THE ADVANCED CARRIER BUNDLE - COMPREHENSIVE IRRADIATION OF MATERIALS IN CANDU POWER REACTORS

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ABSTRACT

The advanced carrier bundle (ACB) provides a means of irradiating specimens of pressure-tube material to high fast-neutron fluences in CANDU[1] *power reactors. This is achieved by removing two fuel elements from the first inner ring of the standard 37-element Bruce-type fuel bundle and replacing them with specimens mounted on a holder. The active samples on their holder will be transferred to a new bundle under water in the irradiated fuel bay, requiring very little handling. The new carrier bundle will then be "back loaded" into the fuelling machine using a specially designed backloader, developed for this program. This provides the capability to recycle radioactive specimens very quickly, and to continue their irradiation with minimal interruption and a quick turn-around. Following irradiation to the desired fluence, the samples will be shipped in a shielded flask to the AECL hot cells for examination and measurement. Initially this program will involve the Ontario Hydro Bruce B reactors.*

INTRODUCTION

Several factors determine the service life of CANDU pressure tubes. These are dimensional changes in the diameter and length of the pressure tubes, the sag of the fuel channel, and the capability of the pressure tube to satisfy the Leak-Before-Break (LBB) criteria.

New pressure tubes satisfy all the dimensional requirements and the LBB criteria. However, changes in the tubes caused by creep and irradiation growth may result in failure to meet the dimensional requirements. Also, as a result of deuterium ingress, changes in the mechanical properties, or any mechanical damage, the probability of LBB can decrease to an unacceptable level. Tubes failing to meet any of the requirements must be replaced, as has been done in Pickering Units 1- 4, or the reactor must be decommissioned as in the case of NPD (1).

The condition of the pressure tubes is monitored by inspection and by surveillence, and periodic replacement of single pressure tubes from "lead" units, with subsequent destructive examination. To develop the capability to predict the service life of the pressure tubes beyond current experience, the CANDU Owners Group (COG) sponsors an extensive research program on the effects of the reactor environment on pressure-tube properties. An important component of this research program is the exposure of test specimens to typical reactor environmental conditions in a series of irradiation experiments. Parametric studies are conducted in the loops in the National Research Universal (NRU) reactor located at AECL's Chalk River Laboratories (CRL). However, these loops operate with some handicaps; a lower fast neutron flux compared to other research reactors, inconsistent water chemistry, and light-water coolant.

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[1] CANDU - CANada Deuterium Uranium is a registered trademark of Atomic Energy of Canada Limited (AECL)

Irradiation damage to pressure-tube specimens can be accelerated relative to power reactors by testing in high fast neuton flux test reactors in the U.S., the Netherlands, and France. Hence, long-term behaviour of the power-reactor tubes can be predicted. Such experiments also have shortcomings. Because they are performed outside Canada, there is little control over escalating costs and general operation, for example, the DIDO reactor in England was recently shutdown. Moreover, there is considerable inconvenience associated with shipping radioactive materials overseas and across international borders. As well, in these offshore experiments, the coolant chemistry and flux spectra may be unrepresentative of CANDU Primary Heat Transport system and reactor neutron fluxes. The use of "carrier bundles" in domestic CANDU power reactors presents a way to avoid most of these disadvantages, albeit at a lower fast flux.

Corrosion and mechanical test specimens have already been irradiated in the Pickering, Bruce, and Point Lepreau reactors inside unfuelled elements of special "carrier" bundles. To date, these have been once-through exposures of small, and initially non-active specimens. Longer irradiations are required for most experiments to achieve measurable deuterium pickup and deformation because these bundles are loaded as new fuel with a limited in-reactor duration. Plans to recycle some of these specimens are limited to using only those with relatively low radio-activity. This means that before recycling, a cooling-off period of about 20 months is required. A much faster turn-around time is necessary to accumulate a higher fast fluence than in the operating power-reactor pressure tubes. This can be achieved using advanced carrier bundles (2).

The ACB provides a means of irradiating specimens of pressure-tube material to high fast-neutron fluences in CANDU power reactors by providing the capability of recycling radioactive specimens and their immediate reloading into the reactor. It can benefit a nuclear station in two ways. First, the ACB can be used as a surveillance tool in which samples of pressure tubes may be irradiated in the reactor to monitor changes in the properties affecting the LBB criteria. Second, the ACB can be used to contribute data to the models used for predicting fuel channel life-limiting properties.

