be the best method of long-term isolation (longer than 300 years). Some countries have already taken practical steps in this direction. Sweden was the first to put in Forsmark an underground storage facility for low- and medium-level radioactive waste from NPPs into service in 1988 in Forsmark. The cost of the first phase of the project (a network of tunnels under the granitic bottom of the Baltic Sea at a depth of 60 m) was US$ 120 million. Experience in servicing this system will prove to be very useful in the future for the construction of deep storage facilities for high radioactive waste.

Underground repositories for high-level radioactive waste which may represent either vitrificated blocks containing the products of fuel reprocessing or the whole of the spent fuel assemblies will be put into service probably after 2000–2010. Such a time gap is explained firstly by a great amount of survey, design and civil engineering works. Secondly, as noted above, a long-term hold-up in shallow storage facilities is required until the residual heat release of the fuel to be buried decreases to an acceptable level depending upon the heat conductivity of materials of the geological formation.

6.3 Ecological Risk Due to:

The technological regulations for every enterprise of a NFC are worked out so that, subject to these regulations, the concentrations of radioactive nuclides in the biosphere would not exceed the maximum permissible concentration. The continuous pollutant discharge levels of the main links of a NFC are depicted in Figure 2.

However, it is imperative that a certain risk exists of an accident occurring both for internal reasons (violation of technological conditions, equipment failures) and due to external impacts (diversion, aircraft impacts, etc.). Let us consider each of the above links of a NRC individually.

6.3.1 Uranium Mining

In the open-cast mining of uranium an internally induced accident can be caused by local initiators (collision of vehicles, landslide) and, as in such cases the kinetic energy is relatively small, it is clear that no release of uranium-bearing substances outside the mine working would occur. On the contrary, the external impact can have much greater energy to initiate a sharp movement of mined rock and to produce aerosols containing natural radioactive nuclides. A low uranium content of ore (0.02–0.2) is the factor limiting the release of aerosols in the atmosphere after an accident.

In the underground mining of uranium an internal accident cannot create an increased (exceeding the background) concentration of natural radioactive nuclides in the above-ground air space. As to the external impact, it can lead to a dusting of the masses of ore hoisted to the surface and prepared for transportation to a hydrometallurgical plant.

It is unlikely that an accident at an enterprise of uranium underground leaching could give rise to a noticeable release of radioactive nuclides in the air basin as they are in diluted aqueous solutions.

The picture of the accident at a hydrometallurgical plant will be probably similar to that at a uranium mine. However, taking into account the presence of uranium concentrate (the end product of the hydrometallurgical plant), the probability of increase in the background will be lower than in the accident at the mine, but higher than in an externally-induced accident at a uranium open cast.

6.3.2 Uranium Enrichment and Fuel Manufacturing

A uranium isotope enrichment plant uses uranium hexafluoride as a working medium; at 20° C it is solid with a high vapor pressure (about 80 mm Hg). Gaseous hexafluoride is pumped through the cascade at a pressure lower than the saturated vapor pressure. When in contact with atmospheric moisture solid uranium hexafluoride is converted into uranyl fluoride. If the contact occurs in the vapor phase, uranyl fluoride aerosols are formed. They can be transferred by air flows over a great distance.

Release of the uranium hexafluoride can take place in depressurized vacuum-tight communications and separation machines. But it will be of a local nature and not lead to exceeding the natural background beyond the production area.

It should be noted that within the separation plants there are neither explosive nor combustible substance in quantities capable of producing a serious explosion and, therefore, an internally-initiated accident is hardly probable.

In the case of externally-initiated depressurized separation equipment and technological communications it is necessary to allow for a softening factor, such as a small absolute quantity of uranium hexafluoride available in the separation cascade. In particular, it is true for a centrifugal facility. It is known that great quantities of solid uranium hexafluoride are available only in special standard vessels of the condensation-evaporation installations at three points of the cascade: feed, product collection and collection of dump. Making the assumption that 20 t of uranium hexafluoride (approximately a daily reserve) is available at the same time in a plant with a capacity of 1 million separation work units (SWU) per year, it is possible to estimate the concentration of uranyl fluoride aerosols in the air basin around the plant provided that the whole uranium hexafluoride is released from cylinders due to an emergency external impact. The approximated estimation shows that in this case the concentration of uranium (in aerosol form) in the air space within the 10 km radius around the plant can be 10^3 to 10^5 times higher than the maximum permissible concentration. Such a situation should be considered to be very serious, but not unavoidable. It is required merely to ensure protection (a thick reinforced concrete ceiling, etc.) and minimize the risk of damage to the cylinders.

The consequence of a hypothetical accident to a plant fabricating fuel elements and assemblies depend not only on the force of the impact, but also on the fuel composition. The explosion caused by any violation of the fabrication process is hardly probable. Dusting of nuclear fuel in the air space around the plant could occur only after an extremely strong external impact (aircraft impact followed by fire, etc.). This is a very unprobable event. Nevertheless if it takes place, dusting of plutonium-containing fuel will aggravate the ecological situation more seriously than in the case of fuel based only on enriched uranium. This is explained in that the specific activity of plutonium-239 is higher by several orders of magnitude than that of uranium-235.

6.3.3 Transportation of Irradiated Fuel

The assessment of the risk from transporting irradiated fuel can be broken down into two issues: the probability of a transport incident and the scale of consequences caused by this incident. During its transportation the fuel is in the power of other departments which are not always competent in handling radioactive materials. A casual concurrence of circumstances can take place, such as the rail disasters in the USSR which occurred in Arzamas (1988) and Bashkiria (1989).

The fuel transport casks are designed taking these circumstances into consideration. Transportation of irradiated fuel must possess an inherent safety guaranteed by the construction of the cask. Protection is ensured:

- from the spontaneous chain reaction (SCR) by a suitable geometry and the use of neutron absorbers;
- from overheating by passive means of heat removal;
- from the biological effects of radiation as well as from external impacts by a 0.4-m-thick steel wall, a massive cover and a reliable seal.

