SAFETY OF NPP WITH WWER-440 AND WWER-1000 REACTORS

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The objective of this paper is neither to evaluate the safety of WWER-reactors, nor to impose any requirements on the power plant. It just points out some facts and problems which had to be accounted for during the last years of operation of Kozloduy NPP.

At present in the world 420 nuclear units produce 17-18% of the electricity and 77 more units are under construction. The percentage of the nuclear energy in different countries varies in a very wide range. For example in France Nuclear power plants produce 75% of the electricity, in Belgium - 60%, in Hungary, Finland and Korea - 50%, in Bulgaria - approximately 35%, In former Chechoslovakia - about 30% and over 12% in the countries of the former USSR. It should be noted that most of the units in Western Europe are in operation, while in Eastern Europe are most of the units under construction. (Figs. 1, 2). The reactors designed in the former USSR are 15% of all reactors in operation and 42% of those under construction. Of all soviet designed reactors the majority are pressurised water reactors (WWER) and at present 44 of these are in operation and 25 under construction. The distribution of the reactors in the different regions of the world with respect to their age is given in Fig. 3.

At present 10 reactors WWER-440/230, 16 reactors WWER-440/213 and 18 reactors WWER-1000 of different modifications are in operation. These operated in Bulgaria are a considerable part of them (Fig. 4).

This statistics shows that 14% of all WWER reactor in operation are at Kozloduy NPP. The total power of Kozloduy NPP is 9% of all nuclear power installed in the eastern part of Europe.

WWER-440

The WWER-440/230 units are designed during the sixties, with the main objective of maximum electrical output and maximum availability. This is reflected in the design basis and later on in the technical solutions such as: low power density in the core; three levels of reactor control and protection before a reactor scram; six primary loops with primary isolation valves both in the hot and in the cold legs; horizontal steam generators with a relatively large water inventory; two turbines, allowing operation at different power levels; a large number of cross-unit connections. allowing common use of systems of neighbouring units.

On the other hand, the big safety margins of most of the technological parameters permit the successful restoration from many transients

The design basis of these unit allow maintenance as well as some repairs „on-line", which is also helped by the low radiation level of the units and the number of inter-unit connections. The applied design solutions, providing a convenient access to the equipment during operation and the operational practice giving a priority to a flexible mode of operation, result in relatively high availability of the units.

The design of the Kozloduy WWER-440 units is following the regulations of the former USSR during the sixties and seventies. These follow mainly a deterministic approach, so the WWER-440/230 units differ from the contemporary safety requirements, some of them not being fulfilled.

For this reason the safety concept of WWER-440/230 applied for its design is different from the modern safety concepts. Some of the major deviations are:

- A low level of the design basis accident;
- Insufficient configuration of the emergency core cooling systems to prevent core damage in case of a complete rupture of a primary loop;
- Common cause failures are not considered;
- Insufficiency of the last physical barrier to prevent radiological releases to the environment;
- Incomplete design solutions with respect to external events;
- Lack of a complete set of design solutions to minimise/prevent the consequences of human errors;

On the other hand the design concept of WWER-440/230, aimed at maximum electrical output, provides some specific characteristics of the plants, enhancing their safety.

These characteristics give the plants features of „internal, incorporated' safety, which is now becoming a part of the design of the plants of the new generation.

These safety features of the WWER-440/230 design are not typical for the new commercial designs of pressurised water reactors. As typical safety features of this type the following can be mentioned:

- Low thermal density in the core and, respectively, a compact reactor core with excellent neutron-physical characteristics with respect to the Xe oscillations. This makes the control of the power shape easy during transient modes and eliminated the demand of special control equipment for suppression of Xe-oscillations;
- Low specific thermal loading of the fuel rods and, as a result, a relatively low heat flux and large DNBR values for a large spectrum of transients. The average fuel temperature during normal operation is relatively low and the gaseous fission products are better contained within the fuel matrix (Fig. 5)[2];
- A large coolant inventory in the primary circuit and in the steam generators. This characteristics is unique for the WWER-440 type of reactors. The large thermal capacity of the reactor coolant systems provides a natural protection in cases of disbalance between heat generation and heat removal. This feature plays a positive role during accidents and transients as follows:
  - The large thermal inertia of the NSSS makes the plant less sensitive to a lot of operational deviations. In most of the PWR types of reactors operational transients initiated in the secondary circuit (and having a higher frequency), lead to more severe transients in the reactor coolant system, often requiring the operation of the pressurizer safety valves and increasing the probability of severe accidents with respect to the core behaviour. In the WWER -440 reactors most of the transients initiated in the secondary circuit are

suppressed in the steam generators by a small deviation of the coolant level, while the influence on the primary circuit parameters is rather weak;

- The large primary coolant inventory makes the plants steady against different accidents such as blackout, complete loss of feed water (e.g. due to a fire in the turbine hall). In these cases severe damages of the core can be expected in 4-6 hours, providing sufficient time for appropriate recovery actions (Fig. 6) [2];
- The large primary coolant inventory is an advantage in case of small LOCA with loss of the high pressure injection system. This advantage is a result of the sufficient time for manual depressurization of the primary circuit and long term cooling using the low pressure injection system;
- In cases of anticipated transients without scram (ATWS) the resulting pressure peak is considerably lower than for PWR reactors. In addition to this, the large DNBR decreases the probability of a boiling crisis (Fig. 7) [2];

