Fuel for Thought

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Abstract
The outstanding performance of CANDU fuel is attributed to a well-rounded development program that combined sound science with excellent engineering. Economic analysis and technology transfer were integrated into the program to ensure successful commercialization. The CANDU fuel program provides useful lessons that are being ignored by policy-makers in their desire to exploit our world-class resources in science and technology to benefit the Canadian economy.

Résumé
La performance remarquable du combustible CANDU est le résultat d'un programme de développement très complet qui combine la science rigoureuse au génie par excellence. On a incorporé au programme une analyse économique et un procédé de transfert de technologie qui ont assuré une commercialisation réussie. Nos politiciens qui veulent exploiter au profit de l'économie canadienne nos ressources de classe mondiale en science et en technologie ne tiennent toutefois pas compte des leçons valables fournies par ce programme.

Purposes

The fuel for CANDU reactors represents a magnificent achievement of Canadian engineering. The first purpose of this paper is to trace the development of the fuel, identifying significant contributions. An occasion such as this Engineering Centennial is a legitimate reason for pride and self-congratualtion, and I cannot recall the development without reliving the excitement and satisfactions of that time. However, anyone who expects just nostalgic reminiscences and a eulogy to the good old days is going to be disappointed. I refuse to rest on our laurels, believing them to make an uncomfortable bed. I am much more interested in learning from the past how to improve the future.

The purpose of learning from our successes, just as much as from our failures, is particularly important and urgent now when many people with no experience in managing a successful technological development talk interminably about a policy for science and technology. Thus, this paper may be seen as a technical report leading to a political tract, if discussing a policy vacuum is political. Between the technical and political parts is an examination of future directions for the CANDU fuel program.

But first I wish to bring the acknowledgements up front, to emphasize that they are no ritual afterthoughts.

Acknowledgements

As always, in recalling the past human memory mercifully mists over periods of distress in favour of pleasant experiences. I still remember the anxious days of the mid-1960s when seemingly endless problems in getting the Douglas Point reactor to work properly caused concern that CANDU might be canned. However, happy memories of exciting and satisfying experiences predominate.

In discussing the subjects with erstwhile colleagues I was reminded of the times when a simple, but ingenious, experiment gave a 'Yes' or 'No' answer, and not just a revision of the last decimal place; when even an in-reactor experiment could be suggested, agreed upon, performed, and the results published in a matter of weeks; when we discussed and interpreted each others results without regard to organizational hierarchies; and when anyone returning from a conference seemed to bring back new results, and new controversies, leading to new experiments.

Some examples of simple, but definitive, experiments are given in the following sections.

Much of the credit for the success of the program is due to the excellent facilities that were available. In its early life the NRX reactor had the highest neutron flux of any research reactor. This fact attracted to Chalk River fuel researchers from other countries, notably those from the U.S. Bettis Laboratory who installed the in-reactor 'loops' that were to prove so valuable to our own fuel program. The NRU reactor, with its much larger loops, subsequently complemented NRX, particularly for engineering tests and now, nearly thirty

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years later, it is still one of the world's best for this purpose. Other lesser facilities were particularly useful to the fuel program in providing valid comparative irradiations quickly and at remarkably low cost: the innovative 'Hydraulic Rabbit' in the NRX reactor, largely due to John Melvin, and the 'Demountable Bundle'[1] in the NRU reactor loops, due to Jim Christie. Other facilities deserving special mention were the laboratory for fabricating experimental fuel specimens and the various shielded 'caves' in which the irradiated specimens were examined.

As so often happens, the whole was greater than the parts. The location of all these facilities within a radius of about one hundred metres gave us a tremendous advantage. Those running an experiment would be consulted by reactor operators when something unforeseen arose; those who had fabricated a specimen would be consulted during post-irradiation examination.

Even more of the credit is due to the people involved, several of whom are recognized in the next section. What made the Chalk River Laboratory so productive, and such a pleasant and inspiring place to work, was the competence and friendly cooperation of many anonymous individuals: Those who operated the reactors and loops; those who prepared the specimens and test equipment, and those who conducted the post-irradiation examination; chemical analysts and metallographers; designers and secretaries; reactor physicists and health physicists; and so many more whose help we took for granted.

No account of CANDU fuel is possible without recognition of Bennett ('W.B.') Lewis' responsibility for every aspect of the program. He epitomized in one person all that was best in the Canadian approach. W.B., although nominally a scientist rather than an engineeer, represented my ideal engineer in directing the fuel program: he had a fundamental and catholic grasp of scientific principles; he continually strove for excellence in all things; he was motivated to see his work applied for the benefit of society; he had a keen appreciation of what was practicable; he always kept in mind the economic implications; and he demonstrated a willingness to make engineering decisions based on existing knowledge, without waiting for the discovery of ultimate scientific truth.

Steps in Developing CANDU Fuel

The fuel is literally and metaphorically at the core of the reactor. The outstanding performance of the fuel, for reliability, economy, and safety, reflects that of the reactor. For both fuel and reactor the success of the product can be largely attributed to the soundly based, well-rounded engineering program for its development.