This paper describes the design and testing of the ACB and its benefits. It also briefly describes the ACB fuel-handling system.

THE ADVANCED CARRIER BUNDLE

The ACB provides experimenters with the capability to recycle radioactive specimens from an irradiated ACB into a new ACB, to allow their immediate reloading into the reactor. The design of the bundle was based on removing two elements from the first inner ring of the Bruce standard 37-element fuel bundle, and replacing them with a dogbone-shaped cross section 'sheath' (Figure 1). The new sheath is closed at one end and open at the other, to permit a specimen holder to be inserted. One end plate of the ACB has a dogbone-shaped opening to accommodate the "dogbone" sheath. The specimens are mounted on the specimen holder, forming a specimen assembly that can be locked into the empty bundle, to make up an ACB (Figure 2). The top of the specimen holder is fitted with a locking mechanism to permit fixing the holder into a new ACB. The radioactive specimen-holder assembly can be transferred to a new bundle under water in the irradiated fuel bay (IFB), thereby minimizing handling and allowing a quick turn-around. The new carrier bundle is then "back loaded" into the fuelling machine for recycling into the reactor core.

The dogbone sheath is designed to accommodate different types of specimens assembled on an appropriate holder. Small holes are provided in the dogbone sheath to allow a small constant flow of water over the specimens. The dogbone sheath is designed to minimize neutron absorption and gamma heating while producing a bundle with hydraulic head-loss similar to that of a standard 37-element bundle. The dogbone sheath is also designed to withstand structural loads, particularly short-term loads during refuelling and long-term eccentric loads, for example those occurring if the bundle is resting against the fuel latches. The centre element of the ACB is a Zircaloy solid rod. This eliminates the normal central fuel element as a heat source, and thus will not degrade the normal Critical Channel Power (CCP) and Critical Power Ratio (CPR).

The fuel bundle dimensions are otherwise identical to those of the standard 37-element Bruce-type fuel bundle. This ensures that the bundle will interface with the existing fuel-handling systems and fuel channel components.

Specimens and Specimen Holders

There are 7 different specimen types plus 4 dimensional variants that may be installed into the ACB. The variations are minor dimensional differences in one or more directions. Different types of specimens are confined to a single bundle that can be positioned in the most desirable axial position in the fuel channel to support and complement the pressure tube and fuel channel surveillance programs (1, 2).

The specimen holders secure the specimens within the dogbone sheath. There are 7 different holder types. The overall dimensions of the specimen holders and their connections to the ACB are always the same. Each specimen holder is attached to a lockable insert to form the specimen holder assembly (Figure 3). As the specimen holders accommodate a variety of specimens, the internal details of the specimen holders vary accordingly.

Table 1 tabulates different types of specimens and specimen holders.

DESIGN ANALYSIS

Physics

Physics analyses were carried out to determine the bundle radial power distributions and the effect of the ACBs on the axial power distribution. These were required for thermalhydraulics calculations. The WIMS multigroup lattice-physics computer code (3) was used. The analysis cases consisted of two reference cases and a variety of single parameter changes, for example, depleted uranium in selected fuel elements, and a solid Zircaloy central rod in place of the normal fuel element. Analyses of reference cases were based on a reference bundle power of 800 kW.

Exploratory and sensitivity analyses were carried out until the final arrangement was judged to be satisfactory from both a physics and thermalhydraulics viewpoint. The input for final thermalhydraulics analysis was determined to be the case with 80% homogeneous coolant void. This case was selected because it produced the highest fuel element power at the anticipated dryout location.

Thermalhydraulics

The basic analysis approach was to compare the fuel and channel flow conditions for a fuel string containing two ACBs, to the conditions in the same channel with a normal fuel string (reference channel). The ACB performance was determined for dryout conditions. When dryout occurs in a channel, a rapid increase in void increases channel flow resistance and decreases flow significantly. The channel power at the onset of incipient dryout is defined as the CCP. If the CCP is similar to or higher than that of the reference channel, then the ACBs would impose no operating penalty, and the design would be considered acceptable for operation.

