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LOADING ASSURANCE METHODS USED IN THE MANUFACTURE OF THE LIGHT WATER BREEDER REACTOR (LWBR)

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FOREWORD

The Shippingport Atomic Power Station located in Shippingport, Pennsylvania was the first large-scale, central-station nuclear power plant in the United States and the first plant of such size in the world operated solely to produce electric power. This program was started in 1953 to confirm the practical application of nuclear power for large-scale electric power generation. It has provided much of the technology being used for design and operation of the commercial, central-station nuclear power plants now in use.

Subsequent to development and successful operation of the Pressurized Water Reactor in the Atomic Energy Commission (now Department of Energy, DOE) owned reactor plant at the Shippingport Atomic Power Station, the Atomic Energy Commission in 1965 undertook a research and development program to design and build a Light Water Breeder Reactor core for operation in the Shippingport Station.

The objective of the Light Water Breeder Reactor (LWBR) program has been to develop a technology that would significantly improve the utilization of the nation's nuclear fuel resources employing the well-established water reactor technology. To achieve this objective, work has been directed toward analysis, design, component tests, and fabrication of a water-cooled, thorium oxide-uranium oxide fuel cycle breeder reactor for installation and operation at the Shippingport Station. The LWBR core started operation in the Shippingport Station in the Fall of 1977 and finished routine power operation on October 1, 1982. End-of-Life testing has been completed and the core was removed and the spent fuel shipped to the Naval Reactors Expended Core Facility for detailed examination to verify core performance including an evaluation of breeding characteristics.

In 1976, with fabrication of the Shippingport LWBR core nearing completion, the Energy Research and Development Administration, now DOE, established the Advanced Water Breeder Applications (AWBA) program to develop and disseminate technical information which would assist U.S. industry in evaluating the LWBR concept for commercial-scale applications. The AWBA program, which was concluded in September, 1982, explored some of the problems that would be faced by industry in adopting technology confirmed in the LWBR program. Information developed includes concepts for commercial-scale prebreeder cores which would produce uranium-233 for light water breeder cores while producing electric power, improvements for breeder cores based on the technology developed to fabricate and operate the Shippingport LWBR core, and other information and technology to aid in evaluating commercial-scale application of the LWBR concept.

All three development programs (Pressurized Water Reactor, Light Water Breeder Reactor, and Advanced Water Breeder Applications) have been conducted under the technical direction of the Office of the Deputy Assistant Secretary for Naval Reactors of DOE.

Technical information developed under the Shippingport, LWBR, and AWBA programs has been and will continue to be published in technical memoranda, one of which is this present report.

ABSTRACT

The LWBR core contained several sizes and arrangements of fuel pellets, fuel rods and module assemblies. Extensive loading assurance methods were devised and implemented during fabrication to ensure that (a) all fuel pellets and fuel rods contained the specified amounts of fissile fuel, (b) all modules contained the specified fuel zoning and (c) the fissile loadings of fuel rods, core compositions and the entire core were known to the desired accuracy. Although the loading assurance methods described were devised for and successfully implemented during fabrication of LWBR, the principles involved are of general applicability.

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I. INTRODUCTION

The core design of the Shippingport Light Water Breeder Reactor (LWBR) (Ref. 1) used a seed-blanket configuration with movable seeds for reactivity control rather than poison control rods. Figure 1 presents a cross-sectional view of the LWBR core showing the location of the types of modules which comprised the core configuration. As shown, the core contained the following types of fuel modules:

1. 12 movable seed modules,
2. 12 stationary blanket modules composed of two blanket regions denoted as standard blanket and power-flattening blanket,
3. 15 reflector blanket modules.

The seed and blanket modules contained both fissile uranium-233 and fertile thorium-232 in fuel rods containing uranium dioxide - thorium dioxide (UO_2-ThO_2) ceramic pellets, while the reflector blanket modules contained only thorium in ThO_2 pellets. The fuel in the seed and blanket regions also included an axial reflector of 10 inches, and in some rods more than 10 inches, of thorium dioxide on the top and bottom. The rods with more than 10 inches improved the reactivity worth of the movable fuel seed as it changed elevation. Radial fuel zoning was employed in the seed and blanket regions to reduce power peaking in the vicinity of the water channels separating seed and blanket. Fabrication of the LWBR core involved mixing UO_2 and ThO_2 powders to form powder blends, pressing powder into pellets, sintering pellets to obtain a solid state solution of the specified density, loading pellets into Zircaloy tubing to produce fuel rods and, finally, assembling completed rods into modules.

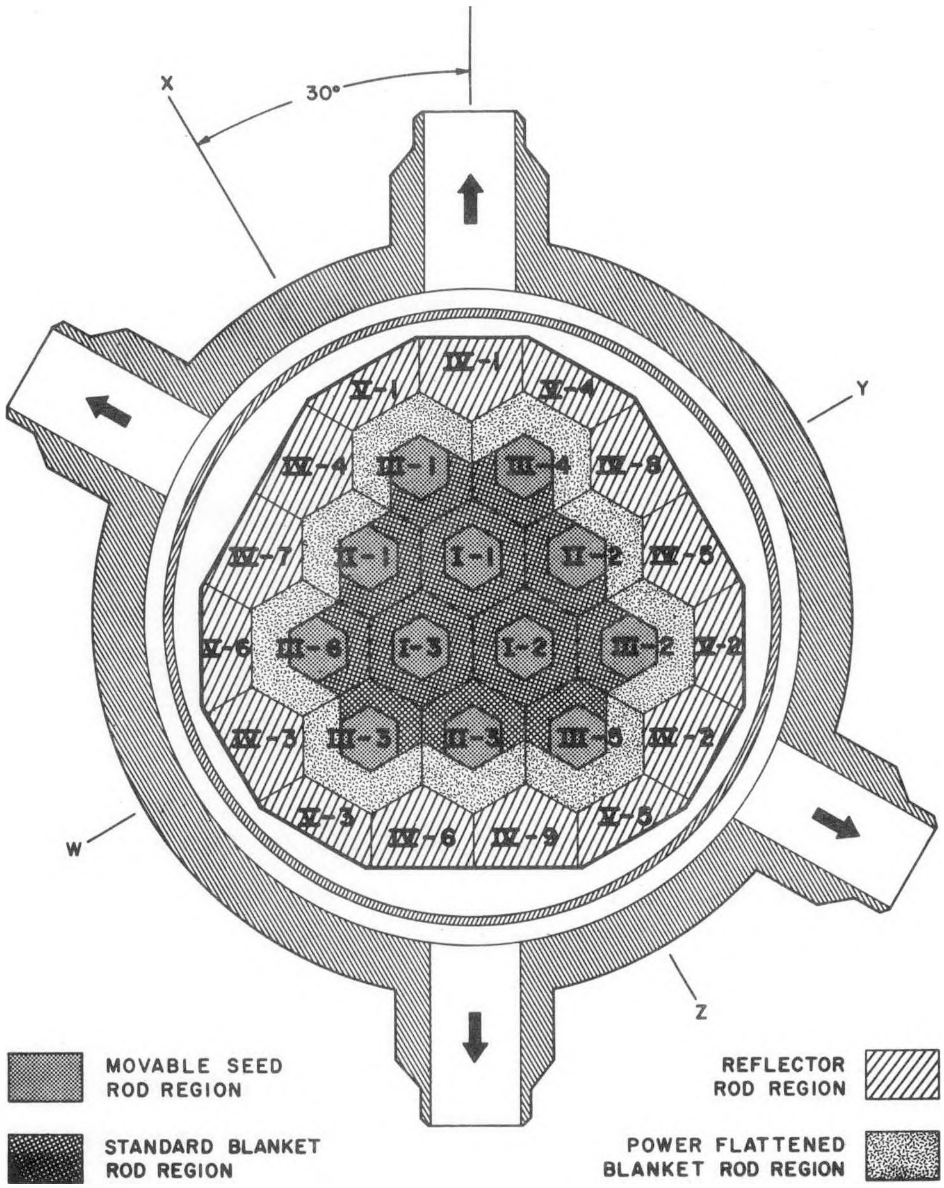


FIGURE 1

LWBR CORE CROSS SECTION SHOWING MODULE IDENTIFICATIONS

Eight types (composition, diameter and length) of fuel pellets containing both fissile and fertile fuel and four types (diameter and length) of fuel pellets containing only fertile fuel were manufactured for the four diameters of fuel rods in LWBR. The fuel pellets were used in 23 types of fuel rods, each with unique dimensional and loading requirements. LWBR fuel rod fabrication is described in Reference 2. The fuel rods were installed in the modules according to specified assembly patterns whereby each rod type was placed in a prescribed region of each module. The fabrication of LWBR modules is described in Reference 3.

Extensive loading assurance methods were developed to ensure that the core was correctly fabricated and that the initial loading was accurately known. The Proof-of-Breeding phase of LWBR, which would be undertaken after the core was dismantled at end of life, required a precise knowledge of the beginning-of-life loading to demonstrate breeding. The LWBR loading assurance methods developed were a combination of fabrication and inspection procedures and involved use of computers at Bettis. This report summarizes the loading assurance methods used during the fabrication of the LWBR core to ensure that (a) all fuel pellets and fuel rods contained the specified amounts of fissile fuel, (b) all modules contained the specified fuel composition and (c) the fissile loadings of fuel rods, core compositions and the entire core were known to the desired accuracy. The LWBR manufacturing operations of concern, from the point of view of loading assurance were urania and thoria powder blending (Section II), fuel pellet fabrication and inspection (Section III), fuel rod assembly and inspection (Section IV) and module assembly and inspection (Section V). These manufacturing operations ultimately determined the fuel content and the fuel zoning of the core.

Figure 2 shows a flow chart of the manufacturing and inspection steps where loading assurance checks were applied. Powder blending required precise weighing of urania and thoria powders to provide loading assurance. Fuel pellet fabrication required accurate inspections to furnish loading assurance and the desired precision in the core fissile loading estimate. Sampled pellets were assayed for uranium content using a combination of destructive and nondestructive methods first utilized in LWBR. Computer programs were used to assist the pellet data analyses. As-built data recorded during fuel

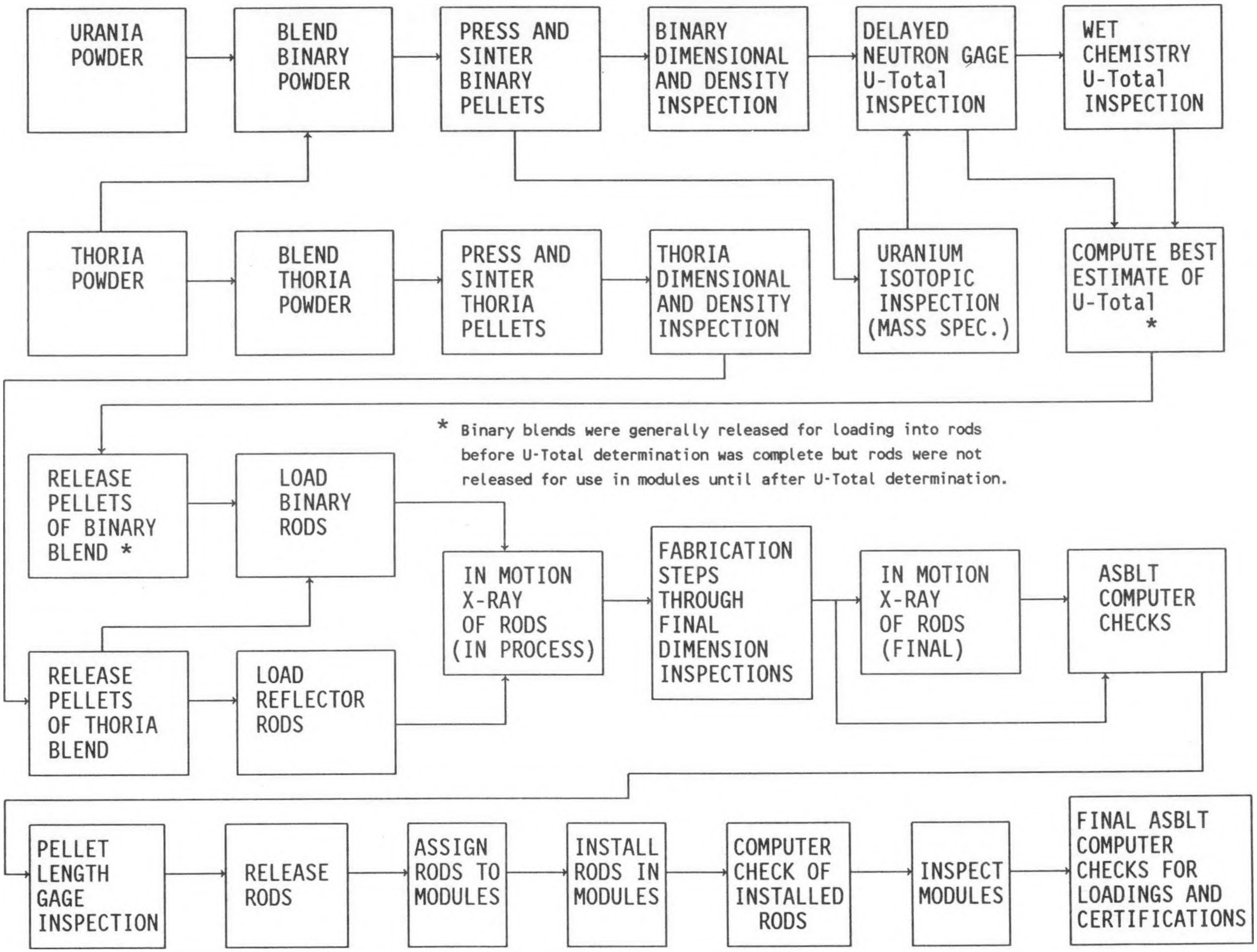


FIGURE 2. LWBR MANUFACTURING AND INSPECTION STEPS RELATED TO LOADING ASSURANCE

rod fabrication and data obtained from fuel rod radiographs were entered into the computer. These data were used to compute fuel rod loadings and to confirm that the fuel rods had been fabricated according to specifications. Module fabrication, inspection and certification procedures utilized a combination of manual and computer assisted methods to ensure that all fuel rods were correctly installed in their proper locations in the modules. The loading assurance methods developed for LWBR ensured that the core was fabricated as specified.

The design concepts of LWBR -- a light water breeder with movable fuel reactivity control -- dictated the loading assurance principles and methods which were needed during manufacturing. The design was new; therefore, new loading assurance concepts were developed. First of all LWBR was a breeder demonstration and breeding is being demonstrated by comparing beginning-of-life fissile loading to end-of-life loading. This requires accurate knowledge of initial pellet, rod, module and core loadings. During the proof-of-breeding (POB) phase, now that the core has been dismantled, some 500 expended rods covering all types are being sampled and nondestructively analyzed. These rods were sampled from at least one module of each type in the core for a total of 12 module samples. Because of core geometry, LWBR at end of life has 9 distinct module types; therefore, the 12 module sample permits a measure of core asymmetry. During core manufacturing, all 24,000 rods fabricated, of which 17,290 were used in the modules, were potential candidates for POB rods, as were all 39 modules. The choice of the specific POB rods and modules was made after the core was built. Therefore, each rod and each module required the same loading assurance attention with regards to proof-of-breeding.

Since the different rod types were comprised of pellets of different diameters and fissile contents, loading assurance had to be considered at the pellet stage. Pellets were produced from blended powders, poured into dies, pressed and sintered; therefore, loading assurance steps were taken at powder blending.

Since LWBR relied on movable fuel for reactivity control, correct placement of the different fuel rod types within the module was crucial to safe, reliable core operation. Lowering reactivity meant moving the seed modules downward to reduce the effective size of the seed fissile bearing region in the core, replacing it with a radially thicker fertile region and decreasing the coupling between seed and blanket. Figure 3 shows the movable fuel control concept used in LWBR. One sketch in Figure 3 depicts the movable seed at an axial elevation corresponding to operating conditions; the other sketch shows the movable seed at the shutdown position. The seed - blanket configuration at any given axial elevation (i.e., thickness of fertile region separating the seed fissile region from the blanket fissile region) relied on precise fabrication of each fuel rod type and correct positioning of each rod type in modules. Furthermore, as fuel pellets and rods were made, some were conditionally accepted for use in the core. For example, a rod containing chipped pellets might be approved for use in core regions where the predicted power density was no higher than 90 percent of the peak power density. Means had to be devised to confirm that all fuel pellet types were correctly positioned in fuel rods, that all rod types were correctly positioned in modules and that all conditional releases were satisfied.

The loading assurance methods described in this report provided traceable paths of powder lots used in pellet blends, pellet blends used in rods, rods used in modules, and all associated inspection results and conditional releases. The traceable paths consisted of written records, computer files, X-ray radiographs and photographs. Computer programs and data files were used to assist and expedite assigning rods to module locations where selective assembly was required. The methods also provided a computerized database of LWBR as-built data which was used to accurately determine the loadings of individual fuel pellet blends, fuel rods, modules and the entire core. These loading assurance concepts were devised and implemented during LWBR fabrication some twelve to fifteen years ago and, therefore, the computer hardware used at that time (for example, card and paper tape punchers and readers) is now outdated. The methods, however, are of general applicability and could be used with modern equipment.