In my perception, with all the benefits of hindsight, the development of CANDU fuel proceeded in five distinct steps. The relevance to policy formulation lies in the fact that our program included all the elements essential to any technological development. Developing an engineering product can be visualized as an athlete ascending a flight of steps to light the Olympic flame. Each step, resting on the previous one, is essential and, despite some overlap, there is a general progression from one to the next until the goal is reached. When we took the first step we did not realize how far we would have to climb, but nowadays anyone responsible for technological development should plan for all five steps.

These five steps provide the outline for the technical part of the paper:

- sound science,
- excellent engineering,
- integrated economics,
- technology transfer, and
- public perception.

Sound Science

The first paradox of CANDU fuel, shared with the CANDU system as a whole, is that although it is a unique and highly successful product, most of the original basic research was done elsewhere. For the CANDU system, nuclear fission, fission reactors, heavy water, heavy-water reactors, pressure tubes, and zirconium-niobium alloys were all discovered elsewhere: for CANDU fuel, uranium dioxide (UO_2) and Zircaloy, its two major constituents.

The second paradox, which explains the first, is that the Canadian program was unusually strong in underlying science. (I distinguish between basic science, which is entirely curiosity driven without regard to any ultimate application, and underlying science, which is deliberately performed in areas of applied relevance to provide greater understanding of critical phenomena.)

The first benefit of this strength in underlying science was that the Canadian team was aware of international developments in nuclear science, and had the necessary expertise to select the best from what was available to synthesize a solution applicable to Canadian conditions.

The second benefit was that the excellence of the research, and of the research facilities, brought to Chalk River scientists from all other countries with significant nuclear-energy programs. Consequently, we had access to new results at an earlier stage and in greater detail than would otherwise have been possible, and we were therefore able to undertake critical assessments of new developments.

When Canada committed its first power reactor, the Nuclear Power Demonstration (NPD) reactor, in 1954, the reference fuel material was metallic uranium with only minor alloying additions, based on the successful operation of similar fuel in the NRX reactor. However, both the U.S. (Bettis Laboratory) and the U.K. (Harwell Laboratory) programs had been experiencing difficulties with this material for their proposed power reactors, and were investigating UO_2. Although this had a lower density than uranium metal, making it less attractive for neutron economy, it was vastly superior in corrosion resistance and dimensional stability under irradiation – the two areas giving problems.

That we obtained access to the promising results on UO_2, and similarly on Zircaloy as the sheathing material, in time to select them for the NPD reactor was due to our having a tripartite exchange to which we were making substantial contributions. Even so, we might not have had the courage to take such a large step had we gained the information only by reading reports. In fact, we participated fully in the key irradiation tests, including the post-irradiation examination, conducted at Chalk River. It was this intimate experience that provided the necessary confidence.

Selecting these two materials was, however, only the start. In the design of CANDU fuel they were used in ways that had not been attempted elsewhere. We did not just adopt, but adapted, these materials to our own requirements in a unique design. The three most important differences were the use of thin collapsible sheathing, the operation at higher central temperatures, and the use of short bundles involving the ends of fuel stacks in positions of maximum power; all of which were required to enhance neutron economy. In each case the bold decision was based largely on favourable experience from empirical testing in the loops of the NRX reactor. The confidence in these decisions, however, was greatly increased by a sound understanding of the underlying phenomena.

The Chalk River team provided international leadership in understanding nuclear fuel behaviour, as illustrated by the following highlights:

–*Alan Ross* determined the effects on the thermal conductivity of UO_2 of porosity and excess oxygen, and discovered irradiation-enhanced elimination of fine porosity; he elucidated the factors controlling fuel-to-sheath heat-transfer, hence explaining the relatively small effect of helium-filling observed by other Chalk River researchers.

–*Ross MacEwan* demonstrated that the appearance of central melting in the fuel could result from migration up a thermal gradient of lenticular pores in the UO_2, and provided much of the information on grain growth in UO_2 needed to interpret structures seen in post-irradiation examination.

–*Mike Notley*, by first irradiating fuel elements to produce large grains in the centre of the UO_2, and then re-irradiating them at a higher power, disproved the claim of the U.S. Hanford Laboratory that these large grains had a much higher thermal conductivity.

–*John May* (on attachment from the U.K.), with others, confirmed this conclusion in a simple laboratory comparator and went on to show that the enhanced conductivity was due to a composition shift to UO_{2-x}.

–*Al Bain* demonstrated the in-reactor healing of cracks in the UO_2 at relatively low temperatures, and showed how dishing in the end-faces of the fuel pellets (a Canadian innovation) could be used to control the longitudinal and diametral strains in the sheath. With *Mike Notley* and others, he defined the fuel-sheath clearances that allowed the use of thin collapsible sheaths, having a thickness-to-diameter ratio one-quarter of that considered necessary in Light Water Reactors to avoid the formation of severe deformations leading to failure.

–*Denis Hardy* defined a stress-relief treatment for the Zircaloy, well short of the full anneal practised elsewhere, that combined adequate strength for the thin sheath with adequate in-service ductility.

