International safety review of WWER-440/230 nuclear power plants

A report on the IAEA's safety evaluation of older plants in Bulgaria, Czechoslovakia, and the Russian Federation

by F. Niehaus and L. Lederman

Over a 15-month period starting in early 1990, teams of specialists from 21 countries and the IAEA performed safety evaluations of 10 Soviet-designed nuclear plants operating in Bulgaria, Czechoslovakia, and the Russian Federation. The reviews were done within the framework of an IAEA programme initiated at the request of the respective national authorities.

Altogether, 10 plants — all of the type known as WWER-440/230 reactors — were evaluated: two at Bohunice in Czechoslovakia; four at Kozloduy in Bulgaria; and two each at Kola and Novovoronezh in the Russian Federation.

Results of the IAEA programme's first phase, which recently concluded, indicate that these plants have serious shortcomings in safety in comparison with international practices. At the same time, however, they have some features that make them less sensitive to disturbances than plants of other types. WWER-440/230 plants to date have collectively accumulated some 160 reactor-years of operation, with high availabilities that compare favourably with those of other plants.

Overall, the IAEA programme identified and ranked some 100 safety issues according to their significance for safety in four categories of increasing severity. Nearly 60% of these issues are of high safety concern and require immediate attention.

At all of these plants, to differing degrees, programmes for safety improvements are being pursued by the operating organizations. National regulatory bodies must recognize that before they can authorize continued operation of these plants, even for a limited period, there is a clear need for special operating regimes and interim compensatory measures to improve safety. In particular, this must include measures to maintain the existing positive safety features of this plant design.

Long-term operation of these plants would require the resolution of the safety concerns and the implementation of permanent, as opposed to interim, hardware and software safety backfits. Some of these actions would entail high costs and long construction times and would only be appropriate if long-term operation of these reactors is intended.

These factors, as well as other problems that could arise owing to ageing and which could severely curtail the foreseen plant lifetime, need to be carefully considered by the countries concerned before they decide on the future operation of WWER-440/230 plants.

All three countries have requested the IAEA to continue its programme on the safety of these reactors. The programme's second phase will concentrate on providing technical advice to ensure that safety improvements reflect the findings and recommendations that reviewers made during the first phase.

This article presents an overview of the IAEA's programme covering the 10 operating WWER-440/230 plants, and briefly looks at plans being discussed for its second phase.

Design concept review

In February 1991, the IAEA conducted a review of the design concept of WWER-440/230 plants. Thirty-two experts from 10 countries and three international organizations participated in the review.

Together with 25 specialists from Russia, they examined detailed information provided by