(NOTE: NOT TO SCALE)

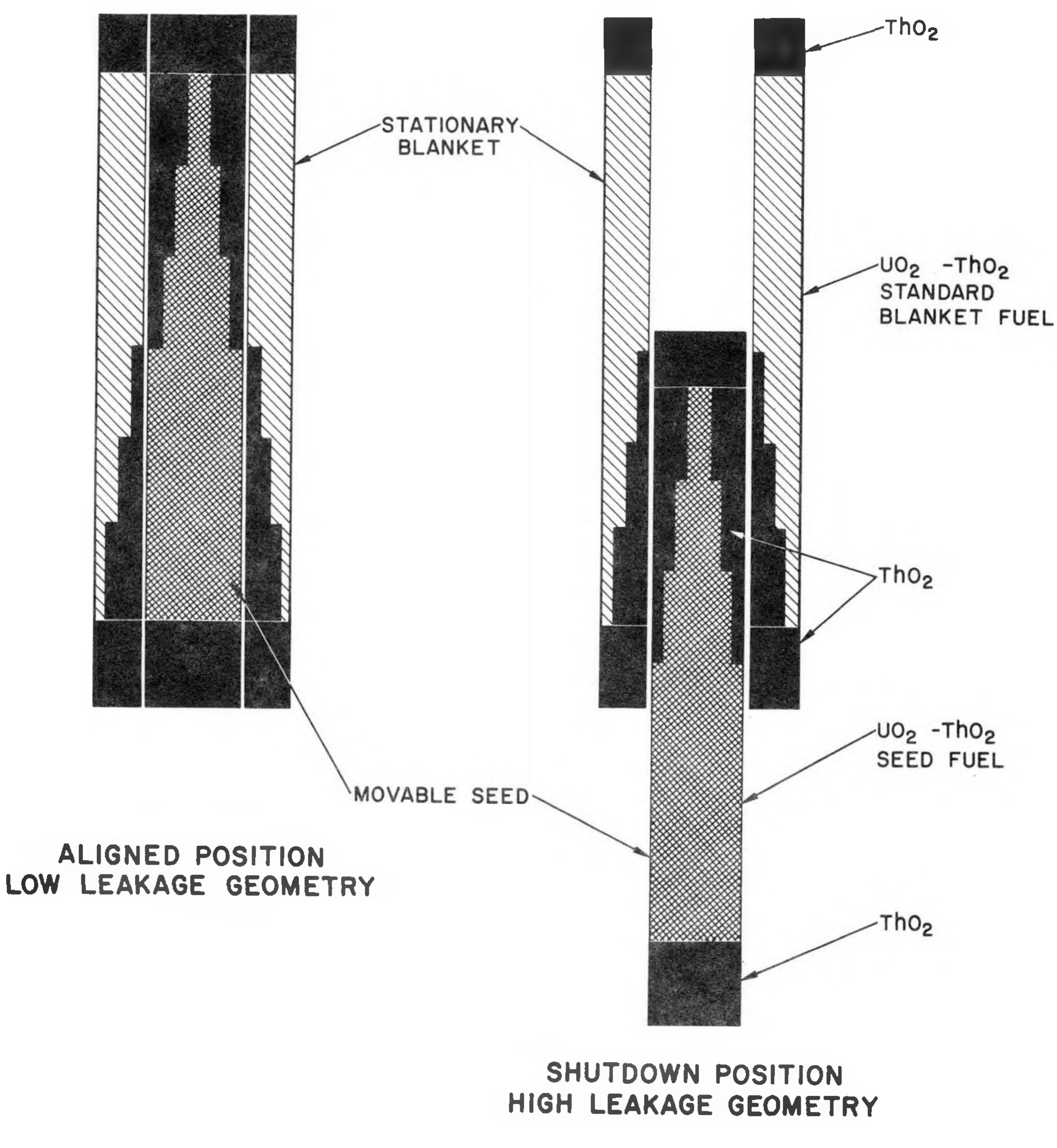


FIGURE 3

MOVABLE FUEL CONTROL

II. URANIA AND THORIA POWDER

Units of urania (uranium dioxide -- UO_2) and thoria (thorium dioxide -- ThO_2) powder called lots were received at Bettis and processed into fuel pellets. The powder lot designations, consisting of three digit numbers, were recorded for traceability of fuel from powder to pellets. The pellets could be either pure thoria or a solution of urania and thoria. Typically, approximately 50 kilograms of thoria powder was weighed out from a lot, assigned a blend identity (defined in Section III.A) and fabricated into a thoria pellet blend.

In producing a binary (urania-thoria) blend, predetermined amounts of urania powder and thoria powder were weighed out from urania lots and thoria lots and preblended in small batches. Two or more batches were then blended together to form a binary blend. Depending on the weight percent urania, each blend weighed a maximum of either 25 or 100 kilograms. The blending operation involved mixing powders in a rotating vee blender for a sufficient length of time to produce a homogeneous urania-thoria mixture. Table 1 shows the types (compositions) of binary fuel required for LWBR along with the corresponding urania weight percent, fissile uranium weight percent and maximum batch and blend sizes in kilograms. For example, the low zone seed composition required binary powder containing nominally 4.98 weight percent urania, which for LWBR was equivalent to about 4.327 weight percent fissile uranium. Low zone seed powder was preblended in batches of 4.5 kilograms or less which were then combined into blends of 25 kilograms or less. Producing a 4.5 kilogram batch of low zone seed binary powder was accomplished by carefully weighing, recording and then mixing 0.2241 kilograms of urania powder with 4.2759 kilograms of thoria powder. Thus, the loading assurance operations employed during powder blending involved the recording of blend identities and their parent powder lots, carefully weighing predetermined amounts of urania and thoria powders to produce the desired fuel composition, preblending the powders in small batches and final blending the batches to form blends.

TABLE 1

URANIA AND THORIA POWDER BLENDING

Composition	UO_2 Weight Percent	$U^{fissile}$ Weight Percent	Preblend Maximum Batch Size (kg)	Maximum Blend Size (kg)
Low Zone Seed	4.98	4.327	4.5	25
High Zone Seed	5.98	5.195	4.5	25
Low Zone Standard Blanket	1.39	1.211	8.5	100
Medium Zone Standard Blanket	1.91	1.662	8.5	100
High Zone Standard Blanket	2.30	2.000	8.5	100
Low Zone Power Flattening Blanket	1.90	1.649	8.5	100
Medium Zone Power Flattening Blanket	2.31	2.005	8.5	100
High Zone Power Flattening Blanket	3.14	2.733	8.5	100

III. FUEL PELLETS

Thoria and urania-thoria powders were pressed into pellets (with end dishes, Figure 4) which were then sintered to achieve the desired density and to remove powder binder additives. The sintered pellets were centerless ground to achieve the desired diameter. Tapers and chamfers were ground, as required, for the various pellet types depicted in Figure 4. Pellet grinding and inspection is described in Reference 4. Sample fuel pellets were drawn from each blend and analyzed for density, uranium content and impurities. All pellets were inspected for length and diameter. Inspected pellet blends were released for loading into fuel rods. Loading assurance steps employed during pellet fabrication are described in this section.

A. Distinguishing Characteristics of Pellets and Blends

Table 2 lists some of the fuel pellet attributes which characterized the fuel pellets required for the various regions and zones in the LWBR core. The blend identity and the first four pellet attributes listed in Table 2 had a role in loading assurance.

The blend identity served as a way to administratively characterize fuel pellets. For thoria pellets, the middle digit of the blend identity - 0, 1, 2 or 3 - indicated pellet diameters corresponding to seed, standard blanket, power flattening blanket or reflector thoria, respectively. For binary blends the middle digit took on the values 1 through 8 denoting low zone seed binary (4.336 weight percent fissile uranium) through high zone power flattening blanket binary (2.733 weight percent fissile uranium) as shown in Table 2. Blend identity tags were assigned to all pellet containers (sintering boats, trays and sample containers) so that the pellet types could be identified from the blend identities recorded on the tags.

As can be seen in Table 2, the combination of fuel pellet diameter and length were unique for each type of fuel pellet. While different pellet types within a core region (for example, standard blanket) were fabricated with the same diameter and some pellet lengths were identical for two different pellet types, no two pellet types were fabricated with identical diameter and length.

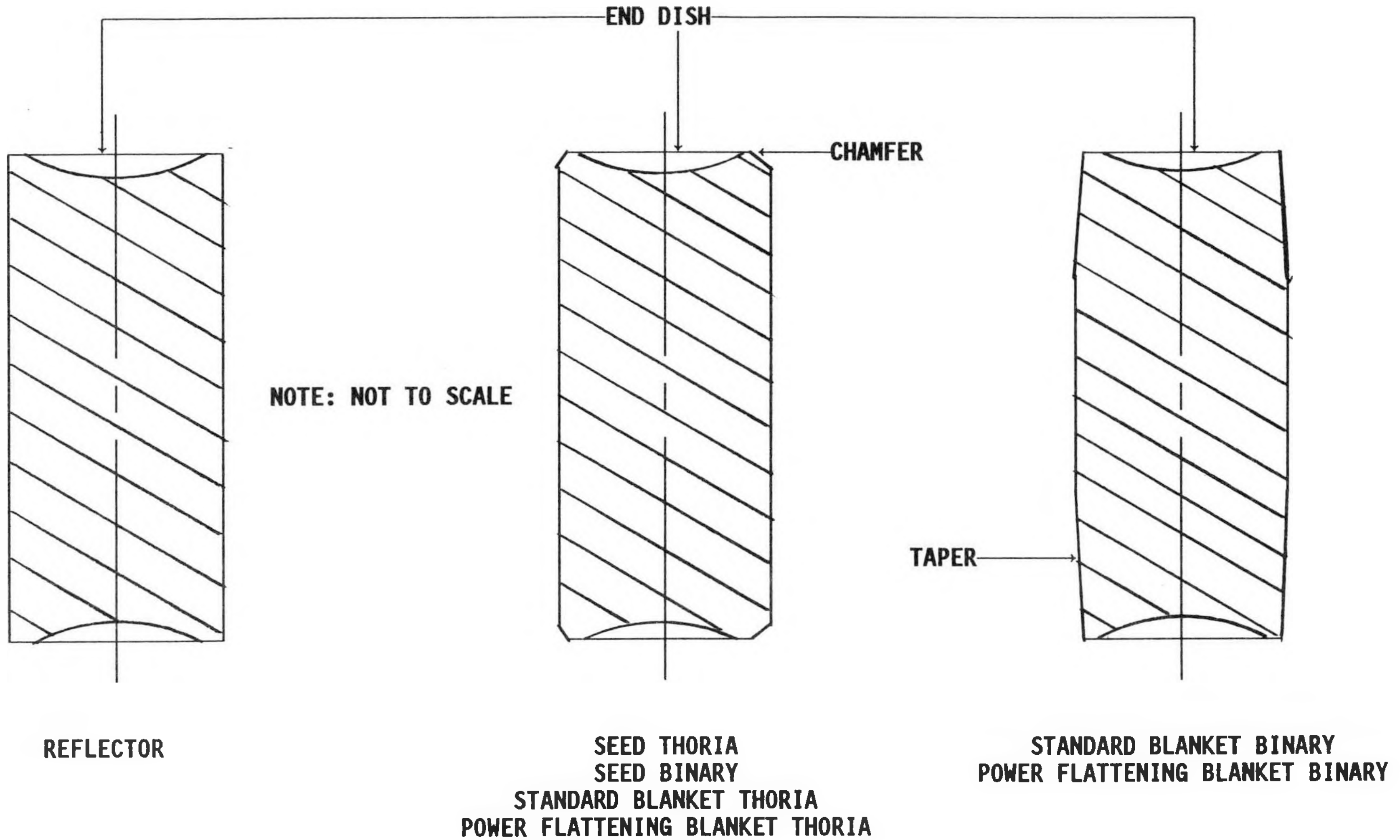


FIGURE 4

CROSS SECTIONS OF TYPICAL LWBR FUEL PELLETS

TABLE 2

PROPERTIES OF LWBR FUEL PELLETS

Parameter	Seed: Thoria	Seed: Low Zone Binary	Seed: High Zone Binary	Standard Blanket: Thoria	Standard Blanket: Low Zone Binary	Standard Blanket: Medium Zone Binary	Standard Blanket: High Zone Binary	Power Flattening Blanket: Thoria	Power Flattening Blanket: Low Zone Binary	Power Flattening Blanket: Medium Zone Binary	Power Flattening Blanket: High Zone Binary	Reflector: Thoria
Blend Identity (form)	XXX-0-YY	XXX-1-YY	XXX-2-YY	XXX-1-YY	XXX-3-YY	XXX-4-YY	XXX-5-YY	XXX-2-YY	XXX-6-YY	XXX-7-YY	XXX-8-YY	XXX-3-YY
Nominal Fissile w/o	0	4.336	5.195	0	1.211	1.662	2.000	0	1.649	2.005	2.733	0
Diameter (in.)	.2555 ±.0005	.2520 ±.0005	.2520 ±.0005	.5105 ±.0005	.5105 ±.0005	.5105 ±.0005	.5105 ±.0005	.4695 ±.0005	.4695 ±.0005	.4695 ±.0005	.4695 ±.0005	.7415 ±.0005
Length (in.)	.530 ±.020	.445 ±.020	.615 ±.020	.615 ±.020	.530 ±.020	.870 ±.020	.785 ±.020	.445 ±.020	.870 ±.020	.785 ±.020	.700 ±.020	.740 ±.020
End Markings	None	1 truncated pyramid	2 truncated pyramids	None	3 truncated cones	2 truncated cones	1 truncated cone	None	3 slashes	2 slashes	1 slash	None
Tapers	No	No	No	No	Yes	Yes	Yes	No	Yes	Yes	Yes	No
Chamfers	Yes	Yes	Yes	Yes	No	No	No	Yes	No	No	No	No
End Dishes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

This feature of the LWBR fuel pellets was used to ensure correct loading of finished fuel rods through the use of in-motion radiography (X-rays) as discussed in Section IV.C. Finished fuel pellets were 100% inspected for length, diameter and ovality via go/no-go gages to ensure that they met fuel performance specifications.

To provide a means of visually identifying the binary fuel type and the fissile content of all binary pellets, end markings were applied to both ends of every binary fuel pellet fabricated for LWBR. Pellet dies used to press pellets were manufactured with the end markings identified in Table 2 (for example, two truncated pyramids on both ends of high zone seed pellets) so that the distinguishing marks were applied to the binary pellets as they were pressed from powder. Binary pellet types were confirmed during fuel rod loading by visual inspection of the pellet ends.

B. Sampling Plan for Binary Pellet Blends

The binary pellet sampling plan specified the selection of twenty pellets from each blend to be used to measure the pellet dimensions, density and weight percent of total uranium. All twenty pellets were measured and weighed to determine density and then analyzed by the Delayed Neutron Pellet Assay Gage (Ref. 5 and Section III.C) to determine the total uranium content. Five of the twenty pellets chosen underwent chemical analysis to determine total uranium content and the remaining fifteen were retained in the event further analyses were required. The final estimate of the total uranium content of the blend, including measurement uncertainty, involved statistically combining the chemistry and Delayed Neutron Gage (DNG) results as described in Reference 6. In addition to the twenty pellets per blend selected for dimensional, density and total uranium content, up to three pellets per blend were selected for use in determining the uranium isotopic content (one pellet sufficed if the blend contained only one uranium oxide powder lot; three pellets were used if the blend contained two uranium oxide powder lots). One pellet per blend was selected for use in determining the pellet impurity levels. Additional retainer pellets were selected for use in the event that additional pellet samples or analyses were required for a blend. For example, if a pellet broke prior to the DNG inspection, the broken pellet was replaced by one of the additional retainers. If adequate DNG inspection statistics (best estimate of total uranium weight percent and its variance) could not be obtained using twenty samples, some of the additional retainers were inspected to improve the statistics.

Seed and blanket binary blends were divided into from 10 to 36 batches of pellets, where each batch was held in a separate container labeled with the blend identity and the batch number (numbered sequentially starting with batch number 1). Note that there was no correspondence between powder batches and pellet blend batches because all batches of a powder blend were blended together (at final blending) prior to pressing pellets. The first pellets pressed for a blend went into the first batch and the last pellets pressed went into the last batch. Batches of a blend generally proceeded through the pellet processing (pressing, sintering, grinding and so on) in either ascending or descending order of batch number. Therefore, gradual variations in pellet properties throughout a blend, if present, might have been correlated against batch number. To ensure that the twenty pellets selected for dimensional, density and uranium inspections represented the entire blend, computer generated random sampling schedules were prepared in advance and a unique sampling schedule was used for each binary blend.

The computerized sampling schedules, examples of which are shown in Figures 5, 6 and 7, ensured that pellets were taken from batches in each blend at random but over all portions of the blend. Pellets comprising the twenty pellet samples were placed in a container with numbered compartments as specified (in random fashion) on the sampling sheet. The pellets assigned to compartments 1 through 5 were destructively analyzed for uranium content using wet chemistry (designated the chemistry pellets) and the sampling sheets ensured that the five chemistry pellets were representative of the entire blend. In using a sampling sheet like the one shown in Figure 5, the inspector recorded the blend identity and the number of batches and signed and dated the sheet. He then used the A, B and C columns on the sampling sheet corresponding to the number of batches in the blend. Inspection procedures were written which defined how Columns A, B and C were to be used to select pellet samples. For example, the procedures and the sheet shown in Figure 5 used with a 14 batch blend would have instructed the inspector to construct the twenty pellet sample as follows:

Select pellet #	from batch #	and place it in compartment #
1	1	11
2	1	17
3	2	4
4	3	5
5	4	14
6	4	16
7	5	6
8	6	1
9	6	15
10	7	12
11	7	18
12	8	10
13	9	7
14	10	13
15	11	9
16	11	20
17	12	8
18	13	2
19	14	3
20	14	19

In this case, the 5 chemistry pellets would come from batches 6, 13, 14, 2, and 3 (first 5 compartments). If the blend was comprised of a single uranium dioxide powder lot, the procedures and column C would instruct the inspector to obtain the single uranium isotopic sample from batch 2 and to obtain the impurity sample from batch 12. NPE, which stands for neutron poison equivalence -- a measure of total neutron poisoning of impurities, designates the impurity sample. The remaining batch numbers listed in column C would identify the batches from which to obtain additional retainer samples if required. If the blend was comprised of two uranium dioxide powder lots, the procedures and column C would instruct the inspector to obtain the three

SEED OR BLANKET PELLET SAMPLING SHEET NO. DNG-20-10-18-651

BLEND ID.................... BATCHES IN BLEND..........

SIGNATURE.................... DATE......................

NUMBER OF BATCHES																	
10		11		12		13		14		15		16		17		18	
A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
1	8	1	4	1	3	1	13	1	11	1	6	1	9	1	14	1	17
1	18	1	19	1	18	1	18	1	17	2	3	1	20	2	5	1	20
2	7	2	1	2	8	2	6	2	4	3	11	2	14	3	7	2	4
2	12	3	2	3	10	3	8	3	5	3	20	3	12	4	11	3	18
3	1	3	12	3	13	3	16	4	14	4	5	4	2	4	20	4	1
3	17	4	11	4	12	4	4	4	16	4	17	5	15	5	10	5	7
4	3	5	8	4	20	5	1	5	6	5	2	5	19	6	16	6	5
4	20	5	18	5	6	5	19	6	1	6	12	6	16	7	13	7	8
5	5	6	3	5	15	6	5	6	15	7	13	7	5	7	19	8	11
5	11	6	15	6	4	7	10	7	12	8	7	8	4	8	3	9	13
6	9	7	5	7	5	7	14	7	18	9	15	9	7	9	9	10	15
6	16	7	13	7	16	8	11	8	10	9	19	10	1	10	15	10	19
7	2	8	7	8	11	8	15	9	7	10	8	11	8	11	12	11	10
7	19	8	14	9	7	9	9	10	13	10	16	11	18	12	6	12	16
8	4	9	9	9	17	10	2	11	9	11	10	12	13	13	8	13	12
8	13	9	16	10	2	10	20	11	20	12	4	13	11	14	1	14	8
9	10	10	10	10	14	11	12	12	8	13	1	14	6	14	18	15	6
9	15	10	20	11	9	12	3	13	2	14	14	15	10	15	4	16	3
10	6	11	6	12	1	12	17	14	3	15	9	15	17	16	17	17	14
10	14	11	17	12	19	13	7	14	19	15	18	16	3	17	2	18	9

C	C	C	C	C	C	C	C	C
8	10	3	7	2	11	6	9	14
2	11	6	5	12	8	4	13	4
4	5	11	1	8	10	13	12	15
3	6	5	10	13	14	5	8	2
1	3	1	9	9	9	15	16	17
6	8	12	12	7	3	16	2	10
5	9	10	4	1	1	7	10	12
9	1	7	8	5	7	9	3	5
7	2	9	3	3	12	14	7	11
10	7	8	2	6	13	12	4	8

USE COLUMNS A, B, AND C CORRESPONDING TO NUMBER OF BATCHES IN BLEND.