–*Mike Notley* developed computer codes for a simplified elastic-plastic model that predicted the releases of fission-product gases and sheath deformations; and later validated the model by ingenious in-reactor experiments to measure internal gas pressure, fuel-stack elongation, and sheath strain. This model, by combining empirical results with an understanding of the phenomena, was simpler than other contemporary models, but at least as reliable.

–*Ross MacEwan* and *Bill Stevens* found that gaseous fission products were immobilized in very fine pores, and hence elucidated the diffusion of rare gases in solids.

–*W.B. Lewis* interpreted experimental results by *Roger Kelly*, *Bill Stevens*, *Bob Hawkings*, and *Bob Hart*, to establish an irradiation-induced mechanism for re-entry of these gases.

–*Brian Cox* and *Eric LeSurf* contributed much to the understanding of the factors controlling the corrosion and hydriding of zirconium alloys, particularly under irradiation.

–*Tony Sawatzky*, and later *Roger Dutton*, provided mathematical analyses that allowed prediction of how hydrogen would migrate under thermal and stress gradients.

–*Chuck Ells* and *Brian Cheadle*, in work primarily aimed at pressure tubes, helped to establish the metallurgical structures to minimize hydriding damage.

–*Gareth Parry* and *Windsor Evans* demonstrated that otherwise brittle hydrides could deform plastically under in-service conditions.

The introduction of UO_2-in-Zircaloy fuel worldwide was not without its setbacks. Here too Canada was well served by a program with a sound scientific foundation.

In the late 1950s researchers at the Bettis Laboratory attributed dramatic fuel failures, including one of theirs irradiated in the NRX reactor, to central melting of the UO_2. This interpretation could have necessitated a reduction in the power output intended for the

CANDU fuel, with a consequent economic penalty. The Chalk River team was able to prove that the structure thought to define melting could be produced by pore migration in solid UO_2, and that the actual temperatures were hundreds of degrees lower than believed.

Early in the 1960s, similarly dramatic failures of Zircaloy-sheathed UO_2 fuel rods that had been test-irradiated with deliberate holes in their sheaths were reported by the U.S. General Electric's San Jose Laboratory. This news was undermining international confidence in the still-new zirconium alloys as sheathing, and designers of Light Water Reactors were contemplating a return to stainless steel. This course was possible for them with enriched uranium, but would have been disastrous for the Canadian program, and we would have been severely taxed to have had to go it alone in developing zirconium technology. Fortunately, however, Mike Notley and others were able to demonstrate that the cause was probably a very high level of fluoride impurities in the San Jose enriched fuel, and that the low levels associated with natural UO_2 resulted in much stabler behaviour.

Late in the 1960s, a worrisome number of fuel failures in Light Water Reactors was attributed to hydriding of the Zircaloy sheaths. Our investigations proved that the hydrogen was being introduced as water adsorbed on the UO_2 fuel, and that this failure mechanism could be avoided by proper drying of the fuel and by good quality control.

In the 1970s, there was some concern in the Light Water Reactor community over observations of fuel densification in service, resulting in large gaps developing within the sheaths. CANDU designers and operators remained unconcerned, largely because of our higher as-fabricated fuel density, our shorter fuel bundles, our horizontal orientation, and because we had not encountered any such problem in our power-reactor fuel. This empirical confidence was reinforced by a good basic understanding of the densification phenomenon from studies by Alan Ross, Mike Notley, and Ian Hastings.

Excellent Engineering

The engineering design of CANDU fuel proceeded in parallel with the scientific studies on which the design was based. The essential design of rodded bundles was selected by the Nuclear Power Group, headed by Ontario Hydro's Harold Smith, working at Chalk River in the mid-1950s on the original design for the NPD reactor. The most important change in the fuel occurred in 1957, when NPD was changed from a pressure-vessel reactor with full-length vertical fuel to a pressure-tube reactor with short horizontal fuel capable of being changed on-power. Since then, CANDU fuel has consisted of 0.5 m-long rodded bundles.

Subsequent to the NPD reactor's startup, the maximum power that could be extracted from a CANDU fuel bundle was increased fourfold, as a result of three distinct factors. When, on going from the Douglas Point to the Pickering reactors, the diameter of the pressure tubes was increased, the bundle diameter increased from eight to ten centimetres, requiring more rods or elements. On going from the Pickering-A to the Bruce-A reactors, the number of elements in each bundle of 10 cm diameter was increased from 28 to 37. The third factor, an increase in the permissible power to be extracted from any individual element, was a direct result of the scientific studies on fuel behaviour. The current maximum power of one megawatt per bundle means that a single bundle, weighing only about 20 kg, generates enough heat to keep a hundred homes warm.

