● a utility-approved and NRC-endorsed requirements document setting forth the design requirements of US and international utilities;
● detailed construction plans supporting the target 36-month passive plant construction schedule;
● probabilistic risk assessments (PRAs) and accident analyses demonstrating that accident prevention and mitigation objectives have been met;
● man-machine interface well defined via functional-based task analyses.

As part of Phase-3, the utilities will make available financial and technical resources for direct application to passive plant design work.

EPRI and the current ALWR programme participants are working now to structure this important next phase. The work is being closely co-ordinated with a major DOE-sponsored programme to support certification of plant designs, and across the board there is enthusiasm, momentum, and very high expectations for this next phase.

In conclusion, there is an active worldwide effort to develop the requirements and designs of advanced passive light-water reactors. These designs offer the promise of being technically more simple and cost competitive when compared to current plants. It is hoped that they will serve as the foundation for an expanded and revitalized nuclear power programme in the United States and the world.

Improvements in current light-water reactors

An overview of plant requirements and global trends

by P.-J. Meyer and W. Grüner

Nuclear reactors have captured a substantial share of the world's electricity generating market providing, during 1988, about 17% of the total electricity generated. Of the 429 nuclear power plants in operation worldwide at the end of 1988, 320 were light-water reactors (LWRs) with a total capacity of just over 263 gigawatts-electric (GWe), or about 85% of today's total installed nuclear capacity of about 311 GWe. Of the 105 nuclear plants under construction, 79 are LWRs. These figures clearly show that LWRs, including both pressurized- and boiling- water reactors (PWRs and BWRs), are today's work horses in nuclear power's contribution to electrical energy production. Countries such as the United States, USSR, France, Federal Republic of Germany, Japan, Republic of Korea and many others have chosen the LWR due to its proven high reliability and economic viability.

As a result of this deployment, several thousand operating years of experience are available to form the basis for future development. Development directions include evolutionary-type improvements in present designs resulting in simplifications in systems design, reductions in construction time, easier maintenance, optimization of core design, improvements in operability and reliability as well as reductions in construction, fuel, operation, and maintenance costs. In the USA, reactor concepts for large (1200 MWe) evolutionary-type and smaller (600 MWe) passive plants are under development, based on design requirements including economic targets specified by the Electric Power Research Institute (EPRI) after several man-years of joint vendor/utility effort.

The development programmes, whether related to design, construction or operation, are based for the most part on well-proven and reliable technologies enabling the operators and the authorities to easily license the new generation of LWRs. Even the smaller reactor concepts,

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designed according to EPRI requirements, use systems and components which have their reference in other plants. The majority of the requirements address problems which have beset planning, construction, and operation.

Characteristics of today's plants

In order to evaluate properly the position of today's plants versus proposals for a new generation of plants, a yardstick of reference has to be established against which the degree of innovation or advancement in safety and economic competitiveness of the new plants can be judged.

The new design concepts claim improvements in constructability, operability, and safety. It is only natural that, as is the case with every new product to be brought on the market, such claims should be checked against the most up-to-date technological level available in each of these areas. By way of selected examples taken from the recently completed Convoy plants in Germany, the state-of-the-art will be illustrated. The three Convoy 1300-MWe PWR plants, which recently started commercial operation, were handed over to the customers within the original budget and in advance of the contractual schedule by an average of 4 months each, showing that the measures taken just to stabilize project implementation were highly successful even in the face of a deteriorating public attitude towards nuclear power. Subtracting special events such as interruptions by court order would indicate that a construction period of 4.5 years is easily attainable for a large 1300-MWe unit. Theoretically, it might be feasible to construct smaller plants with reference to lower quantities of equipment and volume of concrete involved in somewhat less than 4.5 years.

These short construction schedules, which have also been observed in France and Japan for such or similar units, can be realized by a thorough detailed standardization of not so spectacular, but cost and labour intensive items such as valves, piping, supports, embedded parts, and cable trays. These components, which are deployed in large quantities under exacting quality requirements in nuclear power stations, were restricted to a limited number and combinations of types and sizes. They were assembled with the aid of computer databases, from which all of the documents for purchasing, manufacturing, erection, and quality control were derived in a consistent and complete fashion.

Good operability means uninterrupted plant service during internal and external transients, flexibility in following load demand and short revision periods. Low rates of unintended plant shutdown of about one per reactor-year have been consistently achieved over the past 8 years. Automatic load adaption capability for special grid conditions, such as adjusting power output due to power fluctuations or frequency control requirements, as well as continuous operation in case one of the main primary coolant pumps is cut off, is possible through a special control system. This system is inserted between the normal control system and the reactor protection system with the function of stabilizing the transient of parameters outside the normal control band width.