Irradiated fuel has been transported all over the world for a long time and thousands of shipments of gas- and water-filled casks with spent nuclear fuel have been transported to distances of 100 to 4000 km. No serious incidents with radioactivity releases have occurred. Experience shows that the transportation of irradiated nuclear fuel is one of the safest among the transportation of other hazardous freights. Some cases with the "sweeping" of radioactive nuclides on the surface of the cask filled with irradiated fuel are available in the literature. [41] This can lead to the contamination of railways or motor roads. However, such a phenomenon can be evidently avoided by more careful loading operations and appropriate control.

According to assessments [42,43] and taking into account the extra strength of the cask it is possible to assume that only an incident of extreme severity (a shock velocity of more than 110 km/h, a fire longer than 1 hour) can represent a hazard to the transport cask. If we suppose that two casks per day are conveyed along a 5000 km route (which corresponds to the Soviet geography and a Soviet nuclear capacity of 100 GW planned in the period after the year 2000), then such an extreme incident would not occur more frequently than once in a million years. It should be noted that the probability of an accident occurring in transporting irradiated fuel is 10 times less than that of a high-hypothetical accident in an ultimate safety NPP reactor causing damage to the reactor vessel and the possible release of radioactivity into the environment.

For a 500 km route (Western Europe) the probability of an exceptional incident will be 10 times lower, or once in 10 million years.

It follows from the estimation made for a cask containing 3.2 t of irradiated fuel for 150 days cooling time, that an exceptional accident involving a fire can cause the cladding rupture for 10% of the fuel elements and the complete loss of the coolant. As a result, 1.9×10^3 Ci from Kr-85, 0.01 Ci from J-131 and 130 Ci from the sum of fission products will be released into the atmosphere. The Kr-85 cumulative (whole-body) absorbed dose of about 0.4 man.rem can be obtained by 10^6 persons, if the population density is accepted to be 4×10^3 people per sq. km. The population will obtain an average dose of 0.4 rem at a distance of 50 m from the cask on the leeward side. The heavily-contaminated ground will reach about 300 sq. m. The local (an area of 100 km radius) collective dose due to this accident is 0.4×10^{-11} man$*$rem/GW(e)yr.

6.3.4 Interim Storage of Irradiated Fuel

An autonomous interim storage facility is the place where a great mass (up to 3000 t) of irradiated fuel can be accumulated. The design and engineered features ensure an inherent safety via the elimination of such factors as the chain reaction of fission and the overheating of the fuel elements during their storage. Thus, any internally-initiated accident is practically excluded provided that the storage operating rules are observed. When the external factors (aircraft impact, bombardment) occur, the environmental contamination can be so considerable that the evacuation of the population will be necessary. Therefore, the structure of the storage facility must guarantee the fuel integrity under extreme conditions. The above mentioned Swedish repository CLAB which is constructed 30 meters down in the bedrock is an example of a successful decision.

The dry storage facility with pits designed in the USA (Nevada) is an example of a structure not unprotected from extreme external impacts. But in this case the risk is minimized, as can be concluded, by fuel dispersal over a large area to attain a density of 40 kg of fuel per square kilometer of ground surface. Nevertheless, some events, such as aircraft impacts, can lead to several hundreds of kilograms of fuel being released from the capsules onto the ground surface and approximately 10^3–10^5 Ci of radioactivity being converted into aerosols.

6.3.5 Chemical Reprocessing of Irradiated Fuel

A plant for chemical reprocessing of fuel is also designed on the basis of the required inherent (deep subcriticality first of all) safety. The first plants constructed in a hurry for military purposes may have imperfect equipment and this is the most likely explanation for the failure of the cooling system in a tank containing the solution of fission products at the Kyshtym plant in 1957, which caused these products to be released into the atmosphere. [44] The internally-initiated accident at a present day radiochemical plant seems to be scarcely probable.

The up-to-date radiochemical extraction plant, or more precisely its basic process equipment, is adequately protected from external impacts: it is positioned in the chain of underground reinforced concrete "canyons" serving as a biological shield. The volume of the basic equipment is comparatively small and the release of high-level solutions cannot give rise to serious off-site consequences. The tanks for storing highly-active liquid waste are a higher hazard. The total capacity of the tanks at the plant is 1000–3000 cub.m. The total activity of the stored solution is 10^7–10^9 Ci. In the case of aircraft impacts or diversion the release into the air basin can approach the same as in Kyshtym (2×10^6 Ci) and Chernobyl (5×10^7 Ci). The most efficient way of minimizing such a hazard is to construct sufficiently deep underground reservoirs.

At present the potential ecological hazard from the plants for chemical reprocessing of fuel is one of the main reasons that some countries cease their construction. The other obstacle may actually be of small benefit as compared with the complete fuel cycle. While such a concept cannot hinder the development of nuclear power based on thermal reactors, in the future it can become an obstacle to the development of a wide-scale breeder program. The concept of temporary storage now adopted represents a compromise between the supporters and the opponents of the spent fuel recycle. It provides time to improve the technology of spent fuel reprocessing without which the breeder cannot exist.

6.4 Qualitative Classification of Accidental Risk

The degree of hazard to the nearby population due to an accident which has taken place is different for each chain of NFC. It seems to us that the following scale would be useful to assess qualitatively the degree of risk in accidents which can lead to the release of radioactive nuclides into the biosphere:

1. Low risk: the radiation due to the release of radioactive nuclides approaching the natural background level;

2. Medium risk: the accident radiation slightly exceeds the radiation background and there is some anxiety by the population;
3. High risk: the accident radiation strongly exceeds the radiation background and evacuation of the population is required.

According to this scale the ecological risk in the case of an accident at any link of NFC can be estimated as shown in Table 6.4.

The proposed estimation does not pretend to be accurate, but might illustrate the measure of hazard in the case of an accident being initiated at one or another enterprise of NFC.

