SAFETY OF NUCLEAR REACTORS

More realistic appraisal of hazards, surer safety based on increased knowledge, improved organization, and better techniques - this was the over-all picture which emerged from a Symposium on Reactor Safety and Hazards Evaluation Techniques conducted by the International Atomic Energy Agency in Vienna from 14 to 18 May.

Nuclear reactors have, during the first twenty years of their existence, achieved an impressive safety record, possibly exceeding that of any comparable industry. As revealed in a paper by Henri B. Smets of the European Nuclear Energy Agency, there have been recorded during this period of time but six fatalities and less than 30 persons seriously irradiated from reactor accidents. Three of the fatalities, moreover, occurred in a single accident, that which destroyed the SL-1 reactor in the United States on 3 January 1961.

This excellent record was achieved in the early years of the industry by taking very elaborate precautions. In the absence of real knowledge as to what the danger really was, very pessimistic assumptions had to be made. G. Laurence of Canada, describing this early phase to the symposium, noted that it was customary to postulate the worst conceivable accident and to incorporate sufficient safety features to protect against it. This customarily involved utilizing a site remote from habitation, one or more containment shells around the reactor, and instrumentation of such complexity that, in Dr. Laurence's view, it was doubtful that it really added to safety. Another speaker likened this early stage to the first days of the automobile when an English law required any automobile entering a populated place to be preceded by a man on foot carrying a red flag.

The reactor industry's "red flag" stage was probably required by society, since, as the IAEA Director General, Sigvard Eklund, pointed out in his opening remarks to the symposium, the military origins and potentialities of atomic energy are deeply imprinted on the minds of people everywhere and have created a special sensitivity toward the thought of radiation injury. As Dr. Eklund also pointed out, however, the elaborateness of the safety measures taken involved a severe economic penalty to nuclear power in its efforts to compete with alternative sources of power. Thus, O. Kellerman of the Federal Republic of Germany estimated that the cost of safety precautions in atomic power plants aggregates 10% to 20% of total plant costs.

The task of workers in the field of reactor safety has therefore been to find ways of assuring safety to a degree acceptable to the public, but at the same time to do it in ways which are not so prohibitive in cost or other requirements as to deny to society the benefits which reactors can offer.

Evaluation of Hazards

The papers and discussion heard at the symposium indicated that a large measure of success has been achieved in meeting the objectives stated above. One of the areas in which great progress has been made is in the evaluation of the hazards presented by individual reactors. Quite early in reactor history the concept of the "worst conceivable accident" referred to by Dr. Laurance gave way to another one known as the "maximum credible accident". This was defined by R. Boulanger of Belgium as "the most serious accident which one can conceive without implying any clearly impossible circumstance".

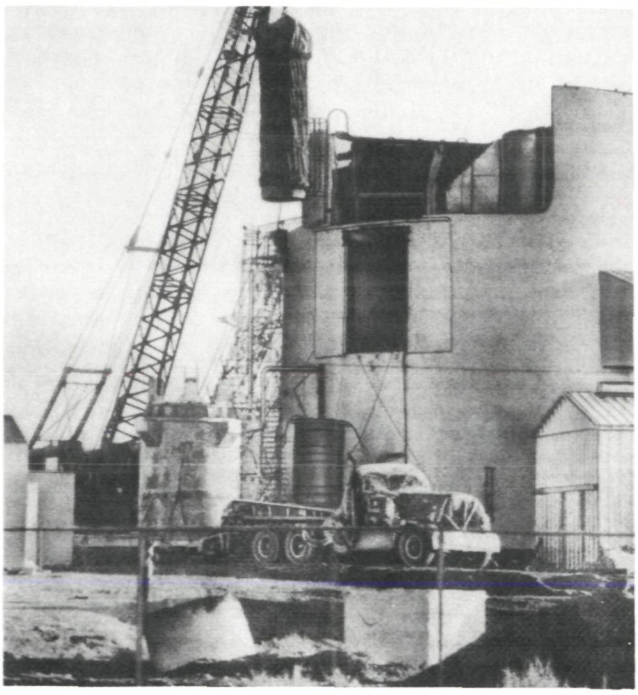
Identifying the maximum credible accident and analysing its possible consequences has become a standard, though not exclusive, basis for evaluating hazards of nuclear reactors in most countries. The fortunate lack of experience with such events in nuclear reactors has, however, prevented precise evaluation. It was pointed out by J. DiNunno of the United States that, because of this absence of data and clear understanding, pessimistic assumptions must still be used regarding potential accidents. A considerable amount of experimental and theoretical work is now in progress in a number of countries to fill in the present gaps in knowledge. Mr. Di Nunno and A. Foderaro presented papers describing such work now taking place in the United States involving a series of experimental reactors devoted exclusively to safety research. In the United Kingdom, as described in a paper by G. R. Bainbridge, there has been a concentration of experimental effort aimed at narrowing the range of uncertainty regarding the more important data affecting the safety of Calder Hall-type reactors. Safety experimentation taking place in France was mentioned by A. Bourgeois, who also described programmes under which nations doing such work are co-operating in a free exchange of results and data.