The short revision periods are attributable on one side to detailed advance preparation work by the operators, but are facilitated on the other hand by a number of features built into the plant by the designer. Containment accessibility during operation, the fuel pool inside the containment, a greatly reduced number of welds subject to in-service inspection, and sophisticated equipment for maintenance and inspection work are the main examples of such features.

Passive safety features have already been incorporated into the current designs of water reactors and even more emphasis has been placed on the application of passive safety principles in the development of new reactor concepts. Yet every reactor depends on a combination of inherent safety features as well as active and passive safety features to insure overall high safety standards and defense-in-depth against all conceivable events. The various portions of these safety elements may differ in various designs with some making more effective use of passive features.

Licensability is an important aspect in safety and a continuation of the design development in small steps, taking into account the background of established, well proven and licensed designs, makes sense. Getting a license for new revolutionary safety concepts depends very much on the political licensing climate in the respective country and the agreed-upon sufficiency of all safety features to meet established requirements.

Requirements for future plants

The perspectives for future reactor concepts vary to a great extent between different countries. In France and the Federal Republic of Germany, a highly standardized, proven, and reliable technology has been developed and shows excellent operating records.

Based on the German Convoy technology, the Federal Republic of Germany is planning future improvements to be introduced in the next generation of PWRs. Electricité de France (EdF) will keep the same principle for its evolutionary programme by improving the design without significant changes. For future standards of French PWRs in the year 2000 and after, a study called "REP-2000" was started by EdF. The objectives: load-following capability, cost-effectiveness, and operational flexibility. For further improving fuel utilization in PWRs, the three French partners (the Commissariat à l'énergie atomique, EdF, and Framatome) have jointly started a programme to assess the feasibility of a convertible spectral shift reactor, RCVS. It is expected that no RCVS will be completed before 2002 or 2005 and no detailed design study will be undertaken before the early 1990s.

In Japan, the development of large PWRs and BWRs is well under way; the APWR is designed by Mitsubishi-

Westinghouse, the ABWR by Hitachi-Toshiba-General Electric. The ABWR has been selected by Tokyo Electric Power Company for the next two units at the Kashiwazaki-Kariwa site. The technical development of the next generation of LWRs in Japan will not be ready before 2005. In order to meet future social and economic needs, this next generation will be aimed at further enhancing the functions of reactor cores including the use of MOX-fuel assemblies, improved fuel performance, enhanced safety design techniques, utilizing more advanced technologies, and improving aseismic technology.

Safety aspects have played a prominent part from the beginning of nuclear power plant construction and operation and continue to do so, supporting a tight network of control and surveillance through regulatory bodies and international agencies based upon very comprehensive sets of codes, rules, and regulations, both at the national and international level. Which safety provisions for nuclear power plants are required to limit risk to public health and safety to an acceptable level are determined in lengthy and exhaustive licensing procedures, integrated by public hearings and followed more often than not by litigations before administrative courts. Public opinion, however, in particular since the Chernobyl accident, has maintained a very reserved position regarding nuclear power, since the public's perception of the risk associated with nuclear energy has been considerably different from the actual level.

Which safety features will contribute to improved social acceptance in the near future is difficult to determine, but the following criteria are believed to point in the right direction:

- Existing plants must be able to continue their good operation, because the feedback of the growing wealth of operational experience is a key element to plant safety.
- Given the age structure of operating plants — about half of the Federal Republic of Germany's nuclear plants are less than 10 years old — and considering the potential of life extension now being investigated, new plants will have to coexist with older ones for several decades with compatible safety concepts.
- New designs, in particular when installed at new sites, should be able to contain consequences within the plant's boundary from accidents beyond the plant's design basis, making emergency measures in the surroundings unnecessary.

Translation of these rather generic criteria into more specific guidelines for plant designers will not be possible on a purely national basis. Indeed, the Chernobyl aftermath has greatly enhanced the understanding that nuclear safety is of truly international concern. Further development in plant safety will have to take place in a co-ordinated manner across national boundaries. This will certainly be true in the European Community beyond 1992, where a consensus will have to be established with regard to applicable codes and standards, at least for the environmental impact of nuclear plants, both for normal operations and unusual upset conditions. It can be expected that those members of the Community which actually do not use nuclear power might also wish to be consulted in this harmonization process.