6.5 Estimation of Cost of Measures to Reduce Accidental Risk

The given discussion of the after-effects of hypothetical accidents at NFC facilities and their normal operation makes it possible to reach the following conclusions:

- The present day state of safety of NPPs and that of NFC facilities of the off-reactor part is such that the ecological risk of the latter is as low as a percentage of the total. The radical increase in NPP safety (lowering the probability of high-hypothetical accidents by two or three orders of magnitude) will lead to the risk due to NFC facilities being comparable with that from a NPP;
- The present day facilities of a NFC possess adequate safety not only under normal operating conditions, but also in internally-initiated accidents;
- The extraordinary external effects (aircraft impact, diversion, etc.) can lead to a non-catastrophic worsening of the ecological situation in the vicinity of the enterprises, such as uranium open casts, uranium enrichment plants, plants for fuel assembly fabrication, shallow storage facilities for spent fuel. Taking into account that these facilities have features engineered at eliminating the spontaneous chain reaction and the means for adequate heat removal from nuclear materials, the ecological consequences of the accident will be essentially weaker than from a high-hypothetical accident at a NPP reactor.
- The accident initiated by the above causes at a present day plant for reprocessing irradiated fuel can evidently have an ecological impact comparable with that due to a high-hypothetical accident at a NPP reactor.
- The ways of increasing the ecological safety of NFC facilities are the use of strong mechanical protection for the process areas where plutonium and concentrated fission products are handled as well as for underground storage reservoirs containing high-level liquid waste and the development of compact, non-aqueous methods of reprocessing spent fuel.
- According to rough estimations the construction of an additional reinforced concrete shield in some process areas will increase the total capital expenditures for the plant by 10–20% . The shield might be needed at plants for uranium enrichment, fuel assembly fabrication and reprocessing of spent fuel. The costs of the three components of a NFC amount to about 60% of the total cost of the NFC. If the capital expenditures are assumed to be half of the cost of the whole process stage, then the additional shield will lead to an increase in the total cost of the NFC by $(10 - 20) \times 0.6 \times 0.5 = 6$–9%. Bearing in mind that the contribution of the NFC to the price of generated electricity is approximately a third, it is possible to conclude that the above measures will cause an increase in the cost of electricity by 2–3%.

7 Conclusion

In this paper some economic aspects of ecological risk due to electricity production from coal-fired power plants and nuclear power plants are investigated which relate to specific conditions in the USSR. These conditions are mainly determined by the Chernobyl nuclear power plant disaster which caused many people to be skeptical and even hateful towards nuclear power. This is a picture similar to the one in the USA after the "Three Mile Island Accident". But in the USSR a peculiarity appears which is caused by social changes in the country. This agitates the public's perception of nuclear power as all of the negative information associated with nuclear industry which was previously hidden, suddenly fell on the public. At the same time the policy of openness in the mass media resulted in very strong public concern about pollution due to organic fuel fired power plants, which indeed in some areas of the USSR, are several times higher than present day sanitary limits. These obstacles make it necessary to reconsider the strategy of power generation in the country.

At present nuclear power plant safety and, particularly, safety as regards hypothetical accidents, has become the central problem determining the future of nuclear power development [1].

The development of safer new nuclear reactors both in the USSR and abroad, which could satisfy the requirements of enhanced and ultimate safety, could be regarded as the answer to this challenge of the community engaged in nuclear power. At present there is a wide spectrum of improved designs and suggestions on both the old and new reactor types. [2]

It seems obvious (particularly relative to the conventional directions in reactor designing) that enhancement of NPP safety would inevitably result in the essential increase of their costs. The question is to what extent this cost increase could be acceptable. Where is the end of the NPP compatibility even when it satisfies the highest safety requirements? To answer these questions it is important to estimate the admissibility of various measures suggested for increasing the safety of existing reactors as well as for understanding and formulating the priorities in the development of new conceptual designs. [3]

The main conclusion from the calculations presented in Section 4 is the following:

- equal efficiency in coal-fired power plant provided with proper environmental protection equipment leads to an additional reserve in the capital cost of a NPP which could be spent for environmental and safety protection of a present day NPP and its fuel cycle facilities.

The reserve for the European part of the USSR is estimated to be 40–50% relative to a NPP based on present day VVER-type nuclear reactors.

The question arises whether this margin is enough to reach an acceptable level of safety. The investigation of the environmental costs of the normal operation of nuclear power plant and its fuel cycle facilities and that of accidental risk from an off-reactor nuclear fuel cycle shows that up to a half of this margin should be consumed for these purposes. So a margin of about 25–55% still exists of present day levelized costs of electricity production from a NPP in the West European part of the USSR which could be spent for the radical improvement of safety of a NPP per se.

We restrict ourselves from judging how much new measures to reduce accidental risk from a NPP will cost because there are now many uncertainties in these estimates.

We finish by stating that there are not large, but still some, reserves which could be spent for NPP safety and this challenges nuclear scientists and engineers to give nuclear power a second breath.

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Appendix: Tables and Figures

Table 4.1: Marginal cost of energetic coal for different economic regions of the USSR, roubles/t of eq. fuel

Economic regions of the USSR	Marginal cost
Urals	39
Middle Volga	45
Central	50
Rostov Region, East Ukraine	55
West Ukraine, Moldova	58
North-West of Russia	51
Central Chernozem Region	51

Table 4.2: Summary of Levelized Discounted Electricity Generation Costs for the Reference Case (discount rate p = 0.1 1/yr.; lifetime 30 years), cop/(kW · hr)

Economic region of the USSR	COAL										NUCLEAR				Ratio Coal/ Nuclear		
	Investment			O & M			Fuel	Total			Invest-ment	O & M	Fuel	Total			
	K,rub/kW			K,rub/kW				K,rub/Kw							k,rub/kW		
	200	330	500	200	330	500		200	330	500					200	330	500
Urals	0.33	0.54	0.81	0.31	0.51	0.77	1.31	1.95	2.36	2.89	0.83	0.55	0.64	2.02	0.97	1.17	1.44
Middle Volga	"	"	"	"	"	"	1.51	2.15	2.56	3.09	"	"	"	"	1.07	1.27	1.54
Central	"	"	"	"	"	"	1.68	2.32	2.73	3.26	"	"	"	"	1.15	1.36	1.63
Rostov Region, East Ukraine	"	"	"	"	"	"	1.85	2.49	2.90	3.43	"	"	"	"	1.24	1.45	1.71
West Ukraine, Moldova	"	"	"	"	"	"	1.95	2.59	3.0	3.53	"	"	"	"	1.29	1.50	1.77
North-West of Russia	"	"	"	"	"	"	1.70	2.34	2.75	3.28	"	"	"	"	1.16	1.37	1.64
Central Chernozem Region	"	"	"	"	"	"	1.70	2.34	2.75	3.28	"	"	"	"	1.16	1.37	1.64

