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ATOMIC ENERGY
OF CANADA LIMITED

ÉNERGIE ATOMIQUE
DU CANADA LIMITÉE

THE CANADIAN R&D PROGRAM TARGETED AT CANDU REACTORS

LES RÉACTEURS CANDU SONT L'OBJECTIF DU PROGRAMME CANADIEN DE R ET D

E.O. MOECK

Presented at the IAEA Technical Committee
Meeting and Workshop on Progress in
Heavy Water Reactor Design and Technology,
Montreal, 1988 December 6-9

Chalk River Nuclear Laboratories
Laboratoires nucléaires de Chalk River

Chalk River, Ontario

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E.O. Moeck (rédacteur)

Communication présentée à la Réunion et à l'Atelier du Comité Technique de l'AIEA sur le progrès réalisé en conception et technique des réacteurs à l'eau lourde, à Montréal, du 6 au 9 décembre 1988

RÉSUMÉ

Les réacteurs CANDU produisent de l'électricité à bon marché et de façon fiable, le risque pour la population étant insignifiant et les conséquences pour l'environnement minimales. Environ la moitié de l'électricité de l'Ontario et le tiers de celle du Nouveau-Brunswick est produite par les centrales CANDU. L'Hydro-Québec et les compagnies d'électricité de l'Argentine, de l'Inde, du Pakistan et de la République de Corée exploitent avec succès des réacteurs CANDU. La Roumanie fera bientôt partie du nombre.

La tradition prouvée d'excellentes performances des centrales CANDU est due en partie au premier objectif du programme énergique de R et D: c'est-à-dire de soutenir et d'améliorer la technique existante de centrale CANDU. Le deuxième objectif est de mettre au point des centrales meilleures qui resteront compétitives par rapport aux autres sources de fourniture d'énergie. Troisième objectif est de continuer d'améliorer notre connaissance des processus qui sont à la base de la sûreté des réacteurs et de mettre au point des techniques meilleures pour atténuer les conséquences d'un état perturbé.

Ces trois objectifs sont examinés dans trois programmes de R et D particuliers dans les secteurs des canaux de combustible de réacteurs CANDU, des frais d'exploitation réduits, des frais d'investissement réduits, de la recherche sur la sûreté des réacteurs et des garanties de l'AIEA. Les travaux sont effectués principalement à trois centres de l'Énergie atomique du Canada limitée: les Laboratoires nucléaires de Chalk River, l'Établissement de recherches nucléaires de Whiteshell et les Laboratoires d'ingénierie de Sheridan Park; il le sont également aux Laboratoires de recherches d'Ontario hydro. En outre, les universités , consultants, fabricants et fournisseurs canadiens offrent leurs compétences dans leur champ de spécialisation.

La Division des Exploitation Avancée des Réacteurs
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ABSTRACT

CANDU reactors produce electricity cheaply and reliably, with miniscule risk to the population and minimal impact on the environment. About half of Ontario's electricity and a third of New Brunswick's are generated by CANDU power plants. Hydro Quebec and utilities in Argentina, India, Pakistan, and the Republic of Korea also successfully operate CANDU reactors. Romania will soon join their ranks.

The proven record of excellent performance of CANDUs is due in part to the first objective of the vigorous R&D program: namely, to sustain and improve existing CANDU power-plant technology. The second objective is to develop improved nuclear power plants that will remain competitive compared with alternative energy supplies. The third objective is to continue to improve our understanding of the processes underlying reactor safety and develop improved technology to mitigate the consequences of upset conditions.

These three objectives are addressed by individual R&D programs in the areas of CANDU fuel channels, reduced operating costs, reduced capital costs, reactor safety research, and IAEA safeguards. The work is carried out mainly at three centres of Atomic Energy of Canada Limited--the Chalk River Nuclear Laboratories, the Whiteshell Nuclear Research Establishment, and the Sheridan Park Engineering Laboratories--and at Ontario Hydro's Research Laboratories. Canadian universities, consultants, manufacturers, and suppliers also provide expertise in their areas of specialization.

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1. INTRODUCTION

At the present time, CANDU* Heavy Water Reactors (HWRs) generate 15% of the electricity produced in all of Canada. In the Province of Ontario, home to 36% of all Canadians, CANDU HWRs currently supply about half of the electricity from two major nuclear sites, Pickering and Bruce, each with eight reactors. This level of nuclear production will increase shortly as the four units at Darlington are commissioned starting in 1989. As a consequence, Ontario enjoys one of the lowest electricity rates and most reliable systems in the world. Electricity in Ontario is produced in the nuclear stations typically at about half the cost of power from stations which burn coal. As well, nuclear power minimizes coal-burning pollution.

Similarly, CANDU supplies almost a third of the power used in the Province of New Brunswick and has been a major contributor to export earnings for that province derived from power sold to the United States. There are CANDU HWR stations based on the CANDU 6 model in New Brunswick, Quebec, Argentina, and the Republic of Korea. Romania has five CANDU 6 units under construction.

Aside from the electricity field, the Canadian nuclear program has given rise to medical technologies that are used to treat an estimated 500 000 patients annually in more than 80 countries. Food and agriculture applications of nuclear technology have led to crop improvements, and contributed to pest control and food preservation.