Prior to the CCP analyses, subchannel analyses were performed, using a variant of the ASSERT computer code (4), to investigate the effects of changes in pin power and subchannel flow losses on the Critical Heat Flux (CHF) in the fuel string. The results of the ASSERT analyses were then applied to the channel thermalhydraulics analyses which were done with the NUCIRC (NUclear CIRCuit) computer code (5).

The primary conclusion of the NUCIRC analyses was that the conservative calculations of CCP for a high-power, inner zone channel containing ACBs in their preferred normal operating positions (positions 4 and 5) showed a modest CCP gain. The analyses also showed that if ACBs are placed in the worst possible positions (position 2 and 3) at the downstream end in the fuel string, the CCP variation is of the same order as normal variations of CCP within the zone.

TESTING

To qualify the advanced carrier bundle for use in the Bruce-type nuclear reactors, it was required to test the bundle under representative in-reactor flow and temperature conditions. Hot loop testing was carried out to verify acceptably low pressure-tube fretting by the ACB under such conditions. Tested under full flow and primary-heat transport temperature at the inlet position and in the orientation known to exhibit the worst vibration characteristics, the ACB did not cause fretting greater than a standard 37-element fuel bundle. As confirmed by visual inspection and post-test characterization, the ACB performed without failure or gross geometrical distortion. The ACB maintained full structural integrity.

As part of the qualification testing program for the ACB, axial fatigue tests were required to determine the resistance to end-plate cracking of the ACB's special end plate. Although it is not planned to place the ACBs on the latch, other than during fuelling, the latch position produces the largest fatigue loads on the end-plates of the bundles. Similar tests were long-established to study end-plate fatigue characteristics of standard bundles (6). To simulate such a condition, an Instron machine was used to apply cyclic loads to the bundle. The axial fatigue test of the ACB in the latched condition showed that the properties of the ACB end plate were not significantly altered by the design change from the standard 37-element end plate.

The lockable insert of the Specimen Holder Assembly remained in place and properly locked throughout the tests.

FUEL HANDLING

New ACB fuel bundles are packaged and handled in the same manner as normal fuel. The bundles will be inspected in the new fuel room for spacer interlocking, cleanliness and mechanical integrity according to existing procedures. The specimen holder assembly will then be installed into the ACB fuel "annulus" and proper function of the specimen locking mechanism will be verified.

After their residence time in the reactor core, the irradiated ACBs are discharged into the Irradiated Fuel Bay (IFB) using the standard remote fuel handling system. The irradiated ACB is first transferred normally from the discharge mechanism to the fuel rotator for visual inspection, and then to the Swing Trough (Figure 4) for reorientation to an upright position. While in the upright position, the irradiated Specimen Holder Assembly will be removed and assembled into a new ACB using the ACB bay tools, i.e., a Handling Tool and an Assembly Tool. The Handling Tool is designed to lift and transfer the ACB (in the vertical position) or other components to various locations within the irradiated fuel bay (Figure 5). The Assembly Tool is designed to unlock and remove the specimen assembly from an irradiated ACB and remount it into a new ACB (Figure 6). The irradiated Specimen Holder Assembly can also be assembled into a shipping fixture using the bay tools (Figure 7). The shipping fixture was designed to ship two Specimen Holder Assemblies to the Chalk River Laboratories using AECL's certified shipping flask. The irradiated ACB fuel annulus (without specimens) is stored as conventional spent fuel in accordance with existing procedures.

To return the new ACB (now with an irradiated Specimen Holder Assembly) to the reactor core, one of the IFB discharge mechanisms will have been replaced temporarily by a Back Loading Facility (BLF). The ACB is first reoriented to the horizontal, then is returned to the fuel rotator for visual inspection using standard site tools. From the rotator the ACB is placed onto the BLF which inserts the ACB into the fuelling machine. A final diametral check is carried out on the bundle simultaneously with back-loading into the fuelling machine.