Except for the in-built safety features, some of the design solutions of WWER-440 benefit their safety characteristics. Such are:

- Multy-loop configuration of the primary circuit. The six primary loops decrease the impact of main equipment failures (such as tripping of a reactor coolant pump, etc.);

- Horizontal steam generators: These enhance the transition to single-phase natural circulation of the primary coolant. It also provides several different routes for decay heat removal both from a tight and from an open primary circuit;

- Primary loops isolation valves on both the hot and the cold legs of each loop provide a possibility for some maintenance operations in the steam generators without draining of the whole primary circuit (which is usually a requirement for the typical PWRs). This eliminates the possibility of a loss of the ultimate heat sink;

- Two turbine-generators. This has a positive effect on the safety parameters of the plant, softening the loads due to transients initiated in the secondary side. The two feed water tanks provides better means for mitigation of transients and accidents. The two independent connections to the electrical grid provides a higher reliability of the electrical supply system of the plant.

Independently of all those positive features, the low DBA level still remains a concern for these units due to the design concepts and their possible upgrades with the objective to bring them closer to the modern safety requirements.

The major deficiencies of the WWER-440/230 can be summarised as follows:

- Insufficient capabilities for emergency core cooling;
- Insufficient diversification and physical separation of the safety systems;
- Deviations from the modern concepts in the control systems;
- Insufficient fire protection capabilities;
- Incompleteness of the last physical barrier (lack of a full containment).

Coming back to Fig. 3, it is obvious that the operation of old plants is not a Bulgarian problem. This is a reason for the development of a world practice to operate nuclear power plants, started under different conditions (old design solutions and old regulations).

Our and the world practice outline the main trends for future upgrades of the WWER-440/230 plants:

- Permanent efforts and short-term measures for increasing of the safety level by improvement of the equipment, operational documentation and safety culture;
- Development of short-term programmes for upgrades, optimising the costs and the expected results. At the same time, for a certain period of time, a special mode of operation may be applied together with compensating measures to improve the safety level;
- Development of long-term strategies, taking into account the remaining resources of the equipment and accurate determining of the remaining life-time.

The main objective of all these programmes should be the preserving and improvement of all the existing positive safety features.

For the last years of operation this approach is already a practice in the operation and management of Kozloduy NPP. The first programmes for safety upgrades of Units 1-4 after 1991 are already completed. They included measures aimed at the improvements of the design, operation, maintenance and safety culture.

The measures completed until this moment fall in the following main groups:

- **Design solutions**
  - Improvements of the integrity of the primary circuit (annealing of the reactor pressure vessel, study of the possibility of the application of the LBB concept, evaluation of the remaining resource of the equipment, qualification of the pressurizer safety valves, avoiding of a pressurised thermal shock);
  - Containing of the radioactive release in the hermetic zone (tightening, local and global leak tightness tests, qualification and modernisation of the containment spray system);
  - Improvement of the I&C systems (qualification of sensors and measurements chains, main control room, information support);
  - Improvement of the electrical supply systems;
  - Improvement of the fire protection (evaluation of the fire hazard, fire detection and announcement systems, fire protection and extinguishing measures);
  - Accident analyses;
  - Reassessment of the seismic response of the plant.
- **Improvement of the operation**
  - Introducing of a new style of plant management;
  - Improvement of the maintenance and repair of the equipment;

- Upgrading and improvement of operational documents, including development and implementation of a new system of normal and emergency operating procedures;

- Implementation of a new system for training of the personnel;

- A new organization of emergency preparedness and accident management;

- Improvement of the safety culture.

Obviously the above listed topics are in compliance with the internationally accepted standards and practices, which inevitably reflects on the current status of the plant.

WWER-1000 UNITS

The nuclear power plants with WWER-1000 type of reactors are the third commercial generation of the Soviet design of pressurised water reactors. Historically several modifications of this type of reactors were put into operation:

- Model 187 - Unit 5 of Novovoronezh NPP;
- Model 302 - Unit 1 of South-Ukranian NPP;
- Model 338 - Units 1 and 2 of Kalininskaya NPP;
- Model 320 - Unified for all other plants in operation;
- Model 392 - Unit 6 of Novovoronezh NPP.

The Model 320 is the one which is at present the most popular, having unified equipment and a high enough level of safety.

The Units with WWER-1000/320 are designed following the regulations of OPB-82. For this reason they are in compliance with the safety standards, currently applied in the international practice. The design principles and the design architecture of the safety systems are in complete agreement with the current international practice. As a result the WWER-1000 units are efficient and economically optimised, with efficient safety systems, satisfying the international requirements.

A general comparison of WWER-1000 to similar PWR plants designed and put into operation in the industrially developed countries (USA, France, Germany) show practically identical layout, techological and safety characteristics.