Developing means of fabricating the bundles constituted a major part of the engineering teamwork led by Ara Mooradian and Ron Page. The scientific studies showed that the use of thin collapsible sheaths was possible, but these could not have been incorporated in the design had it not been for the development of greatly improved methods for the non-destructive testing of thin Zircaloy tubes. The early spot-welded wire-wrap, used to separate the elements and to centre the bundle in its tube, was replaced by spacer- and bearing-pads, thanks to the development of a reliable method for beryllium-brazing these pads. Another development allowed the sealing of individual elements to be done by resistance-force welding, instead of the less efficient argon-arc method. This was important in minimizing the amount of non-productive Zircaloy at bundle ends, and in minimizing the separation between fuel stacks in adjacent bundles that causes power-peaking near stack ends. The *absence* of a gas plenum, another unique feature of the CANDU fuel design that contributes to both economy and safety, was attributable to the thorough understanding of the release phenomena from the scientific studies.

Concurrently, a large program of engineering testing at the Sheridan Park Engineering Laboratory established that the bundles had adequate strength to withstand mechanical and hydraulic loads, provided adequate coolant mixing, and would not subject the pressure tubes to excessive wear. Another major contribution by the group at Sheridan Park in cooperation with Ontario Hydro staff was the development of a quality assurance program for CANDU fuel, associated primarily with Milan Gacesa.

Thermalhydraulics constituted another essential element of the design process. Even today, the application of this subject to fuel design is still largely empirical but, just as in other aspects of the program, based on a very thorough understanding of relevant results and phenomena. Through an awareness and critical assessment of international research in this area, Dé Groeneveld, Don McPherson, Joe Ahmad, and their colleagues were able to provide the designers with critical-heat-flux correlations from which to set maximum permissible power outputs from any fuel channel. Here too, the CANDU team fully exploited discoveries made elsewhere, but added significantly to the international fund of knowledge on the subject through both unique experiments and analysis. Particularly difficult was the analysis of phase separation in a boiling coolant for horizontal fuel channels.

The same thermalhydraulics researchers collaborated with the metallurgical engineers in another large program, to assure the safety of CANDU fuel even in the event of a serious reactor accident. The inclusion of this work in the overall program for developing CANDU fuel followed a long tradition of engineering that safety analysis is an integral part of any engineering design. This simple fact is rarely recognized by our critics or the media. Early work was spearheaded by Denis Hardy, with input from Mike Notley on fuel behaviour. The experiments progressed from laboratory simulations to in-reactor tests on full-size bundles until, in 1982, Dan Meneley and Bill Hancox were able to announce at an international conference that even in the extreme case of a loss of coolant and complete failure of the emergency injection system there would be no fuel melting and fuel-channel integrity would be maintained.

Besides integrating safety into the design, CANDU fuel development adopted two other sound engineering principles: 'Keep it simple,' and 'If it ain't broken, don't fix it.' The most significant change in the very simple CANDU fuel bundle since increasing its diameter was to add a very thin layer of graphite to the inner surface of the Zircaloy sheath, to produce what is termed 'CANLUB' fuel. This modification was introduced to provide greater resistance to fuel failures. In 1970 an increase in the failure rate in the Douglas Point reactor was detected, while the actual level remained at a very low value of under one per cent of all bundles. The threefold response to the problem, and its rapidity, were a tribute to the engineering excellence of a large cooperative team drawn from Atomic Energy of Canada Limited, Ontario Hydro, and the two commercial fuel fabricators, Canadian General Electric and Canadian Westinghouse.

First, the cause of the failures was shown to be a significant increase in fuel power after a prolonged period at relatively low power. Second, Ontario Hydro, from an understanding of the cause, was able to introduce restrictions on the magnitude and rate of power changes during refuelling that reduced the failure rate at the cost of some loss of operational flexibility. Third, CANLUB fuel, with improved tolerance to power increases, was selected from 17 potential solutions on the basis of an extensive reactor-testing program, and developed to the point of being introduced into a major power reactor within two years of the problem appearing.

This successful joint operation, directed in succession by Ron Page, Roy Thomas, and Al Bain, although essentially engineering in nature, again drew upon Chalk River's fund of scientific understanding. Some of the potential failure mechanisms were rejected as a result of this, while others were favoured, notably stress-corrosion cracking of the Zircaloy sheath by volatile fission products at stress concentrations over cracks in the UO_2 pellets. Scientific studies by Clive Wood and Brian Cox on stress-corrosion cracking, and by Dave Williams and Kit Coleman on stress concentrations, were invaluable in directing thinking towards the graphite layer of CANLUB fuel. Rod MacDonald confirmed the stress-corrosion mechanism for failure by irradiating fresh UO_2 pellets in pre-irradiated sheaths and obtaining no failures under conditions that cause failures in elements with both fuel and sheath pre-irradiated.

Even today, the only other remedy available for this failure mechanism is the 'barrier-clad' fuel developed for Light Water Reactor fuel. This is a much more expensive solution that took many more years to introduce than the very simple CANLUB fuel.

Yet another extensive interdisciplinary program, this one, conducted over many years, established how long the utility could safely leave failed fuel in the reactor without serious deterioration of the fuel bundle and radioactive contamination of the reactor's primary coolant circuit. Rod MacDonald, and many others, have shown that even for a CANDU fuel bundle operating at its maximum power, sufficient time exists to detect the failure and discharge the bundle.