Table 4.3: Summary of Levelized Discounted Electricity Generation Costs for Variant (discount rate p = 0.1 1/yr.; lifetime 25 years), cop/(kW · hr)

Economic region of the USSR	COAL										NUCLEAR				Ratio Coal/ Nuclear		
	Investment			O & M			Fuel	Total			Invest-ment	O & M	Fuel	Total			
	K,rub/kW			K,rub/kW				K,rub/Kw							k,rub/kW		
	200	330	500	200	330	500		200	330	500					200	330	500
Urals	0.34	0.56	0.84	0.31	0.51	0.77	1.31	1.96	2.38	2.92	0.86	0.55	0.64	2.05	0.96	1.16	1.42
Middle Volga	"	"	"	"	"	"	1.51	2.16	2.57	3.12	"	"	"	"	1.06	1.25	1.52
Central	"	"	"	"	"	"	1.68	2.30	2.74	3.29	"	"	"	"	1.16	1.33	1.60
Rostov Region, East Ukraine	"	"	"	"	"	"	1.85	2.50	2.81	3.46	"	"	"	"	1.24	1.42	1.67
West Ukraine, Moldova	"	"	"	"	"	"	1.95	2.60	3.01	3.56	"	"	"	"	1.27	1.47	1.73
North-West of Russia	"	"	"	"	"	"	1.70	2.35	2.76	3.31	"	"	"	"	1.15	1.34	1.61
Central Chernozem Region	"	"	"	"	"	"	1.70	2.35	2.76	3.31	"	"	"	"	1.15	1.34	1.61

Table 4.4: Summary of Levelized Discounted Electricity Generation Costs for Variant (discount rate p = 0.1 1/yr.; lifetime 50 years), cop/(kW · hr)

Economic region of the USSR	COAL										NUCLEAR				Ratio Coal/ Nuclear		
	Investment			O & M			Fuel	Total			Invest-ment	O & M	Fuel	Total			
	K,rub/kW			K,rub/kW				K,rub/Kw							k,rub/kW		
	200	330	500	200	330	500		200	330	500					200	330	500
Urals	0.31	0.51	0.77	0.31	0.51	0.77	1.31	1.93	2.33	2.85	0.79	0.55	0.64	1.98	0.98	1.18	1.44
Middle Volga	"	"	"	"	"	"	1.51	2.13	2.53	3.05	"	"	"	"	1.08	1.28	1.56
Central	"	"	"	"	"	"	1.68	2.30	2.70	3.22	"	"	"	"	1.17	1.38	1.65
Rostov Region, East Ukraine	"	"	"	"	"	"	1.85	2.47	2.87	3.39	"	"	"	"	1.26	1.46	1.72
West Ukraine, Moldova	"	"	"	"	"	"	1.95	2.57	2.97	3.49	"	"	"	"	1.30	1.49	1.77
North-West of Russia	"	"	"	"	"	"	1.70	2.32	2.72	3.24	"	"	"	"	1.18	1.39	1.66
Central Chernozem Region	"	"	"	"	"	"	1.70	2.32	2.72	3.24	"	"	"	"	1.18	1.39	1.66

Table 4.5: Summary of Levelized Discounted Electricity Generation Costs for Variant (discount rate p = 0.1 1/yr.; lifetime 30 years), cop/(kW · hr)

Economic region of the USSR	COAL										NUCLEAR				Ratio Coal/ Nuclear		
	Investment			O & M			Fuel	Total			Invest- ment	O & M	Fuel	Total			
	K,rub/kW			K,rub/kW				K,rub/Kw							k,rub/kW		
	200	330	500	200	330	500		200	330	500					200	330	500
Urals	0.39	0.65	0.97	0.31	0.51	0.77	1.31	2.01	2.47	3.05	1.00	0.55	0.64	2.19	0.92	1.13	1.39
Middle Volga	"	"	"	"	"	"	1.51	2.21	2.67	3.25	"	"	"	"	1.01	1.22	1.49
Central	"	"	"	"	"	"	1.68	2.38	2.84	3.42	"	"	"	"	1.09	1.30	1.57
Rostov Region, East Ukraine	"	"	"	"	"	"	1.85	2.55	3.01	3.59	"	"	"	"	1.16	1.37	1.64
West Ukraine, Moldova	"	"	"	"	"	"	1.95	2.65	3.11	3.69	"	"	"	"	1.21	1.42	1.69
North-West of Russia	"	"	"	"	"	"	1.70	2.40	2.86	3.44	"	"	"	"	1.10	1.31	1.58
Central Chernozem Region	"	"	"	"	"	"	1.70	2.40	2.86	3.44	"	"	"	"	1.10	1.31	1.58

Table 4.6: Summary of Levelized Discounted Electricity Generation Costs for Variant (discount rate p = 0.1 1/yr.; lifetime 30 years), cop/(kW · hr)

