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DRY ROD CONSOLIDATION TECHNOLOGY PROJECT RESULTS

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ABSTRACT

The Dry Rod Consolidation Technology (DRCT) Project conducted at the Idaho National Engineering Laboratory (INEL) in 1987 demonstrated the technical feasibility of a dry horizontal fuel rod consolidation process. Fuel rods from Westinghouse 15 x 15 pressurized water reactor (PWR) spent fuel assemblies were consolidated into canisters to achieve a 2:1 volume reduction ratio. The consolidation equipment was operated at an existing hot cell complex at the INEL. The equipment was specifically designed to interface with the existing facility fuel handling and operational capabilities and was instrumented to provide data collection for process technology research. During the operational phase, data were collected from observation of the consolidation process, fuel assembly handling, and fuel rod behavior and characteristics. Equipment performance was recorded and data measurements were compiled on crud and contamination generated and spread. Fuel assembly skeletons [non-fuel bearing components (NFBC)] were gamma scanned and analyzed for isotopic content and profile. The above data collection was enhanced by extensive photograph and video documentation. The loaded consolidation fuel canisters were utilized for a test of the Transnuclear, Inc. TN-24P dry storage cask with consolidated fuel. The NFBC material was stored for a future volume reduction demonstration project.

INTRODUCTION

EG&G Idaho, Inc., prime contractor for the U.S. Department of Energy (DOE) Idaho Operations Office at the INEL participated in a spent fuel consolidation project administered by the DOE Office of Civilian Radioactive Waste Management (OCRWM). The project, authorized under the Nuclear Waste Policy Act of 1982, has contributed technology in the demonstration of methods for disposal of spent fuel.

The DRCT Project accomplishments consisted of (1) demonstrating a horizontal dry consolidation system that provided consolidated spent fuel

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canisters for a spent fuel dry storage cask test, (2) obtaining hot consolidation experimental and remote operational experience data to be used in the development of production-scale dry consolidation equipment, and (3) collecting data technology. Such data will contribute to NRC licensing of consolidated spent fuel storage cask and be utilized by other OCRWM programs, such as the prototypical consolidation demonstration program (PCDP), Monitored Retrievable Storage (MRS), and the repository programs.

The DRCT project consolidated fuel rods from 48 Westinghouse 15 x 15 PWR spent fuel assemblies into 24 fuel consolidation canisters. This paper presents the significant operational and technological results acquired during the DRCT Project and includes descriptions of the dry horizontal consolidation process, existing facilities and fuel handling equipment capabilities relative to consolidation, fuel characteristics, observations made, general data results, and recommendations for future dry consolidation projects.

FACILITY DESCRIPTION

The DRCT equipment was developed at the INEL for remote operation in an existing hot cell complex located at the INEL Test Area North (TAN) facility. The complex consists of a large hot shop (53 m long, 16 m wide, and 22 m high) and an adjoining hot cell (11 m long, 3 m wide, and 6 m high). The hot shop is equipped with remote handling equipment consisting of three wall-mounted Par 3000 and one overhead bridge-mounted Par 7000 electromechanical manipulators which traverse the entire shop. A 91/9 metric ton radio-controlled overhead bridge crane provides remote handling of heavy spent fuel storage casks and facilitates spent fuel handling using a specially designed fuel assembly grapple. The hot shop is a negative air pressure hot cell and is equipped with remote TV, periscopes and shield windows for viewing, radiation monitoring instrumentation, temporary spent fuel storage and cask storage operating equipment, and other standard hot cell systems. Fig. 1 shows the floor plan of the hot shop and hot cell layout.

The TAN hot cell (THC), adjacent to the hot shop, contained the DRCT equipment. A hot cell transporter system is used to transfer irradiated material between the two facilities. The THC remote handling equipment consists of two overhead bridge mounted Par 3000 electromechanical manipulators with 1.7 metric ton chain hoists. Five shield windows provide direct viewing into the THC. Each window station provides two masterslave manipulators for detail remote handling of components and systems. Special tasking light and two periscopes complemented operational viewing and provided magnification for research photographs. Direct viewing of the consolidation equipment operation was also supplemented with in-cell video and periscope-mounted closed circuit TV cameras used on an as-needed basis.

CONSOLIDATION EQUIPMENT DESCRIPTION

The consolidation process and special fuel handling equipment was designed to integrate with the existing TAN facility remote handling capabilities and configurations. The process equipment was specifically configured to allow maximum visibility for research observation of fuel assembly and rod behavior characteristics. The hardware was developed to meet the following basic functional requirements: (1) consolidate one fuel type (Westinghouse PWR 15 x 15), (2) operate for a specific time (5 months), (3) consolidate one fuel rod at a time from 48 fuel assemblies, (4) achieve a 2:1 rod consolidation ratio [in a 21.25 cm (8.5 x 8.5 in.) outside dimension square canister], and (5) be radiation hardened (dose 10^8 Rads) where feasible. The equipment was designed where practicable for remote maintenance by use of existing remote handling equipment and removable component modules. However, because of the research nature of the equipment and limited operational period the equipment was not completely remotely maintainable. In general the equipment performed successfully and allowed accomplishing all project objectives with only minor component and operation problems. For the most part maintenance and operating problems were correctable by remote means. Equipment related problems are described later under recommendations and conclusions.

The satisfactory performance of the equipment is attributed to (1) the extensive cold testing and modification work performed during the fabrication phase and (2) operator training and continuous technical engineering support during the hot operation phase.

Several existing and new equipment fuel handling items were utilized for the transfer of spent fuel assemblies, consolidation canisters, and non-fuel bearing components (skeletons) to and from cask/silo storage within the hot cell complex. Fig. 2. shows a dual cask work platform inside the hot shop with a fuel assembly being remotely removed from a storage cask.

Existing equipment used to support DRCT handling requirements consisted of a storage cask hoisting yoke used for lifting the storage casks, cask lid lifting fixtures required for lid removal, a PWR 15 x 15 fuel grapple modified for hot cell spent fuel assembly and consolidation canister handling, and remote TV systems for operator viewing support. Other minor cask operational equipment was also used as required for routine fuel assembly transfer to support the consolidation process. Approximately 250 fuel assembly and skeleton transfers were successfully performed in the hot shop and hot cell without mishap.

A strongback carrier was provided to support and retain the fuel assemblies and consolidation canister in the vertical and horizontal positions. Horizontal orientation was required to allow loading the fuel into the hot cell for consolidation. The carrier is top-loaded in the vertical position and unloaded in the horizontal position by removing the entire cover lid. A radio-controlled pneumatically actuated lift bail attached to the hot shop 9-(metric) ton crane remotely engages lifting points on the strongback carrier to lift and position the carrier onto or remove it from the hot shop-to-hot cell transporter. The lift bail system rotated the carrier in midair as shown in Fig. 3 (rather than utilizing a down end fixture). Two carriers were provided to improve the efficiency of fuel transfer.

Inside the hot cell the strongback carrier cover was removed using an in-cell horizontal lift fixture (Fig. 4) that was specially designed to be used to perform all fuel assembly, skeleton, canister, and strongback cover lifting. The design included seven sets (2 each) of two pneumatically actuated rotating lifting legs that precisely engaged at mating points on the strongback carrier cover, fuel assembly and skeleton spacer grids, and consolidation canister strongback support. The fixture was supported and positioned by an existing overhead bridge-mounted chain hoist.