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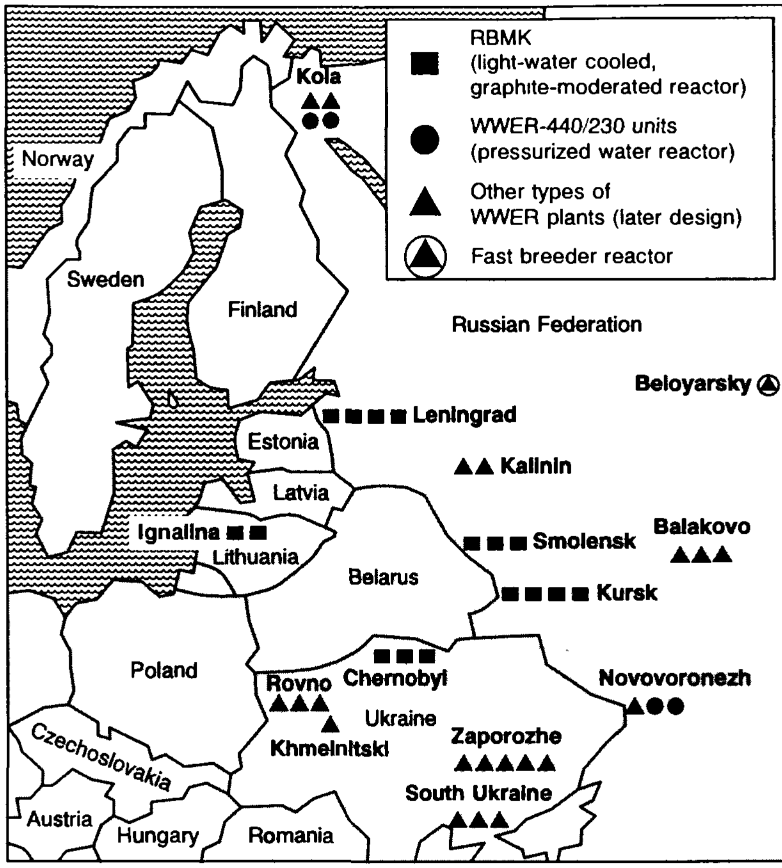
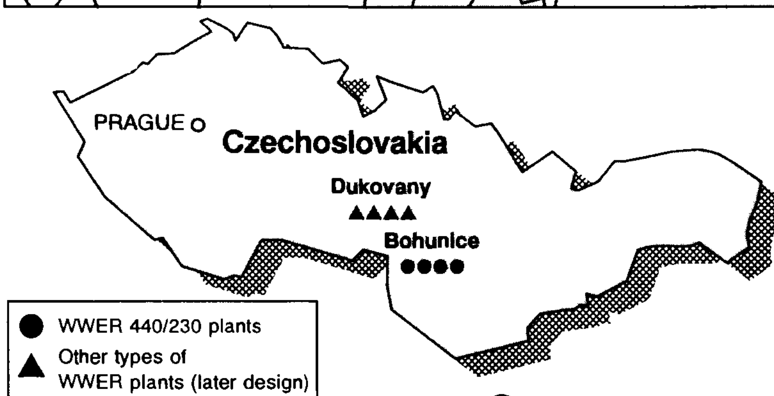
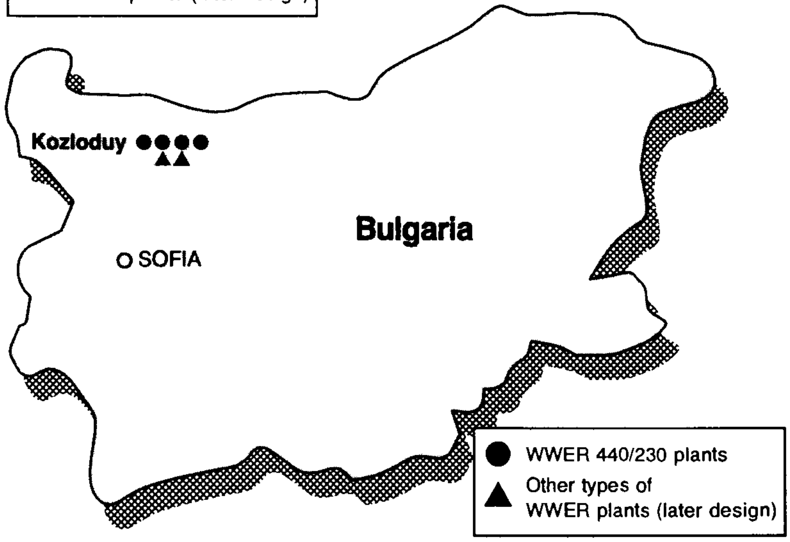
WWER-440/230 plants

	Plant	Unit	Start of operation
Operating			
Russian Federation	Novovoronezh	3	1971
		4	1972
	Kola	1	1977
		2	1980
Bulgaria	Kozloduy	1	1974
		2	1975
		3	1981
		4	1982
Czechoslovakia	Bohunice	1	1979
		2	1981
Shutdown			
Germany	Greifswald (shutdown 1990)	1	1974
		2	1975
		3	1978
		4	1979
Armenia	Armenia (shutdown 1989)	1	1973
		2	1975







The IAEA's programme on the safety of WWER-440/230 nuclear plants covered all 10 operating units of this specific design in the world. Two units in Armenia and four in the eastern part of Germany previously had been shut down. Four of the operating WWER-440/230 units are in Bulgaria, two in Czechoslovakia, and four in the Russian Federation. Also operating in these countries are Soviet-designed nuclear reactors of other types. (*See maps.)*

All types of Soviet-designed nuclear plants represent about 15% of the world's operating reactors. The pressurized light-water reactors known as WWERs (water-cooled, water-moderated energy reactors) are the only type to have been exported. Altogether 44 WWER types of nuclear plants are in operation worldwide (Czechoslovakia, Finland, Hungary, Russian Federation, and Ukraine).