In terms of broad objectives for the national HWR program, low capital cost takes on special significance. This is important particularly in the context of funding for domestic and foreign projects, since both borrowers and lenders may be operating near their limits of credit for many years into the future. Other requirements are that nuclear power stations be of a size appropriate to the grid load demands and grid stability; offer low operating and maintenance costs; provide low fuelling costs with flexibility on fuel options; and assure high reliability, safety and minimal environmental impact. In addition, the broad objectives include recognition of the need for localization and collaborative technology development.

Capital cost reduction is pursued through improvements in the design, such as power uprating, simplification and modularization. Cost reduction is also being achieved through the use of new engineering technologies such as Computer Assisted Design (CAD) which lead to improved productivity and control of quality. Fuelling cost can be reduced by using low-enriched fuel.

Ontario Hydro has been studying a standardized four-unit station design using the Darlington "A" design as a reference. The study objectives are to shorten the schedule for the first unit in service, to reduce the capital cost and to provide high confidence in achieving schedule and cost targets.

The CANDU 3, with a net electrical output in the range of 450 MWe, is the latest and also the smallest power station of the current CANDU family. The CANDU 3 is an advanced design which exploits proven technology to compete with coal-fired generating stations, thereby making nuclear power available to a wide range of utilities with low or uncertain load growth. The CANDU 3 is now

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*CANada Deuterium Uranium, Registered in the U.S. Patent and Trademark Office.

in the detailed design stage. The new model of the CANDU 6 is the Mk2. It has an output from 650 to 800 MWe, depending upon uprating options. An Advanced CANDU is under conceptual design and covers a power range of 700-1150 MWe.

Today, in Canada, that part of the R&D program targeted specifically at CANDU heavy-water reactors has the following three objectives:

(A) to sustain and improve existing CANDU power-plant technology,

(B) to develop improved nuclear power plants that will remain competitive compared with alternative energy supplies, and

(C) to continue to improve understanding of the processes underlying reactor safety and develop improved technology to mitigate the consequences of upset conditions.

The program is structured to span short-term and long-term needs. That is, work in support of existing CANDU reactors invariably provides technology useful to the next generation of CANDUs. Conversely, the improved understanding of aspects such as components and systems, and the tools such as computer codes stemming from long-term R&D, sustain a pool of multidisciplinary expertise available to tackle problems arising in today's plants. This expertise and the associated specialized-research facilities are concentrated mainly at three centres of Atomic Energy of Canada Limited (AECL)--the Chalk River Nuclear Research Laboratories, the Whiteshell Nuclear Research Establishment, and the Sheridan Park Engineering Laboratories--and at Ontario Hydro's Research Laboratories. Canadian universities, consultants, manufacturers, and suppliers also provide expertise in their areas of specialization.

The total annual budget for the above program is about $125M (Canadian) per annum, provided by the Canadian government primarily through AECL and by the Canadian utilities who own and operate CANDU reactors, namely Ontario Hydro, Hydro Quebec, and New Brunswick Power. Some specific R&D activities are funded by AECL's other commercial clients. Most of this program is administered through the CANDU Owners' Group, comprising the above 3 utilities and AECL.

2. CANDU FUEL CHANNELS

A CANDU reactor has several hundred horizontal fuel channels, each consisting of an outer calandria tube and an inner pressure tube. An insulating gas annulus between the pressure tube and calandria tube minimizes heat transfer from the high-temperature heavy-water coolant to the low-pressure, low-temperature heavy-water moderator. R&D on CANDU fuel channels dominates the work in support of objective (A) and the overall goals are:

(i) to obtain a better understanding of pressure tube and calandria-tube behaviour under reactor conditions, and

(ii) to develop improved fuel-channel components.

Fuel channels in existing CANDUs were assembled in situ and as a result are time consuming to replace. A significant R&D program is also under way to develop a factory-assembled fuel channel for future CANDU reactors that will significantly reduce the time required for its installation and replacement.

The R&D program encompasses laboratory investigations, research-reactor irradiation studies, and an extensive program of power-reactor surveillance involving in-reactor examination and destructive examination of fuel channels removed from power reactors by the utilities. By removing fuel channels from power reactors, specific information is obtained on the condition of fuel channels in the reactor, along with a valuable stock of irradiated material for more fundamental studies (1).

2.1 Corrosion and Deuterium Pickup

Some problems have occurred with operational pressure tubes, and the root cause of all these problems has been Delayed Hydride Cracking (DHC). For delayed hydride cracking to initiate, hydrides must be present, and there must be a minimum concentration of stress and size/sharpness of a defect. The hydrogen isotopes that contribute to hydride formation are the sum of the initial as-fabricated hydrogen concentration and the pickup of deuterium from the corrosion reaction. A predictive capability is being developed based on an in-reactor parametric study that is examining the effects of irradiation, temperature and chemistry on corrosion and D_2 pickup (2). Other experiments are investigating the effect of boiling on the local chemistry at the pressure-tube surface. Such information will provide a guide to the useful life of a pressure tube.

Preventative measures that minimize pickup through adjustment to the heat transport chemistry and/or composition of the pressure-tube alloy are also part of the program. Alternatively, the use of metallic inserts in the tube that have a greater affinity for hydrogen than zirconium can prevent precipitation of zirconium hydride and eliminate DHC. Detailed engineering has recently been completed for application of such devices to control pickup at the ends of the fuel channels.

