In the first place, in addition to computing a single generating cost figure for a particular station on the basis of the most reasonable assumptions, estimates should be made of a range of costs under different assumptions for each basic parameter which may be expected to vary substantially over the life of the installation. Secondly, a few studies should be carried out on the costs to be incurred by the power system concerned (and not merely the isolated costs of individual stations) for different types of plant installation all capable of meeting the requirements of the system. These are particularly important in the developing countries where a single nuclear power plant often represents a significant proportion of the total installed capacity of the system for which it is envisaged.

OPERATING EXPERIENCE WITH POWER REACTORS

The principal reactor types now in use for power generation have generally had a satisfactory record of performance and such problems as have occasionally arisen in nuclear power stations have been mostly with conventional components of the plants. This was one of the broad findings that emerged from an international conference on Operating Experience with Power Reactors, held by IAEA in Vienna from 4 to 8 June 1963.

Attended by about 250 scientists and engineers from 27 countries and five international organizations, the conference was one of the largest scientific meetings organized by the Agency and the first on the subject to be held under international auspices.

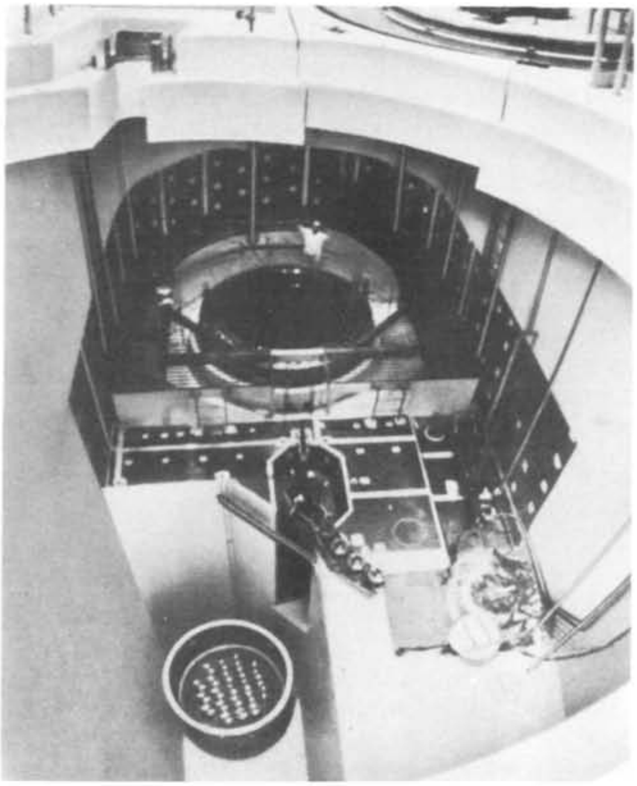
From a panel discussion held at the end of the conference, it could be seen that representatives of the major nuclear power-producing countries now share a growing optimism about both the technological and economic outlook for nuclear power. Leading experts from France, the USSR, the United Kingdom and the USA, who took part in the discussion, envisaged the advent of economically competitive nuclear power by the end of the present decade. This could be achieved with reactor types whose technical soundness had already been established - possibly with some further improvements in design, manufacture of more reactors of the same design and construction of large-sized plants. It was also foreseen that the excellent operating record of the established reactor types might justify less overdesign than at present and this would lead to a substantial reduction in capital costs.

Although economic prospects were touched upon during the panel discussion, the conference as such dealt mainly with the technical aspects of reactor operating experience. It was divided into eight sessions: the first was devoted to general reviews of experience with nuclear power plants in the context of national programmes; the next four discussed experience with specific plants; the sixth dealt with specific plant components; problems of staffing were taken up at the seventh session; and the last session was on fuel cycles and fuel handling. Reports on the experience with about 20 individual plants were given at the conference. As Mr. Pierre Balligand, the Agency's Deputy Director General in charge of Technical Operations, pointed out at the opening session, these plants represented about half of the total installed capacity of nuclear power in the world today.

Light Water Reactors

Power reactors cooled by light water have two main varieties: the boiling water and pressurized water types, both fuelled by enriched uranium. Most of the nuclear power plants in the United States utilize light water reactors, and they are in use in several other countries as well, including the USSR.