Several papers considered the likely causes and possible effects of maximum credible accidents in various specific reactors or types of reactors. Dr. Kellerman's paper indicated that for several of the more prominent types of reactors the maximum credible accident would most likely arise from a rupture of primary piping, causing a loss of reactor coolant. Dr. Boulanger's paper estimated the consequences of simultaneous rupture of both primary and secondary loops in the Belgian BR-3 power reactor. Mr. Bourgeois presented a paper on the safety of natural uranium, graphite-moderated, gas-cooled reactors, considering in some detail accidents which might result from blocking of a channel or from violent collapse. V. Sidorenko of the Soviet Union showed how failure of electric power supply to the motors operating coolant pumps could conceivably lead to a serious accident in a pressurized water reactor.

Several speakers, among them A. Veselkin of the Soviet Union, observed that the time of greatest danger for a reactor may occur when the plant is not operating but is capable of operating. Mr. Veselkin emphasized the need for special precautions at such times. Dr. Laurence, who went into this matter perhaps most extensively, noted that "of the few bad accidents that have occurred anywhere in the world, two happened when the reactor was not operating and the rest when it was being started up after a shutdown". Thus, the most serious reactor accident in history from the point of view of loss of life, the one which destroyed the SL-1 reactor in January 1961, occurred when the reactor was being prepared for resumed operation following a shutdown for maintenance and alterations. This accident and the ensuing investigation, which is still in progress, were described in detail by A. N. Tardiff of the United States.

Two principal effects must be reckoned with in the event of reactor accidents. The first is blast. The second is the massive release of fission products through the walls of the building or the reactor stack. Of the two, the release of fission products is by far the more dangerous. "Blast effects", noted Dr. Foderaro, "have a relatively small range and thus a relatively small potential for damage. Furthermore blast effects can be, and are, simply mitigated by providing a relatively small controlled area around the reactor site."

The intensive investigation of the accident which destroyed the SL-1 reactor at the USAEC's reactor testing station in Idaho has contributed much to the understanding of reactor safety principles. Here the reactor core is being lifted out of the reactor building. It was then shipped to a "hot" cell forty miles away for disassembly and examination



The release of a radioactive cloud following a reactor accident, on the other hand, might conceivably have far-reaching consequences. Accordingly, a basic ingredient in safety analysis is to estimate the contents of such a radioactive cloud following assumed accidents in particular reactors and to calculate its likely dispersion and effects on the surrounding population. A considerable amount of work throughout the world is being done on this problem, and several papers presented to the symposium related to it. For example, M. Suzuki of the Agency's staff presented calculations of the doses from external exposure to radioactive clouds and by inhalation of radioactive aerosol, based upon varying assumptions concerning the characteristics of aerosol, conditions of exposure and biological factors. He found that great variability is to be expected of the doses accumulated in different parts of the body.

Designing Reactors to be Safe

While absence of certainty still compels pessimistic assumptions to be made regarding the possibility of accidents, papers presented to the symposium also made it clear that great progress has been and is being made toward reducing the likelihood of accidents. Thus, Dr. Foderaro said: "The stage is being reached where enough is known so that the selection of reactor parameters and controls can provide a high degree of intrinsic reactor safety." As this statement implies, Dr. Foderaro classified the safety characteristics of a reactor system under two headings: "those that are inherent to the core and those inherent to the control system".

