EARLY DAYS OF CANDU FUEL

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ABSTRACT

I will briefly describe how the original dimensions of the fuel bundle were defined and how the early designs of fuel evolved. I will also touch on some of the historical events of the materials and experiments which effected the fuel programme. Also how I became involved with Canada's Nuclear Fuel programme

INTRODUCTION

The evolution of fuel in Canada can be traced to Dr. George C. Laurence who tried very hard to make a nuclear critical mass, called a pile in those days, in 1939-42, when he experimented with a yellow cake (U_3O_8) & graphite at National Research Council in Ottawa.. He got very dirty building a number of piles of graphite and Yellow cake and therefore he was the first to dirty his hands with natural Uranium fuel. Due to the low of density of Uranium in the yellow cake and the impurities in the graphite (Calcined coke) plus the absorption effect of the paper bags, he was not successful in obtaining a critical mass, but did define the start of Canada's nuclear programme. He was the first person in the world to study neutron multiplication in a large assemblage of carbon and uranium.

Between then and 1957 Canada had become involved with the design and construction of Heavy Water research reactors. First with Zero Energy Experimental Pile (ZEEP), the first reactor in the world to be built outside USA, and then National Research Experiment (NRX) and National Research Universal (NRU). The power reactor programme was still in its infancy as the design of NPD-1 had just been halted and turned into a horizontal pressure tube reactor NPD-2 from a vertical pressure vessel type in 1957.

I have always been puzzled where the basic numbers came from which defined the pressure tube, bundle, element diameters and bundle length. It was not until this year (40 years later) that I was able to trace the original definition of those numbers and how they were chosen, via the CANDU Origins and Evolution committee.

FUEL CHANNEL AND PRESSURE TUBE DIAMETER

The early physics studies for the vertical pressure vessel reactor Nuclear Power Demonstrator (NPD-1) were done at Chalk River by Arthur Ward assisted by Gene Critoph who suggested an optimum homogenous cell of the fuel, coolant and cladding should have a cross-section area of 50 cm^2 . This translated for engineering purposes into a circular fuel channel bore of 3.25 ins.(82.55 mm). Thus the resultant bundle diameter was chosen to fit inside this vertical channel. A 4 metre long rodded fuel assembly of a modified hexagonal array of 19 elements using Zircaloy clad natural Uranium Dioxide (UO_2) was chosen, even though plate and annular designs of metal uranium fuel looked attractive . Whilst this work was going on, the Nuclear Power Group at Chalk River were studying concepts utilizing plutonium fuel cycles. In their studies they looked at the possible use of pressure tubes rather than pressure vessels. The Hanford production N-reactors were using horizontal pressure tubes and the Hanford experimental Plutonium Recycle Test Reactor (PRTR) had already adopted vertical pressure tubes with a 3.25 ins.(82.55 mm) bore with 19 element fuel geometry. Harold Smith suggested that a new concept with pressure tubes be considered with an enriched thorium oxide fuel cycle. Fortunately Dr. Laurence presented a convincing argument for staying with natural uranium and the enriched thorium cycle did not proceed much further. Dr. Lewis favoured this pressure tube approach and directed the team to stop work on the pressure vessel design and produce a horizontal design with pressure tubes in March 1957. So the same diameter was chosen for the pressure tube diameter and the resultant fuel bundle design.

I would like to jump ahead to the larger channel diameter as we know it today. With the larger reactors like Pickering it was necessary to increase the size of the channels to minimize the number of channels required, to keep the size of the reactor as small as possible and allow for even larger reactors in the future. There was a great reluctance on Chalk River's part to go to bigger pressure tubes, as it would require major modification to the loops to accommodate the nominal 4 inch pressure tube and require a major development program for a new element diameter. This problem was resolved by stipulating that the bundles would employ elements of the same diameter as those for NPD and Douglas Point, thus the Pickering fuel bundle design using 28 such elements and standard minimum spacing, resulted in a pressure tube diameter of 4.07 inches (103.38 mm) which has been our standard bore every since.