The DRCT consolidation process machine shown in Fig. 5 and installed in the hot cell (Figs. 6 and 7) was designed, fabricated, and tested at the INEL. The machine processes were semiautomatic computer-controlled with software-directed hold points for operator intervention for fuel handling, tool changeout, and process control steps. A manual override function was provided to allow operator control for off-normal condition recovery. All control functions were located on a pedestal-mounted cabinet attached by pigtail wire to electrical power computer cabinet.

The equipment hardware consisted of several systems and components. A docking system accepted the strongback carrier and lifted it from the hot cell transporter so that the transporter could be returned to the hot shop. A fuel assembly support frame locked and positioned the fuel assembly in preparation for end box removal. A computer controlled (X-Y-Z coordinates) multi-tool head containing either a pneumatically driven drill bit to drill out the center instrument guide tube of the top end box orifice to allow clearance for guide tube cutting or a multi-revolution titanium-coated internal tube cutter.

The end box puller is an electromechanical chain drive mechanism with alignment guides for positioning the fuel assembly end box into the puller. After guide tube cutting is complete, the end box puller is used to exert sufficient force to separate any guide tubes that are not completely cut. The puller mechanism indexes to a home position, allowing clearance for the rod gripper to index onto the fuel rods.

The rod gripper (Fig. 8) is a pneumatically operated two-jaw gripper with three positions for indexing onto the fuel rod, gripping the fuel rod, and releasing the fuel rod. The gripper assembly is X-Y-Z positioned by computer control and has rod pulling force overload capabilities. The gripper pulls one rod at a time onto seven pair of rod placement fingers. The fingers attached to the Z-axis support beam exactly position the fuel rod into a predetermined position in the consolidation canister base. One full rod pulling/placement cycle requires approximately 47 seconds to complete.

The consolidation canister, Fig. 9, was specifically designed to allow ready observation of the fuel rod pulling and canister loading. This provides direct viewing of fuel rod behavior. The canister provides for a rod packing volume reduction of slightly greater than a 2:1 ratio.

The canister is designed to interface with a Westinghouse PWR 15 x 15 fuel grapple and has outside dimensions of 4.3 m long and 21.25 cm square. The canister base includes sheet metal ridges positioned to accurately place the first row of rods to start the rod stack array. The lid is fastened to the base by a series of slots and screws. To replace the canister lid onto the base the lid was installed onto the canister closure assembly, lowered over the rod stack, and mechanically engaged on the screw heads of the base.

A total of 48 Westinghouse PWR 15 x 15 fuel assemblies were consolidated into 24 canisters. Thirty-six of the assemblies were from the Virginia Power Company Surry Power Plant and 12 were from the Florida Power and Light Turkey Point 3 Power Plant. The fuel was available at the TAN hot cell facility having been used in the cask testing program and shipped from the Engine Maintenance and Disassembly (E-MAD) Nevada Test Site Facility where it had been utilized in dry storage examinations. Both reactor fuels have an average burnup range of 25,000 to 35,000 MW/MTU and were characterized from previous research projects. Fuel assembly grouping for consolidation was based on thermal output of the assemblies to balance the heat loads to satisfy the consolidated fuel cask test requirements.

Fig. 10 illustrates the major design features of the Westinghouse fuel assembly.

PROCESS DESCRIPTION

The consolidation process sequence starts with transferring spent fuel from storage locations in the hot shop to the consolidation machine in the hot cell. This is accomplished by use of remote fuel handling equipment. The fuel storage casks or storage silo within the hot shop are prepared for lid removal by sampling the inert cover gas, to verify whether fission product gases, if present, are within acceptable limits and to equalize cask pressure with atmosphere. Cask lid retaining bolts are removed and all remote handling equipment, i.e., lid lift fixtures, fuel grapples, cranes, TV systems, strongback carrier, hot cell transport, etc., are operational. Remote fuel transfer starts as the cask lid is removed. The grapple is connected to a predetermined fuel assembly and removed from the storage cask and top-loaded into the vertically positioned strongback carrier. This step is repeated for a second fuel assembly and an empty consolidation canister. The fuel grapple is replaced onto a support stand, and the crane is used to replace the cask lid on the cask. The strongback carrier lift bail is then connected to the strongback carrier and the carrier is lifted and rotated 90 degrees clockwise and to the horizontal position and placed on the horizontal transporter. The lift bail is disconnected and placed onto a support stand. The carrier is then moved into the hot cell and docking equipment. The docking system lifts the carrier a few inches, thereby freeing the transporter to be removed back into the hot shop. The hot cell shield doors are closed allowing manned entry into the hot shop for replacement of storage cask lid bolts and fuel cask cover gas.

Work proceeds in the hot cell by using the in-cell lift fixture to remove the strongback carrier cover, exposing the two fuel assemblies and empty canister. The canister is moved to the canister loading station and the lid removed. The first fuel assembly is placed onto the fuel support frame and locked into position ready, for end box removal.

The top end box is removed by using an internal tube cutter; each guide tube is cut one at a time. The center instrument tube top end box orifice diameter must be increased to allow the tube cutter to enter. This is accomplished by drilling. With the guide tubes cut, the end box is removed to expose the ends of the fuel rod. The guide tubes are cut slightly above the top grid spacer and below the tops of the fuel rods. This provides clearance for the finger type gripper to attach around those rods located next to the guide tubes. The gripper indexes onto the fuel rods one at a time in a lateral forward motion and is stopped when an actuater plunger internal to the gripper finger contacts the fuel rod end cap. This design successfully sensed the rod length variations that were encountered. See Fig. 11. The gripper finger then clamps around the rod and extracts the rod from the skeleton onto seven pairs of placement fingers. The pull/placement assembly then indexes the fuel rod to place it in the canister. This is repeated 204 times to pull all the fuel rods in the assembly. The fuel assembly skeleton is then removed from the fuel assembly support frame and the second fuel assembly is placed and locked into position. The above steps to cut guide tubes, remove end box, and pull rods are repeated for the second assembly.

At the completion of the second assembly rod pulling the skeleton is placed onto the strongback carrier, removed to the hot shop, transferred to the water pit and placed into a skeleton storage basket for temporary storage. The consolidation canister lid is installed over the rod stack and locked onto the canister base. The canister is then removed from the canister loading assembly and, via the in-cell lift fixture, strongback carrier, and hot cell transporter, is moved to the hot shop and rotated to the vertical position and placed onto a support stand. The storage cask lid is removed and, using the fuel grapple, the canister is transferred to the cask. Two strongback carriers were provided to aid production and speed up fuel transfers between the hot shop and hot cell by allowing fuel handling in both the hot shop and hot cell at the same time.

The operations described above were the major elements making up a consolidation cycle and were repeated 24 times to consolidate 48 fuel assemblies into 24 canisters.

At the conclusion of the operations the consolidation equipment was decontaminated remotely to allow limited hand contact for disassembly. The equipment was subsequently disposed of as contaminated waste.

TECHNOLOGY DATA COLLECTION

Throughout the consolidation process, data were obtained to quantify various parameters of interest and applicability to other consolidation projects. Written logs were maintained by operating personnel to record observations made; still photographs and video tape recordings were made of the consolidation process and events of special interest. Measured data also included: (a) the force required to pull the rods from the assembly; (b) fuel rod diameters; (c) weight, gross volumes, and gross radiation of cutting and drilling chips from the endbox removal operation; (d) weight, gross volume, gross radiation, and elemental analysis for the material (crud) scraped off the fuel rods as they were pulled from the assembly; (e) general contamination levels in the hot cell and on the DRCT; and (f) airborne contamination levels (average) during a complete cycle. Selected fuel assembly skeletons were also subjected to a gamma scan and material samples were taken from various locations on the skeleton. Evaluation of these data using gamma spectroscopy for ^{60}Co, ^{94}Nb, ^{54}Mn and ^{137}Cs; alpha spectroscopy for ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Am, ^{242}Cm and ^{244}Cm; beta spectroscopy for ^{90}Sr; neutron activivation analysis for ^{129}I; and gross and spectral gamma scanning the fuel assembly skeleton hardware was performed to assist in waste classification under the Code of Federal Regulations, 10 CFR 61. Such information will be useful in determining skeleton disposal options.