In Eastern European countries having WWER types of plants, the dependence on nuclear electricity is considerable. In 1991, the nuclear share of electricity production was 48.4% in Hungary, where four later model WWER plants are operating, 34% in Bulgaria, 28.6% in Czechoslovakia, and 12.6% in States of the former USSR.

designers and operators in the USSR. Use was also made of the results of other studies, including an investigation carried out for eastern Germany's Greifswald nuclear power plant in 1989, others performed in the USA, and the minimum requirements for backfitting and safe operation of WWER-440/230 plants prepared in 1989 by the regulatory bodies of Bulgaria, Czechoslovakia, the German Democratic Republic, and the USSR.

In general, the basic design was found to be conservative, showing evidence of the high priority given to plant availability. However, compared to the current practice in the case of other PWRs, the design basis (primary circuit break of 32 mm equivalent diameter) is very limited.

Overall, it was found that the degree of redundancy, diversity, and segregation was low in some of the reactor systems, thus making them susceptible to common-cause failures. For some systems and situations, reliance is put mainly on operator actions, leading to a high probability for human errors.

In addition, the design concept review pointed to differences between various WWER-440/230 plants, confirming the importance of plant specific safety reviews. It has also provided a valuable checklist of problems to be investigated during the safety review missions.

Safety review missions

Safety review missions were conducted at all four individual sites with WWER-440/230 plants in operation, namely: Bohunice, Units 1-2 (Czechoslovakia), 8-26 April 1991; Kozloduy, Units 1-4 (Bulgaria), 3-21 June 1991; Novovoronezh, Units 3-4 (Russian Federation), 12-30 August 1991; and Kola, Units 1-2 (Russian Federation), 9-27 September 1991.

In this series of on-site reviews, international teams of about 15 experts each have assessed not only the plant's specific design deficiencies but also the overall conduct of operations. The scope of the reviews included: core design; system analysis; mechanical and component integrity; instrumentation and control; electric power; accident analysis; fire protection; plant management and organization; quality assurance; operator training and qualification; conduct of operations; maintenance; technical support; and emergency planning.

Basic design deficiencies were confirmed; the value of a number of design strengths and specific plant modifications also became evident.

Moreover, major operational shortcomings were identified. There are serious problems with the effectiveness of management in identifying and correcting shortcomings in nuclear safety; deficiencies in the material conditions of equipment; and shortcomings in fire protection. Additionally, vital operating procedures are frequently incomplete and their use is not enforced. Training programmes are insufficient and there is a lack of adequate simulators.

The missions did not perform detailed reviews of the regulatory bodies of the countries visited. However, it became apparent when reviewing regulatory liaison with the plant that the regulatory role and practices need to be strengthened.