In a review of operating experience with boiling water power reactors, R. J. Ascheri (USA) pointed out that by the end of last year over 2200 million gross kilowatt-hours had been generated by three boiling water reactor plants - the Dresden and the Vallecitos plants in the USA and the Kahl station in the Federal Republic of Germany. Early this year, two more boiling water plants were commissioned in the USA: the Big Rock Point and the Humboldt Bay plants. "The overall performance of the boiling water reactors in these nuclear power plants under standard electrical utility operating conditions," said Mr. Ascheri, "has been uniformly excellent. Their safety, reliability, ease of mainte-



Reactor vessel and storage pit of the Indian Point nuclear power station in the USA. (Picture reproduced from paper presented by W.C. Beattie and R.H. Freyberg)

nance by contact methods, and high degree of availability have been clearly demonstrated."

In a paper on the first two years of operating experience with the Kahl nuclear power station, A. Weckesser and H. Brüchner (Federal Republic of Germany) stated that at no time had the safety of the plant or the environment been at stake, no instabilities had been observed under various operating conditions, and the plant could be operated satisfactorily by normally trained personnel. The satisfactory performance of the plant had contributed to the decision to choose the same reactor type for the first full-sized nuclear power station in the country; this would have an output of 250 MW (electrical), as against the 15 MW of the Kahl plant.

A report on the Experimental Boiling Water Reactor (EBWR) at Lemont, USA, was given by four American authors (E. A. Wimunc and others). The reactor was originally constructed to demonstrate the feasibility of a direct-cycle, natural circulation, boiling water reactor integrated power plant. It was designed to produce 20 MW of heat in the form of saturated steam, which was fed directly to a turbogenerator, generating 5 MW of electricity. Subsequent experiments at power levels ranging from 20 to 40 MW were possible with the initial reactor core. Data were obtained by operating the reactor at various power levels, steam pressures and control rod positions. In July 1959 the plant was shut down for certain modifications with a view to operating the reactor at or near 100 MW (thermal). After these modifications the reactor was subjected to a series of stability tests at power level increases up to 70 MW and it was decided that operation at 100 MW could be achieved safely.

Among plants based on pressurized water reactors, the Shippingport and Indian Point stations in the USA were described in two papers; a report was also given on the initial operational results of the first Belgian nuclear power station (BR-3).

The Shippingport plant, on which a report was submitted by H. Feinroth and two other American authors, has operated for over five years and has been found to integrate readily into a utility system either as a base load or peak load unit. Plant component performance has been reliable. There have been no problems in contamination or waste disposal. Access to primary coolant components has been good, demonstrating the integrity of fuel elements. Each of the three refuelling operations performed since start-up has required successively less time to accomplish.

Indian Point Station Unit No. 1, described in a paper by W. C. Beattie and R. H. Freyburg (USA), has a 585 MW (thermal) pressurized water reactor, and is located on the Hudson River about 24 miles north of New York City. Testing at reactor power levels up to 50 per cent was marked by frequent automatic shutdowns, a large number of which were initiated in the conventional plant. On the nuclear side the main difficulties were associated with the control rod drive system. The station was shut down last November for scheduled piping changes in the conventional plant and for modifications and additions to the control rod drive system. Since it was put back into service last January, test results have closely followed the performance predicted for the reactor.

Different problems encountered during the initial operation of BR-3 were discussed by M. Potemans and M. Guében (Belgium). Among them is the presence of radon in the air in the reactor building and certain auxiliary buildings, the leak rate of primary water and certain mechanical difficulties.

Gas-Cooled Reactors

Papers on power reactors fuelled by natural uranium, moderated by graphite and cooled by gas were presented by British and French participants. A report was also given on the start-up of the Latina power station in Italy, which is based on the same reactor type.