BUNDLE LENGTH

The original NPD-1 core length of 4 metres and a short fuel length or fuel slug of one foot was adopted for the horizontal study. John Foster thought that the 1 foot bundle was very arbitrary and seemed unnecessarily short. So he did a number of calculations on the effect of length on the predicted discharge burnup and came up with the recommendation of dividing the 4 metres by 8, resulting in 50 cms or 19.685 inches. Dr. Lewis had also done a similar study and agreed. The length was rounded down to 19.5 inches (49.53 cm) for simple engineering purposes. So that is how we obtained the magic 19.5 inches bundle length, which has lasted for many years. The designers evidently added two half bundle lengths to fuel channel to each end so that the latch and the rolled joints were not directly in the core! Thus we ended up with 9 bundles in the NPD-2 channel.

So the stage was set for Canada's Power Reactor programme, a horizontal pressure-tubed reactor, cooled and moderated with heavy water (D_2O), short natural uranium UO_2 fuel bundles and on-power bi-directional fuelling. Thus the CANDU (CANadian Deuterium natural Uranium) reactor concept as we know it today was conceived.

ELEMENT DIAMETER

The original fuel element size or diameter of each rod for NPD-1 was chosen to provide a minimum inter-spacing of 0.050 ins (1.27 mm) with the 19 elements fitted within the 3.25 in. fuel channel diameter. It was proposed that the inter-element spacing would be provided by a spiral wire wrap around each element, mechanically joined at each end of the element or rod. It was assumed that this spiral pattern would promote sub-channel coolant mixing. The minimum 50 thou's (1.27 mm) inter-element spacing was recommended by Dave Coates at Civilian Atomic Power Division (CAPD) of Canadian General Electric, Peterborough, based on heat transfer tests performed at Columbia University and other work which was performed during and after the Manhattan Project. These dimensions were used in NPD-2, Douglas Point and Pickering resulting in an element diameter of 0.6 inches (15.5 mm).

MY INTRODUCTION TO AECL

My first contact with Canada's nuclear program was in 1957, when I attended an Engineering Institute of Canada seminar at Peterborough and was introduced to Dr. W. B. Lewis as "WB and his boys". The subject was Nuclear Power which they were developing, but at that time, I had no thought of being involved in this new science, that had evolved from the Manhattan project. I was employed then by Orenda Engines at their test establishment at Nobel, near Parry Sound, Ontario. There we were testing and developing components of the Orenda Iroquois jet engine for the Avro Arrow program.

During 1957 I had experienced the slow down in advanced research. Just before Christmas 1957, I was offered a posting to Chalk River, on attachment to Atomic Energy of Canada Ltd., as Orenda wished to diversify and get in on the ground floor of this budding new industry and science. My first question was where was the location of Chalk River and what was there? I was told it was 300 miles to the east on the Ottawa river, where Atomic Energy of Canada Ltd. had their Nuclear laboratory (CRNL). Even though my wife, Bette was eight and half months pregnant, we moved to Deep River in early January 1958. The temperature was minus 30 Centigrade and the roads at that time, many years ago, from Parry Sound to Deep River via North Bay were just barely passable in the winter.

I reported to work, having settled my family of two and three quarters in the old Staff Hotel. I was seconded to Dr. Laurence's division in Jack Horsman's branch and given an office in building 145. Some of the members of the branch at that time were John Melvin and John Jennekens, who later became president of the Atomic Energy Control board. My room mate at that time was Akira Hirarta on attachment from Japan. His English was extremely limited to "Good Morning". Bette and I have kept in contact with him over the years and his English is now probably better than mine. He is now retired but consulting. I was in complete awe of the number of people working at Chalk River who had either doctorates or masters degrees in a wide range of science disciplines. I was there with a number of other Orenda personnel, one of whom was Dr. George Pon. The objective of my attachment was to learn about the fuel loops, so that Orenda could design and fabricate these systems and other components for this exciting new program.