Both irradiation and hydrogen decrease the flaw tolerance of zirconium alloys (3). The mechanical properties and flaw tolerance of pressure tubes and calandria tubes are being studied as a function of fluence using burst tests, tensile and small-specimen fracture-toughness tests. These continue to extend the insight needed to ensure continued leak-before-break and provide end-of-life criteria.

2.2 Creep and Growth

The dimensions of the calandria tube and pressure tube change during service due to creep and growth (4). The former process is enhanced by irradiation and the latter is solely an irradiation phenomenon. Accelerated tests are in progress in high-fluence test reactors to confirm the predictions that have been used to establish the design allowances in operating reactors. The weight of the fuel and the channel imposes a load that causes the horizontal channel to sag between the end supports. Excessive sag could result in contact with other reactor internals. In addition, the hotter pressure tube may sag and contact the calandria tube between internal supports. Both forms of contact are undesirable. Since sag is largely controlled by creep, there is an extensive program looking at in-reactor creep and diametral expansion. The modelling of the two phenomena has achieved an advanced level of sophistication.

The integrity of a pressure tube may be impaired by the presence of flaws, an excessive concentration of hydrides or deformation beyond design allowances. The collection of such data from power reactors has required the development of sophisticated inspection systems to minimize reactor down time. Improvements have been made in instrumentation, the in-reactor delivery system for the instrumentation and data collection (5). For example, refinement of the ultrasonic method to look at the waves emanating from the crack tip provides precise size and position information for defects.

2.3 Non-Destructive Examination of Fuel Channels

The focus of the program on fuel channel non-destructive examination is to improve existing techniques and to develop new techniques as required. In the case of operating fuel channels, the program addresses several generic needs, including:

(i) locating the tube-to-tube spacer supports,

(ii) detecting and measuring the various parameters affecting pressure-tube integrity such as hydride levels, corrosion levels and signs of cracking, and

(iii) monitoring clearances between fuel channels and reactivity mechanisms.

The second part of the program focuses on providing the inspection techniques that will be required for the manufacture of new fuel-channel components, including end fittings.

2.4 Improved Fuel-Channel Systems

Improving the long-term reliability and the replaceability of CANDU fuel channels will lead to significant cost savings. A program of work to address the design aspects of this goal is underway. It includes activities such as improvements to rolled-joint technology, fuel-channel leak-detection technology, calandria tubes, and tube-to-tube spacers. There is also some work aimed at further understanding on limiting fuel-bundle vibration and the fretting wear that ensues.

In summary, output from the current R&D program on fuel channels is ensuring their continued reliable operation in current reactors and will provide operators with advance warning of the need for maintenance or replacement. Longer term research will provide components with a higher tolerance to in-service conditions and a longer service life (6).

3. REDUCED OPERATING COSTS

The cost of electricity produced by CANDU plants is already among the lowest from nuclear reactors in the world. This is due largely to CANDU's position as a world leader in annual and lifetime capacity factors and a fuelling cost which is typically half that of LWRs. Nevertheless, R&D continues to find ways of reducing the operating costs even further, through the programs described below.

3.1 Chemistry and Materials of Heat Transport Systems

Research in the chemistry and materials of CANDU heat transport systems is aimed at:

(i) keeping radiation fields from corrosion products and fission products as low as reasonably achievable, and

(ii) preventing premature failure of components by corrosion (7).

Although the CANDU system leads the world in terms of low radiation-dose rate and much is understood about the movement of the radioactive species, improvements in the efficacy of decontamination processes are being sought. In particular, the CANDECON process is being modified to better remove contaminated oxide films from stainless-steel components, and the development of a new dilute process for the dissolution of fission products is well advanced.

Steam generators in CANDUs have performed exceptionally well (a hundred times better in terms of leaks than the industry average), but changes in design and operating conditions require reappraisal of the tubing and support materials and the recommended chemistry control regime. Currently, research is targeted at understanding the accumulation of deposits in steam generators and the chemical and corrosion processes that occur within and beneath this deposit. Since the complete retardation and/or removal of such deposits from operating steam generators seems very difficult, it is imperative that the processes are understood and materials and chemistry selected to obviate failure. Most of the studies involve Incoloy-800 as the preferred tubing material and all-volatile treatment as the chemistry of choice for the secondary system.

3.2 Improved Components and Inspection

Improved reliability and performance, combined with reduced maintenance, are necessary for CANDU to achieve its goals of lower construction and operating costs, 94% overall long-term average capacity factor, and 36 months between outages. The program to achieve these goals focuses on improvements to critical out-reactor components and the ability to inspect them. Currently, work is specifically aimed at:

- better technology for valve and gasket sealing and maintenance (8),

- validation and improvements to the steam-generator thermalhydraulics code THIRST,

- improved non-destructive technology for inspecting heat exchange equipment,

- better design guidelines (9) to minimize vibration and fretting wear problems in heat exchange equipment, and

- generic developments to improve the technology for remote repairs in hostile environments (10).