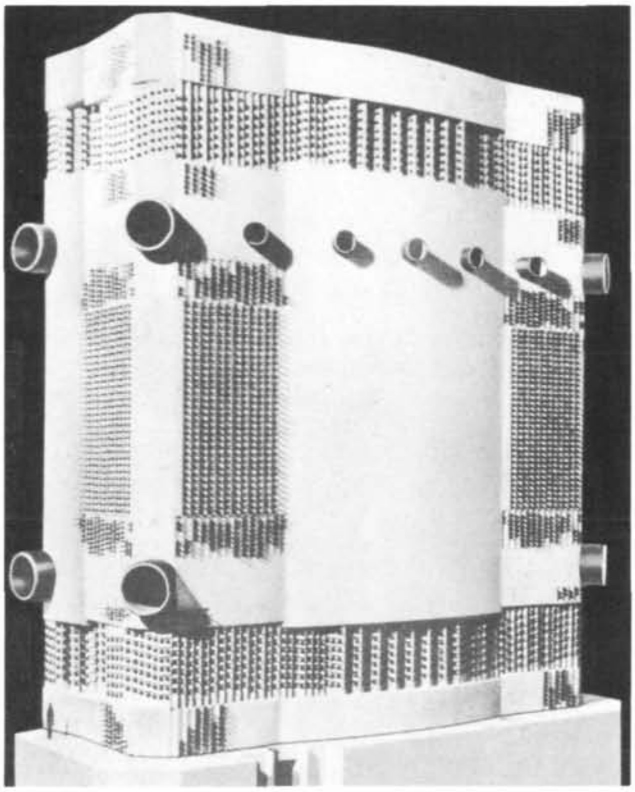
About Calder Hall and Chapelcross, H. McCrickard (UK) pointed out that these stations were designed as dual-purpose plants with the major emphasis on the production of plutonium. Both stations, however, are integral parts of the national electricity grid supply system as base load power stations and supply about 15 per cent of the demand in the regions in which they are located. The power output of the reactors has been increased by more than a third above the initial design figure. The reactors are now achieving overall load factors in excess of 92 per cent in spite of the fact that refuelling is carried out off-load. Increases in load factor have been achieved largely by marked reductions in the time taken for refuelling and by careful planning of essential maintenance work which involves reactor shut-downs. The future operating policy for these two stations depends on the possibility of further increases of reactor power output and an extension of burn-up times, and advances are expected in both directions.

Reporting on the performance of major plant items at Calder Hall, E. L. Desbruslais (UK) pointed out that all the faults that have developed have occurred in the conventional plant and none in the nuclear reactors themselves. He described the difficulties experienced with various plant items and the steps taken to overcome them.

After describing the performance of the nuclear power stations at Berkeley and Bradwell, R. Weeks and G. Shepherd (UK) stated that the stations appeared to be very reliable, and such stoppages as had occurred had been due to non-nuclear parts of the plant. In their view, it would be very nearly true to say that if the availability (i.e. availability for power supply) of the conventional plant could be forecast so could the availability of the station as a whole.

In a review paper, J. Horowitz and J. P. Roux (France) pointed out that reactors fuelled by natural uranium, moderated by graphite and cooled by carbon dioxide are the foundation of the French nuclear power programme. The Chinon reactors (EDF-1, EDF-2 and EDF-3) follow on from the plutonium producers at Marcoule (G-2 and G-3), and this group will account for most of the 850 MW (electrical) to be installed in France by 1965. G-2 and G-3 have been supplying the French national grid since 1959 and 1960 respectively. EDF-1 was undergoing preliminary tests at the beginning of this year before going into power operation, EDF-2 is expected to go into service at the end of next year, and EDF-3 during 1965. The authors stated that the technical feasibility of this reactor type had already been established and it was hoped that their economic viability would be demonstrated by the reactors now under construction.