The layout of the plant with a single reactor and turbine and four primary loops provides similar characteristics for the compared plants. The horizontal steam generators with a relatively high secondary coolant inventory and relatively stable SG level, makes the WWER-1000 plants proof against a number of disturbances. On the other hand, the relatively high coolant inventory to reactor power ratio provides considerably better possibilities of prevention of severe core damages under some emergency situations (complete blackout, anticipated transients without scram, etc.).

Table 1

	Coolant inventory/thermal power, m^3/GWth	
	Kozloduy	Konvoy-1300
Primary circuit	108	99
Secondary circuit	103	61

The comparison of the parameters of the fuel rods and reactor core as well of the technological parameters of the primary circuit for the two types of reactors show that their safety margins are very similar.

Besides the facts mentioned above, it should be noted that at present a very extensive experience has been gained in Bulgaria from the start-up and several years of power operation of Units 5 and 6 of KNPP. At the same time regular activities have been performed, such as:

- Reviews and evaluation of the design;
- Analyses of the forced technical solutions during the construction and beginning of operation of the units;
- Analyses of equipment failures and the related quality of the equipment;
- Analysis of the deviations of Units 5 and 6 from the current regulations in the country (BNSA and its orders);
- Analyses related to replacement of equipment, modifications of systems and constructions;
- Safety analyses, etc.

Based on all stated here, the main conclusion can be drawn that as a whole the Units 5 and 6 at KNPP are designed and constructed with respect to the internationally accepted principles of safety, but they need some improvements, related to modernisation of separate systems and equipment, to introducing of some new systems and to improvement of the system of emergency operating procedures. These improvements will bring the units to a level, comparable to the practice in the industrial countries.

On the other hand it should be clear that a high safety level is not just a single effort, but a continuous process throughout the plant operation, with periodical introduction of new principle solutions, so that the safety level would not stay strongly behind the constantly increasing requirements.

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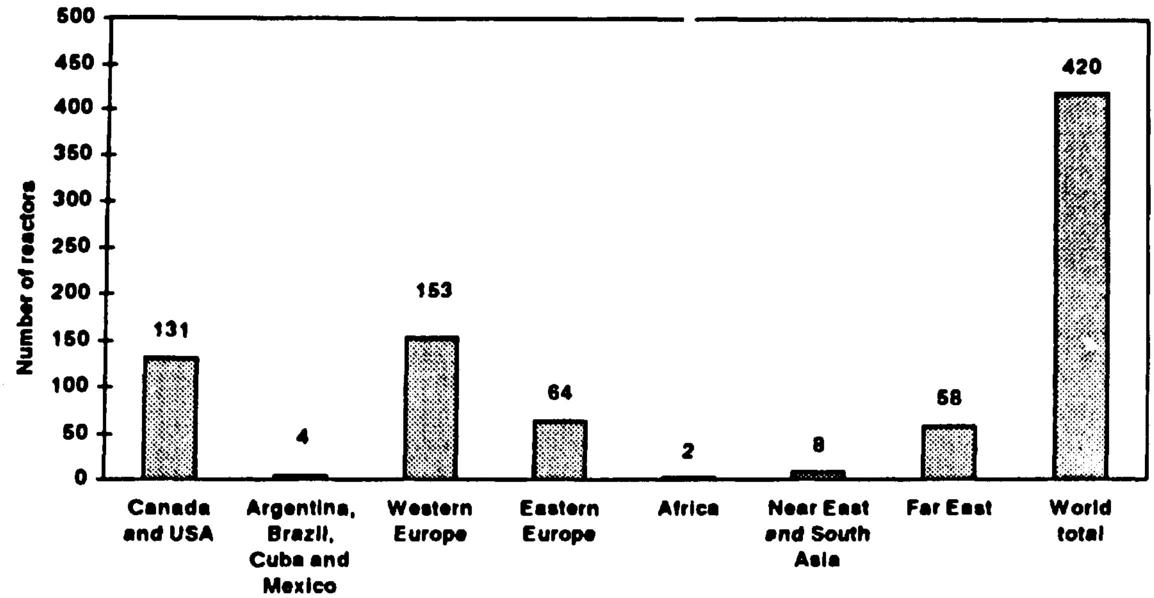


FIG. 1 Number of commercial reactors in the world, including 6 reactors in Taiwan, China (December 1991)
Reference: IAEA - Power Reactor Information System (PRIS). Non-government information