Dr. Foderaro described inherent nuclear mechanisms found in different types of reactors by which the reactors tend to shut themselves down, or at least to return to an acceptable power level, following any sudden increase in power. Thus, for example, a water-cooled reactor known as SPERT I employed in the US safety research programme has been found to respond to these so-called power bursts by the formation of steam, which increases the probability of neutron leakage, and by metal expansion, which both expels moderator fluid and changes the geometry of the core. In so-called solid homogeneous reactors, in which the fissile material is intimately mixed with a solid moderator, power bursts have been found to result in moderator heating which leads to increased leakage of neutrons from the core.

It was pointed out by H. Karwat of the Federal Republic of Germany that the cladding of fuel elements represents "the first containment for the fission products" in a reactor. It is therefore important to design into any reactor core fuel elements and cladding which will maintain their integrity under severe conditions. Dr. Karwat's paper dealt with certain problems in the design of such fuel elements and cladding. A paper by D. Martin of France indicated that analysis of an accident in the French reactor G1 in 1956 has permitted determination of the exact temperature and other conditions under which combustion of certain types of reactor fuel elements can occur.

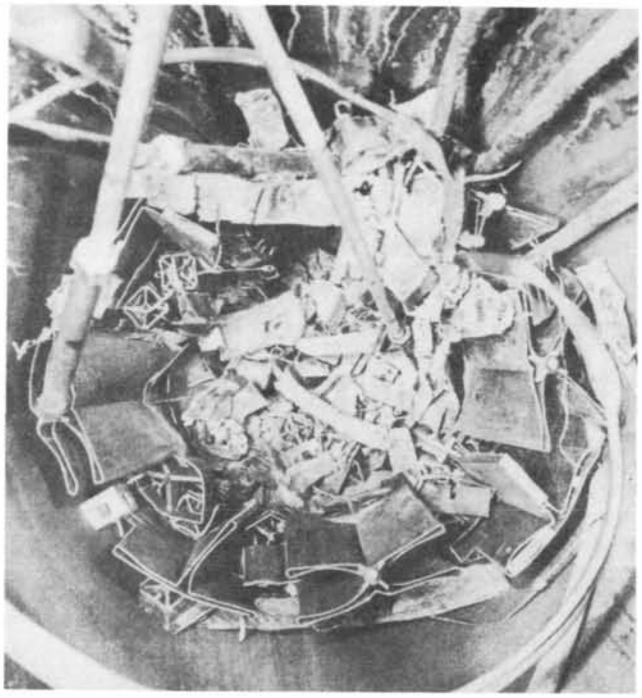
Another set of mechanisms by which reactor accidents can be prevented are those involved in various control systems outside the reactor core. In general, the purpose of these is to sense any abnormal condition and to respond by actuating either a signal to an operator or a device to shut the reactor down. Some of the recent trends in the development of such external control systems were indicated in papers presented by P. R. Tunnicliffe and J. H. Collins of Canada, which related mainly to improvements achieved in the control of the NRX reactor at Chalk River. Mr. Collins noted that the major accident to NRX in 1952 "had clearly demonstrated that the primary shutdown device was unreliable", in that several of the 18 neutron absorbing control rods failed to drive fully into the reactor when released. Following the accident, therefore, the rods were replaced by six electrically driven rods of greater reliability. In addition, an automatic dump of heavy water moderator was provided for as a second, independent shutdown device on the theory that "if one device failed to operate the other would still shut down the reactor".

It was indicated by Mr. Tunnicliffe that Canadian practice is to require instrumentation to accept a relatively great responsibility for the safety of a reactor because of a belief that attempting to achieve safety by relying almost exclusively on nuclear mechanisms "imposes economic penalties on the development of nuclear power". A basic feature of the NRX control system as now employed is to have three independent channels for sensing and announcing any dangerous condition. If two of the three channels are activated by any condition, the coincidence will automatically actuate the reactor shutdown mechanisms. If only one channel senses danger, the result is merely to activate an alarm. Three major advantages are seen for this system. It assures that no dangerous situation will go undetected because of failure of a sensing device. It also prevents costly "spurious" shutdowns caused by activation of a defective sensing device when the reactor itself is operating normally. It was noted by Mr. Collins, for example, that at one time NRX had 275 shutdowns per year, the majority of which were due to defective instrumentation. Finally, the triplication system permits a single instrumentation channel to be taken out of service for maintenance or repair without requiring the reactor to cease operation.

It was indicated in papers by V.S. Rao (India) and K. Becker (Germany) respectively, that both the CANDU reactor at Trombay and the FR-2 reactor at Karlsruhe employ triplicate control systems much like those used at Chalk River.