3.3 Improvements to Current CANDU Fuel

The fuel for CANDU reactors consists of small, robust bundles, approximately 10 cm in diameter by 50 cm long, 12 or 13 of which are loaded into each horizontal fuel channel. The bundles are assembled from 28 or 37 elements containing natural UO_2 pellets. The bundles are pushed along the fuel channel in successive steps, during on-power refuelling, and discharged when they have reached a core-average burnup of about 8.0 MWd/kg, after a residence time of about 1 year in the reactor. To date, 500 000 fuel bundles have been irradiated, with a low lifetime defect rate of about 0.1% on a bundle basis (less than 0.009% on an element basis). Failed fuel is usually detected and replaced without a reactor outage (11). Defected fuel or fuel that has reached burnups of two or more times the average is often examined in detail. Such examinations

(i) identify causes of failure for feedback to operators and fuel fabricators,

(ii) broaden the data base on the performance of CANDU fuel, and

(iii) identify improvements that can be incorporated in subsequent fuels.

Computer codes such as ELESIM and ELESTRES, that model CANDU fuel, are often used to analyze the observed behaviour, evaluate proposed improvements, and predict behaviour at untested conditions such as higher burnup.

3.4 Thermalhydraulics Thresholds

One reason for the low fuel defect rate is the near-zero probability of fuel overrating during normal operation and even during upset conditions. The two independent shutdown systems are set to trip the reactor before any fuel element approaches the critical heat flux (CHF). Since the trip points are conservatively set and the critical heat flux (or critical channel power) is conservatively estimated, there is an incentive to more accurately define both of these to provide larger margins to trip or to raise the permissible operating power.

Research and development are continuing in several related areas. For example, critical channel powers are measured in electrically heated bundles simulating improved fuel designs. While a high-temperature water loop with a power supply of 12 MW has been used for such tests, most experiments are presently carried out with Freon. This permits them to be done more rapidly and at much lower cost. Furthermore, operation at post-CHF conditions can be conveniently explored with lower risk to the equipment. Data from such tests serve to validate advanced thermalhydraulics codes such as ASSERT, used for the analysis of CHF and post-CHF conditions in the subchannels of fuel bundles (12).

3.5 Carbon-14 in Nitrogen Annulus of Fuel Channels

Carbon-14 is produced in the nitrogen gas annulus between the pressure tubes and calandria tubes of Pickering reactor Units 1 to 4 through the ^{14}N (n,p) ^{14}C reaction. The "hot atom" chemistry of ^{14}C and the other reactants present dictate what the products of the reaction will be. It was known from observation that one product was $^{14}CO_2$, arising from small amounts of oxygen that were present as impurities in the annulus gas. During retubing of Pickering reactors 1 and 2, it was discovered that another product of the reaction was a solid particulate that contained ^{14}C, N, O, and H in a complex type of cross-linked $(^{14}CN)_n$ "ladder" polymer. The material was very easily mobilized and presented a significant contamination problem that caused considerable delays and additional costs for work performed in the reactor vault.

Research into the properties and behaviour of this material led to the development of a process for the in-situ oxidation of the material and the subsequent removal of the product $^{14}CO_2$ by a refrigeration/absorber system. Plans are underway to remove $^{14}CO_2$ from the annulus gas of Pickering Units 3 and 4 before they are retubed. All CANDU reactors built subsequent to Pickering Units 1 to 4 use CO_2 in the annulus, and therefore this problem does not arise.

4. IAEA SAFEGUARDS

On-power refuelling of CANDU reactors on a daily basis leads to high capacity factors but requires automatic systems for tracking the movement of irradiated fuel, to safeguard it. Safeguards systems and techniques are in place on most operating CANDU reactors to reliably collect and store information on the disposition of irradiated fuel (13). IAEA inspectors review the information on a regular basis and submit their reports to the respective national governments.

An R&D program is in place to maintain and improve the technologies necessary for safeguarding CANDU fuel. For example, a miniature detector is being developed, together with a delivery system, to scan a close-packed array of irradiated bundles in the storage bays of the Bruce reactors, to verify that they are indeed irradiated fuel and not dummy substitutes.

5. REDUCED CAPITAL COST

There is an on-going challenge for the plant designers to come up with less expensive concepts and designs. Several R&D programs under objective (B) address this challenge.

5.1 CANFLEX, A New Fuel Bundle

One way of reducing the capital cost of a new CANDU plant is to increase the power output from a reactor core of a given size. This can be done by:

(i) increasing the power generated in the fuel bundle, and

(ii) flattening the global radial flux thus increasing the power generated in the fuel channels around the core periphery.

A new fuel bundle, called CANFLEX, is being developed to take advantage of both of these approaches. The 43-element CANFLEX bundle represents an evolutionary step from the proven 37-element bundle and its 28- and 19-element predecessors. Due to a slight reduction in the diameter (and increase in the number) of the peripheral elements in the bundle, relative to the 37-element design, the CANFLEX fuel bundle is expected to be capable of a power output of 1250 kW (vs. 1035 kW) without exceeding the proven linear element rating of 65 kW/m.

If made with natural UO_2, CANFLEX allows reactor designers to take advantage of option (i) above. If made with slightly enriched UO_2 (say, 1.2%), CANFLEX will also open option (ii). During reactor operation, a globally flat neutron flux is achieved via refuelling rates in the inner and outer regions of the core optimized to achieve maximum fuel burnup at maximum power output from the core. Relative to natural uranium, an added benefit of slight enrichment is a reduction in the fuel-cycle cost of up to 35% through use of CANFLEX fuel, for typical costs of natural uranium, fuel fabrication, and on-site storage, transportation, and disposal of the irradiated fuel. Also, the burnup is expected to be 3 times higher and the disposal volume of irradiated fuel 3 times smaller.