COLUMN A -- BATCH IDENTITIES FOR CHEMISTRY W/O AND PELLET ASSAY GAGE SAMPLES

COLUMN B -- LOCATION IN COMPARTMENTED CONTAINER FOR CHEMISTRY W/O AND PELLET ASSAY GAGE SAMPLES

COLUMN C -- BATCH IDENTITIES FOR ISOTOPIC, NPE, AND ADDITIONAL RETAINER SAMPLES

IF A BATCH IS NOT AVAILABLE FOR SAMPLING, SELECT A PELLET FROM THE NEXT HIGHER BATCH OR THE NEXT LOWER BATCH.

FIGURE 5

EXAMPLE OF COMPUTER GENERATED PELLET SAMPLING SHEET FOR 10 TO 18 BATCHES PER BLEND

SEED OR BLANKET PELLET SAMPLING SHEET NO. DNG-20-19-27-651

BLEND ID.................... BATCHES IN BLEND..........

SIGNATURE.................... DATE......................

NUMBER OF BATCHES

19		20		21		22		23		24		25		26		27	
A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
1	6	1	20	1	5	1	18	1	7	1	4	2	18	1	15	1	18
2	10	2	12	2	14	2	8	2	9	3	6	3	14	2	1	3	1
3	5	3	13	3	13	4	14	3	8	4	5	4	8	3	2	4	15
4	15	4	17	4	16	5	5	4	13	6	13	5	7	5	16	5	10
5	1	5	16	6	9	6	4	5	4	7	16	6	19	6	18	7	12
6	7	6	5	7	4	7	9	7	16	8	20	7	11	7	4	8	11
7	19	7	7	8	19	8	16	8	5	9	7	9	6	8	12	10	16
8	17	8	6	9	15	10	7	9	1	10	11	10	13	9	8	11	5
9	11	9	11	10	20	11	13	10	2	11	19	11	1	10	6	12	19
10	18	10	19	11	1	12	6	12	19	13	8	12	5	12	14	13	17
11	3	11	9	12	6	13	17	13	12	14	2	13	17	13	20	14	8
11	20	12	3	13	17	14	20	14	20	15	14	15	12	15	10	15	6
12	2	13	14	14	3	15	3	15	17	16	18	16	10	16	5	16	20
13	13	14	15	15	2	16	12	17	3	17	15	18	4	17	9	17	13
14	12	15	1	16	7	17	19	18	10	18	9	20	9	19	17	19	2
15	9	16	10	17	10	18	11	19	15	20	12	21	20	21	19	20	3
16	14	17	2	18	8	19	2	20	6	21	10	22	3	23	7	21	14
17	8	18	8	19	12	20	15	21	14	22	3	23	16	24	3	24	4
18	4	19	18	20	11	21	10	22	18	23	1	24	2	25	11	25	9
19	16	20	4	21	18	22	1	23	11	24	17	25	15	26	13	26	7

19	20	21	22	23	24	25	26	27
C	C	C	C	C	C	C	C	C
1	18	2	3	21	11	16	22	15
17	5	12	5	3	17	23	23	12
13	13	20	11	1	16	12	20	9
19	12	5	15	4	22	9	17	23
2	10	17	20	12	9	14	15	21
18	4	15	9	11	14	20	9	16
11	8	4	13	22	5	15	3	5
15	7	3	2	15	21	6	1	4
16	3	8	14	16	8	4	13	2
10	15	19	6	10	19	1	6	19

USE COLUMNS A, B, AND C CORRESPONDING TO NUMBER OF BATCHES IN BLEND.

COLUMN A -- BATCH IDENTITIES FOR CHEMISTRY W/O AND PELLET ASSAY GAGE SAMPLES

COLUMN B -- LOCATION IN COMPARTMENTED CONTAINER FOR CHEMISTRY W/O AND PELLET ASSAY GAGE SAMPLES

COLUMN C -- BATCH IDENTITIES FOR ISOTOPIC, NPE, AND ADDITIONAL RETAINER SAMPLES

IF A BATCH IS NOT AVAILABLE FOR SAMPLING, SELECT A PELLET FROM THE NEXT HIGHER BATCH OR THE NEXT LOWER BATCH.

FIGURE 6

EXAMPLE OF COMPUTER GENERATED PELLET SAMPLING SHEET FOR 19 TO 27 BATCHES PER BLEND

SEED OR BLANKET PELLET SAMPLING SHEET NO. DNG-20-28-36-651

BLEND ID..................... BATCHES IN BLEND..........

SIGNATURE.................... DATE......................

NUMBER OF BATCHES

28		29		30		31		32		33		34		35		36	
A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
2	15	1	16	1	5	2	4	1	20	1	10	1	18	1	1	1	19
3	4	2	7	2	16	3	11	4	3	3	3	3	17	3	3	4	4
4	8	3	6	3	3	4	14	5	18	4	9	4	6	5	15	6	20
5	20	4	17	4	15	6	2	6	14	7	7	6	10	6	12	8	7
6	13	6	20	5	13	8	15	7	5	8	14	9	12	8	10	10	11
8	6	7	5	6	17	10	6	8	2	10	4	11	7	10	18	11	17
9	1	8	3	8	11	12	8	10	7	12	1	13	13	13	4	14	1
10	18	10	8	10	18	14	18	13	15	13	13	15	9	14	5	15	18
13	19	13	10	11	1	15	10	14	13	15	5	16	15	17	17	17	16
15	17	14	2	12	14	16	13	15	12	16	2	19	5	18	7	19	5
16	5	15	15	13	10	17	12	18	17	18	8	20	16	20	11	21	2
17	9	17	11	15	6	19	1	19	19	19	17	21	2	22	14	22	12
20	12	18	12	16	4	21	3	21	16	21	11	23	3	23	13	24	10
21	11	19	4	17	8	22	9	22	6	22	12	25	1	25	8	25	14
22	3	21	1	20	7	24	5	25	4	24	18	26	14	26	16	27	6
23	2	22	14	22	9	25	17	26	10	26	20	27	8	28	6	29	8
24	7	23	13	23	12	27	20	27	9	27	6	28	19	30	9	32	3
25	10	25	18	26	19	29	16	29	1	29	16	30	11	31	19	33	9
26	14	27	9	27	2	30	19	30	11	31	19	31	4	33	2	35	15
28	16	29	19	29	20	31	7	32	8	32	15	33	20	35	20	36	13

C	C	C	C	C	C	C	C	C
14	10	5	13	10	7	5	4	13
22	14	15	27	14	31	23	13	18
13	6	14	4	1	13	7	12	9
16	24	25	23	22	15	25	23	22
24	5	28	29	19	5	8	10	28
20	21	23	22	9	30	1	20	6
12	2	2	1	20	2	21	11	27
18	3	11	7	26	12	18	8	26
26	27	7	30	13	17	15	3	2
2	7	29	24	30	19	2	32	3

USE COLUMNS A, B, AND C CORRESPONDING TO NUMBER OF BATCHES IN BLEND.

COLUMN A -- BATCH IDENTITIES FOR CHEMISTRY W/O AND PELLET ASSAY GAGE SAMPLES

COLUMN B -- LOCATION IN COMPARTMENTED CONTAINER FOR CHEMISTRY W/O AND PELLET ASSAY GAGE SAMPLES

COLUMN C -- BATCH IDENTITIES FOR ISOTOPIC, NPE, AND ADDITIONAL RETAINER SAMPLES

IF A BATCH IS NOT AVAILABLE FOR SAMPLING, SELECT A PELLET FROM THE NEXT HIGHER BATCH OR THE NEXT LOWER BATCH.

FIGURE 7

EXAMPLE OF COMPUTER GENERATED PELLET SAMPLING SHEET FOR 28 TO 36 BATCHES PER BLEND

uranium isotopic samples from batches 2, 12 and 8 and the impurity sample from batch 13. Note that each of the fourteen batches in the above example contributed a pellet to the twenty pellet sample and that batches 1, 4, 6, 7, 11 and 14 contributed the remaining six pellets. To ensure that those six pellets would be representative of the entire blend, the computer program which was used to generate the sheets grouped the batches into six groups of either two or three batches, decided at random, and then a batch from each group was randomly selected. For the fourteen batch blend of Figure 5, randomly constructed groups were determined and a batch from each group was randomly selected as depicted below:

Group #	Batches in Group	Batch Selected
1	1,2	1
2	3,4	4
3	5,6	6
4	7,8,9	7
5	10,11,12	11
6	13,14	14

The same computerized procedure was used to generate random sampling sheets for those blends consisting of from 10 to 19 batches. For blends with twenty batches, one pellet was chosen from each batch. For blends consisting of 21 to 36 batches, a random blocking and random selection process similar to that described above was used. The sampling sheets constructed using the computer program ensured that the pellet samples used for the inspections pertinent to loading assurance (density, total uranium content and uranium isotopic content) were unbiased and representative of the entire blend in each case. Furthermore, the sampling sheets provided a record of the binary sampling process.

C. Nondestructive and Destructive Assay of Binary Fuel Pellets

The assays performed on binary fuel pellets to determine uranium content (total and fissile) constituted one of the key loading assurance operations of LWBR fabrication. The assays provided (1) the best estimate and uncertainty of the total uranium content for each binary blend and (2) confirmation that each binary blend satisfied the fissile loading requirements. The assay data were used to determine the fissile loading and uncertainty of binary pellets in each fuel rod, in each composition and in the entire core. All twenty pellets sampled from a blend were nondestructively assayed using the Delayed Neutron Gage (DNG) described in Reference 5. A detailed description of the use of the gage during LWBR fabrication, including the analysis methods, operating experiences and assay results, is contained in Reference 6. A description of the computerized flow of data, which consisted of results from the DNG combined with results from the destructive assay (chemistry) on five of the twenty pellets sampled per blend, is presented below.

For each binary blend fabricated, DNG inspection data were collected, printed and automatically punched on paper tape for each of the twenty pellets assayed. (The reader is directed to Reference 6 for a detailed description of this process). The paper tape was read into the DEC-10 computer * and its contents were stored on disk and verified by comparing the filed data to the data printout produced during the DNG inspection. Results of the geometric inspections on the twenty pellets (diameter, length, weight and density measurements) were manually entered into the DEC-10 computer and stored on disk. The pellet selected from each blend for uranium isotopic inspection (three pellets in the case of blends comprised of two UO_2 powder lots) was analyzed using a mass spectrometer to determine the relative concentrations of U^{232}, U^{233}, U^{234}, U^{235}, U^{236} and U^{238}. These inspection data were manually entered into the DEC-10 computer and stored on disk. DEC-10 computer programs used the filed DNG data, the pellet geometry data and the uranium isotopic data to compute the gage estimates of total uranium content (weight percent total uranium) and related statistics (pellet-to-pellet variation, gage calibration uncertainty and gage weight percent U^{total} uncertainty, Ref. 6). These results were stored in a binary blend data file on the DEC-10 along with the geometry and isotopic data. Upon completion of the DNG inspection,

* The Digital Equipment Corporation DEC-10 computer, with remote terminals, was connected to the Control Data Corporation computer (CDC-6600) on which the fuel rod and module loading assurance calculations were performed.

pellets in compartments 1 through 5 of each twenty pellet sample were destructively analyzed by wet chemistry to determine the total uranium content of each pellet. During the inspections the identities of the sample pellets and their inspection results were carefully maintained for traceability. The chemistry results were manually entered into the DEC-10 computer, verified and filed in the binary blend data file. A computer program performed the necessary computations to combine the gage results and the chemistry results to produce the best estimate of the blend weight percent total uranium and the uncertainty. These results were also filed in the binary blend data file. The related computer operations saved hundreds of man-hours of tedious hand calculations and provided assurance that the calculations were correct.

DNG, chemistry and mass spectrometer inspections used to assay binary fuel pellets provided a reliable and efficient way to determine the total and fissile uranium content of binary fuel manufactured for LWBR. The results confirmed that all binary pellets used in the core were fabricated with the specified uranium content for the respective zones. Since the assay results on binary blends were saved in a computer file, a database existed for later use in computing rod and core loadings.

D. Loading Assurance Results for Fuel Pellets

Table 3 summarizes the rates of pellet rejects for deviant pellet diameter, length and fissile content during LWBR pellet fabrication. As discussed previously, these characteristics were important for loading assurance. Fewer than one percent of the binary pellets were rejected for exceeding the diameter requirements. Fewer than one tenth of one percent of the binary pellets were rejected for exceeding the length requirements. Approximately 850 binary pellet blends of all types were manufactured for LWBR. Of these only one blend (high zone seed) was rejected for failing the fissile loading requirements. The reject rate for thoria pellet diameter ranged from near zero for several campaigns to 3.6% for the first standard blanket thoria campaign. Thoria pellet reject rates and binary pellet reject rates for diameter were similar to each other.

TABLE 3

PELLET REJECT RATES FOR DIAMETER, LENGTH AND FISSILE CONTENT

		Percent of Pellets				Failed
	Number of Blends	Under Diameter	Over Diameter	Under Length	Over Length	Fissile Content
Low Zone Seed						
First Campaign	73	0.8	0.0	0.0	0.0	0
Second Campaign	80	0.9	0.2	0.0	0.0	0
High Zone Seed						
First Campaign	65	0.4	0.0	0.0	0.0	1
Second Campaign	190	1.0	0.0	0.0	0.0	0
Low Standard Blanket	36	1.0	0.2	0.0	0.0	0
Medium Standard Blanket						
First Campaign	82	0.4	0.3	0.1	0.0	0
Second Campaign	98	0.5	1.2	0.0	0.0	0
High Standard Blanket	75	0.6	0.1	0.0	0.0	0
Low PFB	20	0.2	0.1	0.0	0.0	0
Medium PFB	20	0.1	1.2	0.0	0.0	0
High PFB	114	0.2	0.1	0.0	0.0	0
Seed Thoria						
First Campaign	79	2.0	1.2	~0.0	~0.0	-
Second Campaign	62	0.1	0.3	~0.0	0.0	-
Standard Blanket Thoria						
First Campaign	275	3.6	0.5	0.1	0.1	-
Second Campaign	116	0.2	0.1	0.1	0.1	-
PFB Thoria						
First Campaign	107	0.4	0.9	0.0	0.0	-
Second Campaign	88	0.2	0.1	0.0	0.0	-
Reflector	868	2.4	0.7	0.0	0.0	-

IV. FUEL RODS

Fuel pellet blends which passed all criteria for use in LWBR fuel rods were released for loading into Zircaloy tubes. Loading was accomplished at a pair of loading lines consisting of two gloveboxes each, one for binary fuel pellets and one for thoria fuel pellets (Ref. 2). After loading, the rods were sealed by welding end caps to the tube ends and the fuel rods were X-rayed to assess the condition of the fuel pellets and fuel stacks. Rod manufacturing was completed by pickling, corrosion testing and final inspecting, which included a second X-ray. Rods which satisfactorily completed all inspection requirements were released for use in modules, cleaned, lubricated and transferred to the core module assembly area. Loading assurance steps employed during fuel rod fabrication are described in this section.

A. Distinguishing Characteristics of Fuel Rods

Figure 8 shows components and dimensions of seed fuel rods. Figures 9 and 10 show blanket and reflector rods, respectively. Figure 11 shows fuel zone arrangements for seed, blanket and reflector rods. Each fuel rod consisted of Zircaloy tubing containing fuel pellets and a top plenum region for trapping fission gases. The plenum contained an Inconel plenum spring in all rod types plus a stainless steel support sleeve in the blanket and reflector rods. The rods were sealed by Zircaloy endclosures welded on both ends. Reflector fuel rods contained a single stack of thoria pellets; seed and blanket fuel rods contained a stack of thoria pellets at the bottom, a stack of binary pellets in the middle and another stack of thoria pellets at the top. The two endclosures on each rod differed; one was designed to be attached to a module's top or bottom baseplate (fixed end), the other was designed to be free (free end). Approximately half the rods were designed to be held in place at the top of a module (top mounted); the rest were designed to be held at the bottom (bottom mounted). Considering mounting method and fuel zoning, LWBR contained 23 different rod types (8 seed types, 6 standard blanket types, 7 power flattening blanket types and 2 reflector types).