DISCUSSION

The ACB as a Surveillance Tool

To ensure the LBB criteria for the pressure tubes is maintained, a fuel channel Periodic Inspection Program (PIP) is mandated by the CAN/CSA-N285.4-94 Standard. This Standard requires monitoring changes in hydrogen isotope concentration, fracture toughness, and Delayed Hydride Cracking (DHC) velocity. Scrape sampling provides a means of monitoring changes in the hydrogen isotope concentration in a non-destructive manner. However, monitoring changes in the fracture toughness and DHC velocity requires the periodic removal and destructive examination of a surveillance tube. The removal of a surveillance tube is an expensive operation, requiring a reactor outage. ACBs could provide the first practical alternative to the periodic removal of a surveillance tube to monitor fracture toughness and DHC velocity. The ACBs would be used to continue the irradiation of specimens made from a removed surveillance tube. Morover, ACBs could be used to monitor changes in the fracture toughness and DHC velocity without the need of a reactor shutdown.

The ACBs also provide a 1.4 times high fast flux (<1MeV) enhancement, thereby providing fracture toughness and DHC velocity data in advance of the in-service pressure tubes (Figure 8). In this way, the station can continue to be assured of the continued integrity of the pressure tubes in the core of the reactor.

The ACBs Contribution to Predictive Models

The CANDU Owners Group (COG) sponsors programs to assess potential life-limiting factors for pressure tubes, three of these being: Corrosion and Deuterium Ingress, DHC and Fracture, and Radiation Damage and Deformation. The ACBs can be used to contribute data for all three programs. This data has a direct link to the LBB and dimensional criteria that define part of the acceptability of the tubes for continued service.

For the Corrosion program, ACBs allow testing and investigation of material and operational parameters under the exact operating conditions of a specific CANDU reactor. The following four types of testing can be conducted:

i) Monitoring the water side detuterium pick-up rates for comparison with scrape sample data.
ii) Establishing the long term effects of irradiation on the microstructure, thereby determining the various corrosion properties of the tube. This type of information will improve the predictive models for the tubes.
iii) Establishing the temperature dependence for various parameters in the predictive models by comparing data from ACB irradiations at the cooler inlet end of a channel versus data from the hotter outlet end.
iv) Optimizing the water chemistry conditions within the acceptable water chemistry specification. This could be carried out in an instrumented fuel channel in Bruce-B, Unit 6 where the water chemistry can be monitored. The results of this program would help to minimize the deuterium pick-up rates and therefore maximize the service life of the pressure tubes.

The objectives of the DHC and Fracture program are to demonstrate that the integrity of pressure tubes will be maintained over their design life. The current predictive models are based on data from specimens that have a fluence less than that of the lead CANDU reactor. To improve the predictive models, data from specimens with a fluence higher than the lead reactor are required. ACBs can be used to irradiate specimens from the previously removed surveillance tubes to attain fluences greater than the lead reactor. The ACB would supplement results from specimens with an end-of-life fluence that will become available for testing from high flux test reactors at approximately 2003.

The advantage to the stations, particularly Bruce, will be confirmation that further irradiation is not compromising reducing the LBB criteria. Moreover, ACB irradiations will help to provide the relevant data for the analysis of any flaws for specific Bruce-B pressure tube flaws or the generic safety case for the pressure tubes.

The objective of the Deformation program is to characterize the dimensional changes of the pressure tube and the fuel channel over the service lifetime. There are three parts to achieving this objective:

i) An experimental testing program to establish the irradiation creep and growth rates under the range of stress, temperature, and fast flux that envelopess the conditions in CANDU reactors.
ii) To establish the underlying displacement damage mechanisms that result in microstructural and microchemical evolution during irradiation.
iii) To develop and refine predictive models correlating the underlying displacement damage mechanisms to the observed data from the experimatal testing program.

For most of the deformation assessments, the ACBs provides a suitable test environment with a 1.4 times fast flux enhancement over the in-service pressure tubes, and at a cost advantage over specialist test reactors.

CONCLUSIONS

The advanced carrier bundle, and its associated under-water handling tools, are designed to provide a means of irradiating specimens of pressure-tube material to high fast neutron fluences in standard CANDU power reactors. The ACB program offers two key benefits to the CANDU reactors. First, ACBs can be used as a surveillance tool to offset or complement pressure tube surveillance requirements mandated in CAN/CSA-N285.4-94. Second, we believe this will be cost effective way to improve the predictive models used to assess when a reactor's pressure tubes are approaching end-of-life.