The Human Factor in Safety

A noteworthy feature of the symposium was the emphasis placed by many speakers on the human factor in reactor safety. Thus Dr. Laurence commented that most of the accidents that have happened could have been avoided by greater care on the part of operators. T. N. Marsham of the United Kingdom



View of damage sustained by the centre of the SL-1 core. (The two SL-1 pictures are taken from a paper presented to the Reactor Safety symposium by A.N. Tardiff, USA)

commented that an alert operator is often superior to the most elaborate instrumentation in that he can anticipate and thereby prevent a dangerous condition, whereas the instrument's activity may be confined to taking counteraction against danger after it has arisen. Mr. Marsham noted further: "In spite of the satisfactory performance of the (Calder Hall) automatic protection equipment, the value of the reactor operator in ensuring safety has been demonstrated. Under fault conditions operators have taken the correct action in surprisingly short periods and it is considered that safety is considerably enhanced by assuring that the operator is always provided with adequate information on the state of the plant and that he has a worthwhile function to perform irrespective of the degree of automatic equipment installed."

The importance of having operating procedures written out in detail was repeatedly emphasized. R. Charlesworth stated that the existence of such written instructions was a precondition for the licensing of reactors in the United Kingdom. Mr. Collins testified to the existence of over 1000 manuals covering different aspects of the operation of the NRU reactor at Chalk River. Dr. Rao stated that there were some 800 such manuals governing operation of the three research reactors at Trombay.

Several speakers urged the necessity for maintaining a detailed log of everything significant that occurs in the course of a reactor's operation. A. Johnson, of the United States, for example, stated that detailed records should be kept of all malfunctions, misoperations, failures or mishaps.

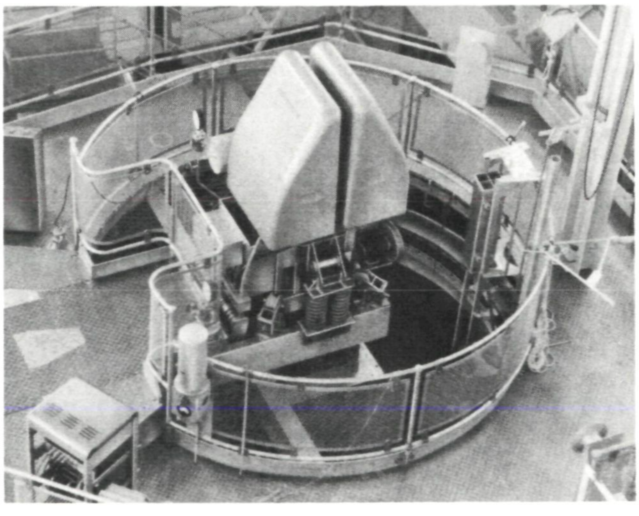
There were several discussions of the most advantageous administrative organization for a reactor plant. R. Vestegaard of Sweden emphasized the importance of having a strong, permanent safety committee composed of senior scientific staff members "to prevent safety from decaying once you have put it there".

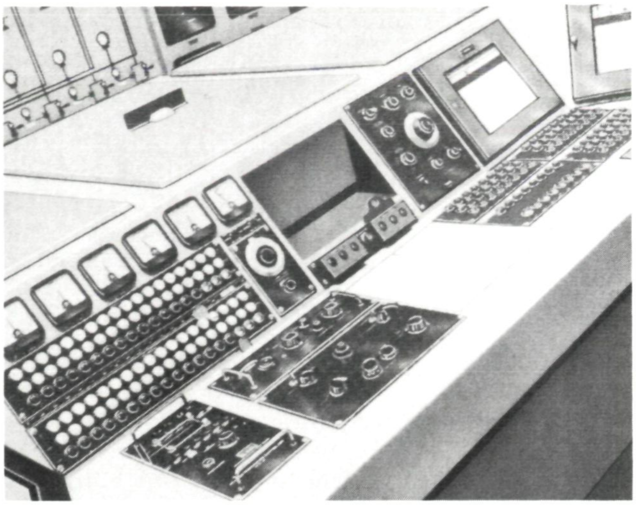
Siting and Containment

Another interesting trend apparent in the papers presented at the symposium was a lessened emphasis on isolated reactor locations as a means of ensuring safety to the environment. This seemed partly based on the cost of transmission lines when power reactors are located far from power consumers, and partly on the difficulties presented by population growth. Thus, W. E. Johnson of the United States observed that "population growth and distribution in the United States today, particularly as evidenced in the expansion of suburban areas surrounding large cities, is such that a presently isolated plant site might no longer be isolated several years from today". A similar observation was made by T. Yamada regarding Japan, under whose existing regulations it is difficult to control increases in population around a reactor site.