The experience gained in the operation of the G-2 and G-3 reactors was narrated by F. Conte (France), who reviewed the main problems from the



External view of the pressure vessel of EDF-3 in France. (Picture reproduced from paper by F. Conte and others)

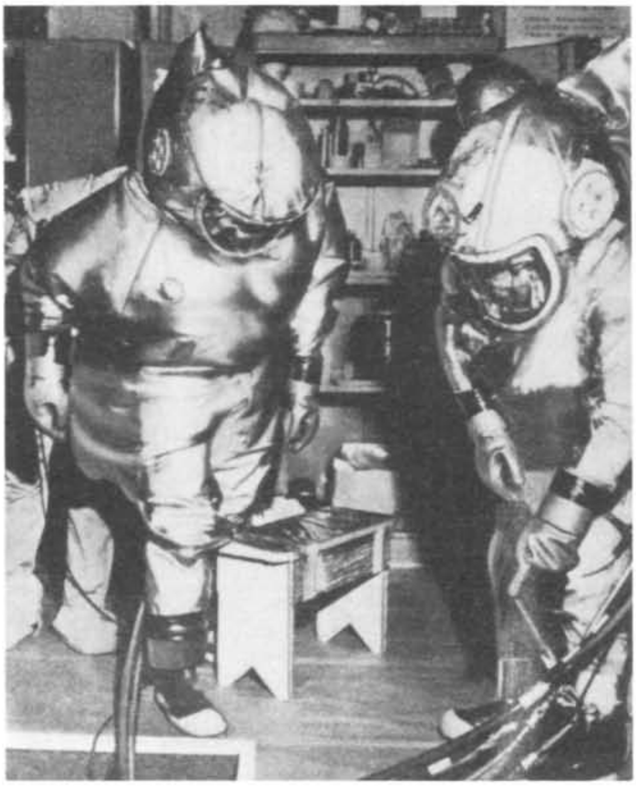
standpoint of technology, safety, performance and organization. The subjects dealt with include the pre-stressed concrete vessel; fuel loading during operation; performance of the installation; automation of control procedures; behaviour of the fuel; the conventional installations for power recovery; access to the interior of the reactor; and personnel organization and training.

P. Bacher and three other French scientists have a paper on experience in neutron physics acquired at Marcoule and Chinon and its value for the graphite reactor programme. They said that the experience gained in the operation of the first graphite reactors in France had proved to be of great value both for future projects and for studies on the operation of large power stations, where problems of control and kinetics are especially important.

Other Reactor Types

The conference also heard reports on several other power reactors, including the heavy water and fast reactor types.

L. G. McConnell (Canada) gave a paper on the initial operating experience with his country's first nuclear power station, the Nuclear Power Demonstration (NPD) plant, which is intended for testing the performance of the Canadian type of station using



Dressing for work inside the reactor vessel of the Enrico Fermi atomic power plant in the USA. (Picture reproduced from paper by R.W.Hartwell)

natural uranium as fuel and heavy water as moderator and coolant. The reactor reached full power in June last year. Progress so far has been favourable; the first high-capacity run of six weeks' duration yielded a capacity factor of 70 per cent. Improvements already made have increased safety, led to better performance and demonstrated potential methods of capital cost reduction for future stations. During December 1962 two simultaneous leaks from the on-power refuelling machine led to an unusual sequence of events in which a considerable amount of hot high pressure heavy water was spilled into the reactor vault where it suffered a slight downgrading in isotopic purity. It was upgraded and the reactor returned to operation by the end of the month. All safety devices operated correctly during the incident, as did the provisions for containment of heavy water.

A report of a different type of heavy water reactor was given by E. Jonson and N. Rydell (Sweden). This is the Ågesta nuclear power plant, a pressurized heavy water reactor of the pressure vessel type, fuelled by natural uranium. The report dealt, among other things, with problems which are particularly important in a high pressure heavy water system, such as

(a) leak tightness against the atmosphere and internally between high and low pressure circuits;

(b) pressure balance between heavy water and light water circuits; and

(c) the evacuation of light water from the heavy water circuits.

Reports on fast reactors (those in which the neutrons are not moderated and are available for converting source material into fissionable material) came from the USSR and the USA. The Soviet fast reactor BR-5 was the subject of a paper by seven Soviet scientists (A. E. Leipunsky and others). They discussed the problems of carrying out repair works with the radioactive liquid metal circuit of the reactor, as well as those of reactor operation after achieving the designed 2 per cent fuel burn-up with some untightness of fuel elements. They described the experience with the discharge of the core, investigations into the condition and tightness of elements and decontamination of the equipment and pipelines of the primary radioactive circuit.