The CANFLEX bundle is expected to be available for large-scale demonstration in a CANDU reactor in 1993. The bundle is also regarded as the design of choice for other fuel cycles in CANDU reactors such as the recycling of uranium and/or plutonium from discharged LWR fuel and the eventual utilization of thorium (14).

5.2 Advanced Computer Technology for CANDU Engineering and Construction

The application of advances in information processing technology to all aspects of the design, engineering and construction of a nuclear generating station is one of several programs to make nuclear power more competitive. This program will result in a reduction of up to 20% in blue- and white-collar labour costs on the next generation of CANDU reactors. Cost reductions of this magnitude are essential for nuclear power to compete effectively with other energy options. The systems required to achieve these goals are being established using vendor software where possible, complemented with in-house developments. These include activities such as:

(i) developing efficient interfaces between vendor software and in-house engineering codes,

(ii) customizing vendor software,

(iii) developing tools not yet available from vendors.

The overall program is being resourced by both the AECL Research Company and its sister organization, CANDU Operations. This, combined with the commitment to use these tools in the CANDU 3 design, will ensure that the systems developed meet the needs of CANDU designers. A phased approach is being used, with design and engineering analysis the top priority. The resulting engineering databases will eventually be integrated with procurement, material management, and other construction systems over the next 5 years.

5.3 Heavy-Water Production Processes

Heavy water represents about a tenth of the capital cost of a CANDU station. Therefore, reducing the cost of producing heavy water can make a significant contribution to reducing the initial cost of a new CANDU plant. On the other hand, the cost of heavy-water upkeep (recovery of leakage, reconcentration to reactor grade and replacement of losses) has been demonstrated to be low, and has only a minor impact on CANDU electricity costs.

Several processes are being studied which offer potential for lower costs. They include processes with the attractive features of hydrogen-water exchange and laser isotope separation (15). AECL has developed an attractive catalyst for hydrogen-water exchange and has demonstrated its performance on a small pilot plant scale. Process optimization studies are in progress and scale-up tests are planned. The process recovers heavy water from steam-reformer hydrogen, and is referred to as CIRCE (Combined Industrially Reformed Hydrogen and Catalytic Exchange). The deuterium source for the CIRCE process can be ammonia synthesis gas (1500 Mg NH_3/d will provide 60 Mg D_2O/a) or the large hydrogen streams used for heavy-oil upgrading (typically equivalent to 100 to 150 Mg D_2O/a). The possibility of demonstrating this process in a prototype plant during the 1990s is being evaluated.

Heavy water can also be recovered from electrolytic hydrogen very cheaply with the AECL catalyst (the CECE or Combined Electrolysis and Catalytic Exchange process). However, 100 Mg D_2O/a requires 700 MW of electrolytic cell capacity; such large-scale water electrolysis to produce industrial hydrogen is not likely to be attractive for several decades.

Laser-based processes are at a much earlier stage of laboratory development. Selective multiphoton decomposition of deuterium containing molecules in a natural mixture with their hydrogen analogues has been demonstrated, and single-step separation factors approaching 10 000 have been obtained. AECL is evaluating a variety of decomposition reactions to find an attractive process. A practical process is not possible with abundant molecules such as water, hydrogen or ammonia. Therefore, an exchange step with water or hydrogen is an essential first step in the process to replenish the deuterium concentration in the recirculating "working" molecule. Detailed studies of formaldehyde and of fluoroform by AECL, Ontario Hydro and others have demonstrated very large separation factors, but the economics of a process based on either of these molecules are at best marginal. Recent studies of the economic factors involved in a laser-based process have shown that the criteria for selecting an attractive reaction are stringent (16).

5.4 Advanced Reactor-Core Concepts

Slight enrichment of uranium offers new possibilities in CANDU core design and fuel management. Calculations done to date show that, while existing CANDUs could readily burn enriched fuel without significant modification to reactor systems and operating procedures, better performance could be achieved with a single repositioning of the adjusters to another set of sites. Slight enrichment also offers the opportunity to trade off a desirable attribute such as a thicker pressure tube or reduced volume of heavy-water moderator against the traditionally excellent neutron economy.

New core concepts, new fuel cycles, and materials trade-offs can be successfully evaluated only with the right sets of data and computer codes. R&D is in progress to measure and analyze nuclear reaction rates in various fuels arranged in CANDU-type lattices in the zero-energy ZED-2 reactor at Chalk River. Recent fuels that have been or are being studied include oxides of plutonium mixed with:

(i) thorium,

(ii) depleted uranium from enrichment-plant tailings, as well as

(iii) oxides of thorium mixed with uranium-233.

Such experiments are used to validate and improve the computation methods comprising basic nuclear data from ENDF/B-V in conjunction with the lattice-cell code WIMS-CRNL, reactor code such as CITATION, and fuel-management code FMDP (17).