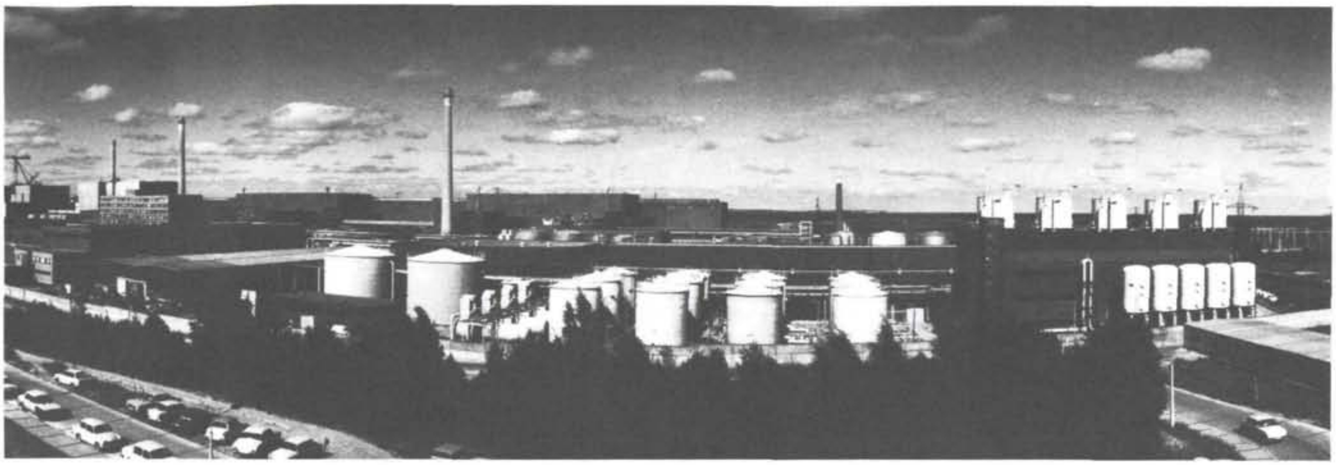
Of particular concern were the findings of the mission to Kozloduy in Bulgaria. On the basis of the findings in June 1991, the Director General of the IAEA wrote to the Prime Minister of Bulgaria and urged him to undertake the necessary steps to upgrade conditions to allow operation of the reactors even on an interim basis. The major shortcomings observed in Bulgaria, particularly those related to the material condition of equipment, were not evident on visits to plants of similar type in Czechoslovakia and in the Russian Federation.

In response to the situation at Kozloduy, an action plan based on a proposal by the World Association of Nuclear Operators (WANO) was worked out and is being implemented. The action plan, financed and supervised by the Commission of the European Communities (CEC), provides for a programme to solve generic safety problems; a programme to solve urgent housekeeping problems; co-operation arrangements with the Bugey nuclear power station in France; strengthening of the role of Bulgaria's regulatory body; and a study of the Bulgarian electricity supply system.

IAEA ASSET missions

The IAEA also carried out a series of missions under its Assessment of Safety Significant Event Team (ASSET) programme. Missions were sent to all 10 WWER-440/230 plants in operation and to Greifswald Units 1-4. The emphasis was on reviewing the operational experience accumulated at these plants, and to assess the appropriateness and thoroughness of corrective actions taken by plant management to prevent recurrences of incidents. In-depth analyses of root causes of selected operational events were performed.

Findings included recommendations to improve certain areas of equipment operability, personnel proficiency, and procedural adequacy; and to enhance plant programmes for the preven-



Greifswald nuclear plant in eastern Germany, which was shut down in 1990.

tion of incidents (i.e., quality control, preventive maintenance, surveillance, and feedback of operational experience). ASSET findings confirmed design deficiencies and operational problems reported by the safety review missions.

Seismic safety review missions

In addition, the IAEA carried out missions to the Bohunice and Kozloduy plants to review their safety with respect to seismic hazards. The original design of WWER-440/230 plants did not take into account external hazards, in particular earthquakes. For this reason, at least the two sites investigated have major weaknesses with respect to seismic hazards. Other external hazards have not been evaluated in detail.

Kozloduy. At Kozloduy, a seismic upgrading was started following an earthquake in Romania (Vrancea) in 1977, which induced an acceleration estimated at 0.1g at Kozloduy and which caused some damage to the plant. The same site was later affected by two other severe earthquakes with their origin at Vrancea, in 1986 and in 1990. On the basis of the IAEA review which included a plant walkdown, it was concluded that Kozloduy has major problems with regard to seismic safety, even for the minimum design acceleration of 0.1g recommended internationally for all nuclear power plant sites. Therefore, a reassessment of the design acceleration was recommended and is now being done.

Bohunice. At Bohunice, a maximum expected intensity corresponding to a design acceleration of 0.25g was adopted for the seismic level. It was based on actual recorded earthquakes with maximum ground acceleration ranges from 0.14g to 0.30g. Measures recommended by the Bohunice mission included a review of the anchorage of safety-related electrical cabinets, seismic ruggedness of on-site emergency power (e.g. diesels, batteries), and a seismically protected service water system.