To expose myself to all the subjects associated with the nuclear program, I was able to move myself around the laboratory attaching myself to various units in Operations. These were the people who operated the research reactors NRX and NRU. They kindly put up with a greenhorn who had not a clue of what was involved, but they would be the people who would operate anything we would build in the future. So I put myself on shift with the people who operated the loops that were then running in NRX. It was here that I met Muts Konyagi and Danny Nishimura and heard about J.A.L. (Archie) Robertson, Mike Notley, Al Bain and Ross McEwan et al. whom I was to work with later. After a number of months on shift at both NRX and NRU, I moved myself into the NRX physics office. It was there I really got my first exposure to reactor physics under the guidance of Don Milley. Art Passanen was in the NRU physics office at that time.

In trying to understand the effect of the enriched fuel being used in the loops, on the flux of the reactor and to estimate the power that the fuel would produce, I tried my hand at calculating the milli-K effect of the fuel on the flux and estimating the individual powers of the fuel elements and the total power produced. It was an excellent learning exercise in neutron physics. I quickly found out that all the neutron physics available then was too ideal to be much use in practice, as they could not give the answers or the data were too coarse for my application. I also found that many of the constants then in use in the calculations of the physics of the reactors were good guess-estimations from the early days of design and had never been revised or defined. So with the kind tutoring of Kushneriuk on the effect of black slabs on neutron flux and Westcott on nuclear cross sections, I staggered through the development of the equations and laboriously calculated by hand, my prediction, with only mechanical calculators for assistance. (This was before the days of microchips and personal computers). In my deliberations I decided to issue a memorandum on the cross sections to be used for enriched fuel loop calculations. These cross sections would be different from those being developed for the power reactors because of the higher neutron velocity in the local area of the flux in the research reactors, due to the light water coolant and the enriched fuel being used. Unfortunately I did not define the conditions in my memo as it was only addressed to those people involved in the loop calculations

I had heard in the short time I had been at Chalk River many tales about Dr.W.B.Lewis and how he read everything that was written at the plant and how at various meetings he could take any expert in any field apart if he thought that they were glossing over something or had not thought something out properly before making a pronouncement in his presence. When Dr. Lewis saw my memo he wanted to know who this Page was, who was recommending nuclear cross sections to be used in calculations, as this was Dr. Lewis' sole domain and he had never heard of me. Many memos later written by Kushneriuk and Westcott explaining my presence and intent, the storm abated. During this period the Avro Arrow and Iroquois engine program had been cancelled and all the employees of Avro and Orenda had been fired. We, on attachment at AECL were still on the Orenda payroll but not associated with the Arrow contract. As a precautionary move, we applied for employment with AECL as insurance against the future. My application crossed his desk in the middle of the nuclear cross section storm, fortunately we did not need immediate employment at that time.

FUEL ENGINEERING

Later in the following year (1959) Dr. A. J. Mooradian asked me to join AECL and to form the Fuel Engineering group, as he was bringing all fuel associated projects and experiments under one roof. Dr. A. J. Mooradian was the true godfather of the CANDU fuel program. He died on October 4, 1996 after a painful battle with cancer, at the age of 74 years. He and Dr. W.B.Lewis drove the programme with clear and far reaching directives and the type of project management that mixed science with engineering realties. This programme involved the research reactor fuels as well as the power reactor fuel bundles J. A. L. (Archie) Robertson was to look after the scientific and fundamental understanding of fuel and 'WE' in engineering were to direct the design, development, irradiation, fabrication development and production of all CANDU power reactor first fuel core loadings.

I was a group of one until George Fanjoy joined me on attachment from CGE, replacing Ray Fortune (CGE). George had been involved with the design of fuel for NPD and had started the design of the Douglas Point fuel bundle. It was the blind leading the blind, as we all had limited knowledge of the fuel and materials that we were developing. At the same time NRU fuel was going through a bad development period after the fuel jammed in the reactor and fuelling machine and caught fire when the fuelling machine was dragged off the reactor in 1958. I volunteered to vacuum some of the spent fuel off the top of the reactor. That was my first taste of protective clothing and wearing a gas mask in an empty reactor hall (receiving 2.5 R in the process).