Economic region of the USSR	COAL										NUCLEAR				Ratio Coal/ Nuclear		
	Investment			O & M			Fuel	Total			Invest- ment	O & M	Fuel	Total			
	K,rub/kW			K,rub/kW				K,rub/Kw							k,rub/kW		
	200	330	500	200	330	500		200	330	500					200	330	500
Urals	0.39	0.63	0.95	0.31	0.51	0.77	1.31	2.01	2.45	3.03	0.97	0.55	0.64	2.16	0.93	1.13	1.40
Middle Volga	"	"	"	"	"	"	1.51	2.21	2.65	3.23	"	"	"	"	1.02	1.22	1.49
Central	"	"	"	"	"	"	1.68	2.38	2.82	3.40	"	"	"	"	1.10	1.30	1.57
Rostov Region, East Ukraine	"	"	"	"	"	"	1.85	2.55	2.99	3.57	"	"	"	"	1.17	1.38	1.65
West Ukraine, Moldova	"	"	"	"	"	"	1.95	2.65	3.09	3.67	"	"	"	"	1.22	1.43	1.70
North-West of Russia	"	"	"	"	"	"	1.70	2.40	2.88	3.42	"	"	"	"	1.11	1.31	1.58
Central Chernozem Region	"	"	"	"	"	"	1.70	2.40	2.88	3.42	"	"	"	"	1.11	1.31	1.58

Table 4.7: Summary of Levelized Discounted Electricity Generation Costs for Variant (discount rate p = 0.1 1/yr.; lifetime 50 years), cop/(kW · hr)

Economic region of the USSR	COAL										NUCLEAR				Ratio Coal/ Nuclear		
	Investment			O & M			Fuel	Total			Invest-ment	O & M	Fuel	Total			
	K,rub/kW			K,rub/kW				K,rub/Kw							k,rub/kW		
	200	330	500	200	330	500		200	330	500					200	330	500
Urals	0.37	0.61	0.92	0.31	0.51	0.77	1.31	1.99	2.43	3.00	0.94	0.55	0.64	2.13	0.93	1.14	1.41
Middle Volga	"	"	"	"	"	"	1.51	2.19	2.63	3.20	"	"	"	"	1.03	1.23	1.50
Central	"	"	"	"	"	"	1.68	2.36	2.80	3.37	"	"	"	"	1.11	1.31	1.58
Rostov Region, East Ukraine	"	"	"	"	"	"	1.85	2.53	2.97	3.54	"	"	"	"	1.19	1.39	1.66
West Ukraine, Moldova	"	"	"	"	"	"	1.95	2.63	3.07	3.64	"	"	"	"	1.23	1.44	1.71
North-West of Russia	"	"	"	"	"	"	1.70	2.38	2.82	3.39	"	"	"	"	1.12	1.32	1.59
Central Chernozem Region	"	"	"	"	"	"	1.70	2.38	2.82	3.39	"	"	"	"	1.12	1.32	1.59

Table 4.8: Summary of Levelized Discounted Electricity Generation Costs for Variant (discount rate p = 0.1 1/yr.; lifetime 25 years), cop/(kW · hr)

Economic region of the USSR	COAL										NUCLEAR				Ratio Coal/ Nuclear		
	Investment			O & M			Fuel	Total			Invest- ment	O & M	Fuel	Total			
	K,rub/kW			K,rub/kW				K,rub/Kw							k,rub/kW		
	200	330	500	200	330	500		200	330	500					200	330	500
Urals	0.21	0.35	0.53	0.31	0.51	0.77	1.31	1.83	2.17	2.61	0.55	0.55	0.64	1.74	1.05	1.25	1.57
Middle Volga	"	"	"	"	"	"	1.51	2.03	2.37	2.81	"	"	"	"	1.17	1.36	1.62
Central	"	"	"	"	"	"	1.68	2.19	2.56	2.98	"	"	"	"	1.26	1.47	1.71
Rostov Region, East Ukraine	"	"	"	"	"	"	1.85	2.39	2.71	3.15	"	"	"	"	1.37	1.56	1.81
West Ukraine, Moldova	"	"	"	"	"	"	1.95	2.49	2.81	3.25	"	"	"	"	1.43	1.62	1.87
North-West of Russia	"	"	"	"	"	"	1.70	2.22	2.51	3.00	"	"	"	"	1.27	1.48	1.72
Central Chernozem Region	"	"	"	"	"	"	1.70	2.22	2.51	3.00	"	"	"	"	1.27	1.48	1.72

Table 4.9: Summary of Levelized Discounted Electricity Generation Costs for Variant (discount rate p = 0.1 1/yr.; lifetime 30 years), cop/(kW · hr)

Economic region of the USSR	COAL										NUCLEAR				Ratio Coal/ Nuclear		
	Investment			O & M			Fuel	Total			Invest-ment	O & M	Fuel	Total			
	K,rub/kW			K,rub/kW				K,rub/Kw							k,rub/kW		
	200	330	500	200	330	500		200	330	500					200	330	500
Urals	0.19	0.33	0.49	0.31	0.51	0.77	1.31	1.81	2.15	2.57	0.50	0.55	0.64	1.69	1.07	1.27	1.53
Middle Volga	"	"	"	"	"	"	1.51	2.01	2.34	2.77	"	"	"	"	1.20	1.39	1.64
Central	"	"	"	"	"	"	1.68	2.18	2.51	2.94	"	"	"	"	1.29	1.49	1.74
Rostov Region, East Ukraine	"	"	"	"	"	"	1.85	2.35	2.68	3.11	"	"	"	"	1.39	1.59	1.84
West Ukraine, Moldova	"	"	"	"	"	"	1.95	2.45	2.78	3.21	"	"	"	"	1.45	1.65	1.90
North-West of Russia	"	"	"	"	"	"	1.70	2.20	2.53	2.96	"	"	"	"	1.30	1.49	1.74
Central Chernozem Region	"	"	"	"	"	"	1.70	2.20	2.53	2.96	"	"	"	"	1.30	1.49	1.74

Table 4.10: Summary of Levelized Discounted Electricity Generation Costs for Variant (discount rate p = 0.1 1/yr.; lifetime 50 years), cop/(kW · hr)