Recommendations from both missions include the replacement of some plant equipment, the installation of additional supports, and the establishment of a basis for prioritizing upgrades related to seismic safety. It should be noted that, on the basis of the seismic walkdowns, a number of simple improvements can be implemented immediately to considerably enhance each plant's capability to withstand an earthquake.

Study of generic safety issues

An initial list of safety issues requiring broad studies of generic interest was agreed upon by the IAEA programme's advisory group in September 1990. The list was later revised in the light of the programme findings.

Still to be compiled is the information on the status of the issues, and on the amount of work already completed and under way in the various countries. Moreover, an evaluation of what further work is required to resolve each one of the issues is also necessary.

In view of this, the IAEA has started the preparation of a series of status reports on the various issues. The main objective is to provide a clear overview of each issue and of the remaining work before final conclusions can be reached. The reports should provide the basis for defining the scope of the required studies to resolve each generic safety issue. They will also compile information on the work already performed or under way in various countries, to prevent duplication of efforts.

Ranking of safety issues

An important part of the IAEA programme was the evaluation of the safety significance of

Area	Category			
	I	II	III	IV
Design				
Core		4		
Systems		5	7	3
Components		2	5	5
Instrumentation and control		4	7	1
Electrical		1	2	2
Accident analysis		4	5	
Fire protection			3	
Total (design)		20	29	11
Operation				
Management	2	3	6	2
Operational procedures		2	1	1
Plant operations	1	2	3	
Maintenance	1	2		1
Training	1	1	3	
Emergency planning		2	3	
Total (operation)	5	12	16	4
Total	5	32	45	15

Ranking of safety issues

the deficiencies identified during the design concept review and safety review missions. The technical knowledge and experience of the international experts who participated in the programme, together with generally accepted current safety principles and objectives such as IAEA Nuclear Safety Standards (NUSS) Codes and Guides and INSAG's Basic Safety Principles for Nuclear Power Plants, formed the basis for the reviews.

Issues related to both design and operation were ranked according to their safety significance in four categories of increasing severity:

Category I. Issues in Category I show a departure from recognized international practices. It may be appropriate to address them as part of actions to resolve higher priority issues.

Category II. Issues in Category II are of safety concern. Defense-in-depth is degraded. Action is required to resolve the issue.

Category III. Issues in Category III are of high safety concern. Defense-in-depth is insufficient. Immediate corrective action is necessary. Interim measures might also be necessary.

Category IV. Issues in Category IV are of the highest safety concern. The defense-in-depth is unacceptable. Immediate action is required to resolve the issue. Compensatory measures have to be established.

To assist the governments of Czechoslovakia, Bulgaria, and the Russian Federation in setting priorities for the corrective measures required at their plants, two programme review meetings were convened by the IAEA in August and October/November 1991. About 1300 specific safety items identified during the safety reviews and in the design concept review were grouped in broader categories representing some 100 safety issues. To facilitate the analysis and consolidation of findings, the results have been compiled in a computerized database.

The meeting report was prepared by an international group of experts and the IAEA staff, and it was reviewed by the programme's Steering Committee. The report evaluates the safety significance of the issues and provides the technical basis for short- and long-term programmes required to improve the safety of WWER-440/230 plants.

Major findings and recommendations

The programme's major findings and recommendations generally are related to design, operations, operational experience, and seismic protection. A brief overview of selected aspects is presented here.

Common-cause failures. The potential for common-cause failures affecting the core decay heat removal is high owing to the layout and design characteristics of the WWER-440/230 reactor. Most systems are installed in the same machine hall without sufficient segregation. Their main components are cooled by the service water system, which is common to two units. There is no segregation in the layout between control and electric supply cables of redundant equipment. The main control room is near the machine hall and no appropriate remote shutdown panel is provided.