Table 4 lists the distinguishing characteristics of the 23 types of fuel rods used in the LWBR core. The two digit rod type number (01 through 08 for seed, 11 through 16 for standard blanket, 21 through 27 for power flattening blanket and 31 and 32 for reflector) formed the first two digits of a seven digit rod serial number engraved on each fuel rod's endclosures. Therefore, the first two digits of a rod's serial number identified the characteristics of the rod as listed in Table 4. For example, a rod whose serial number started with the digits 13 was a high zone standard blanket rod. Even numbered rod types were mounted at the top and odd numbered rod types were mounted at the bottom. A first digit of zero in a rod serial number identified a seed rod; 1 identified a standard blanket rod; 2 identified a power flattening blanket rod; 3 identified a reflector rod. The seventh digit of a fuel rod serial number was determined from the first six digits using an algorithm which permitted only certain combinations of the seven digits to form a valid serial number. The digit 9 was not permitted for any of the first six digits. Given the first six digits of a fuel rod serial number, I_1 through I_6, the seventh digit, I_7, was calculated as follows:

1. $J = 11 \cdot (I_1 - I_2 + I_3 - I_4 + I_5 - I_6) + 264$

2. I_7 = middle digit of J.

For example, the serial number 1302469 is valid because

1. $J = 11 \cdot (1 - 3 + 0 - 2 + 4 - 6) + 264 = 198$

2. I_7 = middle digit of 198 = 9.

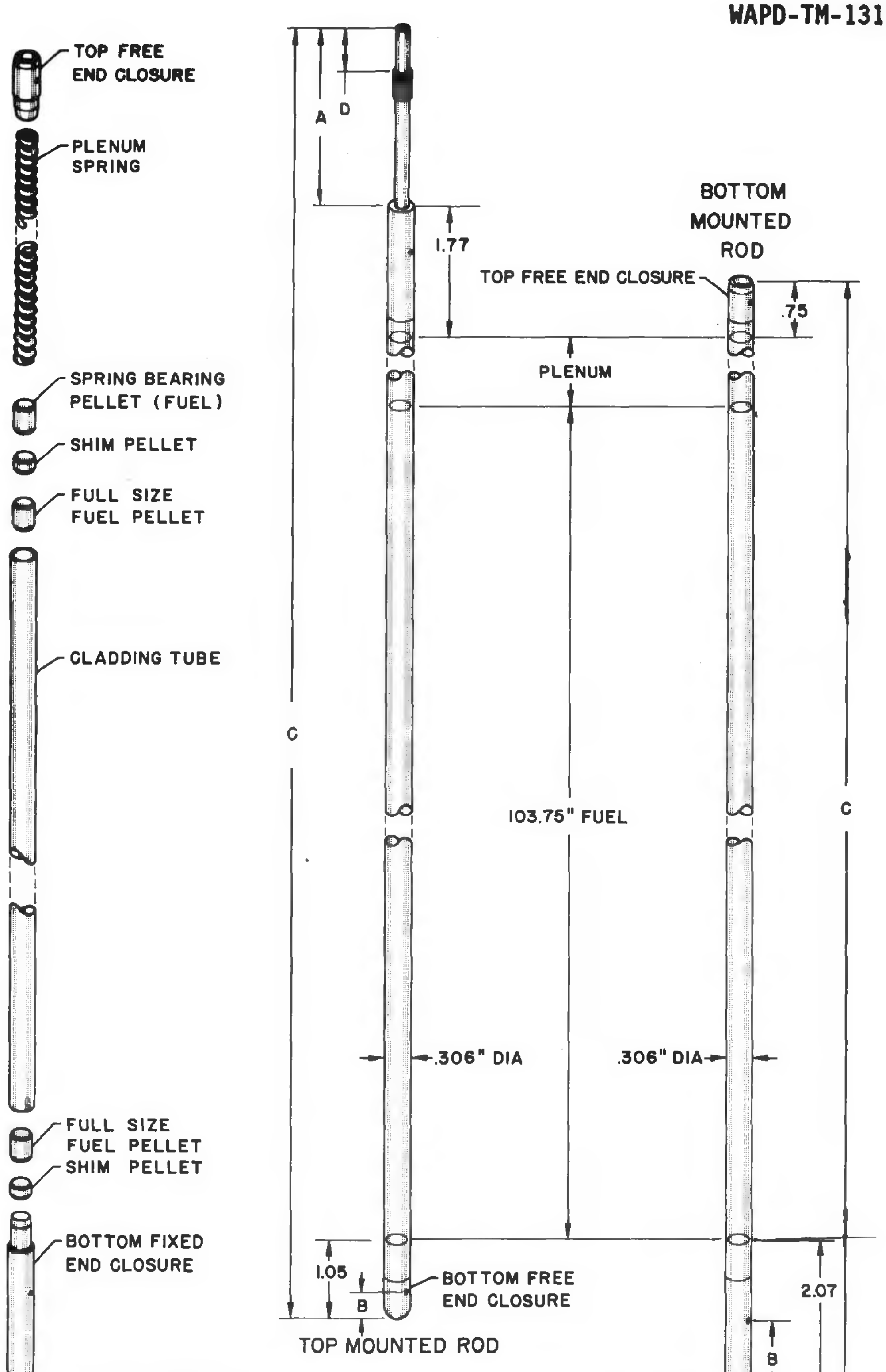
The serial number algorithm was used to detect transcription errors, such as the transposition of consecutive pairs of digits, on inspection records and in computer files. The computers used with the inspection equipment, for example the Pellet Length Gage, were programmed to perform the serial number check to ensure that the proper type of rod was being inspected. The engraved fuel rod serial number was useful for confirming that fuel rods were fabricated correctly and were correctly installed in modules, as will be shown in later sections of this report.

The fuel stack length columns in Table 4 refer to the fuel zones shown in Figure 11. The binary zones were loaded with fissile fuel in UO_2-ThO_2 pellets. These zones had relatively large tolerances (approximately ± one half pellet length) so that partial length binary pellets would not be needed. Tight control of the position of the upper binary-thoria interface in seed rods was maintained by a ±.060 inch tolerance on binary plus bottom thoria stack length (second length column in Table 4). This tolerance was achieved by using thoria pellets of various lengths, called shim pellets, to adjust the stack length. Shim pellets were made by grinding normal length thoria pellets to shorter lengths. The position of the lower binary-thoria interface in blanket rods (both standard and power flattening) was controlled using thoria shim pellets to obtain a ±.060 inch tolerance on bottom thoria stack length. The overall stack length (third length column in Table 4) was controlled as a minimum required length, again using shim pellets. The topmost pellet in all rods was adjacent to the plenum; therefore, a special spring bearing thoria pellet with no end dish was required in this position.

Dimension A in Table 4 and in Figures 8 and 9 is the fixed endclosure stem length; dimension B is the identity hole location (the distance from the end of the endclosure to a hole drilled part way into the endclosure). Each binary rod type was assigned a unique stem length and identity hole location combination. These two dimensions were checked during module inspections to confirm that the different types of rods were installed in the correct module cell locations. The last two columns in Table 4 list the fuel rod outer diameter requirements and the fissile loading (grams per inch) requirements for each rod type.

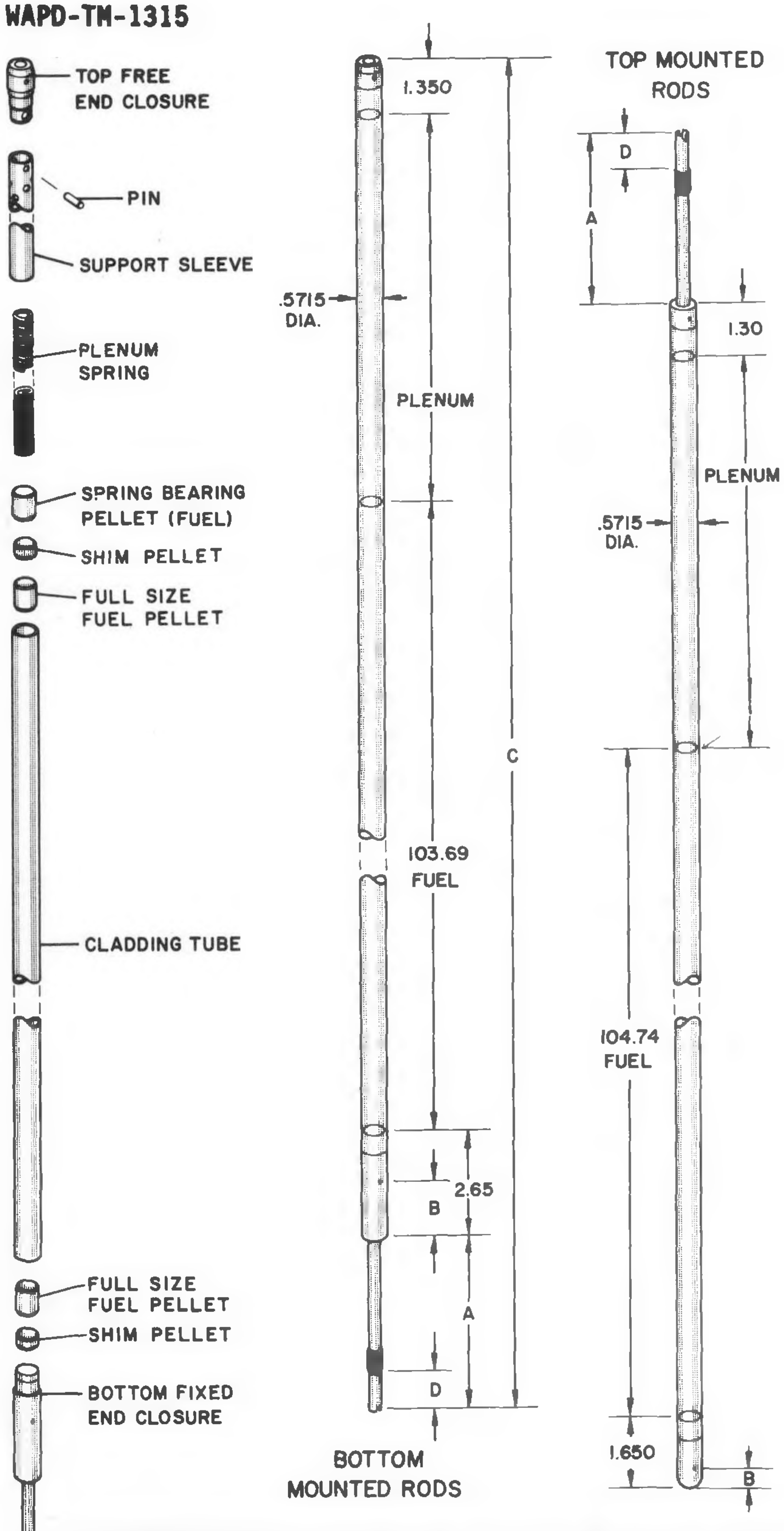
In addition to various dimensions which distinguished fuel rod types, top and bottom mounted rods could be identified by the shape of the endclosure on a rod's free end. The free endclosure on top mounted rods had a spherical end whereas the free endclosure on bottom mounted rods had a flattened end with an axial threaded hole. This characteristic was used during module visual inspections to confirm that only top mounted rods were in top mounted cell locations and that only bottom mounted rods were in bottom mounted cell locations. Power flattening blanket (PFB) rods could be distinguished from standard blanket rods by notches machined into the stem end of all PFB rods.

No notches existed on standard blanket stem ends. All PFB and standard blanket rods were either photographed or radiographed to confirm the presence of notches on PFB rods and the absence of notches on standard blanket rods. These notches provided a visual check during module assembly and inspection (Section V) that PFB and standard blanket rods were correctly installed.



FUEL ROD TYPE NO.	01	02	03	04	05	06	07	08
DIMENSION A	2.40	2.40	2.52	2.52	2.65	2.65	1.75	1.75
DIMENSION B	1.10	.20	1.20	.30	1.30	.40	1.10	.20
DIMENSION C	119.02	119.02	119.14	119.14	119.27	119.27	118.37	118.37
DIMENSION D	.60	.60	.72	.72	.85	.85	.47	.47

FIGURE 8
COMPONENTS AND DIMENSIONS OF SEED FUEL RODS
(All Dimensions in Inches)



FUEL ROD TYPE NO.	11	12	13	14	15	16	21	22	23	24	25	26	27
DIMENSION - A	4.23	4.23	4.35	4.35	4.47	4.47	4.23	4.23	4.35	4.35	4.47	4.47	4.60
DIMENSION - B	1.40	.50	1.50	.60	1.60	.70	1.70	.80	1.80	.90	1.90	1.00	2.00
DIMENSION - C ± .07	121.9	121.9	122.0	122.0	122.1	122.1	121.9	121.9	122.0	122.0	122.1	122.1	122.3
DIMENSION - D	.78	.78	.90	.90	1.03	1.03	.78	.78	.90	.90	1.03	1.03	1.16

FIGURE 9
COMPONENTS AND DIMENSIONS OF BLANKET FUEL RODS
(All Dimensions in Inches)

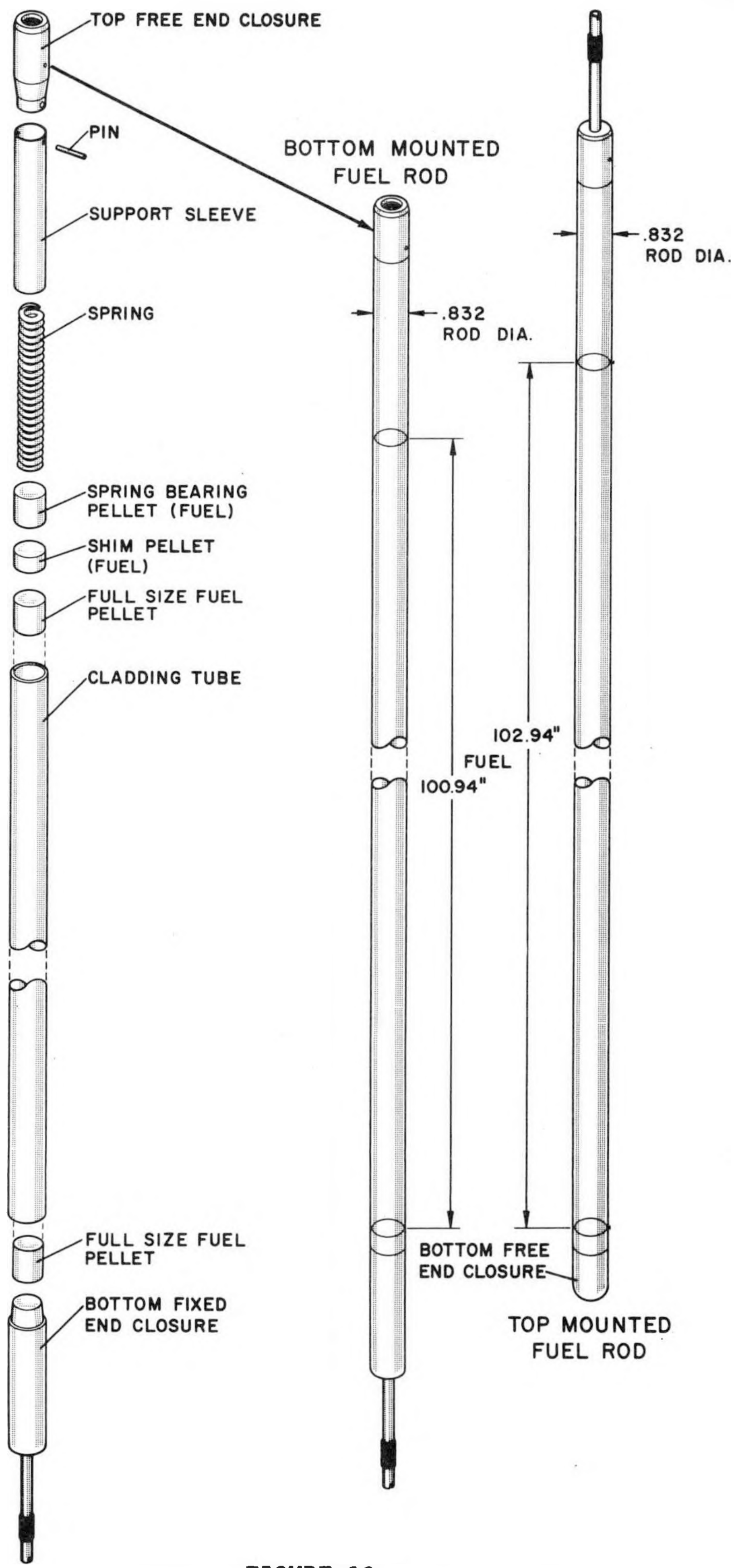
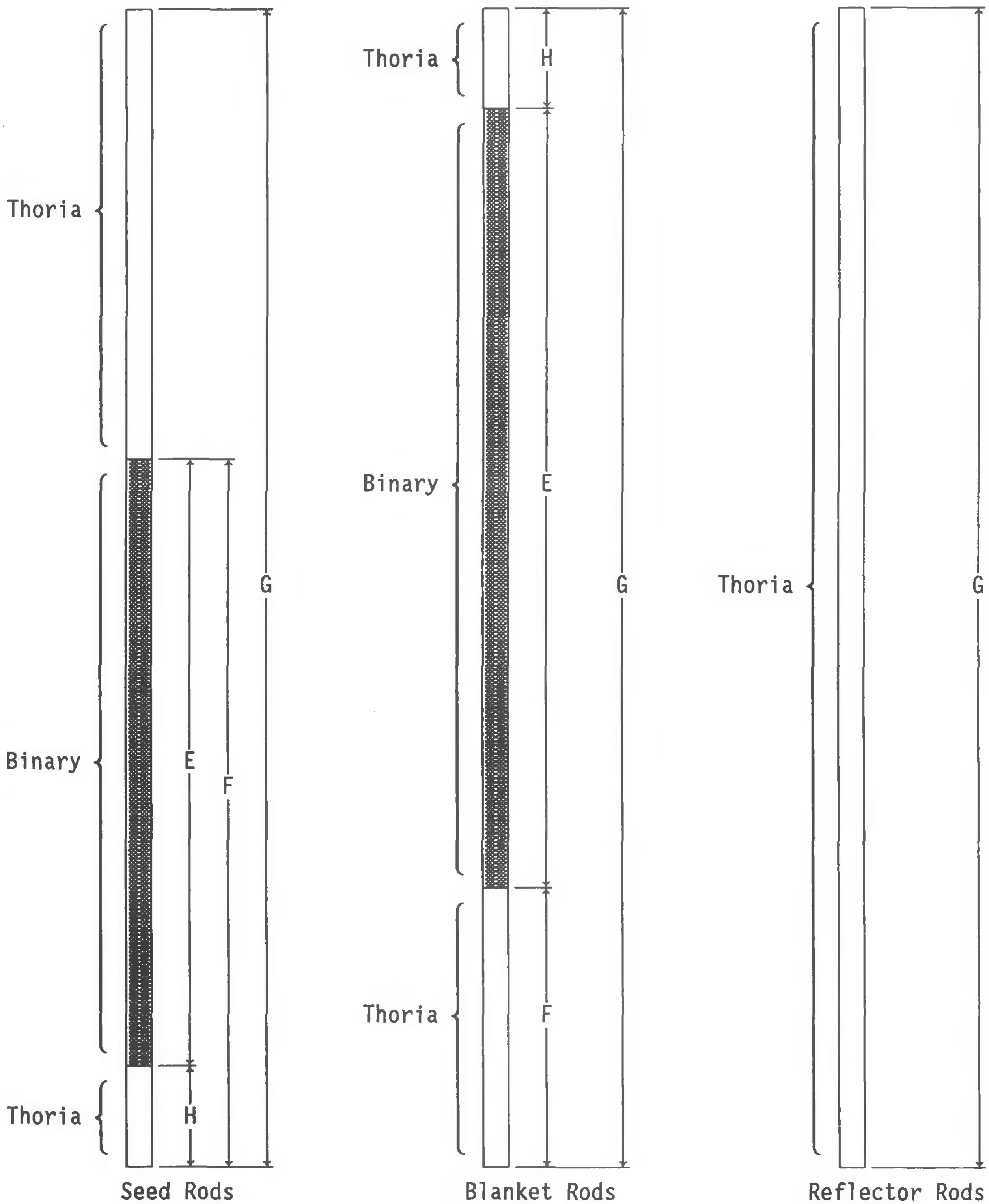


FIGURE 10
COMPONENTS AND DIMENSIONS OF REFLECTOR FUEL RODS
(All Dimensions in Inches)



(Fuel stack dimensions E, F, G and H are listed by rod type in Table 4.)