5.5 Computer Technology for Station Operation and Maintenance

Worldwide, there is a growing interest in significant improvements to the control and safety systems for nuclear power reactors. This is in part a consequence of the accidents at Three Mile Island and at Chernobyl. The need to reduce and hopefully eliminate operator error is being addressed with a program to help the operators during periods of system upset. Advanced computer-system technology, in particular expert systems, are seen as a technology that offers a means of minimizing operator error and stress. This in turn will increase plant availability. The major thrust of this program is to develop an expert system-based Operator Companion for CANDU plants. Ultimately such a system would advise an operator on all aspects of CANDU operation (18).

6. REACTOR SAFETY RESEARCH

The overall objective (C) of the reactor-safety research program is to establish a sound technical basis for the analysis, and mitigation, of postulated accidents in both existing and future CANDU reactors. The approach is to develop the fundamental science pertaining to accident conditions through separate-effects experiments, to develop analytical models that describe the essential phenomena, and to verify the models in large-scale integrated tests.

6.1 Loss-of-Coolant Thermalhydraulics

A unique feature of the CANDU reactor is the configuration of the primary heat-transport system. The behaviour of the system under accident conditions would be particularly influenced by the large array of individual horizontal fuel channels that are connected at the inlet and outlet header pipes. Thus, a thorough understanding of the performance of this configuration under all plausible accident conditions is essential. A two-fluid, one-dimensional, transient code CATHENA has been developed to analyze the thermalhydraulic response of the CANDU primary system (19). In addition to the six conservation equations, constitutive equations are used to calculate mass, momentum, and energy transfer between the two fluids and the wall. The code includes auxiliary models to describe the behaviour of components such as pumps, valves, abrupt area changes, and the reactor pressurizer.

Separate-effects experiments are being done to improve our understanding of such phenomena as horizontal two-phase flow, flow regimes and their constitutive relations, and countercurrent-flow flooding phenomena. Experiments are also being performed to characterize the two-phase flow behaviour of components components such as pumps, steam generators, fuel channels, and flow distribution headers.

Large-scale integrated experiments are being performed in loops that represent the features of the full reactor heat-transport system. Tests have progressed in a stepwise manner from a relatively small facility, RD4, to a full-elevation facility, RD14, which has most of the attributes of the full-scale heat-transport system (20). RD14 consists of two full-scale, full-power, electrically heated channels, full-scale feeders, and two full-height steam generators in a figure-of-eight configuration. The loop is designed so that fluid mass flux, transit times, and pressure/enthalpy distributions in the primary system section of the loop are the same as those in a typical CANDU reactor under both full-power and natural-circulation conditions. The experimental program has included over a hundred experiments covering a variety of conditions and phenomena. These include:

(i) partial inventory two-phase thermosiphoning tests,

(ii) secondary-side depressurization tests,

(iii) small- and large-break LOCAs,

(iv) loss-of-flow simulations, and

(v) two-phase-flow stability tests.

The facility has recently been modified to a multichannel system which provides 5 parallel channels at various elevations for each pass (10 channels in total). The new facility will allow a study of the interaction between parallel channels in both thermosiphoning and blowdown/emergency-coolant-injection transients.

6.2 Fuel-Channel Behaviour at High Temperature

Studies of fuel-channel behaviour at abnormal high temperatures are being carried out to ensure a sound understanding of the conditions under which the residual heat in the fuel channels can be transferred to the moderator, thus preventing the loss of integrity of the fuel channels. Computer models, such as CHAN and CATHENA, have been developed to predict the heat transfer from fuel to the moderator, the resulting temperature transients in the fuel channel, and the deformation of the fuel-channel components. Experimental programs are being carried out to elucidate such phenomena as thermal-contact conductance, pressure-tube sag and ballooning at temperatures less than 700°C, and Zircaloy/steam reactions. In addition, 32 fully integrated tests have been performed which, in combination with the separate-effects tests and modelling, have demonstrated the effectiveness of the moderator as a heat sink (21).

The only situation for which the pressure-tube integrity may be questionable is when the tube is subject to a non-uniform circumferential temperature distribution before it balloons into contact with the moderator-cooled calandria tube (22). To address this situation, several experiments are being carried out, including measurements of circumferential temperature distributions under stagnated two-phase flow conditions, the effect of flowing molten Zircaloy from a fuel bundle onto the pressure tube, pressure-tube embrittlement due to hydrogen/steam reactions, and calandria-tube integrity due to pressure tube rupture.

6.3 Fuel Behaviour at High Temperature

The current focus of the R&D program on high-temperature fuel behaviour is to expand the understanding of fuel behaviour above 1100°C, and any subsequent fission-product release and transport. The program includes separate-effects studies of phenomena associated with severe fuel damage and fission-product release, the development of codes to describe the various phenomena, and in-reactor integrated tests with instrumented fuel elements to benchmark these codes.

The work on severe-fuel-damage is currently focussing on such phenomena as the interaction of Zircaloy and UO_2, emissivity changes, cladding relocation, and fuel oxidation. These phenomena affect fuel temperatures and integrity, which, in turn, affect fission-product releases. Fission-product release experiments are being done to examine the effects of oxidation rates in steam and air, grain growth, oxidation products, and oxide morphology. We now have an extensive database for oxidative release of fission products based on data from more than 60 experiments in the temperature range of 400-1700°C (23). Further laboratory and hot-cell experiments will extend the database to

2600°C, and will examine the effects of the UO_2/Zircaloy reaction on fission-product releases at these high temperatures.