Economic region of the USSR	COAL										NUCLEAR				Ratio Coal/ Nuclear		
	Investment			O & M			Fuel	Total			Invest-ment	O & M	Fuel	Total			
	K,rub/kW			K,rub/kW				K,rub/Kw							k,rub/kW		
	200	330	500	200	330	500		200	330	500					200	330	500
Urals	0.16	0.26	0.38	0.31	0.51	0.77	1.31	1.78	2.08	2.46	0.39	0.55	0.64	1.58	1.13	1.32	1.56
Middle Volga	"	"	"	"	"	"	1.51	1.98	2.28	2.66	"	"	"	"	1.26	1.45	1.68
Central	"	"	"	"	"	"	1.68	2.15	2.45	2.83	"	"	"	"	1.37	1.56	1.79
Rostov Region, East Ukraine	"	"	"	"	"	"	1.85	2.32	2.62	3.00	"	"	"	"	1.47	1.66	1.89
West Ukraine, Moldova	"	"	"	"	"	"	1.95	2.33	2.72	3.10	"	"	"	"	1.55	1.73	1.96
North-West of Russia	"	"	"	"	"	"	1.70	2.17	2.47	2.85	"	"	"	"	1.39	1.57	1.80
Central Chernozem Region	"	"	"	"	"	"	1.70	2.17	2.47	2.85	"	"	"	"	1.39	1.57	1.80

Table 4.11: The Influence of Construction Time on the Ratio of Levelized Discounted Electricity Generation Costs for the Reference Case

Economic region of the USSR	Ratio Coal/Nuclear								
	(Tcpp/Tnpp), year								
	K=200 rub/kW			K=330 rub/kW			K=500 rub/kW		
	0/0	5/5	4/6	0/0	5/5	4/6	0/0	5/5	4/6
Urals	0.97	0.93	0.91	1.17	1.14	1.11	1.43	1.42	1.37
Middle Volga	1.06	1.02	1.00	1.27	1.24	1.20	1.53	1.51	1.46
Central	1.15	1.10	1.07	1.36	1.32	1.28	1.61	1.59	1.54
Rostov Region, East Ukraine	1.23	1.18	1.15	1.44	1.39	1.36	1.70	1.67	1.62
West Ukraine, Moldova	1.28	1.23	1.20	1.49	1.44	1.40	1.75	1.72	1.66
North-West of Russia	1.16	1.11	1.08	1.36	1.32	1.29	1.62	1.60	1.55
Central Chernozem Region	1.16	1.11	1.08	1.36	1.32	1.29	1.62	1.60	1.55

Table 4.12: Upper permissible level of capital cost of NPP (equal efficiency of NPP and CPP)

Economic region of the USSR	K at NPP of enhanced safety, roubles/kW
Urals	580
Middle Volga	630
Rostov Region, East Ukraine	710
West Ukraine, Moldova	735
North-West of Russia	680
Central Chernozem Region	680

Table 5.1: Consumption of land and water for different stages of open NFC per GW(e) · year

NFC stage	Land,ha		Water, $10^6 m^3$	
	temporary	permanently	reusable	completely
Mining and reprocessing of uranium ore				
0.2-0.1%U	20-60	2.0	2.0	2.0
0.1%U	50-200	-	-	
Conversion to UF_6	0.13	0.01	0.01	
Isotope enrichment of uranium	0.15	-	55	
Manufacturing of fuel assemblies	0.02	-	0.03	0.03
NPP (per GW(e)):				
Tower cooling	30-60	0.5	-	20-45
Ponds cooling water	300-800	0.5	$(1/3-2)10^3$	17-30
Long term storage and burial of spent fuel assemblies	-	0.1		-

Table 5.2: Chemical products released to the environment with wastes at different NFC stages, ton/GW(e) · year.

Chemical products / Stage	SO_x	NO_x	CO	Aerosol	Hydro carbons	Fluorides
Mining	10	10	-	1	0.6	-
Ore processing	0.1	14	-	2	2	-
Conversion to UF_6 [1]	9	5	0.2	0.1	0.6	0.07
Isotope enrichment of uranium	1	9	-	0.6	0.1	0.04
Manufacturing of fuel assemblies	-	-	-	9	-	0.01
Total [2]	30	40	0.2	13	3.3	0.12
Production of electricity consumed in NFC [3]	1400	800	24	70	10	-

Chemical products / Stage	Dumping to hydrosphere					
	Sulphates	Nitrates	Chlorides	Fluorides	Na+Ca	NH
Mining	-	-	-	-	-	-
Ore reprocessing	-	-	-	-	-	-
Conversion to UF_6 [1]	14	0.2	4	0.2	14	4
Isotope enrichment of uranium	0.8	0.9	0.4	0.01	-	-
Manufacturing of fuel assemblies	-	-	-	-	-	0.02
Total	40 (83 m^3 of liquid wastes)					
Production of electricity consumed in NFC [2]	1.5×10^{-4} (liquid wastes)					

[1] At the first stage about 1t of NH is released into the atmosphere.

[2] All other NFC releases (dumping) of chemical products are insignificant.

[3] It is assumed that all electricity is produced at the coal power plants.

Table 5.3: Collective radiation doses for whole population of USSR created by continuous pollutant discharges from some links of NFC, man · rem/MW(e) · yr

Source	Collective dose	
	Local (1-100km)	Global (all country)
NPP	1.1×10^{-2}	6.8×10^{-2}
Fuel reprocessing	4.4×10^{-2}	1.2×10^{-1}
Mining	2.8×10^{-4}	
Hydrometallurgy	1.7×10^{-5} *	
Enrichment-uranium fuel fabrication	7.2×10^{-5}	

* the continuation of inhalated Rn-222 to the value of dose constitutes 75%.

Table 5.4: Collective radiation doses from NPPs (100 GW) and reprocessing plants as percentage (%) of that from natural background

Source	Collective dose	
	Local	Global
NPPs	3	0.03
Reprocessing plants	12.8	0.05

Table 5.5: Collective dose committments $S_E^{(d)}$ of public exposure by radioactive releases (dumping) from NFC with LWR in normal operation /28,29/.

NFC stage	$S_E^{(d)}$, man · rem/MW(E) · year
Head-end stage (from mining to fuel manufacturing)	≤ 0.01
NPP(VVER)	≤ 0.04* 0.1**
Back-end (fuel element storage)	≈ 0

* local and regional doses (≤ 1000km)
** global dose (entire world)

Table 5.6: Cost of land alienated for non-agricultural needs, 10^3 rouble/ha.