Consequently, a common cause such as a fire could destroy or prevent the functioning of equipment items that are close together in the turbine hall (common to both units). In view of the operating experience of the WWERs, the probability of such an event is not negligible. It is deemed necessary to install an alternative means outside the machine hall for supplying feedwater.

A fire in a cable gallery could result in a total unavailability of the electric sources feeding the decay heat removal systems. This type of event happened twice at these types of plants: at Greifswald (1975) and at Armenia (1982). After the fire at Armenia, a solution to cope with such an event was designed and implemented. The same type of solution was implemented at Kola and at Bohunice. It consists of a network of power cables with a separate and independent layout from all other cables. Such a modification or an alternative solution should be completed in Novovoronezh and implemented in Kozloduy. In addition, fire protection should be improved in the short term on all sites, especially in the areas of cable galleries and cable trays, with the objective of improving the prevention of common-cause failures of all safety functions.

Additionally, a natural event, such as an earthquake, could affect the source of service water. Potential single failures could result in the complete loss of the service water system. In addition, the service water system pumps, common to two units, are installed close together in the same building. The failure of the service water system would cause a consequent loss of the decay heat removal systems. The diesels which are cooled by service water would also be unavailable. In this case, the only source of electric power left would be the external grid which might also be lost when the plant is unexpectedly shut down.

Interim measures should be taken to reduce the probability of complete loss of service water. These might include improved fire and flooding protection and upgraded inspections, surveillance, and maintenance of the system.

Control room. The main control room is close to the machine hall, and there is a potential for adverse environmental conditions due to steam or a fire, for example. Consequently, modifications to the control room should be made to increase its habitability in accident conditions and to protect it from external hazards. In addition, a remote shutdown panel should be installed sufficiently far away from the control room not to be affected by the same extreme environmental conditions. This panel would allow the operator to keep the plant in safe shutdown conditions.

Accident prevention. Preserving the integrity of the primary circuit is one of the main safety objectives in the area of accident prevention. Therefore, most of the issues related to this topic were ranked in Categories III and IV. They included:

- *Reactor pressure vessel integrity.* Irradiation by high energy neutrons has caused reactor vessel wall embrittlement, especially in the circular weld at the elevation of the reactor core. Some measures have been taken to slow the rate of embrittlement, and others are being studied.
- *Primary circuit integrity.* A major safety concern is the fact that the WWER-440/230 plants are not designed to cope with a primary circuit break of more than 32 mm equivalent diameter. Therefore, it is of high importance to demonstrate that it is possible to detect defects in the primary circuit piping that could evolve into a break. An analysis of the applicability of the leak before break concept is needed. In addition, it is necessary to install and calibrate adequate leak detection systems. Major efforts are required in this area in the short term.
- *Protection against over-pressure.* Protection of the primary circuit against over-pressure is provided by the pressurizer safety valves. These valves are generally pilot operated valves. They are not qualified for water or water-steam mixtures. This means that the primary circuit is not well protected during periods when the pressurizer is full of water and the primary circuit is still closed. Moreover, some of these valves do not fulfil seismic requirements and the layout is such that the potential for common-cause failures cannot be disregarded.

Instrumentation and control (I&C). It was observed in safety review missions that excessive demands are placed on operators, especially in transient conditions, owing to insufficient information, centralization, and automation. Therefore, a control-room design review, based on the accomplishment of main safety functions, needs to be performed to determine what modifications and what additional devices (e.g. a computerized safety parameter display system) would help the operator significantly in an emergency. Operation of the emergency systems should not be inhibited by equipment protection signals or manual actions, at least within a specified time after the initial I&C signal. The most urgent cases where changes in the approach to equipment protection should be made are already known and concern the diesels, the safety injection pumps, and the confinement spray pumps.

Electric power supply. There are two programmes of diesel loading providing for the potential loss of external power and the loss of primary coolant with loss of external power. In the latter case, two out of three diesels are necessary. This introduces, at the level of the diesel load sequencers, a potential for common cause failure of both trains of diesel generators. To prevent this type of failure, a strict independence between the two trains should be effected. The auxiliaries vital to the diesels would also have to be organized in two trains. These include at least I&C, the startup system, the fuel and oil supply, cooling water and batteries. This issue should be addressed with high priority. Short-term compensatory measures have to be implemented, particularly in the areas of fire protection and of surveillance and maintenance operating procedures. The direct-current supplied by the batteries has the potential of common-cause failures, and the design does not fulfill the single-failure criteria. Moreover, reversible motor generators have shown poor reliability and should be replaced by separate battery chargers and invertors.