In-reactor tests have proceeded in two stages. In the first stage, a series of loss-of-coolant transients were carried out with fuel sheath temperatures up to about 1050°C. The main observations of these tests were that fuel sheaths strained to only about 5%, fission gas releases were small, and sizes of fuel pellet fragments differed little from fuel following a normal operation and reactor shutdown. The second stage of these experiments will be carried out in the Blowdown Test Facility in the NRU reactor, beginning in 1989 (24). In these integrated tests, the focus will be on the release of fission products from fuel operating at temperatures in the range 1500-2400°C, and the subsequent transport of the fission products in the primary system.

A suite of codes is being developed to describe the phenomena observed in the separate effects and integrated tests. Examples of the codes are FOXSIM (simulates UO_2 oxidation in air or steam), FROM (a full-range Zircaloy oxidation model), and FREEDOM (simulates fission-product release during oxidation) (25). These sub-models are being incorporated into ELOCA, which describes the behaviour of a CANDU fuel element in high-temperature transient conditions. ELOCA, in turn, is part of an integrated software package, CANSIM, that describes both fuel and fuel-channel behaviour during postulated CANDU accidents.

6.4 Hydrogen Combustion

Hydrogen-combustion studies have focussed on understanding the nature of deflagrations, detonations and transition from deflagration to detonation in containment, and on mitigation techniques (26). Fundamental experiments have been carried out to establish such properties as laminar burning velocities, flammability limits, detonation cell sizes, and the physicochemical effects of diluents. Separate-effects experiments have been performed to examine the effects of gas venting, gas turbulence, and combustion scale. Special facilities for these experiments include the Containment Test Facility, in which intermediate-scale experiments can be done, up to and including atmospheric-pressure detonations. Taken as a whole, the experiments have covered virtually all aspects of the physics and chemistry which influence the progress and consequences of hydrogen combustion. The resulting database is used to develop computer codes describing the various phenomena, such as VENT, which is a mechanistically based code that describes combustion overpressures in a compartment.

6.5 Transport of Aerosols and Fission Products

Transport phenomena of aerosols and fission products are being examined in both basic and integrated tests. A key objective of these tests is to understand the nature of the aerosols emitted to containment. This is being addressed in programs examining the formation and transport of structural-material and fission-product aerosols in the primary system due to high-temperature accidents, aerosol production due to the flashing of two-phase jets from a break in the primary system, and the development of CANDU-specific aerosol codes. Another key objective is to elucidate longer-term containment behaviour, particularly the release of fission-product species (e.g. iodine and tellurium) to the gas phase. Accordingly, a large number of experiments has been carried out to establish the fundamental chemistry of iodine in containment, including the determination of the aqueous thermal chemistry, radiation effects, organic iodide production, and iodine partitioning (27). Many of the characteristics of iodine transport and chemistry are being incorporated into the LIRIC code. Large-scale integrated tests, being conducted in the Radioiodine Test Facility, are being used to verify LIRIC. These tests are duplicating all of the conditions expected in containment, including radiation fields, impurities, and pH ranges.

7. OTHER R&D

In addition to the targeted program described above, R&D is carried out in Canada on a broad range of topics, among them the following:

- management of radioactive wastes, including irradiated fuel from commercial, prototype, and research reactors,
- environmental sciences,
- radiation biology,
- radiation dosimetry, including the safe handling and measurement of tritium,
- isotopic enrichment, including tritium and uranium, and
- fusion breeder blankets.

While this work is often curiosity driven, and with the exception of the management of irradiated CANDU fuel not targeted specifically at CANDU, the R&D results often provide the basis for technology applicable to CANDU reactors. In addition, AECL's laboratories carry out R&D on contract to clients in Canada and abroad which, again, at times contributes to the technology of CANDU reactors. Thus, the Canadian R&D program targeted at the CANDU reactor benefits from other R&D carried out at AECL's laboratories, Ontario Hydro's research laboratory, universities, and industries.

8. SUMMARY

Owners and operators of CANDU reactors in Canada and abroad have amply demonstrated the excellent performance characteristics and low unit energy costs of the CANDU heavy-water reactor system. Nevertheless, research and development continue to support the existing investment in CANDU technology and to provide the basis for future, advanced CANDU designs. The level of the investment in R&D, in excess of $125M (Canadian) per annum, is a clear indication of Canada's commitment to the CANDU product.

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10. REFERENCES

(1) B.A. Cheadle, C.E. Coleman and D.K. Rodgers, Examination of Components Removed from Reactors, CNS International Conference on CANDU Maintenance, Toronto, 1987 November.

(2) B. Cox, Mechanism of Oxidation and Hydrogen Uptake in Zirconium Alloys, AECL-9018, 1985.

(3) L.A. Simpson and C.K. Chow, Effect of Metallurgical Variables and Temperature on the Fracture Toughness of Zirconium Alloy Pressure Tubes, ASTM Special Technical Publication 939, 1987.

(4) A.R. Causey and V. Fidleris, In-Reactor Deformation of Zr-2.5 wt% Nb Pressure Tubes, AECL-9499, 1987.

(5) M.P. Dolbey, CIGAR: An Automated Inspection System for CANDU Reactor Fuel Channel, ASM 8th Int'l. Conf. on Non-Destructive Evaluation in the Nuclear Industry, Orlando, Florida, 1986 November 17-20.