A summary of specific data collected, evaluated, and analyzed includes the following:

1. Pulling forces required to remove the fuel rods from the fuel assemblies were measured. These forces are measured as rods are pulled from the fuel assembly. The measurement accuracy is ± 1.13 kgf (2.5 lbf), and the resolution on the measurement system is 0.45 kgf (1 lbf). Data include the initial breakaway force and continuous pulling forces measured until the rod is free of the fuel assembly. Table I presents a brief summary of the results.

TABLE I. PRELIMINARY ROD PULLING FORCES AND DIAMETERS

	Average	Maximum	Minimum
Rod pulling force in kgf (lbf)			
Breakaway force	18.8 (41.4)	35.8 (78.9)	8.2 (18.1)
Continuous pulling force	11.5 (25.4)	17.0 (37.0)	6.9 (15.2)
Rod diameter in mm (mils)[a]	10.67 (420)	10.72 (422)	10.63 (418.5)

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[a] Turkey Point and Surry as-fabricated fuel rod diameter = 10.72 ± 0.025 mm (422 ± 1 mils).

2. Fuel diameters of selected rods were measured from all fuel assemblies consolidated. The diameters are measured on two axes as the rods are pulled from the fuel assemblies. A special measurement system was fabricated to remotely and automatically make these measurements while operating in high radiation fields over an extended period of time (5 months). Accuracy of the diameter measurement system is better than ± 2.54 E-2 mm (1 mil), and the resolution is 2.54 E-3 mm (0.1 mil). Table I also presents a brief summary of results.

3. Crud spalling samples from the rods were collected during consolidation. Crud samples were collected after each consolidation of fuel rods from two fuel assemblies (408 rods). As shown in Fig. 12, a vacuum system was used to collect the crud that fell from the rods into a tray under the fuel assembly. Tables II, III, IV, and V present average weight, gross radiation level, and elemental and radiochemical analyses data from the crud samples.

4. Small zircaloy and stainless steel particles from the cutting of zircaloy guide tubes, end box center hole drilling, and consolidation of fuel rods were collected. Since zircaloy is pyrophoric, the small particles generated during consolidation constitute a potential fire hazard. Technicians observed an occasional small puff of smoke or dust appearing to come from the fuel rods as they were pulled through the spacer grids. However, no zircaloy fire was observed during rod pulling or guide tube cutting. Table II presents the results of weight and radiation measurements from samples of zircaloy and stainless steel particles collected by the vacuum system.

5. Gamma scanning of an intact fuel assembly and fuel assembly skeleton (after fuel rod removal) was performed. Gamma activities of fuel assembly skeletons and hardware are important to determine the waste classification of the fuel assembly skeletons. Fig. 13 shows gamma scans for a fuel assembly and its skeleton after fuel rods have been removed. In conjunction with the gamma scanning, material samples were taken from selected skeletons scanned. These samples are being analyzed for isotopic and elemental content, and the preliminary results are provided in Table III.

TABLE II. PRELIMINARY DATA FOR SAMPLE WEIGHTS AND RADIATION LEVELS

	Crud Sample Weight (grams)		
	Average	Maximum	Minimum
Weight per sample (crud from two fuel assemblies, 24 samples total)	1.05	5.19	0.06
Radiation level (R/hr) (crud from two fuel assemblies, 23 samples total)	0.647	2.5	0.05

TABLE III. PRELIMINARY DATA FOR CRUD ELEMENT ANALYSIS OF FUEL ASSEMBLIES

	Element Analysis (weight %)				
Fuel Assemblies	Sn	Zr	Nb	Cu	U
Turkey Point four assemblies (average)	0.335	31	0.045	0.105	<0.6
Surry four assemblies (average)	0.120	14.2	0.03	0.12	<0.15
	Fe	Co	Mn	Cr	Ni
Turkey Point four assemblies (average)	16	0.025	0.41	5.2	3.05
Surry four assemblies (average)	5.6	0.04	0.120	0.675	0.425

TABLE IV. PRELIMINARY DATA FOR CRUD SAMPLE WEIGHT AND RADIOCHEMICAL ANALYSIS OF FUEL ASSEMBLIES

	Radiochemical Analysis of Crud Samples (μCi/mg)				
Fuel Assemblies	Weight (grams)	^{3}H	^{90}Sr	^{129}I	^{14}C
Turkey Point four assemblies (average)	1.079	1.8 E-2	1.705 E-3	7.2 E-9	7.83 E-5
Surry, four assemblies (average)	2.371	1.72 E-3	5.33 E-4	9.3 E-9	1.81 E-5

	^{54}Mn	^{60}Co	^{94}Nb	^{125}So	^{137}Cs
Turkey Point four assemblies (average)	5.35 E-4	5.6 E-1	3.5 E-4	5.15 E-2	3.95 E-3
Surry, four assemblies (average)	1.3 E-4	1.09 E-1	1.15 E-4	2.6 E-2	3.35 E-4

TABLE V. PRELIMINARY DATA FOR ZIRCONIUM AND STAINLESS STEEL CHIPS AND FINES

	Sample Weight (grams)		
	Average	Maximum	Minimum
Weight per sample (two assemblies per sample, 22 samples)	7.31	13.2	1.33
Radiation level per sample (R/hr), 22 samples	2.39	20	0.05

6. A significant number of other data were collected. Airborne particulates were collected using a filter system installed in the hot cell at selected locations. Fall-out samples around the consolidation equipment were also collected. In-cell smears were taken at several locations to study contamination levels during consolidation. Smears were also taken on the surfaces of one fuel assembly prior to consolidation. The airborne particulate, fall-out, and smear samples were measured for gross and isotopic radiation levels. Cumulative radiation dose detectors were placed around and near critical machine components to measure the radiation dose. The hot cell gases exhausted through the ventilation system were continuously monitored for fission product emissions. No fission gas release was detected, indicating that no fuel cladding failed during the consolidation process. Small quantities of a radioactive gas were initially released in the hot cell to determine in-cell air flow transit times. The in-cell temperature was measured periodically.

RESULTS AND OBSERVATIONS

In general, the equipment successfully performed the intended operations. Numerous minor problems were encountered during early cold (nonradioactive) testing of mockup fuel assemblies, but these were resolved without major changes to the equipment. The most significant changes made as a result of cold testing included cutter blade geometry changes to improve cutter life, a canister modification to address lid installation problems, and several instances in which pneumatic cylinder sizes were increased to provide more force. Numerous changes were also made in the computer control system software.

The objective of providing consolidated fuel for storage cask testing was clearly accomplished. The perfectly stacked fuel rod arrays achieved in the consolidated canisters met the 2:1 consolidation ratio desired for testing a storage cask with consolidated fuel.

The second objective was to obtain experience and information that could be used in developing prototype production-scale dry consolidation equipment. This objective was also met very well within the obvious constraints of the limited variation among fuel assemblies processed. As noted earlier, the fuel was all of a single design and was selected on the basis of apparent good condition. The observations and test data evaluation results are unique to this fuel and this process; application of these results to other projects must be qualified with the recognition that other fuel designs or fuel with different burnup or crud characteristics could behave differently.