Our first office was part of the library in the Met Bldg 456. Al Lane was my first AECL staff member and he was sent down to Peterborough to decide how we should load the NPD-2 core with the special dimensioned bundles both 7 & 19 element with both 0.25"(.64 mm) and 0.15"(.38 mm) wall thickness. There was a great debate that went on for a number of months whether we should load or even try to make 0.15"(.38 mm) sheathed elements for the 19 element bundle.

One of our first major jobs was to commission the new E-20 loop (now U-2). The problem was to make four 3"(76.2 mm) diameter 19 element bundles to fit the thick pressure tube that had been installed. Nobody had any faith in this new Zircaloy-2 material and made the pressure tube with a wall thickness near to a half an inch (12.7 mm)! This resulted in an inside diameter of only 3 inches (76.2 mm). We assembled these special bundles with screws and special thick end plates which mated into each other. The whole assembly was held together with a birdcage device designed by Gavin McGregor. The irradiation was a success and the E-20 loop worked well. With natural UO_2 fuel in the bundles, the power from these small elements did not approach that expected from NPD-2 at full power, but we had made and irradiated 19 element fuel bundles for the first time in Canada.

Our next task was to test full-scale NPD-2 types of fuel. This required a proper thin walled 3.25 inch (82.55 mm) diameter pressure tube to be installed in E-20. There two fuel designs for NPD-2, the 19 and the 7 element. The 7 element bundle with larger element diameter 1 inch (25.4 mm) was designed to increase the amount of Uranium in the core. To ensure that the large diameter elements in the seven-element fuel bundles would not be overpowered in the high flux of NRU, we used depleted UO_2 fuel. When the irradiation of the six NPD bundles had been operating for some time we noticed that the overall power of the loop fuel was increasing. After scratching our heads and consulting the physicists we realized that the seven-element bundles were breeding plutonium and producing more power than the depletion of the natural uranium U_{235} in 19 element bundles. When we examined the fuel in the hot cells we found that the seven element bundle elements had extensive grain growth with a central void, indicating significant fuel rating. Bettis for a long time assumed this to be due to central melting but were later convinced by the rest of the scientific community that it was just grain growth and pore migration.

URANIUM OXIDE AND AMMONIA DI-URINATE (ADU) POWDER

In 1955 Dr. W. B. Lewis finally agreed to the use of Uranium Dioxide UO_2 instead of Uranium metal with it's high density . Even though Bettis had released the information on UO_2 at the 1954 Geneva Conference and Les Cook (Head of Chemistry and Metallurgy at Chalk River) and others had been recommending this fuel material for some time. His reluctance was due to the lower Uranium density of the oxide which would result in a lower achievable burnup with adverse effect on the neutron economy of the reactor. But uranium oxide offered two major advantages over uranium metal, dimensional stability at high burnups and greatly enhanced corrosion resistance in the case of failures of the Zircaloy cladding. The decision was reenforced by a large number of small element confirmatory irradiations which were done on UO_2 in the period 1955-57 to study its characteristics by J. A. L. Robertson et al. The final irradiation before bundles was a long mechanical wire wrapped NPD-1 element in 1957-58 by Bill Morison and Joe Howieson. Unfortunately it failed when the wire wrap moved in the flow, allowing the element to move toward the wall of the pressure tube, starving the fuel of coolant with the resultant high temperature corrosion.

Producing UO_2 powder from Yellow-cake was difficult in those days until Mines Branch working for Energy Mines &Resources (EMR) and Eldorado produced the ADU process. Joe Howieson reminds me that the Chalk River Metallurgical Branch was a separate organization reporting to EMR's Mines Branch. It was this connection that led to the development of the Ammonia Di-Urinate(ADU) process for UO_2 powder production. Canada was the pioneer in this route. Alan Prince, who later became President of the AECB, was in charge of the EMR work.