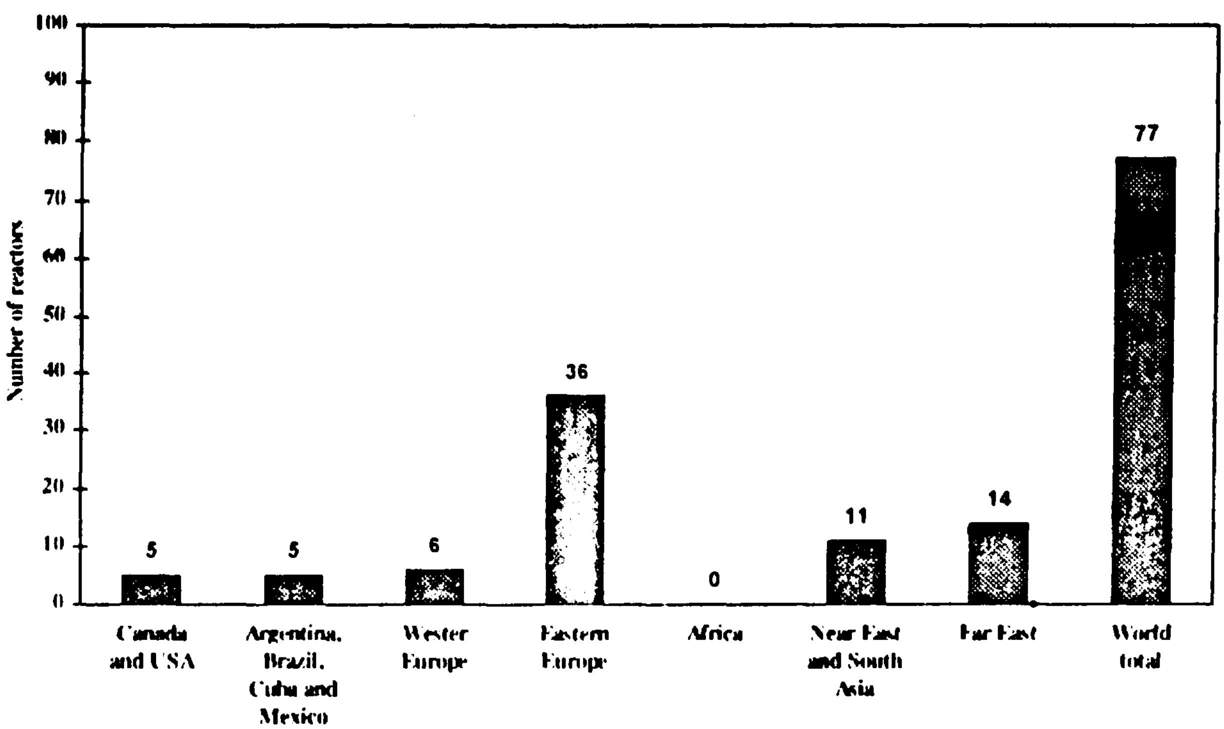


FIG.2 Reactors under construction in the world (December 1991)
Reference: IAEA - Power Reactor Information System (PRIS). Non-governmental information

