Historical and Pictorial Record of Canada's Power Reactor Fuel Bundle Design and Development

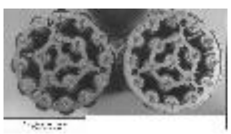
edited by R.D. Page and A.J. Langdon

Summary:

This pictorial record of Canada's power reactor fuel bundles was prepared to historically record the evolution of the power reactor fuel over the years. No one report issued over the years has been able to describe in detail the various changes that these pictures portray. It should be noted that the record does not include WR-1 type fuel or special irradiation of assemblies. "A picture speaks a thousand words".

Full resolution versions of the images contained in this document can be found in the Image Library of CANTEACH web site http://canteach.candu.org listed under the System Index (SI) 37000 - Fuel.

File info: 37000-fuel/fig000_AECL_Symbol_Pick_28.jpg (size: 198 K)
Description: The figures denoted by 37000-fuel/figxxx... below form a "Historical and Pictorial Record of Canada's Power Reactor Fuel Bundle Design and Development", edited by R.D. Page and A.J. Langdon, photography by C. Baskin, CRNL. This pictorial record of Canada's power reactor fuel bundles was prepared to historically record the evolution of the power reactor fuel over the years. No one report issued over the years has been able to describe in detail the various changes that these pictures portray. It should be noted that the record does not include WR-1 type fuel or special irradiation of assemblies. "A picture speaks a thousand words".
Source: *Ron Page, email 2001.08.14 to WJG*



File info: 37000-fuel/fig001_3_inch_end_of_19_el_bundle.jpg (size: 122 K)
Description: This is a photo of the end-plates of the first 3 inch diameter fuel bundles. These were the first 19 element fuel bundles built in Canada and irradiated in the E-20 loop (now U-2) in the NRU reactor. They had to have a diameter of 3 inches to fit in the thick wall pressure tube installed in the E-20 loop to commission it. As the knowledge of the material properties of Zircaloy-2 was not well known at that time, the wall thickness was increased to be conservative. The bundles were assembled by screws as the method of welding the end-plates had not been developed. (circa 1959-60)
Source: *Ron Page, email 2001.08.19 to WJG*

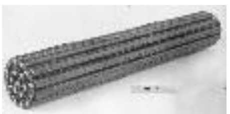
File info: 37000-fuel/fig002_NPD_7_el_Riveted.jpg (size: 152 K)
Description: This is an end view of one of the first NPD 7-element fuel bundles. They were assembled by riveting the elements to the thick end-plates. Later Tungsten-Inert-Gas (TIG) welding was used and later resistance welding to thinner end-plates, thus improving the neutron efficiency of the fuel.
Source: *Ron Page, email 2001.08.19 to WJG*

File info: 37000-fuel/fig003_NPD_7_el_Riveted_Long.jpg (size: 90 K)
Description: This NPD 7 element riveted bundle is in its classic autoclave black.
Source: *Ron Page, email 2001.08.19 to WJG*

File info: 37000-fuel/fig004_NPD_7_end_welded.jpg (size: 73 K)
Description: This end plate on the NPD 7 is now assembled by TIG welding to a thinner end plate.
Source: *Ron Page, email 2001.08.19 to WJG*

File info: 37000-fuel/fig005_NPD_7_long.jpg (size: 69 K)
Description: In some colour photos the rusty colour on the surface of fuel bundles is from endurance testing in the lab and comes from the iron oxide from the carbon steel piping, even though the bundles rested in a Zircaloy pressure tube.
Source: *Ron Page, email 2001.08.19 to WJG*

File info: 37000-fuel/fig006_NPD_19_end.jpg (size: 135 K)
Description: The end view of a NPD 19 element assembled by TIG welding.
Source: *Ron Page, email 2001.08.19 to WJG*

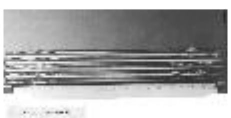


File info: 37000-fuel/fig007_NPD_19_element.jpg (size: 82 K)
Description: The 19 elements are spaced by two wires wrapped around each elements and spot welded to the sheaths, one turn per length of element.
Source: *Ron Page, email 2001.08.19 to WJG*

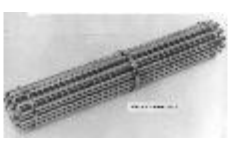
File info: 37000-fuel/fig008_Douglas_Point_19 el_wire_wrap.jpg (size: 85 K)
Description: The Douglas point 19 element bundles were wire wrapped but the helix around the element was doubled. Thicker wires were attached at each end to act as bearing pads so the bundles could slide through the pressure tubes with minimum wear to the tubes.
Source: *Ron Page, email 2001.08.19 to WJG*