To a considerable extent, the decreased emphasis on isolation seems also attributable to changed attitudes on the part of the public in different countries. On the one hand, there appears to be greater confidence that reactor plants can be good neighbours. There is also evidence of a tendency to relax any former insistence on absolute safety which might have jeopardized the ability of particular countries to derive social benefits from reactors. Thus, Mr. Yamada's paper showed that even a country as sensitive to radiation hazards as Japan has accepted the idea that absolute safety cannot be required of reactors any more than of other industries. Accordingly, decisions whether or not to license reactors in Japan are being based on criteria which balance social benefit and potential hazard. Similarly, V. Serment of Mexico indicated that his country had determined to accept certain risks in locating research reactors in order to reduce costs and make it easier to derive benefits from atomic energy. A paper on the criteria to be used in the siting of reactors by J. Tadmor of Israel advocated giving considerable weight to the benefit expected from the facilities.

View of the top of a research reactor showing control rod gear box covers (Photo UKAEA)





Console containing controls of the NRU reactor at Chalk River, Canada (From a paper presented to the symposium by J.H. Collins, Canada)

Most early power reactors have been surrounded with large containment shells in order to protect the environment in case of accident. Mr. Vestegaard contended that, with increased knowledge of what really happens in reactor accidents, this emphasis on containment, as well as the emphasis on isolation, would be found to have been excessive. In the meantime, however, improved forms of containment are being developed. The paper by Mr. Johnson described several new containment concepts being developed in the United States, including one which would assure "that there will be absolutely no uncontrolled release of radioactive material to the atmosphere". R. Mattera compared the degrees of safety and the costs involved in two types of containment which have been tried in France, one made of steel and the other of pre-stressed concrete. Both types are designed to contain maximum pressures in case of accident without the assistance of any cut-off device. P. Verstraete described a Swiss approach to the problem of containment which involves locating reactors in underground rock caverns.

Tasks for the Future

While many advances towards desired objectives in reactor safety were noted at the symposium, there was also repeated and frank acknowledgement of things which remain to be accomplished. Several such items were mentioned by speakers who constituted a "summing up" panel at the concluding session. Frank Farmer of the United Kingdom commented on the vast complexity of the reactor safety field, which he attributed to the large variety of reactor types, fuels, fuel claddings and other components now in use. He stated that some aspects of the subject were not yet completely understood and he cautioned against any tendency to oversimplify. Dr. Farmer recommended that an effort be made on an international scale to codify what was known about the various aspects of reactor safety, such as the consequences of accidental release of various isotopes and the behaviour of different materials under irradiation.

A paper presented by G. Page of Australia had earlier commented on the lack of a "published guide to standard principles and criteria for important and potentially hazardous matters, especially prepared for newcomers to the field". As examples of topics which might be covered, Mr. Page mentioned "the safety principles to be adopted in the design and operation of the project, including the relative importance of mechanical and electrical shutdown devices and administrative control, and the degree of supervisory control by senior staff".

His comments tied in with remarks made by Pierre Balligand, IAEA Deputy Director General for Technical Operations, at the symposium's opening session. Mr. Balligand stated that a principal reason for convening the symposium was to help the Agency in its long-term effort to establish a set of minimum safety standards to be complied with in the construction of reactors.

Another need for the future was referred to by the Director General, Dr. Eklund, at the opening session. Commenting on the feeling of some in the reactor industry "that there is a double standard in safety requirements by which nuclear undertakings are compelled to be safer than all others", and that this imposes an economic penalty on nuclear power, Dr. Eklund pointed out that the price which society is willing to pay for material progress is one which industry cannot and should not want to control. On the other hand, Dr. Eklund said, it is important that the nuclear industry provide correct information about the real meaning of reactor hazards in order to permit "the necessary comparisons with other risks involved in a modern society". Ultimately, the Director General concluded, reactor engineering should aim to make reactors completely safe at little cost, but until this is achieved it should be able "at any time to present an account to society indicating what degree of safety can be obtained at what cost".