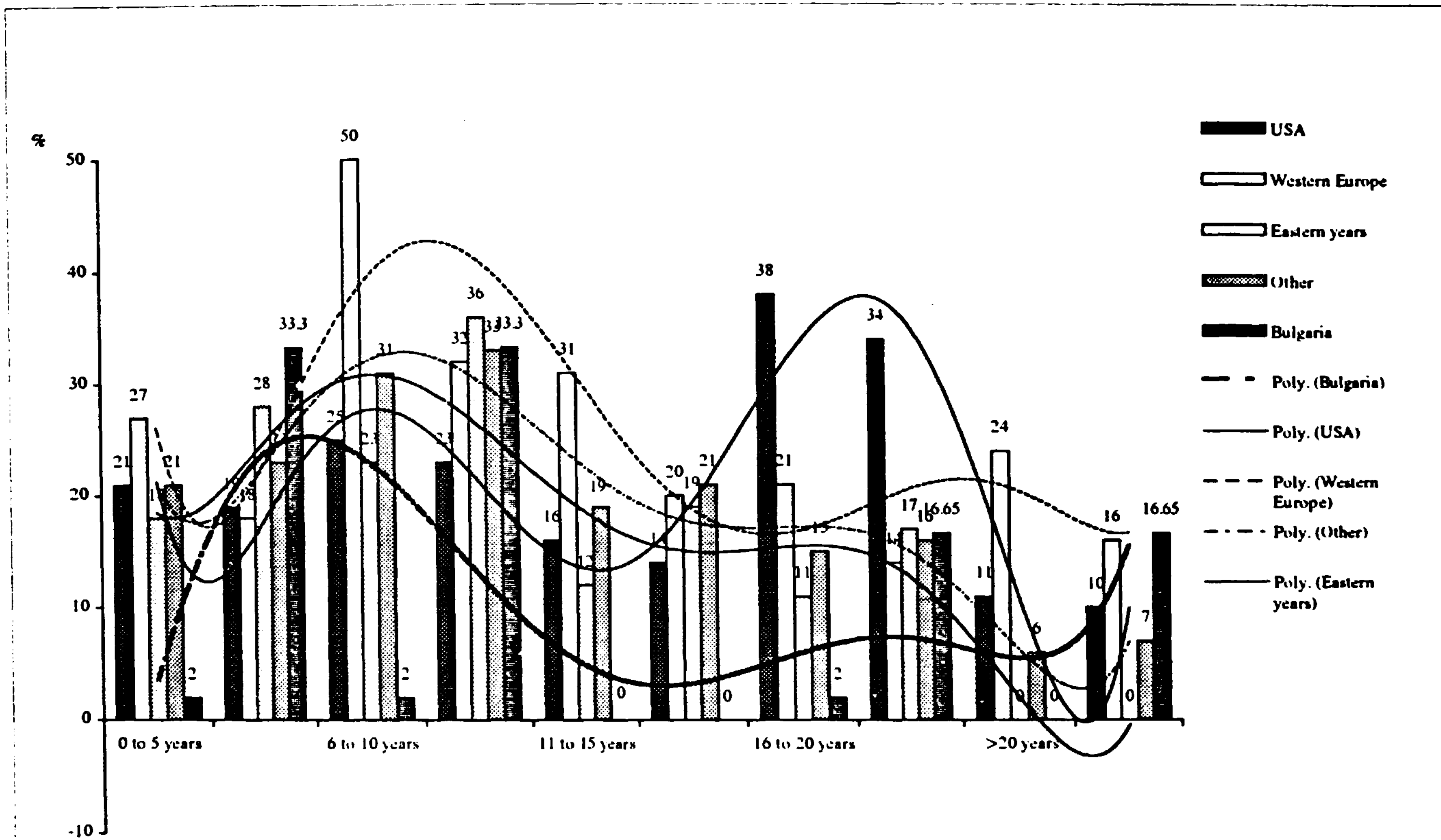


FIG.3. Distribution of the operating comercial reactors in the world depending on thier age

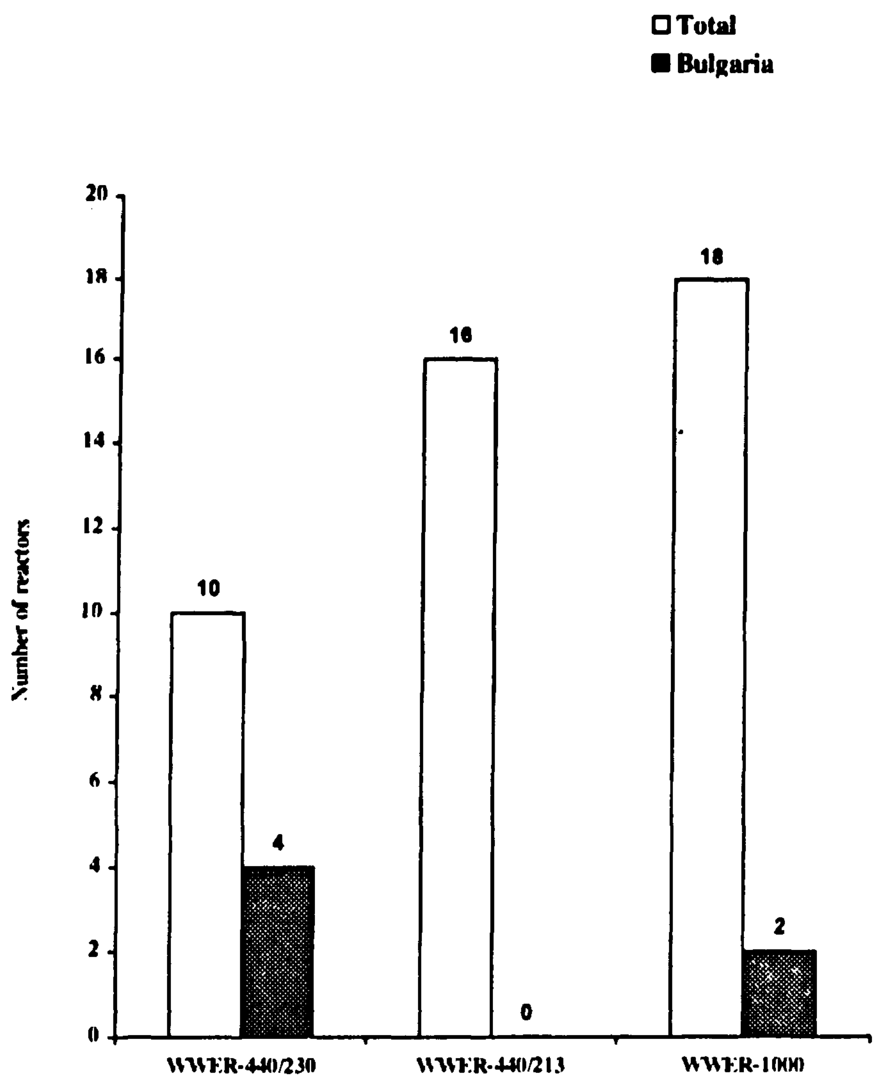
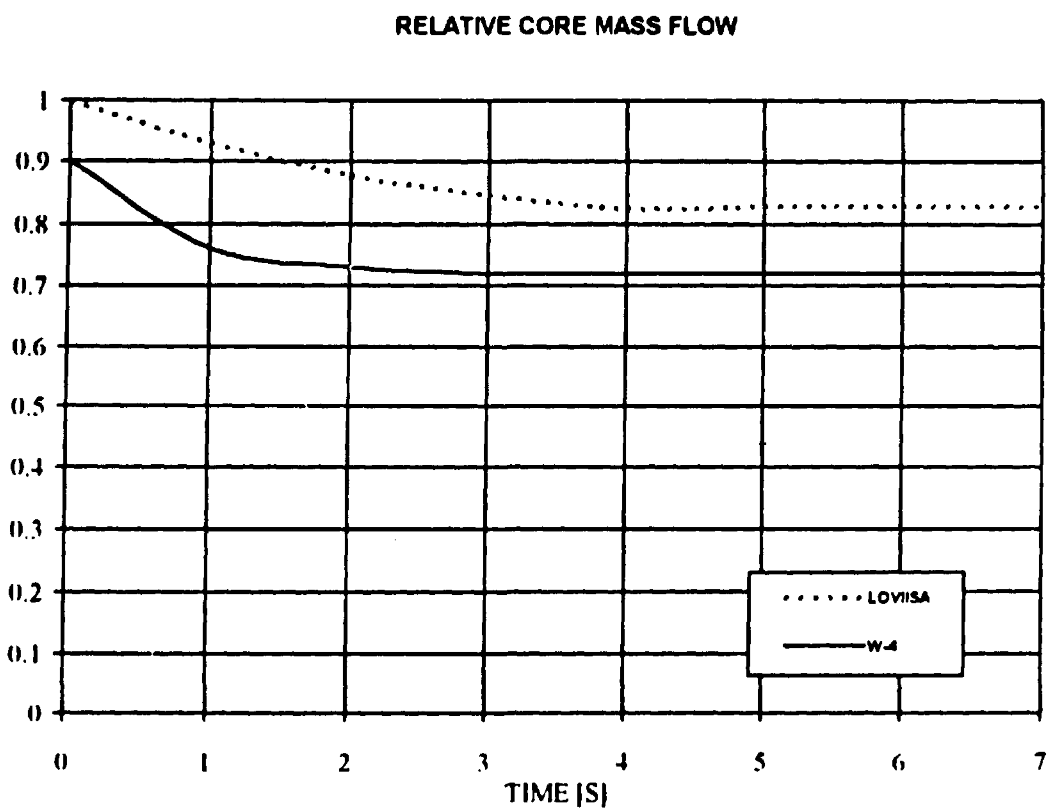