File info: 37000-fuel/fig009_DP_19_el_Colour.jpg (size: 66 K)
Description: An example of the DP 19 element bundle covered in the iron oxide and showing the extra wire pads which are partially ground to a flat surface contoured to fit the pressure tube.
Source: *Ron Page, email 2001.08.19 to WJG*

File info: 37000-fuel/fig010_NPD&DP_19_Element.jpg (size: 153 K)
Description: A comparison of the NPD & DP 19 element bundles. Note that the DP bundle now assembled by resistance welded of end plates to the elements.
Source: *Ron Page, email 2001.08.19 to WJG*



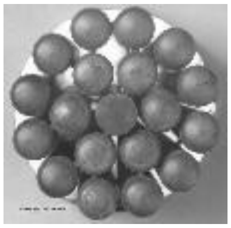
File info: 37000-fuel/fig011_AMF_Twisted_Tape_Brazed_19_el.jpg (size: 78 K)
Description: During the development of the wire wrapped 19 element bundles for Douglas Point, there was growing concern of the possibility of inter-element fretting of the thin .015 in. thick fuel sheaths. A study was launched to come up with different ways of spacing the elements and also to delete the end plates. The following bundles are an illustration of what were considered. The first example is the twisted tape bundle for so-called better mixing. The center element was made strong enough to take the fueling machine loads and the outer elements were recessed for the fueling machine side stops. Did not graduate.
Source: *Ron Page, email 2001.08.19 to WJG*



File info: 37000-fuel/fig012_Welded_Belly_Band_AMF_bundle.jpg (size: 108 K)
Description: Another design during this period was held together by belly bands and used welded spacers. Did not graduate. AMF stands for American Machine and Foundry who was contracted to produce Uranium metal fuel for NRX and NRU Research reactors at Chalk River. They were later bought out by Canadian Westinghouse.
Source: *Ron Page, email 2001.08.19 to WJG*

File info: 37000-fuel/fig013_Early_AMF_Brazed_Bundle.jpg (size: 57 K)
Description: Another design using brazing of the ferrule spacers to the elements were tried. Again did not graduate. But Zr-Be brazing was introduced.
Source: *Ron Page, email 2001.08.19 to WJG*

File info: 37000-fuel/fig014_Domed_End_Cap_Brazed_AMF_Bundle.jpg (size: 89 K)
Description: To reduce the amount of Zircaloy in the end caps of the elements, thin domed end caps brazed to the sheath were tried. They had insulating pellets inside. The bundle was assembled with two planes of fixed spacers and bearing pads on the outside elements. All brazed to the sheath using both resistance heating and induction heating to melt the braze alloy.
Source: *Ron Page, email 2001.08.19 to WJG*



File info: 37000-fuel/fig015_Domed_End_Cap_End_View_with_fixed_brazed spacers.jpg (size: 106 K)
Description: The end view of the above bundle with fixed brazed spacers and domed end caps.
Source: *Ron Page, email 2001.08.19 to WJG*

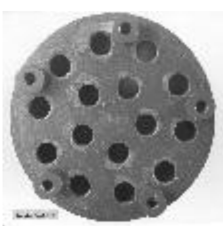
File info: 37000-fuel/fig016_Two_Fixed_Plane_Brazed_AMF_19el_Bundle.jpg (size: 79 K)
Description: This bundle has two planes of spacers. The domed end caps have been replaced by normal solid ones to better survive the fueling machine side stop loads and remove the need of brazing the elements ends. The bearing pads were now standard.
Source: *Ron Page, email 2001.08.19 to WJG*

File info: 37000-fuel/fig017_End_View_2_Fixed_Plane_Brazed_19 el.jpg (size: 92 K)
Description: The end view of the same bundle. The chamfer on the end caps was to accommodate the chamfer on the side stops.
Source: *Ron Page, email 2001.08.19 to WJG*

File info: 37000-fuel/fig018_DP_Brazed_Dev_Replacement_Bundle.jpg (size: 96 K)
Description: After a number of defects during irradiation in NRU the design was abandoned and end plates were reintroduced. This bundle had no spacing and was not irradiate.
Source: *Ron Page, email 2001.08.19 to WJG*