The deposition of thick layers of corrosion products on the sheath was a non-problem for CANDU reactors, thanks to the early control of coolant chemistry provided by Bob Robertson and Merv Allison, and subsequent understanding of the phenomenon by Ken Burrill and Derek Lister. Ironically, the deposit is known as 'crud,' a centuries-old term retroactively attributed to Chalk River Unidentified Deposit.

An account of the engineering development of CANDU fuel would be incomplete without recognition of the contribution by chemical engineers. In the 1950s they developed a flow sheet for the production of UO_2 powder from U_3O_8 ('yellowcake'). Once again, the basic process (via ammonium diuranate) was already known and the achievement of the development by Bill Bourns, Verne Watson, and John Yatabe was in defining conditions to produce powder capable of yielding high-density pellets reproducibly. This characteristic is much more important in CANDU reactors, with their emphasis on neutron eonomy, than in Light Water Reactors. Their success can be judged from the fact that their process is still in commercial use thirty years later and that the original development is almost forgotten.

Integrated Economics

To be successful, an engineering product not only has to perform as intended, it also has to be cost-competitive. From the start of CANDU development, W.B. Lewis saw with great clarity that economic nuclear energy depended on low fuelling costs, since relatively high capital costs are inevitable; and that the way to this goal lay in the strict application of neutron economy. He directed the technical development of the CANDU design according to this guiding principle.

In common with those who directed the development programs for other reactor types, he sought to increase the thermodynamic efficiency of CANDU reactors. However, he appreciated that this was only a means to reducing costs, and not an end in itself. Economics is the ultimate design criterion, not the narrower engineering criterion of thermodynamic efficiency.

Neutrons are the currency of nuclear fission. Any neutron wasted has to be replaced by the provision of fresh nuclear fuel – at a cost. This point was made dramatically by W.B. Lewis when he derived a value of $2,860 per gram of neutrons (in 1961, when gold was about $1 per gram). This conversion is an example of how abstruse physical principles must be translated into simple rules if they are to be readily used in design.

During the design of the first CANDU reactor, before the term CANDU had been coined, a simple running indicator of the neutron economics of the design was provided by the estimated fuel burnup achievable with natural uranium (megawatt-days output per tonne of uranium). W.B. Lewis kept his 'fever chart,' similar to the temperature chart of a hospital patient, showing changes in estimated burnup. A measurement showing the neutron-absorption cross-section for a fission-product to be greater than previously accepted made the trace dive to a low that would have been only marginally economic; the achievement of a few per cent increased density for the UO_2 restored the situation. Those who had the responsibility for explaining to W.B. Lewis any of their results that affected his fever chart understand the meaning of 'neutron economy imposed a healthy discipline on the design.' Relieving a reactor designer of this discipline by allowing enriched uranium is like giving a government a printing press: when a problem arises it prints more money instead of solving the problem.

The selection, in 1958, of zirconium over aluminum as sheathing material for CANDU fuel was essentially an economic decision applying the principle of neutron economy. In an alloy-development program, Kim Krenz and his colleagues obtained promising results with respect to the corrosion resistance in hot water of a relatively cheap aluminum-nickel-iron alloy. However, in the thickness needed for strength equivalent to that of the zirconium alloy Zircaloy, then being developed by the Bettis Laboratory, aluminum would have absorbed more neutrons. This operating cost would have more than offset the lower initial cost of aluminum.

The same principle was also responsible for the selection of short fuel bundles, which facilitated on-power refuelling and hence contributed to neutron economy by allowing neutron-absorbing fission products to be removed at the optimum time.

By minimizing the wall thickness, avoiding a gas plenum, and by eliminating the flow-, support-, and control-components found in the fuel assemblies for Light Water Reactors, but not essential to the fuel's function, the UO_2 content of CANDU fuel bundles was brought above 90 per cent by weight. The rest is zirconium alloy, with no stainless steel or other strongly neutron-absorbing materials found in Light Water Reactor fuel.

As a result of the CANDU fuel being designed to maximize neutron economy, Ara Mooradian and I predicted in a 1960 issue of Nucleonics that CANDU reactors would achieve fuelling costs of less than one 'mil' (milli-dollar) per kilowatt-hour. At the time this was thought to be optimistic, even unrealistic, but in the 1970s it was achieved by Ontario Hydro at their Pickering Nuclear Generating Station, and is still being realized in the original 1960 dollars.

Technology Transfer

'Technology transfer' are trendy buzz-words these days, although there is still a very poor understanding of how to achieve it. By way of contrast, means of transferring CANDU technologies developed in the laboratories to commercial exploitation were incorporated in the program from the start, before the phrase was invented. In the early days it was unchallenged government policy that technology developed in government laboratories at public expense should be freely transferred to Canadian industry with the objective of generating new commercial activity. More recently, this policy has been criticized for not providing a source of funds for ongoing research and development. However, there is no question that it was implemented most successfully, particularly in the case of CANDU fuel.