An important part of the information obtained was derived from off-normal events. The more significant of these events are described in the following paragraphs.

The fuel rods were flexible and also tolerant of limited mishandling. On a few occasions, the end of a fuel rod was pushed back into the fuel assembly because the gripper head was not accurately aligned as it moved to engage the fuel rod. The fuel rod was already positioned against the bottom end fitting of the fuel assembly and therefore reacted to the load through column buckling. Lateral rod displacements of about 4 cm were observed between spacer grids and yet the rods were apparently undamaged. The flexibility was also exhibited in the ease with which a perfect stacking array was maintained. Although some of the rods were somewhat bowed as observed in the fuel assembly, their weight and flexibility were adequate to hold them in place in the consolidated stack.

Equipment breakdowns occurred with several components. The inconvenience in making repairs, especially in the hot cell when fuel had to be removed to allow personnel entry, emphasized the need for modular replacement capability for production equipment. Quick subassembly replacement and off-line repair will be necessary if high throughput is to be economically achieved. Specific breakdowns included two failures in the radio receiver mounted on the carrier/strongback lifting bail and failures in carriage position sensors on the DRCT machine. Preliminary investigation indicates that the receiver failure was caused by a supply voltage surge. The cause of the position sensor failure is not yet known. None of the equipment was radiation-hardened, although some radiation hardening consideration was given to material selection if other operational features were not impacted. This philosophy was consistent with overall program objectives of single mission use.

As rods were removed from certain fuel assemblies, the unrestrained (top) end of the assembly tended to twist and lift off the support frame. This resulted in a mislocation of the fuel rods, and the automatic positioning system designed to grip the rod at a predetermined position had to be overridden and the gripper head positioned through manual input into the control system. One of the in-cell manipulators was used to bear down on the fuel assembly at the upper spacer grid and was usually effective in holding the top end of the assembly on the docking system table; however, even with this supplemental clamping, some of the fuel assemblies required manual alignment of the gripper head. This was apparently due to minor differences in the irradiated fuel assemblies or to excessive slack in the fuel clamping system or to system wear. These observations identify the need for effective restraint of the top end of the fuel assembly and for a method of referencing the carriage positioning coordinate system to the specific assembly being consolidated.

End box removal by internal cutting of the guide tubes was difficult, and nearly all assemblies had some tubes that were not cut completely through the wall. This required additional cuts on selected guide tubes, high forces to pull the end box and break the partially cut tubes, and, in some cases, use of a remote manipulator to twist the endbox and fatigue a few of the partially cut tubes. Limited visibility into the center of the fuel assembly made it impossible to determine if all guide tubes were completely cut. Since the end box puller system did not include an indication of applied load, the drive chain was damaged when it was subjected to an excessive load while removing an end box still partially attached to the rest of the assembly. An important lesson learned through this experience is that cold testing of very representative mockup fuel is important in preventing unforeseen machine and fuel assembly behavior. The fuel assembly drawings used during the design of tube cutting equipment did not provide sufficient detail of the tube configuration. Cold testing, also based on assembly drawings and as fabricated mockups, therefore did not assess equipment performance under completely representative conditions for irradiated fuel assemblies.

Installing the lid on the fuel canister was sometimes difficult, but this was a result of a research-oriented canister design. The canister was designed to provide maximum fuel stack visibility from outside the cell, and consequently compromises were made with regard to convenience in attaching the lid.

As an experiment to assess feasibility of alternate end box removal methods, the guide tubes on the last fuel assembly were cut below the top spacer grid instead of between the top spacer grid and the top end box. The guide tubes were cut in essentially the same manner as at the original location but with a cutter designed to extend farther into the guide tubes. As had been expected, some of the rods moved with the spacer grid and end box (still solidly linked together by the guide tubes spanning between them) as they were pulled away from the fuel assembly. Three of the fuel rods were pushed back into the fuel assembly with a manipulator and prying tool when the end box was partially removed. Fortunately, the rods moving with the spacer grid were all located in an outer row of the fuel assembly and were restrained from further movement by inserting wooden wedges between them and adjacent rods near the bottom end of the fuel assembly. The endbox and spacer grid were then pulled from the fuel assembly. About seven fuel rods were pulled 6 to 15 mm out of the fuel assembly as removal of the end box and spacer grid was completed; the others remained in place.

The DRCT machine had originally been designed to operate in the above manner. A comb system was included in the equipment design and was intended to be inserted through the fuel assembly to maintain the fuel rods in their original positions in the absence of the top spacer grid. Such positioning was essential to automatic operation of the gripper assembly during rod pulling. Considerable difficulty was experienced in forcing the comb system through the fuel assembly, although no obstructions were noted. Apparently, the friction between the fuel rods and comb fingers was high enough to cause the air cylinder to stall. Repeated attempts at comb insertion, limited movement of individual rod ends with a manipulator, and added force pushing the comb into place (supplied through a manipulator) finally achieved proper insertion. Rod pulling then proceeded in the normal manner.

Rod pulling forces ranged between 8.2 kgf (18.1 lbf) and 35.8 kgf (78.9 lbf). There was typically a high initial "breakaway" force and then a constant load until the rod had been pulled through the last (top) spacer grid. This suggested that the majority of the sliding friction load occurred between the rods and the top grid spacer. This was substantiated when the rods were pulled from the last assembly for which the top spacer grid had been removed with the end box. In this case, the pulling forces on the rods were generally lower and decreased as the rod was removed through successive spacer grids.

The drilling and cutting chips were collected with a filtered vacuum system after each consolidation cycle. These samples were subsequently examined to determine weight and radiation fields. The average weight was 7.31 g/cycle. Gross radiation measurements showed contact readings of about 2.39 R/h.

Similar to the manner in which the cutting chips were collected and analyzed, the debris that dropped from the assembly was collected as the rods were pulled. The average amount of crud and zirconium slivers that was collected was 1.05 g/cycle. Gross contact radiation measurements were about 0.647 R/h.

In-cell contamination and general background radiation readings were lower than had been anticipated, with general fields reading about 150 mR/h and surface contamination typically ranging from 5 to 30 mR/h. Smears taken near the end box removal area were higher, with readings of up to 600 mR/h. The major isotope detected was ^{60}Co. Filters in the hot cell waste gas duct were changed after the eighteenth and twenty-fourth cycles. Contact readings were about 300 mR/h on the first change and 800 mR/h on the second change. At least part of the reason for the higher readings on the second change was that in-cell cleanup was started prior to filter changeout and some loose contamination was resuspended in the hot cell environment. Analyses planned for samples taken from airborne contamination samples are expected to be limited to gross radiation readings and some isotopic determinations.

Another parameter of interest was the depth of scratches in the fuel cladding as a result of pulling the rods through the spacer grids. A simple mold was used to press dental surface impression material onto selected scratched areas on two of the rods. The impression material was removed, decontaminated as much as practical, and then prepared and measured with an optic compactor. Scratch depths were too shallow for accurate measurement but were less than 0.025 mm on the eight samples taken. Measurements of cladding slivers scraped off by the spacer grids may also be taken to further quantify scratch depth. Scratch depth is of interest in understanding potential phenomena that could damage the cladding and contribute to failure during subsequent handling or storage.

The observations and analyses performed on the radiological and physical measurements all support the feasibility of dry consolidation.

This support is provided as much by what was not observed or measured as by the actual measurements. Specifically, no surprises were encountered that would cause concern about the viability of this approach.