The design of the ACB has been completed, and comprehensive design reviews are being carried out, with licensing applications to be made soon. The design is the result of over two years design, analysis and development work involving several groups at AECL, Ontario Hydro and Zircatec Precision Industries.

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HOLDER Type	SPECIMEN Type
A	Curved Compact Fracture (two sizes)
B	Tensile & Cantilever Beam
C	Corrosion (Thin type only)
D	Transverse and/or Longitudinal Growth
E	Transverse and Longitudinal Stress Relaxation
F	Bulk Specimen
I	Tensile

TABLE 1: SPECIMENS AND SPECIMEN HOLDERS

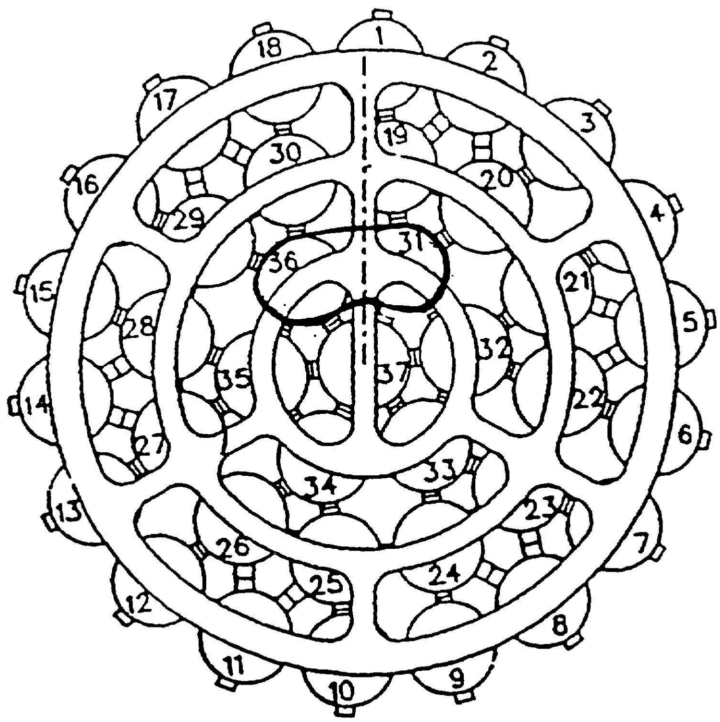

FIGURE 1: THE ADVANCED CARRIER BUNDLE

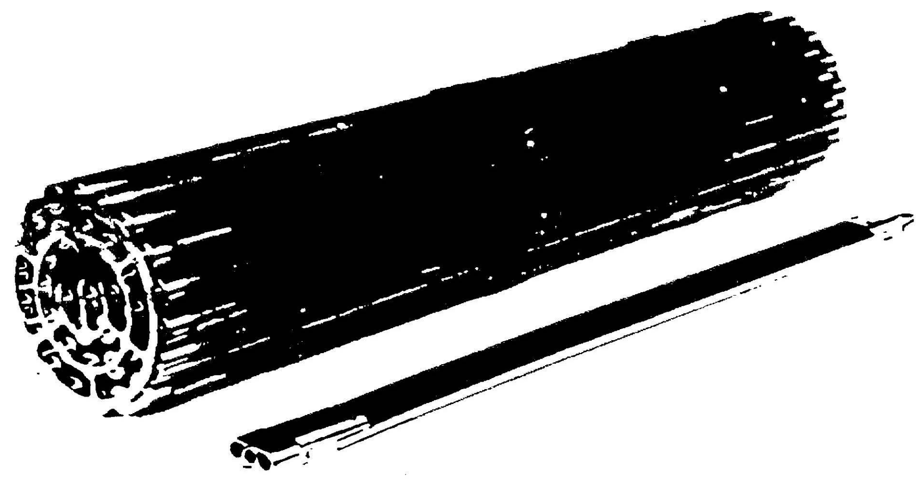

FIGURE 2: THE FUEL ANNULUS AND SPECIMEN HOLDER ASSEMBLY

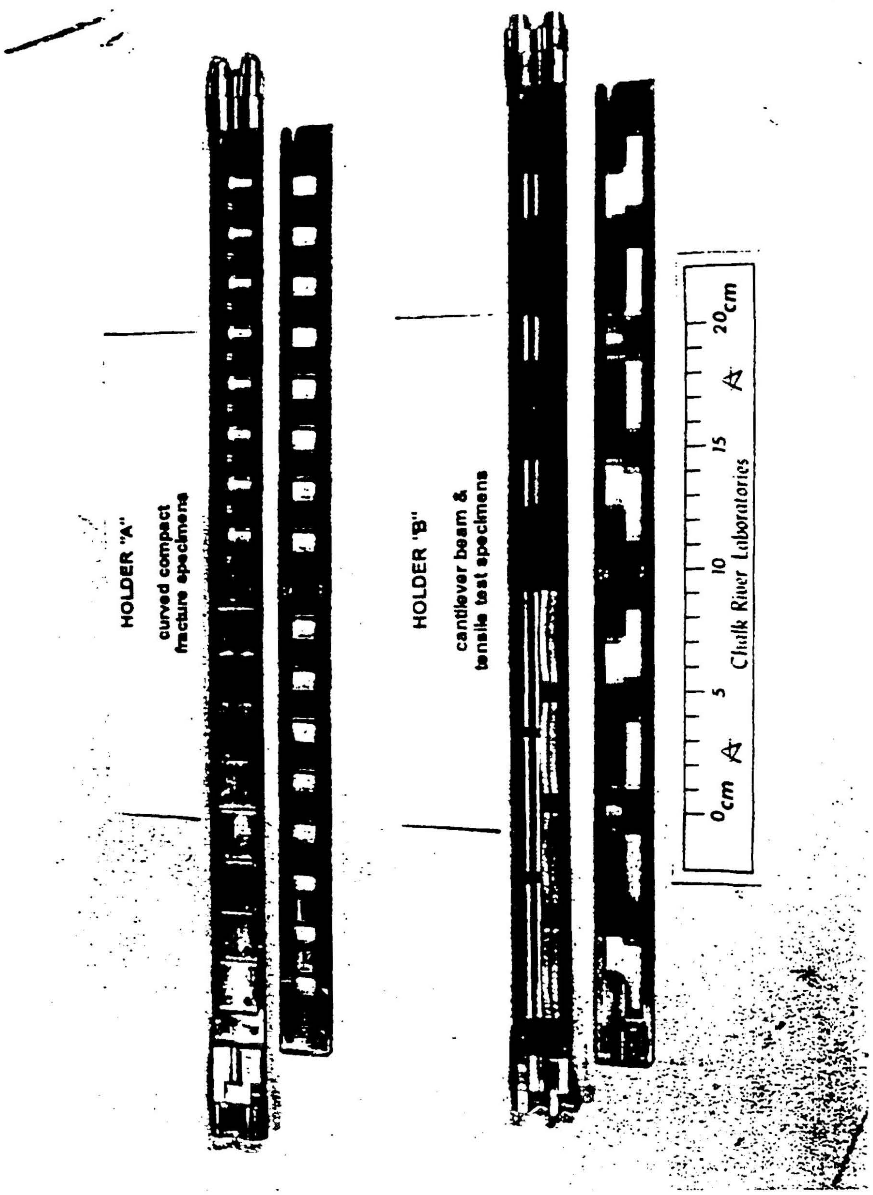

FIGURE 3: TYPICAL SPECIMEN HOLDER ASSEMBLY & SPECIMENS

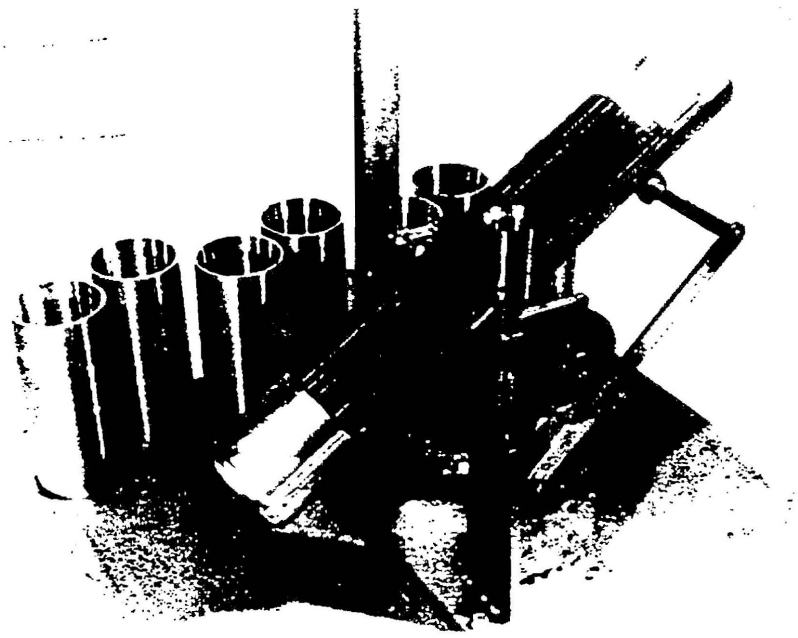

FIGURE 4: SWING TROUGH