First, the technology for UO_2-powder production was transferred to the appropriate commercial organization, Eldorado Nuclear Limited, which further developed the process. Concurrently, the design of the fuel bundle was being pursued with manufacturing methods very much in mind. In developing the process for making the fuel pellets, John Runnalls and Geoff Chalder co-opted the expertise for mass production of industrial ceramics that existed in Canadian General Electric's (CGE) Carboloy Division. Later, the processes selected for sealing and assembling the various components into a fuel bundle owed much to developmental programs by CGE and Canadian Westinghouse, which produce CANDU fuel commercially. By now, these two companies have manufactured more than half a million CANDU fuel bundles, worth about a billion dollars, which have generated half a trillion kilowatt-hours, or ten times the total electricity produced in all Canada in 1950.

Several mechanisms were employed to transfer the technology. The conventional one, the transmission of technical reports, predominated in the process for powder preparation. For fuel-bundle fabrication, the awarding of development contracts to the commercial fuel companies proved most effective: the literally day-to-day technical supervision of commercially motivated groups by individuals who were themselves active in relevant research ensured a very detailed two-way exchange of experience. Close cooperation with the utility groups responsible for operational research on the fuel performance not only provided another means to keep the development program relevant to market needs but also meant that resulting improvements were more readily accepted by the utility customer. This benefit was well illustrated by the industry's very rapid introduction of CANLUB fuel.

One mechanism stands out from all others. The best vehicle for technology transfer is people, not paper. Many engineers who participated in the early development of CANDU fuel at Chalk River moved back, or on, to other organizations, carrying with them an intimate understanding of the technology. Others, without working at Chalk River, shared in the development through contracts, visits, and meetings. Personal contacts made while working together towards a common objective proved invaluable later: when problems arose, it was easy and natural to pick up a phone and call a friend who could help. Furthermore, it is valuable not just to the nuclear industry but to the country as a whole to have individuals in education, production, regulation, government, and elsewhere who are thoroughly knowledgeable in the technology.

Public Perception

Even after scientific, engineering, economic, and industrial feasibilities are established, a new technology is not itself established until public acceptance is assured. Back when biotechnology was just baking and brewing, an engineer sponsoring a new technology had a hard enough job selling the idea to decision-makers in industry and government. However, the ground-rules for technical and economic assessments were known, and one could count on the decision-makers being advised by appropriately qualified professionals who would be held responsible for any advice given. Nowadays, the same requirements still hold but, in addition, the public has to be convinced that the technology is desirable. Politicians can afford to support very few unpopular causes, however beneficial these may be for the long-term future of the country.

In this regard, nuclear energy got off to a good start. There was widespread public support for the development of a new energy source to replace the dwindling stocks of conventional oil and to reduce pollution. Internationally, both environmentalist and church organizations supported this development. However, gaining public support is not something that is done once and for all; it must be regained and sustained day after day. Taking this final step in introducing a technology is like having to run up a 'down'-escalator. Ironically, just when the CANDU system delivered on its earlier promise, during the oil crises of the 1970s, public support declined and we found ourselves further down the escalator than we had been.

The CANDU system is recognized as one of the major achievements of Canadian engineering, selected by the Engineering Centennial Board as one of the top ten of the last hundred years. Its outstanding record for reliability, economy, and safety has been established in open competition with the world's best.

Regrettably, the Canadian public is largely unaware of this cause for national pride. Our media are always ready to hold us responsible for failings in foreign nuclear industries, however irrelevant to the CANDU system, but are silent on our successes. An Olympic gold medal, or even an Oscar nomination, will secure major media coverage, but who knows that CANDU reactors have occupied, year after year, about half the top ten places in the international league table for performance of power reactors?

I believe that the present situation is serious. Some countries, less well endowed with alternative energy sources than Canada, have accepted the economic and health penalties inherent in foregoing nuclear energy. Many disparate but well-organized special interest groups believe that they can occupy the moral high ground by opposing nuclear energy. It is their critical views that are predominantly reported by media that are largely ignorant of, if not actively hostile to, technology. The media are the source of virtually all public information, but they are not accountable and are often irresponsible. We have seen how successful the tactics of social activists have been in stopping the seal hunt on purely emotional grounds.

In the near future, I see only increased difficulties. The disposal of nuclear wastes must be resolved in the next few years, for low-level wastes, for mine tailings, and for used fuel. Nobody wants wastes, only the products causing them, so this issue will yield only negative publicity. Any malfunctions of nuclear stations anywhere, however trivial, will similarly lead to only negative publicity, while even perfect performance will go unrecognized. Oil and natural gas again seem to be plentiful, and electricity shortages are unlikely to occur until the mid-1990s, by which time it will be too late to react. The *absence* of health and environmental harm due to the operation of existing CANDU stations will continue to go unnoticed. What concerns me most is that many of the technical people do not see public acceptance as a problem, and certainly not as *their* problem.

The situation is serious but not hopeless. Engineers do not have to be lectured on social responsibility. Without engineering, Canada would be among the poorest Third World countries, unable to afford all our enviable social programs. The engineering profession in Canada has a code of ethics that could well be adopted or adapted by other professions, including those arch-critics, the media.