We had difficulty in producing pellets and NPD fuel had relatively low density compared with today's production 10.2 vs 10.7 gm/cc. Also, obtaining pellets with U/O > 2.0 was not achieved until later in the production. The quality of pellets re-chipping and size of dish and shoulder produced many debates; the pellet chamfer came later. Vibratory compaction and swaging were also explored as alternative ways to produce elements without pellets. Norton Co. In Niagara Falls demonstrated UO_2 fusion and provided different grades of fused powders for vibratory compaction work. This small sideline was to come back to haunt them when people started asking what happened to the waste.

WIRE WRAP

Element spacing was tried with mechanical wire wrap attached to either end of the element but was quickly changed to resistance spot-welded to the sheath to prevent movement in the coolant flow. For Douglas Point, the 19 element bundle the wire wrap pitch was increased to promote coolant mixing and better spacing along the elements length and extra thick wire was attached to the outer elements as bearing pads. The end caps were resistance welded as well as the elements to the end plate thus getting rid of the laborious tungsten inert gas (TIG) welding. The rest of the nuclear world took a long time to copy our use of resistance welded elements.

SPLIT SPACER DESIGN

During the development of Douglas Point bundles a growing concern of possible significant element fretting was expressed and a directive was issued to come up with alternative designs without wire spacing and if possible no end-plates for replacement fuel. This led to a number of innovative designs, such as the twisted tape, ring spacers, brazed end caps. Some never graduated beyond the prototype phase, but two distinct programmes did emerge. The Zirconium-beryllium braze programme and tube-in-shell bundle. The brazing programme was developed at American Machine & Foundry (AMF), Port Hope, later Westinghouse Canada and now Zircatec. This technique of joining Zircaloy led to a bundle design without end plates and all the elements joined together by three planes of spacer to a thick central element. Though it was a very strong bundle it did not work under irradiation due to the lack of longitudinal expansion of the elements. Joe Howieson dropped one from the roof at Westinghouse to prove its strength to his staff. So we replaced the two end planes of spacers with end plates and cut the centre plane of spacers in half. To prevent inter-locking of the spacers, they were then skewed relative to each other and thus the split-spacer bundle design as you know it today was born. That is a very simplistic story, as we went through a long list of methods to produce the spacers until we settled on the beryllium coated method with induction heating. We looked for other alloys of Zirconium but none work as well as beryllium. The same wide ranging search occurred with bearing pads of different designs, such as rollers and graphite to name a few. The design of end plates for the Pickering 28 element went through many phases until an accountant at Westinghouse Canada came up with the classical simple design. The simple designs are always the hardest to achieve.

The Tube-in Shell design was an attempt to remove the heat by passing the water through tubes in a large tube filled with vibratory compacted fused UO_2, rather than around elements. The whole assembly was brazed at both ends. Unfortunately the outer annulus was a weak point with respect to heat transfer and the low Uranium density and difficulty in manufacture did not allow it to progress beyond the first irradiation. The UKAEA copied us but were a bit surprised when we dropped it in favour of the split-spacer bundle. They did the same when we put some Zr-Nb $2^1/_2$% fuel elements under irradiation thinking we were developing high strength fuel elements, whereas we were only getting some early experience with Zr-Nb $2^1/_2$% until the pressure tubes could be put into the U-2 loop. A welded bundle was also tried both with flexible wire spacers and solid spacers, but was dropped, as we saw corrosion and cracks around the spacers after irradiation, due the coolant chemistry.

Sheath collapse forming longitudinal ridging and into the axial gap during irradiation was initially a major worry but the choice of diameteral clearance .002 to .005" (0.0508 to 0.127 mm) appeared to be a good guess and the axial clearance was always kept conservative . We were initially puzzled by circumferential ridges but they never really caused any problems.

MATERIALS

Various alternative fissile, structural materials and coolants have been used or developed for the power and research reactor programmes, including high power booster fuel designs. Some of these fissile materials were due to the search for higher density fuels to improve the neutron economy and others compatible with organic coolants. In the end UO_2 and Zircaloy-4 are still our standard materials and booster rods are no longer used for xenon poison override.