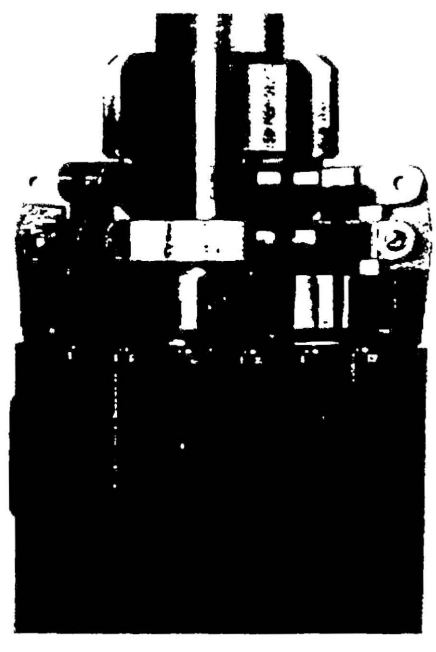

FIGURE 5: HANDLING TOOL

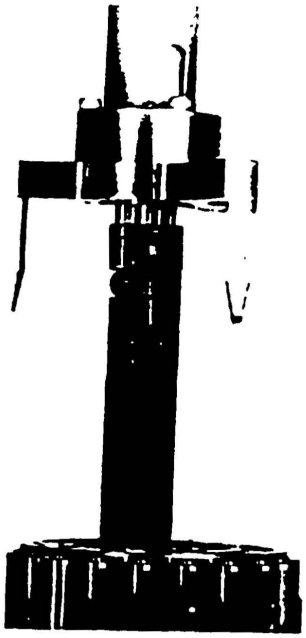

FIGURE 6: ASSEMBLY TOOL

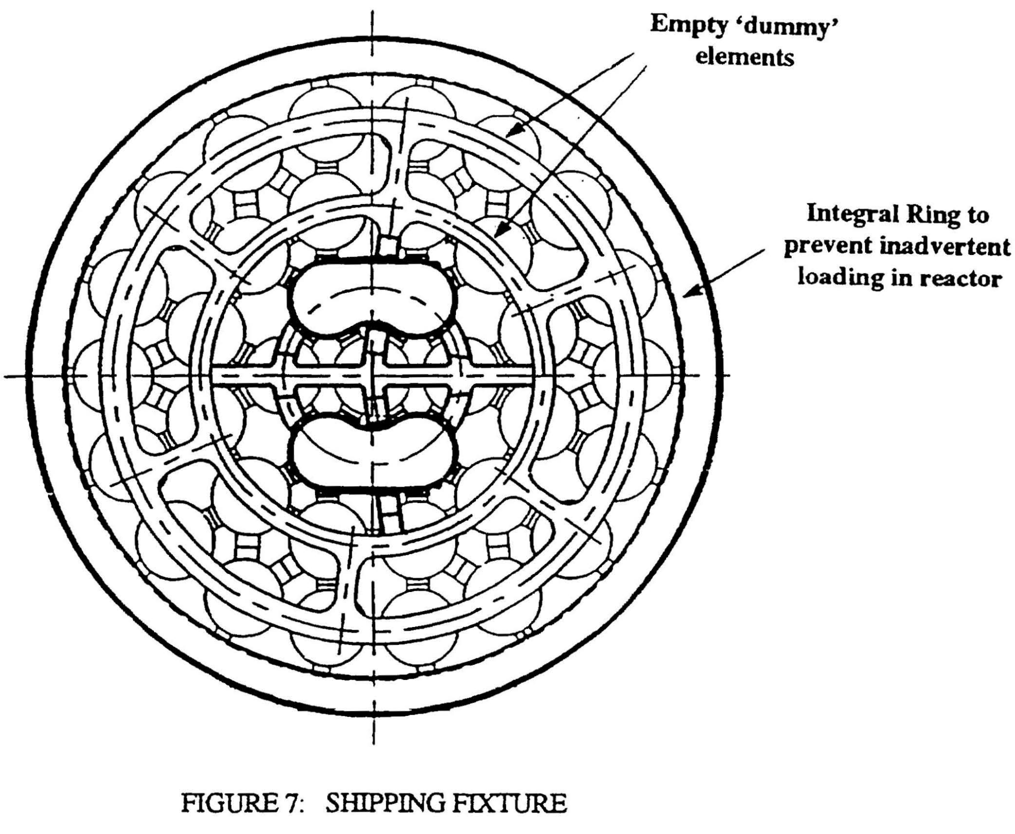

FIGURE 7: SHIPPING FIXTURE

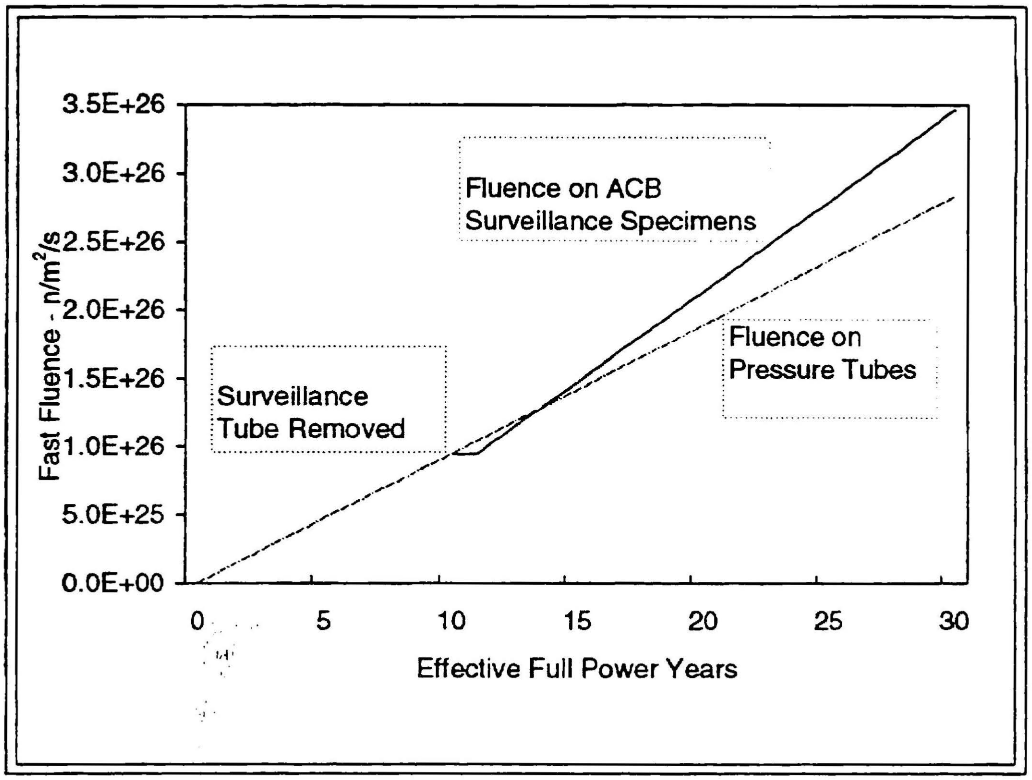

FIGURE 8: TYPICAL FLUENCE ACCUMULATION:
PRESSURE TUBES AND ACB SURVEILLANCE SPECIMENS