But few members of the public are aware of all this. The nuclear industry has been ineffectual in addressing ethical issues associated with nuclear energy, and many individual engineers are uneasy dealing with them. Some of those in the CANDU fuel community are among the exceptions to these generalizations, but all of us must communicate our convictions more effectively if we are to assure a safe, economic, and virtually inexhaustible energy source for our children and for their children.

Future Directions

Those of us who were involved in the development of CANDU fuel can take comfort from the fact that the technical program is now in the hands of those who have already contributed much to the technology, including Ross MacEwan, Mike Notley, Alan Lane, Milan Gacesa, Clive Wood, and Ian Hastings. Theirs is now the responsibility for ensuring that the CANDU system remains available to future generations. That this is possible, through fuel recycling, has already been demonstrated at the scientific stage, and much of the constituent engineering is developed. However, the next step, economic feasibility, is proving much more difficult than we had expected. Although fuel recycling will eventually become economic as depletion of uranium resources causes price increases, the recent glut of uranium has removed any sense of urgency in the commercial introduction of fuel recycling. Those responsible have the difficult task of maintaining and improving the technology in the face of a public perception that their work is not needed.

This difficulty is compounded by two others:

- the necessity to maintain a response capability as insurance against operating troubles arising in the fuel of the CANDU system, which represents a $30 billion national investment; and
- the necessity to remain competitive with international reactor vendors who are constantly improving their products. As in all technologies, those who do not maintain an active, market-oriented development program will soon find themselves overtaken by their competitors.

Fortunately, developing to the point of commercialization the Slightly Enriched Uranium fuel cycle for CANDU reactors provides one means to bridge the gap. If expected reductions in the costs of enrichment services arrive while uranium is still relatively abundant, there will be a significant economic opportunity for this cycle. Much of the required fuel technology is available, but a large-scale demonstration could conceivably reveal both problems and unforeseen opportunities.

I also believe that the currently underchallenged skills of the fuel development team should be exploited to develop an industrial process for the immobilization of nuclear fuel wastes. In at least one interim scenario for fuel recycling, the valuable plutonium would be extracted for recycling with fresh uranium, while the very radioactive fission products would be left with the now depleted uranium as waste for disposal. The process used to produce UO_2 fuel pellets could probably be modified to incorporate the small amounts of fission products, yielding an extremely stable, corrosion-resistant waste form. The fuel team, with experience in processes capable of accepting radioactive feed for a thorium fuel cycle, could develop a remotely operated process with the spinoff benefit of a more economic automated process for fabricating conventional CANDU fuel. Exploiting existing expertise in this way would be preferable to building a new team in the waste management program.

The long-term stability of the design for the CANDU fuel bundle, largely unchanged for 25 years, makes it easy to forget the large number of developmental avenues that were explored but not pursued. These include:

- uranium alloys and aluminum alloys, the original reference materials for fuel and sheath, respectively;
- swaged, and later vibratory-compacted ('Vipac'), UO_2 powder;
- uranium silicide, as an alternative to UO_2 with a greater uranium density (although it is being exploited for research reactors);
- zirconium-chromium-iron alloys as a sheathing material capable of operating in dry-out or even in a steam coolant;
- graphite-coated particles of uranium carbide in a graphite matrix as a fuel element to provide superheated steam;
- annular and tube-in-shell fuel elements to allow more fuel to be packed into a given cross-section;
- fuel elements with conductive graphite discs between hollow UO_2 pellets as a design for high burnup at high power;
- a vertical string of CANDU fuel bundles on a central

support tube for a CANDU Boiling Light Water Reactor; and

- uranium-carbide fuel in zirconium-niobium sheaths for operation in a CANDU reactor with organic liquid as coolant.

All these avenues appeared attractive initially, and for most the exploration successfully surmounted major technical barriers. Ultimately, however, each failed the test of competitiveness with the design of sintered-UO_2 in Zircaloy sheaths assembled in horizontal bundles, on criteria of safety and economy.

Any argument that all this research and development (R&D) was wasted ignores the fact that R&D, like geological exploration, is inherently inefficient, with many avenues having to be explored to determine the best route. According to a dictum of Ara Mooradian, R&D pays for itself if it correctly identifies blind alleys – and wild geese that should not be chased further. Without the very well rounded capability of the CANDU fuel development team, the progress of CANDU fuel could well have been side-tracked into a costly, even calamitous, direction. This capability is going to be just as necessary in the future for the same reason.

Lessons Learned

It is ironic that politicians and academics continue to pontificate on a science-and-technology policy, while ignoring lessons from past Canadian achievements that rank with the world's best. The CANDU nuclear system is just one of these, and its fuel program alone has several valuable lessons for Canadian policy.

Research that is intended to provide economic and industrial benefits should be mission-oriented. Once the mission is assigned, the research program becomes a means to an end, and not an end in itself. Conceptually, it is simple to proceed from the mission to the objectives, and hence to the research program itself. This ensures that the research is relevant, that all necessary research is undertaken, that economics are considered along with technical factors, that the program is performed to an agreed schedule and end-point, and that commercialization is an integral part of the objective.