The increase of the share in the electricity market by almost a factor of 4 (from 10 to 40%) during the past 10 years is the best evidence for the economic competitiveness of nuclear energy in the Federal Republic of Germany. The terms of reference of the German energy market are likely to change after 1992, since the European Community's aims include deregulation and the elimination of obstacles to the exchange of goods and services within the Community. The predictability of world market energy prices will presumably be not much better than in the past, so a prudent design target for generating cost should be fixed at the lowest expected level within the Community. It is thus likely to be represented by the cost of nuclear energy in France, where early rationalization of type and series production of plants have been instrumental in obtaining the present export volume.

However, countries with smaller electrical grids are also considering nuclear energy as a possible option. Since some of these countries do not have sufficient indigenous energy resources, they are obliged to import energy. These countries could be identified as potential users of smaller nuclear power plants in order to stabilize the future energy market. Besides the aspect of low generation costs, the reduced budget needed for smaller plants compared to large units is also of vital interest. Moreover, the introduction of nuclear energy within a national energy development programme provides several spin-off effects. A multitude of diverse and qualified industrial efforts are necessary during construction. Later, during the operating phase, a well-equipped and highly effective service industry is necessary for long-term reliable plant operation.

Trends of further development

Having established, by way of a few examples, the terms of reference for the state-of-the-art of LWR technology, consideration has been given to the most promising areas of further development for nuclear power. From the general trends outlined above, the following areas will merit further attention:

- A considerable reduction in construction time and costs requires the availability of a complete standardized set of planning and construction documents far in advance of the actual start of construction. The standardization of systems and components with the respective engineering completed for the entire plant as well as construction drawings, commissioning procedures, and documentation is of great importance.
- The main incentives for further optimization of the fuel and core design and for special improvements of the fuel management methods result from the following targets: (1) reduction of the fuel cycle cost by means of (a) increased average discharge burnup up to

45–50 megawatt days per kilogram uranium for PWRs, and (b) improved uranium utilization through design optimization and implementation of advanced in-core management strategies; (2) improved operating flexibility through core and plant design for (a) flexible cycle length of up to 2 years; (b) stretch-out capability; (c) full consideration of the present and future requirements for load-following operation of 10% per minute over a wide power range; and (3) saving of natural uranium resources and further promotion of reprocessing technology to enable plutonium recycling. The various measures required for the realization of these targets are not independent of each other so that a careful overall evaluation and optimization of all contributing factors is necessary.

● Anticipative monitoring of the primary pressure boundary through appropriate combination and integration of various monitoring systems, is already available and separately covers such items as leaks, vibrations, fatigue, and loose parts. The information gained therefrom will extend the time range of preventive maintenance and enhance the reliability of the pressure boundary.

● The margins built into the design of engineered safeguards should be reviewed, taking into account the increased body of knowledge from safety-related research and development work performed during the past years by several institutions in international co-operation.

● The results thus obtained can be channelled into the continuing work on management procedures for accidents beyond the design basis. Extensions of the operator's grace period for taking action in a departure transient from normal operation beyond the present design basis value of 30 minutes is presently being investigated.

● Monitoring the plant during transients and mobilizing the plant's resources for appropriate countermeasures makes complete and correct information on the status of the plant essential. Advances in the man–machine interface have been realized by a process information system first introduced in the Convoy plants. The system processes and concentrates, via interactive video display units, all relevant information on plant parameters in forms most congenial to the operator on duty. Further development into a comprehensive digitalization is under way.

● Careful evaluation of the possibilities of introducing passive elements into engineered safeguards combined with a thorough drive for simplification can bring about advantages in maintenance, hence radiation exposure and possibly availability.

In the areas of constructability and operability, future development work will concentrate on maintaining and improving the economic edge of nuclear power in the face of changing conditions in the energy market. Shortening the construction period and lengthening the operating cycles between revisions are the most promising items.

International market

An expansion of electrical energy generation from large as well as small nuclear power plants can be expected in the next decade. In a number of countries planning for sites, licensing and engineering studies are already under way, in preparation for the time that increased capacity is required by electric grid expansion plans. For streamlining their marketing activities, Framatome and Siemens have recently agreed to form a joint company which will be responsible for internationally marketing of a nuclear power plant to be developed. In Japan, the joint development of the APWR and the ABWR has been continuing with the US vendors and their Japanese licensees.

For the time being, the international market for further nuclear plants is stagnating because most of the industrial countries have low near-term energy demand growth patterns. On the other hand, the developing countries, which have or are expecting to have large energy demand growth rates, are not able to finance nuclear installations or are restricted in their budgets for the next years. Thus, the main task in promoting nuclear energy cannot only be the solution of technical problems but rather the development of financing models to overcome this international burden.