FIG.4. WWER-type of reactors in operation



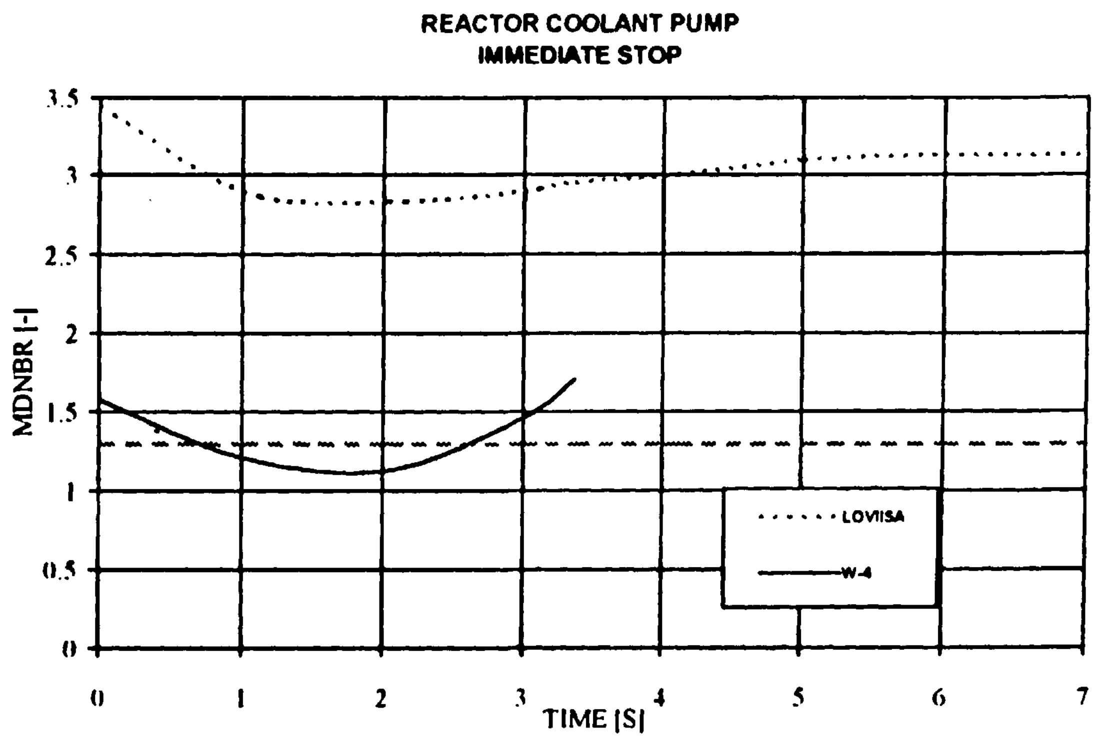
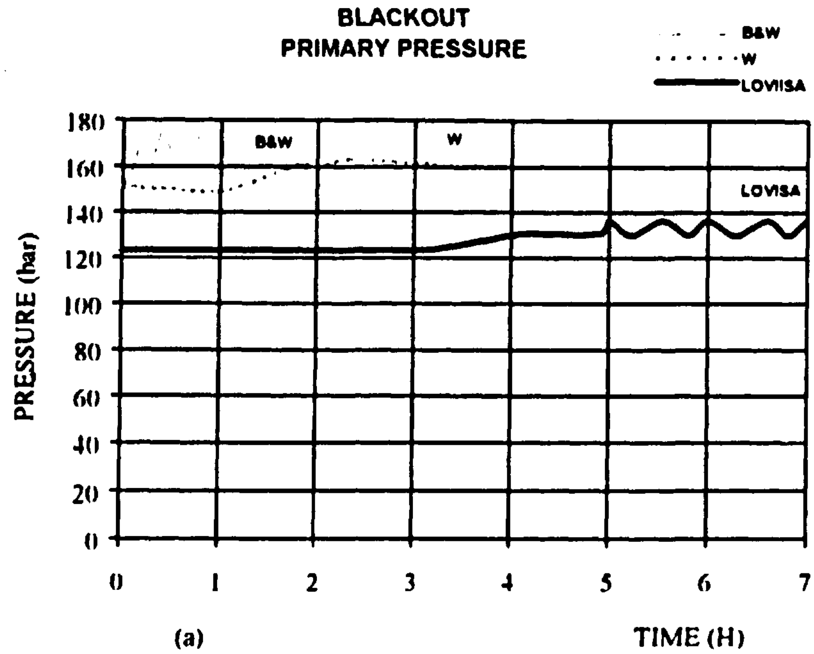