FIGURE 11
FUEL ZONE ARRANGEMENTS FOR LWBR FUEL RODS

TABLE 4

PHYSICAL CHARACTERISTICS OF LWBR FUEL RODS

Rod Type	Core Region	Binary Zone Type	Fuel Stack Lengths E (1)	F (1)	G (1)	H (2)	Fuel Pellet Lengths Binary	Thoria	Stem Length A (3)	Identity Hole Location B (3)	Outer Diameter	Fissile Loading (grams/inch)
			Binary	Binary plus Bottom Thoria	Minimum Overall	Bottom Thoria						
01	.	Low	42.000±.232	51.780±.060	103.740	9.78	.445±.020	.530±.020	2.400±.040	1.100±.030	.3060±.0015	.3379±.0081
02	.	Low	42.000±.232	50.920±.060	103.740	8.92	.445±.020	.530±.020	2.400±.040	.200±.030	.3060±.0015	.3379±.0081
03	.	Low	56.000±.232	65.780±.060	103.740	9.78	.445±.020	.530±.020	2.525±.040	1.200±.030	.3060±.0015	.3379±.0081
04	Seed	Low	70.000±.232	78.920±.060	103.740	8.92	.445±.020	.530±.020	2.525±.040	.300±.030	.3060±.0015	.3379±.0081
05	.	High	84.000±.318	93.780±.060	103.740	9.78	.615±.020	.530±.020	2.650±.040	1.300±.030	.3060±.0015	.4078±.0098
06	.	High	84.000±.318	92.920±.060	103.740	8.92	.615±.020	.530±.020	2.650±.040	.400±.030	.3060±.0015	.4078±.0098
07	.	Low	42.000±.232	51.780±.060	103.740	9.78	.445±.020	.530±.020	1.750±.040	1.100±.030	.3060±.0015	.3379±.0081
08	.	Low	42.000±.232	50.920±.060	103.740	8.92	.445±.020	.530±.020	1.750±.040	.200±.030	.3060±.0015	.3379±.0081
			Binary	Bottom Thoria	Minimum Overall	Top Thoria						
11	.	Low	42.000±.275	53.500±.060	103.690	8.19	.530±.020	.615±.020	4.225±.040	1.400±.030	.5715±.0020	.3843±.0115
12	.	Low	42.000±.275	51.500±.060	104.740	11.24	.530±.020	.615±.020	4.225±.040	.500±.030	.5715±.0020	.3843±.0115
13	Standard	High	70.000±.530	25.500±.060	103.690	8.19	.785±.020	.615±.020	4.350±.040	1.500±.030	.5715±.0020	.6425±.0193
14	Blanket	Medium	56.000±.445	37.500±.060	104.740	11.24	.870±.020	.615±.020	4.350±.040	.600±.030	.5715±.0020	.5325±.0160
15	.	Medium	84.000±.445	11.500±.060	103.690	8.19	.870±.020	.615±.020	4.475±.040	1.600±.030	.5715±.0020	.5325±.0160
16	.	High	84.000±.530	9.500±.060	104.740	11.24	.785±.020	.615±.020	4.475±.040	.700±.030	.5715±.0020	.6425±.0193
			Binary	Bottom Thoria	Minimum Overall	Top Thoria						
21	.	Low	42.000±.402	53.500±.060	103.690	8.19	.870±.020	.445±.020	4.225±.040	1.700±.030	.5275±.0020	.4463±.0134
22	.	Low	42.000±.402	51.500±.060	104.740	11.24	.870±.020	.445±.020	4.225±.040	.800±.030	.5275±.0020	.4463±.0134
23	Power	High	70.000±.488	25.500±.060	103.690	8.19	.700±.020	.445±.020	4.350±.040	1.800±.030	.5275±.0020	.7423±.0223
24	Flattening	Medium	56.000±.360	37.500±.060	104.740	11.24	.785±.020	.445±.020	4.350±.040	.900±.030	.5275±.0020	.5418±.0163
25	Blanket	High	84.000±.488	11.500±.060	103.690	8.19	.700±.020	.445±.020	4.475±.040	1.900±.030	.5275±.0020	.7423±.0223
26	.	High	8.4000±.488	9.500±.060	104.740	11.24	.700±.020	.445±.020	4.475±.040	1.000±.030	.5275±.0020	.7423±.0223
27	.	Medium	84.000±.360	11.500±.060	103.690	8.19	.785±.020	.445±.020	4.600±.040	2.000±.030	.5275±.0020	.5418±.0163
					Minimum Overall							
31	Reflector				100.940			.740±.060			.832±.042	0
32	.				102.940			.740±.060			.832±.042	0

(1) See Figure 11.
(2) Reference dimensions since dimensions E, F and G determine H. See Figure 11.
(3) See Figures 8, 9 and 10.
(4) All dimensions in inches.

B. Fuel Pellet Stacking and Loading Into Fuel Rods

Fuel pellet stacks were made to required lengths and loaded into fuel rods at two separate loading lines during LWBR fabrication. Rods of only one type were loaded on a given loading line. That is, each line was scheduled for loading rods of a single type during a specific time interval. Each fuel rod's top and bottom endclosures were engraved with the 7-digit rod serial number. The bottom endclosure was pressed into the tubing and welded before the tubing was positioned in the loading line ready to receive pellets.

Binary fuel pellets were vacuum degassed in a high temperature furnace and transferred to the binary glovebox located at the opposite end of the loading line from the tubing. Only binary pellets of the correct type, confirmed by the middle digit of the blend identity (Table 2) and by the end markings, for the rods being loaded were placed in the binary glovebox. The pellets were placed end to end in sufficient quantity to produce the required binary stack length (measured to the nearest thousandth of an inch). A relatively wide tolerance band on binary stack lengths (dimension E in Table 4) ensured that the binary stack could be produced without the need for binary shim pellets. Using binary shim pellets would have required grinding pellets containing fissile uranium which would have produced fissile bearing dust. The rod serial number, measured binary stack length and binary blend identity and pellet quantity for each binary blend used in the stack * were recorded on a stacking data sheet. The binary pellets were then transferred to the thoria glovebox, located between the binary glovebox and the empty tubing, for weighing.

The binary pellets were restacked onto the thoria stacking vee (by binary blend identity for stacks comprised of more than one blend), weighed and the weight of each different blend of the binary stack was recorded to the nearest tenth of a gram on the stacking data sheet. To ensure that no weighing error had been made, a calculation of binary linear density (grams per inch) was made for each different blend of the binary stack before proceeding to the

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* Most rods contained binary pellets from only one blend.

thoria stacking operations. The calculation involved computing the linear density for the i^{th} binary blend of the stack, B_i, given the weight of the i^{th} binary blend, W_{Bi}, the quantity of pellets in the i^{th} binary blend, n_i, the total number of binary pellets, n, and the total length of the binary stack, E, as follows:

$$B_i = \frac{W_{Bi}}{(n_i/n)\ E} = \frac{n\ W_{Bi}}{n_i\ E}$$

Each calculated binary linear density B_i was compared to an acceptable range for the binary type being loaded. The stacks were reweighed if the calculated linear density fell outside the specified range. After checking the binary weights via the linear density calculation, thoria pellets were added to the thoria stacking vee at the bottom end of the binary stack. Thoria shim pellets (partial lengths) were used to meet the relatively tight requirement for length F in Table 4. Thoria pellets were then added to the top end to meet the requirement for length G in Table 4. The topmost thoria pellet was a special plenum spring bearing pellet, with no end dish, for contacting the plenum spring which held the pellet stack in place within the rod. Lengths E, F and G were recorded to the nearest thousandth of an inch. The total fuel stack was weighed and the total thoria stack weight was recorded to the nearest tenth of a gram. The thoria stack weight was checked by calculating the thoria linear density, T, from the thoria weight, W_t, and the stack lengths E and G as follows:

$$T = \frac{W_t}{G-E}$$

If the calculated thoria linear density fell outside a specified range, the stacks were reweighed and remeasured. Originally the measuring and recording of stack lengths were manual operations. Later, equipment was installed which automatically transferred length measurement data to a programmable calculator for calculating and recording stack lengths. After confirming the weights and lengths, the fuel pellets were transferred into the tubing in proper sequence. The plenum spring and sleeve were inserted into the tubing, then the top endclosure was inserted and welded in place.

The stacking data sheets prepared at the time of rod loading constituted the permanent record of the fuel content of each fuel rod fabricated for LWBR. Data pertinent to rod loading assurance and data needed for calculations of the as-built core were entered into the computer from the stacking data sheets for each fuel rod. These data included the following:

1. fuel stack lengths E, F and G in Table 4
2. total thoria fuel weight
3. identity of each binary blend in the rod
4. quantity of pellets used from each binary blend
5. weight of pellets used from each binary blend.

The ASBLT computer program (Ref. 7) maintained a database of binary blend data (Section III) and a database of fuel rod data (including the above) and used these data to calculate the fissile and fertile loadings for all binary fuel rods fabricated for LWBR. ASBLT also calculated the fuel rod loading precision, that is, the uncertainty in fissile loading at the 95% confidence level. These computer calculations saved thousands of man-hours of hand calculations as well as providing assurance that the calculated rod loadings were correct and that the rod fissile loadings met the specified requirements.

C. In-Motion Radiography

Assembled fuel rods were passed through an X-ray machine and radiographed while in motion. Several radiographs were taken of each rod producing different rotational views of the internal characteristics of each rod. Two sets of radiographs were made for each rod -- one shortly after the rod loading operation (In-Process, one orientation) and one after the rod was finished (Final, several rotational orientations to view the entire rod circumference). The radiographs were used to inspect assembled fuel rods for external and internal dimensions and for pellet integrity as described in References 8 and 9. The radiographs were read by a Film Dimensional Gage (Ref. 8) which determined the dimensions E, F, G, A and B in Table 4 along with the lengths of the first two pellets in the bottom thoria stack and the last two pellets in the top thoria stack and recorded the results for use in the ASBLT program on the CDC-6600 computer. ASBLT compared the fuel stack lengths (E, F and G) obtained from both the In-Process and Final radiographs to those recorded during rod loading and required that they agree to within ±.050 inch, which allowed for pellet stack settling and expansion during transport. All dimensions checked by ASBLT were required to meet the specified values in Table 4.

The lengths of the first and last two pellets in a rod were checked by the ASBLT computer program because of limitations of the Pellet Length Gage (PLG), an electro-optical measuring device which is described in Reference 9. The PLG was used to measure the length of each fuel pellet from the radiographs. Fuel pellet lengths and fuel rod types were directly related as shown in Table 4; therefore, the PLG was used to verify that each rod contained only the required pellets in each zone and that the binary/thoria interfaces were located per the drawing requirements. Reference 8 describes the in-motion radiography inspection process and presents typical radiographs of LWBR fuel rods (page 26) showing that binary and thoria pellets could be distinguished from one another by the pellet lengths. In addition, pellet diameters were measured from the film to confirm that standard blanket rods contained no seed or power flattening blanket pellets and that power flattening blanket rods contained no seed pellets. Both the ASBLT computer program and the PLG were used to verify that the first two digits of each fuel rod serial number were consistent with the loading requirements for each fuel rod. The fuel rod radiographs, the PLG and the ASBLT computer program combined to form an inspection process which ensured that each LWBR fuel rod was manufactured according to specifications and that the loading requirements for each fuel rod had been satisfied. Fuel rods which passed the loading assurance inspections described in this section and other fabrication inspections were released for use in modules of the LWBR core.

D. Loading Assurance Results for Fuel Rods

Approximately 24,000 fuel rods were processed for LWBR, of which 17,290 were used in the core. The loading assurance controls described above detected no occurrences of misloaded rods, that is, rods loaded with incorrect binary pellet types. Some rods, however, were rejected for failing other loading assurance checks such as external and internal dimensions. Table 5 presents a summary of the numbers of rods rejected because of conditions related to loading assurance. The data in Table 5 were obtained from Reference 2 which presents more detailed rod yield information. In Table 5, external dimension refers to stem length, identification hole location and rod outer diameter. Internal dimension refers to pellet stack lengths.

The individual fuel rod fissile loading precision requirement was ±0.25 relative percent at the 95% confidence level. The composition loading precision requirement was ±0.1 relative percent at the 95% confidence level. All core rods and compositions met these requirements based on data available at the time of module rod selection. After binary pellet fabrication was completed, a reanalysis of the binary blend data was performed as described in Appendix A. The main purpose of the reanalysis was to improve the rod and composition loading and precision estimates by combining the blend data collected for all blends produced of each type. As shown in Appendix A, the reanalysis improved the loading precision values for each of the eight binary compositions in the core. Loading precisions of individual rods, in general, also improved. However, for some rods, the loading precision was poorer after the reanalysis than before. For ten standard blanket core rods the loading precision after the reanalysis exceeded the ±0.25 percent requirement. Loading precisions for these ten rods ranged up to ±0.3 percent.

TABLE 5

NUMBER OF RODS WHICH FAILED LOADING ASSURANCE CHECKS

	Seed	Standard Blanket	Power Flattening Blanket	Reflector
No. of Rods Loaded	10,462	4,943	5,094	3,690
Rods Rejected Because Of:				
External Dimension	68	5	3	20
Internal Dimension	7	12	3	7
Fissile Loading	0	0	0	0
Loading Precision	0	0 *	0	0

* All standard blanket rods met the loading precision requirement during module rod selection; however, 10 core rods exceeded the requirement after blend reanalysis.

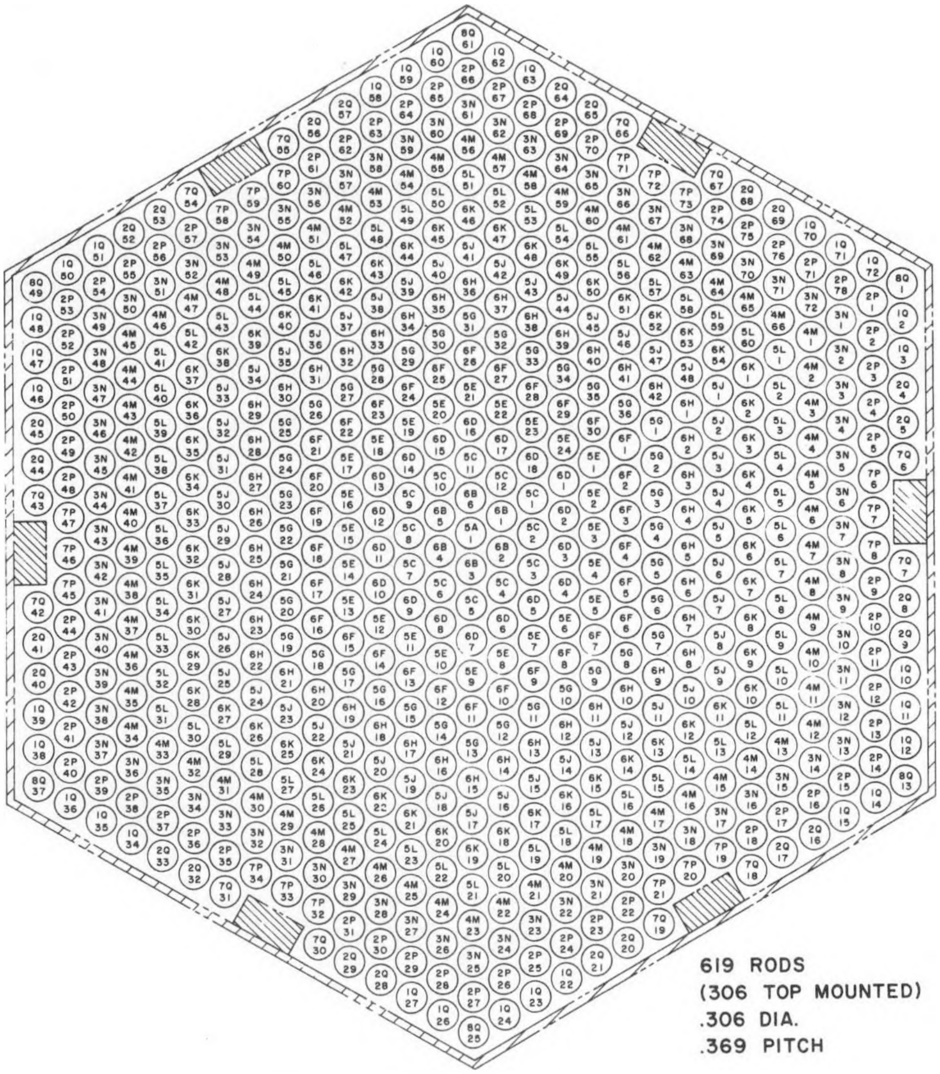
V. MODULES

Fuel rods released for use in the LWBR core were selectively assigned to and installed in modules (Ref. 3). Manufacturing processes and inspection procedures were devised and implemented to ensure that the correct rods were assigned to every cell of each module and to verify that they were, in fact, installed. A module certification process was implemented prior to shipment to confirm that each module contained the correct fuel rods. This section describes the loading assurance steps employed during module assembly.

A. Module Characteristics

Figure 1 (Page 2) shows that the LWBR core was comprised of five module types, designated Type I through Type V, and contained 39 module assemblies. The Type I, II and III modules (total of 12) consisted of a central movable seed module inside a stationary blanket module. The 12 Type I, Type II and Type III seed modules were of identical design. Type I blanket modules contained only standard blanket fuel rods. Type II blanket modules contained standard blanket rods adjacent to the four sides of the seed hexagon nearest to core center and power flattening blanket rods adjacent to the two sides away from the core center. Type III blanket modules contained standard blanket rods in the three sides nearest to core center and power flattening blanket rods in the three sides away from the core center. Fissile fuel, in binary fuel rods described in section IV, was contained only in the Type I, II and III modules at beginning of life. Module Types IV and V (total of 15) were reflector modules and they contained only thoria reflector rods and no fissile fuel at beginning of life.

Figure 12 shows the fuel rod arrangement, by grid cell, for seed modules. A total of 619 rods were located in 15 concentric hexagonal rows, designated A through Q (omitting I and O), where each hexagonal row contained a specific rod type (01 through 08 as characterized in Table 4, Page 31). For example, the grid cell for the 29th position of row M was designated as cell 4M29, where the digit 4 before the letter M specified that a type 04 low zone seed rod (70 inch binary stack length) was required in that cell. The leading zero was omitted from the rod type portion of the grid cell identification in seed modules. As stated in section IV, fuel rods with even rod type designations were attached to the module's upper baseplate and those with odd rod type designations were attached to the module's lower baseplate. In similar fashion, Figures 13 through 15 define the fuel rod arrangements for Type I, II and III blanket modules. Figures 16 and 17 show the fuel rod arrangements for Type IV and Type V reflector modules. Cell identifications for reflector modules omit the first digit (3) of the rod type number. For example, cell 1J9 in a type IV reflector module required a type 31 (bottom mounted) reflector fuel rod whereas cell 2J10 required a type 32 (top mounted) reflector fuel rod. The loading assurance steps implemented during module fabrication provided assurance that only acceptable and validly released rods were assigned and installed in modules according to the grid cell - rod type pairings shown in Figures 12 through 17.