File info: 37000-fuel/fig019_DP_
Dev_small_mid_plane_Bearing_Pads.jpg (size: 87 K)
Description: The design of the replacement bundle for Douglas Point and NPD was slowly beginning to make progress. The fixed plane was dropped and replaced with a split spacer and a small pad in the center plane only. Thus the elements could now expand independently.
Source: *Ron Page, email 2001.08.19 to WJG*

File info: 37000-fuel/fig020_Tube-in-Shell_Vib_Compacted_Bundle.jpg (size: 63 K)
Description: Whilst all this development was going on a radical bundle design was tried. It was called the Tube-in Shell bundle. Instead of passing the heavy water coolant over and around the fuel, it was decided to try passing the cooling water through the fuel. This bundle was filled with vibratory compacted UO2 powder, thus it had relatively low Uranium density compared to the sintered pellets. It was all brazed in assembly which was very difficult. After two defects during irradiation the design was dropped from further development. It had a major weakness with respect to heat transfer, the coolant tubes had excellent heat removal but the eccentric outer annulus was very poor.
Source: *Ron Page, email 2001.08.19 to WJG*



File info: 37000-fuel/fig021_End_View_Tube-in-Shell.jpg (size: 132 K)
Description: This an end view of the Tube-in-Shell bundle. The traces of the braze alloy are evident around the tube ends.
Source: *Ron Page, email 2001.08.19 to WJG*

File info: 37000-
fuel/fig022_DP_Brazed_Split_Spacer_Development_Bundle.jpg (size: 74 K)
Description: The design has now matured and the spilt-spacers are now canted to prevent interlocking and a full length bearing pad has been added in the center plane. This bundle has seen endurance testing in the Sheridan Park loop and the braze alloy has a higher corrosion rate than the normal Zircaloy, thus the white appearance at the joints of the bearing pads.
Source: *Ron Page, email 2001.08.19 to WJG*

File info: 37000-fuel/fig023_DP_19_el_End_View.jpg (size: 128 K)
Description: This is a Westinghouse made bundle after they took over from AMF. Note the grounding electrode marks on the end caps from resistance welding of the end plate to the elements.
Source: *Ron Page, email 2001.08.19 to WJG*

File info: 37000-fuel/fig024_CGE_Development_bundles.jpg (size: 124 K)
Description: These end views are of two CGE development bundles where the use of welded bearing pads and spacers were tried. Also a variant of the end plate in two pieces. Note that the inner element caps are flat. This design did not go into production.
Source: *Ron Page, email 2001.08.19 to WJG*

File info: 37000-fuel/fig025_DP_Production_Brazed_split_spacer.jpg (size: 77 K)
Description: The final production bundle was a brazed split spacer design with three planes of bearing pads. This design of bundle was used as replacement fuel for both Douglas Point and NPD power reactors in Canada. It was also used in Kanupp, Pakistan and Rapp I & II, India.
Source: *Ron Page, email 2001.08.19 to WJG*

File info: 37000-fuel/fig026_NPD_7&19&DP_Brazed_Split_Spacer.jpg (size: 116 K)
Description:
Source: *Ron Page, email 2001.08.19 to WJG*

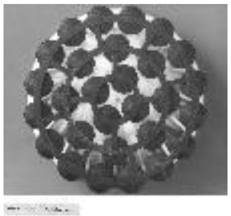
File info: 37000-fuel/fig027_NPD_7&19_DP_19_and_spilt_spacer_bundle.jpg (size: 109 K)
Description:
Source: *Ron Page, email 2001.08.19 to WJG*

File info: 37000-fuel/fig101_Early_wire_wrap_28_el.jpg (size: 94 K)
Description: During the development of the replacement D.P. design there were two other reactor fuel projects being developed. They were fuel bundles for Pickering A and Gentilly - 1 Boiling Light Water (BLW) reactors. Both these reactors were going to use 4 inch diameter pressure tubes vs the 3.25 inch of D.P. & NPD. Keeping the same size of elements as the D.P. 19 and .050 inch spacing between elements, the 28 element Pickering design was developed. CGE still preferred the wire warp rather than the toxic Beryllium braze. This wire wrap design was not favoured.
Source: *Ron Page, email 2001.08.20-21 to WJG*

File info: 37000-fuel/fig102_End_view_28_el_wire_wrap.jpg (size: 115 K)
Description: The end plate for the 28 element Pickering bundle took many forms which are illustrated in the following photos.
Source: *Ron Page, email 2001.08.20-21 to WJG*