Since we cannot be world-class in all areas of modern science and technology, the missions must be selected very carefully to match and satisfy national objectives. This is properly a government responsibility, but governments instead concern themselves with the management of research and development, a subject in which they – politicians, bureaucrats, and consultants – are generally neither experienced nor competent.

Canadian governments, both Conservative and Liberal, have a disastrous record for fumbling science and technology. The current Conservative government slashed funds for institutions with proven performance, without having any guiding policy for science and technology. At the 1986 National Liberal Convention, when a resolution on science and technology policy came to the vote, 'messengers and beaters had to be sent into the gossiping corridors to round up a quorum of 50 concerned Liberals before a vote could be legal.' (A. Fotheringham, 1986–12–02).

High-technology industries can be grown out of resource industries. International competition in high technology is intense. Our natural advantages lie in our natural resources, and in our well-educated human resources. Opportunities for Canada are therefore to be found in adapting technologies initiated by other people for other purposes to our own particular circumstances.

Basic, or curiosity-driven, research, while vital for the advancement of mankind in the long-term, rarely benefits directly those who fund it. Basic research in Canada, in universities and elsewhere, had a negligible effect on the development of CANDU fuel. It should be recognized as an altruistic activity. Canada, as an affluent nation, should devote a fair share of its resources to basic research, without expecting economic returns from it.

Even in a mission-oriented program there is a need for research at a fundamental level on topics underlying the mission, to provide a good understanding of the relevant phenomena. This is one essential input for wise guidance of the program, and can be an invaluable resource in tackling unforeseen problems.

Applied research is an essential step from the international pool of basic scientific research to the development of technologies for social benefit. Some countries with outstanding records in basic science, notably the U.K., have been largely unsuccessful in reaping the commercial benefits from the resulting technologies. Germany in the 19th century, the U.S. in the mid-20th century, and latterly Japan, have been very successful in exploiting discoveries made elsewhere. Each in its turn has emphasized applied R&D.

Other essential inputs are economic and market analyses for the product before devoting major resources to the R&D program. Any mission-oriented program should incorporate a plan for commercialization. To this end, Canadian schools of engineering should pay more attention to these aspects in their courses. This could have the spinoff benefit of making the universities' own applied research more relevant to national needs. In a 1986 poll of more than 400 technology-driven companies in Canada, only 6.4 per cent rated university R&D as very important, while 24 per cent said it was not important at all. As necessity is the mother of invention, market forces drive innovation.

The program has to be designed with the transfer of technology to industry in mind from the start. The CANDU fuel program offers useful experience on mechanisms for technology transfer. Those funding the R&D must decide at a very early stage how they are to obtain a return on their investment, since technology, once transferred, cannot be untransferred.

Even when technology is imported from abroad, a substantial effort in science and technology is required to absorb and support it. To have a proper understanding of the real potential, and problems, of a technology, those responsible should be working on some aspect of it; the published literature probably does not reveal either the most promising prospects or the troublesome problems if these have commercial implications.

Science-and-technology activities are also needed far beyond the innovation stage. Any new product is a delicate transplant from a laboratory, that has to be carefully nurtured if it is to establish itself in its new and competitive environment. Unless technical support is available quickly to solve unforeseen problems that arise, the transplant will be rejected and will probably not have another chance.

Most modern technologies require large inter-disciplinary programs, with expensive, efficient support services combining underlying and applied science, engineering development and design, safety, economic and market analysis, and the operation of test facilities as well as pilot and prototype plants. Universities, with other priorities, do not provide this broad capability, nor do most of the laboratories of Canadian industry, dominated as it is by multinational corporations. In these circumstances, Canada has evolved some excellent government laboratories, but the conventional wisdom is that government R&D is 'bad' while R&D in universities is 'good,' and R&D in industry 'best.' A proven and uniquely Canadian means of managing inovation all the way from fundamental research to commercialization should not be rejected for doctrinaire reasons.

Performing mission-oriented R&D in large, multidisciplinary laboratories is not an automatic recipe for success. Researchers must realize that society does not owe them a living; they must sell the benefits of their work to those who pay for it. The cost of freedom from irrelevance is eternal vigilance. Responding to demands for accountability, the government has introduced extensive and time-consuming review mechanisms that may themselves have already passed the point of optimum efficiency.

However, these reviews have the greatest difficulty assessing the quality and worth of the R&D. I would recommend the formula of backing individuals and institutions with a proven track record for fulfilling their missions. There is an unfortunate tendency to set up new laboratories for new missions, and not to exploit existing resources by modifying a mission in the light of changing circumstances.

These lessons are obvious to many of us who worked in the CANDU fuel program. They have general relevance when tested against other Canadian achievements in engineering. Now they have to be learned by our policy-makers if the Canadian economy is to benefit from the program's excellence in science and engineering.

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Notes

1. A misnomer, it was the demountable nature of the elements in the bundle that was innovative.