An issue of concern to the project was zirconium pyrophoricity (spontaneous combustion of zirconium), which was observed and documented in the literature for high surface-to-volume ratio of zirconium fines. Although no extraordinary precautions were taken to prevent pyrophoric events during the consolidation process (such as establishing an inert atmosphere or special debris catch basins), the quantities of zirconium chips and fines were limited by the frequent collection and segregation of samples. No pyrophoricity was observed during the project.

All of the observations and evaluations described above must be considered and applied with the realization that the fuel used in the project was of a single design, relatively clean, and of similar burnup. Other fuel could have resulted in significantly different behavior. Of particular question would be the general applicability of rod pulling forces, rod flexibility and tolerance to rough handling, crud characterization, and the radiological characteristics of the entire process.

RECOMMENDATIONS

The DRCT experience demonstrates the viability of dry fuel rod consolidation. It also provides generic information that can enhance future consolidation projects. The following "lessons learned" are applicable to dry consolidation processes in general:

- The majority of the elapsed time during a consolidation cycle was taken up in fuel handling rather than in fuel assembly end box removal and rod pulling. It is recommended that fuel handling processes be emphasized in future consolidation projects.
- To avoid unnecessary delays due to equipment failures, the equipment should be fabricated in modules to permit quick replacement of parts or subassemblies and "off-line" repair.
- Relatively small assembly-to-assembly dimensional differences or small differences in assembly position in the fuel assembly support frame caused some problems in alignment of the rod puller. It is recommended that an indexing system be incorporated to allow the puller head position coordinate system to be referenced to each assembly.
- Difficulties encountered in guide tube cutting were due in part to incomplete fuel assembly design details available during machine development and testing. An in-depth knowledge of the fuel assembly and very representative testing should be performed before the machine is put into service.
- Even though the extent of contamination had been considered relatively limited, efforts to decontaminate the machine were ineffective in reducing levels acceptable for nonradioactive storage or for ready maintenance or modification. Since relatively clean fuel was used and the machine received limited use, it can be expected that decontamination of production equipment will be very difficult.

The following conclusions and recommendations are based on experience that may be strongly affected by the condition of the fuel. However, if the observed behavior is typical, consideration of the following items would be important in the design of future consolidation equipment:

- The top spacer grid, when removed with the end box, tended to pull fuel rods from the bundle. A method of holding the fuel rods during spacer grid removal would be needed if this technique were used on a production basis.

- The fuel rods are very flexible and require fairly uniform support along their length during handling. However, the flexibility contributes to the ease of stacking in the horizontal position.

- No pyrophoric events were observed during the process; however, accumulated quantities of zirconium particles were limited, and the operation used in cutting the guide tubes may be less likely to cause ignition of fires than other potential cutting methods.

- The fuel assembly should be clamped securely in place during rod removal because some twisting can be expected in the skeleton as the weight of the rods is removed.

The INEL Dry Rod Consolidation Technology Project is considered a success. It demonstrates the feasibility of dry horizontal consolidation and the ability to establish perfectly stacked arrays for a consolidation ratio of more than 2 to 1. It is expected that the knowledge gained in this project will be beneficial to future dry rod consolidation projects.

Fig. 1. Test area north (TAN) hot shop/hot cell floor plan.

Fig. 2. Remote fuel transfer from a storage cask located in the dual cask work platform inside the hot shop.

Fig. 3. Remote radio-controlled strongback carrier lift bail rotating the fuel assembly consolidation canister strongback carrier.

Fig. 4. In-cell lift fixture lifting a Westinghouse 15 x 15 PWR, fuel assembly.

Fig. 5. Fuel consolidation project in-cell equipment.

Fig. 6. Consolidation equipment installed inside the TAN hot cell looking south.

Fig. 7. Consolidation equipment installed inside the TAN hot cell looking north.

Fig. 8. Fuel rod gripper removing a fuel rod from a mock-up fuel assembly.

Fig. 9. Consolidation canister base and lid.

Fig. 10. Sketch of Westinghouse 15 x 15 PWR fuel assembly.

Fig. 11. Fuel rod stack in canister base showing variable rod length.

Fig. 12. Crud collected from two consolidated fuel assemblies.

Fig. 13. Gross gamma scan of fuel assembly and skeleton.

Fig. 14. Preliminary data on distribution of ^{60}Co and ^{94}Nb in skeleton fuel assembly.

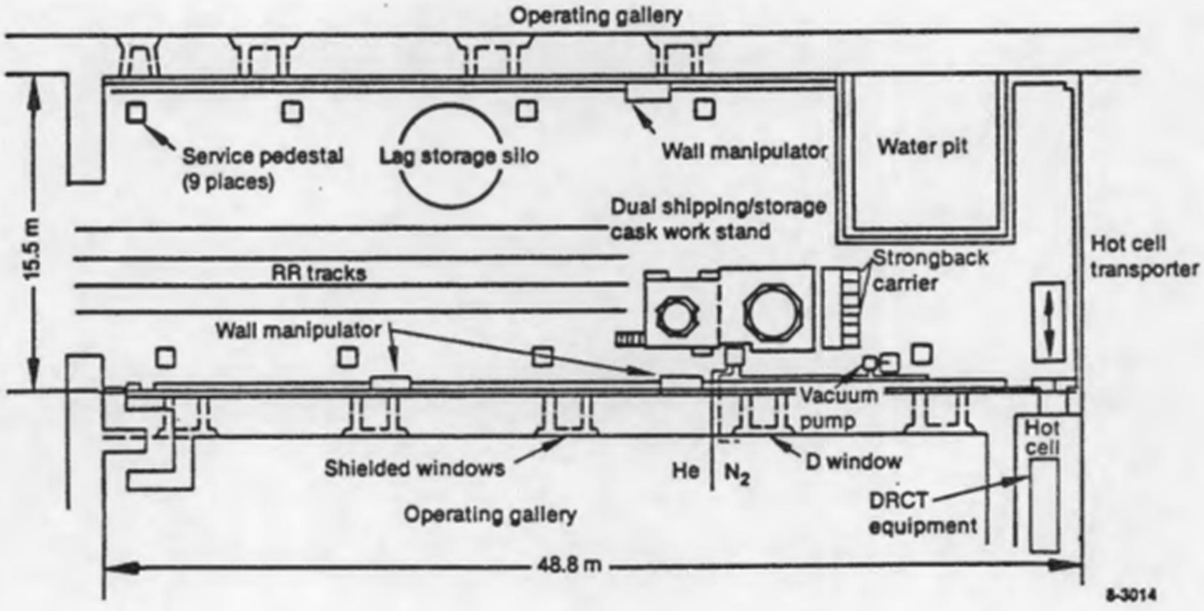


Fig. 1. Test Area North (TAN) hot shop/hot cell floor plan.