Region of the USSR	Type of alienated land*	
	I	II
North Russia (Karelia, Komi, Arkhangel'sk and Murmansk regions)	20-60	10-50
Non-Chernozem region (Mari, Vladimir, Vologda, Niznegorod regions...)	20-40	10-30
Central and Chernozem regions:		
- Chernozem	40-60	30-50
- other soils	20-50	10-30
North Caucasus, Rostov region, Ukraine:		
- Chernozem	70-90	60-70
- other soils	30-70	10-50
Kaliningrad, Leningrad, Moscow regions	40-100	20-80
South Urals, West and East Siberia, Far East of Russia	10-40	5-30

* I - arable land, afforestation, personal plots, hayfields and pastures after melioration.
II - hayfields and pastures.

Table 5.7: The discounted costs of safety, environmental protection for different NFC stages, 0.011 cop/kW · h)

Stage / Damage	Head-end	NPP	Back-end	Total NFC
Resources: - land - water	 0.5-6 0.03-0.1	 1-20 0.3-6	 10^{-3}-10^{-2} ---	 2-25 0.3-6
Chemical contamination	10^{-3}-10^{-2}	-	-	10^{-3}-10^{-2} (0.5)
Fog generation	-	0 - 20	-	0 - 20
Loss of fish	-	0 - 20	-	0 - 20
Radioactive contamination	0.006	0.06	-	0.06
Total damage	0.5-6	3.30*	0.01	4.40

* At the reactor stage of NFC the correct allowance for summarized damage from fog generation and consumption of natural resource is made.

Table 6.1. Change in the VVER-1000 fuel composition under irradiation. Burnup 40 GW · d/t

Fuel composition before irradiation, kg		Amount of burnt fuel, kg		Composition of irradiated fuel, kg	
U-238	956	U-238	27,5	U-238	928.5
U-235	44	U-235	32,1	U-235	11.9
				U-236	5.6
				Plutonium Isotopes	10.6
				Np-237	0.5
				Am-241,243	0.35
				Cm-244	0.02 5
				Fission nuclides	42.1
Total Enrichment	1000kg 4.4%	Total	59.6kg		

Table 6.2: Producers of enriched uranium

Firm, country	Process	Capacity in 1985, 10^6 SWU/yr	Price $ 1986 per SWU	Investment $ 1986 per SWU/yr	Power cost $ 1986 per SWU
DOE, USA	Gas diffusion	27.3	125-135	300-400	40-80
EURODIF, France	Gas diffusion	10.8	90-100	300-400	70-80
URENCO: Britain, Netherlands, FRG	Gas centrifuges	2	115-130	400-500	3-5
Techsnab-export, USSR	Gas diffusion	2.5*	100-125	Unknown	Unknown

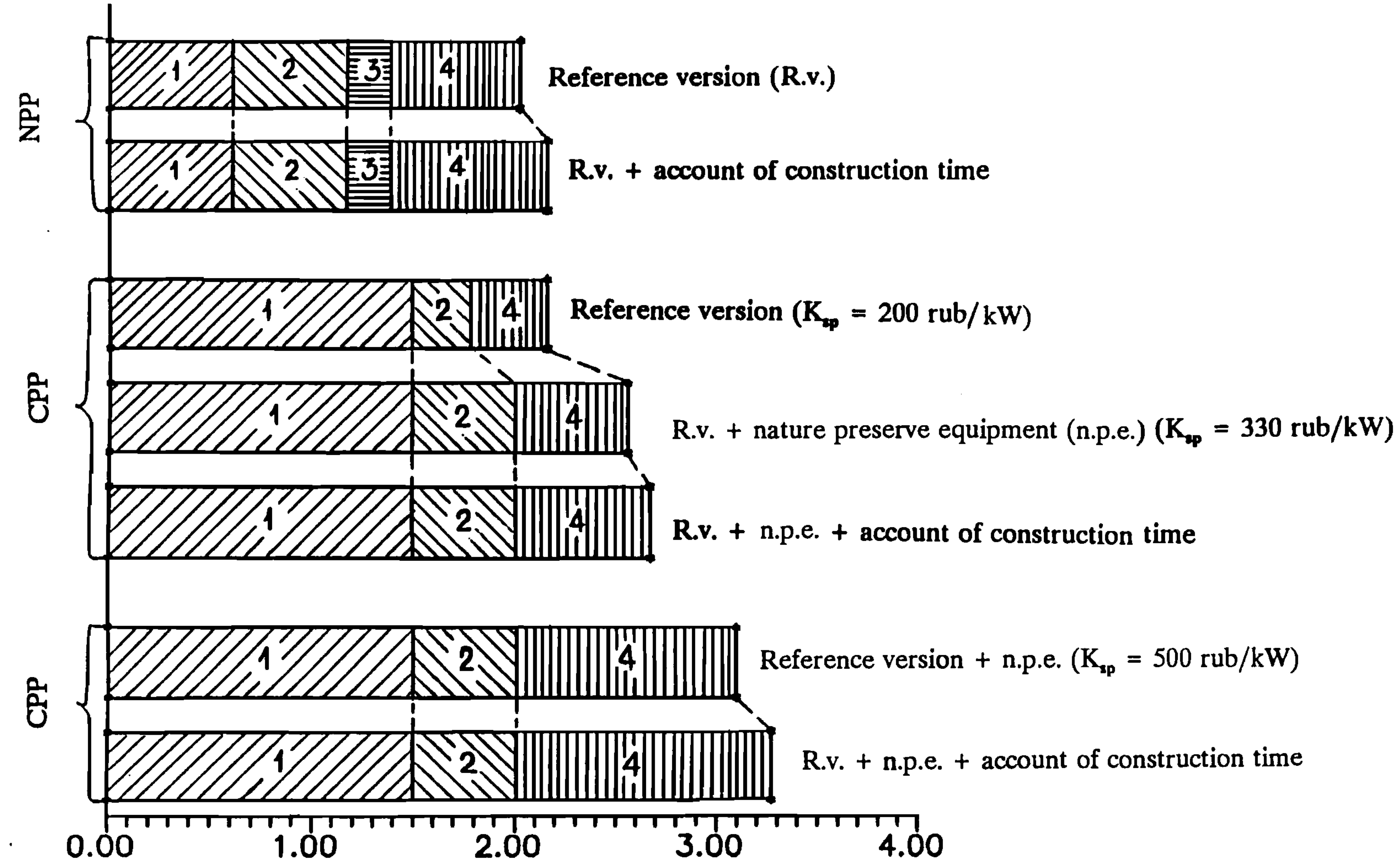
*Deliveries for export

Table 6.3: The comparison of the capital outlays for various enrichment techniques