619 RODS
(306 TOP MOUNTED)
.306 DIA.
.369 PITCH

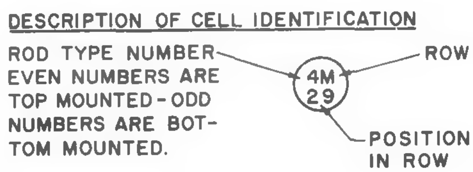


FIGURE 12

CROSS SECTION OF MOVABLE SEED MODULE SHOWING CELL IDENTIFICATIONS AND ROD TYPES

(All Dimensions in Inches)

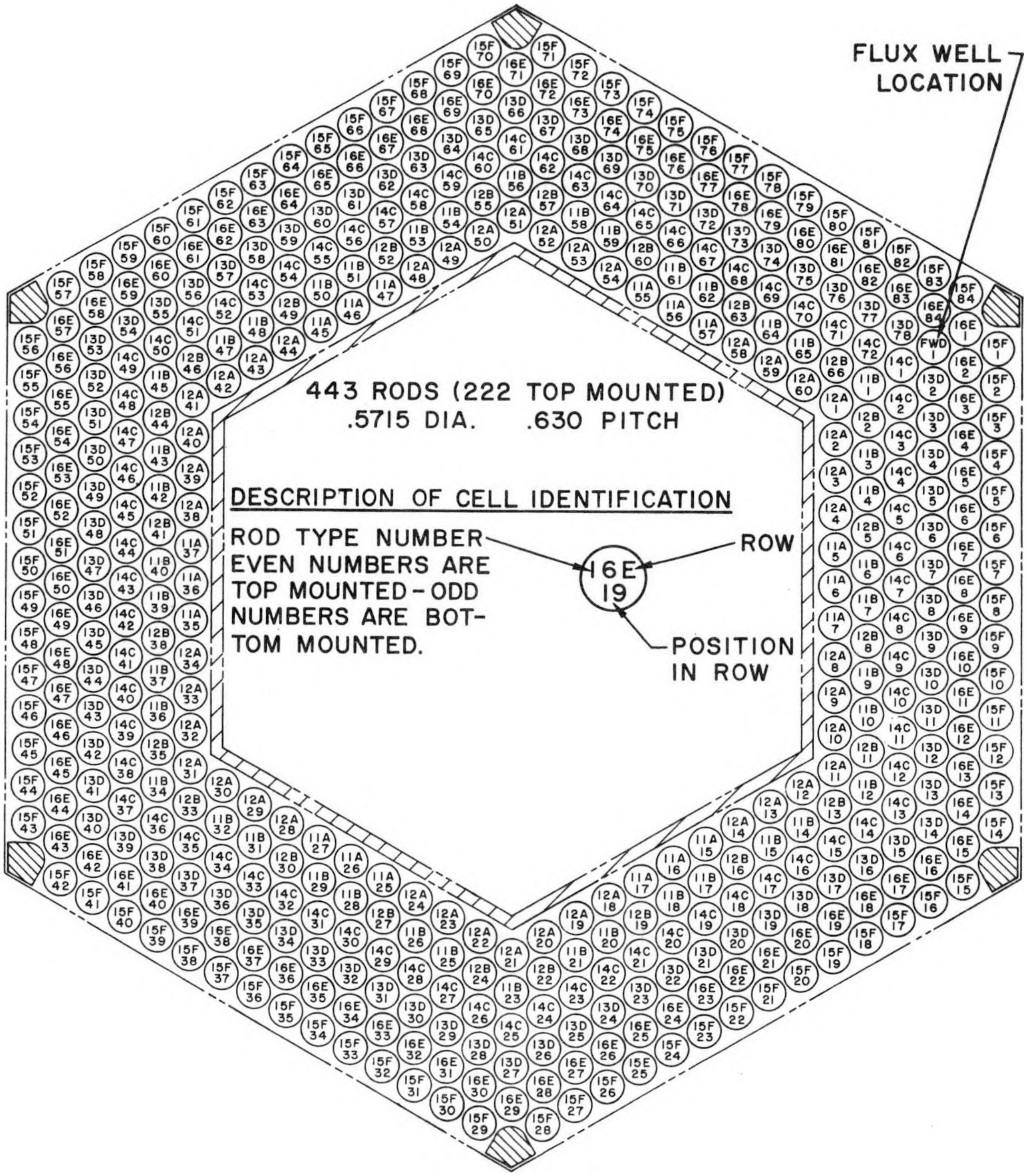


FIGURE 13

CROSS SECTION OF TYPE I BLANKET MODULE SHOWING CELL IDENTIFICATIONS AND ROD TYPES

(All Dimensions in Inches)

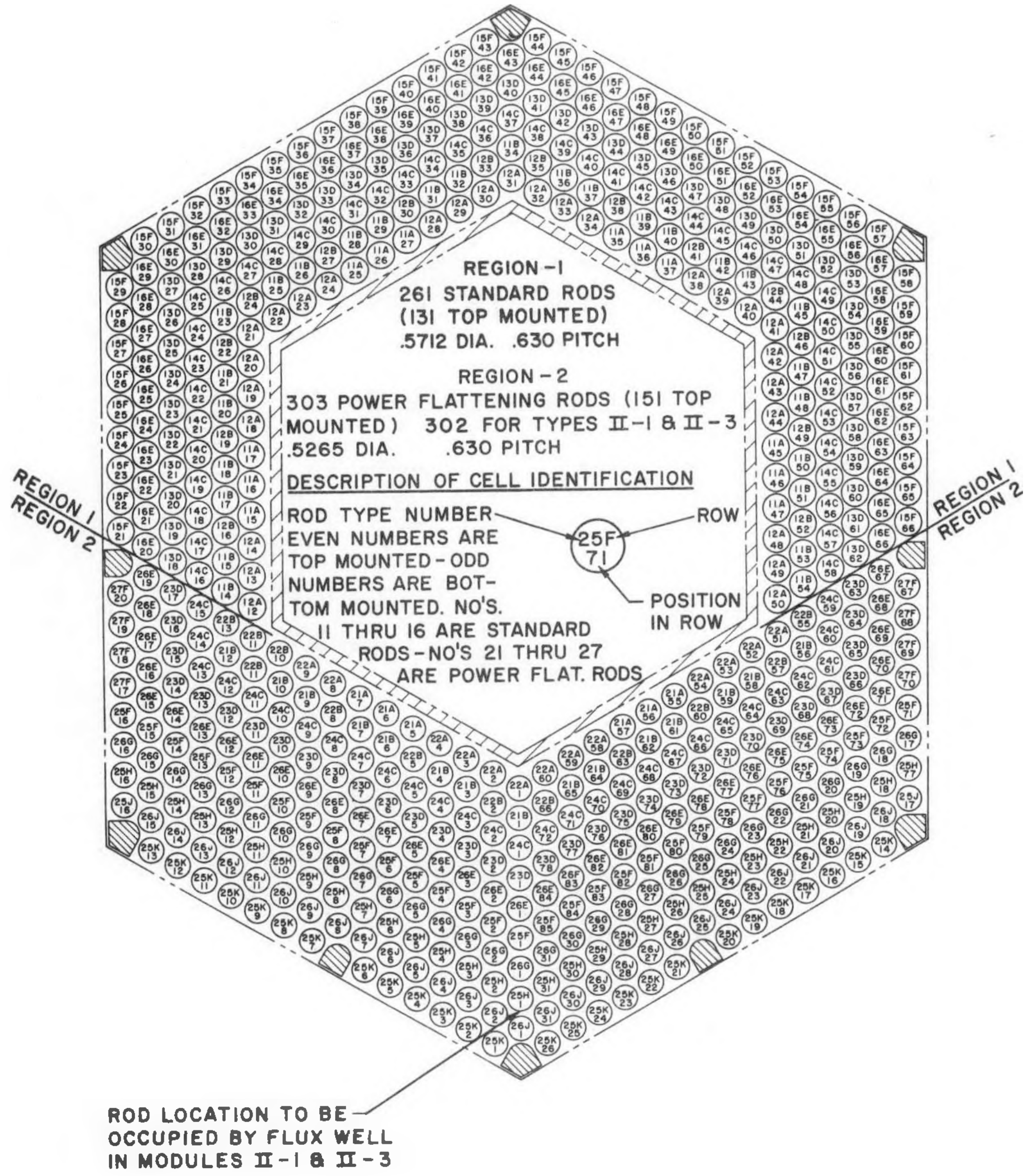


FIGURE 14

CROSS SECTION OF TYPE II BLANKET MODULE SHOWING CELL IDENTIFICATIONS AND ROD TYPES

(All Dimensions in Inches)

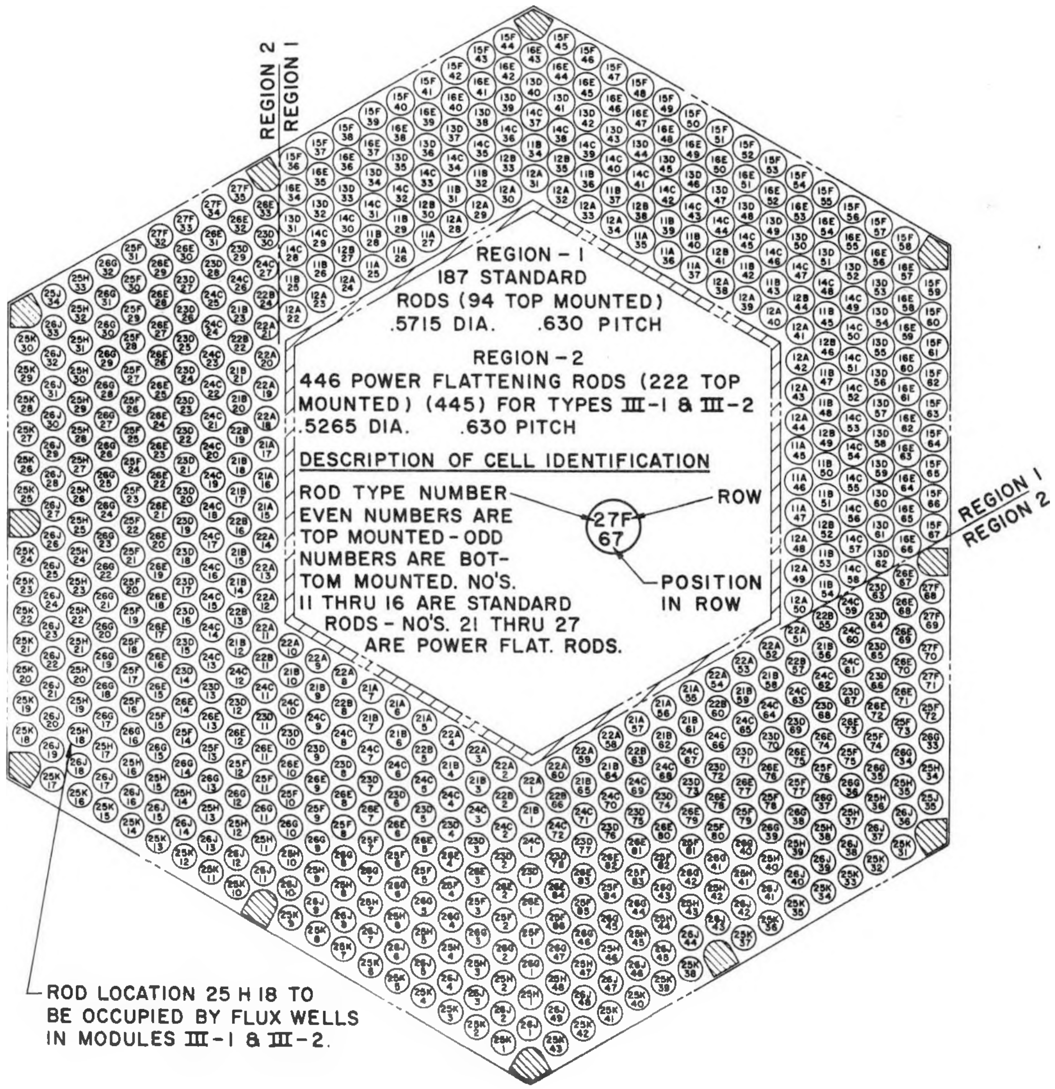
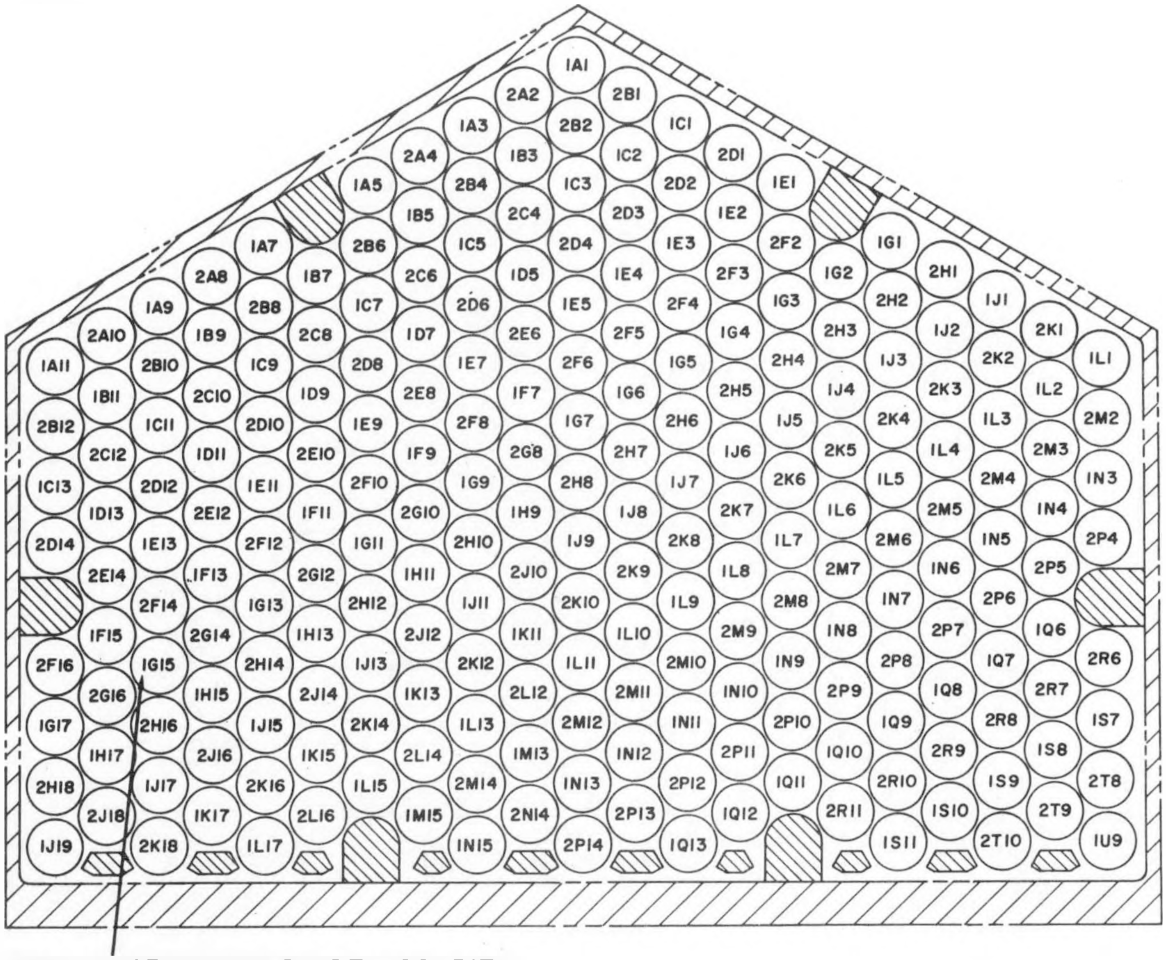


FIGURE 15

CROSS SECTION OF TYPE III BLANKET MODULE

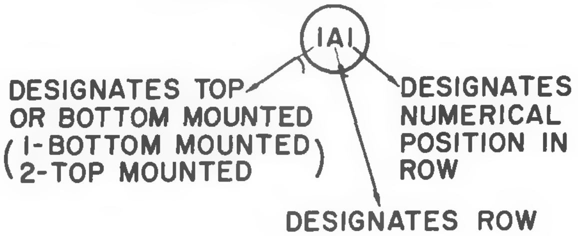
SHOWING CELL IDENTIFICATIONS AND ROD TYPES

(All Dimensions in Inches)



ROD LOCATION 1G15 TO BE OCCUPIED
BY FLUX WELL IN MODULE IV-7

IDENTIFICATION LEGEND
EXAMPLE:

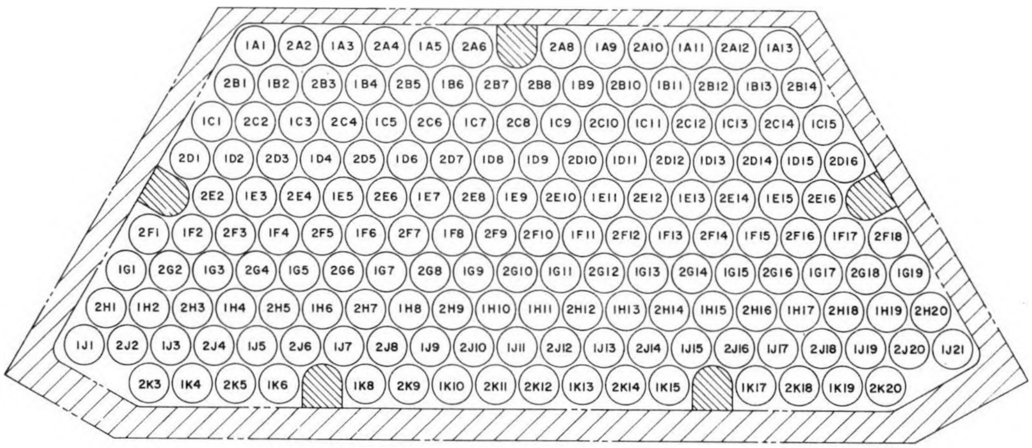


228 RODS (113 TOP MOUNTED)
.832 DIA.
.900 PITCH

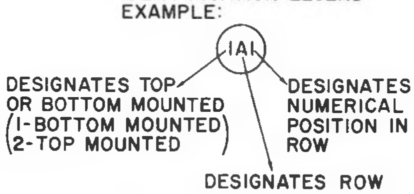
FIGURE 16

CROSS SECTION OF TYPE IV REFLECTOR MODULE
SHOWING CELL IDENTIFICATIONS AND ROD TYPES

(All Dimensions in Inches)



IDENTIFICATION LEGEND
EXAMPLE:



166 RODS (84 TOP MOUNTED)
.832 DIA.
.900 PITCH

FIGURE 17

CROSS SECTION OF TYPE V REFLECTOR MODULE SHOWING CELL IDENTIFICATIONS AND ROD TYPES

(All Dimensions in Inches)

B. Selection and Assignment of Rods for Modules

Prior to installing fuel rods in a module, a preliminary list of candidate rods was prepared for that module identifying the installation sequences (first cell, second cell and so forth), the corresponding grid cell identifications and the serial numbers of the fuel rods tentatively assigned to the cells. All fabrication and inspection records for the fuel rods listed were reviewed by quality control personnel to confirm that the rods and the fuel pellet blends which they contained conformed to specifications and had been released for use in the core. Once approved, the candidate list became the official rod installation list for the module. The rod assignment list was keypunched on computer cards from which a listing was printed for use during rod installation. A deck of rod installation cards was called the "master deck" for rod installation in a module. The master decks were retained and used during fuel rod installation, discussed in Section V.C., and during module certification, discussed in Section V.E., to confirm correct assembly of modules. The master decks for reflector modules were prepared by hand as were those for the first two seed assemblies fabricated. Computer automation, described below, was later developed to streamline and expedite the rod selection and assignment process. This computer automation was implemented for ten of the twelve seed modules and all of the blanket modules and enhanced loading assurance.