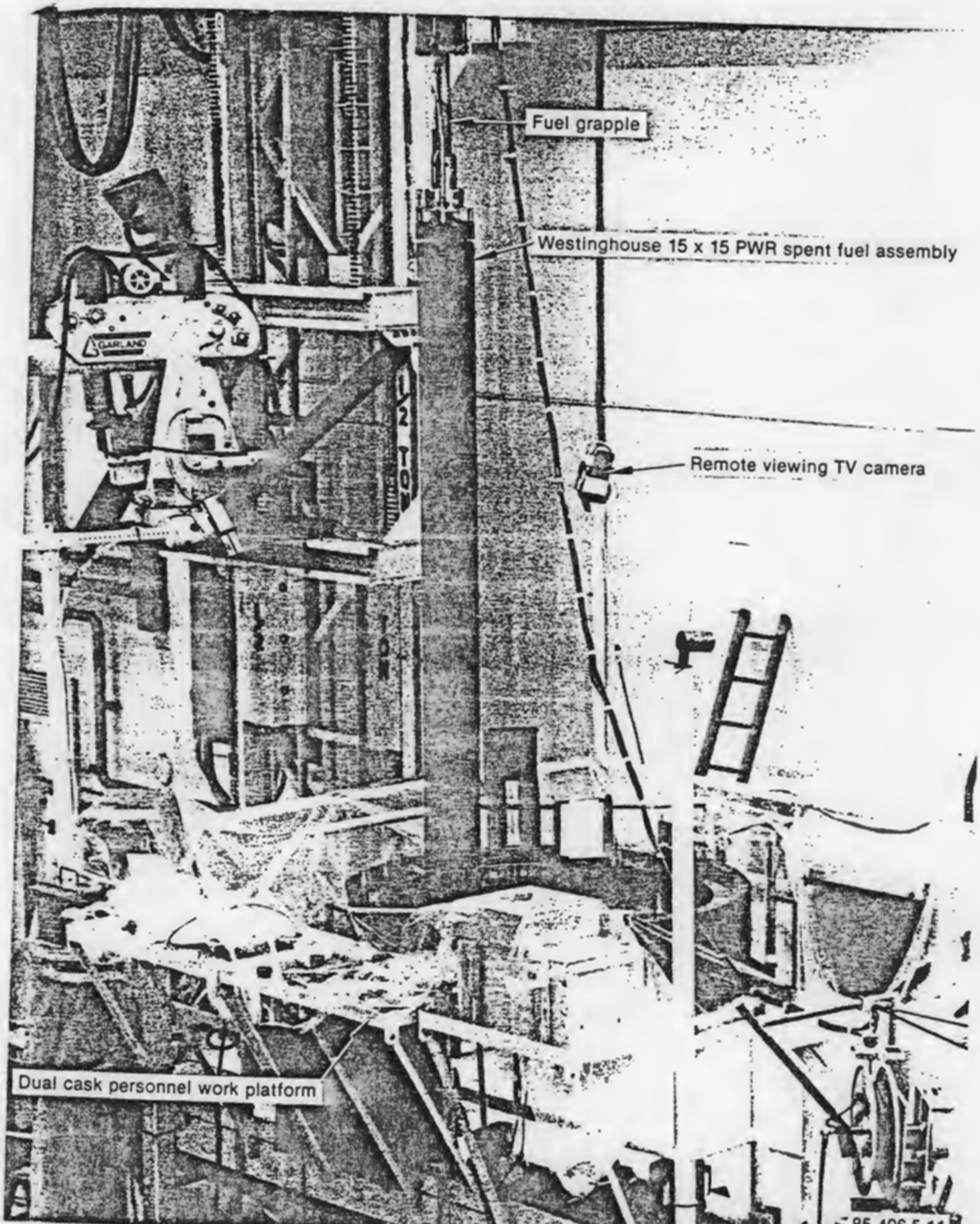
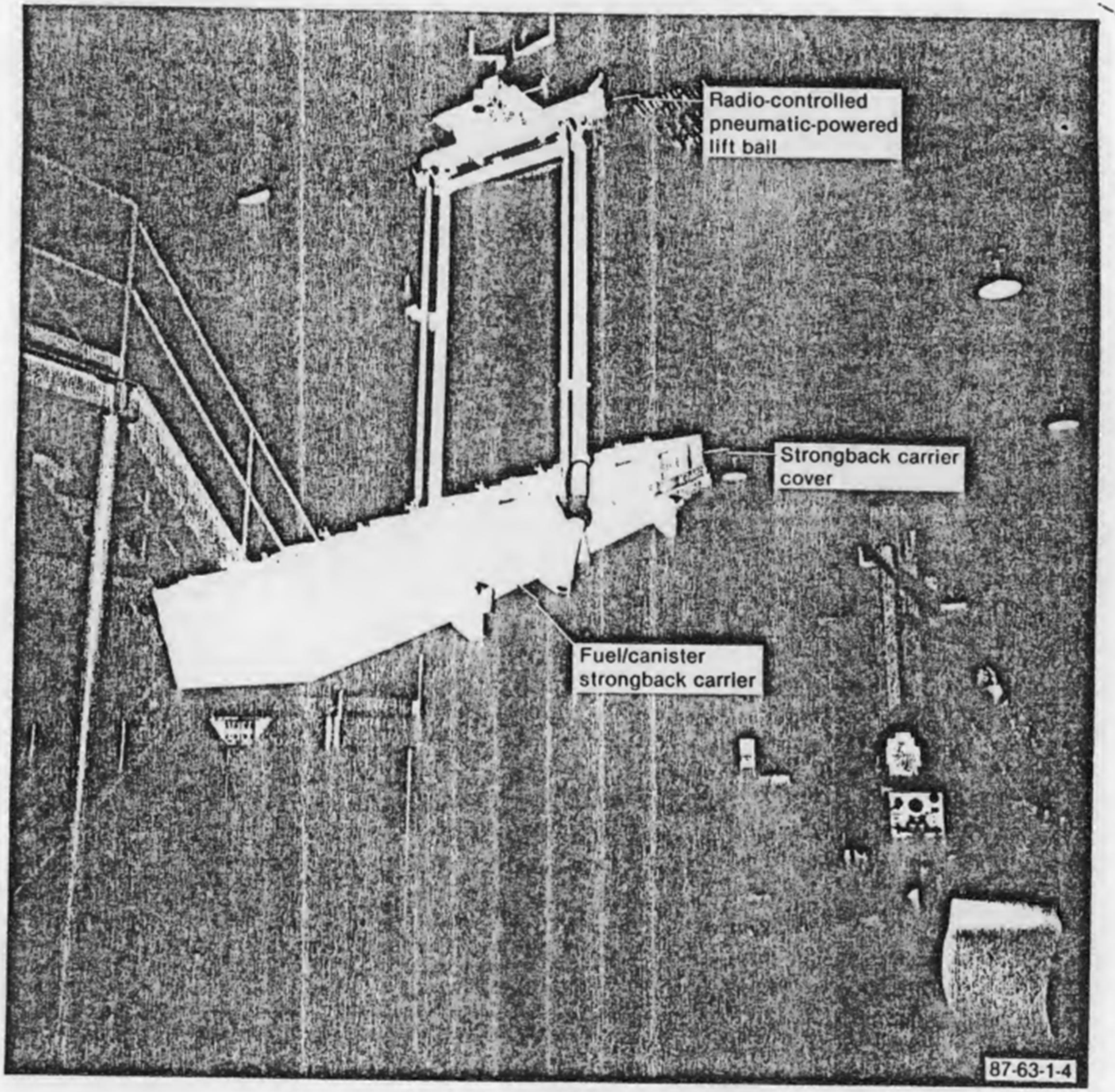