Process	Capital outlays, $ per SWU/yr	Consumption of electricity kWh/SWU	Consumption of labor and materials
Gas diffusion	High (300-400)	High (2400)	Low
Gas centrifuges	High (400-500)	Low (100)	Low
Laser isotope separation	Low (100)	Low (100)	Low

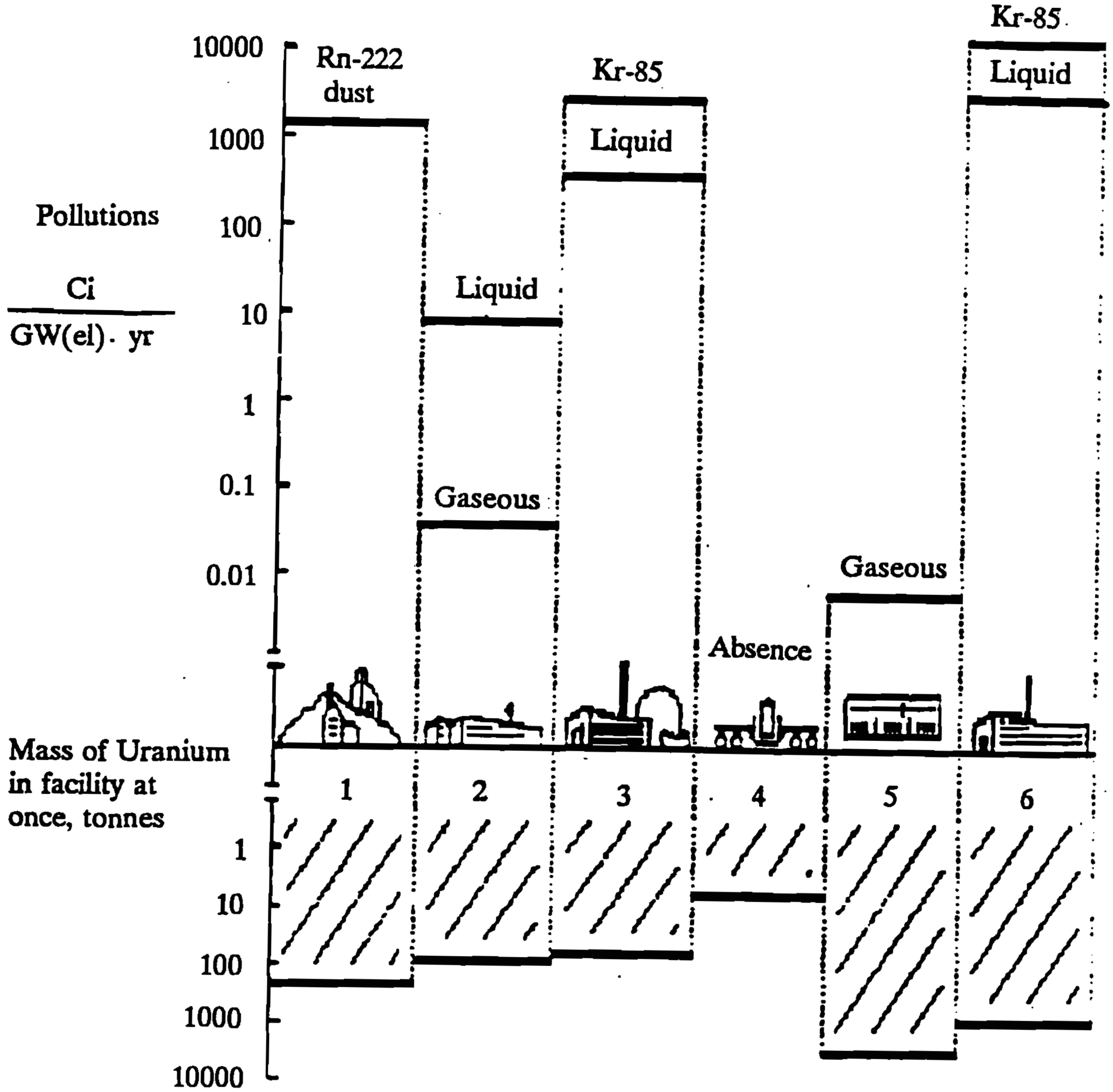
Table 6.4: The degree of potential risk from an accident to nuclear fuel cycle facilities

Facility	Degree of risk	
	Internally-initiated accident	Externally-initiated accident
Open-cast mining of uranium	Low	Medium
Underground mining of uranium	Very low	Low
Underground leaching of uranium	Very low	Very Low
Hydrometallurgy	Very low	Low
Isotopic uranium enrichment	Low	Medium-High
Enrichment-uranium fuel assembly fabrication	Low	Medium
MOX fuel assembly fabrication	Low	Medium-High
Transportation of spent fuel	Very Low	Low
Autonomous shallow interim storage of spent fuel	Low	Medium
Autonomous underground storage of spent fuel	Low	Low
Chemical reprocessing of spent fuel	Low-Medium	Medium-High



Components: 1 - fuel; 2 - operation; 3 - first core loading; 4 - capital

Figure 1: Specific discounted costs, cop/kW*hr



1 - open-case mines and mills
2 - uranium enrichment
3 - nuclear power plant
4 - shipment of spent fuel (SF)
5 - interim storage of SF
6 - chemical reprocessing of SF

Figure 2: Routine pollutions of the facilities of NFC