The American fast reactor, the Enrico Fermi Atomic Power Plant, was described by R. W. Hartwell. The plant, which utilizes a 100 MW (electrical) fast breeder reactor, was essentially completed in December 1961, and since then systems and components have been extensively tested. This pre-operational test programme has been extremely valuable in verifying the design and indicating the modifications needed. The more important modifications were described in the paper; all the problems encountered, said Mr. Hartwell, have proved manageable.

Experience gained during the post-construction testing of three nuclear power plants constructed under the Power Reactor Demonstration Programme of the US AEC was given in a paper by C. A. Pursel (USA). These are the Elk River Reactor, the Hallam Nuclear Power Facility and the Piqua Nuclear Power Facility, and represent three different reactor concepts, namely natural circulation boiling water, sodium graphite, and organic cooled and moderated, respectively.

Mr. Pursel also presented a paper reviewing the evolution of the US civilian power programme.

Other Topics

Apart from these reports on different nuclear power plants, there was a discussion of problems encountered with specific plant components. For example, a paper by G. N. Ushakov and five other Soviet authors described the design of the steam generators of the USSR First Atomic Power Station and discussed the possible causes of failures that occurred in the pipes. Problems concerning reactor vessels were discussed by French participants. Other topics discussed included measurement of leak-rate from containment structures and efficiency of shutdown and safety equipment.

At the session on fuel cycles and fuel handling, papers were given by British and French participants, and an important subject touched upon was fuel cycle costs. C. Allday (UK) said that although the economics of power reactors of the current British type were dominated by capital costs, fuel costs were not unimportant. "With capital committed," he said, "it is only by reducing costs associated with the fuel cycle and reactor operation that savings can be made in the cost of power generated." At the same time, as A. Johnson (UK) pointed out, while theoretically an improvement of about 20-30 per cent can be made in the fuel cost component by the selection of advanced fuel replacement policies, practical considerations limit the economies that can be made in the early stages of the operation of the first reactors. "Initially effort will be directed towards preventing increases in generating costs arising from unplanned shutdowns or power reductions caused by lack of flexibility or faulty judgement."

Some of the magnox fuel elements manufactured by the UK Atomic Energy Authority. 1. Calder Hall element; 2. Latina element; 3. Bradwell Mk III element; 4. Tokai-Mura graphite sleeve; 5. Tokai-Mura element; 6. Hunterston sleeve; 7. Hunterston element; 8. Berkeley Mk. 1B. (Picture reproduced from paper by C. Allday)

According to Mr. Johnson's review, the most important recent developments concerning fuel cycles have been:

(a) the commissioning of the first "on-load" refuelling machines in the UK:

(b) the successful irradiation of "Magnox" fuel elements in excess of their design levels;

(c) the development of predictive computer programmes which have many applications in operation power reactors; and

(d) the economic argument in favour of flexibility of enrichment.

Problems of unloading and refuelling during reactor operation - instead of during shutdowns - were also discussed by R. A. de Cremiers (France). He described the complexity of these problems and stated that at the Marcoule Centre the unloading programmes are prepared by an electronic computer system using punched card techniques.

The conference also discussed problems of staff selection, training and organization for nuclear power plants.

Trends and Prospects

In the panel discussion at the end of the main sessions, the principal speakers were Fernand Conte, of the Marcoule Centre of the French Atomic Energy Commission; Coningsby Allday, of the Risley Centre of the UK Atomic Energy Authority; Claude Andrew Pursel, of the US Atomic Energy Commission; and N. Aristarkhov, of the Institute of Power and Physics, Moscow.

All four of them spoke in reply to two main questions: (1) what reactor types could be considered as proven and meriting special attention in the next decade; what part would these reactors play in the long-range future; would they be superseded by entirely different types; and (2) how could the experience gained so far be best transmitted to new reactor projects in the developing countries?