FIG. 5. Relative core mass flow rate and minimum DNDR in case of a reactor coolant pump seizure



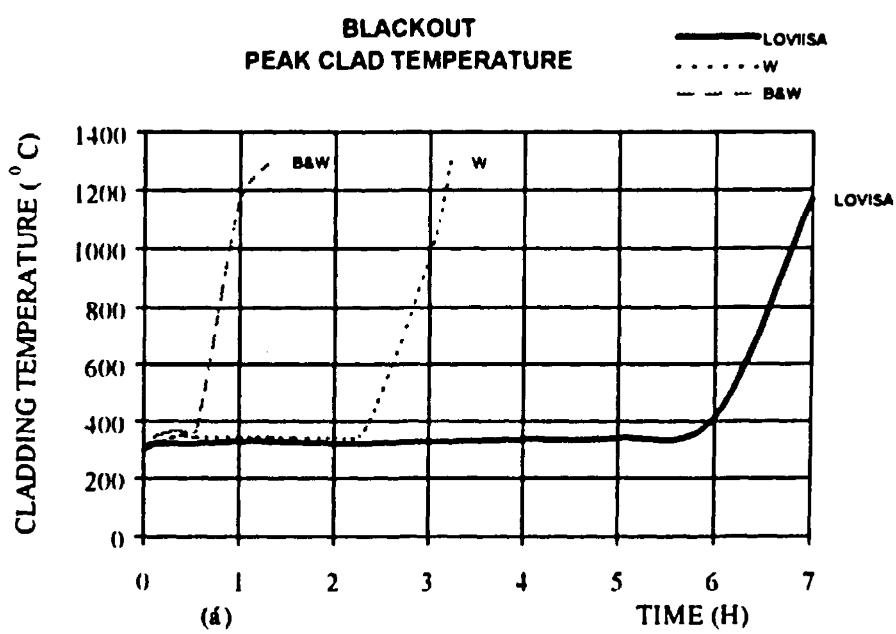
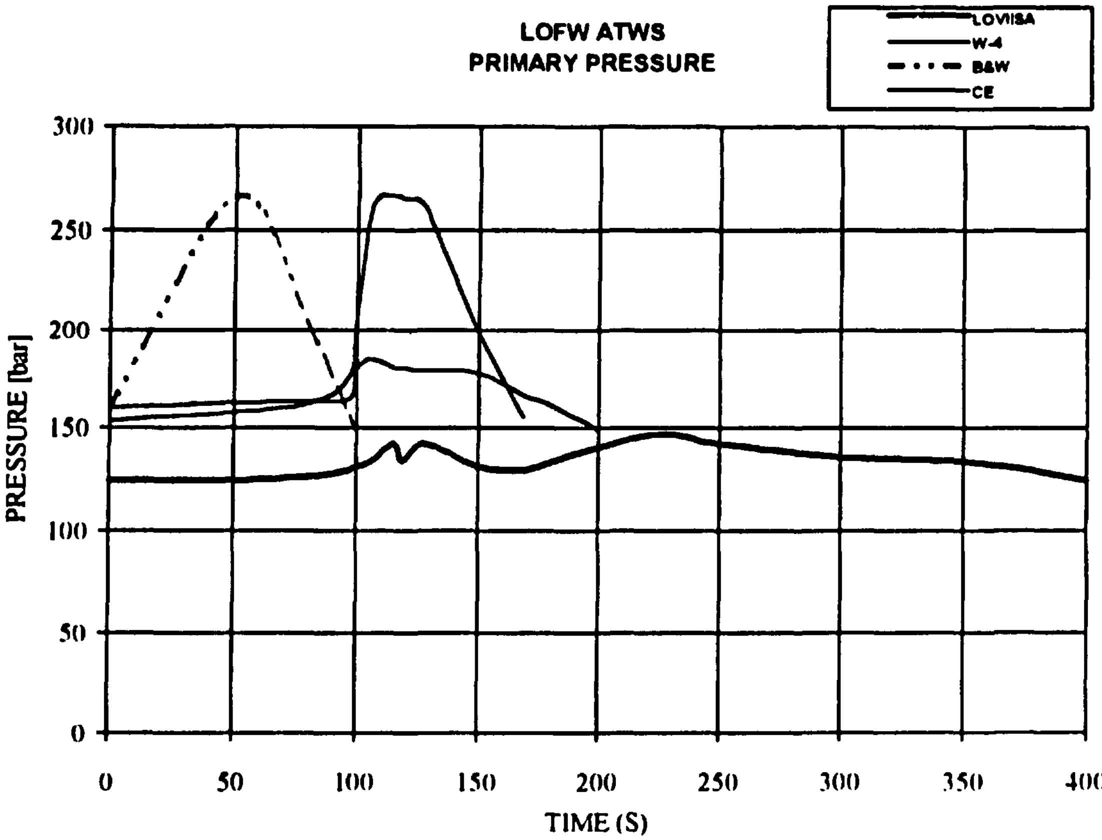