Figure 19 shows an example of a fuel rod assignment list which was prepared using the computer. Manufacturing orders were transmitted to the various fabrication areas via Engineering Notices and the rod assignment lists were attachments to the Engineering Notices. The program which prepared the list in Figure 19 also punched the master deck which contained similar information and which was maintained by the Product Inspection Records (PIR) Group. This was done so that a rod would not be inadvertently assigned to more than one module. The PIR file contained up to date information concerning rods installed, rods assigned and rods released and still available and was used during rod selection as discussed below. The example in Figure 19 was prepared by computer and identified the fuel rods to be installed at installation sequences 385 through 411 of module L-GU51-01. This was the type I blanket module assembly assigned to the I-3 module location in Figure 1.

ATT. TO 73307 #81469 MODULE L-GU51-01 PAGE 5 OF 7
3-Sep-76 18:25 46.3

SEQ	CELL	ROD S/N	RELEASE	GRID REQUIREMENTS		ROD REQUIREMENTS
385	15F36	1503200	18799	RB	DIA	95%
386	15F37	1503504	18633	RB	DIA	95%
387	15F38	1504052	18706	RB	DIA	
388	15F39	1502844	18766	RB	DIA	95%
389	15F40	1500386	17208	RB	DIA	95%
390	15F41	1504575	17442	RB	DIA	95%
391	15F44	1511478	19068	RB	DIA	
392	15F45	1507765	19074	RB	DIA	95%
393	15F46	1510700	15609	RB	DIA	95%
394	15F47	1504088	21726	RB	DIA	95% DIA
395	15F48	1508434	19360	RB	DIA	95%
396	15F49	1500846	15560	RB	DIA	
397	15F50	1507637	19393	RB	DIA	95%
398	15F51	1507628	19386	RB	DIA	
399	15F52	1508387	19056	RB	DIA	95%
400	15F53	1508039	17242	RB	DIA	95%
401	15F54	1501569	19072	RB	DIA	
402	15F55	1504786	15584	RB	DIA	
403	15F58	1500112	18706	RB	DIA	
404	15F59	1503228	19060	RB	DIA	95%
405	15F60	1508233	18778	RB	DIA	95%
406	15F61	1504465	19360	RB	DIA	95%
407	15F62	1501046	17218	RB	DIA	95%
408	15F63	1513081	20632	RB	DIA	95%
409	15F64	1505814	19360	RB	DIA	95%
410	15F65	1504007	21146	RB	DIA	DIA
411	15F66	1501248	20522	RB	DIA	

FIGURE 18

EXAMPLE OF COMPUTER GENERATED ROD ASSIGNMENT LIST

The items listed opposite each installation sequence include the grid cell identity, the serial number of the assigned fuel rod, the rod release number (the rod release was the document which gave permission to use the rod in the core), and code letters identifying any special requirements for specific rod-cell pairs. For example, installation sequence 394 (the 394th rod installed in module L-GU51-01) was grid cell 15F47 which was assigned fuel rod 1504088. This rod was released for use via rod release number 21726. Grid cell 15F47 had special grid requirements, codes RB and DIA, and rod 1504088 had special rod requirements, codes DIA and 95%. These codes indicated special handling for grid cell 15F47 and fuel rod 1504088 in that the rod had to satisfy the grid cell requirements and the cell location had to satisfy the rod requirements. The special handling codes used during fuel rod assignment were defined as follows:

RB - fuel rod bow requirements imposed by a support grid. Evaluations of as-built grid dimensions were used to determine such requirements. Fuel rod bow (initial non-straightness) was measured during fabrication (Ref. 10) and evaluated to produce indicators for determining acceptable grid cell - fuel rod pairings to meet both grid requirements and rod requirements.

RF - force requirement imposed by a support grid

BF - combination of RB and RF

DIA - as a grid requirement indicated that only a rod having a specific diameter range could be used in the cell; as a rod requirement indicated that the cell had to be acceptable for a rod of a specific diameter range. The specific diameter range ensured that the as-built grid dimensions were compatible with the assigned rod's diameter to satisfy design requirements for such conditions as spring deflection and rod-to-grid panel clearance.

STR - indicated a rod which was conditionally accepted after the straightness inspection (Ref. 10) and which could be used provided a cell with suitable grid dimensions existed, that is, one which permitted the use of such a rod.

XX% - indicated a rod which could be used only in certain regions of the core based on inspections of the rods for such conditions as pellet chips and fuel pellet quality. The rod was limited to installation in regions where the core power was predicted to be no greater than XX% relative to the peak power regions.

It is not the intent of this report to describe the above grid and rod requirements in detail. The intent here is to state that such requirements existed during module assembly and that computer automation was used to maintain a database of grid and rod requirements and to locate acceptable pairings of grid cells with fuel rods. The computer automation expedited the rod selection process and provided assurance that the rods assigned to a module satisfied the requirements.

C. Fuel Rod Installation

Fuel rods were transferred to the module assembly area and installed in grid cells as specified by the fuel rod assignment lists discussed in the previous section. The master deck for a module, which was prepared along with the printed listing and which contained the installation sequences and corresponding grid cell identifications and assigned fuel rod serial numbers, was entered into the DEC-10 computer and saved in a disk file prior to the start of rod installation. This file was used by a computer program which verified correct rod installation. The loading assurance procedures employed during rod installation involved a combination of administrative steps, computer verifications and manual inspections.

The rod installation procedures required that a manufacturing technician determine which fuel rod (serial number) was to be installed next, by referring to his copy of the rod assignment list. The technician located the rod and removed it from its storage port. A product inspector read the serial number directly from the rod which was selected, recorded the serial number on a data sheet and compared the recorded serial number to the serial number on his copy of the rod assignment list to confirm that the correct rod had been selected by the manufacturing technician. The product inspector used a checking gage to confirm that the stem length and identity hole location were correct for the type of rod being installed (Section IV). The inspector also verified that a valid rod release existed for that rod at the time of installation.

During rod installation, the module was supported in a vertical position with its rod support grids in place. The manufacturing technician installed a rod pull tool in the grid cell identified on the rod assignment list for the current installation sequence. The product inspector verified that the rod pull tool had been placed in the correct grid cell and documented the verification. The selected rod was then placed in position under the module and attached to the rod pull tool. A second manufacturing technician read the serial number directly from the rod and recorded the installation sequence, grid cell identity and fuel rod serial number on a module assembly inspection data sheet. The product inspector confirmed that the correct rod had been positioned for pulling and also confirmed that the first two digits of the rod serial number corresponded to the grid cell identity (first digit of grid cell identity for seed and reflector, first two digits for standard and power flattening blankets). The rod was then pulled up into the module. Later, approximately once each 8 hour shift, the data recorded on the module assembly inspection data sheets (installation sequences, grid cell identities and rod serial numbers as actually installed) were entered into the DEC-10 computer. A computer program was used to compare the installation data to the master file to confirm that all rods had been correctly located in the module. If a loading error was detected by the program, a message was typed instructing the inspector to notify cognizant personnel. Rod installation was then halted until the problem was resolved or corrective action was taken. As each transaction was entered into the computer, a record of the verification was transmitted to the PIR file discussed in Section V.B and was retained in the master file. The master file was examined daily to confirm that no loading errors had occurred during fuel rod installation.

D. Loading Assurance Inspections After Rod Installation

After all fuel rods had been installed in a module, but before the top and bottom baseplates were installed, the top and bottom of the module were examined visually by a quality inspector and a loading assurance representative to confirm that top and bottom mounted rods had been installed in the correct grid cells. The loading assurance representative was not part of the manufacturing organization; he was the nuclear design and analysis manager, who served as Manager of Loading Assurance, or the loading assurance manager's representative from within the nuclear design and analysis group. The threaded end connectors of bottom mounted rods and the spherical end connectors of top mounted rods were visible at the bottom of the module. The threaded end connectors of top mounted rods and the hole ends of bottom mounted rods were visible at the top. For blanket modules, the notches on the end connector stems were visible on power flattening blanket rods; no notches were present on standard blanket rods. The two ends of the module were photographed and the photographs were inspected to again confirm that top and bottom mounted rods were installed correctly and, in the case of blanket modules, that standard and power flattening blanket rods were installed in the correct cell locations.

After the top and bottom baseplates had been installed and all rod nuts had been installed (but not torqued) on the end stems to fasten the rods to the baseplates, a nylon checking fixture was positioned on each baseplate and used to verify that each grid cell contained the correct rod type. The checking fixture was designed to permit .02" of the rod end stem to protrude above the fixture with the correct rod type installed in each cell. If the wrong rod type was installed in any cell, the end connector would either protrude too much above the checking fixture or would not extend to the top of the fixture. Reference 3 contains photographs of seed and blanket modules with the respective checking fixtures in position during the rod type inspection. The rod type inspection was conducted independently by four people, each of whom wore thin gloves to feel the end connectors. One of the four people was the Manager of Loading Assurance or his representative. The module's ends with the checking fixture in place were photographed and the photographs were reviewed by quality inspectors and the Manager of Loading Assurance (or his representative) to verify that they showed that all cells contained the correct rod type. The visual inspections after rod installation and baseplate installation, while they could not verify that the assigned rod (serial number) was installed in each cell, did verify that the correct rod type was installed in each cell of each module. The verification of the correct rod type in each cell location was very important because it ensured that the correct fuel type was present everywhere in the core.

E. Module Certification

Prior to shipping a finished module to the Shippingport Atomic Power Station for installation in the LWBR core, an extensive certification process was conducted. Fabrication records for all of the module's components were reviewed to confirm that the module had been fabricated according to specifications. With respect to loading assurance, the ASBLT computer program (Ref. 7), which had been used to maintain files of as-built pellet blend, fuel rod and module data, was used during certification to produce the lists of rods and binary blends in the module and to compute its fissile and fertile loadings.

Because of the importance of the ASBLT and PIR computer files to the certification process, extensive verification and checking were conducted on the files during certification of a module. ASBLT was used to read both sets of files and to compare the rod installation data to the master deck file, for the module being certified, to verify that all rod serial numbers and cell locations matched. The loading data sheets (see Section IV.B.) for the rods in the module were retrieved and the stack lengths, stack weights and binary blend identities were reentered into the computer and compared by computer to the data filed at the time each rod was loaded. This step verified the data needed for the module loading calculation. After completing the above checks and verifications on the as-built data for a module and for the rods in that module, the final loading of fissile and fertile fuel could be computed with assurance that the result would be accurate.

After all modules had been fabricated, inspected and certified, the ASBLT program was used to compute the fissile loading by composition (binary fuel zone) and the uncertainty in composition fissile loading to demonstrate that the requirement on fissile loading uncertainty had not been exceeded. A compilation and summary of the as-built data pertinent to loading assurance for the LWBR core is included in Appendix A to Reference 11.

F. Module Loading Assurance Experiences

No incorrectly installed rods, that is, top-mounted rod in bottom-mounted cell or incorrect rod type in a cell location, were found during the module inspections described in section V.D. There were, however, several cases where, upon final review, rod releases were rescinded and affected rods were removed from modules and replaced. Although some rework was done on individual modules, e.g., replacement of rods, no modules were rejected.

On one occasion, two incorrect rods were installed in a module but the errors were detected within a few hours of rod installation. Several weeks prior to installation of rods into the two affected cells, engineering reviews had resulted in a change in two assigned rods. A revised Engineering Notice was prepared and routed and the changes were recorded in the loading assurance computer files. Subsequently, the voided Engineering Notice was erroneously issued to module assembly personnel who installed two rejected rods. On the next shift, the inspector entering data into the computer from the installation records received warning messages that incorrect rods had been installed. Several weeks had elapsed between the paperwork change and the installation of the two rods in question. Humans had forgotten the events; however, the loading assurance procedures had been followed and the information was in the computer to detect such an error. Unfortunately, in the first few hours after the incident was detected, no one could confirm that the computer was correct and it was erroneously concluded that the computer files were in error. Two days later, rod release reviews clarified the situation. The computer files were correct but those responsible for maintaining the computer files had retained no record of a change being made. Procedures were modified to require recording any changes made to rod assignment lists both in the files themselves and on paper. Such an incident did not occur again.

VI. SUMMARY AND CONCLUSIONS

During the fabrication of the LWBR core, manufacturing and inspection procedures were developed and implemented to provide assurance that individual modules were manufactured according to the loading specifications. The loading assurance methods employed were a combination of administrative procedures and checks, product inspections and computer verifications. This report describes the loading assurance methods implemented during the four stages of manufacturing - urania and thoria powder processing, fuel pellet fabrication, fuel rod assembly and module assembly.

During urania and thoria powder blending, records were maintained of the powder lots used in each fuel blend. Predetermined quantities of urania and thoria powder, in the relative amounts needed to produce the specified compositions, were weighed and preblended in small batches. Batches were blended together to produce homogeneous blends of urania-thoria powder.

Fuel powder was poured into dies and pressed into pellets. Pellet dimensions and end markings provided visual identification of the fuel composition in the pellets. Pellets were sampled from each blend and analyzed, both destructively and nondestructively, for uranium content. The Delayed Neutron Pellet Assay Gage and related computer automation provided a high level of assurance that the fissile content of binary blends was determined with the required precision. Binary blend data were filed in the computer for use in calculating fuel rod, module and core composition loadings.

Loading assurance steps employed during the assembly of fuel rods ensured that the as-built dimensions and fuel content of each rod were known and met design specifications. X-rays were taken of finished fuel rods to further confirm that they were correctly assembled. Computer files of fuel rod inspection data and grid inspection data were used by a program which assisted in the selection of rods to be used in module assemblies.

Administrative procedures, computer verifications and visual, tactual and dimensional inspections ensured that all module assemblies contained the correct rod types in each grid cell. The final loadings of the core modules, core compositions and the entire core were computed by the ASBLT computer program which maintained a database of LWBR fuel loading data. These computer calculations eliminated thousands of man-hours of tedious and error prone hand calculations and provided a high degree of assurance that the LWBR core loadings were accurately determined. A permanent record of core loading is provided by written records, computer files, radiographs and module photographs. The loading assurance methods employed during LWBR manufacturing provided a high degree of assurance that the core was loaded with fuel according to its design requirements.

Appendix A presents as-built loading information for the LWBR core. The best estimate beginning-of-life fissile loading of LWBR is 501016.1 grams (U^{233} plus U^{235}) with a precision (two standard deviations) of 0.034 percent. The data presented in Appendix A show that the loading precision of each of the eight individual compositions met the required 0.10 percent.

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IX. GLOSSARY

ASBLT	Computer program written for the CDC-6600 computer at Bettis to process as-built fuel loading data, Reference (3)
BASEPLATE	Module structure which holds one end of the fuel rods in the module (two per module, top and bottom)
BATCH	Portion of a blend
BINARY	Urania/thoria mixture (UO_2-ThO_2)
BINARY BLEND FILE	Computer file containing data for binary fuel pellet blends
BINARY STACKING VEE	V-shaped trough onto which binary fuel pellets were stacked end to end when the stacks were measured during fuel rod assembly.
BLEND	Unit of fuel, powder or pellets, binary or thoria, processed as an entity
BLEND IDENTITY	Sequence of digits (XXX-Y-ZZ) designating a fuel blend, Y designated the zone type
BOTTOM-MOUNTED	Fuel rods supported by the baseplate at the bottom of a module
CALIBRATION CURVE	Correlation between weight percent fissile uranium and counts per gram of pellet measured by the delayed neutron gage
CAMPAIGN	Period of time in LWBR manufacturing during which fuel pellets or fuel rods for a given zone were fabricated
CDC-6600	Control Data Corporation computer on which the ASBLT program executes at Bettis
CELL	A location in a module which contains a fuel rod, the support grids define the module cells
CHAMFER	Fuel Pellet Characteristic, see Figure 4
CHECK DIGIT	Seventh digit (c) of a rod serial number (TTNNNNC), depends on first six digits and forms a valid serial number
CHECKING FIXTURE	A nylon template used to check that each cell of a module contained the proper rod type
CHECKING GAGE	A gage used just prior to installing a rod in a module to confirm that the end stem and identity hole location were correct for the rod type

CHEMISTRY PELLETS	Pellets sampled from a blend and used to destructively determine uranium content
COMPOSITION	A binary fuel mixture of urania and thoria of a specific weight percent urania
DEC-10	Digital Equipment Corporation system 10 computer which is part of a timesharing system at Bettis
DELAYED NEUTRON GAGE	Device used to nondestructively assay fuel pellets for uranium content
END DISH	Fuel pellet characteristic, see Figure 4
ENDCLOSURE	Zircaloy plug which sealed pellets in tubing
FINAL-BLENDING	The operation of blending several powder pre-blends or batches into a complete powder blend
FIXED END	The end of a fuel rod which is attached to a module's baseplate
FREE END	The end of a fuel rod which is not attached to a module's baseplate
GAGE CALIBRATION UNCERTAINTY	Uncertainty in weight percent total uranium caused by the calibration curve used with the delayed neutron gage
GRID	Module structure which supports the rods in a module on a triangular pitch
GRID CELL	A location within a module where a fuel rod is located
GRID CELL IDENTIFICATION	The identity of a grid cell of the form TTXNN where TT identifies the rod type required in the cell, X is the row letter within the module and NN is the cell number within the row
GRID LEVEL	Axial location within a module where a fuel rod support grid is located
GRINDING	Pellet fabrication step where sintered pellets were ground to their final shape
IDENTITY HOLE	Hole located at a specific location depending on rod type in each bottom endclosure, see Figures 8, 9 and 10 and Table 4
IN-MOTION RADIOGRAPHY	Inspection process whereby fuel rods were x-rayed to record internal characteristics, Reference (4)
INSTALLATION SEQUENCE	The order of installing rods in a module's grid cells