Each of the speakers spoke mainly on the reactor types developed in his own country, without attempting any direct comparative estimate of other types. They reaffirmed that the types already established had had extremely satisfactory records of performance; that they could be economically competitive, either immediately or in the near future; that they could and would be developed further; that in the meantime work would be done on new types; and that eventually the full potential of nuclear power would be realized from fast breeder reactors, i.e. reactors which would convert normally non-fissionable thorium or uranium-238 into fissionable materials and thus produce more fuel than they would consume. As Mr. Aristarkhov said, the future of nuclear power rested with reactors using fast neutrons, but he did not want this forecast to imply that thermal reactors (those in which a moderator is used to slow down the neutrons, like the ones now used for power generation) were going to be abandoned in the near future. In fact, as he put it, one could expect "a state of peaceful co-existence" between thermal and fast reactors even after the latter had been fully developed. This point was also made by Mr. Pursel, who explained that the US nuclear power programme, as outlined in a recent report to the US President, did not envisage giving up the present types in favour of breeder reactors.

Mr. Conte and Mr. Allday described the satisfactory performance of the gas-cooled natural uranium reactors developed in France and Britain and were confident that, in terms of costs of power generation, they would break even with conventional power stations by the end of the 1960's. Referring to the fact that most of the troubles so far experienced in nuclear power stations had arisen in the conventional components of the plants rather than in the nuclear reactors themselves, Mr. Conte said that there was obviously a case for subjecting the conventional components to the same degree of scrutiny and supervision as was given to the nuclear components. He also referred to the limitations imposed upon reactor performance by the elaborate safety requirements adopted at present and thought that it might be possible to make them less stringent.

As regards British experience, Mr. Allday said that the present Magnox stations (Calder Hall, Chapelcross, Berkeley and Bradwell) could already be regarded as technically established. The Advanced Gas-Cooled Reactor was more attractive as it would have a lower capital cost and greater development potential; although it was still in the stage of development one could already be confident as to its technical soundness. In the long run, fast reactors would offer a great range of development potential, but the problem at the moment was to develop a satisfactory fuel for such reactors. Referring to the failure of conventional equipment reported by many speakers at the conference, Mr. Allday said that this was a matter which manufacturers of such equipment should certainly examine, but he did not think it was necessary to launch an organized effort on the nuclear power front to solve this problem. Besides, it ought to be remembered that trouble with conventional equipment manifested itself at the start; "nuclear trouble", if it should develop, would show later.

In the opinion of Mr. Pursel, light water reactors were the "most" proven as a reliable, economical source of electrical energy for commercial use. These reactors, he said, were considered by purchasers and users "to be very satisfactory in their systems and to be economically competitive in their specific application". As to the long-term outlook, Mr. Pursel thought that the ultimate equilibrium condition for a nuclear economy would be a mixture of burner reactors (i.e. the present types in which the primary aim is to get the maximum energy from the immediate utilization of the reactor fuel) and breeder reactors (i.e. those in which the emphasis will be on the production of new fuel simultaneously with the generation of power from the fissionable materials already present).

Mr. Aristarkhov said that the information given at the conference had shown that all the established reactor types had lived up to expectations. Of the three major types, viz. reactors moderated and cooled by light water, those moderated by graphite and cooled by water, and those moderated by graphite and cooled by gas, the USSR had worked on the first two but had no experience of the third. A large pressurized water plant was being built near Voronezh. Mr. Aristarkhov said that as one working on a fast reactor he could not be quite objective about different types. It was true that certain difficulties had been experienced with the fast reactor system, but he had no doubt that they could be overcome. As regards present types, he felt that much improvement could be achieved by removing the current troubles with conventional components.

A statement on the heavy water reactor was made by Mr. McConnell of Canada, who said the fuel costs for this type were lower than any reported for other types.

Regarding nuclear power projects in the developing countries, it was generally agreed that it would be advisable to choose an established reactor type rather than one that was still in the experimental stage. If, however, such a country was prepared to share the risks and responsibilities of developing a yet unproven type or adapting a proven type to local conditions, joint projects could be undertaken. In any case, the participation of scientists and engineers of the developing countries in reactor projects undertaken there was essential in all circumstances. The role of IAEA in the training of technical personnel from these countries, in disseminating information on nuclear power technology, and in arranging possible joint projects was emphasized by several speakers.