File info: 37000-fuel/fig103_28_el_dev_bundle_Flexible_spacers.jpg (size: 96 K)
Description: CGE tried very hard to come up with a satisfactory design using only welding as the means of assembly. The angled bearing pads were welded at two points. The flexible spacer did not survive irradiation or endurance testing. The lack of redundancy in the bearing pads received a negative point in the design review. The end plate design changed again.
Source: *Ron Page, email 2001.08.20-21 to WJG*

File info: 37000-fuel/fig104_28_el_welded_Dev_Bundle.jpg (size: 84 K)
Description: 28 element with welded spacers and bearing pads. Note that one of the pads welds have failed and the pad is missing. Note two piece end plate.
Source: *Ron Page, email 2001.08.20-21 to WJG*



File info: 37000-fuel/fig105_28_el_dev_bundle_end_view.jpg (size: 126 K)
Description: A close up of the two piece end plate on the welded 28 element development bundle.
Source: *Ron Page, email 2001.08.20-21 to WJG*

File info: 37000-fuel/fig106_CGE_28_el_straight_welded_bearing_pads_dev_bundle.jpg (size: 90 K)
Description: CGE still trying to develop the welded 28 element bundle, now with welded straight pads and more than one plane of inter-element spacers. Single piece end plate.
Source: *Ron Page, email 2001.08.20-21 to WJG*

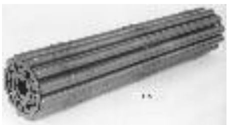
File info: 37000-fuel/fig107_28_el_Pickering_production_bundle.jpg (size: 93 K)
Description: Westinghouse came up with the final production design of the Pickering 28 element bundle. It had brazed spacers and bearing pads and a classical simple end plate design proposed by an accountant.
Source: *Ron Page, email 2001.08.20-21 to WJG*

File info: 37000-fuel/fig108_CGE_28_el_brazed_pad_dev_bundle.jpg (size: 90 K)
Description: CGE was now using brazed pads and spacers and again a different end plate design. CGE traded wire wrap technology with Westinghouse for brazed technology.
Source: *Ron Page, email 2001.08.20-21 to WJG*

File info: 37000-fuel/fig109_Pickering_28_inside_a_PT.jpg (size: 126 K)
Description: A closeup of the classical Pickering 28 element end plate with the bundle inside a Zr-Nb 2.5% pressure tube. Note the thickness of the pressure tube. The hoop stress on pressure vessels is directly proportional to diameter; hence the small diameter pressure tube walls can be much thinner than the thick walls required for a PWR pressure vessel. Thin Zr walls do not absorb many neutrons; hence the moderator can be placed outside the fuel area in a low pressure calandria. This is the essence of pressure tube reactor design vs. pressure vessel reactor design.
Source: *Ron Page, email 2001.08.20-21 to WJG*

File info: 37000-fuel/fig110_Gentilly-1_BLW_18_el_&_CST.jpg (size: 487 K)
Description: The fuel for the Gentilly-1 was maximized by large diameter elements with a central structural tube to hold the 10 bundles in the vertical pressure tubes. The fuel worked well but, with the success of Pickering proven by the mid 70's, the 10 % (approximately) lower TUEC of BLW-type reactors was not big enough to warrant continued operation nor to justify the funding of continued development. In addition, G-1 experienced control problems (related to coolant voiding and the use of direct cycle heat transport system) and serious service water system corrosion problems. Hence, the plant was shut down and decommissioned
Source: *Ron Page, email 2001.08.20-21 to WJG*

File info: 37000-fuel/fig111_Early_37_el_bundle.jpg (size: 116 K)
Description: As a backup design to the 28 element Pickering bundle, a 37 element was proposed. This was a hand built solid steel bundle with mechanical wire wrap. The 37 element was later developed for the Bruce and 600 Mwe reactors.
Source: *Ron Page, email 2001.08.20-21 to WJG*



File info: 37000-fuel/fig112_Gentilly-1_BLW_18_el.jpg (size: 78 K)
Description: B&W of Gentilly -1 Boiling Light Water 18 element fuel bundle.
Source: *Ron Page, email 2001.08.20-21 to WJG*

File info: 37000-fuel/fig113_Bruce_28_element.jpg (size: 95 K)
Description: Initially it was thought that the 28 element bundle would meet Bruce requirements but when the design of the reactor was uprated, it was necessary to develope the Bruce 37 element, to meet the channel power requirements. Note the staggered plane of bearing pads at end of the bundle to meet Bruce Channel requirements.
Source: *Ron Page, email 2001.08.22 to WJG*