LOADING	Amount of nuclear fuel in pellets, rods, compositions, or the core
LOADING LINE	Fabrication area where fuel pellets were inserted into tubing to form fuel rods
LOT	Unit of urania or thoria powder, one lot of powder supplied several blends
LWBR	Light Water Breeder Reactor
MASTER DECK	A deck of computer cards containing the rods installation list for a module
MODULE	An assembly of fuel rods held by grids which support the rods
MODULE ASSEMBLY INSPECTION DATA SHEET	Inspection record containing fuel rod serial numbers and grid cell identities (as-installed)
NEUTRON POISON EQUIVALENCE (NPE)	A measure of the neutron losses to expect (in the LWBR neutron flux spectrum) due to impurities in the fuel
NPE	See Neutron Poison Equivalence
PELLET ASSAY GAGE	See Delayed Neutron Gage
PELLET LENGTH GAGE	Device which examined fuel rod x-rays and evaluated pellet lengths Reference (5)
PELLET-TO-PELLET VARIATION	Variation in weight percent total uranium among pellets of a blend
PIR	See Product Inspection Records
PITCH	Spacing between adjacent fuel rod centers or grid cell centers
PLENUM	Void region (except for spring and sleeve) at the top of each fuel rod into which fission gasses can escape
POWER FLATTENING BLANKET	Fixed blanket region surrounding the outer modules which assists to flatten the radial power shape within the center modules
PRE-BLENDING	The operation of blending urania and thoria powders in amounts less than required for a complete blend, blending part of a blend
PRESSING	Pellet fabrication step where powder was poured into dies and pressed into pellets
PRODUCT INSPECTION RECORDS (PIR)	The group at Bettis responsible for maintaining fabrication and inspection records

PULL SEQUENCE	See Installation Sequence
REFLECTOR	Region surrounding the twelve seed/blanket modules comprised of thoria fuel to reduce radial neutron leakage
REGION	Seed, standard blanket, power flattening blanket or reflector in the LWBR core
RELEASE	Official permission or document for a component to proceed to the next fabrication step (e.g., pellet blends were released for loading in rods)
RETAINER SAMPLE	A sample pellet set aside and retained for possible future inspection
ROD ASSIGNMENT	see Rod Selection
ROD INSTALLATION	The operation of inserting a fuel rod into a module grid cell by pulling it up through the cell at each grid level and into correct position
ROD INSTALLATION LIST	A printed list giving the installation sequences, grid cell identities and assigned fuel rod serial numbers for a module
ROD PULLING	See Rod Installation
ROD SELECTION	The process of selecting appropriate rods for use in a module
ROD SERIAL NUMBER	Sequence of seven digits (TTNNNNC) identifying a specific fuel rod
ROD TYPE NUMBER	Sequence of two digits (TT) identifying the characteristics of fuel rods, first two digits of a fuel rod serial number (TTNNNNC)
SAMPLING PLAN	Procedure for selecting samples for inspection from a population to be inspected
SAMPLING SHEET	Pre-printed form specifying how to select fuel pellet samples for inspection
SAPS	Shippingport Atomic Power Station
SEED	The axially moving portion of a module in the LWBR core containing binary fuel of relatively high uranium weight percent compared to blanket regions
SHIM PELLETS	Thoria pellets of varying lengths, shorter than the normal thoria pellets, used to meet the stack length requirements

SINTERING	Pellet fabrication step where pressed pellets were heated in an oven to increase density and to drive off certain impurities
SLEEVE	Metal cylinder around the spring in the plenum region of a fuel rod
SPRING BEARING PELLET	Special thoria pellet with no end dish on the end which is to be in contact with the plenum spring at the top of a fuel rod
STACK	A group of pellets, placed end to end, either prior to loading into tubing or in a fuel rod
STACKING DATA SHEET	Inspection form on which fuel rod stacking information were recorded during rod loading
STANDARD BLANKET	Fixed region of a module in the LWBR core, surrounding the seed region, containing lower uranium weight percent than the seed
STEM	Portion of a fixed endclosure which attaches to the baseplate, it's length was used to distinguish rod types in modules, see Figures 8, 9 and 10 and Table 4
STEM END	See Fixed End
STEP	Thoria portion of a region within a module in the LWBR core
TAPER	Fuel pellet characteristic, see Figure 4
THORIA	Thorium dioxide (ThO_2)
THORIA STACKING VEE	V-shaped trough where thoria pellets were stacked and binary and thoria pellets were weighed during fuel rod assembly
TOP-MOUNTED	Fuel rods supported by the baseplate at the top of a module
TUBING	Zircaloy tube into which fuel pellets were loaded to form fuel rods
TYPE I	Designation for one of the three central modules in the LWBR core comprised of a seed assembly surrounded by a blanket assembly containing only standard blanket rods
TYPE II	Designation for one of the three modules in the LWBR core comprised of a seed assembly surrounded by a blanket assembly containing standard blanket rods on four sides and power flattening blanket rods on two sides

TYPE III	Designation for one of the six modules in the LWBR core comprised of a seed assembly surrounded by a blanket assembly containing standard blanket rods on three sides and power flattening blanket rods on three sides
TYPE IV	Designation for one of the nine 5-sided reflector modules which surround the seed-blanket modules in the LWBR core
TYPE V	Designation for one of the six 4-sided reflector modules which surround the seed-blanket modules in the LWBR core
URANIA	Uranium dioxide (UO_2)
ZONE	Portion of a fuel rod or of the LWBR core containing binary fuel of a given weight percent uranium, a composition

APPENDIX A

AS-BUILT BEGINNING-OF-LIFE FUEL LOADINGS FOR THE LWBR CORE

Appendix A to Reference A-1 presented as-built uranium isotopic loadings and thorium loadings for each LWBR module and the entire core. Those loadings were based on data obtained and analyzed during the fabrication of LWBR. After all blends were completed and analyzed for certification, all data were collected by composition and used to reanalyze the LWBR pellet blend uranium contents. This was done to improve the precision of the core loading determination. As a result, the final as-built loadings of LWBR fuel rods, compositions, modules and the entire core determined after the reanalysis are slightly different than those published in Reference A-1.

As LWBR fuel blends were manufactured, some pellets from each blend were assayed for uranium content both nondestructively, using the Delayed Neutron Pellet Assay Gage (DNG, Ref. A-2), and by wet chemistry. Reference A-3 describes use of the DNG to assay ThO_2-UO_2 pellets for uranium content. During manufacturing, the DNG was calibrated for each composition by chemically analyzing twenty pellets from the first blend of a composition after they had been assayed by the DNG. To obtain a curvature for the calibration curve (DNG counts per gram of pellet versus weight percent U^{total} from chemistry), twenty pellets from each of two other composition calibrations were included. For the early compositions, preproduction fuel and fuel from a mockup were used to obtain the curvature. Loading values obtained during manufacturing were used for certification and were the basis of core performance analyses presented in Reference A-1.

To improve the precision of the as-built loading determinations for Proof-of-Breeding (POB) purposes, all binary pellet blend loading data were reanalyzed upon completion of fuel pellet production. In the reanalysis, DNG calibration curves were obtained by combining chemistry and DNG data for all blends originally assayed. Data for the twenty calibration pellets from the first blend of a composition plus five chemistry pellets from each subsequent blend were combined. For example, since high zone power flattening blanket consisted of 114 blends, 585 chemistry analyses were available for the reanalysis (20 from the calibration blend plus 5 from each of 113 blends) compared to twenty during the original calibration.

Table A-1 shows the number of binary pellet blends which were produced and assayed for each of the eight core compositions, the uranium (U^{total}) weight percents measured during pellet fabrication (certification values), the uranium weight percents from the reanalysis and the percent changes in the uranium weight percent values. Table A-2 presents the total fissile uranium (U^{233} plus U^{235}) loadings (in grams) for each composition along with the composition loading precision values (2 standard deviations). The method for calculating composition loading precision is described in Appendix C to Reference A-4. Both the certification and reanalysis values are contained in Table A-2. These values are based only on the fuel rods which were actually installed in the LWBR core. The reanalysis had little effect on the total fissile loading of individual compositions but significantly improved the loading precision for most compositions. The core loading precision was calculated by summing the composition precision values by region (seed, standard blanket and power flattening blanket) then calculating the root mean square sum over the three regions. The assumptions are that the composition loading precision values within a region are perfectly correlated (because the calibration curves were developed by region) and that there is no correlation between different regions. An additional uncertainty of 0.020 percent has been added to the core loading precision to account for the stated uncertainty in the National Bureau of Standards U_3O_8 standards used in the DNG qualification. The as-built total fissile uranium loading of the LWBR core determined after the reanalysis is 25 grams lower (.005 percent) than the certification loading presented in Reference A-1. The total beginning-of-life fissile loading precision (at the two standard deviation level) improved from 0.045 percent based on certification data to 0.034 percent after the reanalysis.

Table A-3 shows as-built fissile and fertile (Th^{232}) loadings for individual seed and blanket modules after the reanalysis. Reflector module loadings were not affected by the reanalysis because they contained only thorium-bearing rods when built. Even though reflector module thorium loadings have not changed, they are presented in Table A-4 for completeness.

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A-2. S. Milani and C. J. Emert, "The Delayed Neutron Pellet Assay Gage", WAPD-TM-1088, November, 1974.

A-3 C. J. Emert, S. Milani and W. J. Beggs "Nondestructive Assay of UO_2-ThO_2 Fuel Pellets Using the Delayed Neutron Pellet Assay Gage", WAPD-TM-1368, June, 1979.

A-4. B. R. Beaudoin, et al, "ASBLT-A System of DATATRAN Modules Which Process Core Fuel Loading for Use in As-Built Calculations", WAPD-TM-1316, February, 1979.

TABLE A-1

COMPOSITION AVERAGED URANIUM WEIGHT PERCENT

Composition	Number of Blends	Composition Averaged Uranium Weight Percent		Relative Percent Difference
		Certification	Reanalysis	
Low Seed	142	4.40805	4.40892	+ 0.020
High Seed	259	5.28464	5.28421	- 0.008
Low Standard Blanket	34	1.23376	1.23394	+ 0.015
Medium Standard Blanket	89	1.69507	1.69455	- 0.031
High Standard Blanket	72	2.03825	2.03748	- 0.038
Low Power Flattening Blanket	17	1.68088	1.68165	+ 0.046
Medium Power Flattening Blanket	16	2.04331	2.04419	+ 0.043
High Power Flattening Blanket	114	2.79077	2.79092	+ 0.005

TABLE A-2

COMPOSITION FISSILE LOADING AND PRECISION

Certification Loadings

Composition	Fissile Loading Grams	Fissile Loading Precision (2σ) %	Fissile Loading Precision (2σ) Grams
Low Seed	61279.4	0.040	24.5
High Seed	137311.0	0.047	64.5
Low Standard Blanket	15992.2	0.048	7.7
Medium Standard Blanket	42683.0	0.040	17.1
High Standard Blanket	57674.8	0.045	26.0
Low Power Flattening Blanket	10235.9	0.051	5.2
Medium Power Flattening Blanket	13577.6	0.055	7.5
High Power Flattening Blanket	162287.3	0.036	58.4
Core	501041.2		

Region	Pooled Loading Precision Grams (2σ)
Seed	89.0
Standard Blanket	50.7
P. F. Blanket	71.1
Core	124.7
	0.025 %
NBS	+0.020 %
Total	0.045 %

Reanalysis Loadings

Composition	Fissile Loading Grams	Fissile Loading Precision (2σ) %	Fissile Loading Precision (2σ) Grams
Low Seed	61291.6	0.028	17.2
High Seed	137292.7	0.018	24.7
Low Standard Blanket	15994.2	0.038	6.1
Medium Standard Blanket	42664.8	0.025	10.7
High Standard Blanket	57652.7	0.025	14.4
Low Power Flattening Blanket	10240.7	0.045	4.6
Medium Power Flattening Blanket	13583.4	0.051	6.9
High Power Flattening Blanket	162296.0	0.021	34.1
Core	501016.1		

Region	Pooled Loading Precision Grams (2σ)
Seed	41.9
Standard Blanket	31.2
P. F. Blanket	45.6
Core	69.3
	0.014 %
NBS	+0.020 %
Total	0.034 %

Loading Differences (Reanalysis - Certification)

Composition	Grams	Δ%
Low Seed	12.2	0.020
High Seed	-18.3	-0.013
Low Standard Blanket	2.0	0.013
Medium Standard Blanket	-18.2	-0.043
High Standard Blanket	-22.1	-0.038
Low Power Flattening Blanket	4.8	0.047
Medium Power Flattening Blanket	5.8	0.043
High Power Flattening Blanket	8.7	0.005
Core	-25.1	-0.005

NOTE

NBS above refers to the stated uncertainty of U_3O_8 standards used in the qualification of the Delayed Neutron Pellet Assay Gage.

TABLE A-3

SEED AND BLANKET MODULE AS-BUILT THORIUM AND URANIUM LOADINGS

Module		Rods	Thorium KGS	U^{232} Grams	U^{233} Grams	U^{234} Grams	U^{235} Grams	U^{236} Grams	U^{238} Grams	$U^{fissile}$ Grams
Seed	I-1	619	433.6147	0.1201	16505.0631	215.1256	13.0424	2.6810	48.9240	16518.1055
	I-2	619	433.6079	0.1169	16506.8538	218.0206	14.9572	3.2162	48.6640	16521.8110
	I-3	619	433.9167	0.1045	16522.8832	215.8019	12.2114	2.7027	48.8307	16535.0946
	II-1	619	433.8883	0.1099	16529.3869	215.2188	11.7990	2.5739	48.5555	16541.1859
	II-2	619	433.6602	0.1092	16528.3833	216.0380	12.4637	2.7440	47.8502	16540.8470
	II-3	619	434.0956	0.1099	16568.7193	215.2073	11.4925	2.4951	45.8565	16580.2118
	III-1	619	433.5754	0.1173	16505.2743	214.1215	12.2596	2.4767	49.0329	16517.5339
	III-2	619	433.8788	0.1145	16545.4475	214.1671	11.0157	2.3384	47.4479	16556.4632
	III-3	619	434.0789	0.1123	16557.8034	214.1147	10.9097	2.3239	47.4616	16568.7131
	III-4	619	434.0882	0.1105	16552.1354	214.0401	10.8559	2.2851	47.3402	16562.9913
	III-5	619	434.1120	0.1087	16561.9899	213.9365	10.6920	2.2462	46.6906	16572.6819
	III-6	619	434.0431	0.1118	16557.2385	214.9617	11.4061	2.4524	47.3923	16568.6446
Seed Totals		7428	5206.5598	1.3456	198441.1786	2580.7538	143.1052	30.5356	574.0464	198584.2838
Standard Blanket	I-1	443	1299.4597	0.1347	16166.4917	220.0169	15.6999	4.4143	42.1187	16182.1916
	I-2	443	1299.3759	0.1362	16163.8999	218.5444	14.8531	4.0751	42.1966	16178.7530
	I-3	443	1299.3059	0.1365	16161.4597	217.0675	13.9776	3.7319	42.2417	16175.4373
	II-1	261	765.6521	0.0791	9325.3658	125.4961	8.2669	2.2217	24.5671	9333.6327
	II-2	261	765.9130	0.0773	9323.9242	126.8454	9.0555	2.5329	24.3911	9332.9797
	II-3	261	765.7185	0.0782	9329.0786	126.1201	8.5594	2.3522	24.3182	9337.6380
	III-1	187	548.5081	0.0549	6619.9542	90.1087	6.4244	1.8102	17.2081	6626.3786
	III-2	187	548.6961	0.0549	6623.2774	90.3974	6.5914	1.8645	17.2553	6629.8688
	III-3	187	548.6268	0.0546	6618.4147	90.5019	6.6767	1.9099	17.1801	6625.0914
	III-4	187	548.6944	0.0553	6623.6409	90.1971	6.4773	1.8203	17.3210	6630.1182
	III-5	187	548.7241	0.0547	6626.3910	90.2678	6.4980	1.8326	17.2833	6632.8890
	III-6	187	548.4654	0.0536	6619.6555	91.2640	7.0997	2.0693	17.1794	6626.7552
Standard Blanket Totals		3234	9487.1400	0.9700	116201.5536	1576.8273	110.1799	30.6349	303.2606	116311.7335
Power Flattening Blanket	II-1	302	741.3941	0.1183	15590.0455	202.4254	16.2290	4.7295	77.9479	15606.2745
	II-2	303	743.5177	0.1175	15644.8132	198.7211	14.8508	3.9247	90.4751	15659.6640
	II-3	302	741.3666	0.1159	15588.4118	192.9084	13.2568	3.4450	95.4699	15601.6686
	III-1	445	1092.2558	0.1749	23155.5913	291.5709	21.1420	5.6830	132.6487	23176.7333
	III-2	445	1092.0290	0.1710	23131.0250	305.9767	26.2944	7.5757	117.1465	23157.3194
	III-3	446	1094.4784	0.1730	23212.3422	289.3668	20.5340	5.3376	141.3380	23232.8762
	III-4	446	1094.3607	0.1743	23197.7446	310.1999	27.3259	7.9383	112.0175	23225.0705
	III-5	446	1094.5572	0.1744	23201.8592	303.6750	25.1625	7.1628	120.0289	23227.0217
	III-6	446	1094.3042	0.1732	23210.8088	295.4383	22.6161	6.0081	136.1600	23233.4249
Power Flattening Blanket Totals		3581	8788.2637	1.3925	185932.6416	2390.2825	187.4115	51.8047	1023.2325	186120.0531
Core Totals (Excluding Reflector)		14243	23481.9635	3.7081	500575.3738	6547.8636	440.6966	112.9752	1900.5395	501016.0704

TABLE A-4

AS-BUILT REFLECTOR MODULE THORIUM LOADINGS

Module	Rods	Thorium KGS
IV-1	228	1390.1154
IV-2	228	1389.5998
IV-3	228	1389.5612
IV-4	228	1389.5176
IV-5	228	1390.0589
IV-6	228	1389.3334
IV-7	227	1383.8720
IV-8	228	1389.8551
IV-9	228	1389.6448
V-1	166	1012.0343
V-2	166	1012.3931
V-3	166	1011.8760
V-4	166	1012.3381
V-5	166	1012.6418
V-6	166	1011.3698
Reflector Totals	3047	18574.2113

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