FIG.6 Primary pressure (a) and peak cladding temperature (б) after station blackout



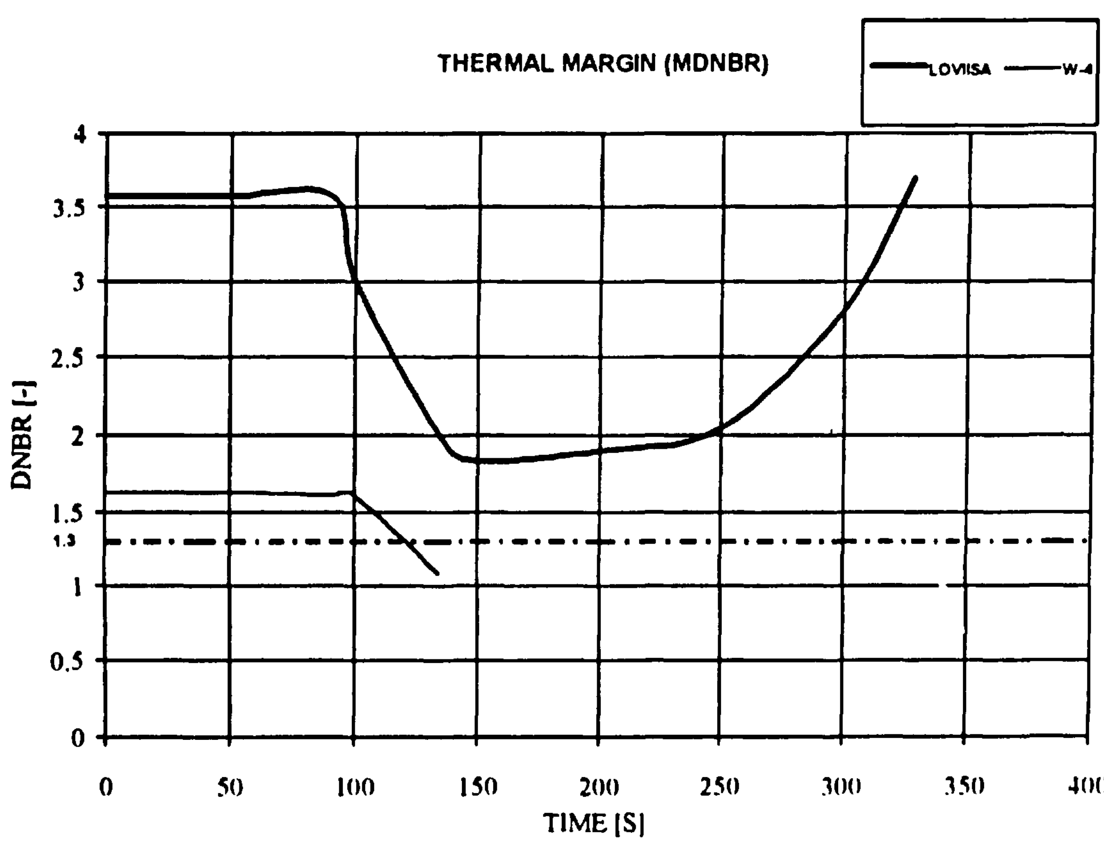


FIG.7. Primary pressure (above) and minimum DNBR (below) after loss of feed water without reactor scram