Fire protection. Poor design with regard to fire protection of the station buildings and of the layout of systems, and poor housekeeping habits, create a significant risk of fire with a potential for failure of whole safety functions in the WWER-440/230 plants.

In the area of fire prevention, flammable material used for the roofs, floor coverings, wall painting, and cable coatings should be replaced by non-flammable material. As an interim measure, sections of roofs or floors or walls covered with flammable material should be divided by means of non-flammable strips.

More generally, an inventory of all flammable material of the plant should be performed and adequate measures taken (such as the installation of automatic fire detection and extinguishing systems) to limit the risk of fire.

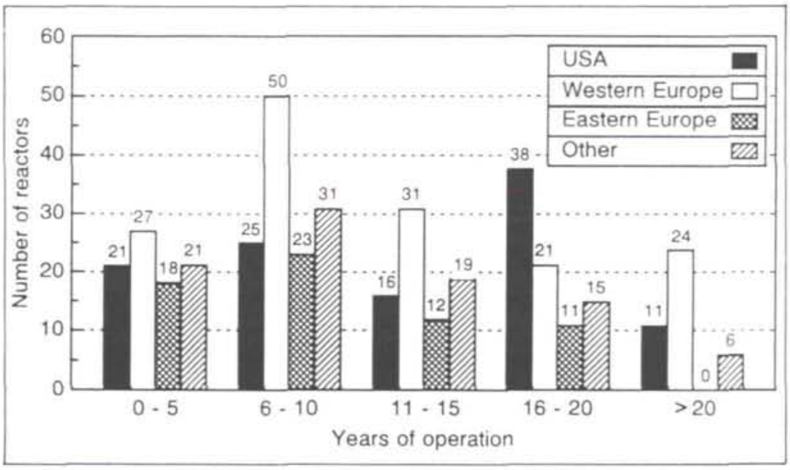
With respect to fire detection, only areas such as transformers, cable corridors, and diesels are covered. Other sites with high fire risks or with high safety consequences in the event of fire, such as the turbine oil tanks, the safety injection pump room, the reactor hall, the service water pump building, or even the main control room are generally not equipped with fire detection systems.

In all areas where a fire would have severe consequences for safety, automatic fire detection and extinguishing systems should be installed. A preferable long-term measure would be relocation or new installation of redundant equipment into different, separated fire areas.

Accident analysis. Most issues discussed indicate the need for accident analysis. A systematic approach to accident analysis is necessary to ensure that all relevant accidents or transients have been evaluated and that the analyses consider appropriate levels of detail, data and boundary conditions, application of the single failure criterion, assumptions concerning operator action, and common mode failures. Accidents not considered so far, including accidents beyond the design basis, and confinement analysis, should be included.

Conduct of operation. There are significant differences between the operating practices at WWER-440/230 plants and international practices, largely because the WWER operators were isolated from the international community until recently. The safety review missions concluded that immediate attention is needed at the plants to improve the approach to operations, to improve the standards of maintenance, and to instill a higher sense of safety awareness in their staff. In a number of instances, the key elements necessary to establish a safety culture were missing. While many of the design issues will take many months or years to fully solve and implement, most of the operational issues can be addressed immediately at the plant level.

Operating nuclear plants grouped by years of operation



The programme's next phase

The IAEA is in a unique position among intergovernmental organizations for the work ahead. This stems from its long-standing co-operation with Eastern European countries, and the experience gained in the framework of the WWER-440/230 programme, coupled with a range of regular safety services and activities. The IAEA is able to provide the necessary technical advice to ensure both that the assistance programmes respond to genuine safety needs and that priorities are consistent with long-term safety requirements being developed at the international level.