(6) B.A. Cheadle, Confidence in Fuel Channel Components, Proceedings, CNS Conference, St. John, New Brunswick, pp. 357-360, 1987 June.

(7) D.H. Lister and R.S. Pathania, AECL Research Programs in Systems Chemistry, AECL-7079, 1984 May.

(8) C.A. Kittmer, J.A. Aikin and J.W. Reinwald, Advanced Techniques for Valve Packing Removal, CNS International Conference on CANDU Maintenance, Toronto, Canada, 1987 November.

(9) M.J. Pettigrew, C.E. Taylor and J.H. Tromp, Vibration of Heat Exchanger Tube Bundles in Two-Phase Cross-Flow: Design Guidelines, presented at the 1988 ASME Winter Annual Meeting - International Symposium on Flow-Induced Vibration and Noise, Chicago, Illinois, 1988 December.

(10) C.A. Kittmer and A.J. Harrington (Ontario Hydro), In-Situ Sampling for Pressure Tube Deuterium Concentration, presented at the Remote Techniques for Inspection and Refurbishment of Nuclear Plants Conference, British Nuclear Energy Society, Stratford-upon-Avon, UK, 1988 November.

(11) I.J. Hastings (Editor), Proceedings of the International Conference on CANDU Fuel, 1986 October 6-8, Chalk River, Canada, Canadian Nuclear Society, ISBN 0-919784-13-5, 1986.

(12) M.B. Carver, A. Tahir, J.C. Kiteley, A.O. Banas, D.S. Rowe, and W.I. Midvidy, Multidimensional Simulation of the Distribution of Flow and Phases in Horizontal Bundles, International Topical Meeting on Thermal-hydraulics and Nuclear Reactors, Seoul, Korea, 1988 October, Proceedings to be published by Korean Nuclear Society.

(13) C.W. Zarecki and R.M. Smith, The Canadian Safeguards Program, AECL-7084, 1981 December.

(14) R.E. Green, P.G. Boczar and I.J. Hastings, Advanced Fuel Cycles for CANDU Reactors, Canadian Nuclear Association Conference, Winnipeg, 1988 June; available as AECL-9755.

(15) M.R. Galley, Future Trends in Heavy Water Production, Fourth Pacific Basin Conf., Vancouver, AECL-7547, 1983 October.

(16) R.D. McAlpine, D.K. Evans and M. Ivanco, Selective Multiphoton Decomposition Studies Relating to the Separation of Hydrogen Isotopes, AECL-9207, 1986 June.

(17) F.N. McDonnell, A.R. Dastur and A.D. Lane, Advanced Reactor Core Concepts, Focus for Reactor Physics Activities in Canada, Proc., Volume I, pp. I-59 to I-68, International Reactor Physics Conference, Jackson Hole, Wyoming, 1988 September.

(18) H.E. Sills and J.W.D. Anderson, Operations Decision Support Systems for CANDU Nuclear Plant Operations, Proc. of Canadian Nuclear Association Conference, Winnipeg, Canada, 1988 June.

(19) D.J. Richards, et al., CATHENA: A Two-Fluid Code for CANDU LOCA Analysis, Proc. of 3rd Int'l. Topical Mtg. on Reactor Thermalhydraulics, Rhode Island, U.S.A., 1985 October 15-18, pp. 7.E-1 to 7.E-4.

(20) D.J. Richards, Validation of the CATHENA Two-Fluid Code Using RD-14 Experiments, Proc. of Int'l. ENS/ANS Conference on Thermal Reactor Safety, Avignon, France, 1988 October.

(21) H. Tamm, et al., Overview of the Technical Basis for the Safety of CANDU Reactors, presented at the Int'l. Symposium on Nuclear Safety, Tokyo, Japan, 1987 December, AECL-9559.

(22) H.E. Rosinger, et al., The Determination and Verification of Circumferential Temperature Distributions in CANDU-PHW Reactor Fuel Channel Assemblies Under Coolant Flow Stagnation, Proc. of Int'l. ENS/ANS Conference on Thermal Reactor Safety, Paper #163, Avignon, France, 1988 October.

(23) F.C. Iglesias, et al., Measured Release Kinetics of Ruthenium From Uranium Oxides in Air and Steam, Proc. of Int'l. ENS/ANS Conference on Thermal Reactor Safety, Avignon, France, 1988 October.

(24) P.J. Fehrenbach and J.C. Wood, Description of the Blowdown Test Facility COG Program on In-Reactor Fission Product Release, Transport and Deposition Under Severe Accident Conditions, AECL-9343, 1987 May.

(25) L.D. Macdonald, et al., A Transient Fission Product Release Model for Radioactive and Stable Species, presented at the IAEA Technical Committee Meeting, Preston, England, 1988 September.

(26) K.N. Tennankore, et al., Hydrogen Combustion Issues and Containment Integrity, Proc. of the Int'l. Conference on Nuclear Containment, Cambridge, England, 1988 April, AECL-9094.

(27) F. Garisto, et al., Reactor Safety Chemistry at Whiteshell, Proc. of the Int'l. Conference on Water Chemistry of Reactor Systems, British Nuclear Society, Bornemouth, U.K., 1986.

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