Fig. 2 Carlan Muller

Fig 3. Carlan Mullen



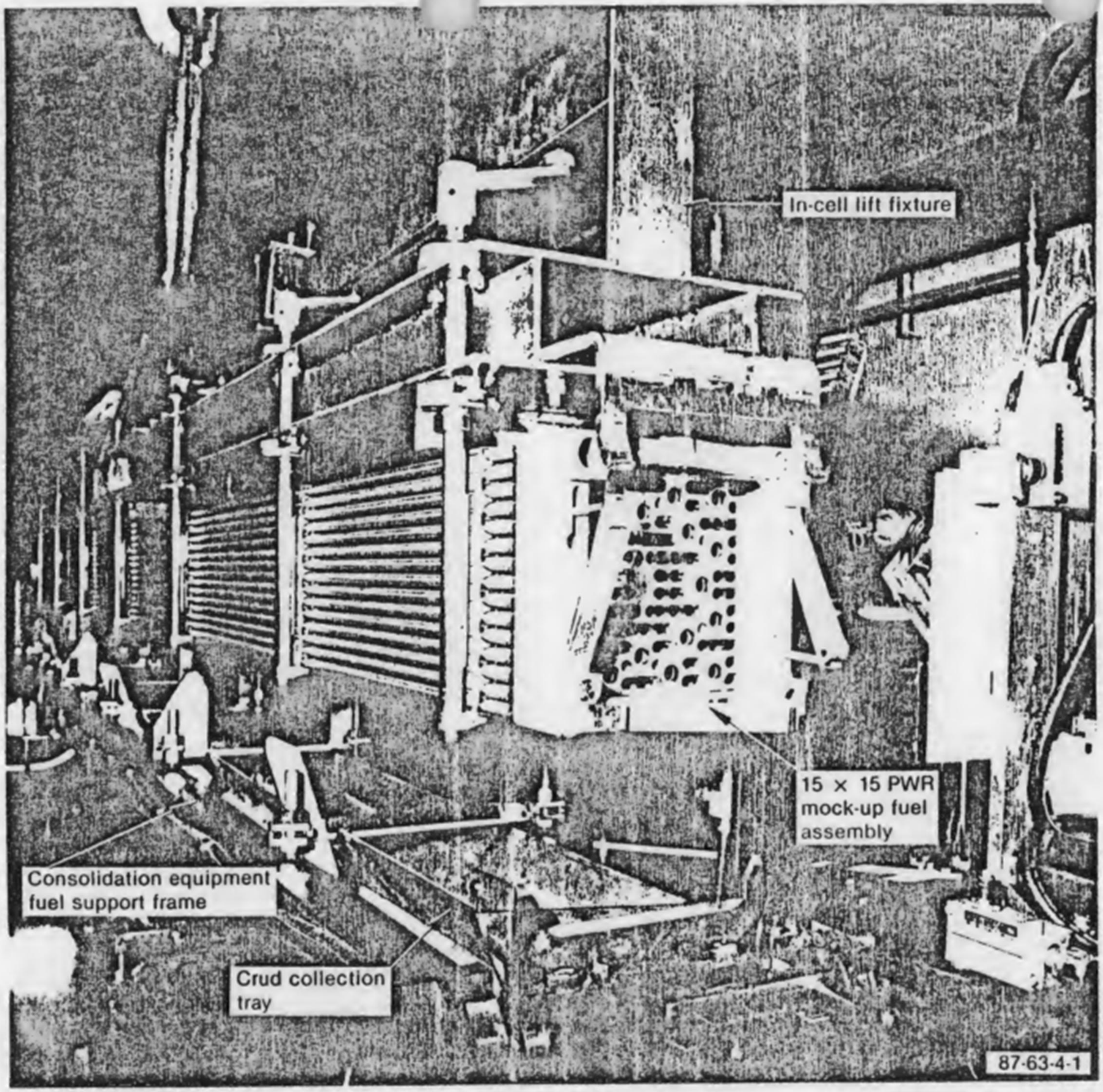


Fig. 4
Carlan
Mullen

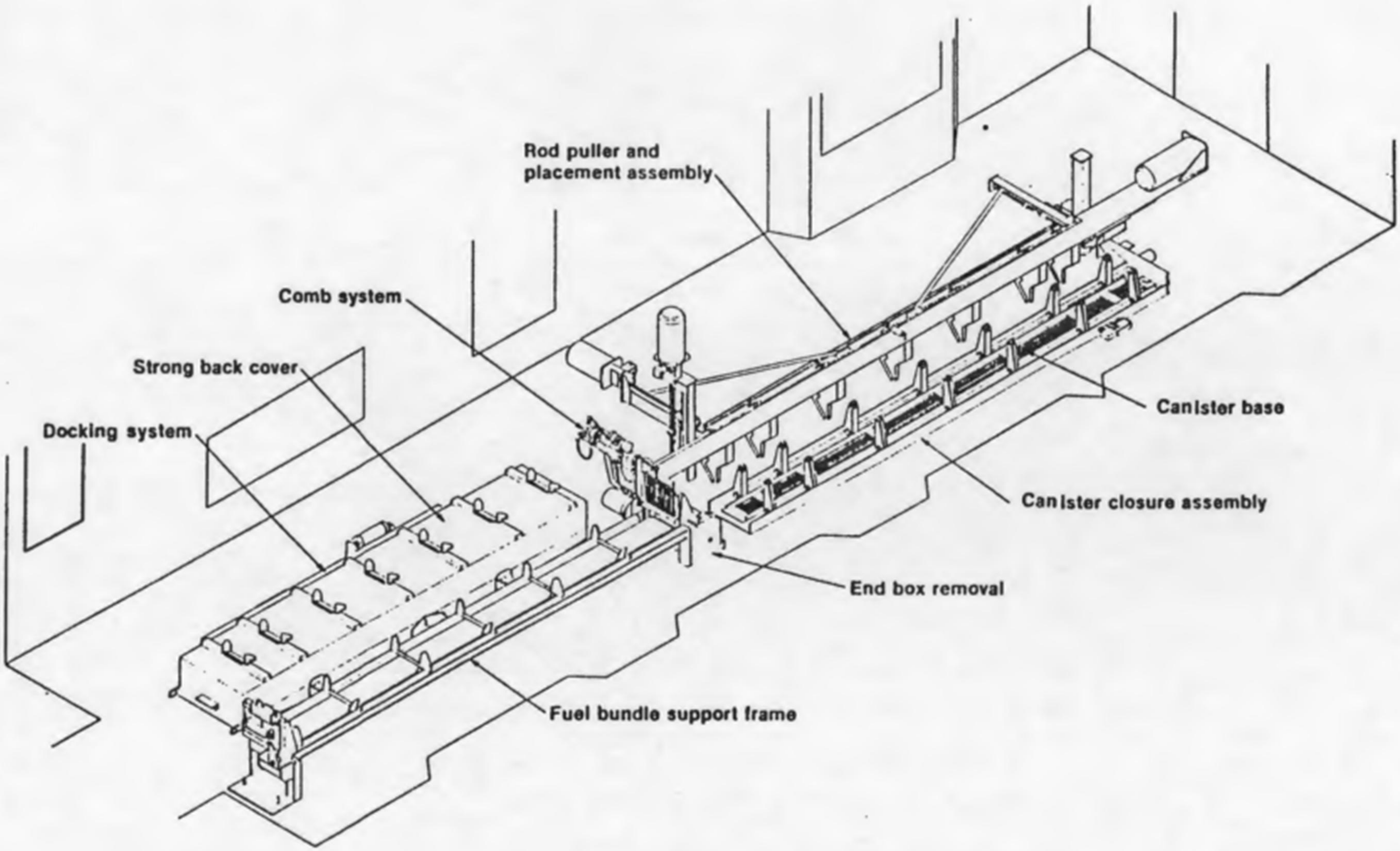


Fig. 5. Fuel consolidation project in-cell equipment.