File info: 37000-fuel/fig114_Bruce_37_element_bundle.jpg (size: 321 K)
Description: The Bruce 37 element had minor differences from the other 37 elements that were developed. The end caps were squared and the bearing pads were staggered at each end of the bundle.
Source: *Ron Page, email 2001.08.20-21 to WJG*

File info: 37000-fuel/fig115_End_view_Bruce_37_el.jpg (size: 116 K)
Description: The end view of the Bruce 37 element bundle. Note the grounding electrode marks of the resistance welder.
Source: *Ron Page, email 2001.08.20-21 to WJG*

File info: 37000-fuel/fig116_Bruce_37_el_&_hands.jpg (size: 99 K)
Description: This photo gives a perspective of the size of the Bruce 37 element bundle relative to the man's gloved hands. The bundles weighed approx 50 lbs and were 49.5 cm long and 10 cm in diameter.
Source: *Ron Page, email 2001.08.20-21 to WJG*

File info: 37000-fuel/fig117_End_view_Bruce_booster_rod.jpg (size: 134 K)
Description: The Bruce booster rods were designed to extend the window of the period shut before the Xenon poison prevented reactor startup. They were manufactured from enriched uranium Zircaloy alloy which was co-extruded with Zircaloy. The six 18 element bundles in an assembly was held together by ferrules and belly bands and strung together on a central structural tube. They had limited use in Bruce and were withdrawn from service.
Source: *Ron Page, email 2001.08.20-21 to WJG*

File info: 37000-fuel/fig118a_Bruce_booster_&_37_el.jpg (size: 124 K)
Description: The comparative sizes of a Bruce Booster bundle and the 37 element bundle.
Source: *Ron Page, email 2001.08.20-21 to WJG*

File info: 37000-fuel/fig118b_Bruce_ Booster_ rod_ Assembly.jpg (size: 563 K)
Description: This drawing of the Bruce Booster Rod Assembly demonstrates how it is assembled into a complete rod of six bundles.
Source: *Ron Page, email 2001.08.20-223 to WJG*

File info: 37000-fuel/fig119_Gentilly-2_600_MWe_37_el.jpg (size: 119 K)
Description: The Gentilly 2 600 MWe reactor 37 element bundle differed from the Bruce 37 in that the end caps were conical to accommodate the fueling machine side stops and the end bearing pads were not staggered. When the Bruce 37 and the 600 MWe 37 were irradiated together, this irradiation was paid for by the Common Programme between Ontario Hydro and AECL. This programme grew into the CANDEV (CANDU Development) programme funded by the utilities and AECL. This was later formalized into the CANDU Owners Group (COG) programme of all the nuclear utilities, this supported and funded common development programmes. The 600 MWe 37 element fuel bundle is been used in the folowing reactors: Gentilly-2, Quebec; Point Lepreau, New Brunswick; Cordoba, Argentina; Cernavoda, Romania; four reactors at Wolsung, South Korea; and two in China.
Source: *Ron Page, email 2001.08.20-22 to WJG*

File info: 37000-fuel/fig120_Bruce_booster_Pickering_28_Bruce&600_MWe_37_els.jpg (size: 163 K)
Description: A comparison of the Bruce booster bundle with the power reactor fuel bundles for Pickering A & B, Bruce A& B 37 element and the Gentilly-2 600 MWe reactors.
Source: *Ron Page, email 2001.08.20-21 to WJG*

File info: 37000-fuel/fig121_Bruce_Fueling_Machine.jpg (size: 209 K)
Description: Bruce Fueling Machine.
Source: *Ron Page, email 2001.08.20-21 to WJG*

File info: 37000-fuel/fig122_Fuel_Eng_Coat_of_Arms.jpg (size: 252 K)
Description: The coat of arms is protected by AECL Proprietary and Final Preliminary Draft. The shield is divided into quadrants by red tape. Superimposed on it is a bastard bundle. The upper left quadrant represents the engineering terms of fuel behaviour. The upper right quadrant represents terms developed in manufacture of fuel. The lower left quadrant represents terms of heat transfer and corrosion. The lower right quadrant represents the mystical chemical symbols of the coolant chemistry. Above the shield is the Omnipresent bull moose of our founder Dr. Ara J. Mooradian. Superimposed is a bird cage representing a fuel carriage. Above which is the loop rampant and unstable. Underneath the shield is the banner burnt at both ends by Burnup and Burnout. Upon which the motto is inscribed 'Caveat Emptor' - 'Let the buyer beware' or 'If it fails do not blame us!' Below which rests 'The never completed final report'.
Source: *Ron Page, email 2001.08.20-21 to WJG, The Fuel Engineering Coat of Arms was designed many decades ago by Alan Lane and Ron Page for an Engineering Ball at Deep River.*