I did know until recently that Zircaloy-2 was discovered and developed by Bettis for the US submarine fuel by an accident when they were trying to find an improved alloy compared to Zircaloy-1. In 1952 by the accidental addition of a small amount of stainless steel to a Zircaloy-1 ingot, Dr. Kroll and his associates found that there were beneficial effects by adding small amounts of iron, nickel and chromium. This new alloy named Zircaloy-2 had a better corrosion resistance than Zircaloy-1. Later they found that by replacing the nickel component with iron produced an alloy which cut the hydrogen absorption in half and had good corrosion resistance. This was initially called Nickel-free Zircaloy-2 and later became known as Zircaloy-4, as we know it today. It was not until 1954 that these early Zirconium Alloys were unveiled by WAPD US Bettis Lab. at the United Nations Atoms for Peace Conference, at Geneva. After this announcement Zircalloy-2 became the accepted cladding alloy.

Corrosion of Zircaloy and its H_2 pickup were a major worry with the early production alloys but with time it was never a real problem as long as a high degree of cleanliness and good quality control were maintained. In fact some Russian visitors gave me a hard time when I dropped autoclaving of the bundles before irradiation. They wanted know why we had done such a radical thing, when the rest of the world was still autoclaving. It should be remembered that thirteen 7-element bundles were left in NPD during its whole operating life without failure. They were a bit white when they came out but none the worse for that exposure to the coolant for such a long time.

I must record that we observed our first stress corrosion crack sheath failure in a test we did in the Heavy Water Component Test Reactor (HWCTR) in the US, when we did our first bundle power shift during the irradiation. We did not recognize what had happened at the time, as the Americans dropped the string of bundles in the bays. Because Dr. Lewis and Dr. Mooradian wished to prove that the bundles could achieve the political/scientific target of 10,000 MWd/teU (240 kWh/kgU), we were prevented from doing any power shifts in our loops until much later.

DRYOUT

We were rough on some of our fuel experiments as we pioneered the first in-reactor heat transfer tests in the world, when investigating Fog-cooling, a mixture of steam and water coolant. We defined the word 'Dryout' of the coolant on the sheaths as compared to the departure of nucleate boiling. From the fog cooling experiments we progressed into a full boiling programme for the development of the Boiling Light Water (BLW) reactor and later Boiling Heavy Water reactors. The in-reactor heat transfer of tests ended up with full-scale reactor bundle heat transfer tests in the U-1 loop, again first in the world. 37 and 22 element bundles were used with central element providing space for the instrumentation. The bundles were designed for central melting using enriched Thoria fuel with a central void and thick sheathing, as we wished to get the maximum power out of the six bundle string (4.5 MW from six bundles). The tests culminated with pump rundown experiments, where the pumps were shut off before the reactor was tripped. During these tests I saw the effect on the reactor neutron flux as the channel voided due to the large scale boiling and dryout, causing the flux to peak before collapsing due to the reactor shut down.

FUEL COSTS

The simple design of the fuel with good neutron economy led to one of the objectives of the fuel programme, which was to demonstrate that fueling costs of less than 1 mill/kWh were achievable and this was done in the late 60's and early 70's as the production volume grew and the bundle discharge burnups were obtained.

ORGANIZATION

In one of my early presentations at CRNL, I showed a chart of our fuel organization and team players and was accused of saying that Fuel Engineering was the centre of the universe. But I was only trying to show how complex a multi-project fuel programme was, with all the inputs from the various companies, organizations and scientific disciplines.

CONCLUSION

I have tried to briefly trace the history of the early fuel dimensions and materials and the start of Fuel Engineering with a very limited description of the problems we faced in those early days of the programme. It was an exciting time and I was very lucky to have taken part in such a wonderful team effort, where the members were from all forms of disciplines of science and engineering.

This successful fuel programme is Dr. A. J. Mooradian's real legacy, as he taught us how to lead and direct such a complex programme. He and Dr. W.B.Lewis drove the programme with clear and far reaching directives with a type of project management that mixed science with engineering realties.