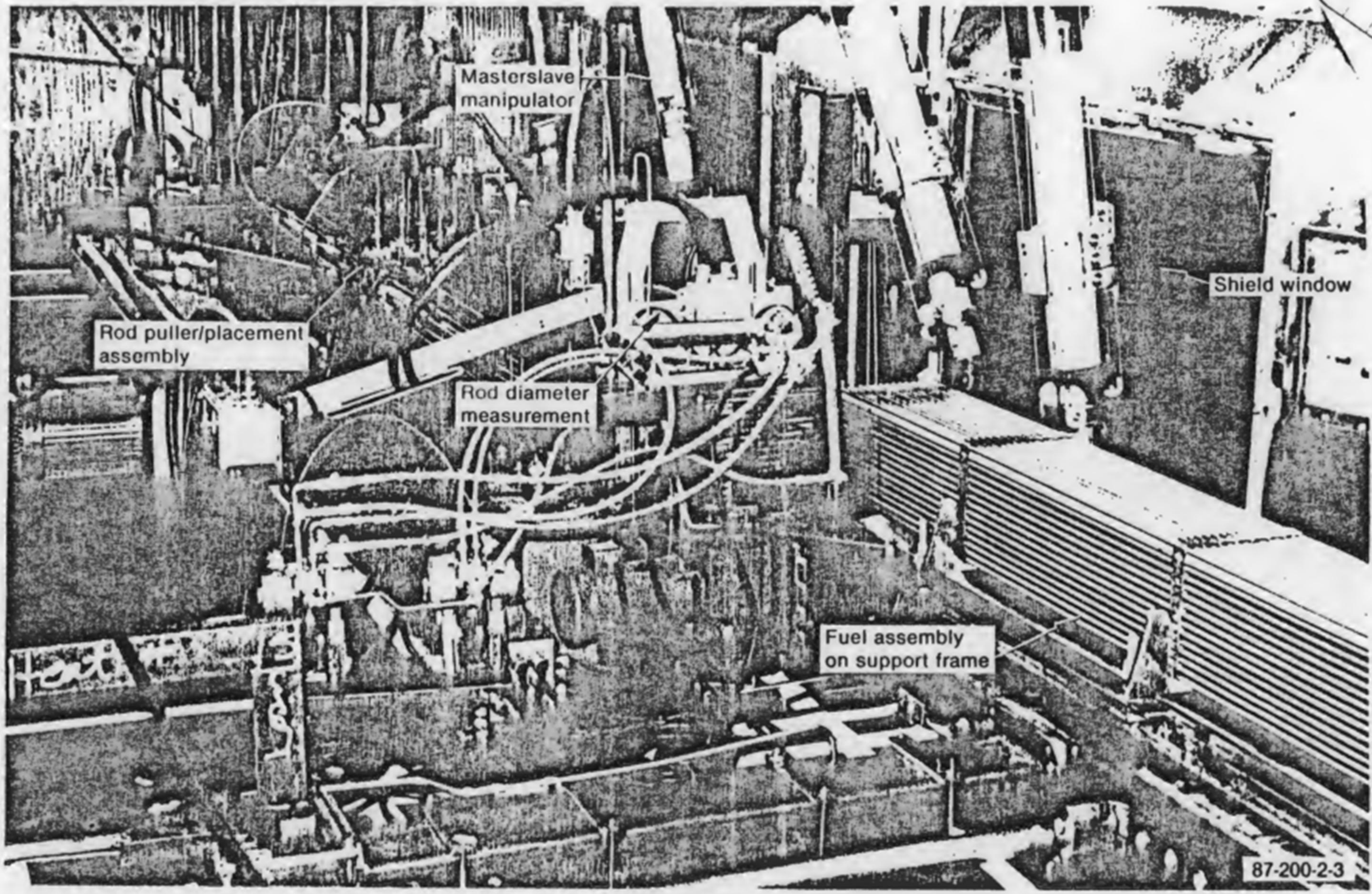


Fig. 6 Carlan Mullen

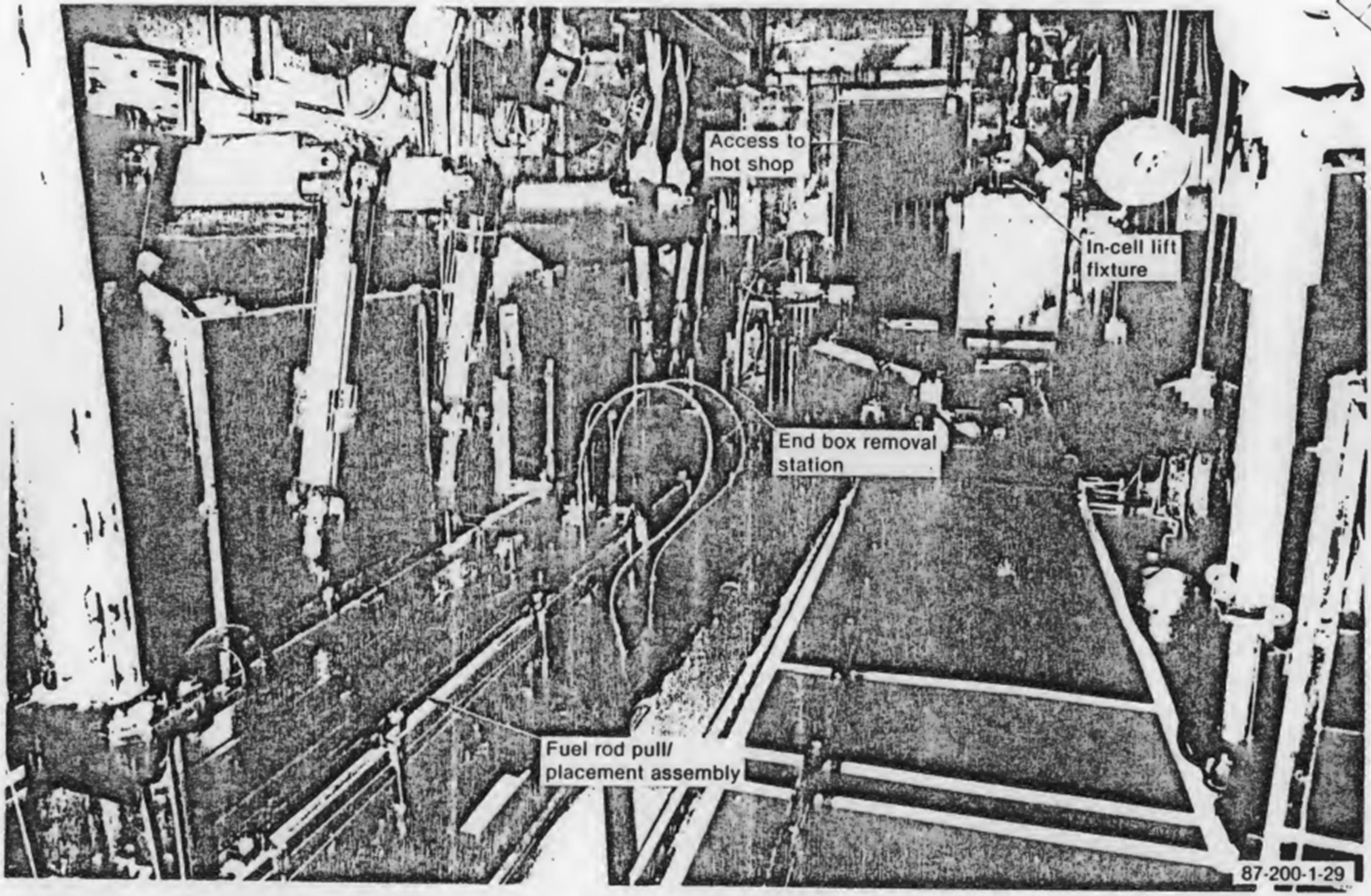


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Fig. 7 Carlan Mullen