File info: 37000-fuel/fig201_Double_Length_Bundle.jpg (size: 120 K)
Description: There was always the question of double length bundles as the fueling machines magazines were two bundles long. I always had great doubts of its practicability. Late in the programme a couple of bundles were built. The dimensional stability of the bundle was poor due the long elements. There was a large problem in trying to find a means of making a rigid plane in the center plane of the bundle to improve the stability of the elements. The handling of the 100 lb. bundle presented too many problems both in manufacture and at the stations. It was not developed further.
Source: *Ron Page, email 2001.08.20-22 to WJG*

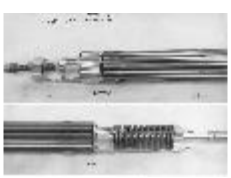
File info: 37000-fuel/fig202_25_ton_flask_over_NRU.jpg (size: 240 K)
Description: The 25 ton flask is used to remove irradiated fuel strings from the U-2 and U-1 loop test sections in the NRU research reactor at Chalk River.
Source: *Ron Page, email 2001.08.20-22 to WJG*

File info: 37000-fuel/fig203_J-rod_Flask_over_NRU.jpg (size: 198 K)
Description: The NRU reactor was the first reactor in the world to use on-power fueling. That was way back in the late 1950's. It is still operating as of August 2001 but it is reaching the end of its useful live and needs replacing. All the power reactor fuel bundles were tested for performance in this reactor, either in the U-2 or U-1 light water cooled loops. Each loop test section could accommodate six bundles vertically in a string.
Source: *Ron Page, email 2001.08.20-22 to WJG*

File info: 37000-fuel/fig204_Universal_Hot_Cells.jpg (size: 263 K)
Description: The Universal Hot Cells were used to examine irradiated fuel bundles and to disassemble the strings of fuel. The fuel bundles were examined and measured for dimensional changes and individual elements were cut out of the bundles for more detailed examinations.
Source: *Ron Page, email 2001.08.20-22 to WJG*

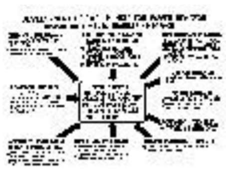
File info: 37000-fuel/fig205_Bundle in Hot Cells.jpg (size: 143 K)
Description: A 19 element fuel bundle being remotely moved by special tongs in the hot cells. This bundle had been irradiated to over 8,500 Mwd/tonne U at a heat rating of 43 W/cm. Note the circumferential ridges at the UO2 pellet interfaces.
Source: *Ron Page, email 2001.08.20-22 to WJG*

File info: 37000-fuel/fig206_Milling_the_end_plate.jpg (size: 155 K)
Description: To disassemble a fuel bundle in the hot cells remotely, the end plates were cut apart by a milling machine.
Source: *Ron Page, email 2001.08.20-22 to WJG*



File info: 37000-fuel/fig207_Fuel_bundle_carriage.jpg (size: 139 K)
Description: For fuel bundle testing in the verticle loops at NRU, six fuel bundles were assembled via a fuel carriage tensioned at one end with a spring, sometimes called a ‘birdcage’. The six bundle assembly was essentially 1/2 of a CANDU fuel channel.
Source: *Ron Page, email 2001.08.20-22 to WJG*

File info: 37000-fuel/fig208_Bundle_strength_testing.jpg (size: 178 K)
Description: Each type of bundle was strength tested in a compression test rig at temperature before and after irradiation. Irradiated bundles were some times stronger than the limit of the machine capabilities. These test was necessary to ensure that the bundles could withstand the fueling machine and hydraulic loads.
Source: *Ron Page, email 2001.08.20-22 to WJG*



File info: 37000-fuel/fig901_Fuel_Bundle_Development.jpg (size: 749 K)
Description: Generic diagram of what the central role that fuel played and what teams had to coordinate to get the various fuel programmes designed and into production.
Source: *Ron Page, email 2001.08.20-22 to WJG*

File info: 37000-fuel/fig902_Fuel_Engineering_center_of_Universe.jpg (size: 571 K)
Description: Specific diagram of what the central role that fuel played and what teams had to coordinate to get the various fuel programmes designed and into production.
Source: *Ron Page, email 2001.08.20-22 to WJG*

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