The programme's second phase, therefore, will focus on helping countries make the best use of assistance they receive through, for example, the CEC and WANO. Such assistance should be in line with the recommendations of this programme's first phase and should not duplicate work already completed or initiated internationally or within the framework of national programmes. An important feature of such assistance will be the role of national regulatory bodies and the strengthening of the technical capabilities.

It further has been suggested that the IAEA participate in the co-ordination between the OECD group of 24 countries as a special technical adviser for identifying priorities and providing technical recommendations. Presently, to varying degrees, programmes for safety improvements are being pursued at each of the 10 plants reviewed by the IAEA.

The scope of activities started in 1992 focus on three major areas where assistance is required: the resolution of problems specific to each plant and country; study of generic safety issues; and co-ordination with other bilateral and international programmes.

In co-operation with the CEC, the IAEA intends to establish and manage a centralized database where all assistance programmes related to nuclear safety in Eastern Europe would be registered. The database should include a comprehensive registry of the safety issues, and any programmes that are initiated, planned, or completed. Relevant data should include information about the organizations involved, programme objectives, scope, schedules, levels of effort and costs, and anticipated results. The IAEA will be available for technical advice so that specific proposals can be more easily approved and monitored by organizations providing financial support.

Additionally, the IAEA has undertaken a number of other activities related to the safety of older nuclear plants having Soviet-designed reactors. They include continuation of a technical co-operation programme to develop a safety analysis for WWER-440/213 plants; an international programme on the safety of RBMK reactors; and a programme on the safety of WWER-1000 nuclear plants. ❒

Programme direction, scope, and support

The IAEA's international programme for assisting countries operating Soviet-designed WWER-440/230 plants is designed to complement other relevant national, bilateral, and multilateral activities. The programme is extrabudgetary and depends on voluntary contributions from Member States and organizations. *(See table.)*

The fundamental objective is to provide assistance for performance of comprehensive safety reviews to identify design and operational weaknesses that need to be corrected. The reviews form the technical basis for decisions on enhancing safety that must ultimately be taken by the countries operating those plants.

The programme was initiated following an advisory group meeting in September 1990 to establish the technical scope and a work programme. The meeting had 42 participants from 19 Member States and from the Commission of the European Communities (CEC) and the World Association of Nuclear Operators (WANO).

The agreed programme included:

- a review of the design concept in order to obtain an overview of the safety aspects of WWER-440/230 plants;
- safety review missions by teams of international experts to the individual reactor sites in order to evaluate plant specific design deficiencies and the conduct of operations, maximum use being made of the IAEA's experience in the provision of safety services — particularly through Operational Safety Review Teams (OSART) and Assessment of Safety Significant Events Teams (ASSET) missions; and
- studies on matters of generic safety concern such as reactor pressure vessel embrittlement, the applicability of the leak before break concept, accident analysis re-evaluations using modern computer codes, and the conduct of probabilistic safety assessments.

A Steering Committee with delegates from Bulgaria, Czechoslovakia, France, Germany, Spain, Switzerland, United Kingdom, and the Russian Federation was established to monitor the programme and to provide technical guidance on the resolution of safety issues and the prioritization of activities. The United States joined the Steering Committee in October 1991

Observers from the Nuclear Energy Agency of the Organisation for Economic Co-operation and Development (NEA/OECD), the CEC, WANO, and the World Bank regularly attend meetings of the Steering Committee, and the International Nuclear Safety Advisory Group has established a subgroup in this area.

Country/ International organizations	Amount (US dollars)	Contribution (man-days)
Argentina		6
Austria	32 500	10
Belgium		56
Bulgaria		61
Canada		32
Czechoslovakia		75
Finland		151
France		454
Germany	156 000	260
Hungary		48
Italy		32
Japan		50
Netherlands	175 000	20
Norway	3 000	
Russian Federation		404
South Africa		20
Spain	150 000	153
Sweden		12
Switzerland	76 500	96
United Kingdom	50 000	187
United States		206
Yugoslavia		20
CEC		106
OECD/NEA		21
WANO		67
World Bank		20
Total	643 000	2 567